GEOLOGICA ULTRAIECTINA

Medelingen van de
Faculteit Aardwetenschappen der
Rijksuniversiteit te Utrecht

No. 92

LATE NEOGENE FORE-ARC BASIN EVOLUTION IN THE CALABRIAN ARC (CENTRAL MEDITERRANEAN); TECTONIC SEQUENCE STRATIGRAPHY AND DYNAMIC GEOHISTORY

With special reference to the geology of Central Calabria

JANPIETER VAN DIJK

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With special reference to the geology of Central Calabria

LAAT NEOGENE VOOR-BOOG BEKKEN EVOLUTIE IN DE CALABRESE BOOG
(CENTRALE MIDDELLANDSE ZEEGEBIED);
TEKTONISCHE SEKWENTIE-STRATIGRAFIE EN DYNAMISCHE GEOHISTORY

Met speciale referentie naar de geologie van centraal Calabrië

(met een samenvatting in het Nederlands)

PROEFSCHRIFT
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AAN DE RIJKSUNIVERSITEIT TE UTRECHT
OP GEZAG VAN DE RECTOR MAGNIFICUS, PROF. DR. J.A. VAN GINKEL
INGEVOLGE HET BESLUIT VAN HET COLLEGE VAN DEKANEN
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JOHANNES PETRUS VAN DIJK

geboren op 31 augustus 1961, te 's-hertogenbosch

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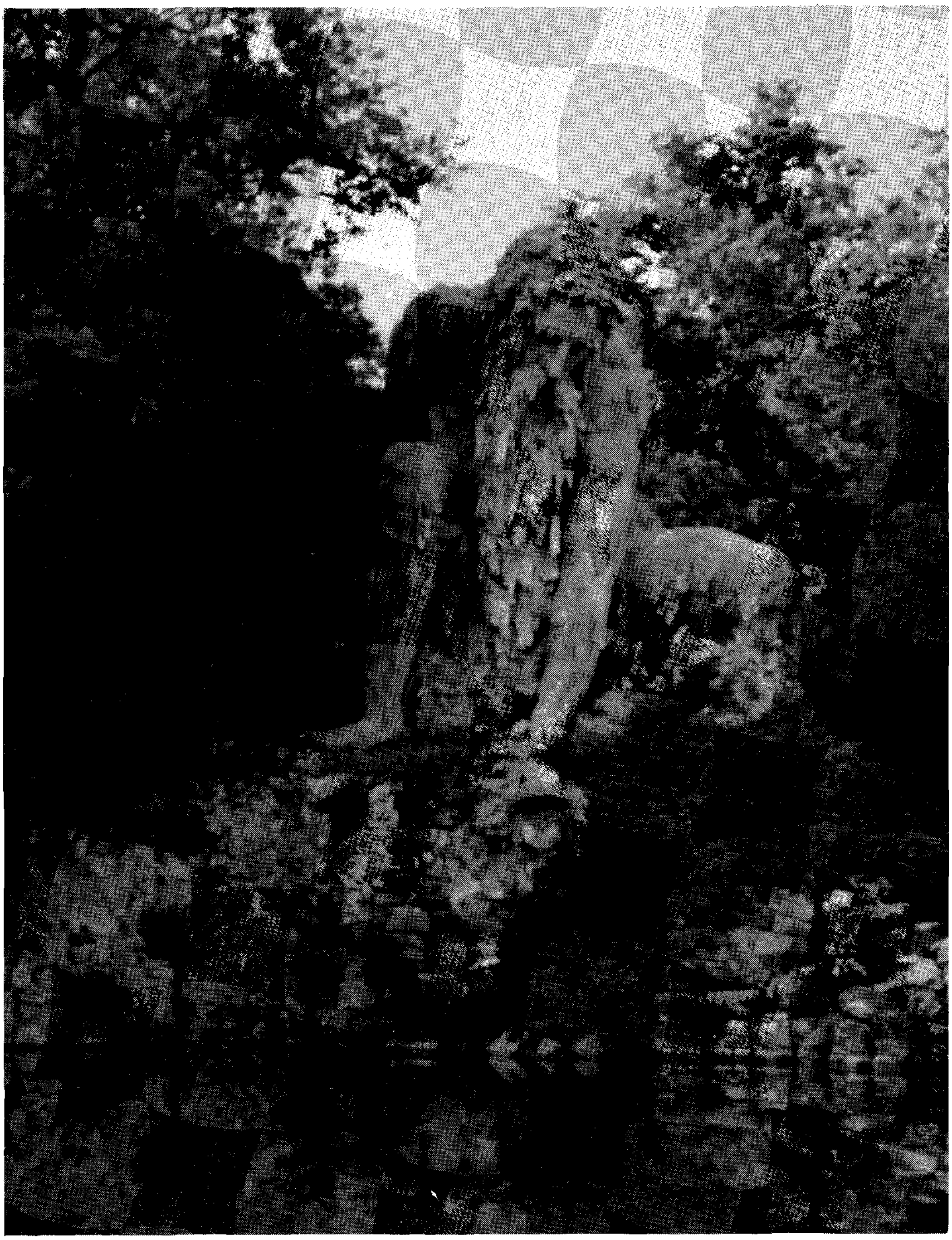

L'Appennino (~1581)
Jean Boulogne detto il Giambologna (Douai, 1529 - Firenze, 1608)
Parco della Villa Demidoff, Pratolino; h m 10

per Dora

Die Bäume

Denn wir sind wie Baumstämme im Schnee.
Scheinbar liegen sie glatt auf, und mit kleinem Anstoss
sollte man sie wegschieben können. Nein, das kann man nicht.
denn sie sind fest mit dem Boden verbunden.
Aber sieh, sogar das ist nur scheinbar.

Franz Kafka
Betrachtung, 1913

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IN THE CALABRIAN ARC (CENTRAL MEDITERRANEAN);
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With special reference to the geology of Central Calabria

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SUMMARY

Depositional sequences and their relation to relative fluctuations in sea level is one of the main issues in present-day Earth Sciences. The generation of depositional sequences is controlled by the interplay of tectonics, sediment supply and eustatic sea level fluctuations (e.g. Haug, 1900; Suess, 1906; Grabau, 1913; Stille, 1924; Kuenen, 1939; Krumbein and Sloss, 1956; Fisher and Brown, 1972; Frazier, 1974; Payton, 1977; Burton et al., 1987; Cloetingh, 1988; Wilgus et al., 1988; Galloway, 1989; Walker, 1989). In order to establish the relative importance of these factors in foreland areas, previous studies have focused on the relation between tectonic activity and facies migrations on one hand and subsidence patterns on the other (Allen, 1986; Kleinspehn and Paola, 1988; Flemmings and Jordan, 1989, 1990; Cross, 1990; Angevine et al., 1990; Macdonald, 1991). Comparing such data with forward models created many controversies; these were probably mainly due to the variability in parameters used in geophysical models, and to the discrepancy in scale between geophysical and geological models.

In the present study, detailed tectonic and stratigraphic data from the Calabrian fore-arc area (southern Italy) are used together in order to show the relations between the various parameters and their role in the genesis of depositional sequences. The Late Neogene of Central Calabria was chosen because of its interesting position along the external side of the Central Mediterranean Calabrian Arc (Finetti, 1982; Moussat, 1983; Boccaletti et al., 1984; Mantovani et al., 1985; Kastens et al., 1988; Patacca and Scandone, 1989). Rapid facies changes, ranging from continental to open marine, complex tectonically-defined unconformities within very small sub-basins, and a wide range of phenomena reflecting syn-depositional tectonic activity were known to occur. Furthermore, there is a thick, heterogeneous pile of Messinian clastic evaporites and continental deposits, reflecting major eustatic sea level fluctuations in this time interval. During field campaigns from 1983 till 1990, a number of local geological problems related to complex stratigraphic relationships and tectonic deformations of the area had to be overcome. Data are presented in the form of detailed stratigraphic colums, composite structural profiles and paleogeographical maps which display encountered reflections of syndepositional tectonics. Additional information from literature includes maps of basement structure, seismic sections and borehole data. An extensive review of previous geological literature is provided.

Tectonic sequence stratigraphy and basin evolution

The basin evolution of central Calabria can be divided in the following stages:
A. Strike-slip Cycle: late Serravallian - Early Pliocene (11.0 - 4.0 Ma)
1. Tension stage (Basin opening): late Serravallian - middle Messinian (11.0 - 5.5 Ma)
2. Transpression stage (Basin fill): middle Messinian - Early Pliocene (5.5 - 4.0 Ma)
3. Compression phase (Basin closure; basin inversion): middle Pliocene (4.0 Ma)
B. Extension Episode: Late Pliocene - Early Pleistocene (4.0 - 1.0 Ma)
C. Uplift and collapse Phase: middle Pleistocene - Recent (1.0 - 0.0 Ma)
The tectonostratigraphic succession can be subdivided into 14 depositional sequences, bounded by unconformities (Van Dijk, 1990, 1991). Phenomena reflecting syndepositional tectonics were studied in great detail. The use of specific criteria has made it possible to establish whether an unconformity can be linked to a tectonic pulse. Using this method, depositional sequences could be characterized in terms of relative sea level fluctuations. The tectonostratigraphic origin of the different sequence boundaries is similar: they reflect a "Composite tectonic event" comprising a pulse of uplift and regression (tilting and erosion along the margin; progradation of clastic wedges

into the basin), followed by rapid subsidence and onlap.
The regional, eustatic Messinian sea level fluctuations appear to be associated with tectonic pulses; the unconformities which confine the Messinian events and wich are defined by the sea level drop and rise, respectively, both reflect a composite tectonic event.

Tectonics and basin kinematics

There are various sets of faults which have been grouped into a number of fault systems and patterns. Activity of the fault systems can be traced in time accurately. Thrust belts facing the basin margins are present along major intra-arc shear zones and along all major basin marginal faults.

Based on this systematic analysis of basin evolution combined with a review of the literature on basement structure and seismic sections, a new structural model for the Calabrian Arc is presented (Van Dijk and Okkes, 1988, 1990, 1991): There are three tectonic patterns: (A) NW-SE trending oblique thrust zones, determining a set of N130 trending segments, (B) SW-NE to E-W trending thrust zones, and (C) Radial and concentric tensional fault systems in the Southern Tyrrhenian back-arc area. The latter faults, combined with dome-shaped uplift centers determine the actual arc. Patterns A and B are regarded as the on-shore representation of the Calabrian accretionary wedge. An important feature here is the widespread occurrence of back-thrust phenomena along the fault zones.
Patterns A and B can be linked to the Middle Miocene - Early Pliocene development of oblique, convergent intra-arc shear zones ("Strike-slip Cycle"), which coincides with the back-arc rifting of the central Tyrrhenian Vavilov Basin. The Late Pliocene - Early Pleistocene Extension Episode coincides with the rifting of the southern Tyrrhenian Marsili Basin (Kastens et al., 1990). Pattern C, active during the post-mid Pleistocene Uplift Phase can be linked to the collapse of the southern Tyrrhenian Basin and the extensional thrust belt collapse (cf. Dewey, 1989) with rapid uplift of the arc.

In the area, the following basin models can be applied:
1. Thin-skinned pull-apart basins. An example is the Late Miocene Crotone Basin. It is situated in between two intra-arc oblique shear zones and displays normal faulted tensional margins, developing into oblique thrusts showing monoclinal flexure.
2. "Harmonica basins". This is a new term introduced. It relates to thrust-wedge basins which originate within a conjugate system of oblique shear zones.
3. "Detached slab basins". This new term indicates basins which lie upon a thin slab facing the subduction trough. An example is the Pliocene Crotone basin, which is detached at a depth of about 2 km. This can be regarded as a restabilization phenomenon of an overthickened accretionary wedge.
4. Strike-slip basins. These are small basins within strike-slip fault zones determined by a wide range of faults and folds, showing a Riedel shear pattern. They are wedge-shaped and show high frequency uplift and subsidence patterns.
5. Intra-arc synclinal basins. The Catanzaro basin is an example of this type of basins. It is situated in between two obliquely convergent shear zones, which are facing each other. Both margins show monoclinal flexure, and major active wrench faults.
These basins are all special types of thrust-wedge basins and, therefore, their structural evolution reflects aspects of the kinematic development of the fold-and-thrust belt (cf. Butler, 1982; Moore and Sample, 1986; Platt, 1986; Cooper and Williams, 1989; McClay, 1992). They commonly show a half-graben shape with sediment transport and deposition concentrated along major NW-SE trending transversal fault zones. A new feature is the recurrent inversion (in late Burdigalian, mid Pliocene and mid Pleistocene times) related to back-thrusting along the thrust-wedge.

The recurrent composite tectonic events can be linked to the dynamics of the accretionary complex, as presented in mathematical models (e.g. Dahlen, 1990). Each composite event represents one pulse in the progressive evolution of the accretionary-wedge system. Accretion and wedge thickening results in out-of-sequence thrusting, reflected by tilting, uplift and regression along the basin margin. These events are followed by restabilization of the taper of the Coulomb wedge by in-sequence thrusting along its toe, reflected by tensional faulting, subsidence and rapid onlap along the basin margin. The evolution of the area thus reflects the pulsating advancement of the thrust-wedge by means of an alternation of long episodes of underthrusting, and interrupting, short pulses of contraction and subsequent extension.
The conjugate set of oblique shear zones indicates an E-W directed axis of effective

compressive stress. This reconstruction is in agreement with the results of published small-scale measurements (Moussat, 1983; Philip, 1987). An interference of three components explains this (local) effective stress axis: A) Strike-slip dynamics: E-W compression due to differential displacement of the two arc segments, B) Thrust-wedge dynamics: alternating NW-SE extension and pulses of NW-SE compression due to wedge extension and contraction resp., and C) Regional stress field: Large-scaled plate kinematics resulted in NE-SW and NW-SE directed components of compressive stress. The NE-SW directed component increased in late Burdigalian, mid Pliocene and mid Pleistocene times.

Dynamic geohistory analysis

A computerized geohistory analysis system was designed. This system contains a relational stratigraphic database (lithology, biostratigraphy, paleobathymetry) and programs for decompaction and loading correction (backstripping) calculations and for graphical presentation (Sleep, 1971; Perrier and Quiblier, 1974; Watts and Steckler, 1976; Van Hinte, 1978; Sclater and Christie, 1980; Bond and Kominz, 1984; Gradstein and Fearon, 1989; Lerche, 1990). Tectonic subsidence curves of the various basin types within the Calabrian Arc and for the foreland and back-arc regions are generated and compared.

Three-dimensional computer-aided reconstructions of the Neogene development of the Central Mediterranean are presented for the Tyrrhenian back-arc Basin and the Crotone fore-arc Basin. The method consists of extrapolating data provided by geohistory analyses within a kinematic frame obtained by terrane analyses, balancing cross-sections and paleomagnetism. Two presentation methods are discussed: Time-Snapshot Plots (synthetic landscapes) show a restoration of paleogeography and subsurface geology, whereas Dynamic Geohistory Plots which are premiered in this study, show the development in time of a transect through the area. These latter plots can be used to illustrate and investigate the effects of phases in basin evolution in both stratigraphic as well as tectonic senses.

The results of the dynamic geohistory analysis have led to the following conclusions: The Central Mediterranean basins show a large variety of subsidence/uplift and accumulation patterns, both spatial and temporal. Synchronous tectonic pulses can be recognized in the entire Central Mediterranean area. Specific episodes of high-frequency tectonic activity are the Early Miocene, Late Miocene (Messinian) - Early Pliocene, and Pleistocene - Recent. Spreading episodes in the Tyrrhenian back-arc area alternate with phases of overthrusting in the surrounding Apennines, in contrast to what was expected. Convex-upward subsidence curves and large subsidence rates in the back-arc area can not be explained by classical rifting models, and appear not to be characteristic for foreland areas only. Rates of vertical oscillations vary considerably between basin marginal and basinal areas, and are one order of magnitude larger that the possible amount of eustatic sea level variations. The "Cloetingh model" of intra-plate stress fluctuations may be applied to explain high amplitudes of basinal and marginal subsidence and uplift patterns in the basins adjacent to the Calabrian Arc.

Central Mediterranean kinematics and geodynamics

The new structural model for the Calabrian Arc has considerable implications for the understanding of the kinematic evolution of the Central Mediterranean. Thus, a new kinematic model is proposed, in which this evolution is considered to be marked by an alternation of the translation of the arc either to the SE (gravitationally) or to the NE (compression). An important element in this model is the activity of a horsetail set of shear zones.

Combining basin evolution analysis, the structural model and some considerations concerning large-scale kinematics with geodynamic mechanisms as discussed in literature, a new geodynamic synthesis is proposed, which recognizes the following components:
The southeastward displacement of the Calabrian Arc is related to the interplay of two processes: (a) Passive subduction due to gravitational sinking of the relict Ionian oceanic slab and related roll-back and retreat of the hinge zone (Van Bemmelen, 1974; Ritsema, 1979; Moussat, 1983; Malinverno and Ryan, 1984; Kastens et al., 1988; Patacca and Scandone, 1989; De Jonge and Wortel, 1990), and (b) asthenosphere inflow, upwelling and convection in the back-arc region (Van Bemmelen, 1969; Locardi, 1986; Channell and Marechal, 1989). These two processes resulted in a gravitational displacement of the Calabrian lithosphere Element, a detached supracrustal slab,

to the southeast (cf. Van Bemmelen, 1974; Horvath et al., 1981; Van Dijk and Okkes, 1988, 1991; Wang et al., 1989).

Superimposed on these relatively endogenic, arc-related mechanisms, is a pulsating regional compression, which resulted from transpressive movements of the African Plate relative to the European Plate, in a NW, N to NE direction.

An important feature dominating the latest stage in evolution of the arc is rupture and detachment of the subducted lithosphere slab (cf. Görler and Giese, 1978; Van Dijk and Okkes, 1988; 1990; Wortel and Spakman, in press.), triggered by regional compressive stress. The collapse of the back-arc area is linked to lithosphere rupture or "blob detachment" and sinking into the mantle, while rapid uplift of the arc and extensional thrust-wedge collapse is related to elastic "snap-back" or "rebound" of non-detached lithosphere remnants.

A geodynamic cycle is recognized comprising the following stages in time:

(1) Translation Stage, (2) Tension Stage, (3) Transpression Stage and (4) Compression Stage. In the post-Eocene evolution of the Central Mediterranean, three cycles can be recognized: Cycle A: Oligocene - late Burdigalian, Cycle B: Langhian - late Early Pliocene and Cycle C: Late Pliocene - Recent. Remarkable is the regularity of the cycles, the shortening of their duration in the course of time, and the fact that they are composed of 3, 2 and 1 episodes of 6(4+2) Million years. The late Miocene-Recent evolution shows a periodicity of 2(1+1) Million years.

A mechanism for tectonic sequence stratigraphy in thrust-belts

According to the "Cloetingh-model" (Cloetingh et al., 1985; Cloetingh, 1988), both third- and second-order fluctuations in relative sea level can be related to fluctuations in intra-plate stress. The following calibrations between second-order and third-order sequences in the Calabrian Arc and the sea level curve of the "Exxon group" (Haq et al., 1987) support this view: (a) The tectonically controlled sequences in the Calabrian basins are comparable in magnitude and in timing with the third-order, unconformity-bound depositional sequences. (b) The geodynamic cycles in the Central Mediterranean correlate with second-order trends in sea level rise and fall. The transition from Translation Stage (compressive stress increase) to Tension Stage (compressive stress release) shows fragmentations, basin origination and major onlaps. The Transpression Stage (large stress oscillations) is characterized by accelleration of subsidence, high accumulation rates and high frequency of tectonic pulses. The switch-back to the Translation Stage, the Compression Stage, is characterized by basin inversion, uplift and the creation of major angular unconformities.

A new mechanism is presented, the so-called "Stress-transmission mechanism", to explain the supposed link between inter-plate stress and third- and second-order depositional sequences within the thrust-belt: Thrust-wedge dynamics will depend on the relative velocities of the roll-back of the subduction hinge zone (V_{rb}), and the displacement of the supracrustal slab (V_{sl}) (cf. Dewey, 1980). Small fluctuations in the regional inter-plate stress field (axis C) mainly controlled the thrust-wedge dynamics (axis B) by blocking the roll-back process. This provoked phases in thrust-wedge growth ($V_{sl}>V_{rb}$), which are reflected by the "Composite tectonic events". Short compressive pulses controlled the genesis of third-order depositional sequences, while larger scale stress fluctuations controlled the geodynamic cycles reflected by second-order depositional sequences.

This "tectono-eustatic" mechanism provides a satisfactory explanation for the spatial and temporal link between regional tectonics, which are possibly related to global, periodic plate reorganizations, and pulses which control the genesis of third- and second-order depositional sequences along active plate margins.

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TEKTONISCHE SEKWENTIE-STRATIGRAFIE EN DYNAMISCHE GEOHISTORY
Met speciale referentie naar de geologie van centraal Calabrië

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SAMENVATTING (SUMMARY IN DUTCH)

De relatie tussen depositionele sekwenties en relatieve zeespiegelfluktuaties is een van de belangrijkste themas in de Aardwetenschappen van vandaag. Het ontstaan van depositionele sekwenties wordt gekontroleerd door een interaktie van tektoniek, sedimentaanvoer en eustatische zeespiegelbewegingen (e.g. Haug, 1900; Suess, 1906; Grabau, 1913; Stille, 1924; Kuenen, 1939; Krumbein and Sloss, 1956; Fisher en Brown, 1972; Frazier, 1974; Payton, 1977; Burton et al., 1987; Cloetingh, 1988; Wilgus et al., 1988; Galloway, 1989; Walker, 1989). Om vast te stellen hoe groot de relatieve rol is die deze faktoren spelen in voorland gebieden, hebben eerdere studies de nadruk gelegd op de relatie tussen faciesmigratie aan de ene kant, en dalingspatronen aan de andere kant (Allen, 1986; Kleinspehn en Paola, 1988; Flemmings en Jordan, 1989, 1990; Cross, 1990; Angevine et al., 1990; Macdonald, 1991). Het vergelijken van dat soort gegevens met wiskundige modellen heeft geleid tot vele kontroverses: Deze lijken voornamelijk het gevolg van de variabiliteit in gebruikte parameters in de geofysische modellen, en van de diskrepantie in schaal tussen geologische en geofysische modellen.

In de huidige studie worden tektonische en stratigrafische gegevens van het Calabrese voorboog gebied (in zuid Italië) in samenhang gebruikt om de relaties tussen de verschillende parameters en hun rol in de genese van depositionele sekwenties te illustreren. Het Laat Neogeen van centraal Calabrië is gekozen om zijn interessante positie langs de buitenzijde van de centraal-Mediterrane Calabrese Boog (Finetti, 1982; Moussat, 1983; Boccaletti et al., 1984; Mantovani et al., 1985; Kastens et al., 1988; Patacca en Scandone, 1989). Het is bekend dat in het gebied snelle facies overgangen, variërend van kontinentaal tot open marien, komplexe, tektonisch bepaalde diskordanties ("unconformities") binnen kleine sub-bekkens, en een brede variatie aan fenomenen die syn-depositionele tektonische aktiviteit reflekteren, aanwezig zijn. Verder is een dikke, heterogene stapel klastische, evaporitische en kontinentale Messinien afzettingen aanwezig, die belangrijke zeespiegelfluktuaties in dit interval reflekteren. Gedurende een aantal veldkampagnes van 1983 tot en met 1990 moesten een aantal lokale geologische moeilijkheden worden overwonnen, gerelateerd aan komplexe stratigrafische relaties en tektonische deformaties in het gebied. Data worden gepresenteerd in de vorm van gedetailleerde stratigrafische kolommen, samengestelde strukturele profielen en paleogeografische kaarten die aangetroffen reflekties van syn-depositionele tektoniek weergeven. Daarnaast werden aanvullende literatuurgegevens zoals kaarten van ondergrondstruktuur, seismische sekties en olie-exploratie boringen gebruikt. Er is een uitgebreid overzicht van voorgaande geologische literatuur bijgevoegd.

Tektonische sekwentiestratigrafie en bekkenevolutie

De bekken evolutie van centraal Calabrië kan worden onderverdeeld in de volgende stadia:
A. Zijschuivings-cyclus ("Strike-slip Cycle"): laat Serravallien - Vroeg Plioceen (11.0 - 4.0 Ma)
1. Rek stadium (Bekken opening): Laat Serravallien - midden Messinien (11.0 - 5.5 Ma)
2. Transpressie stadium (Bekken vulling): midden Messinien - Vroeg Plioceen (5.5 - 4.0 Ma)
3. Kompressie stadium (Bekken sluiting; bekken inversie): midden Plioceen (4.0 Ma)
B. Extensie Episode: Laat Plioceen - Vroeg Pleistoceen (4.0 - 1.0 Ma)
C. Opheffings en "collapse" ("ineenstortings") Fase: midden Pleistoceen - Recent (1.0 - 0.0 Ma)
De tektono-stratigrafische opeenvolging kan worden onderverdeeld in 14 depositionele sekwenties, begrensd door diskordanties (Van Dijk, 1990, 1991). Verschijnselen die syn-depositionele tektoniek weerspiegelen, werden in groot detail bestudeerd. Het gebruik van specifieke kriteria heeft het mogelijk gemaakt vast te stellen of een disko-

rdantie kan worden gekoppeld aan een tektonische puls; Door deze methode te gebruiken, konden depositionele sekwenties worden gekarakteriseerd in termen van relatieve zeespiegel-bewegingen. De tektono-stratigrafische oorsprong van verschillende sekwentiebegrenzingen is vergelijkbaar: Deze begrenzingen weerspiegelen een "Samengestelde tektonische gebeurtenis" ("Composite tectonic event") die een puls van opheffing en regressie (terugschrijden van de strandlijn) bevat (kanteling en erosie aan de bekkenrand; de uitbouw van klastische sedimentwiggen in het bekken), direkt gevolgd door snelle daling en transgressie en "onlap" (vooruitschrijden van de strandlijn).

De regionale, eustatische zeespiegelfluktuatie van het Messinien blijkt te zijn geassocieerd met tektonische pulsen: de omsluitende diskordanties die respektievelijk worden gedefiniëerd door zeespiegeldaling en stijging, reflekteren beide een "Samengestelde tektonische gebeurtenis".

Tektoniek en bekken-kinematiek

Verschillende aanwezige breuksets kunnen worden verdeeld in een aantal breuksystemen en patronen. De aktiviteit van deze systemen kan nauwkeurig in de tijd worden gevolgd. Opschuivingsgordels die naar de bekkenrand toe zijn geschoven zijn aanwezig langs belangrijke intra-boog zijschuivingszones en langs alle belangrijke bekkenrandbreuken.

Gebaseerd op een kombinatie van systematische analyse van bekkenevolutie met een beschouwing van de literatuur aangaande ondergrondstruktuur en seismische sekties, wordt een nieuw struktureel model voor de Calabrese boog gepresenteerd (Van Dijk en Okkes, 1988, 1990, 1991): Er zijn drie tektonische patronen aanwezig: (A) NW-SE strekkende oblique opschuivingszones die een set van N130 strekkende segmenten bepalen, (B) SW-NE tot E-W strekkende opschuivingszones, en (C) Radiale en koncentrische rekbreuk systemen in het zuidelijke Tyrrheense achter-boog gebied. De patronen A en B worden beschouwd als het aan wal gedeelte van de Calabrese opschuivingswig ("thrust-wedge"). Een belangrijk verschijnsel is het uitgebreide voorkomen van "back-thrust" ("terug-opschuif") fenomenen langs de breukzones.

De patronen A en B kunnen worden gekoppeld aan de Midden Miocene - Vroeg Pliocene ontwikkeling van oblique, konvergente intra-boog zijschuivingszones ("Zijschuivings-Cyclus"), die kan worden gerelateerd aan het opengaan in het achter-boog gebied van het centrale Tyrrheense Vavilov Bekken. De Laat Pliocene - Vroeg Pleistocene Rek Episode valt samen met het opengaan van het zuidelijke Tyrrheense Marsili Bekken (Kastens et al., 1990). Patroon C, dat aktief is gedurende de post-midden Pleistocene Opheffings Fase, kan worden gekoppeld aan het ineenstorten van het zuidelijke Tyrrheense Bekken en aan de extensieve "collapse" van de opschuivingswig (cf. Dewey, 1989), die gepaard gaat met een snelle opheffing van de boog.

De volgende bekkenmodellen kunnen in het gebied worden toegepast:

1. "Thin-skinned pull-apart basins" ("Dunhuidige uiteentrek-bekkens"). Het Laat Miocene Crotone Bekken is een voorbeeld. Het is gesitueerd tussen twee intra-boog oblique zijschuivingszones en wordt aan de randen begrensd door normale rekbreuken, die zich ontwikkelen tot scheve opschuivingen met monoklinale flexuren.
2. "Harmonica basins" ("Harmonika-bekkens"). Dit is een nieuwe term. Hij duidt op opschuivingswigbekkens die ontstaan binnen een konjugaat systeem van scheve zijschuivingszones.
3. "Detached slab basins" ("Losse schol-bekkens"). Deze nieuwe term duidt op bekkens die op een dunne schol liggen, die in de richting van de subduktietrog schuift. Een voorbeeld is het Pliocene Crotone Bekken, waarvan de basis los is geraakt op een diepte van ongeveer 2 km. Dit kan worden beschouwd als een restabilisatiefenomeen van een te dikke opschuivingswig.
4. "Strike-slip basins" ("Zijschuivings-bekkens"). Dit zijn nauwe bekkens binnen zijschuivingszones, die worden bepaald door een uitgebreide groep van breuken en plooien die een "Riedel-patroon" weerspiegelen. De bekkentjes zijn wigvormig en laten hoog-frekwente opheffings- en dalingspatronen zien.
5. "Intra-arc synclinal basins" ("Binnen-boog synklinale bekkens"). Het Catanzaro Bekken is een voorbeeld van dit bekkentype. Het is gelegen tussen twee scheef-konvergerende zijschuivingszones, die naar elkaar toe bewegen. Langs beide randen ontstaan monoklinale flexuren en belangrijke, aktieve zijschuivingszones.

Al deze bekkens zijn speciale vormen van "thrust-belt basins" ("opschuivingsgordel-bekkens"), en hun strukturele evolutie is daarom een weerspiegeling van de kinematische ontwikkeling van de "fold-and-thrust belt" ("plooi-en-opschuivings-gordel") (cf. Butler, 1982; Moore en Sample, 1986; Platt, 1986; Cooper en Williams, 1989; McClay, 1992). Ze bezitten gewoonlijk een half-slenk vorm, met sedimenttransport en -afzetting gekoncentreerd langs grote, NW-SE strekkende transversale breukzones. Een extra, nu voor de Calabrese Boog onderkend verschijnsel is de steeds wederkerende inversie (in het laat Burdigalien, het midden Plioceen en het midden Pleistoceen), gerelateerd aan "back-thrusting" langs de opschuivingswig.

De veel voorkomende "Samengestelde tektonische gebeurtenis" kan worden gekoppeld aan het dynamische gedrag van de opschuivingswig, zoals wiskundige modellen hebben laten zien (bv. Dahlen, 1990). Elke samengestelde gebeurtenis weerspiegelt een schok in de progressieve evolutie van het opschuivingssysteem. De groei en het dikker worden van de wig resulteert in "uit-sekwentie" ("out-of-sequence") opschuiving, hetgeen te zien is door kanteling, opheffing en regressie langs de bekkenrand. Deze gebeurtenissen worden gevolgd door restabilisatie van de hoek van de "Coulomb wig" door "in-sekwentie" ("in-sequence") opschuiving langs zijn voet, hetgeen kan worden afgeleid uit rekverbreuking, daling en snelle transgressie langs de bekkenrand. De evolutie van het gebied weerspiegelt op die wijze het pulserende vooruitgaan van de opschuivingswig door een afwisseling van lange episodes van onderschuiving, en interrumperende korte pulsen van kontraktie en daaropvolgende extensie.

De konjugate set van scheve zijschuivingszones indiceert een E-W gerichte as van effektieve kompressieve spanning. Deze rekonstruktie is in overeenstemming met gepubliceerde resultaten van studies van kleinschalige meetgegevens (Moussat, 1983; Philip, 1987). Een interferentie van drie komponenten verklaart deze (lokale) effektieve spannings-as: As A) Zijschuivingsdynamiek: E-W druk door de laterale verplaatsing van twee boogsegmenten, As B) Opschuivingswig dynamiek: afwisselende NW-SE rek en schokken van NW-SE gerichte druk door kontraktie-extensie van de wig, en As C) Regionaal spanningsveld: Grootschalige plaatbewegingen resulteren in NE-SW en NW-SE gerichte komponenten van druk. De NE-SW gerichte komponent neemt in grootte toe in het laat Burdigalien, het midden Plioceen en in het midden Pleistoceen.

Dynamische "geohistory" analyse

Er werd een komputer-gestuurd systeem voor "geohistory" analyse ontwikkeld. Dit systeem bevat een relationele databank (lithologie, biostratigrafie, paleobathymetrie) en programma's voor de berekeningen van dekompaktie- en sedimentbelastings-korrekties ("backstripping") en voor de grafische presentatie (Sleep, 1971; Perrier en Quiblier, 1974; Watts en Steckler, 1976; Van Hinte, 1978; Sclater en Christie, 1980; Bond en Kominz, 1984; Gradstein en Fearon, 1989; Lerche, 1990). Tektonische dalingsgrafieken van verschillende bekkentypes binnen de Calabrese Boog en van de voorland en achter-boog gebieden worden gepresenteerd en onderling vergeleken.

Een driedimensionale, komputer-gestuurde rekonstruktie van de Neogene ontwikkeling van het Centraal Mediterrane gebied wordt gepresenteerd, met name van het Tyrrheense achter-boog Bekken en van het Crotone voor-boog Bekken. De methode bestaat uit het extrapoleren van gegevens die door "geohistory" analyse worden verkregen, binnen een raamwerk van bewegingen dat wordt afgeleid uit "terrane" analyse, het balanceren van strukturele profielen en paleomagnetisme. Twee presentatiemethoden worden bediskussiëerd: De "Tijd-Momentopname Plot" (synthetische landschappen) laat een rekonstruktie zien van de paleogeografie en de geologie van de ondergrond. De "Dynamische Geohistory-Plot" - die in deze studie voor het eerst wordt gepresenteerd-, daaraantegen, laat de ontwikkeling zien langs een bepaalde doorsnede door het gebied. Deze laatste plot kan worden gebruikt om de effekten van bepaalde fasen in de bekkenontwikkeling te illustreren, in zowel een stratigrafische als ook een tektonische zin.

De resultaten van de dynamische "geohistory" analyse hebben tot de volgende konklusies geleid: De bekkens in het centrale Middellandse zeegebied laten een brede variatie aan dalings- en opheffingspatronen zien, in zowel ruimte als tijd. Synchrone tektonische pulsen kunnen worden herkend in het gehele centrale Mediterrane gebied. Specifieke episoden met hoog-frekwente tektonische aktiviteit zijn het Vroeg Mioceen, Laat Mioceen (Messinien) - Vroeg Plioceen, en het midden Pleistoceen - Recent. Episoden van oceanische spreiding in het Tyrrheense achterboog gebied alterneren met fasen van overschuiving in de omringende Apennijnen, in tegenstelling tot wat werd verwacht. Convexe dalings-kurves en grote dalingssnelheden in het achter-boog gebied kunnen niet worden verklaard met de huidinge modellen voor "rifting", en blijken niet karakteristiek te zijn voor voor-boog gebieden. De snelheden van vertikale oscillaties verschillen aanmerkelijk tussen bekkenranden en meer interne arealen, en zijn een orde van grote hoger die veroorzaakt door eustatische zeespiegelfluktuaties. Het "Cloetingh model" van intra-plaat spannings-fluktuaties kan worden toegepast om de hoge amplitudes van marginale en bekken-interne dalingen en opheffingen in de bekkens direkt langs de Calabrese Boog, te verklaren.

Centraal Mediterrane kinematiek en dynamiek

Het nieuwe strukturele model voor de Calabrese Boog heeft belangrijke implikaties voor het begrip van de kinematische evolutie van het centrale Mediterrane gebied. Er wordt dan ook een nieuw kinematisch model voorgesteld, waarin de evolutie is gekarakteriseerd door een afwisseling van de translatie van de boog naar het SE (gravitationeel) en naar het NE (kompressief). Een belangrijk element in dit model is de aktiviteit van een "paardestaart-groep" van zijschuivingszones.

Door het kombineren van de analyse van bekkenevolutie, het strukturele model en een aantal implikaties met betrekking tot grootschalige kinematiek, met geodynamische mechanismen zoals die in de literatuur zijn bediskussiëerd, wordt er een nieuwe geodynamische synthese voorgesteld die de volgende onderdelen bevat:
De verplaatsing naar het zuidoosten van de Calabrese Boog is gerelateerd aan de interaktie van twee processen: (a) Passieve onderschuiving door het zinken van de rudimentaire Ionische oceanische korst ("slab") in de mantel onder invloed van de zwaartekracht, en het daaraan gekoppelde "roll-back" ("terugrollen") ofwel terugschrijden van het buigpunt (cf. Van Bemmelen, 1974; Ritsema, 1979; Moussat, 1983; Malinverno en Ryan, 1984; Kastens et al., 1988; Patacca en Scandone, 1989; De Jonge en Wortel, 1990), en (b) De instroom van asthenosfeer, opwelling en konvektie in het achter-boog gebied (Van Bemmelen, 1969; Locardi, 1986; Channell en Marechal, 1989). Deze twee processen resulteerden in de gravitationele verplaatsing van het Calabrese lithosfeer Element, een losse schol, naar het zuidoosten (Van Bemmelen, 1974; Horvath et al., 1981; Van Dijk en Okkes, 1988, 1991; Wang et al., 1989).
Gesuperponeerd op deze, relatief endogene, aan de boog gerelateerde mechanismen, is een pulserend regionaal kompressief spanningsveld, dat onstaat door de transpressieve beweging van de Afrikaanse Plaat ten opzichte van de Europese Plaat, in een NW, N of NE richting.
Een belangrijk aspekt dat de laatste periode van ontwikkeling van de boog domineert, is het breken en loslaten van de onderschoven ("gesubduceerde") aardkorst (cf. Görler en Giese, 1978; Van Dijk en Okkes, 1988, 1990; Wortel en Spakman, in druk), een proces dat wordt geïnitiëerd door regionale kompressie. Het ineenstorten van het achter-boog gebied is gekoppeld aan het breken van de aardkorst en het wegzinken in de mantel van de "lithosfeer-blob", terwijl de snelle opheffing van de boog en de extensieve "collapse" van de opschuivings-wig samenhangt met de elastische terugslag ("snap-back" ofwel "rebound") van niet-losgelaten korstrestanten.

Een geodynamische cyclus kan worden herkend die de volgende stadia bevat (Fig.1):
(1) Translatie Stadium, (2) Rek Stadium, (3) Transpressie Stadium, en (4) Kompressie Stadium. In de post-Eocene ontwikkeling van het centraal Mediterrane gebied kunnen drie cycli worden onderscheiden: Cyclus A: Oligoceen - Vroeg Mioceen (laat Burdigalien), Cyclus B: Midden Mioceen (Langhien) - laat Vroeg Plioceen, en Cyclus C: Laat Plioceen - Recent. Opvallend zijn de regelmaat van de cycli, de verkorting van hun duur in de loop van de tijd, en het feit dat ze zijn samengesteld uit 3, 2 en 1 episodes van 6(4+2) miljoen jaar. De Laat Miocene tot Recente ontwikkeling laat een periodiciteit zien van 2(1+1) miljoen jaar.

Een nieuw paradigma voor tektonische sekwentie-stratigrafie in opschuivings-gordels

Volgens het "Cloetingh model" (Cloetingh et al., 1988), kunnen zowel derde orde als ook tweede orde zeespiegelbewegingen worden gekoppeld aan fluktuaties in het intra-plaat spanningsveld. De volgende koppelingen tussen tweede orde en derde orde sekwenties in de Calabrese Boog, en de zeespiegelkurve van de "Exxon groep" (Haq et al., 1987), ondersteunen deze zienswijze: (a) De door tektoniek gekontroleerde sekwenties in de Calabrese Boog zijn vergelijkbaar met de derde orde, door diskordanties begrensde afzettingssekwenties, in zowel grootte als ook plaatsing in de tijd. (b) De geodynamische cycli in het centrale Middellandse Zee gebied korreleren met de tweede orde schommelingen in zeespiegeldaling en -stijging. De overgang van het Translatie Stadium (toename van kompressieve spanning) naar het Rek Stadium (relaxatie van kompressieve spanning) laat opbreking, het ontstaan van bekkens en grootschalige transgressies zien. Het Transpressie Stadium (grote spanningsfluktuaties) is gekarakteriseerd door een acceleratie van daling, hoge afzettingssnelheden en hoog-frekwente tektonische schokken. De ommezwaai terug naar het Translatie Stadium, het Kompressie Stadium, is gekarakteriseerd door bekkeninversie, opheffing en het onstaan van belangrijke hoekdiskordanties.

Een nieuw mechanisme, het zogeheten "Spannings-transmissie mechanisme" ("Stress-transmission mechanism"), wordt gepresenteerd, om de voorgestelde koppeling tussen inter-plaat spanningsveld en derde en tweede orde depositionele sekwenties binnen de overschuivingsgordel te verklaren: De dynamika van de opschuivingswig hangt af van het verschil tussen de relatieve snelheden van de "roll-back" (V_{rb}), en de verplaatsing van de bovenkorstschol (V_{sl}) (cf. Dewey, 1980). Kleine fluktuaties van het intra-plaat spanningsveld (as C) kontroleerden de dynamiek van de opschuivingswig (as B) door het blokkeren van het "roll-back" proces. Dit veroorzaakte de schokken in groei van de opschuivingswig ($V_{sl}>V_{rb}$), die door de "Samengestelde tektonische gebeurtenis" worden gereflekteerd. Korte kompressieve pulsen kontroleerden de derde orde sekwenties, terwijl spanningsveld fluktuaties op een grotere tijdschaal de geodynamische cycli kontroleerden die zijn weerspiegeld in tweede orde depositionele sekwenties.

Dit "tektono-eustatische" mechanisme levert een goede verklaring voor de koppeling tussen regionale tektoniek, die waarschijnlijk gerelateerd is aan globale, periodieke plaattektonische reorganizaties, en pulsen die de genese van derde en tweede orde depositionele sekwenties langs aktieve plaatgrenzen bepalen.

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GENERAL INTRODUCTION

Ce livre doit être jugé dans son ensemble,
et alors il en ressort une terrible moralité...
"le seul éloge" que je sollicite pour ce livre est
qu'on reconnaisse qu'il n'est pas un pur album
et qu'il a un commencement et un fin.

Charles Baudelaire
Letter to Poulet-Malassis, 9th Dec. 1856
regarding "Les fleurs du mal" (1855)

GENERAL INTRODUCTION

SCOPE OF THE INVESTIGATION

One of the major topics of the present-day Earth Sciences regards the global fluctuations in sea level, related unconformity-bound depositional sequences, and their origin in terms of eustatic sea level fluctuations, tectonic activity and sediment supply. Regional or global relative sea level fluctuations have been recognized for a long time (Haug, 1900, 1907; Suess, 1906; Grabau, 1913; Schuchert, 1916; Stille, 1920, 1924; Kuenen, 1939; Umgrove, 1946; Krumbein and Sloss, 1956; Wheeler, 1958; Sloss, 1963; Fisher and Brown, 1972; Frazier, 1974), through the recognition of regional transgressions and regressions, and sedimentary episodes and cycles bounded by unconformities.

The topic has become a major issue since the publication on seismic stratigraphy, the AAPG Memoir 26 edited by Payton (1977). A subdivision was proposed in first order (50+ Ma), second-order (3-50 Ma), third-order (0.5-3 Ma) and higher-order (4th-6th) depositional sequences. Initially, discussion focussed on the main factor controlling the origin of the sequences, whereby two opposing opinions were advocated: global, glacio-eustatic sea level fluctuations as the major factor on one hand, and local and regional tectonics as major control on the other (Pitman, 1978; Bally, 1981; Watts, 1982; Matthews, 1984; Cloetingh et al., 1985; Haq et al., 1987; Burton et al., 1987; Gradstein et al., 1988; Embry, 1989; Cloetingh, 1991; Vail et al., 1992).

In the course of time, this dispute has slowly fallen into the background, and, with the publication of the Volume 42 of the SEPM edited by Wilgus et al. (1988), the creation of depositional sequences can now (again) be viewed in the light of the continuous, dynamic interplay between sea level, tectonics and sediment supply (Galloway, 1989; Walker, 1989; Miall, 1990). This interplay provides the so-called "accomodation space", which is the space between the sediment-water interface and the sea level, available to be filled with sediment. There is a general consenses that first-order sequences are controlled by "tectono-eustatic" mechanisms related to plate tectonic processes such as sea-floor spreading (cf. Pitman, 1978). Higher-order sequences (4th-6th order) seem to be linked to Milankovitch cycles and variations within depositional systems. However, there is still no agreement on which factor is the major control in the genesis of third- and second-order depositional sequences. The "Exxon Group" (see e.g. Vail et al., 1992; p. 643) still advocates glacio-eustatics as the major control, admitting, however, that "*Tectonism has the greatest influence on increasing and decreasing accommodation space.*" (Vail et al., 1992; p. 636). Also, the authors state that tectonics work on 1st, 2nd and 3rd order scale (basin evolution, subsidence-uplift alternations and folding/faulting, repectively; Vail et al., op. cit.; p. 619). Much work has in the meanwhile been done on the possible role of tectonic mechanisms. It has convincingly been shown by e.g. Cloetingh et al. (1985) that regional stress fluctuations may generate second- and third-order depositional sequences. Furthermore, whether or not a global pattern of synchronous unconformities and stratigraphic signals exists, remains a major topic (Hays, 1983; Hallam, 1984; Miall, 1984, Ch. 4; Parkinson and Summerhayes, 1985; Burton et al., 1987; Sengör, 1990, pp. 21, 165; Cathles and Hallam, 1991).

In general, attention has focussed on the analysis of depositional sequences of passive margins. Apart from the present study (Chs. 2 and 3; Van Dijk, 1990, 1991), few studies are available which describe successions along active plate margins in terms of unconformity-bound depositional sequences (Gelati and Gnaccolini, 1988; various papers in Macdonald, 1991; Postma and Fortuin, in press.). In foreland basin settings, tectonic control on the creation of unconformities is much more evident than in extensional settings. Furthermore, these areas are more sensitive to register syndepositional tectonics. Reflections such as growth faults, angular unconformities, slides and slumps, hiatusses, rapid facies changes etc. are frequently observed. Therefore, the characterization of unconformities in terms of the interaction of relative sea level fluctuations and tectonic activity can well be attempted in these settings.

Two approaches can be and have been followed to tackle the problem (Flemmings and Jordan, 1989). The first approach is the study of facies patterns and their links with the tectonic activity of the region. The second approach consists of a burial history analysis, in order to reveal characteristic subsidence patterns which might be indicative of certain types of tectonic activity. Both datasets can be compared with the outcome of computerized basin simulations.

(1) Facies patterns in foreland basins have been studied for a long time (Allen, 1986; Kleinspehn and Paola, 1988; Cross, 1990; Angevine et al., 1990; MacDonald, 1992). From the outcome of these studies, a major controversy arose (Flemmings and Jordan, 1989): Authors disagree with respect to the interpretation of facies migrations (progradation versus retrogradation) in terms of thrusting events versus quiescence episodes. Two interpretations exist, which have both been approximated in various forward modelling exercises:

a. Thrusting events or episodes are characterized by influx of coarse material into the basin, reflected by outgrowth of clastic deltaic or submarine fan wedges. This is due to sudden erosion of the thrust-wedge. Episodes in between thrusting events, "quiescence episodes" are characterized by onlap due to subsidence of the thrust-wedge as an isostatic response to loading ("slow response").

b. Quiescence episodes are characterized by the outgrowth of clastic wedges into the basin. This is related to isostatic restabilization and accompanying erosion. Thrusting events are characterized by basin deepening and narrowing, due to thrust-wedge loading ("instantaneous response").

(2) The geohistory analysis method (Sleep, 1971; Perrier and Quiblier, 1974; Watts and Steckler, 1976; Horowitz, 1976; Van Hinte, 1978; Ungerer et al., 1984; Guidish et al., 1985) is an important tool for the study of relative sea level fluctuations. It provides a quantified image of the relation between tectonic subsidence, accumulation and paleobathymetry. Input data for this (computerized) method comprise age (biostratigraphic data), paleobathymetry (micropaleontological and/or lithofacies data) and lithological data.

Not all authors agree that geohistory analysis can give straightforward answers to questions regarding the absolute contribution of sea level fluctuations in the creation of unconformity-bound depositional sequences. Standard subsidence curves for a number of specific settings can be modelled, using various physical parameters. A widespread idea is that deviations of real subsidence curves from these standards can be interpreted in terms of eustatic sea level fluctuations. This approach was followed by e.g. Hardebol et al. (1981) for passive margins, and was advocated by Vail et al. (1990, 1992) for active margins.

Passive margins show decelerating, concave upward curves (so-called "Sclater curves"; e.g. Sclater and Christie, 1980). The basic shape of subsidence curves in foreland basins is convex upward (Beaumont, 1980; Allen et al., 1986; Angevine et al., 1990). This idea implies that acceleration in the subsidence curve can be interpreted as reflecting an increase in thrust propagation velocity (or, in other words, a thrusting "event"), or the approach of an advancing thrust front to the studied site. Recently, forward models of Flemmings and Jordan (1990) have shown that this relation is much more complex. For example, for foreland areas a reverse relation, where acceleration follows the thrusting event, can also occur.

Another widespread idea is that if global records of subsidence curves can be compiled, the hypothesis that global sea level variations exist can be tested. Guidish et al. (1984) and Burton et al. (1987) gave convincing evidence that this idea, at the moment, is far from realistic due to the large amount of uncertainties in the various datasets.

Basin evolution in foreland areas and its reflections in unconformity-bound depositional sequences have been modelled by some authors on scales varying from regional subduction zones to local thrust-wedge basins (Kleinspehn and Paola, 1988; Flemmings and Jordan, 1989, 1990; Cross, 1990; Angevine et al., 1990; Slingerland and Furlong, 1990; Franseen et al., 1991; Sinclair et al., 1991; Peper, 1992). For a number of reasons, the results of these models are highly heterogeneous and are difficult to compare with geological datasets (e.g. Allen, 1986):

Large scale tectonophysical forward modelling

exercises use elastic as well as Maxwell visco-elastic properties of lithosphere, as well as depth-dependent rheologies. Thermo-elastic models have also been presented. All these approaches give different results.
Mathematical thrust-wedge models generally model overall geometries of thrust-belts (generally based on critical taper angle of the thrust wedge; Chapple, 1978; Davis et al., 1983), and have provided little information on their internal structure thus far. This implies that the models do not give any information on the basins within the thrust-belt.
The timescales involved differ between the various models. Loading responses of the lithosphere depend on the applied lithosphere rheology model. Slow, time dependent, as well as instantaneous responses are used in the models. Both pulses of thrusting as well as thrusting episodes have been modeled.
Erosion and transport equations used in the models greatly differ in realism. This results in widely varying facies migration models. The most sophisticated models use a diffusional law whereby the transport rate of material is proportional to the topographic gradient (Begin et al., 1981; Flemmings and Jordan, 1989; Leeder, 1991).

One of the purposes of the present study is to perform an integrated geological investigation. This can provide a detailed dataset which can be compared to the outcome of these synthetic stratigraphic models. This comparison can give important clues and place constraints to input parameters of the modelled processes. Examples are lithosphere properties and behaviour, timing of thrusting and loading response, thrust-wedge dynamics, and erosion-deposition balance.
We investigated stratigraphic sequences of Neogene basins in the Calabrian Arc (Central Mediterranean). The Calabrian Arc was chosen for a number of reasons:
The area has been used many times as a classical example of an orogenic arc. The various kinematic models as have been presented for the arc indicate that there is a wide variety of basin kinematic mechanisms that have been active. The Neogene stratigraphy shows rapid facies changes from continental to open marine. Complex, tectonically defined unconformities are known to be present. These reflect sedimentation in many small fault-bounded subbasins. A wide range of phenomena indicating syndepositional tectonics are known to occur. Furthermore, deposits belonging to the Messinian Stage are present in the external Calabrian basins. These deposits mirror sea level fluctuations which are known to have been of regional importance. One specific area, the Central Calabria area, was chosen for a number of reasons. These will be outlined after an extensive review of the available literature.
Some specific problems had to be overcome during the investigation:
(a) Local tectonic and stratigraphic datasets had to be compiled through detailed mapping, in order to construct reliable sequence stratigraphic models.
(b) Specific basin kinematic models had to be developed for the basins in the Calabrian Arc, which were in agreement with the Neogene kinematic evolution of the arc.
(c) Computer systems for stratigraphic data management and geohistory analysis had to be developed, using existing software elements.
(d) All geological data had to be translated into a relational, geographically-linked, quantitative format, using calibrated codations (mapping information, biostratigraphy, facies, paleobathymetry).
(e) For a comparison with forward models, a review of published geodynamic syntheses regarding the Central Mediterranean was needed to define the regional setting of the study area. A preliminary comparison with published forward models is performed.

REMARKS ON THE GEOGRAPHICAL AND GEOLOGICAL SETTING

The Central Mediterranean area comprises the southern Italian regions Puglia, Campania, Basilicata, Calabria and Sicily. The marine areas form part of the Tyrrhenian, the Adriatic, the Ionian, and the Pelagian Seas. The present study focusses on the central part of the region of Calabria, which comprises parts of the provinces of Cosenza, Catanzaro, and of the future province of Crotone. The relief of southern Italy ranges from sea level to over 2000, or even 3000 m (Mount Etna volcano) and is locally highly accidented. Submarine depths amount up to 3000 m (Pannekoek, 1969). The area is characterized by a Mediterranean climate showing warm and dry summers and relatively mild and humid winters, resulting in mostly clear sunny weather throughout the year, with mean anual temperatures of about 18 degrees. The area shows great variations in geological structure, lithology, physiography and vegetation, and a rather instable landscape with numerous landslides. Extensive reviews and discussions regarding various geographical aspects of Calabria can be found in

Panizza (1968), Heilmann (1972), Guérémy (1972), Van Asch (1980), Sorriso-Valvo (1984) and Ibbeken and Schleyer (1991).

The Neogene evolution of the Central Mediterranean system is dominated by the migration of the Calabrian Arc to the southeast, overriding the African Plate and its promontories (Argand, 1916; Boccaletti and Guazzone, 1972). The main tectonic elements of the Calabrian Arc are the Southern Apennines fold-and-thrust belt, the "Calabria-Peloritani", or simply Calabrian block and the Sicilian Maghrebides fold-and-thrust belt. The foreland area is formed by the Apulia Platform, which is part of the Adriatic Plate, and the Ragusa or Iblean Platform, which is an extension of the African Plate. These platforms are separated by the Ionian Basin. The Tyrrhenian oceanized basin is regarded as the back-arc basin.
Paleogeographic reconstructions have been presented by the "Villefranche Group" (Moussat, 1983; Rehault et al., 1984, 1986), Hill and Hayward (1985), the "Dercourt Group" (Dercourt et al., 1985, 1986; De Wever and Dercourt, 1985; Ricou et al., 1985), the "RCMNS Geodynamics group" (RCMNS, 1986), Finetti and Del Ben (1986), Gealy (1988), the "ODP Leg 107 Group" (Kastens et al., 1988), Patacca and Scandone (1989), Dewey et al. (1989), Alvarez (1991) and Mantovani et al. (1992). These paleogeographic configurations are based on palinspastic reconstructions and balanced cross sections, stratigraphical and paleogeographic considerations, and plate tectonic reconstructions.
The geological history of the Central Mediterranean can be subdivided as follows: Triassic-Middle Cretaceous "Mesogea Stage" of Neotethyan rifting, with rifting of small oceanic basins such as the Liguride, the Pennine, and the Ionian Basins, between the African Plate and the European Plate, with small "microplates" in between such as the Iberian, the Alboran and Adriatic Microplates. The Middle Cretaceous - Late Eocene stage, with subduction of the Ligurian oceanic basin below the European Plate along an active margin between Gibraltar and the Alps. The Oligocene - Early Miocene stage, characterized by drifting of small "microplate" fragments such as the Corsican-Sardinia, the Kabylian and the Calabrian blocks to the southeast, overriding remnants of the Neotethys. During this stage, the Western Mediterranean basin opened through oceanic spreading. The Middle Miocene - Recent stage is characterized by the drifting of the Calabrian block still further to the southeast, coupled with the opening of the Tyrrhenian basin.

The central position of Calabria has led to an extremely complex association of thrust systems, gravitational tectonics and transpressive as well as transtensive wrench faulting, all on various scales and with various interacting directions. Basin types comprising piggy-back basins, tensional grabens, pull-apart basins and small strike-slip basins have been created. The interaction of all these processes has resulted in a wide variety of terrains within the arc. Basically, Calabria consists of a crystalline basement complex of Hercynian and Alpine nappes, a complex zone of Mesozoic-Paleogene elements and Oligocene - Lower Miocene "flysch" sequences, and Neogene sedimentary sequences, present in small basins and in part as chaotic thrust zones along major fault zones within the arc.

REVIEW OF PREVIOUS LITERATURE

As the Calabrian Arc has been studied for over more than a century it seems appropriate to give a review of the earlier literature which concerns the area under investigation. All mentioned literature has been used and critically reviewed in the present study. For details concerning the older literature, i.e. from before 1973, the reader is refered to the review of Ogniben (1973), which has been used in cases when the original manuscripts were not available. Ippolito (1959) presented a complete bibliography of the literature on the Calabrian geology as published up till that moment.
Interesting books, reviews and important "milestones" concerning the geology of the Calabrian Arc are the following: Cortese (1895), Limanowski (1913), Quitzow (1935), Caire et al. (1960), Caire (1961), Grandjacquet et al. (1961); Ogniben (1969, 1973), Caire (1970, 1975, 1978), Burton (1971), Amodio-Morelli et al. (1976), Dubois (1976), Grandjacquet and Mascle (1978) and Moussat (1983). It must be noted, that the earlier works were mainly dedicated to the evolution of the basement rocks of the area. The Neogene sedimentary successions were merely regarded as "post-orogenic" infill of "neo-tectonic" tensional features. In the course of time, however, a shift can be observed in the temporal significance of these terms, from post-Eocene to post-Early Miocene to post-Miocene.

Basement structure of Central Calabria

The basement of Central Calabria, outcropping in the Sila and Serre massifs, has been subject to many previous investigations. A large number of tectonic units and subunits can be distinghuished, which consist of Paleozoic granites, diorites, tonalites, medium and high-grade metamorphic rocks, such as gneisses and schists and some marls and dikes. The crystalline terrains are covered by Mesozoic limestones and Paleogene sandstones and conglomerates. The tectonic units can be divided into four groups: (1) The lowermost units, consisting of low-grade metamorphic limestones and outcropping in a number of tectonic windows, (2) Intermediate units, consisting of a number of thin slices of schists and gneisses, comprising cataclastic rocks and slices of ophiolites, and (3) The uppermost units, comprising a number of "klippe" structures, composed of kinzigitic paragneisses, and granitic rocks with a Mesozoic-Paleogene cover. These uppermost units are classified as "Incerta sedis" (A.-Morelli et al., 1976) because their mutual relationships are unclear. The map of Figure 2 in Chapter 6 (Van Dijk and Okkes, 1990) gives a general overview of the relation between the different Calabrian basement units.

Data concerning the crystalline nappes as outcropping along the southern edge of the Sila Massif ("Pre-Sila Area") can be found in Bonfiglio (1964b), Brosse (1968), Ogniben (1973), Dubois (1970, 1976), De Roever (1972), Amodio-Morelli et al. (1976), Bonardi et al. (1976), Dietrich (1976, 1988), Zanettin Lorenzoni (1980, 1982), Gurrieri et al. (1982) and Lorenzoni et al. (1983). These authors all use different subdivisions and geometrical schemes for the complex structure of the area. Table 1 of Chapter 1 of the present study, and Figure 1 of Appendix 1b, show overviews of the relations between the various tectonic units as described in literature.
The southern margin of the Catanzaro depression is formed by the northern slope of the Serre basement massif. The structure of this area has been described by Caire (1970), Amodio-Morelli et al. (1976), Borsi et al. (1976), Lorenzoni et al. (1976), Paglionico and Piccaretta (1976) and Moresi et al. (1978). The area consists of a complex association of metamorphic nappes with a northeastern vergence (from bottom to top: Pomo phyllites Unit, Castagna gneiss & schist Unit, Polia-Copanella dioritico-kinzigitico Unit with the Cardinale tonalites Subunit), overthrust by the Stilo Unit (Paleozoic basement with Mesozoic-Paleogene cover) with a northwestern vergence.

The various descriptive models and explanatory hypotheses will not be discussed in detail. Van Dijk and Okkes (1990) gave a subdivision into 6 groups of models, which are not mutually exclusive, as they each treaten a specific area and/or timeslice of the Calabrian evolution:
(1) Calabro-Apennino Suture Model (Caire, Grandjacquet, Glangeaud, 1950-1962; Dubois, 1970-1976; De Roever c.s., 1976):

From Middle Cretaceous to Eocene N-S directed shortening occured, followed by superficial "écaillages post-nappes" and Post - Oligocene radial external shortening, resulting in "African vergence". The E-W trending Sangineto depression which separates northern Calabria from "Lucania" or Basilicata, is envisaged as a (oceanic) suture zone, while northern Calabria is regarded as a stack of N-verging nappes.
(2) Concentric Orogene Model (Argand and Lugeon, 1906-1922; Caire, 1970-1978; Ogniben, 1972-1975):

From Middle Cretaceous - Recent, progressive migration of thrust nappes from internal to external took place, along the southern margin of the European Plate. External directed gravitational sliding resulted in internal verging units.
(3) Double Chain Model (Haccard et al., 1972-1978; Wezel, 1975; Amodio-Morelli et al., 1976):

From Cretaceous - Eocene, a "Europe-verging" chain was constructed, which in the Oligo - Miocene overthrusted an "Apennine-verging" chain. During the Neogene, progressive external directed thrusting occured.
(4) Two Blocks Models: These models divide the Calabrian Basement in two separate blocks, Southern and Northern Calabria, on basis of Alpine and Burdigalian tectonics.

(4a) Bonardi, Cello, Lorenzoni, Scandone c.s. (1979-1982):

These authors favour a separated evolution up to the Middle Miocene. The Northern Calabrian Block has been affected by late Burdigalian tectonics, the Southern Block shows no traces of this tectonic phase. Remarkable are the indications for Middle Miocene and Late Miocene basement thrusting (Zanettin-Lorenzoni c.s.).

(4b) Boccaletti, Tortorici c.s. (1982-1986):

These authors subdivide the arc in two parts: Northern Block (part of the Apennine Chain) and Southern Block (part of Maghrebide Chain), separated by the SW-NE trending dextral Capo Vaticano - Soverato Fault Zone. Only the Northern Block has been affected by Alpine metamorphism.
(5) Transtensional Mesozoic Continental Margin Models (Bouillin c.s., Teale & Santonioni c.s.,

1984-1987):

According to these models, the northern Calabrian Mesozoic - Paleogene terranes represent a NW-SE trending transcurrent continental margin of a Mesozoic - Paleogene oceanic basin (part of the Tethys). Subsequently, Paleogene eastern directed thrusting took place, as evidenced in the Southern Apennines (Knott, 1987).

(6) Neogene Basement thrusting Model (this paper)

In agreement with some aspects of the models 4a and 4b, back-thrusting of the basement has been observed along the traces of the major NW-SE and NE-SW thrust zones (see fig. 4). Examples are: The base of the Cariatides along the Rossano-San Nicola Zone, the "Amantea Wedge" (see also Ortolani et al., 1979), "Tiriolo Wedge" and "Catanzaro Wedge" along the Catanzaro Zone, the "Antonimina-Agnana Wedges" along the Torbido Zone, and basement wedges near Samo in the Bianco Zone. The northern Calabrian back-thrusting has occurred in the late Early Pliocene as can be established in the Catanzaro Zone and can be deduced from fault/thrust systems in the Bianco Zone and Petilia-Rizzuto Zone. Southern Calabrian back-thrusting has occurred in the late Burdigalian, possibly extending into the late Serravallian and also possibly occurred in the mid-Pliocene. In both areas, back-thrusting possibly occurred even in the Pleistocene.

Late Neogene - Quaternary deposits of Central Calabria

The Late Neogene deposits of the Central Calabrian realm comprise five groups of successions which can be characterized as follows: (1) The lowermost units are continental, lacustrine and lagoonal coarse clastics, sandstones and turbidite successions. Locally, they are severely tectonized along major faults zones. The rocks have been assigned by various authors to the Oligocene, Lower Miocene, and/or Serravallian. (2) The Upper Miocene sequences consist of basal shallow marine conglomerates and sandstones ("Helvetian" of the older literature), followed by open marine clays with local intercalations of sandstone units. (3) The uppermost Miocene, Messinian successions comprise marine limestones and evaporites (gypsum, salt) and alluvial clastics. (4) The Lower Pliocene to Lower Pleistocene successions consist of open marine marls and clays, with intercalated sandstones and conglomerates which represent migrating barrier island systems (5) The Upper Pleistocene and Holocene continental and shallow marine conglomerates and sandstones are present in fluvial and coastal terraces. The total thickness of the Upper Neogene to Quaternary amounts up to circa 2.5 kilometers. Within various stratigraphic levels, a melange mass is intercalated, which is called "Argille Scagliose Varicolori", consisting of multicolored, scaley clays, with inbedded exotic blocks ranging in size from a few cm to some tens of km. Various interpretations exist with respect to the genesis of this mass, envisaging tectonic as well as sedimentary mechanisms, which will be discussed below.

Only a few previous publications deal with data concerning the structure and stratigraphy of the Upper Neogene of the studied area. In most cases, the stratigraphic successions are described as parts of the Crotone Basin and in continuity with the units along the Ionian coast up to Catanzaro. The following review concerns the literature on the studied area, and also the general literature on the Upper Neogene stratigraphy and tectonics of the Calabrian Basins:

The first geological maps were published by Cortese, Aichino and Novarese from 1886 to 1890. Four 1:100.000 sheets comprise the southeastern margin of the Crotone Basin:

Sheet 237 S. Giovani in Fiore
Sheet 238 Crotone
Sheet 242 Catanzaro
Sheet 243 Isola di Capo Rizzuto

Cortese (1895) described the successions in an explanatory note. He distinguished the following units:

a) a basal series with **conglomerati** overlain by **arenarie a Clipeastri** followed by **argille grigio-azzurrognole** of Tortonian Age.

b) a **formazione gessoso-solfifera**, consisting of **calcare siliceo, gessi** and **arenazzolo** of Late Miocene - Early Pliocene Age.

c) **Conglomerati inferiori, marne azzurre and sabbie gialle** of Pliocene Age.

d) **Sabbie giallastre** and **argille sabbiose a Cyprina islandica** of Pliocene - Pleistocene Age ("Piano Siciliano").

e) Quaternary **terrazzi marini, terrazzi fluviatili, depositi lacustri** and **conoidi detritici**.

f) Recent **dune, spiagge, conoidi attuali** and **fluviali**.

Some other works dating from the last century which partly treat the sediments in the Crotone Basin are:

De Bosniaski (1879) described some fauna from

sections in Pliocene clays near Cutro.
De Stefani (1884) described some general features of the Calabrian Tertiary geology.
Cortese (1896) described the geology of Northern Calabria.
Millosevich (1899) reported on the evaporites near Strongoli.

De Lorenzo (1904), Gignoux (1909, 1913), Cortese (1909), De Stefano (1913), Ruggieri (1941, 1949, 1953) and Selli (1962a) described successive stages in the development of the Upper Pliocene - Quaternary terraces along the Ionian coast. They interpreted these terraces as subsequent marine abbrasion levels related to a pulsating eustatic sea level drop, or as resulting from extensional faulting, related to the post-Calabrian pulsating uplift of a Calabrian highland erosional surface. Gignoux envisaged a tilting along the Ionian side of Calabria, and a foundering of an ancient "Tyrrhenide land mass" along the Tyrrhenian coast.

The fauna in the Miocene of Calabria was studied by Checchia-Rispoli (1925) with special regard to the *Clypeaster* species.

Lembe (1931) recognized the same features as Gignoux (op. cit.) along the Tyrrhenian side of the Aspromonte area, and assigned them to the uplift history of Calabria.

Signorini (1942) gave a general outline of the so-called "Bacino del Neto" with the **Formazione gessoso-salifera**. He was also the first to recognize the allochtony of the Argille Scagliose and related structures in the Crotone Basin along the external side of Calabria.
Quitzow (1935) and Migliorini (1952a, b) described the Tortonian - Quaternary successions of Northern Calabria with a subdivision similar to the one used by Cortese.
Ducci (1949) described geomorphological features focussing on landslides in the vicinity of the village of Selli.
Graulich (1954) and Malaroda (1955) published some results of studies near Strongoli of Messinian and Pliocene sediments.
Francaviglia (1955) described some aspects of the geology near Torre Melissa and Strongoli.

Ogniben (1955) analysed the northern sector of the Crotone Basin, focussing on the problem of the "Argille Scagliose", which he interpreted as a chaotic sedimentary-tectonic melange. He reconstructed four different levels, intercalated in the Tortonian - Messinian deposits as gravity slides, with younger beds partly deriving from externally situated (to the east or southeast of the area, in the recent Ionian Sea) and uplifted older levels. This model was followed by Bonfiglio (1964a) and further extended by Roda (195) for the so-called "Cariatidi" thrust mass along the northeastern border of Northern Calabria.

Selli (1962, 1975) summarized the knowledge on the Tertiary of Calabria. He divided the deposits into the following series:
Mesoautoctono e neoautoctono miocenico:
Molasse a Clipeastri ("Elveziano medio-superiore")
Marne argillose ("Elveziano superiore-Tortoniano-Messiniano basale")
Formazione gessoso-solfifera ("Messiniano inferiore")
followed by a Pliocene - Pleistocene succession (Selli, 1958).

The most thorough investigation of the geology of the Crotone Basin was published by Roda (1964a) who gave a revision of the sediments and divided them into several partly new formations defined by lithology and microfauna. These formations were grouped into three sedimentary cycles:

Middle Miocene - middle Messinian cycle:
1) **Formazione di S. Nicola** (Ogniben, 1955)
2) **Argille marnose del Ponda** (Ogniben, 1955)
3) **Formazione del Tripoli** (Ogniben, 1955)
4) **Formazione evaporitica inferiore**

Middle Messinian - Infra Pliocene cycle:
1) **Formazione detritico-salina**
2) **Formazione evaporitica superiore**
3) **Conglomerato delle Carvane**
4) **Marna argillosa dei Cavalieri**
5) **Molassa di Zinga** (Ogniben, 1955)

Middle Pliocene - Pleistocene cycle:
1) **Argilla marnosa di Spartizzo** (Ogniben, 1955)
2) **Molassa di Scandale** (Ogniben, 1955)
3) **Argilla marnosa di Cutro**
4) **Molassa di S. Mauro**

Roda stressed the fact that the formations established were only provisional and should have to be defined more precisely on a later date. He only scarcely described the structure and stratigraphy of the southeastern part of the Crotone Basin and he referred several times to the tectonic complications of this area. He discussed the struc-

ture of the basin and its sedimentary and tectonic history. His main conclusions are as follows:
The sedimentary history of the basin can be divided into three cycles as mentioned above. After a "Helvetian-Tortonian" transgression, the first cycle was closed with a tectonic phase with mainly tensional folding and faulting (with NW-SE or N-S axis) accompanied by an intercalation of Argille Scagliose of Messinian Age. This pulse propably resulted in erosion of parts of the evaporite succession. At the end of the second cycle, compressional folding occurred with a N-S axis during the "Infra Pliocene". The most important tectonic phase is of Calabrian Age with faulting with SW-NE (northern part) to N-S (southern part) trends.

Several later works by Roda (1964b, 1965a, 1965b, 1965c) and Di Grande (1967a, 1967b, 1972) deal with sections and some small areas in the central part of the Crotone Basin, using the formerly described sedimentary-tectonic concept. These authors presented the results of sedimentary and micropaleontological analysis of mostly Pliocene sediments.
In his later works, Roda (1966, 1967, 1970, 1971) summarized again the Mio-Pliocene sedimentary history of Calabria.

A comprehensive 1:25.000 mapping of Calabria was performed by the "Compagnia Areo Richerche" from 1958 to 1963, financed by the "Cassa per il Mezzogiorno" (Cassa per il Mezzogiorno, 1967-1972; Burton, 1965). The results were summarized by Burton (1971). The area investigated in the present study comprises the following sheets:
Sheet 237-2-NO Petilia Policastro
Sheet 237-2-NE S. Severina
Sheet 237-2-SO Sersale
Sheet 237-2-SE Marcedusa
Sheet 238-3-SO Cutro
Sheet 242-1-NO Cropani
Sheet 242-1-NE Botricello
Sheet 243-4-NO S. Leonardo di Cutro
Sheet 242-1-SO Sellia Marina
Sheet 237-3-SE Taverna
Sheet 242-4-NE Simeri e Chrichi
Sheet 242-4-SE Catanzaro
Sheet 242-4-NO Tiriolo
Sheet 242-4-SO Caraffa di Catanzaro
Sheet 242-3-NO Squillace
Sheet 242-3-NE Marina di Catanzaro
Sheet 242-3-SO Soverato
Detailed descriptions as explanatory notes belonging to 1:100.000 sheets were given by the following authors:
Sheet 237 S. Giovanni in Fiore: Burton (1962)
Sheet 238 Crotone : Henderson (1962)
Sheet 242 Catanzaro : Pezzotta, Burton & Hughes (1973)
Sheet 243 Isola di Capo Rizzuto : Hughes (1961)
The authors added large amounts of micropaleontological and petrological data of the outcropping rocks in the area but did not assign sample locations, which makes their data hard to evaluate.
The following lithostratigraphic scheme was used:
1) "Miocene Medio-Superiore (Elveziano-Tortoniano)": $\mathbf{M}_{2\text{-}3}$: conglomerates, sands and clays.
2) "Miocene Superiore (Sarmaziano)": $\mathbf{M}_3$: limestones, evaporites, conglomerates,
sands and clays.
3) "Pliocene-Calabriano": a) $\mathbf{P}_1$: Lower Pliocene conglomerates and sands.
b) $\mathbf{P}_{1\text{-}2}$: Lower Pliocene clays.
c) $\mathbf{P}_{2\text{-}3}$: Upper Pliocene clays.
4) "Quaternario: Pleistocene": **Q**: marine terraces, q: continental terraces; conglomerates and sands
5) "Olocene": dunes, beach, rivers, debris cones, etc.
Furthermore, the sediments are indicated with upper indices like "cl" for conglomerates, "s" for sands, "ar" for arenites, "a" for clays, etc.
The Pliocene clays are subdivided according to a combination of faunal contents and lithological characteristics, discriminating between a Lower Pliocene, an Upper Pliocene and a Calabrian association.
The authors recognized several, partly local, discordances and gaps in the sedimentary record:
-between crystalline basement and Miocene conglomerates
-within the Miocene cycle between conglomerates and clays/sands
-within the evaporitic cycle at the base of the upper conglomerates
-at the base of the Lower Pliocene conglomerates
-at the base of the Upper Pliocene clays
-at the base of the Pleistocene terraces and of the Holocene sediments
Being quite precise in the indications of the distribution of lithologies, these 1:25.000 maps have been very usefull in the current research. The accompanying synthesis, however, lacks a detailed analysis of syndepositional fault kinematics.

In a brief paper, Burton (1970) made some remarks concerning the Alpine tectonic evolution of Calabria which contains some interesting

points:
- In Early Miocene times ("post-Aquitanian - pre-Helvetian"), a strong paroxysmal phase took place, in which the main overthrust structures where formed, and former substratum was folded. Burton was the first author who recognized this tectonic phase in (northernmost) Calabria (Lucania area). This hypothesis was consistent with conclusions of Grandjacquet (1969, 1971) for the Lucania area, and was later confirmed by the works of Dietrich (1976), Grandjacquet and Mascle (1978) and Meulenkamp et al. (1986) in Calabria.
- In early Middle Miocene times, radial outward movements caused the main, concentric and radial fold structures of the substratum which was subsequently transgraded by the "Helvetian" transgressive sands.
- Late Miocene intercalations of Argille Scagliose slides occurred from the external side inwards into the Calabrian basins. Burton regarded the exposed parts of the Carvane conglomerate Fm in the study area to the same cycle as the intercalated Argille Scagliose, both being of external origin. He hypothesized that in the Messinian - Pliocene boundary interval, a switch from external to internal souce area occurred, related to the early Pliocene transgression.
- During a "Ponto-Pliocene" tectonic phase, the folds which were already formed during the previous phase were additionally folded, and also major tensional faulting occurred.

Guérémy (1972) presented a geomorphological study of Central Calabria comprising interesting maps and profiles of the southern part of the Sila Massif. A peculiar conclusion regards the high plain on the Sila massif. Guérémy stated that this abrasion level had a Middle Oligocene age. He based this conclusion on observations along the southern margin of the Sila Piccola, where the high plain seems to dip below the Oligo-Miocene deposits.

Selli (1962, 1975) presented some geological profiles. Some peculiar details are the following:
- He concluded from observations near Sellia Marina, that the deposition of the lower Messinian "Calcare di Base" limestones was followed by a late Messinian - earliest Pliocene phase of submarine sliding to the southeast, followed by an Early Pliocene onlap.
- He reconstructed a post-early Pleistocene reverse fault along the southeastern border of the village of Scandale.

Ogniben (1973) presented a comprehensive review of the geology of the Calabrian Arc. He used a tectono-stratigraphic approach in which the rocks are subdivided into so-called "Tectonostratigraphic Complexes". He assigned the Neogene deposits of the Crotone Basin to his "**Complesso Post-orogeno**", while the intercalations of Argille Scagliose in the northern part of the Basin were assigned to the "**Complesso Anti-Sicilide**". Ogniben formulated the following conclusions with respect to the Postorogenic deposits:
1. The postorogenic complex is a sequence which unconformably overlies the unilaterally verging orogenic belt and is characterized by detrital supply by postorogenic uplift.
2. The dips of the deposits are bilaterally: At the internal side, they dip towards the Tyrrhenian Basin, whereas at the external side they show a dip towards the Ionian Sea.
3. The basal part of the successions belongs to the *Globorotalia menardii* biozone.
4. The succession is constituted of: (a) *Clypeaster* containing molasse, (b) *G. menardii* bearing shales, (c) Sulphiferous Series with restricted environmental facies, (d) a Lower Pliocene cycle starting with an "anomalous transgression" due to normal sea level reestablishing after the close of the evaporitic cycle, and ending with a folding phase, (e) An Upper Pliocene - Lower Pleistocene cycle, with again an "anomalous transgression" at the base, which is related to a lateral spreading nappe" into the postorogenic Bradana-Gela foretrough (foredeep), (f) Continental deposits of the highlands erosion surface, extending over the Calabrian marine deposits, (g) Terraces, alluvial fans and lacustrine deposits, (h) Versilian coastal plains and Recent fluviatile and littoral deposits.
5. The uplift of the large continental Early Pleistocene erosion surface and the tilting to the Ionian Sea was accompanied by foundering of the Tyrrhenian sea (post mid-Pliocene).
6. The Messinian and Early Pliocene paleogeography greatly differed from that of today. The Sila Piccola formed a sill which separated organogene pelagic sedimentation in the south from detrital sedimentation north of it. Sediments derived from Calabria, exept in Messinian times, when sediments came from the East.
7. The Pliocene - Pleistocene history can be reconstructed by using tephra layers.
8. A model of a dessicated Mediterranean in Messinian times does not fit with marine evaporites and upper Messinian restricted marine successions in Calabria.
9. The Late Messinian inversion of detrital supply

to eastern sources can be explained by moderate sea level lowering, rather than by foreland uplift.
10. The Early Pliocene transgression is accompanied by deposition of basal conglomerates in southern Calabria, indicating an emerged ridge and allowing an estimate of sea level rise of about 200-250 m.
11. The anomalous mid-Pliocene transgression is linked to sliding of a nappe into the Lucanian-Calabrian-Sicilian foredeep.
12. The Upper Pliocene Strongoli sandstones in the Crotone Basin separate middle Pliocene and Upper Pliocene cycles. They represent the sliding of the lateral spreading nappe.
Ogniben agrees with the general view that the Argille Scagliose nappe slided from east to west from an external, high area in the Ionian sea, in late Messinian times. However, he ascribes this to a sea level lowering, as he sees no conclusive evidence for a foredeep uplift.

Guerrera (1973) published a small geological map and accompanying explanatory notes concerning the geology of the northern margin of the Catanzaro depression.

Dubois (1971, 1976), in his doctorate Thesis, focussed on the Northern Calabrian basement structure, with emphasis on the Pre-Sila area, but also included the Late Neogene stratigraphy in his profiles. His stratigraphic subdivisions were based upon previous literature. He placed the thick basal sequences of continental deposits in the Oligocene - Lower Miocene.
A peculiar point in the synthesis of Dubois is the fact that he regarded the Argille Scagliose in the Crotone Basin as being of internal provenance, i.e. according to him, the allochtonous masses were transported by sliding down from the nearby Sila Massif.

Amodio-Morelli et al. (1976) published a synthesis of the Calabrian geology with an accompanying 1:500.000 geological map (Bonardi et al., 1976). Special emphasis lay on the crystalline basement.

The formation concept of Roda (1964a) was also used by Martina et al. (1979) who dealt with microfauna studies of some sections in the Messinian evaporites of the Central Crotone Basin.

Philip & Tortorici (1980) and Tortorici (1981) synthesized tectonic data from northern Calabria. Combining the tectonic data with available stratigraphic studies, the authors came to the following sedimentary-tectonic history:
1) Tortonian - Early Pliocene: N-S extension. Sedimentation was controlled by a number of NW-SE horst and graben structures. Small paroxysmic phases occurred at the Tortonian - Messinian transition and in the middle Messinian.
2) Middle Pliocene: E-W compression. Fold structures and reverse faults were generated, and transcurrent movements occurred.
3) Middle Pliocene - Pleistocene: E-W extension. In the Crotone Basin extensional faulting occurred along N-S, NW-SE and NNE-SSW trending fault zones.

Moussat (Doctorate Thesis; 1983) and Moussat et al. (1983) presented the results of neotectonic studies in some selected areas of the Calabrian Arc.
By using previously published stratigraphic schemes and measurements of small scale "decrochements" in the Catanzaro and Rossano areas they describe a Neogene tectono-sedimentary history with a predominant extensional regime, interrupted by short compressional events. These events occurred in the Middle Pliocene and Middle Pleistocene. The Middle Pliocene event, causing sinistral movement along NW-SE trending faults, reverse faulting and folding with NW-SE to N-S axis, was placed in the (lower part of the) *Globorotalia crassaformis* Zone of Colalongo & Sartoni (1979) (early Late Pliocene). Measurements on small scale structures indicated that the compression axis was directed N30-70, and the extensional axis was directed NW-SE.
Based on his neotectonic studies, Moussat (1983) designed a kinematic concept for the Calabrian Arc which includes differential movements along NW-SE trending parallel segments separated by intra-arc shear zones. He inferred a sinistral displacement for the Northern Calabrian shear zones. Within this concept, the Crotone Basin can be regarded as a pull-apart basin.

Meulenkamp et al. (1986) and Meulenkamp & Hilgen (1986) summarized the results of a series of stratigraphic fieldworks on the Neogene successions along the Ionian coast of Calabria (1980-1985), including the first results of the present study (Van Dijk, 1985). They presented a general tectonostratigraphic concept for the Late Neogene basin development of the Calabrian Arc. The authors subdivided the arc into a number of NW-SE trending segments, confined by broad fault zones. Northern Calabria was divided into a northern, a central and a southern segment.

They arrived at the following conclusions for Northern Calabria:

- Tectonized remnants of ?Oligocene - Lower Miocene coarse clastics are present along the fault-bounded margins of the Sila Massif. Near Sersale, these remnants are overthrust by a granite.
- The oldest deposits in the Sila Piccola area, below the middle Miocene sandstones, are tentatively regarded as Serravallian in Age (Oligo-Miocene of Burton, 1971 and Dubois, 1971, 1976).
- Serravallian - Tortonian coarse clastics with overlying fines are present in the Crotone Basin and in the southern segment.
- A major tectonic phase occurred at the transition from the Tortonian to the Messinian. The Messinian deposits were formed during two distinct sedimentary cycles. Intra Messinian tectonics resulted in the deposition of huge conglomerate bodies in the southern segment, and "Lago Mare" deposits such as the Carvane conglomerates in the Crotone Basin.
- During the earliest Pliocene, allochtonous masses were formed with Argille Scagliose and disrupted Messinian - lowermost Pliocene deposits.
- Late Early Pliocene compressional tectonics resulted in reversed oblique-slip movements along the major shear zones.
- Upper Pliocene and Lower Pleistocene successions of the Crotone Basin reflect a development characterized by migrating barrier systems in open marine environments and by rapid subsidence.
- Post - Late Pliocene southeastwards thrusting and tensional faulting was responsible for the shaping of the recent morphology.

Specific points are the following:

- The late Burdigalian and Late Pliocene - Early Pleistocene phases of compression were characterized by NW-SE directed shortening. Infra-Pliocene tectonics were dominated by E-W stress and NE-SW directed shortening due to oblique-slip along the major shear zones.
- The Argille Scagliose levels along the northern margin of the Crotone Basin were regarded as late Messinian gravitational slides (cf. Ogniben, 1955 and Roda, 1964a). These have their counterparts in late Messinian - Early Pliocene allochtonous masses to the south, in the Crotone Basin.
- The Crotone basin was regarded as a strike-slip basin, locked between two intra-arc shear zones (cf. Moussat, 1983).
- Within the studied area, a NW-SE trending, sinistral intra-arc shear zone was recognized, the Petilia-Rizzuto shear zone. Along this zone, the southern margin of the Crotone Basin, late Early Pliocene thrusting towards the margin can be observed, related to a regional compressional phase.

During the present investigation, some additional papers were issued concerning the Calabrian Arc:

Cosentini et al. (1990) presented the results of a structural analysis of the terrace deposits of the Crotone Peninsula.

Leg 107 of the Ocean Drilling Program, during which a number of holes were drilled in the Tyrrhenian Basin, had a profound impact on the scientific community occupied with the Late Neogene Central Mediterranean evolution. The results were published in two ODP volumes (Kastens et al., 1987 and 1990), and in a number of small papers (Leg 107 Scientific Drilling Party, 1986a, 1986b, 1987; Kastens et al., 1986, 1988).
An important discovery was that the rifting of the southern part of the back-arc basin was much younger (Late Pliocene-Pleistocene) than previously assumed (Messinian-Pliocene). Furthermore, an enormous amount of data became available on the stratigraphy of the basin, which gave a profound insight in the processes of rifting and foundering.

Scandone and Patacca (Conference 1986; printed 1990) published an important synthesis of the Middle Miocene - Recent development of the Apennines system. They convincingly showed that synchronous tectonic pulses can be recognized throughout the Late Neogene, which relate to major phases of shortening within the fold-and-thrust belt and to the development of major unconformities.

Smale et al. (1990) published a short note on to the first results of a study of the Neogene deposits of the Crotone Basin. Their results confirmed the evolution as outlined by Roda and coworkers (e.g. 1964). Smale's PhD. Thesis on the evolution of the Crotone Basin was isued as an internal report at the University of South Carolina, Columbia SC.

Stratigraphic sections

Within the present study area, a number of stratigraphic sections are exposed which have been intensively studied in the past, because of their chronostratigraphic significance.

Gignoux (1910, 1913) established the Calabrian Stage and indicated a number of typical sections near Santa Maria di Catanzaro, in the vicinity of Catanzaro, in the southeast of the present study area. During the sixties, these sections and the nearby section of Caraffa di Catanzaro, were subject to many studies (Emiliani et al., 1961; Banner and Blow, 1965; Selli, 1967a, 1967b; Lamb, 1969; Bayliss, 1969; Smith, 1969; Bandy and Wilcoxon, 1970). The outcrops near Santa Maria obtained the official status of stratotype section of the Calabrian Stage during the Congress on the Mediterranean Neogene in Bologna in 1970 (Selli, 1971). This proposal was followed by a flood of, generally critical, literature (e.g. Berggren, 1971; Hays and Berggren, 1971; Lamb and Beard, 1971; Ruggieri, 1972a, 1972b; Brolsma and Meulenkamp, 1973; Drooger, 1973; Gradstein, 1973; Sprovieri et al. 1973). This was finally followed by a consensus on the presence in the section of numerous hiatusus and reworking phenomena due to its shallow water depositional environment. Consequently, the Santa Maria sections appeared not suitable as stratotype section.

Several studies were presented dealing with the section of Le Castella in the southeastern part of the area, comprising Upper Pliocene to Pleistocene sediments. The section was proposed as Calabrian Stratotype by Selli (1961) and as a Plio-Pleistocene boundary stratotype in 1965 at the Seventh INQUA Congress. The most important studies concerning the section are those of Emiliani et al. (1961), Selli (1961), Colalongo (1965), Bandy & Wilcoxon (1970), Selli (1971) and Ruggieri (1972a, 1972b).

The Vrica Section in the Central Crotone Basin was chosen as Neogene-Quaternary boundary Stratotype at the 27th International Geological Congress (Moscou, 1984; Pasini & Colalongo, 1982) after several proposals by Pasini et al. (1975), Selli & Cati (1977) and Selli et al. (1977). Extensive studies and references to a very extensive literature on the subject can be found in Selli et al. (1977), Colalongo & Sartoni (1979), Colalongo et al. (1982), Tauxe et al. (1983), Pasini et al. (1984), Combourieu-Nebout (1987), Hilgen (1991), Verhallen (1991) and Zijderveld et al. (1991).

Seismic sections and drilling results

Data concerning hydrocarbon exploration in the Central Mediterranean area are summarized by Beneo (1951, 1955), Marchetti (1956), Flores (1959, 1981), Rocco (1959), Vercellino and Rigo (1970), Mulder (1973), Mattavelli et al. (1983), Pacchiarotti (1984), Dainelli and Pieri (1986), Pieri and Mattavelli (1986), Mattavelli and Novelli (1987), Novelli et al. (1987) and Bouma (1990). Only few seismic sections and drilling results concerning the Central Calabrian area are available:

Bronzini (1959) described three wells, the "Scandale 1" (already mentioned by Ogniben, 1955), "S. Leonardo 1" and the "C. Cimiti 1" (from the "Societa Montecatini"). He noted a NW-SE trending monoclinal structure along the coast of Le Castella, defining the southeastern border of the basin.
Roda (1964a, 1965a) dealt with several oil research wells in the centre of the Crotone Basin. He used them to reconstruct the Tortonian to Pliocene stratigraphy. These are "Bruchetto 1", "Capo Cimiti 1" (Societa Montecatini), "Scandale 1" (Societa Sori), "Scandale 2" (Societa Montecatini) and "Rocca di Neto 1" (Societa Montecatini).
An off-shore well near Crotone, "Perrotta 2", was analysed by Crescenti (1972) who described a continuous Messinian - Pliocene succession.

Auroux et al. (1985, their fig. 11) presented a seismic section in the off-shore part of the Crotone Basin which shows tensional graben structures filled with Upper Miocene and Pliocene sediments.
Flores (1981, his fig. 8) and Pacchiarotti (1984) gave some schematic cross sections through AGIP off-shore gas fields along the Calabrian Arc near Crotone and Ciro.
Finetti & Morelli (1972, 1973) published results from seismic campains of the OGS of Trieste in the Ionian region. An important conclusion which derived from their work was the recognition of the continuity of the overthrust as already described from the Taranto Gulf ("Metaponte Nappe"; Ogniben, 1969) with the overthrust as described from the south of Sicily ("Gela Nappe"; Beneo, 1955; Ogniben, 1960).
The off-shore structure of the NE-SW trending Crotone-Spartivento Basin and the External Calabrian Arc were analysed by several groups of authors by means of bathymetric and seismic profiles:

Some data from exploration activities were published by Mulder (1973; Shell International Petroleum Company) and Biju-Duval et al. (1974; Inst. Français du Petrole).
Rossi & Sartori (1981), using results of a 1971 to 1975 seismic campain, described the structure of the region, dividing it into a number of quasi-parallel, NE-SW trending zones. These are, from northwest to southeast: Calabrian Slope, Crotone-Spartivento Basin, Crotone-Spartivento Slope or Inner Transitional Zone, External Calabrian Arc and Outer Transitional Zone ("Cobblestone Area"). Numerous salt diapirs (originating from Messinian evaporite levels) were described from the Crotone-Spartivento Basin in the Gulf of Squillace. According to the authors, the basin was formed by means of extensional Plio-Pleistocene faulting. Selli (1973) had already depicted a NW-SE reflection seismic section in the same area (his fig. 5.E, see Rossi & Sartori, their fig. 9) which shows a small salt diapir in the Pliocene succession.
Morlotti et al. (1982) described some gravity cores which were taken in the External Calabrian Arc region. They contain chaotic Pliocene deposits with Upper Cretaceous to Messinian fragments.
The structure of the Ionian Calabrian margin was synthesized by Fabbri et al. (1982) combining all available data.
Makris et al. (1986) presented a number of seismic refraction profiles through the southern part of the off-shore Calabrian Arc.
The NW-SE seismic section M-60 situated in the off-shore Crotone Basin, was published by Finetti (1981, 1982). His interpretation of the section shows a set of numerous NW and SW-verging listric reverse faults cutting the whole sequence from Mesozoic up to Pliocene and also effecting the Calabrian basement. Finetti (1982) and Finetti & Del Ben (1986) synthesized the structure of this Calabrian "Fore Arc Scraping Zone".

Geophysical investigations

Some studies of satellite lineaments concerning Calabria have been published by Biju-Duval et al. (1975, their fig. 7.2) and Bodechtel & Münzer (1978, their fig. 1). Many of the observed lineaments in the studied region coincide with reconstructed faults. An important morphotectonic element which was recognized by Bij-Duval et al. (op. cit.) is the Sila Piccola quasi-circular dome, situated in the basement massif and dominating the present-day morphology of the present study area.
For extensive reviews and compilations concerning geophysical datasets on aeromagnetics, bouguer anomalies, heat flow, seismicity, paleomagnetics and seismic sections, we refer to reviews of Finetti and Morelli (1972); Finetti and Morelli (1972, 1973); Lort (1977); Finetti (1980, 1981, 1982, 1984); Rehault et al. (1983), AGIP (1984); Finetti and Del Ben (1986), Spakman (1988, 1990) and Dañobeitia and Pinet (1990).

SPECIFIC QUESTIONS REGARDING THE CALABRIAN GEOLOGY

When the present study was initiated, a number of specific problems regarding the Calabrian geology needed to be tackled:

Lower Miocene successions; Argille Scagliose

A tectono-sedimentary melange, the so-called "Argille Scagliose Varicolori" (ASV; multicolored scaley clay melange) is intercalated at different stratigraphic levels, varying from Lower Miocene to Pleistocene, within the successions along the external side of the arc. It contains exotic blocks of all types of basement and sedimentary rocks ranging from Paleozoic till Pleistocene, which range in size from a few mm. to tens of km.
In Calabria, an external gravitational origin is generally accepted for this melange, as a slide nappe (Ogniben, 1955, 1960a, 1960b, 1973; Bonfiglio, 1964a; Roda, 1965a; Caire, 1973) or as an olistostrome (Görler, 1978b). In that approach, the slide masses originated from an external elevated area (possibly a ridge within the accretionary wedge), in Middle Miocene (Langhian; southern Calabria and Peloritani) and in Latest Miocene (middle Messinian; northern Calabria) time. This mechanism is known as "retrocharriage".
An alternative explanation for the northern Calabrian ASV was favoured by Dubois (1976), and Grandjacquet and Mascle (1978). This explanation was proposed for the Sicilian and southern Calabrian ASV by Meulenkamp et al. (1981, 1986). The model follows the approaches of Flores (1955, 1959), Beneo (1955), Marchetti (1956), Durand-Delga and Mattauer (1961) and Caire (1970, 1975) for the Maghrebian (North African and -classical- Sicilian) Early Miocene ASV. It hypothesizes an "internal", gravitational origin for the melanges as olistostromes, gravitational slides, or huge décollement nappes. The origin of these masses could then be local

Paleogene - Lower Miocene successions which were overlying the nearby Calabrian Massif, or more distant terrains within the, at present submerged, Tyrrhenian Sea. This second hypothesis is known as the "Ultra-hypothesis" (Durand-Delga, 1980).
As a third possiblity, a mixed tectonic origin with both internal, back-arc and external, fore-arc source area, has also been hypothesized (Caire, 1957; Coutelle, 1976), which completes the range of possible models and a dispute which is continuing for over 30 years now, since the Hans Stille memorial symposium in Stuttgart in 1956 (Coutelle and Deteil, 1989). Wezel (1974) and Görler (1978b) proposed yet another possible genetic model, which ascribes part of the deformation of the ASV to shearing and material flow within the accretionary wedge. It can thus be appreciated that a study on the nature of these ASV masses and their emplacement mechanism can give important insight into the basin kinematics of the Calabrian Arc.

The origin of the "Argille Varicolori" lithology has been placed in an Oligocene - Early Miocene "Austro-Alpine" "flysch basin" which extended from the North African margin (present-day Maghrebian chain) up to the Central Apennines along a NE-SW trending strip (Durand Delga, 1955, 1961, 1967; Wezel, 1970). In this whole area, the turbite "Numidian flysch" sequences are capped by the Aquitanian-Burdigalian, so-called "Numidian sandstone", a quartzose sandstone unit, named after the roman area Numidia in Algeria (Ficheur, 1891; p. 237; Flandrin, 1948; Caire and Mattauer, 1960). Basin margin equivalents of this sandstone, coarse clastic submarine fan deposits, and tuffitic volcanoclastic deposits are found in the Monte Peloritani and in other parts of northeastern Sicily (Broquet, 1968; Carmiscano et al., 1987).

A problem related to the genesis of the Argille Scagliose is the recognition of a late Burdigalian tectonic phase in Calabria. Grandjacquet (1969, 1971) was the first to recognize contractional tectonics affecting the Aquitanian-Burdigalian "Argille en Blocs" facies. The structures were sealed by late Burdigalian transgressive deposits, in the Lucania area (southern Apennines). His findings were confirmed by Burton (1970) and Dietrich (1976) who found the "Argille en blocs" facies of Grandjacquet in the Coastal Chain, overridden by crystalline (Liguride) nappes. The tectonic phase was also described from Sicily by several authors (Wezel, 1974; Carmisciano et al., 1978, 1981; Courme and Mascle, 1988). Bonardi et al. (1980, 1984) stated that no late Burdigalian tectonic phase had taken place in Calabria. This was based on their observation that the Oligocene-Lower Miocene "Stilo-Capo d'Orlando Formation" sealed the Eocene-Oligocene thrust nappes and continued into the Langhian, after which it was capped by Argille Scagliose. This view was challenged by Meulenkamp et al. (1986), who described large late Burdigalian décollement nappes from southernmost Calabria, capped by and imbedded in Argille Scagliose masses. Altogether, it seems that the Calabrian basement rocks have suffered their last major tangential displacements in late Burdigalian times.

In the southern part of the studied area, the lowermost deposits, coarse clastics and turbidites overlying crystalline basement, have been assigned to the Oligocene-Lower Miocene (Dubois, 1976) or to the Serravallian (Burton, 1971; Meulenkamp et al., 1986). Some indications for thrust relations with basement rocks can be found in the literature (Lorenzoni and Z.-Lorenzoni, 1976; Meulenkamp et al., 1986) but ages are unclear.
In the northern part of the studied area, Argille Scagliose is present within the Upper Miocene of the Crotone Basin. These deposits were described as gravitational slides with external (Ogniben, 1955) or possibly internal (Dubois, 1976; Meulenkamp et al., 1986) origin. Basal terrigenous deposits in the Central Calabrian area have been described to the Oligo-Miocene by some authors (e.g. Dubois, 1976).

Messinian successions

The Messinian evaporites and continental deposits within the Calabrian Arc are involved in a discussion wich started during the 1960s and early 1970s with the discovery of an evaporite layer below the entire Western Mediterranean Basin during DSDP Leg 13 (Hsü et al., 1972). An enormous amount of literature has been dedicated to this topic, as well as numerous conferences (e.g. Drooger, 1973; Catalano et al., 1978). For extensive reviews concerning various topics related to the "Messinian salinity crisis" (Ruggieri, 1967), one is referred to the following theses and articles: Decima and Wezel (1971), Hsü (1972), Heimann (1977), Cita (1978), Rouchy (1981), Hsü (1985), Müller (1986); Benson (1984, 1991), Benson and Rakic-El Bied (1991) and Cita (1992). The following subjects have been treated and discussed in literature:

Several basin models have been proposed to account for the genesis of the evaporites. These models differ with respect to the magnitude of eustatic sea level fluctuation, the depth of the basin in which the evaporites were formed, and the magnitude of syn-depositional Messinian and post-depositional Pliocene-Quaternary vertical movements. The models can roughly be divided into four groups: Deep dessicated basin models, Shallow dessicated basin models, Deep brine models, and Mixed basins models. The controversies between these models are born from different interpretations of sedimentary facies, microfauna, and seismic sections.

Successions which originated in small marginal basins and which can now be found exposed on land, can be subdivided into four parts: 1. The pre-evaporite, normal marine successions, 2. The "Lower Evaporites" successions, 3. The "Upper Evaporites" successions, and 4. the "Lago Mare" continental successions. In principle, this subdivision can be recognized all over the Central and Eastern Mediterranean. In the Western Mediterranean, somewhat different successions have been described which comprise several intercalations of open marine sediments. The uppermost continental deposits are covered by hemipelagic muds and marls (the "Trubi marls" of Sicily; Baldacci, 1886), which represent the so-called "Early Pliocene flooding event", or "Zanclean deluge" (see e.g. Cita, 1972).

In-between the Lower and Upper Evaporites series, an erosional, often angular unconformity is present, related to an "intra-Messinian tectonic event". Intra-Messinian tectonics have also been inferred from seismic profiles (see references in e.g. Patacca and Scandone, 1989). The starting and the ending of the Messinian crisis may also have been related to tectonic pulses. This tectonic activity may have been responsible for the closing of the straits which probably passed along the northern and the southern side of the present-day Gibraltar Isthm, and for the opening of these same straits or, more propably, of the Gibraltar Strait proper (see for a discussion Weijermars, 1988).

The Messinian salinity crisis was associated with southern hemisphere glacial events, testified by distinct peaks in oxygen isotope curves. Estimates of a global eustatic sea level lowering associated with this glaciation amount up to 70 m (Benson, 1991). Estimates of the local eustic drop in sea level in the Mediterranean amount up to 2000 m (Cita, 1992).

The successions in the Calabrian fore-arc basins show a detailed record of the Messinian. Detailed studies can give insight into the role of tectonic activity during the Messinian with respect to the origin of depositional sequences, and may give clues to the recognition of signals related to eustatic sea level fluctuations.

The limit between Northern and Southern Calabria

The southern and northern segments of Calabria ("megasegments" of Meulenkamp et al., 1986) show clear differences not only in stratigraphy but also in basement composition (Caire et al., 1960; Grandjacquet et al., 1961; Ogniben, 1973). They are separated by a narrow depression, the Catanzaro depression, which is filled with Upper Neogene deposits. The question is why these differences between the two segments exist, in what respect they were separated during the Late Neogene, and where the boundary between the blocks can be found. Authors who studied the basement rocks place the boundary along the SW-NE trending Capo Vaticano - Soverato Line (e.g. Boccaletti et al., 1984), whereas authors studying the Neogene successions tend to indicate the northern margin of the Catanzaro depression as the limit (e.g. Caire, 1970; Ogniben, 1973). Several authors postulated the existence of a major "Apennine" fault zone or shear zone along the Catanzaro depression (Beneo, 1951). Relative displacements were considered sinistral (Caire, 1962, 1970, 1975; Moussat, 1983) or dextral (e.g. Boccaletti et al., 1984). On the other hand, the Catanzaro Isthm has also been regarded as a purely tensional graben (e.g. Ghisetti and Vezzani, 1979, 1982a, b). The controversies with respect to the Catanzaro Isthm are to a certain extent similar to the discussions related to the structural setting of the Rhine Depression at the beginning of this century (cf. Cloos, 1957; pp. 248-257).

Tectonostratigraphy; sequence stratigraphy

A peculiar feature of the coarse clastic basin margin successions along the external margin of the Calabrian Arc is the "progressive tilting and recurrent cannibalism". This phenomenon basically comprises two possibly interrelated features: (1) the Oligocene -Recent deposits show dips of bedding planes which become progressively smaller in younger deposits. This implies a progressive tilting along relatively stable hingelines or axes of flexure (Caire, 1970; Görler, 1978a). (2) Many successions show high amounts of coarse material in their basal parts, which comprise extremely immature, reworked material of older deposits. This indicates that cannibalism is a common feature in these areas (Broekman, pers. comm., 1984). The successions often contain products of debris flows, olistostromes and slide masses. The persistence of the two phenomena calls for an explanation in terms of basin margin activity and relative sea level fluctuations for this specific setting.

The tectonic activity along the Calabrian Basin margins shows an image which is repeatedly similar: In the transitional time intervals in between depositional episodes, initial uplift and block faulting results in regression and erosion ("Fragmentation"). Basin inward settings show shallowing and coarsening upwards. This is followed by subsidence and onlap along the margins ("Restabilization"). This particular sequence of events (termed the "F-R model") was stressed by Meulenkamp (pers. comm, 1983) and Hilgen (1983).

Fault kinematics and arc dynamics

A conjugate set of NW-SE and NE-SW trending fault zones has been recognized by a number of authors (Moussat, 1983: NW-SE trending zones; Boccaletti et al., 1984 and Meulenkamp et al., 1986: a conjugate set). The authors, however, differ in opinion with regard to the exact strike of these fault zones and also with respect to the sense of shear. Furthermore, the deeper structure of these fault zones and their relation with the off-shore accretionary wedge system has not been resolved yet. Pull-apart and strike-slip basins, related to the inferred transcurrent movements, were indicated by several authors but were not elaborated in detail. One of the problems involved is the nature of the intersections of these shear zone systems, and their mutual relationships; Do they displace one another and in what direction?
On the other hand, a number of authors stressed the importance of transversal and radial (trans)tensional fault systems intersecting the arc, and related triangular and rectangular grabens (Dubois, 1976; Ghisetti and Vezzani, 1981, 1982a).
These differences in opinion are reflected by the tremendous variation in models with regard to the kinematics of the Calabrian Arc and related origin of the oroclinal shape, which will be reviewed in Part 3 of the present study. No detailed study on the tectonostratigraphy and on marginal faults delimiting the Calabrian Basins along the external side of the arc is available. Therefore, merely general conclusions can be found in the literature regarding the timing of the Neogene kinematics of the arc. A detailed stratigraphic study is necessary to provide the high-resolution framework which is needed to constrain the timing of tectonic activity.

A middle Pliocene compressional phase has been documented in the northern Calabrian basins (Roda, 1964; Burton, 1970; Tortorici, 1980; Moussat, 1983; Meulenkamp et al., 1986). Observed features include folding (Roda, Burton, Tortorici, Moussat, op. cit.) and locally superficial thrusting towards the basin margins (Meulenkamp et al., op. cit.). Moussat (1983) documented small-scale deformational features in Miocene sediments. All features point to an E-W oriented principle axis of compression.
The main question regards the relation between deformation and the activity of NW-SE trending shear zones intersecting the arc. Are the deformations confined to the northern Calabrian area? Are they the result of sinistral shear and thus of local origin, or are they linked to a regional compression which must have affected the entire arc?
The question if basement is involved in reverse faulting activity is closely related to this issue. Meulenkamp et al. (1986) regarded the thrust contacts between basement and sedimentary rocks, most of them encountered in southern Calabria, as expressions of late Burdigalian sliding of large nappes to the south(east). Lorenzoni and Z.-Lorenzoni (1976) and Ortolani et al. (1979) reported reverse fault relations between basement rocks and ?Oligocene - Upper Miocene sediments, both in the Sila area.

The Neogene development of the Calabrian Basins is characterized by an overall tensional regime, interrupted by brief compressive tectonic pulses with local folding and thrusting (Philip and Tortorici, 1980; Tortorici, 1981; Moussat, 1983). From a comparison of these data with data from seismic surveys and other geophysical datasets of the Tyrrhenian Basin, Moussat concluded that the short tectonic pulses (mid Pliocene and mid Pleistocene) coincide with phases of intensivation of rifting and stretching in the Tyrrhenian back-arc basin.
Therefore, it is generally accepted that the opening pulses of the back-arc area are "equilibrated" by overthrusting and related uplifts along the arc. In the literature, there is general agreement with respect to this matter.
Meulenkamp (1982) and Meulenkamp and Hilgen (1986) observed that numerous brief and episodic tectonic pulses in the Calabrian Arc and Hellenic

Arc are synchronous. The authors distinghuised compressive phases from fragmentation or short uplift phases within the areas, but correlated the tectonic pulses as a general phenomenon, irrespective of their specific impact in the different areas. They furthermore noted that the majority of these pulses correspond with the third-order depositional sequences of Vail et al. (1977). The authors speculated that intra-plate stresses may have controlled this evolution by fluctuating from compressive to extensional stress, following the model of Cloetingh et al. (1985) and Cloeting (1988). Regression and uplift coincide with a shift from regional tension to compression. Transgression and onlaps coincide with a shift from regional compression to tension.

At first sight, these two views seem to be, at least in part, in contradiction. Combining them would lead to the remarkable implication that regional compression and stretching in the back-arc area are synchronous. If we take into consideration that the arc may have been created by passive subduction of a relic lithosphere slab and related roll-back of the subducted hinge-zone (Van Bemmelen, 1974, Ritsema, 1979, Moussat, 1983; Malinverno and Ryan, 1984; Kastens et al., 1988; Patacca and Scandone, 1989; De Jonge and Wortel, 1992), this combination becomes even more peculiar.

Moussat (1983; p. 51) already mentioned this type of discrepancy, because he noticed that the two major compressive phases (mid Pliocene and mid Pleistocene) could be recognized up to the Po plain in northern Italy. He resolved it by stating that the acceleration of movements of larger plates (Europe-Africa) could have provoked an acceleration in subduction velocity along the arc, by some kind of hypercollisional, microplate extrusion mechanism (cf. Caire, 1973; Brunn, 1976; Tapponier, 1977), which may have pushed the arc from behind and accelerated the subduction.

It is therefore of importance to establish a number of facts: What is the precise relation between vertical tectonics and eustatic sea level fluctuations? What is the timing of major stretching and subsidence events in the Tyrrhenian basins? What type of tectonic mechanism is responsible for the tectonic pulses observed along the margins of the Calabrian basins?

METHODS

In order to resolve some basic questions related to basin kinematics and sequence stratigraphy, fieldwork was carried out in the central part of the Calabrian Arc between 1983 and 1989. The area comprises the Catanzaro depression, the southern margin of the Sila Massif ("Pre-Sila Area"), and the southwestern margin of the Crotone basin ("Petilia-Rizzuto Fault Zone"). This specific area was chosen for the following reasons:

It is situated in the central part of the fore-arc region of the Calabrian Arc. It may therefore be expected that this area is extremely sensitive to vertical movements supposed to reflect thrust-wedge dynamics. This mobility resulted in a large number of very small basins. These basins show unconformities along the basin margins, while in adjacent areas the basin inward equivalents of the same successions and unconformities can be observed.

It was furthermore expected that the link between the southern and the northern Calabrian segments can be found in this area.

The area is intersected by a number of transversal as well as arc-parallel intra-arc fault zones. Therefore, it provides an exellent oppertunity to study the relation between basin kinematics and motions along intra-arc fault systems.

Due to rapid Pleistocene uplift of the Sila Massif, the area shows deeply incised valleys which allow to reconstruct a relatively complete stratigraphic succession. For the same reason, the fault zones can be studied at various structural levels, as they are eroded up to a depth of circa 2 km.

The Crotone Basin is one of the few areas in Italy where a complete Middle Miocene - Middle Pleistocene stratigraphic record can be studied, also including Argille Scagliose levels. Especially the Messinian interval is well represented and displays a thick sequence with rapid horizontal and vertical facies changes.

Along the external margin of the Calabrian Arc, fieldwork for more than 15 years has been performed by the Stratigraphy Department of the Institute for Earth Sciences. A number of unpublished reports were available -including sample analysis results- which information could be used in the present study.

The area has been mapped on a 1:25.000 and locally on a 1:10.000 scale, using the topographical maps of the Istituto Geographico Militare (IGM; Florence). Aerial photographs of parts of the studied region were used which were obtained from the IGM (Series 9-8-1983; photographs 943-945, 859-861, 815-819). Emphasis was laid on the analysis of the Late Neogene deposits, whereby detailed mapping revealed the present-day geological structure, and sampling of key sections

and the analysis of planctonic foraminifera provided the biostratigraphic framework. Special attention was paid to the registration of phenomena which could give straightforward indications for syndepositional tectonic activity. Furthermore, the various lithofacies were compared with existing facies models, in order to provide an indication of depositional systems and bathymetry estimates.
A relational database system was designed for a personal microcomputer to store field data, outcrops and locations, stratigraphic data and interpretations, mesoscopic structural data and sample information.

SUMMARY OF THE CONTENTS OF THE THESIS

The various chapters of this thesis (apart from Chapter 4) have previously been published as separate articles. The order in which they are presented here does not always coincide with the order in which they were published, as it is based upon their contents with respect to the problem treated. This implies that, apart from overlaps, the contents of the chapters do not always reflect the precise current views of the writer on the subject. Updated conclusions are summarized in the final chapter of this study ("Synthesis and discussion").

In part 1 of the present study (Chapters 1 to 3, Appendix I) the main results of the field studies are presented. In Chapter 1 (Van Dijk, submitted), the structural and stratigraphic evolution of the Petilia-Rizzuto shear zone is described, with emphasis on the syndepositional tectonic activity. In Chapter 2 (Van Dijk, 1990) and Chapter 3 (Van Dijk, 1991), the evolution of the Crotone Basin is described. Chapter 2 focusses on the reconstruction of depositional sequences, while Chapter 3 describes the interrelation between basin kinematics in terms of thrust-wedge dynamics and the genesis of the depositional sequences.

Part 2 of this study (Chapters 4 and 5, Appendix 2) is dedicated to the geohistory analysis of Central Mediterranean successions. In Chapter 4, the results of the geohistory analysis are presented. This analysis provides a quantified image of the vertical movements along the Late Neogene basin margins. Chapter 5 (Van Dijk, in press.) is dedicated to the elaboration of the principles and applications of the so-called "dynamic geohistory method". This method involves the computerized three-dimensional reconstruction of sedimentary basins.

Part 3 of the thesis (Chapter 6; Appendix 3) comprises a paper (Van Dijk and Okkes, 1991) which followed earlier papers by Van Dijk and Okkes (1988, 1989 and 1990), in which the outcome of the regional analysis is discussed within the framework of the Neogene evolution of the Central Mediterranean. A new structural model for the Calabrian Arc is presented, and some preliminary implications for the kinematics and geodynamics of the region are discussed.

In the final part, "Synthesis and Discussion", the principle outcomes of the study are summarized. Some general ideas are expressed concerning mechanisms which may account for the temporal and spatial interplay between regional tectonic mechanisms and local basin kinematics and their effects on the genesis of depositional sequences.

PART 1

TECTONOSTRATIGRAPHY AND STRUCTURE OF CENTRAL CALABRIA

CHAPTER 1
Structure and stratigraphy of the Petilia-Rizzuto Fault Zone
(Calabrian Arc, Central Mediterranean).
Preprint from: Van Dijk (submitted); Submitted to Tectonics, 30 pp.

CHAPTER 2
Sequence stratigraphy, kinematics and dynamic geohistory
of the Crotone basin (Calabrian Arc, Central Mediterranean):
an integrated approach.
Reprint from: Van Dijk (1990); Mem. Soc. Geol. Ital., Vol. 44, pp. 259-285.

CHAPTER 3
Basin dynamics and sequence stratigraphy in the Calabrian Arc
(Central Mediterranean); records and pathways of the Crotone Basin.
Reprint from: Van Dijk (1991); Geol. Mijnbouw, Vol. 70, pp. 187-201.

APPENDIX I
The geology of Central Calabria.

Ncopp' a na strada ianca e sulagne
Miezza a ll'addore e all'aria 'e campagna
na caretta piccerella chianu chianu senne va...
Tira, tira, tira 'o ciuciariello
sta carrettella tirala tu...

'O Ciucciariello
Nino Oliviero, Roberto Murolo; Napoli, 1947

Janpieter van Dijk, PhD-Thesis, 1992
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CHAPTER 1

LATE NEOGENE KINEMATICS OF INTRA-ARC OBLIQUE SHEAR ZONES:

THE PETILIA-RIZZUTO FAULT ZONE

(CALABRIAN ARC, CENTRAL MEDITERRANEAN)

Submitted to: Tectonics

Abstract. The kinematics of intra-arc shear zones play a key role in the secondary shaping of orogenic arcs such as the Calabrian Arc (Central Mediterranean). Comparison of the Neogene structural development of the Petilia-Rizzuto Fault Zone and the basement structure of the bordering Sila massif reveals that the fault zone is the surface expression of a deep NW-SE trending sinistral crustal oblique shear zone. This shear zone continues over a length of more than 130 km across the northern segment of the Calabrian Arc, and shows a post-Eocene sinistral displacement of about 50 km. We reconstructed the Late Neogene fore-arc basin development and syndepositional tectonics along the fault zone in great detail by analysing the middle Miocene - Recent tectonostratigraphy. A strike-slip cycle can be recognized, whereby the subsequent activity of R-shears, tensional faults and P-shears, positive flower structures and principle displacement wrench faults, can accurately be traced in time. Observed phenomena are discussed in terms of the activity of a conjugate system of oblique thrust zones within the growing accretionary complex. The evolution of special types of thrust-belt basins is illustrated. These include oblique thin-skinned pull-apart basins, oblique rhomboidal "harmonica" basins and "detached slab" basins (new terms introduced here), evolving one into the other. A new feature illustrated is the recurrent basin inversion through backshear motion and out-of-sequence thrusting along the wedge. The fault patterns and the style of inversion tectonics imply an E-W directed axis of effective compressive stress in this part of the arc. This resulted from an interaction of (A) Local E-W directed compression related to a differential displacement of two parallel segments of the arc (generated by the displacement to the southeast of the Calabrian Arc and opening of the Tyrrhenian back-arc Basin), (B) Alternating NW-SE directed compression and extension (related to thrust wedge dynamics with phases of accretion and underthrusting respectively) and (C) Regional, compressive inter-plate stress (middle Messinian - middle Pliocene). All structures are overprinted by post-mid Pleistocene extensional faulting (related to rapid uplift of intra-arc massifs) and reversal along thrust planes and transcurrent faults. This extensional collapse reflects isostatic adjustments in response to plate rupture which was provoked by regional compressive stress.

INTRODUCTION

Over the last decades, a number of explanatory kinematic models has been proposed for the Neogene evolution of the Central Mediterranean Calabrian Arc (Fig. 1). One of the key features in these models are the intra-arc shear zones. These zones separate the arc into segments, and the differential movement of these segments should explain the bend-shape of the arc ("Secondary Arc" model sensu Ries and Shackleton, 1976; "Orocline" or "Non-rotational arc"; see Marshak, 1988 for a discussion concerning terminology). For an extensive review of these models, we refer to Van Dijk and Okkes (1990, 1991). Models favouring a radial development of the arc, such as oroclinal bending ("Bending Models"; Ghisetti and Vezzani, 1982a, 1982b) or radial divergent movement of crustal blocks related to radial spreading of the back-arc basin ("Radial Drift Models"; Dubois, 1976; Wezel, 1981, 1985; Finetti and Del Ben, 1986), emphasize the existence of transtensional or purely tensional radial shear zones. Models favouring a development along an E-W trending dextral southern Tyrrhenian shear hypothesize the existence of E-W trending dextral shear zones ("Sphenochasm Models"; Vogt et al., 1971; Locardi et al., 1976; Boccaletti and Dainelle, 1982; Boccaletti et al., 1984, 1986; Selli, 1985). Models based on differential movements to the SE of parallel segments assign a key role to NW-SE trending shear zones and their NE-SW trending conjugates. These last models imply sinistral shear in the north and dextral shear in the south of the arc. This model is part of a group of "Translation Models" (Moussat, 1983; Auroux et al., 1985, 1987; Meulenkamp et al., 1986; Meulenkamp and Hilgen, 1986), which finds its roots in a folding model of Carey (1962, 1976, his Fig. 143) for the Mendocino orocline, and which was recently also applied to the Alboran Arc by Frizon de Lamotte et al. (1991). No general agreement exists regarding the trend of these shear zones; it varies from $N120^0$ (Moussat, 1983) to $N135^0$-140^0 (Meulenkamp et al., 1986).

In order to clarify and resolve major contradictions between the proposed models, there is a great need of detailed field data from the Neogene terrains of the arc. Therefore, we carried out a detailed 1:25.000 (southern part) and 1:10.000 (northern part) mapping of the Neogene terrains of the central area of the arc during a number of field campaigns from 1983 till 1991. These detailed field studies resulted in new kinematic basin models and in a new structural model for the Calabrian Arc which is based on a comparison of data on basement structure, Neogene basin development, and seismic sections (Van Dijk and Okkes, 1988, 1990, 1991). According to this model, the post-Eocene development of the arc is controlled by two sets of oblique shear zones, a NW-SE and a NE-SW trending conjugate system. These structures are genetically linked with thrusts observed in the off-shore Calabrian Accretionary Wedge. As such, the outcropping terrains of the arc can be regarded as an emerged part of the accretionary prism (Van Dijk, 1985; Van Dijk and Okkes, 1988, 1990, 1991; see also Casero et al., 1988 and Roure et al., 1990, 1991 for the Southern Apennines and Sicilian Maghrebides). These structures are overprinted by a post-middle Pleistocene pattern of concentric and radial (trans)tensional faults (Fig. 1).

The present paper summarizes the available stratigraphic and structural data concerning the Petilia-Rizzuto Fault Zone (PRFZ; Fig. 1). The PRFZ represents one of the major NW-SE trending intra-arc shear zones. It has been defined by Van Dijk (1985) and Meulenkamp et al. (1986) as a major break between the tectonostratigraphic successions of the southern segment (Sila Piccola area) and the central segment (Crotone Basin) of northern Calabria (Fig. 2). It is named after the villages of Petilia Policastro and Capo Rizzuto (Fig. 2). The authors interpreted the fault zone as a sinistral shear zone, whereas Boccaletti et al. (1984) hypothesized dextral shear along a major fault zone which coincides with the northeastern continuation of the PRFZ (Van Dijk and Okkes, 1990). On the other hand, many authors postulate the existence of a major ENE-WSW or E-W to ESE-WNE trending sinistral (e.g. Caire, 1962, 1975) or dextral (e.g. Boccaletti et al., 1984, 1985, 1986) fault zone intersecting the studied area or trending along its southern margin.

Features which are indicative of syn-depositional tectonic activity will be presented within a high-resolution stratigraphic framework. It will be shown how our kinematic basin models derive from the integration of all available data concerning deep structure and Neogene evolution. The present paper will focus on the role of the intra-arc shear zones in the kinematics of thrust-belt basins. As such, this case study has served as an example for other areas and timeslices. In addition, we will relate the basin evolution to the kinematics of the arc and discuss our models in a regional context.

TECTONOSTRATIGRAPHIC FRAMEWORK & SEQUENCE STRATIGRAPHY

The area under investigation comprises a complex association of upper Serravallian to Recent sedimentary terrains which overly the Sila basement. This basement shows a thrust nappe pile composed of Paleozoic granitic and metamorphic rocks, remnants of a Mesozoic - Paleogene ("Panormide") cover, ophiolitic, mid-Cretaceous to Paleogene ("Liguride") metasedimentary rocks, and an Early Miocene tectonostratigraphic Complex consisting of slices of basement rocks and middle Oligocene to Lower Miocene clastic successions (Table 1). For a more detailed documentation of the Upper Neogene and references to facies models, we refer to Van Dijk (1990). Figure 5 shows the composite stratigraphic columns for various sectors defined in Figure 6.

The reconstructed tectonostratigraphy gives a remarkably detailed picture of especially the middle Miocene to Lower Pliocene interval, which contains a high number of unconformities in marginal areas.

The lowermost Late Neogene units consist of upper Serravallian - lower Messinian continental and shallow to open marine clastic deposits (Mesoraca Group, Belcastro Group and Caccuri Group), which can be subdivided into two main sequences. A lower Messinian transgressive limestone and gypsum level ("1st" or "lower evaporites"; Scavino Group) can be traced over the whole area. A thick succession of middle-upper Messinian marginal coarse clastic deposits (Teodoro Group), and basinal clastic evaporites ("2nd" or "upper evaporites"; Lucrezia Group) covered by continental deposits ("Lago Mare"; Carvane Group) are present in the northern and the southern-central part of the area, respectively. Remnants of lowermost Pliocene open marine marls and clays have been preserved in the southeastern part of the area, while in the southwest a thick sequence of Lower Pliocene clays (Tesorerato Fm) is present. Lower Pliocene marine sands and conglomerates (Belvedere Fm) are also found in an upfaulted block in the north (Crotone Basin). The base of middle - Upper Pliocene deposits (Baretta Fm) can only be traced in the northern area (Crotone Basin), while in the central area Upper Pliocene - Lower Pleistocene deposits (Cutro Fm, San Mauro Fm) occur in downfaulted blocks. In the whole area, Upper Pleistocene continental and marine deposits are present in fluvial and coastal terraces.

Figure 5 also shows a subdivision of the reconstructed tectonostratigraphy into unconformity-bound sequences. Van Dijk (1990, 1991) extensively discussed the sequence stratigraphic aspects of the Crotone Basin, focussing on sea level versus tectonic control on the origin of the sequence boundaries.

TECTONIC STRUCTURE

We subdivided the Neogene part of the investigated area into a number of fault-bounded sectors (Fig. 6). These sedimentary sectors are each characterized by a unique tectonostratigraphic succession (Fig. 5). Furthermore, we subdivide the basement into sectors as well (Fig. 6), each displaying their characteristic association of tectonic units. The latter subdivision is based on available literature data and on limited field observations (Table 1). A number of composite cross sections show the principle structural features of the region (Fig. 3). Combining the data regarding the distribution and geometry of the Neogene successions and the Sila basement, the following general conclusions can be drawn:

The Petilia-Rizzuto Fault Zone (PRFZ; Fig. 6) can be defined as a NW-SE trending, 10 km wide zone (basement Sector 5 north of the Arietta Fault Zone, and sedimentary Sectors 3, 2 and 5A). Due to a rapid Pleistocene-Recent uplift of the Sila massif, various structural levels of the fault zone (in a vertical sense) crop out in the study area. Three levels can be recognized: The deepest structural level comprises the basement of the Sila exposed in the northwestern part of the area (Sector 5). An association of NW-SE trending intershuffled basement wedges is present, showing overthrust relations with a northeast or a southwest vergence. The intermediate structural level is exposed in the central part of the area (Petilia-Mesoraca area; sedimentary Sector 3; Fig. 3c). It shows complex fault-bounded relations between relatively complete middle-upper Miocene successions and basement rocks. This area is characterized by a NW-SE trending braided zone of anastomosing normal as well as reverse faults. The highest structural level occurs in the southeastern part of the area (sedimentary Sector 2; Fig. 3b). It comprises Messinian to Lower Pliocene deposits which form part of a southwest-west-northwest verging thrust belt.

The disrupted terrains of the thrust belt are characterized by rootless anticlines cut by forelimb forethrusts and forelimb backthrusts (cf. De Feyter and Menichetti, 1986 in the Northern Apennines). Detachments occur along and within lower-upper Messinian evaporites. Deformation is restricted along the thrust soles within melange zones with thicknesses of several tens of metres. These show a sheared argillitic matrix of scaley clays, heavily deformed inbedded blocks with diameters of up to several tens of metres, and shear zones along gypsum streaks and veins. The imbedded slivers of Scavino limestones and Carvane conglomerates (Figs. 3b-d) are often lenticular shaped and overturned, and show compressive deformation such as pitted pebbles in the conglomerates. These are probably isolated horses (cf. Morley, 1988; his Fig. 5) plucked out of the steep forelimbs of anticlines in the lower thrust sheet. They also resemble the hard-rock "knockers" as described from other accretionary wedges (e.g. Karig, 1979). Interesting, comparable features are present along thrust zones near the village of Careri in southern Calabria: Striated boulders of gypsum conglomerate of several

metres in diameter which are present along the thrust sole detachment levels within the Messinian can be interpreted as "thrust-sheet ball-bearings".
The southwestern part of the area (basement Sectors 1, 4 and 6, continuing into sedimentary Sector 1a; Fig. 3a) can be regarded as one single structural block, the Sila Piccola block, which is delimited to the northeast by the PRFZ. This block is intersected by the NE-SW trending Tribisina and Sersale Fault Zones, and by the NW-SE trending Albi-Sellia Fault Zone. Zones of overthrusting, cataclasis and mylonitization are present in basement rocks and in Upper Oligocene - Lower Miocene deposits (Sersale Fm) along these fault zones. Large N-S trending normal fault zones locally dominate the structural pattern. The Neogene successions in this area are relatively condensed and gently dip to the south-southeast. NW-verging (low-angle) thrusts occur along the Sersale and Tribisina Fault Zones.
The northern part of the area (basement Sector 2 and its sedimentary cover in Sectors 4 and 5B-E; Fig. 3d) is part of the so-called "Sila Grande block" and of the Crotone Basin. The sedimentary successions along the Sila margin (the N-S trending Cropani-Savelli Fault Zone) show a monoclinal dip to the east, the axis of which locally coincides with east-verging steep basement thrusts. This area is intersected by numerous N-S, NNE-SSW and NE-SW trending normal faults.

The results of a quantitative analysis of the mapped faults intersecting the area are shown in Figure 7. Maxima of strikes occur in a NW-SE, NE-SW, N-S and E-W direction. Only subtle differences exist between fault strikes maxima in the various sectors, although distinct fault zones can be recognized on the map (Fig. 2). Together these NW-SE and NE-SW trending faults seem to form a nearly orthogonal conjugate system.
The (recent) overall overprint of tensional faults is of particular importance. Tension gashes filled with syntectonic gypsum fibres reflect the reversal of movement along most thrust zones (Fig. 3). Along some basement wrench faults, both sinistral reverse and dextral normal movement occurred (Fig. 8b).

BASIN DEVELOPMENT

The tectonostratigraphic data clearly indicate a separate development of the southeastern Sila Piccola block, the PRFZ, and the northeastern Crotone Basin. The Sila Piccola was characterized by a basin opening to the south-southeast. This evolution was controlled by tilting and faulting along NE-SW trending fault zones (Tribisina Fault Zone, Sersale Fault Zone, see Fig. 6), and faulting along NW-SE trending faults. The Crotone Basin shows a basin opening to the E, with a basin margin following the present N-S trending margin of the Sila basement. In the PRFZ, a large number of very small basins originated each displaying its own characteristic stratigraphic sequence. These basins were mainly defined by NW-SE and small E-W trending faults (Fig. 2). The activity along these faults resulted in many local unconformities and a complex configuration of basin margin deposits, characterized by rapid facies changes, fault scarp breccia wedges, debris flow deposits and slide-blocks. The recurrent uplift and subsidence of these small adjacent fault-bounded blocks neatly fits the term "touche-de-piano tectonics" ("keyboard tectonics") (cf. Brock, 1956, p. 33).
Figure 10 summarizes the various aspects of the late Neogene evolution of the region, which will briefly be described in the next paragraphs. We distinguish eight successive episodes (Figs. 10a-g). For each episode, the development of the southern area (Sila Piccola), central area (PRFZ) and the northern area (Crotone Basin) will be summarized. We used the following criteria in determining syn-depositional tectonic activity (Fig. 10h): Growth faulting, general patterns of facies distribution which reveal the trend of depositional systems, occurrences of coarse clastic marginal facies, slumps and slides, and sediment transport directions inferred from channel fills, foresets, etc. Furthermore, basin margin phenomena such as buried block-faulted terrains, angular unconformities, etc. (see for a discussion Van Dijk, 1991), give evidence for the tectonic activity responsible for the shaping of the basins. In most cases, this activity continued during the subsequent deposition of the sedimentary successions.

?Late Serravallian - Tortonian episode (Fig. 10a; ca. 11 Ma - 6 Ma)

In the Crotone Basin, a middle Tortonian transgression (Caccuri conglomerate-sandstone Fm) was followed by rapid subsidence (Lepre clay Fm of the Neogloboquadrina acostaensis Zone). This development was mainly controlled by a N-S orientated, fault-bounded margin. The margin was intersected by N120^0 and N080^0 trending faults which defined areas with subtle differences in sedimentary infilling. A submarine fan body, intercalated within the Tortonian clay successions and overlain by clays onlapping along the margin, reflects a short phase of relative sea level fluctuation. In the Sila Piccola area a transgression was accompanied by growth faulting to the south-southeast (Belcastro sand Fm, followed by the rapidly onlapping Valle clay Fm). Within the PRFZ, initial basin development in the late Serravallian - Early Tortonian occurred along N120^0 trending faults, delimiting small areas with a strong differential subsidence, each building up its own record (Mesoraca Fm; Neogloboquadrina continuosa Zone - N. acostaensis Zone). N60^0-N80^0 faults played a minor role. In general, an evolution from continental to marine environments took place. In these small areas, we were able to reconstruct the most comprehensive succession for this period. In the transitional area between the Sila Piccola and the PRFZ (between Arietta and Cropani) growth faulting occurred along N060^0-N080^0 trending structures. This can be inferred from the presence of large wedges of basal conglomerates along these growth fault scarps.

Early Messinian episode ("1st Evaporite Phase"; Fig. 10b; ca. 6.0 - 5.5 Ma)

This episode started with a transgression in the Sila Piccola area and the PRFZ (conglomerates and clays of the Globorotalia conomiozea Zone; various members of the Scavino Fm). The deposits overly remnants of block-faulted and eroded upper Serravallian - Tortonian successions. This indicates a short tectonic pulse at the Tortonian - Messinian transition. The transgressive sediments are overlain by marls and diatomites (Verzino Fm), which reflect the onset of restricted conditions related to the Messinian salinity crisis. In the Crotone Basin sapropelitic layers and slumps are intercalated in lower Messinian marine clays (Lepre Formation) which are followed by deposits of the first evaposite phase (Trabbese clastic gypsum Fm). In the Sila Piccola area and PRFZ the "lower evaporites" are clastic limestones of various types (Scavino Fm; "Calcare di Base"). They are a marginal equivalent of the gypsum deposits in the Crotone Basin.

Middle Messinian episode ("2nd Evaporite Phase"; Fig. 10c; ca. 5.5 - 5.2 Ma)

The basin development during this episode can be best reconstructed from the successions in the PRFZ. A phase of strong fragmentation can be inferred from the Teodoro Formation. This is a complex association of coarse clastics and limestone olistostromes which is present along the basin margins. It consists of allochtonous limestone slabs which derived from the Scavino Fm ("Calcare di Base"). The deposits were confined by N140^0 and small N090^0 trending growth fault scarps which define limited sedimentation areas along the margins of small basins in which turbidite sequences developed. These sequences contain megaturbidites which are mainly constituted of limestone fragments. The internal structures of these mass flow deposits strongly resemble those of the megaturbidites described by Seguret et al. (1984, Fig. 3 and 6) for the compressional margins of the Eocene South Pyrenean basins. These were termed "seismoturbidites" by Mutti et al. (1984). The complex pattern of small marginal basins constituted the NW-SE oriented margin of a larger evaporite basin to the east and northeast in which a succession of fine-grained sediments with intercalated gypsum arenites, halites and sandstones was deposited ("upper evaporites"). This evaporite basin probably is the most southwestern segment of a system of NW-SE trending half grabens which were all filled with middle-upper Messinian evaporites. The grabens together constitute the middle-late Messinian Crotone Basin. Less deformed equivalents of this half graben system can be seen in seismic profiles off-shore Crotone (see Auroux et al., 1985). In the Sila Piccola area, remnants of successions deposited during this episode are coarse clastics such as scarp breccias, olistostromes and debris flow products. These are found along NW-SE trending fault scarps at the base of large conglomerate bodies of middle-late Messinian Age. The total pattern (Fig. 10c) suggests folding and thrusting of the basement on a regional scale, with a N140^0 trending axis situated within the present-day Sila Piccola area.

Late Messinian episode ("Lago Mare Phase"; Fig. 10d; ca. 5.2 - 5.0 Ma)

During the deposition of the late Messinian continental "Lago Mare" successions, partial erosion of the evaporite sequence occurred which indicates a relative lowering of sea level. The following observations indicate that this sea level drop was associated with tectonic activity: Small, mesoscopic growth faults are observed in the Carvane conglomerates. Upper Messinian coarse clastics both vertically and laterally grade into fine-grained lagoonal deposits in the Sila Piccola area. These features are both present along the SW-NE trending Tribisina Fault Zone, which acted as a hingeline to the south.

Early Pliocene episode (Fig. 10e; ca. 5.0-4.0 Ma)

Both in the Sila Piccola area and in the PRFZ, coarse clastics locally overlying basement rocks reflect the increase in supply of clastic material due to a tectonic pulse at the Messinian - Pliocene transition (Arvano sand Fm and Calamo conglomerate Fm). These deposits are covered by clays and marls of the Sphaerodinellopsis Acme Zone, which reflect the Early Pliocene "flooding". Clear indications for the fact that the early Pliocene flooding event was associated with tectonic activity (see also Van Dijk, 1990, 1991), are also present near the villages Ardore and Benestare in southern Calabria, were small (mesoscopic) growth faults can be observed in successions of upper Messinian conglomerates and sandstones and (probably shallow marine) basal Pliocene sands and "Trubi" marls. Remnants of lowermost Pliocene fines are present in the southern part of the PRFZ, along the Tribisina Fault Zone, and in the Botricello-Tenese region. The earliest Pliocene events were shortly afterwards followed by limited tectonic activity (block faulting) along the basin margin and a subsequent transgression in the Sila Piccola area (clays of the Globorotalia margaritae Zone). The episode came to a close in the late Early Pliocene by an overall regression in the Crotone Basin (coarse clastics of the Belvedere Fm). In the Sila Piccola area slumping to the south (Cosco Member of the Tesorerato Fm; Globorotalia margaritae-Globorotalia puncticulata Zone) points to a steepening of the Ionian slope.

Late Early Pliocene phase ("Basin inversion phase"; Fig. 10e; ca 4.0-3.0 Ma)

The effects of this tectonic phase can nowadays be studied at various structural levels: In the Petilia-Mesoraca area, large N130^0-N135^0 basement faults cut through the overlying sediments. Reverse faulting to the SW along these faults and along N140^0 and N120^0 trending faults occurred (Figs. 8b and c). These faults can be linked to thrust zones of various crystalline units in the Sila which occur in a narrow, NW-SE trending zone (Sector 5). In the Marcedusa-Botricello area, the Messinian deposits were thrusted in an east-southeastern and in a northwestern direction (Figs. 8b and c), i.e. towards the basin margins. This resulted in a horizontal shortening of about 5 to 10 km. In the south, near M. Tenese, SSW-directed thrusting occurred with related antithetic faulting (Fig. 3b, profile c). We assign the southward directed sliding of Lower Pliocene clays in the Sila Piccola area (Tesorerato Fm) to this phase (Fig. 8). However, it can not be excluded that this phenomenon is younger. It indicates a steepening of the Ionian slope due to tilting. This assumption is in agreement with the observed slumping in the top of the succession (Cosco Mb).

Late Pliocene - Early Pleistocene episode (Fig. 10f; ca. 3 - 1 Ma)

The onset of this episode can not be reconstructed in the studied area. The Crotone Basin rapidly subsided and a complex pattern of migrating barrier systems developed (Baretta Fm; Cutro Group; G. puncticulata Zone, Globorotalia crassaformis Zone). In the Sila Piccola area, no successions belonging to this episode are present, and, therefore, the PRFZ seems to have delimited the area of deposition. We were, however, unable to reconstruct the marginal facies up to now. In the extreme southwest of the area, near Catanzaro, deposits belonging to the G. puncticulata Zone unconformably overly the late Early Pliocene thrust wedges. The uppermost deposits (Cutro Fm; San Mauro Fm; Globorotalia inflata Zone) indicate a rapid Late Pliocene regression which was followed by an Early Pleistocene transgression. Remnants of the transgressive deposits are present in the Crotone Basin and in the Catanzaro depression.

Middle Pleistocene - Recent episode (Fig. 10g; 1 Ma - Recent)

The youngest episode was characterized by uplift and tensional faulting which affected all previous deposits. Upper Pliocene - middle Pleistocene successions are intersected by NNE-SSW and NNW-SSE trending small tensional faults, some of which are arranged in fairly continuous fault zones. Furthermore, antithetic faulting along NW-SE and SW-NE trending faults occurred, as indicated by NW dipping remnants of Upper Pliocene sandstones (Mauro Fm). Along the margin of the Sila numerous N-S trending tensional, listric faults occur, which originated in response to the rapid dome-shaped uplift of the Sila Piccola massif (see below). Synsedimentary tilting to the east-northeast occurred, reflected by tapering in the Upper Pleistocene deposits near Le Castella (Millazian, Neotyrrhenian; Selli, 1962) in the southeast of the study area (see also Cosentini et al., 1990). The chaotic debris flow deposits of the Magliacane Formation reflect the instability of relief related the rapid Late Pleistocene uplift. The episode was characterized by the formation of several coastal and alluvial terraces probably defined by glacio-eustatic sea level fluctuations in combination with uplift of the Sila massif. The overprint of extensional reversal of movement along thrust faults and wrench faults (see above) is also placed in this episode.

DEEP STRUCTURE AND KINEMATIC MODEL

In order to reveal the regional subsurface structure of the area, we compared our data with published information on the basement structure, seismic profiles and aeromagnetic data (see Fig. 11 and the references in the figure captions). This comparison led to the following conclusions:

A. Lateral continuity: The surface-trace of the PRFZ can be followed through the Sila massif on recently published maps up to the village of Luzzi (north of Cosenza). Its continuation, still farther to the NW, up to S. Sosti (east of Belvedere Maritimo), can be seen on published maps (Fig. 11a). In those regions, the fault zone cuts the Central Crati Valley and defines the northern margin of the Coastal Chain. Satellite lineament maps show a large number of lineaments which coincide with the NE and SW limits of the PRFZ (Fig. 11b). Aeromagnetic maps of the Central Mediterranean reveal an aproximately N130^0 trending rectilinear magnetic anomaly which corresponds with our Sila Piccola block. Furthermore, the general trend of the anomalies in the region is N130^0 (Fig. 11b). We propose to call this large linear structure the Petilia-Sosti Zone, which can clearly be traced over a length of 130 km. This quite impressive lateral continuity strongly suggests that the fault zone represents a crustal shear zone.

B. Basement structure: The Petilia-Sosti Zone delimits two areas in northern Calabria with clearly different thrust nappe geometries (Fig. 11a). We interpret the zone as the surface trace of the NE-directed overthrust of the Monte Gariglione Unit over the Longobucco Unit. Parts of the Monte Gariglione Unit situated to the northeast of the Petilia-Sosti Zone can be regarded as tectonic flakes which were displaced relatively further to the northeast. It should be kept in mind, however, that thrusts along the strike of the zone do not necessarily indicate a deeper oblique character. They may also be remnants of positive flower-structures which developed as a reaction on lateral movements along a subvertical shear zone. The patterns of distribution of rock-types and overthrust zones (Fig. 11c) points to a post-Eocene sinistral displacement of circa 50 km. A large part of this movement may have taken place during the Late Oligocene - Early Miocene timespan (Van Dijk and Okkes, 1991). Data on mesoscopic structures in the basement indicate a sinistral wrenching (Fig. 8d). Along the trace of the N-S trending fault zone which determines the margin of the Crotone Basin, west verging thrusts were observed in the basement (Pezzota et al., 1973).

C. Seismic sections: The NE-SW trending Sersale and Tribisina Fault Zones can be regarded as the surface traces of southeast verging thrusts similar to structures observed in the seismic profile M-60 in the Gulf of Squillace (Finetti, 1981, 1982; Finetti and Del Ben, 1986).

D. Basin configuration: The Neogene basin configuration indicates that the Sila Piccola block forms a structural high with respect to the Crotone Basin. The data reveal synsedimentary activity along the PRFZ since at least the late Serravallian. Figures 11a-g demonstrate that the fault zone was active during each episode and that it separated a northern from a southern area of deposition. Progressive tilting of strata in the southwestern area to the southeast, and synsedimentary faulting and hingeline activity along the NE-SW trending fault zones has been reconstructed. This supports the interpretation that these fault zones can be regarded as surface traces of southeast verging thrusts. The reverse faults (Figs. 8b and c) in the sedimentary cover can be interpreted as backthrusts. As such, they fit into the patterns of vergences as indicated by basement structure and seismics.

All data support a kinematic model (Figs. 12 and 13) in which the Petilia-Sosti Zone is a deep oblique sinistral convergent shear zone, created by differential displacements of two crustal blocks: the Sila Grande block in the northwest, and the Sila Piccola block in the southwest. The displacement to the southeast of the Sila Piccola block provoked the activity along the NE-SW trending Sersale and Tribisina thrust zones. The model implies dextral shear along the NE-SW trending shear zones. This results in a picture of a conjugate set of two intersecting oblique shear zones, a transversal one (NW-SE; "Apennine") and a longitudinal one (NE-SW; "Anti-Apennine"). The present-day Petilia-Rizzuto Fault Zone can be seen as the intensely deformed belt between the two blocks, and includes the sedimentary cover which was backthrusted upon the Sila Piccola block in mid-Pliocene times.

In terms of models based on modern accretionary complexes (Davis et al., 1983; Silver et al., 1985, Byrne et al., 1988, and references therein) and on the results of experimental studies (e.g. Malaveille, 1984; Byrne et al., 1988), the Sila basement played the role of a backstop. Limited out-of-sequence thrusting (cf. Morley, 1988) along the NE-SW trending thrust zones contributed to the wedge-shape of this backstop. It dips beneath the fore-arc basin, whereas, more externally, the thrust wedge dips steeply arcward beneath the backstop (cf. Byrne et al., 1988, their Figure 13b). The southeastward directed movement provoked backshear motion within the sedimentary cover of the fore-arc basin. Backthrust phenomena are common along the margins of Calabrian Basins (e.g. the Cariatidi thrust mass along the northeastern margin; see Van Dijk and Okkes, 1988, 1990, 1991), and also in the southern Apennines (Grandjacquet and Mascle, 1978; Roure et al., 1990, 1991).

The Petilia-Sosti Zone may represent a deep SW-dipping crustal shear zone branching from a mid-crustal detachment at a depth of about 25 km (see also suggestions by Van Dijk and Okkes, 1991). The shear zone may have acted as a brittle-ductile zone between two terranes within the arc (Van Dijk and Okkes, 1988, 1990), resembling the Palomares Shear Zone in the Betic Cordilleras described by Weijermars (1987).

We propose that the following basin models may be applied: The Crotone Basin can be regarded as a thin-skinned oblique pull-apart basin (Van Dijk, 1985; cf. Royden, 1985 for the Vienna Basin), locked between two intra-arc oblique shear zones. The basin evolved into a "detached slab basin" (Van Dijk, 1990; see below). For the basins evolved in the areas along the southern margin of the Sila Piccola block, we propose the name oblique rhomboidal "harmonica basins" (Fig. 12). This is because their evolution in plan view -within the oblique conjugate fault system- resembles the movement along the sides of a fold-up winerack. In profile, they are situated upon a set of paralell sliding thrust slices, resembling a folding-wall. The Petilia-Sosti transverse shear zone separates these two areas, and played an alternating role: During certain episodes sediment transport and deposition was concentrated along the fault zone (cf. Ricci-Lucchi, 1986 for the Northern Apennines), whereas during others the fault zone formed a positive hinge zone between two differentially tilting areas.

These specific basin types, one evolving into the other, are special cases or end-members of a tremendous variety of basins occurring within (oblique) fold-and-thrust belts (Kingston et al., 1983). This group of basins is known as "intra- and inter-arc", "trench associated" (Kingston et al., op. cit.), "supra-complex", "fore-arc", "subduction related" (Klemme, 1980) or "foreland satellite" (Ricci-Lucchi, 1986) basins. We prefer the term "thrust-belt basins", which is short, more general and unrelated to specific features of the contractional plate margin. Other end-members belonging to this group are "piggy-back basins" (Ori and Friend, 1984; related to in-sequence thrusting) and "summit basins" (Geist et al., 1988; along the internal, back-arc margin; they are equal to the "intra-deep" or "back" basins of Boccaletti et al., 1990).

A new feature which has come forward from our studies is the recurrent inversion of all these types of thrust-belt basins through backshear motion, related to accretion phases with out-of-sequence thrusting. In the light of knowledge on the complex behaviour and evolution of thrust-belts (e.g. Butler, 1982; Moore and Sample, 1986; Platt, 1986; Gillcrist et al., 1987; Morley, 1988; Cooper and Williams, 1989; McClay, 1992) this "mixed-mode" evolution (cf. Gibbs, 1987) can be appreciated. It indicates that contraction and extension, display a wave-like shifting (waxing and waning) through the thrust-belt. Van Dijk (1990; see below) showed that these recurrent inversions (late Burdigalian; Van Dijk and Okkes, 1989, 1991; mid Pliocene; op. cit. and this paper, mid Pleistocene; op cit. and Argnani and Trincardi, in press.) are a response to a switch from tensional to compressional trends in regional interplate stress (see further).

The presented model shows affinity with models as have been described for the Aleutian Arc, Sunda Arc and Makran region (Karig, 1979; Lewis et al., 1988; Geist et al., 1988; Marshak, 1988, and references therein), with respect to the combination of oblique thrusting along the accretionary prism and the development of conjugate strike-slip fault systems within the segmented arc. In our model, however, the conjugate systems are also obliquely convergent.

KINEMATIC EVOLUTION

The differential movement of the Sila Grande and Sila Piccola blocks relative to one another started in the late Serravallian - early Tortonian with the generation of en-echelon N120°-N130° trending synthetic Riedel shears within the PRFZ. These structures delimited the oldest basins (Fig.

10a). This proces continued during the Tortonian - early Messinian with basin formation in the Sila Piccola block by tilting due to movement to the southeast, and by the opening of the Crotone Basin. These two areas were linked by left stepping en echelon N060°-080° trending antithetic Riedel shears creating a "staircase" geometry of the basin margin. During this stadium, the Sila Piccola block moved continuously to the southeast along the NE-SW trending thrust zones. The anti-Riedel shears played a subordinate role in the basin generation.

The middle Messinian tectonic phase can be considered as the next step in the development of the sinistral shear zone. N140° trending P-structures were formed, which connected the Riedel shears. These P-shears were interconnected by small E-W tensional faults. The monoclinal folding of older deposits along the N-S trending margins can be regarded as flexure of the cover overlying steep east-verging reverse faults. This proces is comparable with the activity of the "Duwi flexure" in the Gulf of Suez, as described by Jarrige et al. (1990, their Figure 12). All these structures defined the complex margin of the late Messinian - Early Pliocene northeasterly situated Crotone basin (Fig. 10c). The evolution of this basin was characterized by the progressive development of a number of semi-paralell half grabens with the steep margins along NW-SE trending shear zones.

The last stadium in development of sinistral shear is the late Early Pliocene inversion phase. Figure 13 shows a 3-D cartoon of the relations between the various directions of movements in the late Early Pliocene, using the interpreted deeper structure of the fault zones. The model shows how the oblique sinistral activity of the PRFZ and the southeastward out-of-sequence thrusting within the accretionary complex caused the basin inversion and backthrusting to the SW to W to NW along the fault zone (Figs. 8b and 8c). The Sila Piccola block bended to the south and formed a steep slope, followed and/or accompanied by backthrusting to the NW.

The development along a NE-SW cross-section (compare the insets of Figs. 10a-e) shows that a small Messinian - Early Pliocene half graben was inverted in late Early Pliocene times by thrusting of the sedimentary infill towards its steep margins, partly along pre-existing faults (cf. Meulenkamp et al., 1986). This development shows affinity with the model proposed by Tricart and Lemoine (1986) and reviewed by De Graciansky et al. (1988) for the progressive development of Eocene halfgraben systems into contracted Oligocene megamullions in the Western Alps. It also shows inversion along intrabasinal faults similar to the model of Welbon (1988). Furthermore, the Tortonian - Early Pliocene development can be projected onto the so-called "Strike-slip Cycle" as defined by Mitchell and Reading (1978) and Reading (1980) (Fig. 9). In this case it reflects the progressive development of a sinistral transpressive shear zone.

The Late Pliocene - Pleistocene episode was characterized by a tensional regime with large subsidence rates in the Crotone basin (Van Dijk, 1990, 1991). This can be regarded as a new stadium with probably mainly differential vertical movements along the PRFZ which are, however, hard to reconstruct. Van Dijk (1991) concluded that the Late Pliocene - middle Pleistocene evolution of the Crotone Basin can be interpreted in terms of a response to instability in the thrust-wedge due to rapid, pulsating accretion along the trench in the External Calabrian Arc (seismic profile M-60; Finetti, 1981, 1982). The basin was situated upon a shallow slab, detached at a depth of circa 2 km along a decollement zone within the Messinian evaporites, which slided to the southeast. This slab, facing the subduction trough, thus helped to restabilize the critical taper of the Coulomb wedge, which increased as a result of underplating (Van Dijk, 1990, 1991; using suggestions of Van Bemmelen, 1976; Davis et al., 1983; Platt, 1986; Dahlen, 1990). The PRFZ probably delimits the slab to the southwest. This implies a late dextral (and thus reversed) transcurrent movement, which is in conformity with the data (see above). An analogous feature, though younger, can be observed in seismic sections along the southern Sicilian "Gela nappe" front (Trincardi and Argnani, 1990).

The rapid post-middle Pleistocene uplift of the Sila massif (0.1-0.5 cm/yr; Van Dijk, 1991), the extensional overprint and the reverals of thrust and transcurrent movements show all characteristics of an extensional collapse as proposed by Dewey (1988) for the late Alpine Mediterranean region. Reversals along thrust planes can also be seen in seismic profile M-60 (Finetti, op. cit.). Extensional collapse-related reversal of transcurrent movement can, in fact, explain the apparent paradox as present in the datasets from other shear zones in the Calabrian Arc such as the Gela-Catania Fault Line and the Pollino Fault Zone (Fig. 1).

DISCUSSION

The proposed geometric and kinematic model illustrates the hypothesis of Van Dijk and Okkes (1990, 1991) of two intersecting oblique shear zone systems. Our data do not support the Bending and Radial drift models as outlined in the introduction. The Sphenochasm Models predict an E-W trending dextral shear zone in the studied region, as an extension of a southern Tyrrhenian dextral shear related to the rotational opening of the back-arc basin. There is, however, no indication of any E-W trending shear zone. The dextral N060^0 trending Sersale and Tribisina Fault zones may, on the other hand, be related to this vector. Contradictions between N120^0 trending and N140^0 trending wrench fault zones as postulated by various authors (see introduction) seem to be based on a geographical bias in the acquisition of structural data. Differentially moving N130^0 trending segments in the arc as envisaged by the Translation models will generate N120^0 to N140^0 oriented (transversal) wrench fault sets. The preferential development of one of the sets may be linked to the simple shearing of the segment involved, while both sets can be present along the margins of the segments (Fig. 14).

The conjugate set of oblique shear zones indicates an E-W directed axis of effective compressive stress (Fig. 12). This is in agreement with the results of small-scale measurements of Moussat (1983) in this part of the arc. In order to explain this (local) effective stress axis, we propose the interference of three components (Fig. 14): A differential displacement of the two arc segments, during which the more centrally positioned segment moved relatively faster, created a sinistral shear with a local ENE-WSW directed compressive stress (axis A of Fig. 14; cf. Sanderson and Marchini, 1984; Naylor et al., 1986). Furthermore, NW-SE extension prevailed during phases of subcretion/underplating/underthrusting (terminology after Scholl et al., 1980; Moore and Sample, 1986; Platt, 1986; Brown and Westbrook, 1988; coherent underplating of rootless thrust sheets below the Calabrian Arc is shown by Finetti, 19812, and by Mostardini and Merlini, 1986). A NW-SE directed component of compressive stress was active during phases of accretion (axis B of Figure 14; responsible for transtension along the shear zone). In addition, locally generated body forces, originating from pressure gradients due to gravity and acting normal to the trend of the wedge (cf. Platt et al., 1989) are responsible for a continuously acting radial compressive stress (NW-SE to NE-SW through E-W). The existence of a regional compressive NE-SW directed stress in middle Pliocene and in middle Pleistocene times is well known from the Central Mediterranean (axis C of Fig. 14; see for an extensive review Philip, 1987). Modern geodynamic syntheses of the region (see for an extensive review Van Dijk and Okkes, 1990, 1991) relate the southeastward displacement of the arc to the interplay of two processes: Passive subduction due to gravitational sinking of the relict Ionian oceanic slab and related roll-back and retreat of the hinge zone (Van Bemmelen, 1974; Ritsema, 1979; Horvath et al., 1981; Moussat, 1983; Malinverno and Ryan, 1984; Patacca and Scandone, 1989; De Jonge and Wortel, 1992), and asthenosphere inflow, upwelling and convection in the back-arc region (Van Bemmelen, 1969; Locardi, 1986; Channell and Marechal, 1989). This resulted in a gravitational displacement of the Calabrian lithosphere Element, a supracrustal slab, to the southeast (cf. Van Bemmelen, 1974; Horvath et al., 1981; Dijk and Okkes, 1988, 1991; Wang et al., 1989).

In such a system, thrust wedge dynamics will depend on the relative velocities of the roll-back of the subduction hinge zone (V_{rb}), and the displacement of the supracrustal slab (V_{sl}) (cf. Dewey, 1980; see also Jarrard, 1986a, b). In previous papers (Van Dijk, 1990, 1991), we proposed that small fluctuations in the regional inter-plate stress field (axis C) (cf. Cloetingh, 1988) mainly controlled the thrust wedge dynamics (axis B) in the following way: Small pulses in compressive regional stress temporarily blocked the roll-back process (V_{rb}->0) which provoked phases in thrust-wedge growth ($V_{sl}>V_{rb}$). This resulted in so-called "Composite tectonic events" (Figs. 9 and 15) of uplift/regression (thrust wedge contraction and accretion) rapidly followed by fragmentation(subsidence)/onlap (thrust wedge extension and restabilization of the wedge taper). In the same way, larger scale stress fluctuations resulted in basin inversion through backshear motions. This plate coupling mechanism also provides a satisfactory explanation for the fact that tectonic pulses which control the genesis of third- and second-order depositional sequences (Van Dijk, 1990) are synchronous in different Mediterranean areas. The NE-SW directed regional compressive stress in the Central Mediterranean (axis C) may have been generated by a NE-ward displacement of the African Plate (Mantovani, 1982; Mantovani et al., 1985) or by dextral transpression along the North African boundary zone and related "microplate" motions.

The observed strike-slip cycle coincides with the opening of the Central Tyrrhenian back-arc Basin, the Vavilov Basin. The Late Pliocene - middle Pleistocene episode coincides with the opening of the southern Tyrrhenian Marsili Basin. These data support a link between displacement of the arc to the southeast and shear along NW-SE trending intra-arc shear zones. The strike-slip cycle implies that the regional NE-SW trending compressive stress component (axis C) slowly changed from tensional to compressional from middle Messinian up till late Early Pliocene time (Fig. 14). The late Early Pliocene compressive phase coincides with a temporal cessation of back-arc rifting (see Van Dijk, in press. for details and discussion regarding Tyrrhenian spreading and subsidence patterns).
The post-middle Pleistocene extensional collapse can be related to isostatic restabilizations resulting from rupture and detachment of the subducted slab (cf. Görler and Giese, 1978 and Spakman, 1988, see also Van Dijk and Okkes, 1988, 1991; Wortel and Spakman, in press.) provoked by an increase in regional compressive stress (Van Dijk and Okkes, 1988, 1990, 1991). The rapidly rebouncing non-detached remnants of this slab are in fact situated below the Sila Piccola dome-shaped massif. The uplift and extensional collapse of those arc massifs and the extensional collapse of the Marsili back-arc basin (Van Dijk, in press.) are together responsible for the present-day semi-circular arc-shape of the Calabrian Arc.

CONCLUSIONS

The Petilia-Rizzuto Fault Zone acted as an oblique sinistral shear zone between the Sila Piccola block and the Sila Grande block since at least the middle Miocene. It is part of a 130 km long intra-arc shear zone which separates two NW-SE trending terranes and which shows a post-Eocene sinistral displacement of approximately 50 km. Detailed tectonostratigraphic analysis reveals that the development of the shear zone shows a strike-slip cycle with a late Serravallian - middle Messinian tension stage, a middle Messinian - Early Pliocene transpression stage, and a late Early Pliocene compression phase with basin inversion and major backshear motion. New kinematic models for thrust-wedge or supra-complex basins have been illustrated, such as thin-skinned pull-apart, rhomboidal "harmonica", and "detached slab" basins. A characteristic feature is the recurrent inversion of the basins through backshear motion linked to pulses in thrust-wedge growth. The stress field which controlled this evolution was created by an interaction of local intra-arc shear, thrust-wedge dynamics (alternating underthrusting episodes and accretion pulses) and regional plate interactions.

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FIGURE CAPTIONS

Figure 1: Tectonic map and cross-section of the Central Mediterranean.

a. Schematic tectonic map of the Calabrian Arc.
Based on: Van Dijk and Okkes (1990, 1991) and references therein, and Argnani et al. (1987) and Argnani (1990) for the area south of Sicily, Makris et al. (1986) for the Calabrian Accretionary Wedge, Wezel (1985) and Finetti (1982) for the Tyrrhenian Basin.
The inset shows the location of the studied area. PRFZ: NW-SE trending intra-arc Petilia Rizzuto Fault Zone.
Examples of reversal of transcurrent movements (see text for a discussion): PFZ: Pollino Fault Zone (Ghisetti and Vezzani, 1982c: post-Messinian dextral; Moussat, 1983; sinistral) and GCFZ: Gela-Catania Fault Zone.
b. Schematic NW-SE cross-section of the Calabrian Arc.

Figure 2: Schematic tectonostratigraphic map of the studied area.

For the stratigraphic legend see Fig. 4. The map is based on a 1:25.000 and 1:10.000 mapping of the Neogene part of the region (1983-1988). The basement has been compiled and modified after 1:25.000 maps of Burton (1962) and Pezzota et al. (1973) and on the papers mentioned in table 1. The information concerning the Neogene structure on the maps and profiles of Hughes (1961), Roda (1964), Selli (1962, 1973, 1975), Dubois (1976), Tortorici (1981) and Cosentini et al. (1989) has been critically reviewed.

Figure 3: Schematic tectonostratigraphic cross sections of the studied area.

For the locations of the sections see Fig. 6. For the stratigraphic legend see Fig. 4.
Note that late Early Pliocene thrusts are consequently cut by often steeper dipping, normal faults.
a. NW-SE cross section of the southwestern area (Sila Piccola).
b. NW-SE and NE-SW cross section of the Marcedusa-Botricello area.
Note the antithetic listric faulting and related melange formation (Steccato Zone) near T. Tenese, which is related to instability of the hanging wall of south vergent thrusts.
c. SW-NE cross sections of the Mesoraca-Petilia Policastro area.
d. W-E cross section of the southern part of the Crotone Basin.

Figure 4: Legend for the Figures 2, 3 and 5.

Figure 5: Schematic tectonostratigraphic composite schemes for the studied area.

a. Compiled after Van Dijk (1990). The column for the Simeri area has been slightly modified for the upper Messinian deposits. Thicknesses are indicated in meters. We dated the deposits by means of analyses of planctonic foraminifera of some 160 clay samples according to the biostratigraphic zonations of Zachariasse and Spaak (1982) and Spaak (1983). See for legends the Figures 4 and 5b.
b. Legend for Figure 5a.

Figure 6: Schematic subdivision of the studied area.

The subdivisions only serve as descriptive concept because the boundaries between these sectors are not always discrete. Fault zones (associated with overthrusts, cataclasis and intense mylonitization) which delimit the basement sectors continue along the boundaries of the Neogene sectors. It can, therefore, be appreciated that they also defined the areas of differential sedimentation or subbasins. The locations of the cross sections of Fig. 3 are indicated.

Figure 7: Quantitative analyses of mapped faults.

a. Total dataset of faults. We measured strike and length along the strike on the map. The faults have been taken from our 1:25.000 and 1:10.000 maps.

b. The data on faults, separated according to the Neogene sectors they intersect.

Figure 8: Examples of quantitative analyses of some tectonic features.

a. Lower hemisphere equal-area stereogram of fault surfaces and slickensides contained in them, along the base of the Tesorerato clay Formation in the southwestern area (Simeri-Cropani Sector).
Plotted are poles to fault surfaces and striations. Contour intervals are 1.0, 0.5 and 0.25 % per 1% of area. The high angle between pitches of slickensides and poles to flat-lying fault surfaces indicates a gravitational sliding to the southeast. Exceptions occur along E-W striking dextral faults.
b. Lower hemisphere equal-area stereogram of mapped reverse faults. Plotted are poles to fault surfaces.
Indicated are the segments in which faults fall which occur in resp. the southeastern, central, and northwestern part of the PRFZ. This reveals a spatial rotation of the direction of contraction from northwest via west to southwest. An exception is the Monte Tenese thrust which shows a southeastern vergence.
c. Lower hemisphere equal-area stereogram of mesoscopic reverse faults and folds.
The data suggest thrusting towards NNW-W-SSW with some minor exceptions.
d. Lower hemisphere equal-area stereogram of mesoscopic faults with striations measured in granitic rocks in the Petilia-Mesoraca area.
The data fit into a sinistral wrench fault model with well developed Riedel (sinistral N120^0), antithetic Riedel (dextral E-W), and P (reverse sinistral N140^0) Shears. Note the occurrence of dextral tensional faulting along Riedel shears.

Figure 9: Synthetic diagram for the late Serravallian - Recent basin development of Central Calabria.

Slightly modified after Van Dijk and Okkes (1991). The late Serravallian - Early Pliocene episode consists of a Tension Phase of Basin Opening (late Serravallian - early Messinian), a Transpression Phase of Basin Fill ("flysch phase"; middle Messinian - Early Pliocene) and a Compression Phase with Basin Inversion (late Early Pliocene). The "uplift-subsidence composite pulses" created unconformities which bound depositional sequences reflecting sea level fluctuations. These can be correlated with third-order pulses of the Haq et al. (1987) global chart (Van Dijk, 1990). Rotations are based on paleomagnetic data of Scheepers et al. (1990).

Figure 10: Paleogeographic maps of the studied area.

Indicated are the criteria used for the reconstruction of the area. Deposits belonging to a certain episode are indicated on the map only where they have been encountered. The basin-fill cartoons on the left side of the figures are extrapolated from lithostratigraphic correlations.
a. Late Serravallian - Tortonian
b. Early Messinian
c. Middle Messinian
d. Late Messinian
Indicated are the various subunits of the Caravane conglomerate; Caravane Subunit (CaSu), Campizzi Subunit (CamSu), Petilia Policastro Subunit (PPSu) and Belvedere Subunit (BelSu). Subtle lithofacial differences and the positioning along fault zones indicate that these clastics may have been transported and deposited within narrow faulted zones.
e. Early Pliocene
f. Late Pliocene - Early Pleistocene
g. Middle Pleistocene - Recent
Indicated are large fault zones which dominate the recent morphology: 1. Marcedusa Fault Zone (NNW-SSE), 2. Cuturella-Battaglia Fault Zone (NNE-SSW), 3. Lagudoci-Altilia Fault Zone (NNE-SSW) and 4. Tacina Fault Zone (NNW-SSE). The Sila Piccola dome-shaped massif has previously been recognized on sattelite images by Biju-Duval et al. (1975).
h. Legend for the Figures 10a-g.

Figure 11: Comparison of basement structure and other data along the trace of the Petilia-Sosti Zone.

a. Geological structure.
From: Van Dijk and Okkes (1991)

Southwest of the fault zone, a structure has been described showing a number of superimposed nappes of which the Monte Gariglione gneiss Unit is the uppermost one. These nappes were reconstructed in the Sila Piccola and in the Coastal Chain and are regarded as a "Europe verging" (i.e. displaced to the north to northwest) Alpine (Late Eocene) nappe chain (De Roever, 1972; Haccard et al., 1972; Amodio-Morelli et al., 1976, Grandjacquet and Mascle, 1978). In the northeast, a NE-verging nappe-sequence with the Longobucco Unit as uppermost nappe was reconstructed in the Sila Greca basement area. The Longobucco Unit has been overthrusted by the Monte Gariglione Unit in the northwestern part of northern Calabria (Amodio-Morelli et al., 1976, Zanettin Lorenzoni, 1982). It is generally accepted that this structure indicates that the nappe chain in the southwest has overthrusted the NE-verging chain (see also Elter and Scandone, 1980) in a "later stage" (? Early Miocene).

The geology of the Neogene of the northwestern area is based on published maps by Boccaletti et al. (1984, 1985), Lanzafame and Tortorici (1981), Tortorici (1981), Cello and Sdao (1983) and Moussat (1983). The Petilia-Sosti Zone coincides with a major zone of normal faulting, which delimits the N-S trending Coastal Chain.

b. Magnetic anomalies and satellite photo lineaments.

From: Van Dijk and Okkes (1991)

The trace of the fault zone coincides with a high density of satellite lineaments as well as with a regional trend in magnetic anomaly contours and maxima.

c. Offsets of traces of overthrusts within the northern Calabrian basement.

The traces of the overthrust contacts in the Late Eocene Alpine chain in the northern part of northern Calabria suggest a post-Eocene sinistral offset of circa 50 km. (1 and 2). The occurrences of rocks belonging to the Longobucco Unit ("Hercynian Chain") and those belonging to the Monte Gariglione Unit suggest a sinistral displacement of about 50 km. (3). The two parts of the Monte Gariglione Unit on either side of the Petilia-Sosti Zone are clearly different. The northern part consists of medium grade metamorphic rocks, the southern part of high grade metamorphic rocks, apart from some remnants in the Petilia-Mesoraca area (Gurrieri et al., 1978). This provides an internal sinistral lateral displacement with an offset of 50-85 km. (4). Erosional effects, the relation between inclination of overthrusts and differential uplifts may considerably alter this preliminary estimation. All data, however, indicate a displacement in the same sense and of more or less the same order of magnitude. This strongly pleads in favor of a sinistral shear along the fault zone.

Figure 12: Structural model for the studied area.

Modified after Van Dijk and Okkes (1991). The complex structure along the fault zone which resulted from the late Early Pliocene contractional movements can be regarded as a combination of two fault patterns: 1. Superficial shallow thrusting of the cover consists of two groups of faults: A. large curved thrusts to the SW in the sedimentary cover are the southwestern component of a large flower structure which resulted from sinistral transpressive movements along a NW-SE trending zone in the subsurface (terminology after Harding, 1985; Sanderson and Marchini, 1984; Naylor et al., 1986). B. (N)NW-(S)SE trending sinistral faults generated thrusting (backthrusting as a response to the large listric SE-vergent fault zones) to the (N)NW. 2. Arrays of N160^0 to N140^0 trending reverse faults and thrust systems are the result of duplex formation between Riedel Shears in a sinistral shear zone (cf. Woodcock and Fisher, 1986).

Furthermore, Large N130^0-135^0 trending principle displacement faults cut the whole sequence and displaced parts of it. These faults constitute a distinct system present within the Crotone Basin (see also Van Dijk, 1991). The dextral character of the N-S trending margin of the Crotone Basin was already hypothesized by Burton (1972).

The southern area shows the typical "harmonica basins": In the triangular areas near the intersection points of the conjugate fault zones two types of faulting can be seen: tensional (listric) faulting in the larger angle between the fault zones (Meulenkamp et al., 1986; cf. Geist et al., 1988, their fig. 11), and thrusting and tectonic stacking in the smaller angle. Basin inversions show reversal of faulting along the tensional listric faults.

The circular Sila Piccola massif was recognized on satellite photos by Biju-Duval et al. (1975) as a dominant geomorphological feature. The radial pattern of tensional faults within the massif indicates that it was created in absence of any horizontal regional, unidirectional, compressive or tensional stress field (cf. Withjack and Scheiner, 1982). Therefore, we conclude that this is a purely uplift-related phenomenon.

Figure 13: Schematic synthetic block diagram of the Petilia-Rizzuto Shear Zone for the late Early Pliocene.

Note that the southeastern part of the Sila Piccola block, showing an imbricate fan of thrust wedges, has been indicated as Simeri-Cropani block. See for a discussion the text.

Figure 14: Diagram for the combinations of local and regional stress in the area.

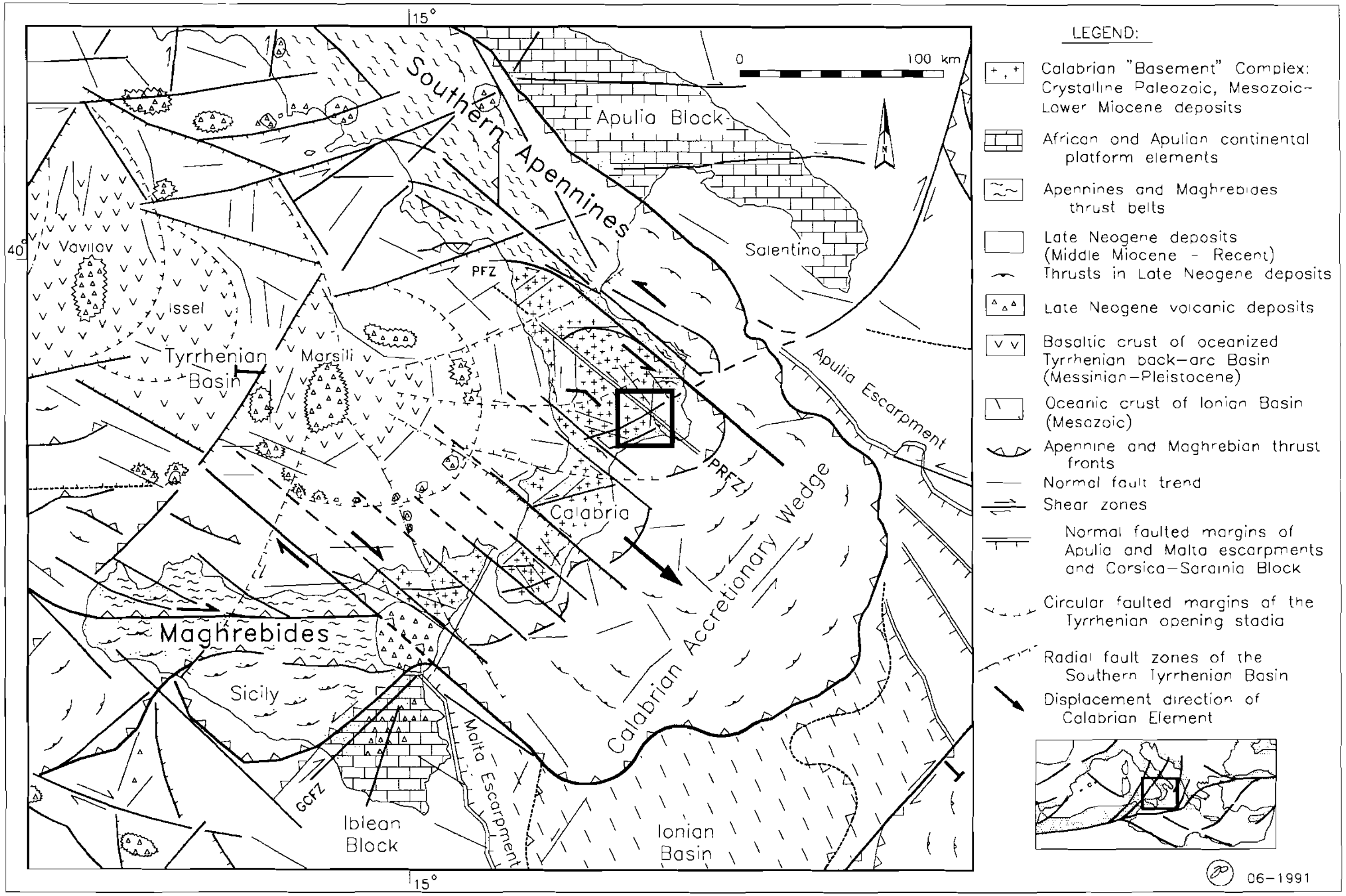
a. Schematic map of a segment of the Calabrian Arc with stress axis.
Basically, the following stress axes can be distinghuished: 1. A local ESE-WNE direction of compression is created by the sinistral simple shearing of the area. 2a. A NW-SE direction of extension is active during times of continued roll-back of the subducted Ionian slab and accompanied arc migration to the southeast with sediment underthrusting/underplating along the thrust wedge. 2b. A NW-SE direction of compression is active during times of stagnation of roll-back of the subducted slab (induced by an increase of regional compressive stress) which creates accretion along the thrust wedge and uplift of the basin margin. 3. A regional compression is active during times of plate reorganizations, resulting from NW-N-NE directed motion of the African Plate. This provided two components of compressive stress, a NW-SE and a NE-SW directed component.
The stress states 1. and 2a. are parallel to the shear zone and result in transtension along the faults. Stress states 2b. and 3. are perpendicular to the fault zone and result in transpression along the fault zone. The activity of conjugate strike-slip fault sets may be favored over thrust faulting in periods when a rotation of the axis of minimum compressive stress from vertical to horizontal occurs. That may be caused by the increase of overburden loading due to accumulation of thick slope sediment packages or by rapid accretion along the wedge (cf. Lewis et al., 1988).
The diagram is valid for the northeastern part of the arc; the southwestern part displays a mirrored image with effective N-S axis of compression. For references see the text.
The small cartoon at the bottom shows variations in strike of wrench faulting within the arc, accomodating for NE-SW directed shortening. The arc as a whole shows a southeastern directed wedge-shaped intrusion, while the central block is extruded in the same direction. SI = Sila block; SE = Serre block; AP = Aspromonte - Peloritani block

b. Flow-chart for effective stress fluctuations in the northern Calabrian realm during the Miocene-Recent evolution of the arc.

Figure 15: Thrust-wedge dynamics and the composite tectonic event.

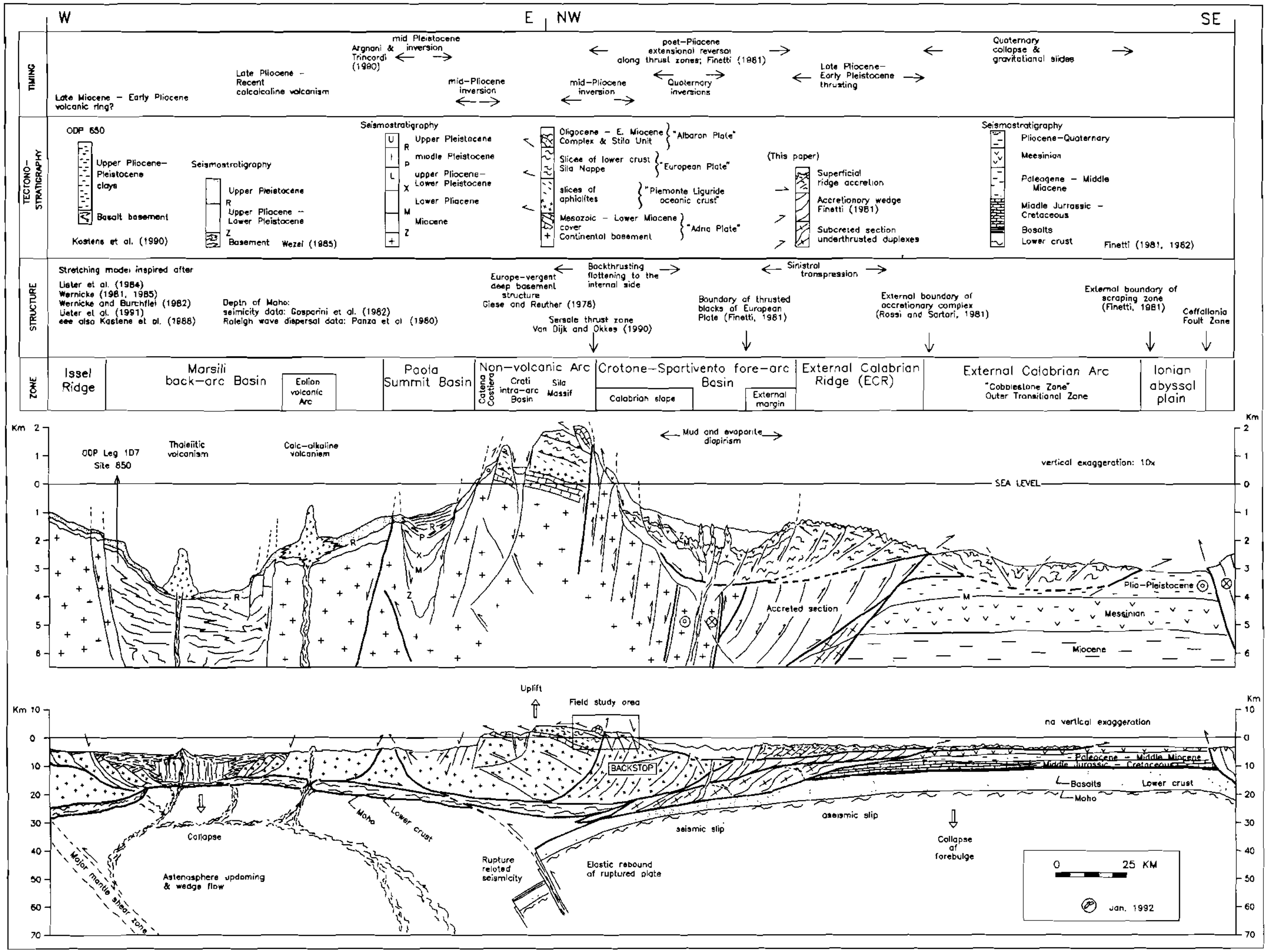
Inspired after Van Bemmelen (1976), Davis et al. (1983), Platt (1986) and Dahlen (1990).
Note that the extensional behaviour of the wedge during the underplating episode mirrors the model of a convergent-extensional active margin as proposed by Aubouin et al. (1984).

Table 1: Literature synopsis of the basement subdivision of the studied area.



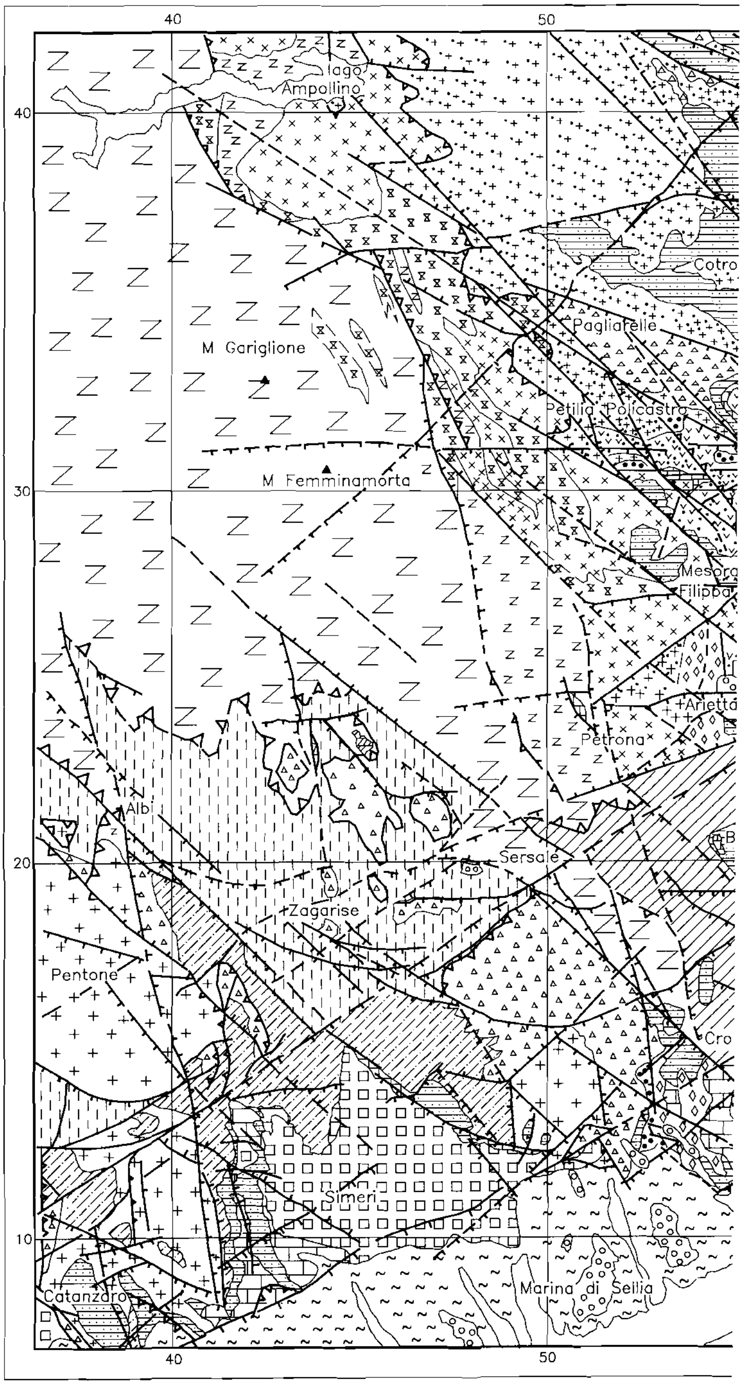
15°
40°
Southern Apennines
Apulia Block
Salentino
Apulia Escarpment
Vavilov
Issel
Tyrrhenian Basin
Marsili
PFZ
PRFZ
Calabria
Calabrian Accretionary Wedge
Maghrebides
Sicily
Malta Escarpment
GCFZ
Iblean Block
Ionian Basin
0
100 km
LEGEND:
Calabrian "Basement" Complex: Crystalline Paleozoic, Mesozoic-Lower Miocene deposits
African and Apulian continental platform elements
Apennines and Maghrebides thrust belts
Late Neogene deposits (Middle Miocene - Recent)
Thrusts in Late Neogene deposits
Late Neogene volcanic deposits
Basaltic crust of oceanized Tyrrhenian back-arc Basin (Messinian-Pleistocene)
Oceanic crust of Ionian Basin (Mesozoic)
Apennine and Maghrebian thrust fronts
Normal fault trend
Shear zones
Normal faulted margins of Apulia and Malta escarpments and Corsica-Sardinia Block
Circular faulted margins of the Tyrrhenian opening stadia
Radial fault zones of the Southern Tyrrhenian Basin
Displacement direction of Calabrian Element
06-1991

Fig. 1a

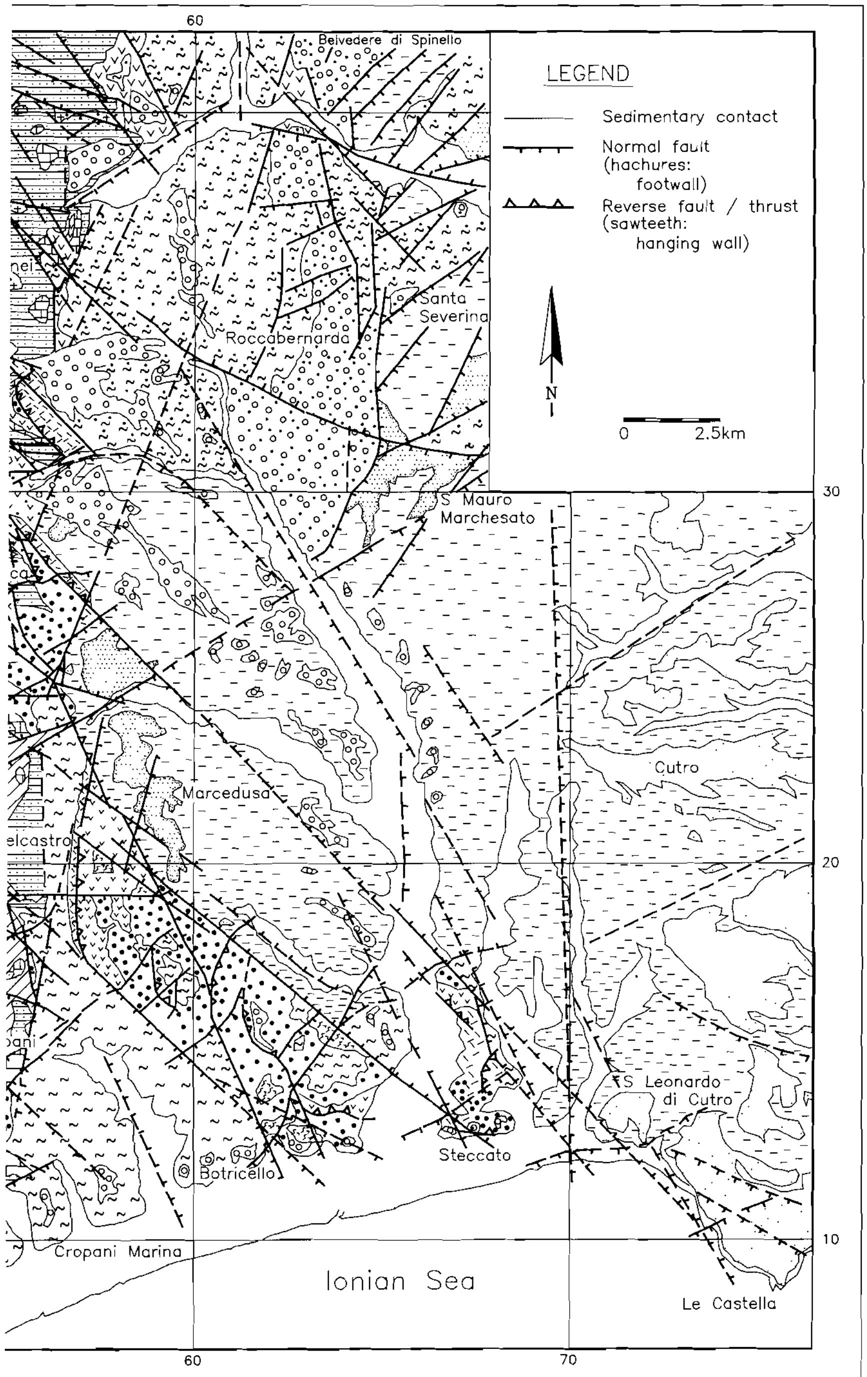


W
E
NW
SE
TIMING
TECTONO-STRATIGRAPHY
STRUCTURE
ZONE
Late Miocene – Early Pliocene volcanic ring?
Late Pliocene – Recent calcalcaline volcanism
mid Pleistocene inversion
Argnani & Trincardi (1990)
mid–Pliocene inversion
post–Pliocene extensional reversal along thrust zones; Finetti (1981)
Quaternary inversions
Late Pliocene– Early Pleistocene thrusting
Quaternary collapse & gravitational slides
ODP 650
Upper Pliocene– Pleistocene clays
Basalt basement
Kastens et al. (1990)
Seismostratigraphy
Upper Pleistocene
Upper Pliocene – Lower Pleistocene
Basement
Wezel (1985)
Upper Pleistocene
middle Pleistocene
upper Pliocene– Lower Pleistocene
Lower Pliocene
Miocene
Oligocene – E. Miocene Complex & Stilo Unit
"Alboran Plate"
Slices of lower crust Sila Nappe
"European Plate"
slices of ophiolites
"Piemonte Liguride oceanic crust"
Mesozoic – Lower Miocene cover
Continental basement
"Adria Plate"
(This paper)
Superficial ridge accretion
Accretionary wedge Finetti (1981)
Subcreted section underthrusted duplexes
Pliocene–Quaternary
Messinian
Paleogene – Middle Miocene
Middle Jurassic – Cretaceous
Basalts
Lower crust
Finetti (1981, 1982)
Stretching model inspired after
Lister et al. (1984)
Wernicke (1981, 1985)
Wernicke and Burchfiel (1982)
Lister et al. (1991)
see also Kastens et al. (1988)
Depth of Moho:
seismicity data: Gasparini et al. (1982)
Raleigh wave dispersal data: Panza et al (1980)
Europe–vergent deep basement structure
Giese and Reuther (1978)
Backthrusting flattening to the internal side
Sersale thrust zone
Van Dijk and Okkes (1990)
Boundary of thrusted blocks of European Plate (Finetti, 1981)
Sinistral transpression
External boundary of accretionary complex (Rossi and Sartori, 1981)
External boundary of scraping zone (Finetti, 1981)
Cefallonia Fault Zone
Issel Ridge
Marsili back–arc Basin
Eolian volcanic Arc
Paola Summit Basin
Non–volcanic Arc
Catena Costiera
Crati intra–arc Basin
Sila Massif
Crotone–Spartivento fore–arc Basin
Calabrian slope
External margin
External Calabrian Ridge (ECR)
External Calabrian Arc
"Cobblestone Zone"
Outer Transitional Zone
Ionian abyssal plain
Km
ODP Leg 107 Site 650
Tholeiitic volcanism
Calc–alkaline volcanism
Mud and evaporite diapirism
vertical exaggeration: 10x
SEA LEVEL
Accreted section
Plio–Pleistocene
Messinian
Miocene
Uplift
Field study area
no vertical exaggeration
BACKSTOP
Paleocene – Middle Miocene
Middle Jurassic – Cretaceous
Basalts
Lower crust
Moho
Lower crust
Collapse
Major mantle shear zone
Astenosphere updoming & wedge flow
Rupture related seismicity
Elastic rebound of ruptured plate
seismic slip
aseismic slip
Collapse of forebulge
0
25 KM
Jan. 1992

Fig. 1b



40
50
lago
Ampollino
Cotro
Pagliarelle
M Gariglione
Petilia Policastro
M Femminamorta
30
Mesora
Filippa
Arietta
Petrona
Albi
Sersale
20
Zagarise
Pentone
Cro
Simeri
10
Marina di Sellia
Catanzaro



LEGEND
Sedimentary contact
Normal fault (hachures: footwall)
Reverse fault / thrust (sawteeth: hanging wall)
N
0
2.5km
60
70
30
20
10
Belvedere di Spinello
Santa Severina
Roccabernarda
S. Mauro Marchesato
Marcedusa
Cutro
S. Leonardo di Cutro
Steccato
Botricello
Cropani Marina
Ionian Sea
Le Castella

Fig. 2

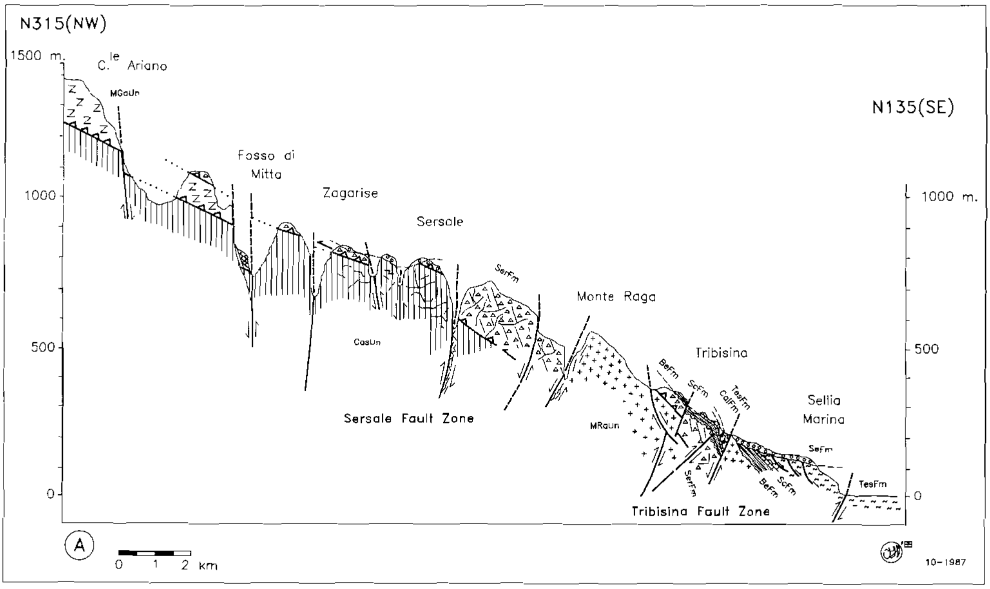

N315(NW)
N135(SE)
1500 m.
1000
500
0
1000 m.
500
0
C.le Ariano
Fosso di Mitta
Zagarise
Sersale
Monte Raga
Tribisina
Sellia Marina
Sersale Fault Zone
Tribisina Fault Zone
A
0 1 2 km
10-1987

Fig. 3a

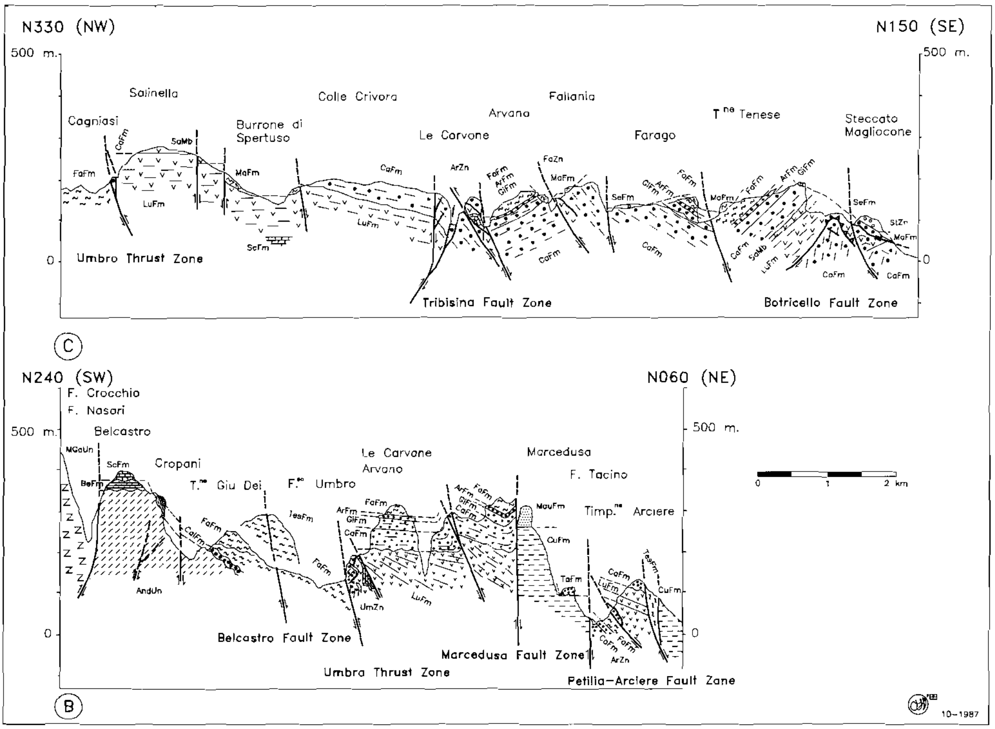

N330 (NW)
N150 (SE)
500 m.
0
Salinella
Cagniasi
Burrone di Spertuso
Colle Crivoro
Le Carvone
Arvano
Faliania
Farago
T.ne Tenese
Steccato Magliocone
Umbro Thrust Zone
Tribisina Fault Zone
Botricello Fault Zone
C
N240 (SW)
N060 (NE)
F. Crocchio
F. Nasari
Belcastro
Cropani
T.ne Giu Dei
F.so Umbro
Le Carvone
Arvano
Marcedusa
F. Tacina
Timp.ne Arciere
Belcastro Fault Zone
Umbro Thrust Zone
Marcedusa Fault Zone
Petilia–Arciere Fault Zone
0 1 2 km
B
10-1987

Fig. 3b

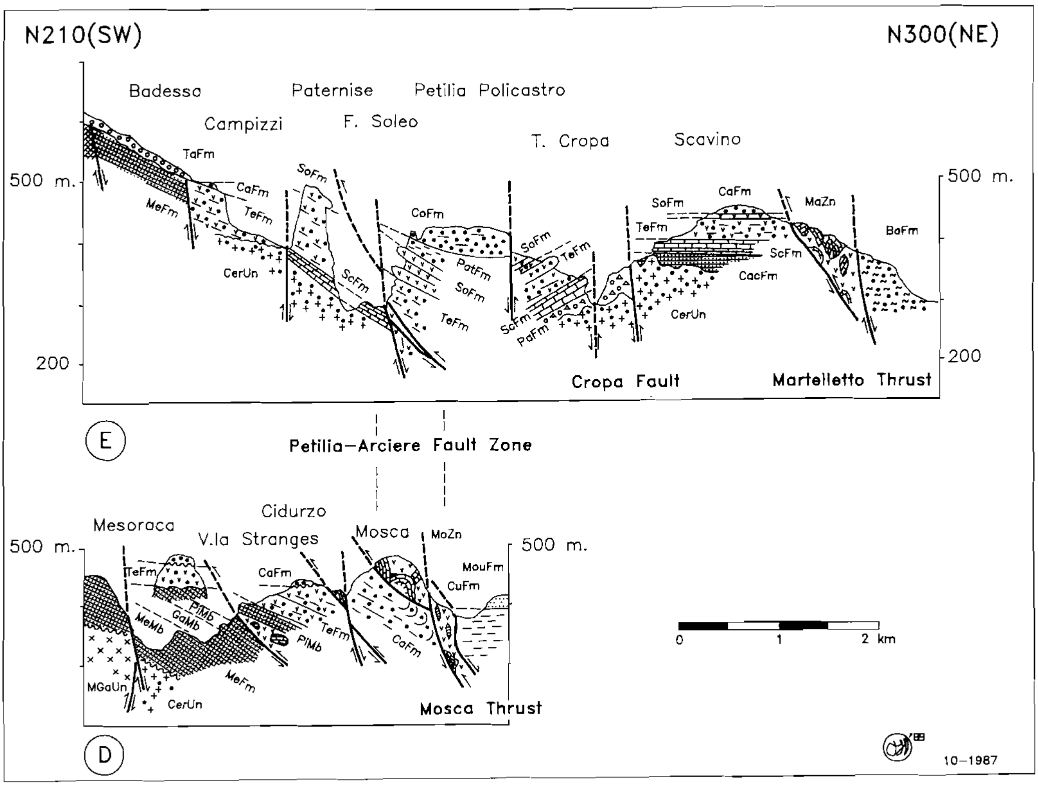
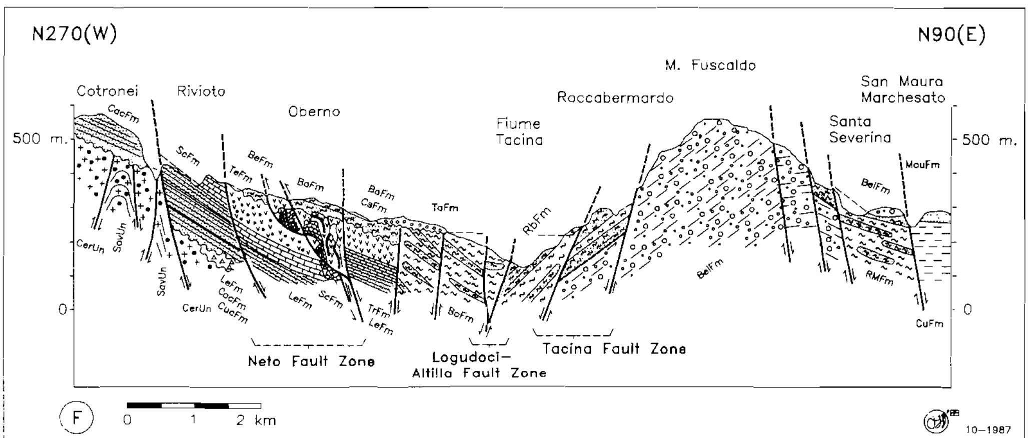

N210(SW)
N300(NE)
Badessa
Campizzi
Paternise
F. Soleo
Petilia Policastro
T. Cropa
Scavino
500 m.
200
TaFm
CaFm
MeFm
TeFm
SoFm
CerUn
ScFm
CoFm
PatFm
PaFm
SoFm
TeFm
CaFm
MaZn
BaFm
CacFm
Cropa Fault
Martelletto Thrust
E
Petilia–Arciere Fault Zone
Mesoraca
Cidurzo
V.la Stranges
Mosca
MoZn
TeFm
CaFm
PlMb
GaMb
MeMb
MouFm
CuFm
MGaUn
CerUn
Mosca Thrust
0
1
2 km
D
10–1987

Fig. 3c

Fig. 3d


N270(W)
N90(E)
Cotronei
Rivioto
Oberno
Fiume Tacina
Roccabermardo
M. Fuscaldo
San Mauro Marchesato
Santa Severina
500 m.
0
CacFm
SoFm
BeFm
TeFm
BaFm
CaFm
TaFm
RbFm
BelFm
MouFm
CerUn
SavUn
LeFm
CocFm
CucFm
ScFm
TrFm
BoFm
RMFm
CuFm
Neto Fault Zone
Logudoci–Altilla Fault Zone
Tacina Fault Zone
F
0
1
2 km
10–1987

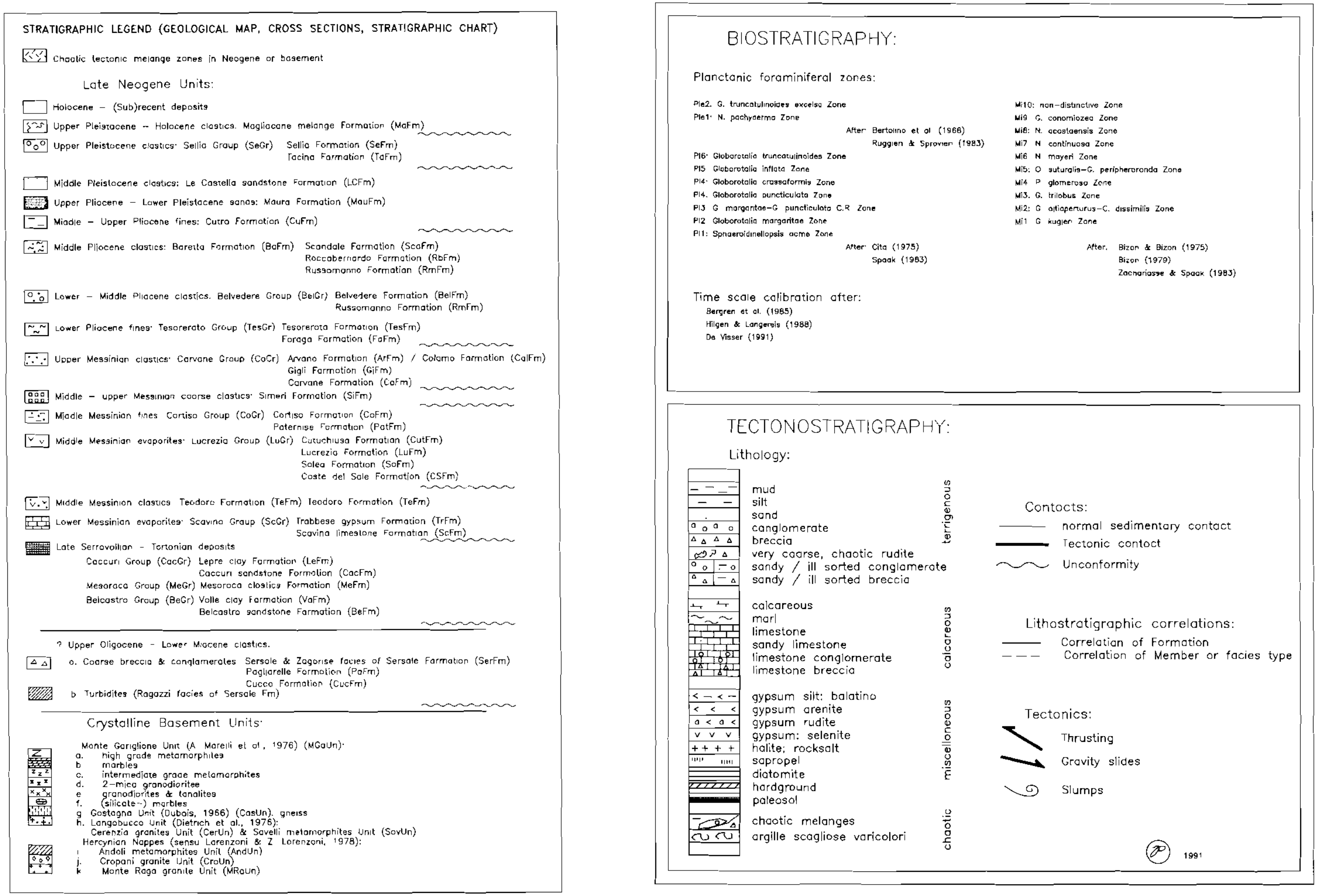

STRATIGRAPHIC LEGEND (GEOLOGICAL MAP, CROSS SECTIONS, STRATIGRAPHIC CHART)
Chaotic tectonic melange zones in Neogene or basement
Late Neogene Units:
Holocene – (Sub)recent deposits
Upper Pleistocene – Holocene clastics. Magliacane melange Formation (MaFm)
Upper Pleistocene clastics: Sellia Group (SeGr) Sellia Formation (SeFm)
Tacina Formation (TaFm)
Middle Pleistocene clastics: Le Castella sandstone Formation (LCFm)
Upper Pliocene – Lower Pleistocene sands: Maura Formation (MauFm)
Middle – Upper Pliocene fines: Cutro Formation (CuFm)
Middle Pliocene clastics: Baretta Formation (BaFm) Scandale Formation (ScaFm)
Roccabernardo Formation (RbFm)
Russomanno Formation (RmFm)
Lower – Middle Pliocene clastics. Belvedere Group (BelGr) Belvedere Formation (BelFm)
Russomanno Formation (RmFm)
Lower Pliocene fines: Tesorerato Group (TesGr) Tesorerato Formation (TesFm)
Foraga Formation (FaFm)
Upper Messinian clastics: Carvane Group (CaCr) Arvano Formation (ArFm) / Colamo Formation (ColFm)
Gigli Formation (GiFm)
Carvane Formation (CaFm)
Middle – upper Messinian coarse clastics: Simeri Formation (SiFm)
Middle Messinian fines Cortiso Group (CoGr) Cortiso Formation (CoFm)
Paternise Formation (PatFm)
Middle Messinian evaporites: Lucrezia Group (LuGr) Cutuchiusa Formation (CutFm)
Lucrezia Formation (LuFm)
Solea Formation (SoFm)
Coste del Sole Formation (CSFm)
Middle Messinian clastics Teodoro Formation (TeFm) Teodoro Formation (TeFm)
Lower Messinian evaporites: Scavino Group (ScGr) Trabbese gypsum Formation (TrFm)
Scavino limestone Formation (ScFm)
Late Serravallian – Tortonian deposits
Caccuri Group (CacGr) Lepre clay Formation (LeFm)
Caccuri sandstone Formation (CacFm)
Mesoraca Group (MeGr) Mesoraca clastics Formation (MeFm)
Belcastro Group (BeGr) Volle clay Formation (VaFm)
Belcastro sandstone Formation (BeFm)
? Upper Oligocene – Lower Miocene clastics.
a. Coarse breccia & conglomerates Sersale & Zagorise facies of Sersale Formation (SerFm)
Pagliarelle Formation (PaFm)
Cucco Formation (CucFm)
b Turbidites (Ragazzi facies of Sersale Fm)
Crystalline Basement Units:
Monte Gariglione Unit (A Moresi et al., 1976) (MGaUn):
a. high grade metamorphites
b marbles
c. intermediate grade metamorphites
d. 2-mica granodiorites
e granodiorites & tonalites
f. (silicate-) marbles
g Gastagna Unit (Dubois, 1966) (CasUn). gneiss
h. Longobucco Unit (Dietrich et al., 1976):
Cerenzia granites Unit (CerUn) & Savelli metamorphites Unit (SovUn)
Hercynian Nappes (sensu Lorenzoni & Z Lorenzoni, 1978):
i Andoli metamorphites Unit (AndUn)
j. Cropani granite Unit (CroUn)
k Monte Raga granite Unit (MRaUn)
BIOSTRATIGRAPHY:
Planctonic foraminiferal zones:
Ple2. G. truncatulinoides excelsa Zone
Ple1: N. pachyderma Zone
After: Bertolino et al (1968)
Ruggieri & Sprovieri (1983)
Pl6: Globorotalia truncatulinoides Zone
Pl5 Globorotalia inflata Zone
Pl4: Globorotalia crassaformis Zone
Pl4. Globorotalia puncticulata Zone
Pl3 G margaritae–G puncticulata C.R Zone
Pl2 Globorotalia margaritae Zone
Pl1: Sphaeroidinellopsis acme Zone
After: Cita (1975)
Spaak (1983)
Mi10: non-distinctive Zone
Mi9 G. conomiozea Zone
Mi8: N. acostaensis Zone
Mi7 N continuosa Zone
Mi6 N mayeri Zone
Mi5: O suturalis–G. peripheroronda Zone
Mi4 P glomerosa Zone
Mi3. G. trilobus Zone
Mi2: G altiaperturus–C. dissimilis Zone
Mi1 G kugleri Zone
After. Bizon & Bizon (1975)
Bizon (1979)
Zachariasse & Spaak (1983)
Time scale calibration after:
Bergren et al. (1985)
Hilgen & Langereis (1988)
De Visser (1991)
TECTONOSTRATIGRAPHY:
Lithology:
mud
silt
sand
conglomerate
breccia
very coarse, chaotic rudite
sandy / ill sorted conglomerate
sandy / ill sorted breccia
terrigenous
calcareous
marl
limestone
sandy limestone
limestone conglomerate
limestone breccia
calcareous
gypsum silt: balatino
gypsum arenite
gypsum rudite
gypsum: selenite
halite: rocksalt
sapropel
diatomite
hardground
paleosol
miscellaneous
chaotic melanges
argille scagliose varicolori
chaotic
Contacts:
normal sedimentary contact
Tectonic contact
Unconformity
Lithostratigraphic correlations:
Correlation of Formation
Correlation of Member or facies type
Tectonics:
Thrusting
Gravity slides
Slumps
1991

Fig. 4

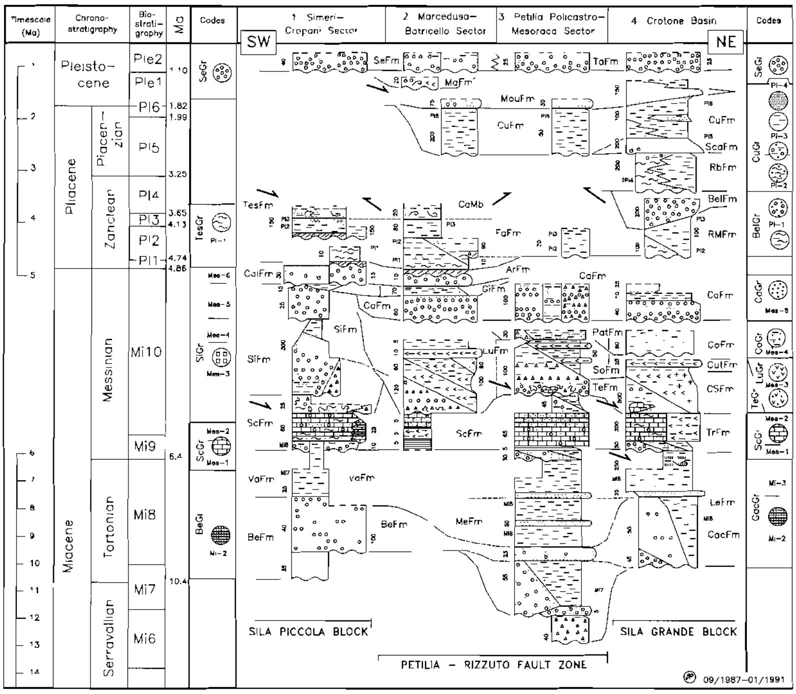


Fig. 5a

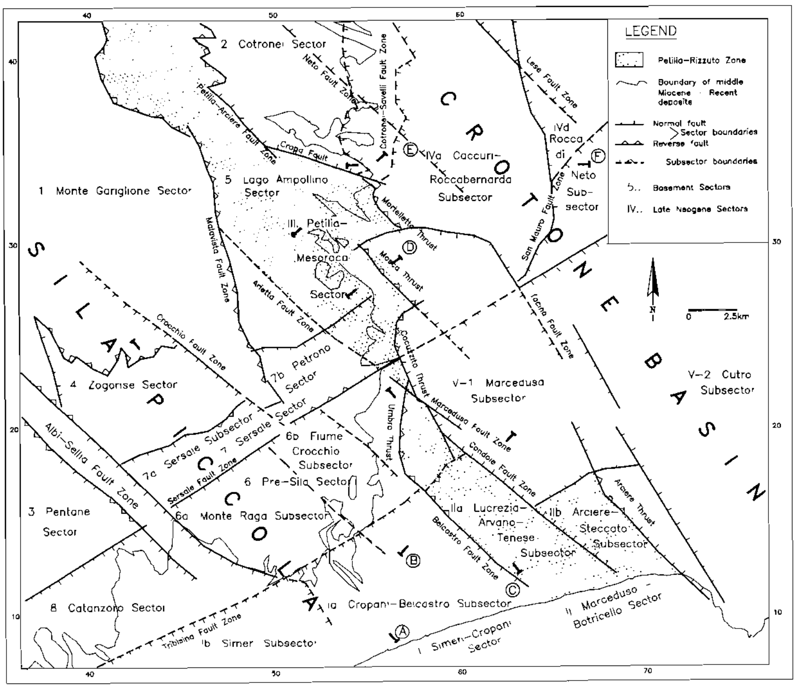


Fig. 5b

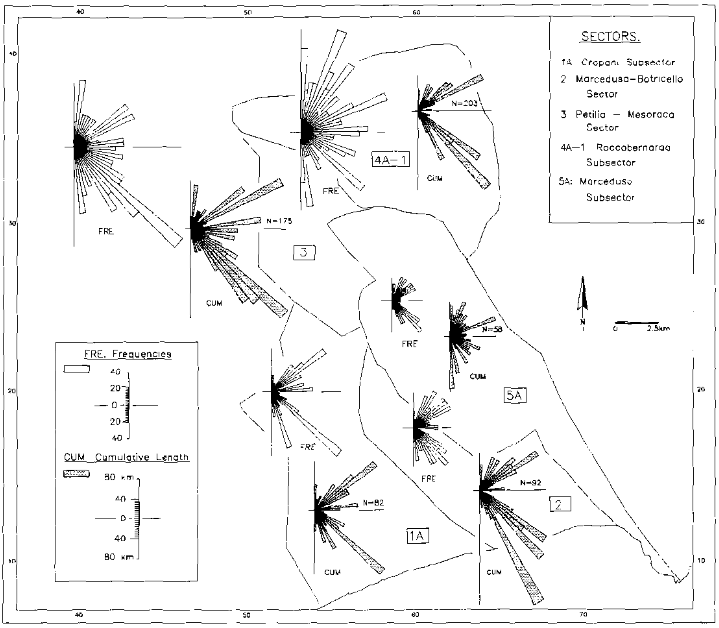

SECTORS.
1A Cropani Subsector
2 Marcedusa–Botricello Sector
3 Petilia – Mesoraca Sector
4A–1 Roccabernarda Subsector
5A: Marcedusa Subsector
FRE. Frequencies
CUM Cumulative Length
N=203
N=175
N=58
N=82
N=92
4A–1
3
5A
1A
2
0 2.5km

Fig. 7b

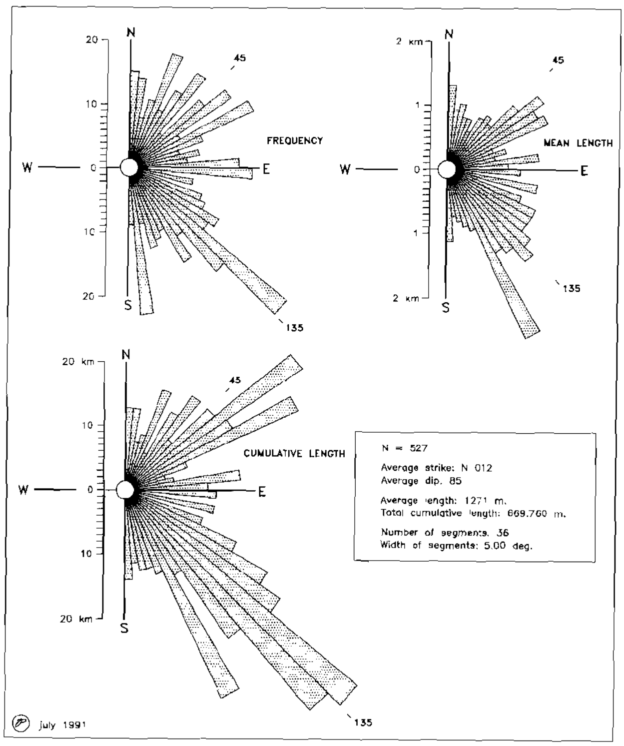

FREQUENCY
MEAN LENGTH
CUMULATIVE LENGTH
N = 527
Average strike: N 012
Average dip. 85
Average length: 1271 m.
Total cumulative length: 669.760 m.
Number of segments: 36
Width of segments: 5.00 deg.
july 1991

Fig. 7a

Fig. 8b

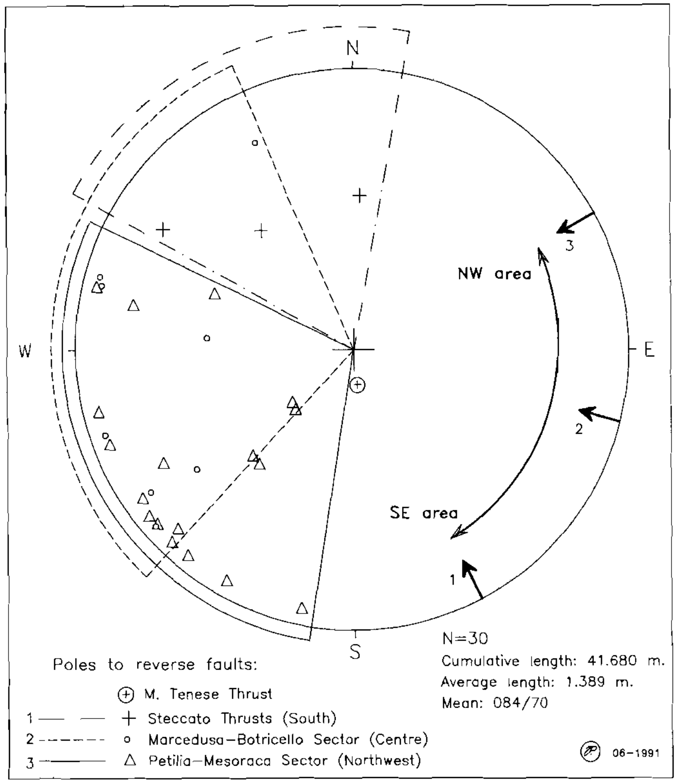

N
W
E
S
NW area
SE area
1
2
3
Poles to reverse faults:
M. Tenese Thrust
1 Steccato Thrusts (South)
2 Marcedusa–Botricello Sector (Centre)
3 Petilia–Mesoraca Sector (Northwest)
N=30
Cumulative length: 41.680 m.
Average length: 1.389 m.
Mean: 084/70
06–1991

Fig. 8a

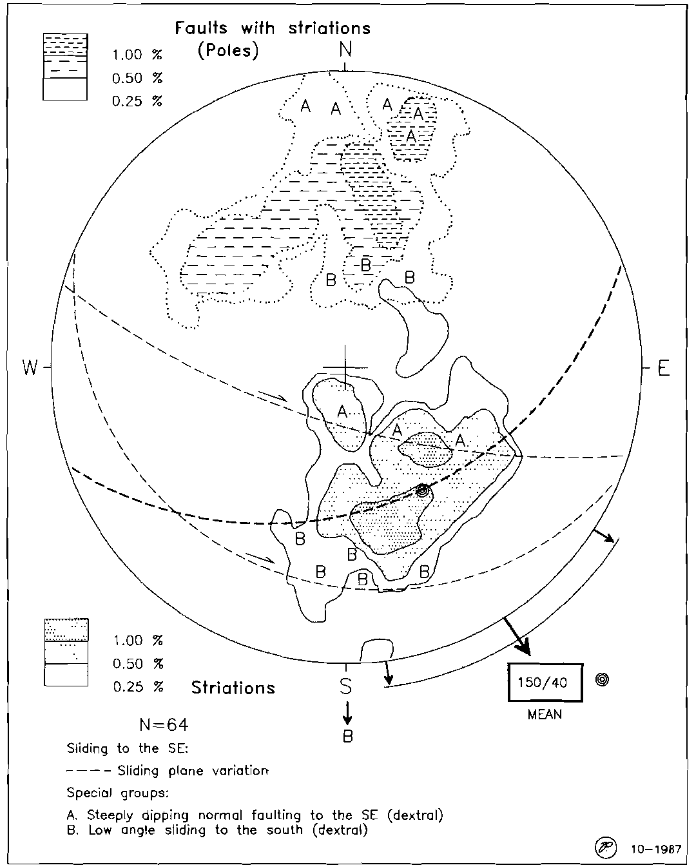

Faults with striations
(Poles)
1.00 %
0.50 %
0.25 %
N
W
E
S
A
B
1.00 %
0.50 %
0.25 %
Striations
N=64
B
150/40
MEAN
Sliding to the SE:
Sliding plane variation
Special groups:
A. Steeply dipping normal faulting to the SE (dextral)
B. Low angle sliding to the south (dextral)
10–1987

Fig. 8d

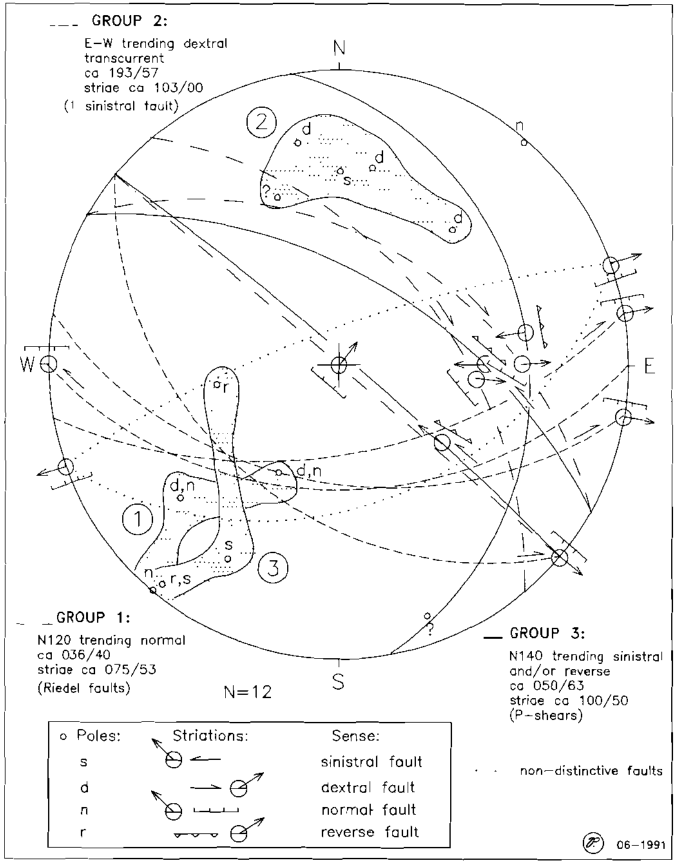
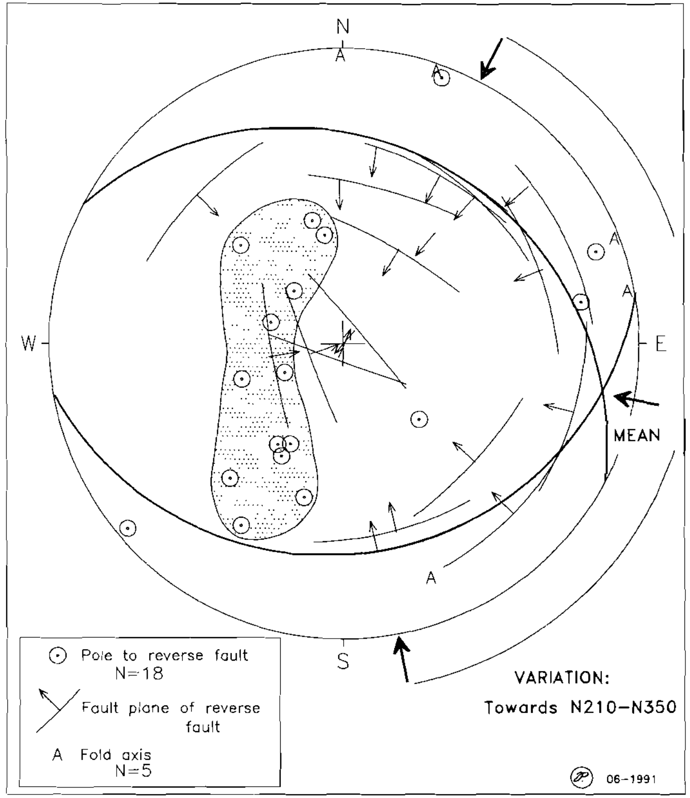
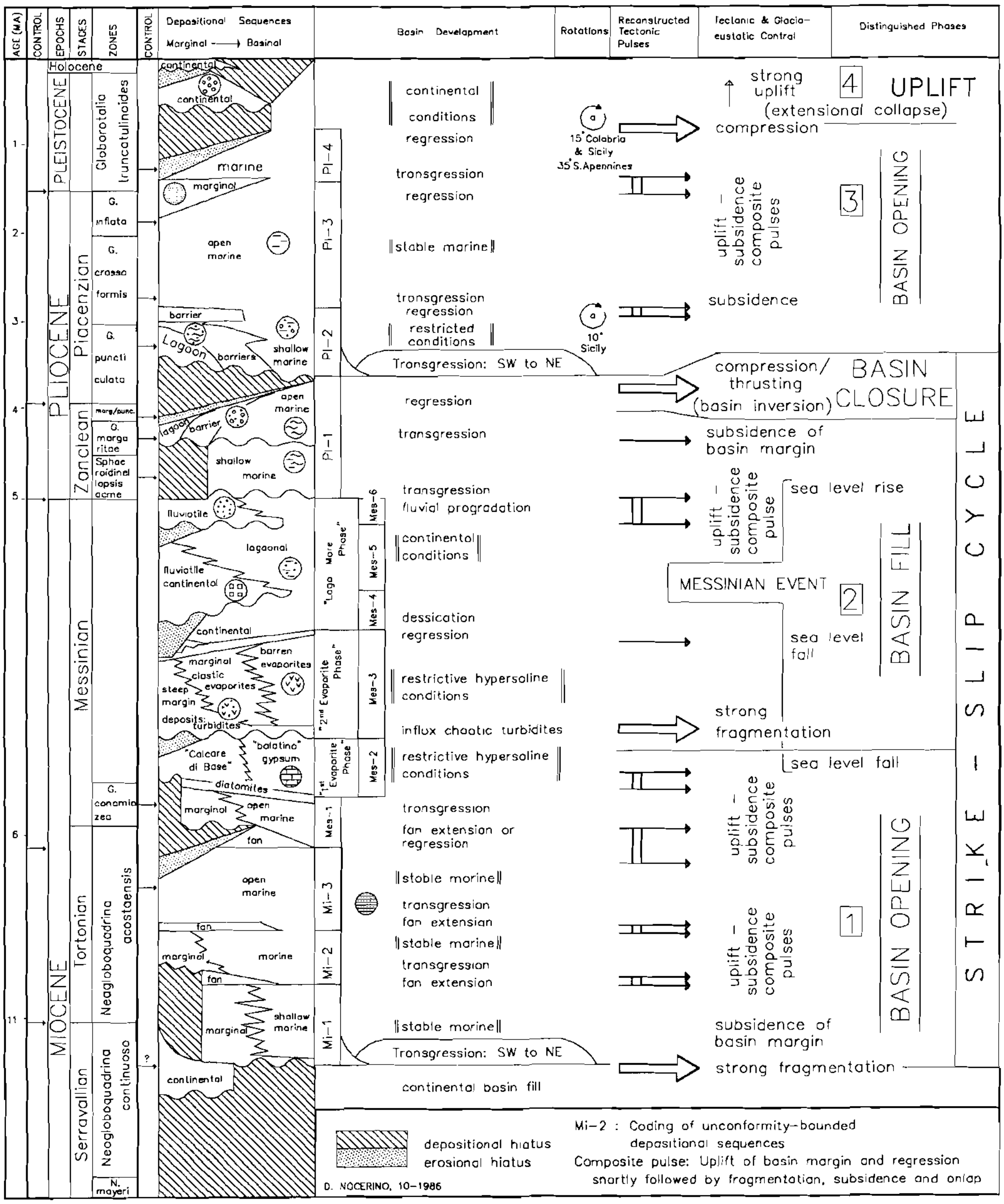

GROUP 2:
E–W trending dextral
transcurrent
ca 193/57
striae ca 103/00
(1 sinistral fault)
N
W
E
S
GROUP 1:
N120 trending normal
ca 036/40
striae ca 075/53
(Riedel faults)
N=12
GROUP 3:
N140 trending sinistral
and/or reverse
ca 050/63
striae ca 100/50
(P–shears)
o Poles:
Striations:
Sense:
s
sinistral fault
d
dextral fault
n
normal fault
r
reverse fault
non–distinctive faults
06–1991

Fig. 8c


N
W
E
S
MEAN
Pole to reverse fault
N=18
Fault plane of reverse
fault
A Fold axis
N=5
VARIATION:
Towards N210–N350
06–1991



AGE (MA)
CONTROL
EPOCHS
STAGES
ZONES
Depositional Sequences
Marginal → Basinal
Basin Development
Rotations
Reconstructed Tectonic Pulses
Tectonic & Glacio-eustatic Control
Distinguished Phases
Holocene
PLEISTOCENE
PLIOCENE
MIOCENE
Piacenzian
Zanclean
Messinian
Tortonian
Serravallian
Globorotalia truncatulinoides
G. inflata
G. crassaformis
G. puncticulata
G. margaritae
Sphaeroidinellopsis acme
G. conomiozea
Neogloboquadrina acostaensis
Neogloboquadrina continuosa
N. mayeri
continental
marine
marginal
open marine
barrier
Lagoon
barriers
shallow marine
fluviatile
lagoonal
fluviatile continental
barren evaporites
marginal clastic
steep margin deposits
evaporites
turbidites
"Calcare di Base"
"balatino" gypsum
diatomites
fan
Pl-4
Pl-3
Pl-2
Pl-1
Mes-6
Mes-5
Mes-4
Mes-3
Mes-2
Mes-1
Mi-3
Mi-2
Mi-1
"Lago Mare Phase"
"2nd Evaporite Phase"
"1st Evaporite Phase"
continental conditions
regression
transgression
stable marine
restricted conditions
Transgression: SW to NE
fluvial progradation
dessication
restrictive hypersaline conditions
influx chaotic turbidites
fan extension or regression
fan extension
continental basin fill
15° Calabria & Sicily
35° S.Apennines
10° Sicily
strong uplift
(extensional collapse)
compression
uplift - subsidence composite pulses
subsidence
compression/ thrusting (basin inversion)
subsidence of basin margin
uplift - subsidence composite pulse
sea level rise
MESSINIAN EVENT
sea level fall
strong fragmentation
4 UPLIFT
3 BASIN OPENING
BASIN CLOSURE
2 BASIN FILL
1 BASIN OPENING
STRIKE - SLIP CYCLE
depositional hiatus
erosional hiatus
Mi-2 : Coding of unconformity-bounded depositional sequences
Composite pulse: Uplift of basin margin and regression shortly followed by fragmentation, subsidence and onlap
D. NOCERINO, 10-1986

Fig. 9

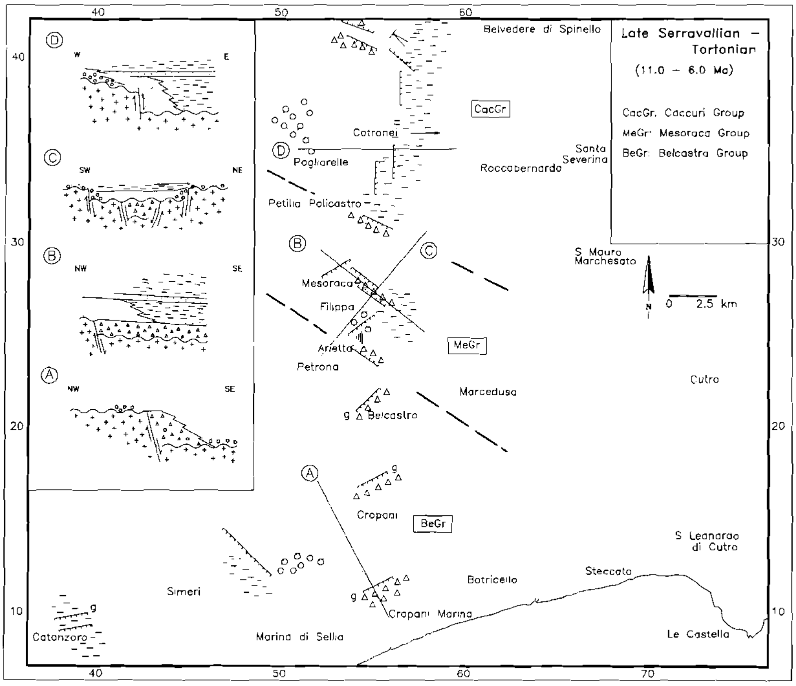


Fig. 10a

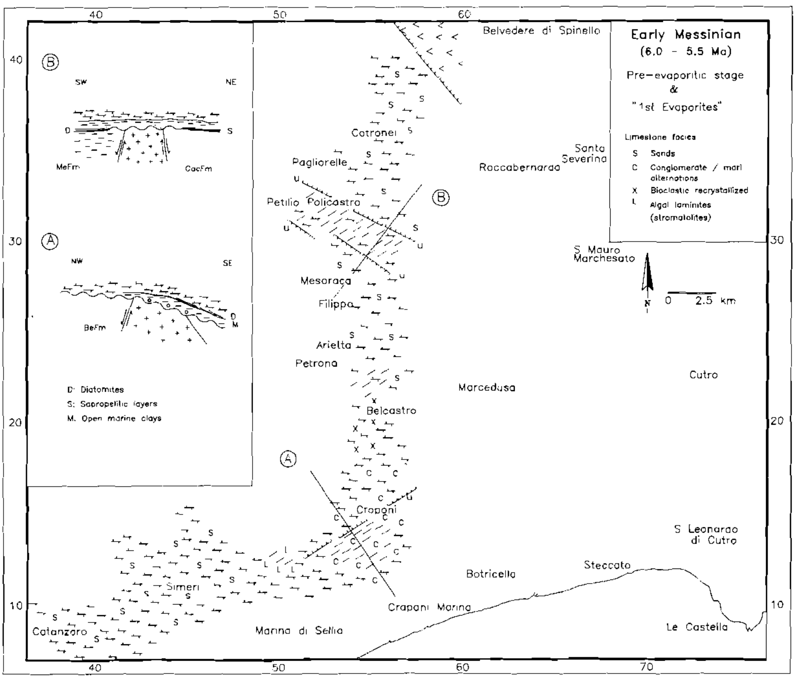


Fig. 10b

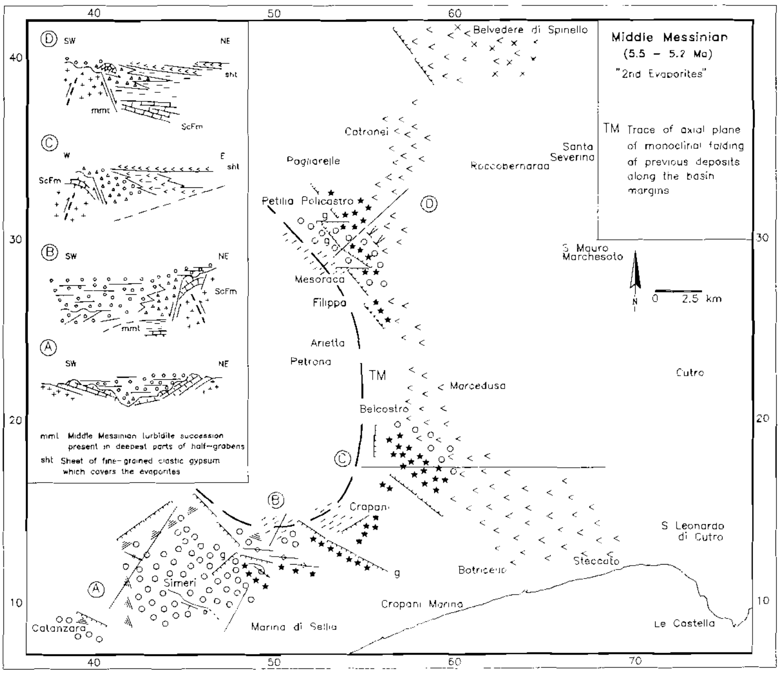


Fig. 10c

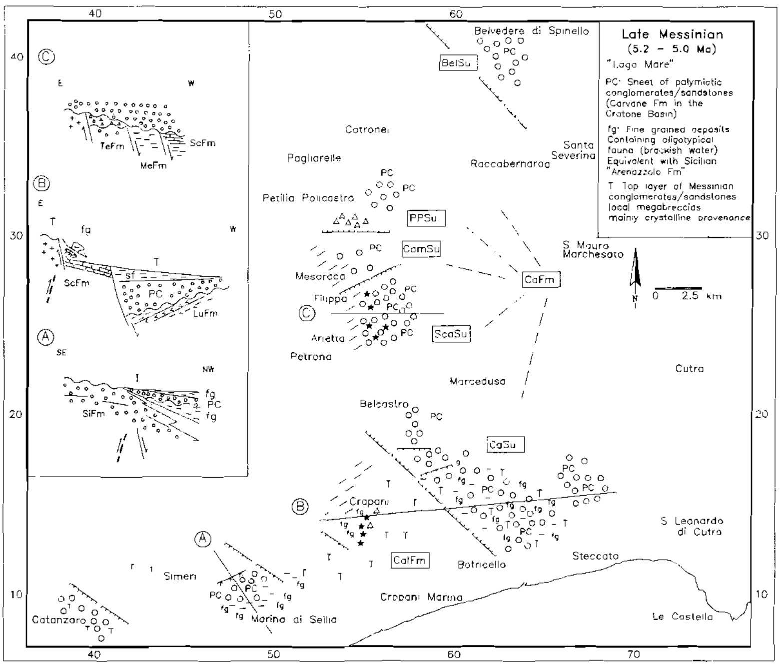


Fig. 10d

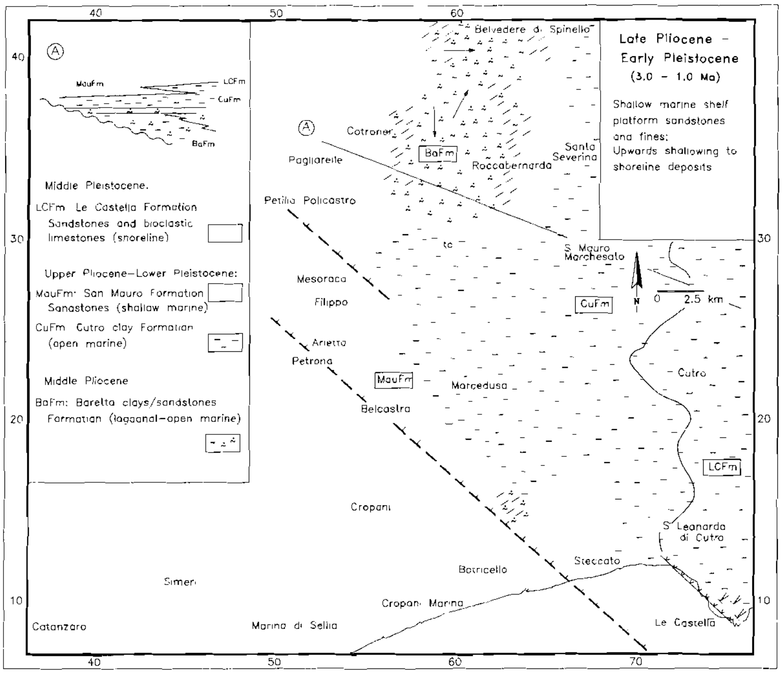


Fig. 10e

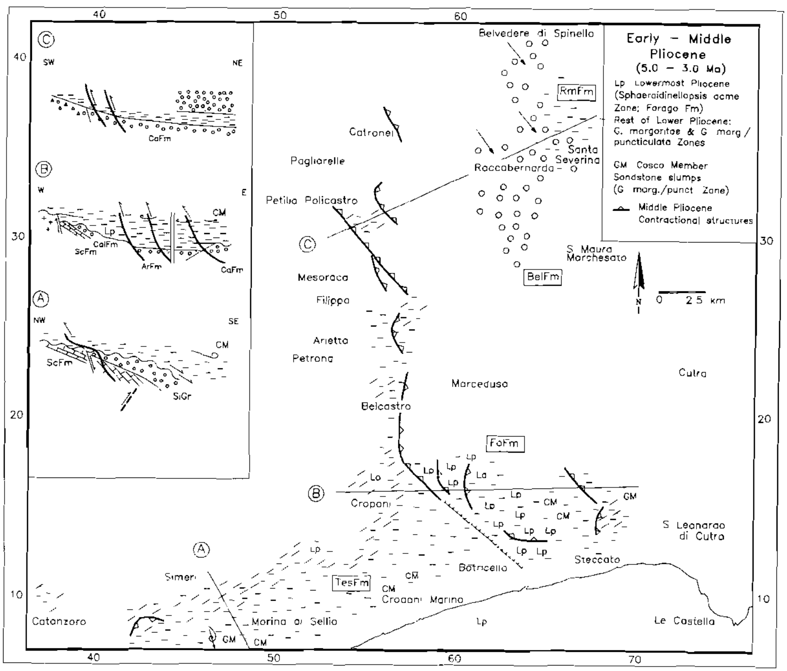


Fig. 10f

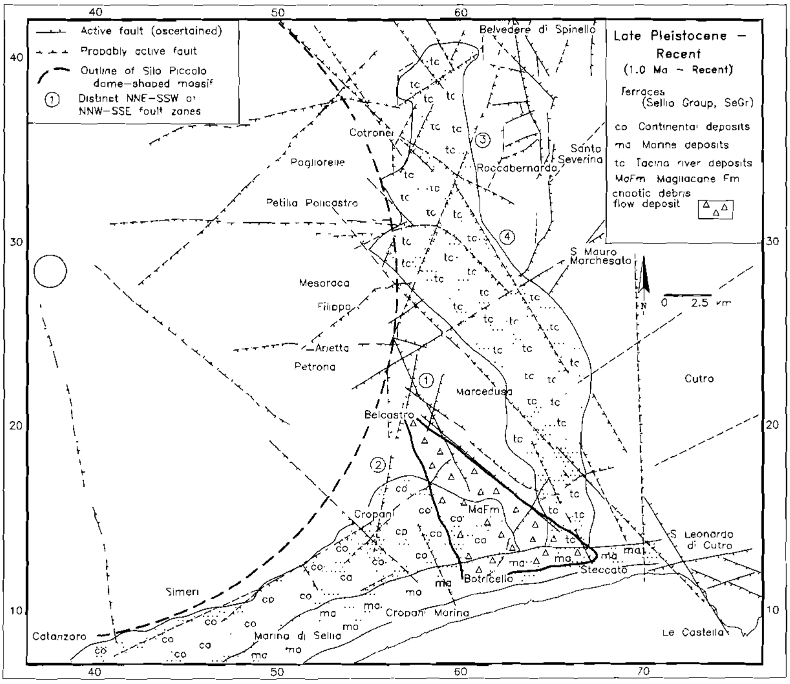


Fig. 10g

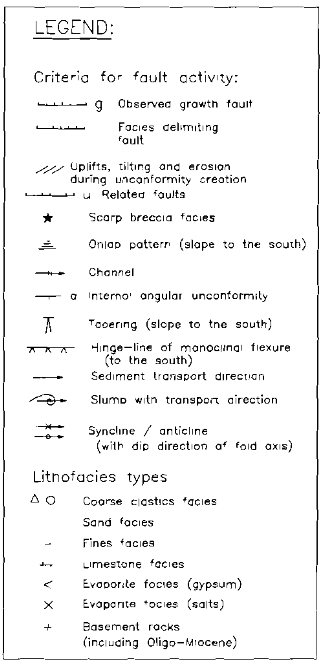


Fig. 10h

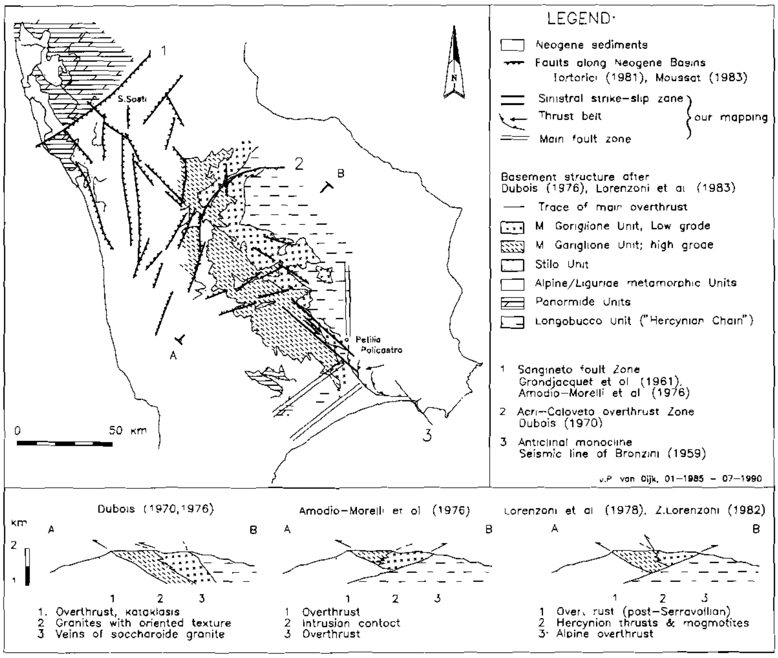
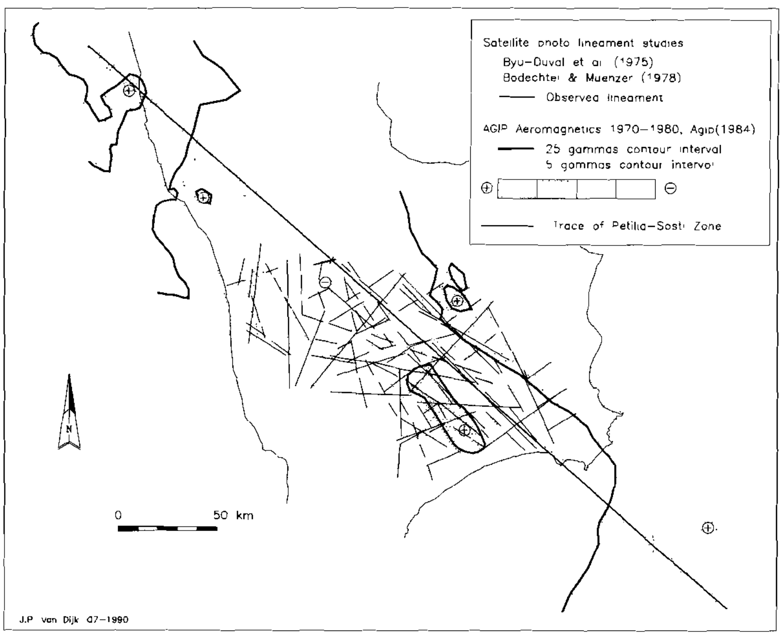
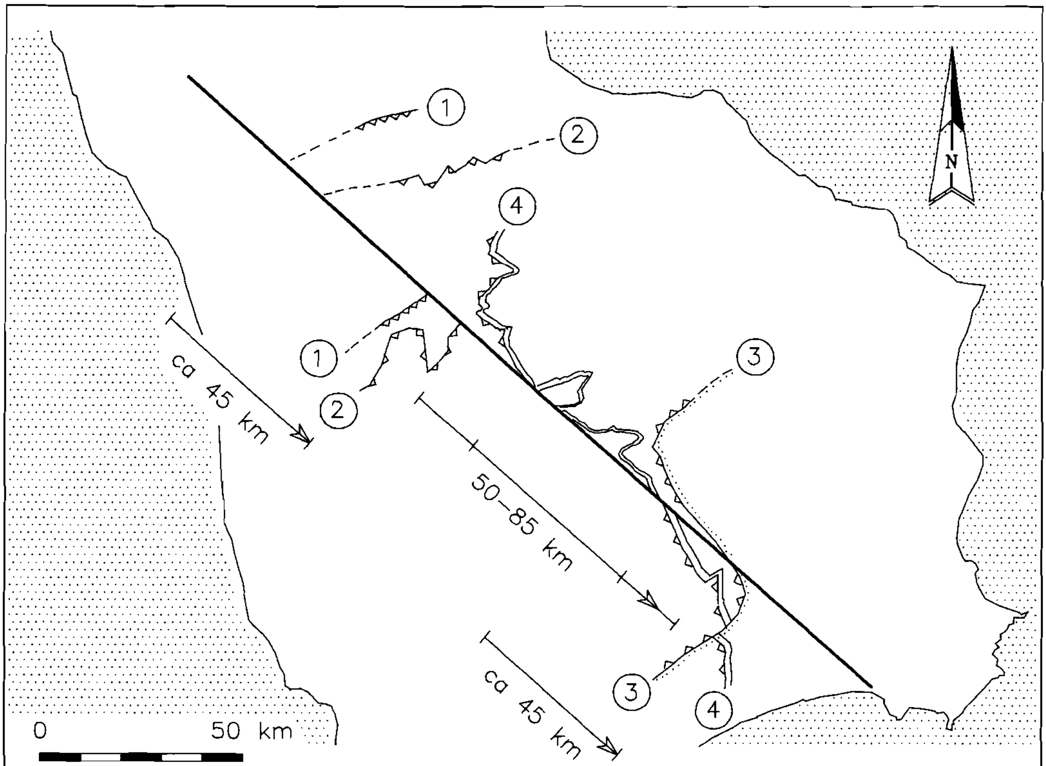


Fig. 11a

Fig. 11b





(1.) Overthrust between crystalline and metasedimentary Liguride units within the "Alpine chain".
(2.) Overthrust between M. Gariglione Unit (high grade) and the units of the "Alpine Chain".
(3.) Overthrust between M. Gariglione Unit and the units of the "Hercynian chain".
(4.) Overthrust within the M. Gariglione Unit between high grade ("kinzigites") and low grade metamorphites.

First mentioned = upper unit

© 1987

Fig. 11c

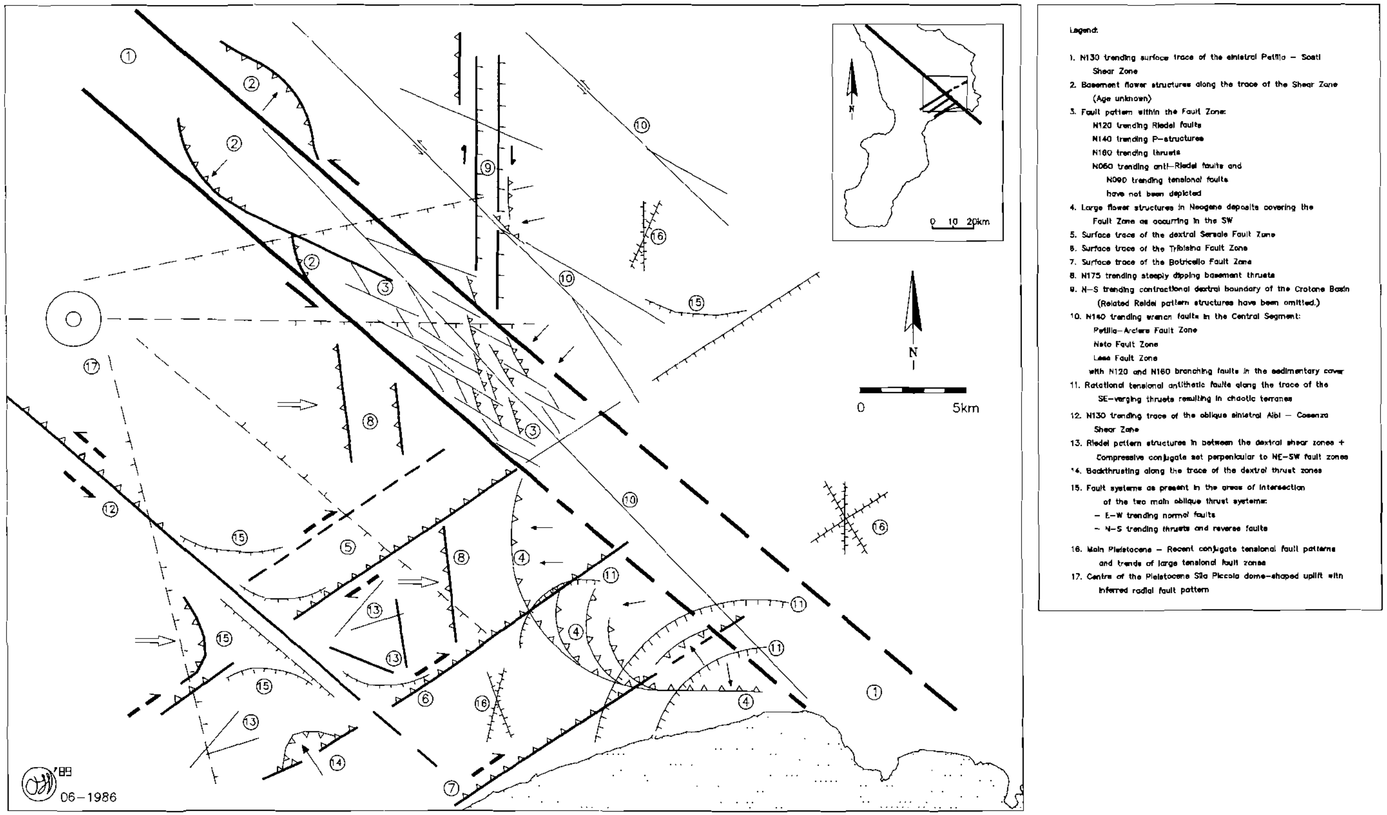

Legend:
1. N130 trending surface trace of the sinistral Petilia – Sosti Shear Zone
2. Basement flower structures along the trace of the Shear Zone (Age unknown)
3. Fault pattern within the Fault Zone:
N120 trending Riedel faults
N140 trending P-structures
N160 trending thrusts
N060 trending anti-Riedel faults and
N090 trending tensional faults
have not been depicted
4. Large flower structures in Neogene deposits covering the Fault Zone as occurring in the SW
5. Surface trace of the dextral Sersale Fault Zone
6. Surface trace of the Tribisina Fault Zone
7. Surface trace of the Botricello Fault Zone
8. N175 trending steeply dipping basement thrusts
9. N–S trending contractional dextral boundary of the Crotone Basin (Related Reidel pattern structures have been omitted.)
10. N140 trending wrench faults in the Central Segment:
Petilia–Arciere Fault Zone
Neto Fault Zone
Lese Fault Zone
with N120 and N160 branching faults in the sedimentary cover
11. Rotational tensional antithetic faults along the trace of the SE-verging thrusts resulting in chaotic terranes
12. N130 trending trace of the oblique sinistral Albi – Cosenza Shear Zone
13. Riedel pattern structures in between the dextral shear zones + Compressive conjugate set perpendicular to NE–SW fault zones
14. Backthrusting along the trace of the dextral thrust zones
15. Fault systems as present in the areas of intersection of the two main oblique thrust systems:
– E–W trending normal faults
– N–S trending thrusts and reverse faults
16. Main Pleistocene – Recent conjugate tensional fault patterns and trends of large tensional fault zones
17. Centre of the Pleistocene Sila Piccola dome-shaped uplift with inferred radial fault pattern
0 10 20km
N
0 5km
06–1986

Fig. 12

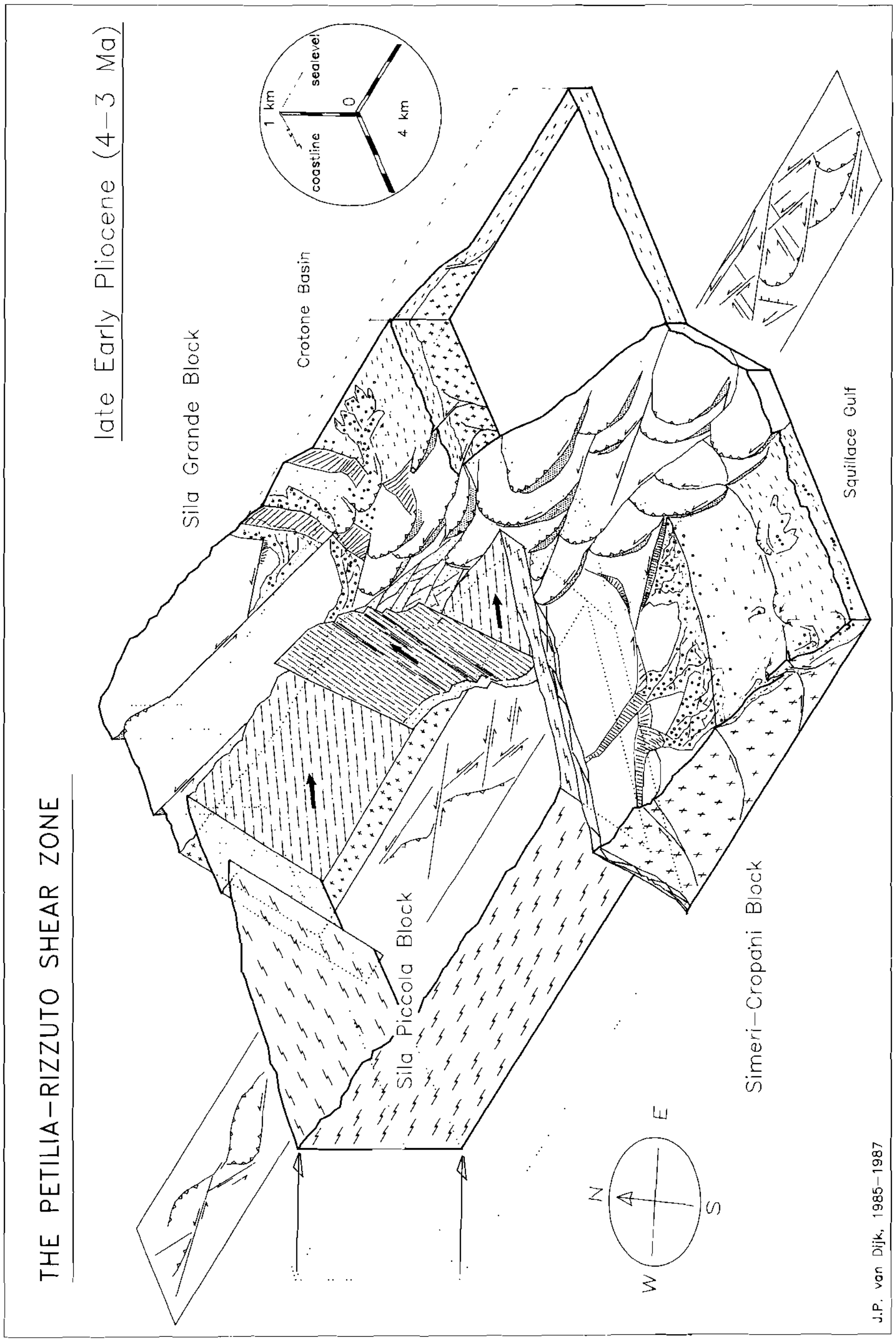

THE PETILIA–RIZZUTO SHEAR ZONE
late Early Pliocene (4–3 Ma)
Sila Grande Block
Crotone Basin
coastline
sealevel
1 km
0
4 km
Squillace Gulf
Sila Piccola Block
Simeri–Cropani Block
N
E
S
W
J.P. van Dijk, 1985–1987

Fig. 13

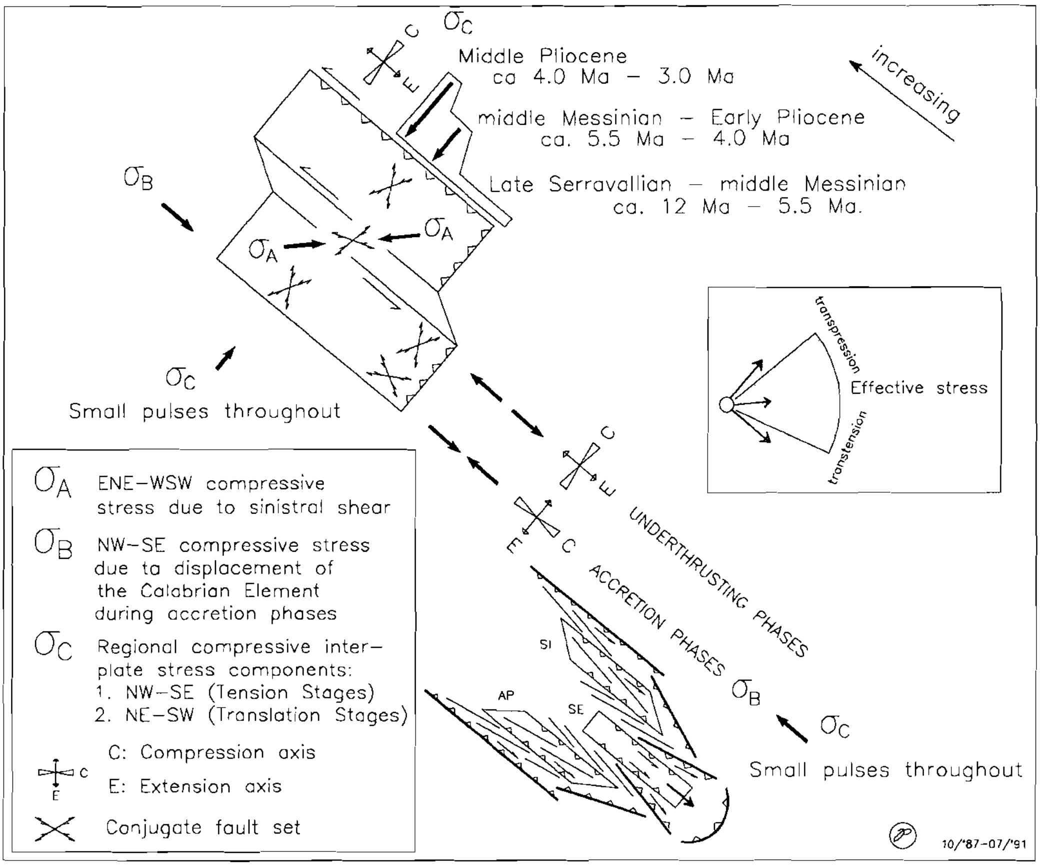


Fig. 14a

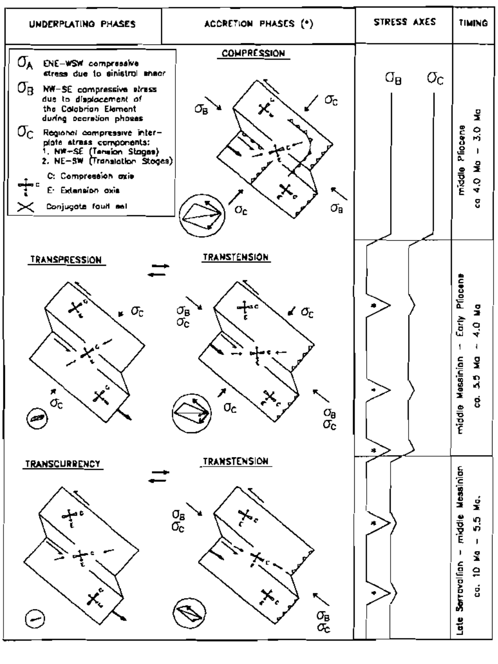


Fig. 14b

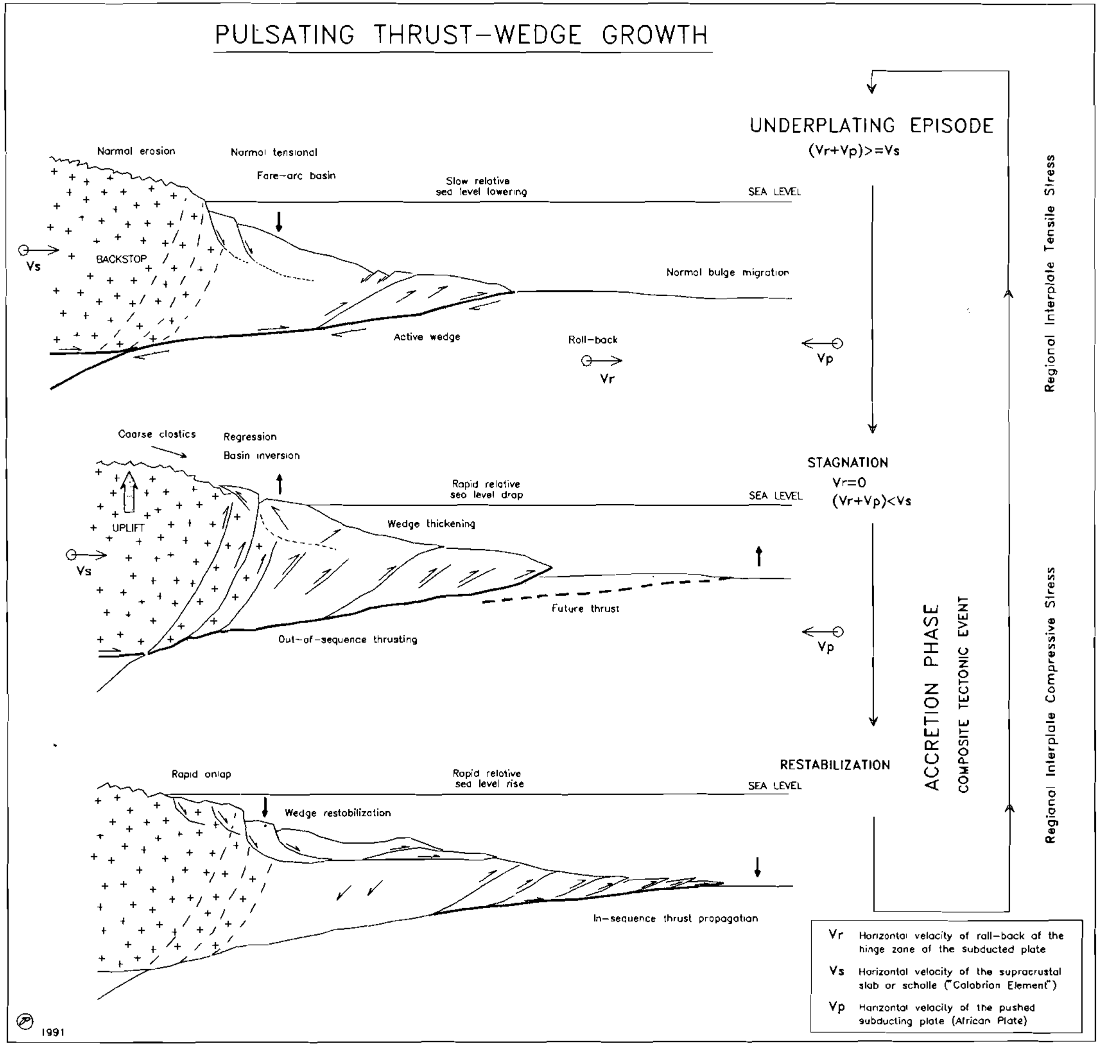
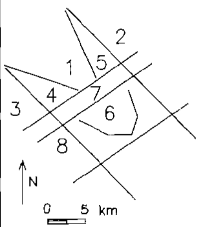

PULSATING THRUST-WEDGE GROWTH
UNDERPLATING EPISODE
(Vr+Vp)>=Vs
Normal erosion
Normal tensional
Fore-arc basin
Slow relative
sea level lowering
SEA LEVEL
BACKSTOP
Vs
Normal bulge migration
Active wedge
Roll-back
Vr
Vp
Regional Interplate Tensile Stress
Coarse clastics
Regression
Basin inversion
STAGNATION
Vr=0
(Vr+Vp)<Vs
Rapid relative
sea level drop
SEA LEVEL
UPLIFT
Wedge thickening
Vs
Future thrust
Out-of-sequence thrusting
Vp
ACCRETION PHASE
COMPOSITE TECTONIC EVENT
Regional Interplate Compressive Stress
RESTABILIZATION
Rapid onlap
Rapid relative
sea level rise
SEA LEVEL
Wedge restabilization
In-sequence thrust propagation
Vr Horizontal velocity of roll-back of the hinge zone of the subducted plate
Vs Horizontal velocity of the supracrustal slab or scholle ("Calabrian Element")
Vp Horizontal velocity of the pushed subducting plate (African Plate)
1991

Fig. 15

Basement Sectors



1. Monte Gariglione Sector
2. Cotronei Sector
3. Pentone Sector
4. Zagarise Sector
5. Lago Ampollino Sector
6. Pre–Sila Sector
7. Sersale Sector
8. Catanzaro Sector

This paper: Sectors	Signature	Used names:	Ogniben (1973)	Burton (1971)	Dubois (1976)	A. Morelli et al. (1976)	Lorenzoni et al. (1978) Z. Lorenzoni (1982)	Z. Lorenzoni (1980)	Gurrieri et al. (1981)	Lorenzoni et al. (1982)
							BARI SCHOOL			
1		Monte Gariglione Unit (MGaUn) (Amodio–Morelli et al., 1976): High grade metamorphites (Kinzigites) Marbles	Kinzigitic Formation	gruppo degli scisti biotitici e gneiss: SBG Complesso di gneiss e scisti biotitici	Nappe superieure: (8a) (gneiss a sillimanite (8m) Mambres (8a)	(19) gneiss Marmi Gneiss		(4) high grade metamorphic gneisses (3) intermediate grade metamorphic rocks	(5) "Formazione Kinzigitica" (4) gneiss biotitici	(4) "Kinzigitic Formation" gneisses high & medium grade
5		Intermediate grade metamorphites 2–mica granodiorites granodiorites, tonalites (silicate) Marbles	Sila granitic Batholite Falda di Aspromonte	gruppo graniti rocce connesse: γ' (see below)	(8b) (see below)	(20) granodiotiti graniti, tonaliti Unita' del Monte Gariglione	Monte Gariglione Unit	(2) granodiorites, tonalites, granites (6) Marbles and silicate marbles	(1) Magmatici Hercynici 2a Cyclus graniti/ granodioriti (2, 3) Magmatici Hercynici 1o Cyclus granodioriti & tonaliti	(2) 2–mica grano–diorites & granites (2nd Cycle) (3) grano–diorites/ tonalites (1st Cycle)
4 & 3		Castagna Unit (Dubois, 1966) (CasUn) Dynamo–metamorphic gneiss	Falda di Castagna	sbg (see above)	Nappe intermediaire: (18) (Unita di Castagno)	(7) Unita di Polia–Copanella (gneiss)	Castagna Unit (dynamo–metamorphic gneisses) Alpine Range	Monte Gariglione Unit (1–6) (8) Castagno Unit (gneiss) Alpine Chain	Unità di Monte Gariglione (1–5)	Monte Gariglione Unit (2–4) (5) Castagna Unit (gneiss, tonalites, grano–diorites) Alpine Chain
2		Longobucco Unit (LonUn) (Dietrich et al., 1976) Cerenzia granites (CerUn) Savelli metamorphites (SavUn)	Falda di Aspromonte	gruppo graniti e rocce connesse: serie γ Rocce acide	Nappe superieure: (8b)	(6) Unita di Longobucco (graniti)	Longobucco Unit (granites)	(9) Longobucco Unit (granites) Hercynian Chain	(6) Unita di Longobucco (graniti/ grano–dioriti ad Al2SiO3	(15) 2–mica granodio–rites/ granites
6 7		Hercynian nappes (Lorenzoni et al., 1980): Andali metamorphites (AndUn) Cropani granite (CroUn) M. Raga granite (MRaUn)	Sila granitic Batholite Calabride Complex	γ' Rocce acide fogliettate granito γ biotitico Sila–S. Elia Unit	(schistes epi–meso zoneaux) Nappes Calabraises	(20) see above (6) see above	Hercynian Range			(19) Metamor–phites (18) Dioritic & tonalitic gneisses (15) Hercynian Range
1 3 4 6 8		Coarse clastics Turbiditic fines Oligo–Miocene (Dubois, 1976) Sersale Formation (SerFm)		M^{cl}_{2-3} M^{ar-a}_{2-3} M^{a-s}_{2-3} Miocene medio–superiore	(n1) Oligo–Miocene (Miocene 1)	(38) Tortoniano–Pliocene inf.				

sept. 1987

Table 1

Mem. Soc. Geol. It.,
44 (1990), 259-285, 14 ff.

SEQUENCE STRATIGRAPHY, KINEMATICS AND DYNAMIC GEOHISTORY OF THE CROTONE BASIN (CALABRIAN ARC, CENTRAL MEDITERRANEAN): AN INTEGRATED APPROACH

J.P. VAN DIJK (*)

ABSTRACT

A comprehensive study on the Late Neogene tectonostratigraphic development of the Crotone Basin is presented. The basin is situated on the accretionary wedge along the external side of the Calabrian Arc (Central Mediterranean). The results of our analysis provide a detailed insight into the relative role of local tectonic activity of the thrust wedge and regional relative sea level fluctuations in the creation of unconformity bound depositional sequences.

The tectonostratgraphic significances of the sequence boundaries of the Early-Late Miocene and Late Pliocene-middle Pleistocene sequences are remarkably similar. They reflect a «composite tectonic event» comprising an uplift/regression pulse, followed by a rapid subsidence/onlap. Each composite tectonic event, in turn, represents one pulse in the progressive evolution of the accretionary wedge system. We regard the middle Messinian-Early Pliocene phases of basin fill and tectonic inversion, and the Late Pleistocene-Recent uplift phase as reflections of the increase of regional stress in the Central Mediterranean

KEY WORDS: *Central Mediterranean, foreland basins, strike-slip, sequence stratigraphy, Neogene*

RIASSUNTO

Il presente lavoro riguarda l'evoluzione tettonostratigrafica tardo Neogenica del Bacino di Crotone, situato al di sopra del prisma di accrezione del margine esterno dell'Arco Calabro (Mediterraneo Centrale). Esso comprende una dettagliata visione interpretativa del ruolo relativo dell'attività tettonica locale del prisma di sovrascorrimento, rispetto alle fluttuazioni regionali del livello marino, nella creazione di sequenze deposizionali limitate da superfici di discordanza. L'evoluzione tettostratigrafica può essere divisa in quattro stadi: 1) Stadio tardo Serravalliano/eo-Messiniano, caratterizzato da una progressiva espansione del bacino; 2) stadio Messiniano medio/eo-Pliocene, caratterizzato da intenso fagliamento e sequenze complesse, sovrapposto alla crisi di salinità Messiniana; 3) stadio tardo Pliocene/eo-Pleistocene, caratterizzato da un onlap pulsante; 4) stadio tardo Pleistocene/Recente, caratterizzato da forti movimenti verticali collegati al sollevamento del basamento della Sila. Alla fine dello stadio 2 la tettonica compressiva regionale della fase medio-Pleistocene è responsabile dell'inversione del bacino e del sovrascorrimento della copertura verso i margini. L'evoluzione del bacino è controllata da movimenti sinistrali lungo due zone di taglio crostali convergenti dirette NW-SE. Secondo questa visione l'evoluzione medio Miocenica/eo-Pliocenica (stadi 1 e 2) riflette un ciclo di strike-slip, nel senso di MITCHELL & READING (1978). Il significato tettostratigrafico dei limiti delle sequenze opposte negli stadi 1 e 3 è marcatamente simile: esso riflette un «evento tettonico composito» che comprende una pulsazione di sollevamento/regressione, seguita da rapida subsidenza/onlap. Ogni evento composito a sua volta rappresenta una pulsazione nell'evoluzione progressiva del sistema costituito dal prisma di accrezione. Le fasi di deposizione e inversione tettonica (stadio 2) medio-Messiniano/ eo-Plioceniche e la fase di sollevamento tardo Pliocenica ad Attuale (stadio 4) sono qui interpretate come un riflesso dell'aumento dello stress regionale nel Mediterraneo Centrale.

INTRODUCTION

The Calabrian Arc in the Central Mediterranean Area is situated in between three important orogenic belts: the Western Mediterranean E-W trending North African belt, the NW-SE trending Apennine belt and the Eastern Mediterranean NW-SE trending Hellenide-Dinaride belt (for general descriptions, we refer to MANTOVANI *et alii*, 1985; FINETTI & DEL BEN, 1986; PATACCA & SCANDONE, 1989). Related to its position in the central part of the young orogenic Mediterranean system, the Calabrian Arc appears to be highly interesting for the analyses of the interaction between sea level fluctuations and tectonics on various scales and the formation of unconformity-bound depositional sequences (see discussions in VAIL *et alii*, 1977; BURTON *et alii*, 1987; HAQ *et alii*, 1987; SLOSS, 1988; CLOETINGH, 1988). Both have been proved to be important: during the

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Messinian a sea level-drop and the subsequent sudden rise are thought to be of global importance (BENSON, 1984; MÜLLER, 1986) while the large-scale tectonic activity of the area easily can be appreciated. In this paper we will focus on the tectonostratigraphic aspects of the Neogene evolution of the Crotone Basin, which is situated at the northeastern, external side of the Calabrian Arc (figs. 1 and 2).

Previous studies on the Crotone Basin mainly deal with the stratigraphy but gave little information as to the tectonic setting and development of the basin (OGNIBEN, 1955; RODA, 1964, 1965b; BURTON, 1971; MEULENKAMP *et alii*, 1986; see for historical references OGNIBEN, 1973). Basin models for the Calabrian Arc are generally discussed within kinematic frameworks for the whole area (GHISETTI & VEZZANI, 1981; MOUSSAT, 1983; BOCCALETTI *et alii*, 1984). VAN DIJK & OKKES (1988, 1990 and in press.) and VAN DIJK (1991) reviewed the various existing models and proposed a new tectonic model for the Crotone Basin as an oblique (transpressive) piggy-back basin, locked between two intra-arc shear zones. The present contribution shows how the reconstruction of sequence stratigraphy from conventional stratigraphy provides insight into the evolution of the foreland basin. Some examples of geohistory analyses illustrate the phases in basin development as recognized.

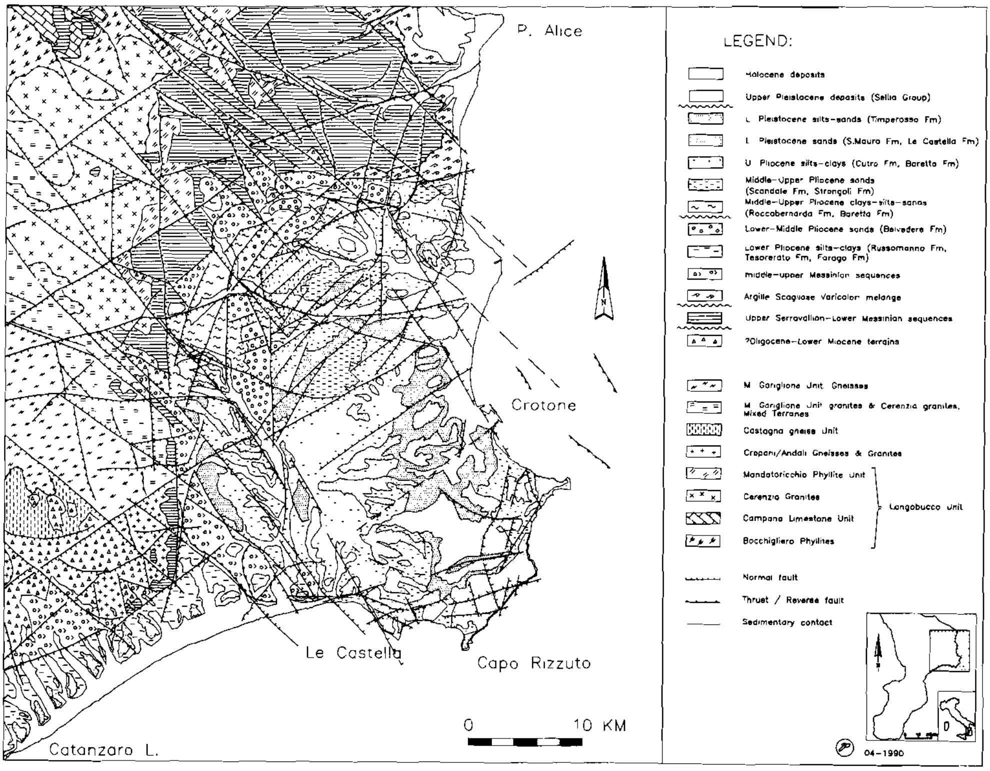


Fig. 1 - Geological map of the Crotone Basin. Basement structure was compiled and modified after BURTON (1971), DUBOIS (1976), AMODIO-MORELLI *et alii* (1976), ZANETTIN-LORENZONI (1982) and GUERRIERI *et alii* (1982). The basement structure clearly indicates the continuation and significance of the faults as recognized in the Neogene, and can also be used to detect Neogene overthrust tectonics.

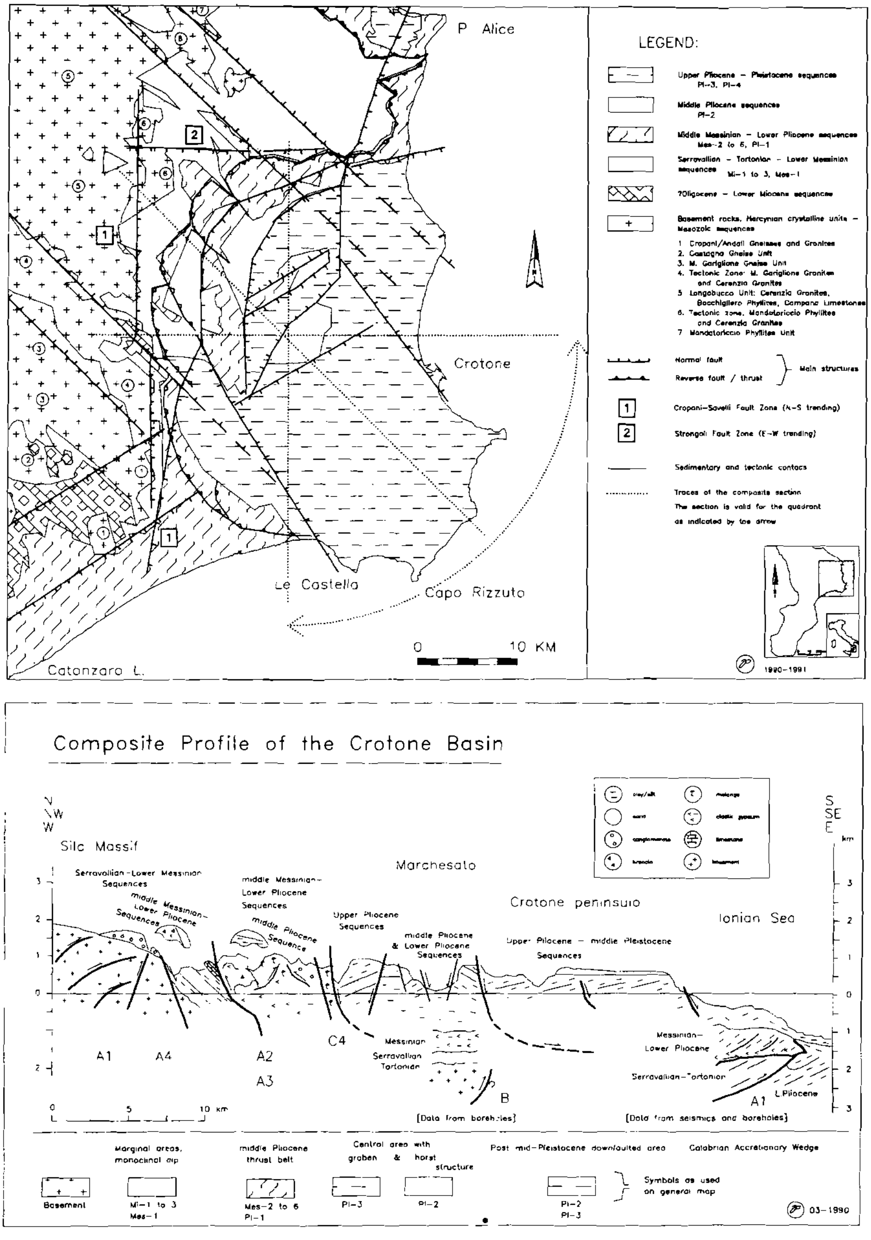


Fig. 2 - Geological structure of the Crotone Basin. *a*) Simplified geological sketch-map of the area. *b*) Composite cross-section of the Crotone Basin. Note that the section can be read in a N-S, as well as in an E-W or NW-SE sense. Modified from: VAN DIJK (1991). The letters A, B and C refer to fault patterns.

METHODS

We gathered our data during a number of field campaigns between 1983 and 1989 in the internal area of the Crotone Basin (fig. 3). The results were compared and appended with previously published field studies, seismic sections, borehole data and satellite photography studies (fig. 3). This resulted in 1:25.000 and 1:10.000 geological maps and stratigraphic correlation charts which are supported by biostratigraphic assignments to about 100 samples taken from key locations. Fig. 4 illustrates the methods we used to reconstruct the unconformity-bound depositional sequences from the field sections. This exercise resulted in detailed «composite tectonostratigraphic schemes» (i.e. composite columns with indications of existing relations along unconformities; see fig. 6) which are each representative for one specific, tectonically defined area (fig. 5). This concept shows affinity with the concept of «suspect allochtonous tectonostratigraphic terranes» (terminology of IRWIN,

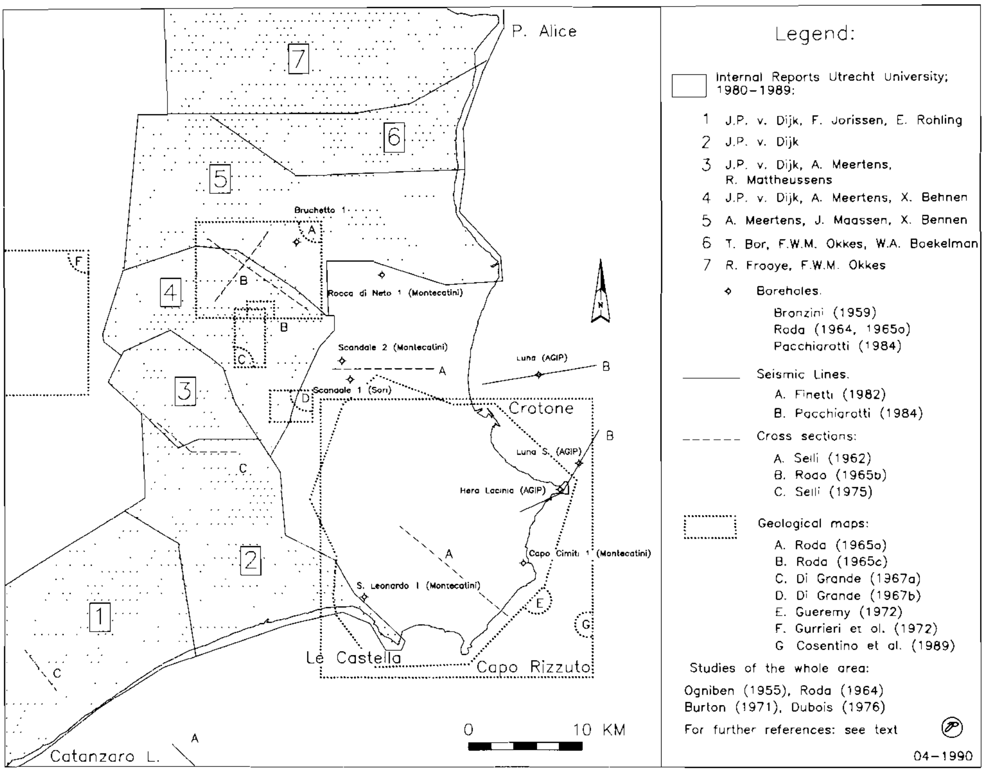


Fig. 3 - Locations of the areas which were mapped and the additional information from literature which was used in this study.

Fig. 4 - Flow chart illustrating the method of reconstructing unconformity-bound depositional sequences from field sections. Note that both from field sections as well as from composite stratigraphy geohistory diagrams can be processed. In this paper, the second approach was followed. The reason for this, is that separate field sections each display only a condenced part of the total tectonostratigraphic record. Processing the composite record results in an image which does not show the vertical movements of one specific point in the basin, but shows a subsidence/uplift path which is representative for a tectonically defined area. The elements presented in this paper are of the 3rd and 4th abstraction level.

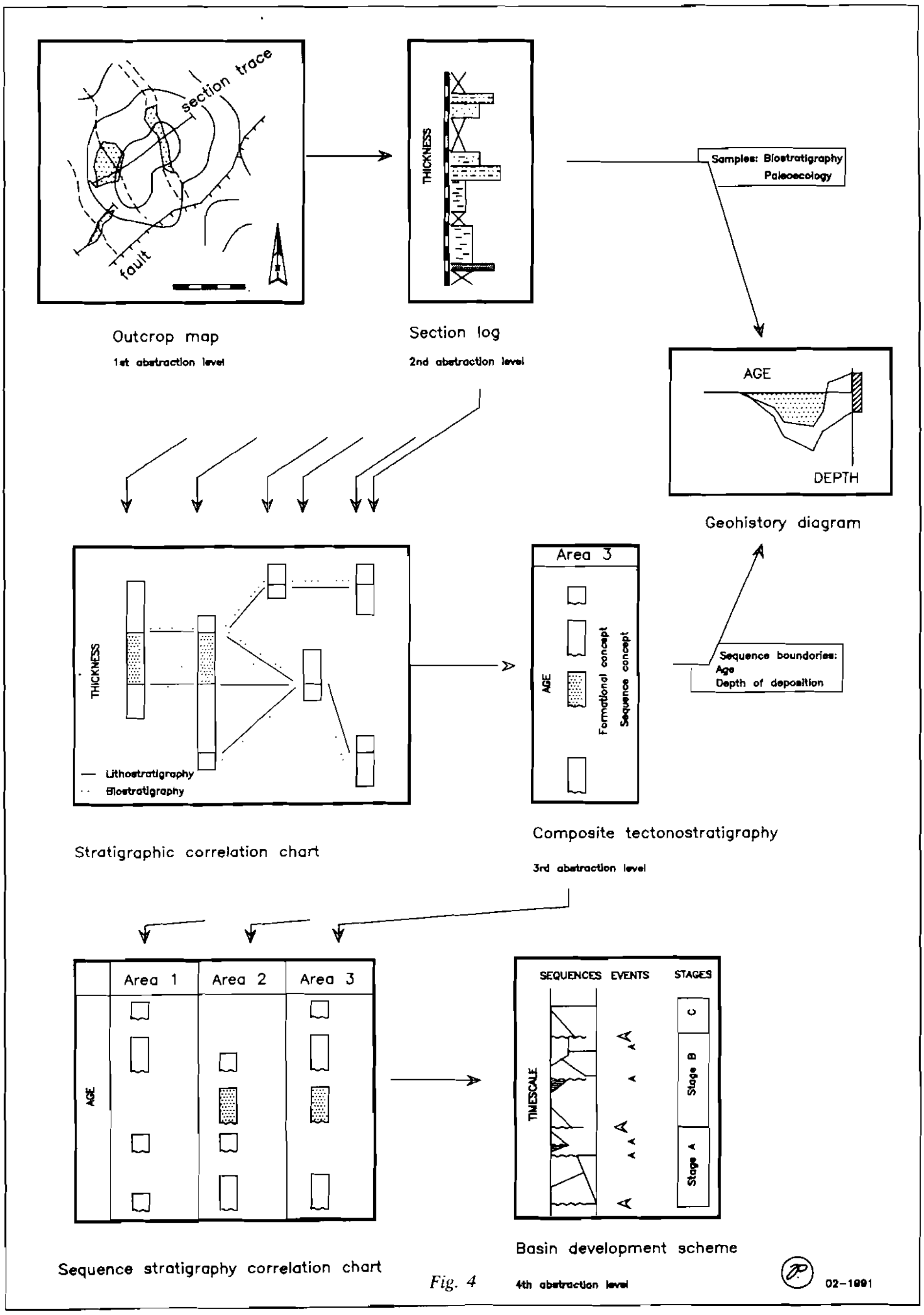

section trace
fault
Outcrop map
1st abstraction level
THICKNESS
Section log
2nd abstraction level
Samples: Biostratigraphy
Paleoecology
AGE
DEPTH
Geohistory diagram
THICKNESS
Lithostratigraphy
Biostratigraphy
Stratigraphic correlation chart
Area 3
AGE
Formational concept
Sequence concept
Composite tectonostratigraphy
3rd abstraction level
Sequence boundaries:
Age
Depth of deposition
Area 1
Area 2
Area 3
AGE
Sequence stratigraphy correlation chart
SEQUENCES
EVENTS
STAGES
TIMESCALE
C
Stage B
Stage A
Basin development scheme
4th abstraction level
02-1991

Fig. 4

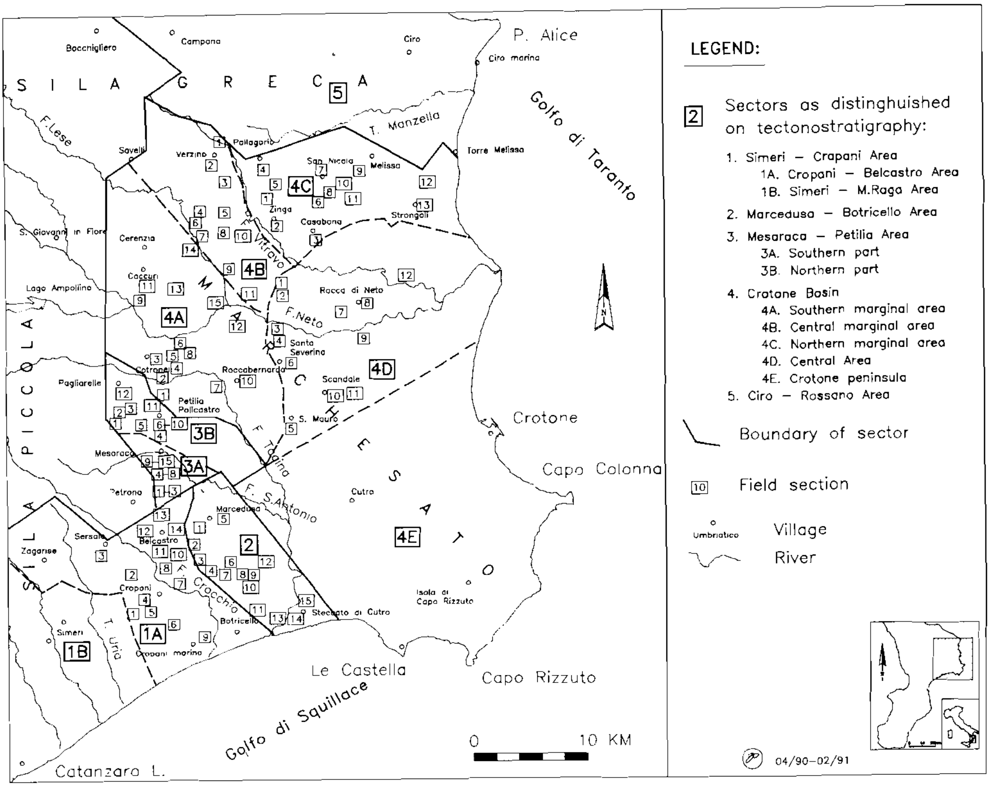


Fig. 5 - Subdivision of the Crotone Basin based on the tectonostratigraphic schemes of fig. 6. Separate land sections are indicated and numbered as in fig. 6.

1972; CONEY *et alii*, 1980; SCHERMER *et alii*, 1984; proposed to apply to the Calabrian Arc by VAN DIJK & OKKES, 1988, 1990). Finally a general basin development scheme has been constructed (fig. 8). The composite tectonostratigraphic schemes were processed to construct geohistory diagrams of different settings, using available information on biostratigraphy (age) and lithofacies (depth of deposition). Our software is based on the procedures for decompaction and loading correction as proposed and discussed by HOROWITZ (1976) and VAN HINTE (1978) and reviewed by GUIDISH *et alii* (1985). We used the algorithms as presented by STAM *et alii* (1987). Furthermore, the available data were combined and elaborated by means of newly designed methods (see for a full discussion VAN DIJK, in press.) into three-dimensional representations of calculated topography, the so-called Time-Snapshot Plots, or «synthetic landscapes».

TECTONIC STRUCTURE OF THE BASIN

The present-day configuration of the Crotone Basin can be characterized as follows (figs. 2a and b; after VAN DIJK, 1991): The remnants of Miocene to recent terrains are present in a quadrangular area confined to the west by a N-S and to the north by an E-W trending normal fault zone (resp. Cropani-Savelli Fault Zone and Strongoli Fault Zone). Three zones or areas can be recognized from the internal to the external side, both in an E-W, as well as in a N-S direction: A) Along the fault-bounded margins of the Sila Massif (N-S and E-W fault zones), Middle to Upper Miocene sequences are present which overlie basement and show a monoclinal dip towards the basin centre. B) The central zone (Marchesato area) comprises Upper Miocene to Lower Pliocene terrains, which are folded and thrusted towards the basin margins in the N and W. This tectonization can be linked to a middle Pliocene tectonic phase. C) The external area (Crotone Peninsula) in the SE comprises relatively undisturbed Upper Pliocene-Pleistocene sediments. Areas B and C are separated by post-Middle Pleistocene N-S, NNE-SSW and NE-SW trending normal faults with vertical displacements of several hundred metres which dominate the present geomorphology. Externally, thrusts have been documented in seismic profiles which show overthrusting and decollement of Upper Miocene and Lower Pliocene sequences.

SEQUENCE STRATIGRAPHY

The detailed tectonostratigraphic records of various areas (fig. 5) of the Crotone Basin are presented in fig. 6. These areas have primarily not been distinghuished solely on the basis of jumps in stratigraphic successions (MEULENKAMP *et alii*, 1986), but have been defined following tectonic criteria using the structural elements as have been recognized in the area (VAN DIJK, 1991; see the above described terrane concept). Fig. 6 shows how sequences have been reconstructed through conventional lithostratigraphy correlation. Along unconformities, these lithostratigraphic correlations coincide with biostratigraphic/chronostratigraphic levels which evidences the existence of specific time-synchronous sequence boundaries. In that way, a number of unconformity-bound depositional sequences can be distinghuished, which are comparable in magnitude with the third-order cycles of VAIL *et alii* (1977) and HAQ *et alii* (1987) as used in seismostratigraphy. In order to be able to detect which sequence boundaries are associated with tectonic pulses, we set up a series of criteria for syn-sedimentary tectonic activity along the basin margin which we used for this purpose (fig. 10; see also KRUMBEIN, 1942; SHANMUGAM, 1988 and EMBRY, 1990 for this type of approach). These criteria are exclusively based on field observations, which will not be discussed in detail; fig. 10 summarizes the total amount of data, indicating which phenomena can be observed. By means of combinations of these criteria, we could establish the amount of certainty with which the sequence boundaries can be linked to tectonic pulses or relative sea level fluctuations (or both). The latter can than still be due to tectonic activity, but on a larger scale than the studied basin, or to glacio-eustatic activity.

The unconformities which separate the Serravallian/Tortonian and Pliocene/Pleistocene sequences seem to record a standard tectonic signal (fig. 9): Each unconformity can be interpreted as the reflection of a small chain of tectonic events which we choose to call a «composite tectonic event», comprising a short phase of uplift and erosion of the basin margin, accompanied by the outgrowth of a submarine fan body (comparable to a Low Stand Systems Tract); this phase is followed by a rapid subsidence and back stepping of the basin margin resulting in a regional onlap (Transgressive Surface followed by a High Stand Systems Tract).

We distinguish the following sequences:

?Oligocene – Lower Miocene deposits: Remnants of ?Oligocene-Lower Miocene clastic deposits are present in the central area in small rhombic blocks delimited by N120 and N140 normal or reverse faults (Petilia-Policastro, Caccuri and San Nicola; see fig. 2), and in the south in the Sila Piccola area (SW-part of fig. 2; west of Cropani and Sersale). The deposits are strongly tectonized; they often show low angle thrust contacts with basement (Sersale, Zagarise) and are sometimes overthrusted by crystalline units (M. Raga and Pagliarelle; M.S. Barbara). We tentatively correlate the sequences in the Sila Piccola area and the remnants in the central area with the Paludi Fm (ZUFFA & DE ROSA, 1978) further north in the Ciro-Rossano Area, and with the Upper Oligocene-Lower Miocene Complex (sensu VAN DIJK & OKKES; 1988; 1990; Stilo-Capo d'Orlando Fm of BONARDI *et alii*, 1984; see also MEULENKAMP *et alii*, 1986) of southern Calabria. This correlation is based on similarities in lithofacies and tectofacies. Given the fact that biostratigraphic studies have up to date not resulted in any clear solutions these records can, alternatively, also be assigned to the Langhian-Serravallian (following the assignments of BURTON, 1971 and MEULENKAMP *et*

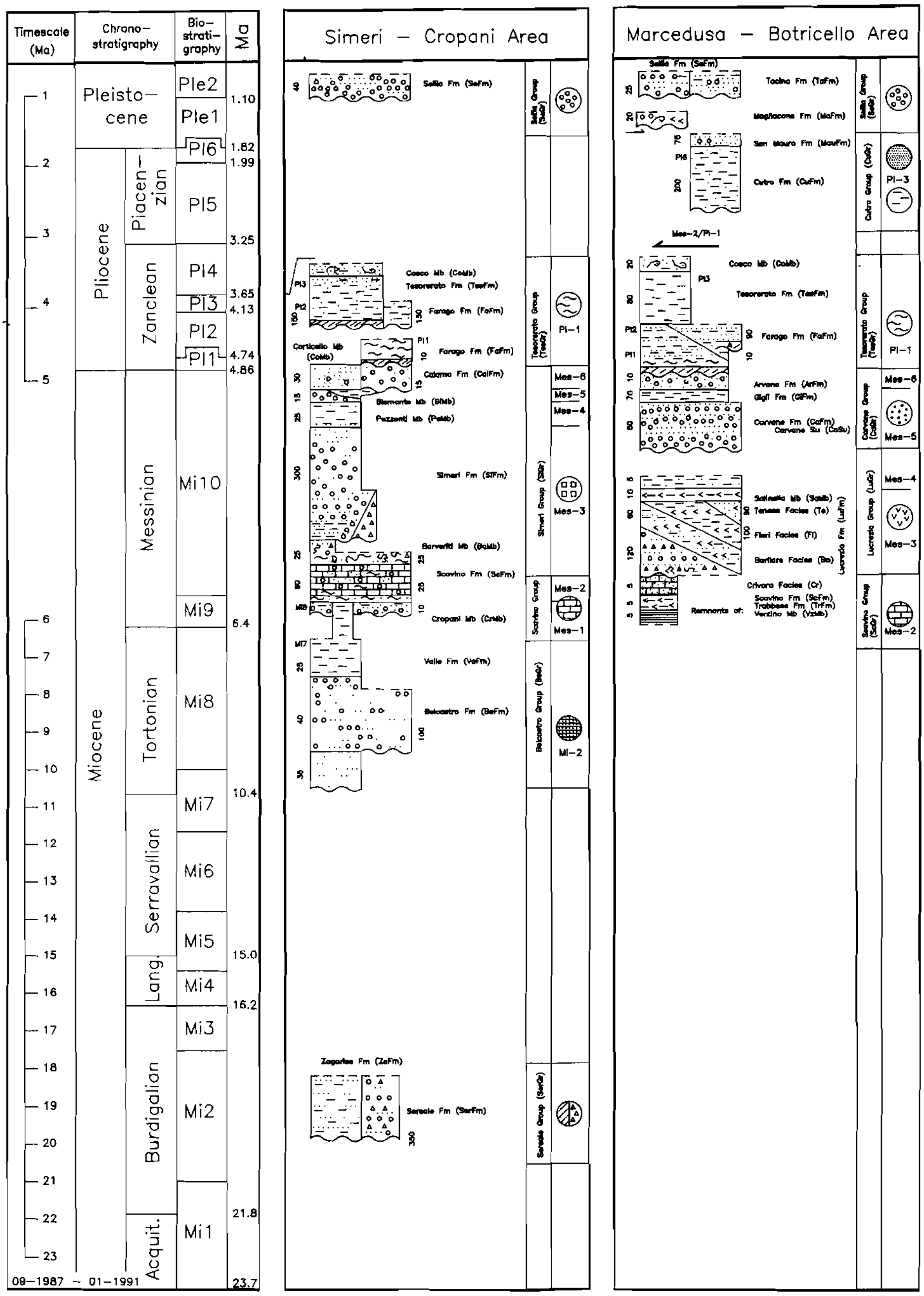
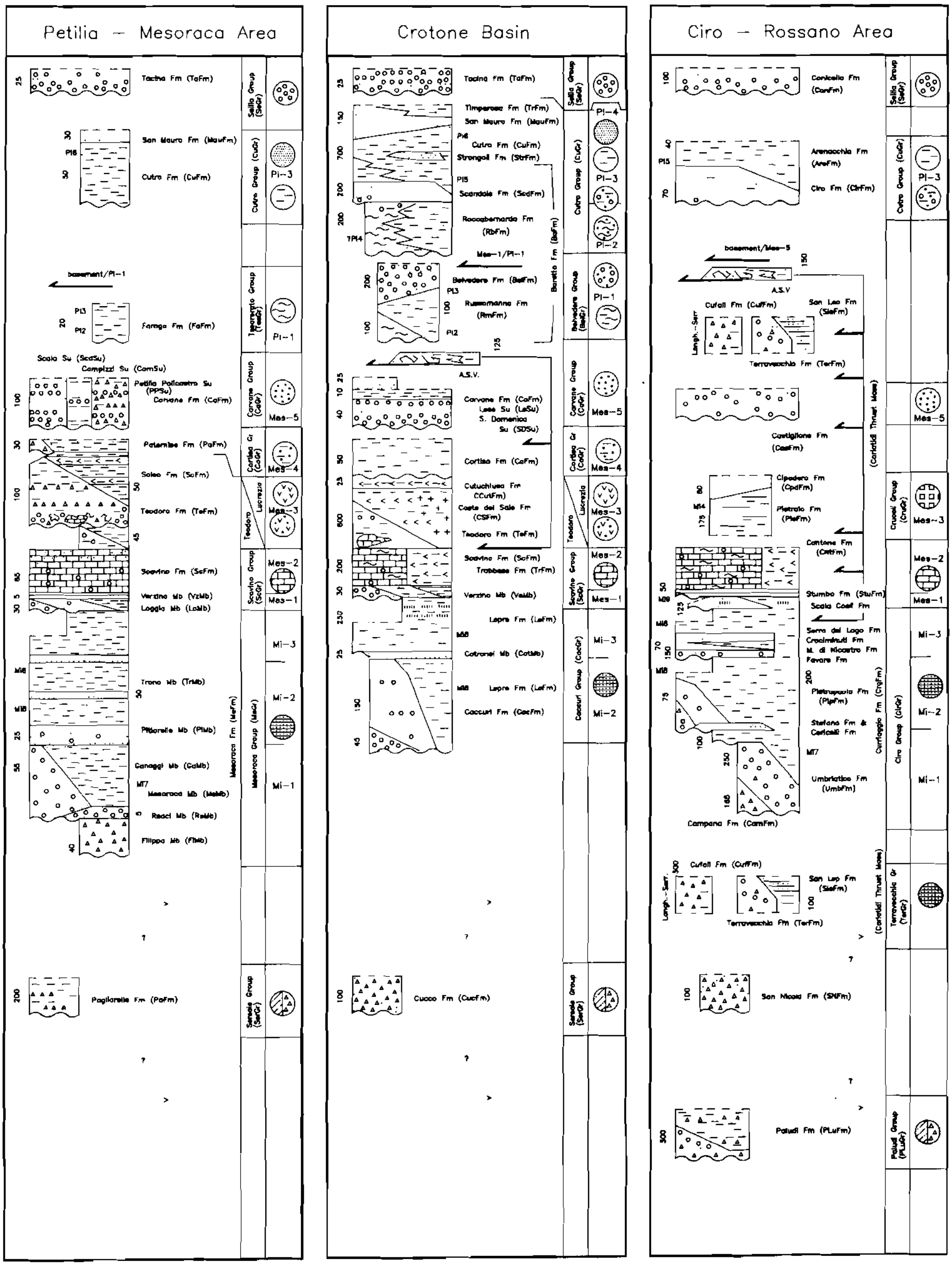


Fig. 6 - Tectonostratigraphic correlation charts and composite schemes. Note that the maximum thickness of the formation as indicated in the composite stratigraphic schemes does not always coincide with the thickness as indicated in the correlation charts. This is due to the fact that the final total thickness is obtained using cross sections and additional information from boreholes. For the location of the areas and the sections see fig. 5. *a)* Composite tectonostratigraphic scheme for the studied area. *b)* Correlation chart for the Cropani-Simeri Area.



c) Correlation chart for the Marcedusa-Botricello Area. *d*) Correlation chart for the Mesoraca-Petilia Area; southern part. *e*) Correlation chart for the Mesoraca-Petilia Area; northern part. *f*) Correlation chart for the Crotone Basin; southern marginal area. *g*) Correlation chart for the Crotone Basin; central marginal area. *h*) Correlation chart for the Crotone Basin; northern marginal area. *i*) Correlation chart for the Crotone Basin: central area.

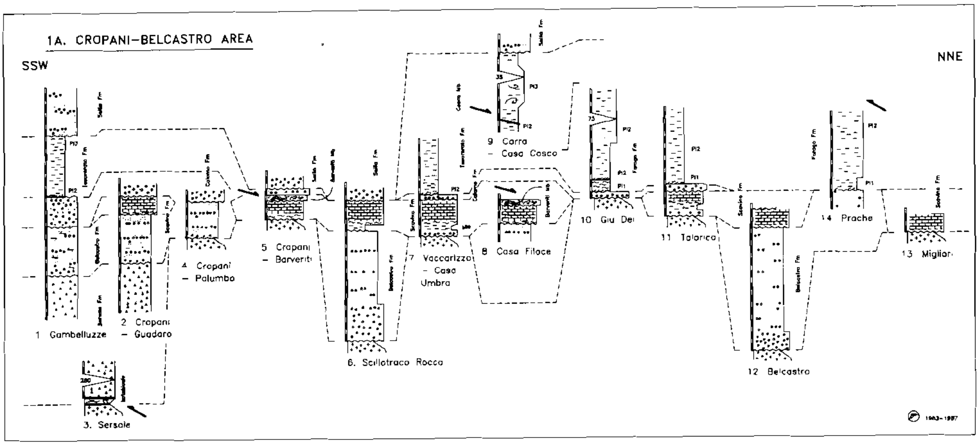


Fig. 6 b

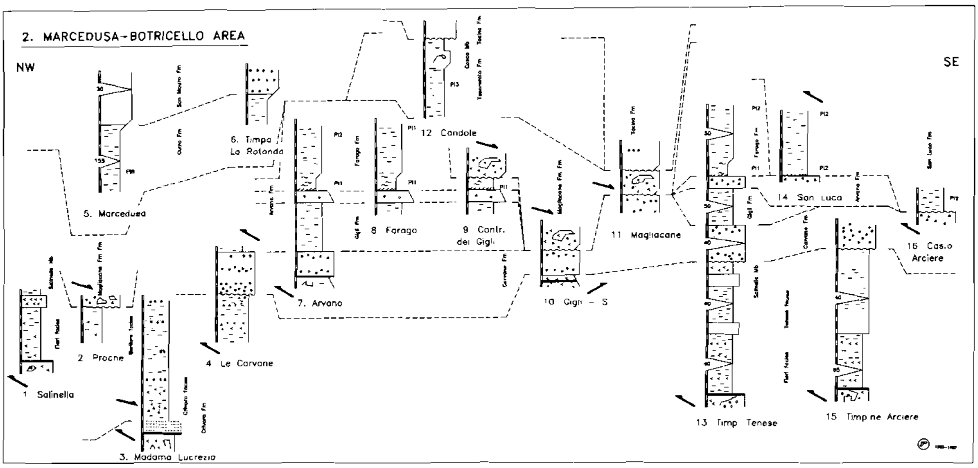


Fig. 6 c

alii, 1986 for the Sersale Fm and Zagarise Fm in the Sila Piccola). Both options have been indicated in fig. 6.

Upper Serravallian-Tortonian sequences (Mi-1 to Mi-3): This group of thick, shallow marine arkosic deposits can be subdivided into three depositional sequences, each of which apparently comprises a standard succession (fig. 9), and which are separated by unconformities of the standard type as described above. The total image reflects the continuous growth of the basin to the NW with a pulsating back stepping basin margin; each pulse comprises an initial uplift phase followed by rapid subsidence («composite tectonic event»). The N-S trending Cropani-Savelli fault zone constitutes the basin margin for the

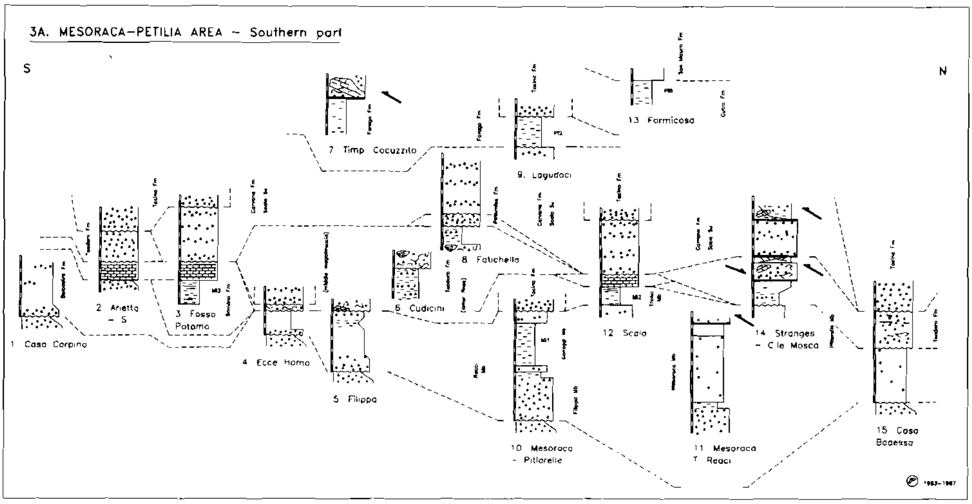


Fig. 6 d

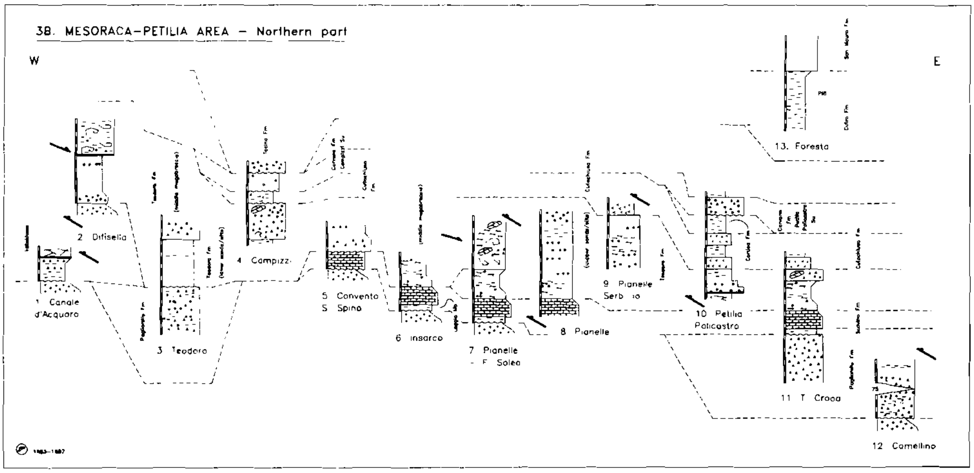


Fig. 6 e

Tortonian sequences. Subtle facies changes in the shallow marine deposits were confined by small parasitic faults trending E-W and N120. The sedimentation area was confined by two NW-SE trending fault zones (fig. 2a), as is suggested by: 1) the startling difference in overall stratigraphy with the areas north and south of these fault zones (see fig. 6), and 2) the very rapid facies changes and unconformities along N120 trending fault-bounded blocks as we documented in the Mesoraca-Petilia area (fig. 6).

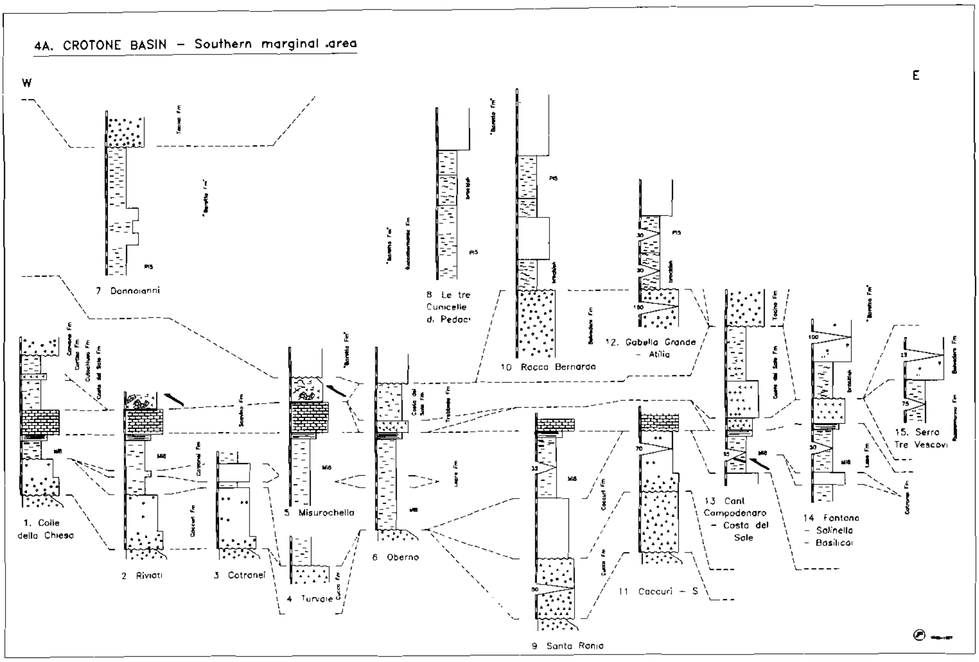

4A. CROTONE BASIN – Southern marginal area
W
E
7 Donnoianni
8 Le tre Cunicelle di Pedaci
10 Rocca Bernarda
12. Gabella Grande – Atilia
1. Colle della Chiesa
2 Riviati
3 Cotronei
4 Turvale
5 Misurochella
6 Oberno
9 Santa Ronia
11 Caccuri – S
13 Cant Campodenaro – Costa del Sole
14 Fontana – Salinella – Basilicoi
15. Serra Tre Vescovi

Fig. 6 f

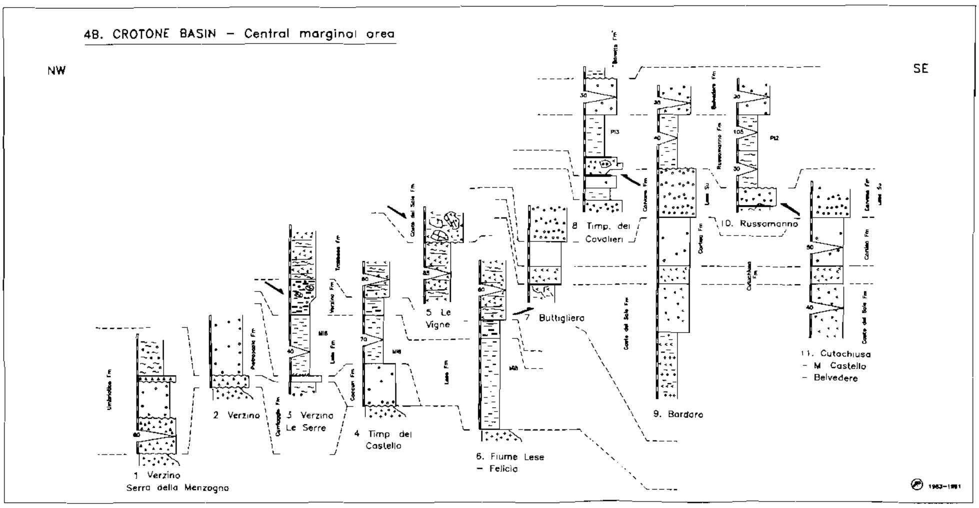

4B. CROTONE BASIN – Central marginal area
NW
SE
1 Verzino Serra della Menzogna
2 Verzino
3 Verzino Le Serre
4 Timp dei Castello
5 Le Vigne
6. Fiume Lese – Felicia
7 Buttigliero
8 Timp. dei Cavalieri
9. Bardaro
10. Russomanno
11. Cutochiusa – M Castello – Belvedere

Fig. 6 g

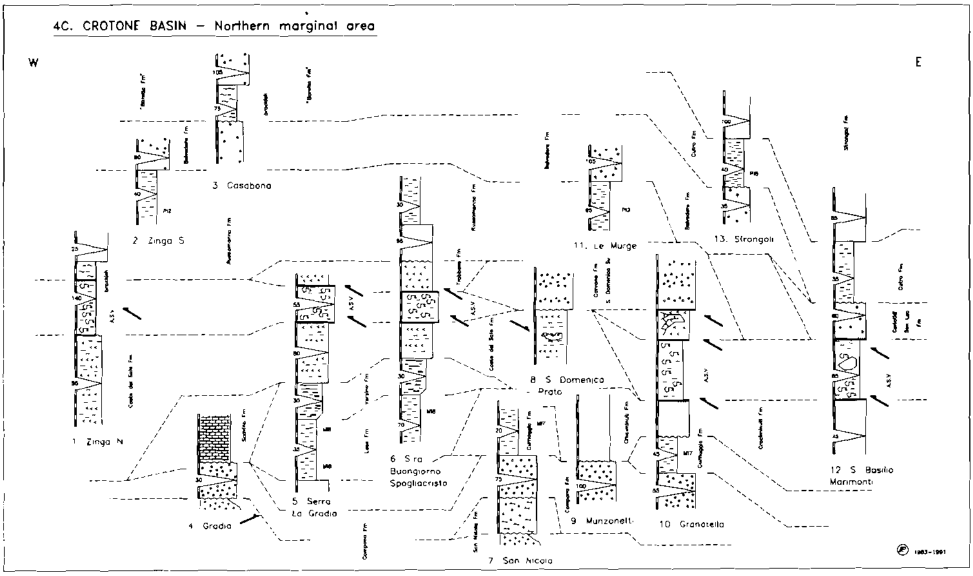

4C. CROTONE BASIN – Northern marginal area
W
E
1 Zinga N
2 Zinga S
3 Casabona
4 Gradia
5 Serra La Gradia
6 S.ra Buongiorno Spagliacristo
7 San Nicola
8 S. Domenica Prato
9 Munzonelli
10 Granatella
11 Le Murge
12 S. Basilio Marimonti
13 Strongoli

Fig. 6 h

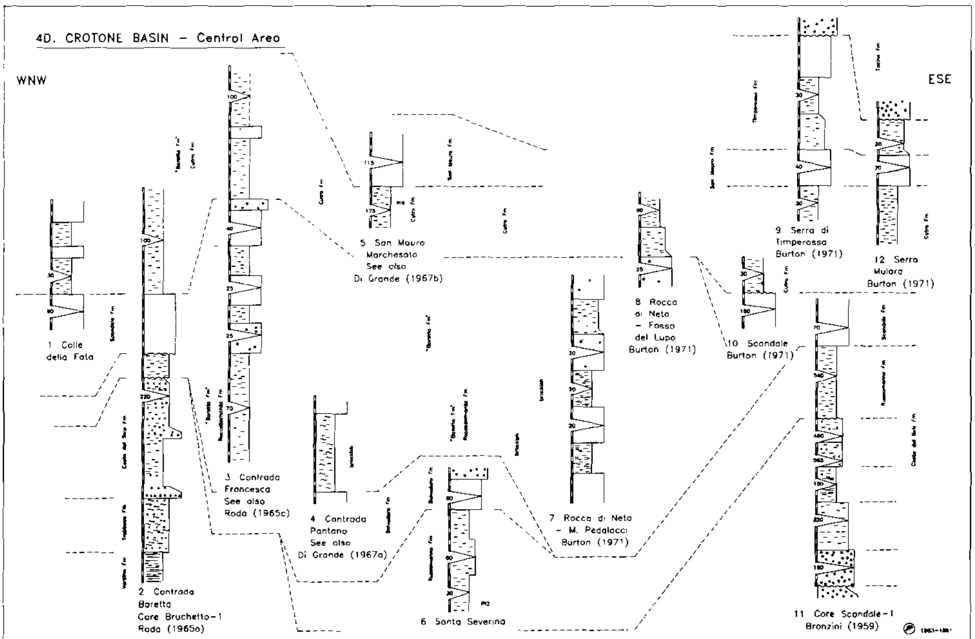

4D. CROTONE BASIN – Central Area
WNW
ESE
1 Colle della Fata
2 Contrada Baretta Core Bruchetto-1 Roda (1965a)
3 Contrada Francesca See also Roda (1965c)
4 Contrada Pantano See also Di Grande (1967a)
5 San Mauro Marchesato See also Di Grande (1967b)
6 Santa Severina
7 Rocca di Neto – M. Pedalacci Burton (1971)
8 Rocca di Neto – Fosso del Lupo Burton (1971)
9 Serra di Timperossa Burton (1971)
10 Scandale Burton (1971)
11 Core Scandale-1 Bronzini (1959)
12 Serra Mulara Burton (1971)

Fig. 6 i

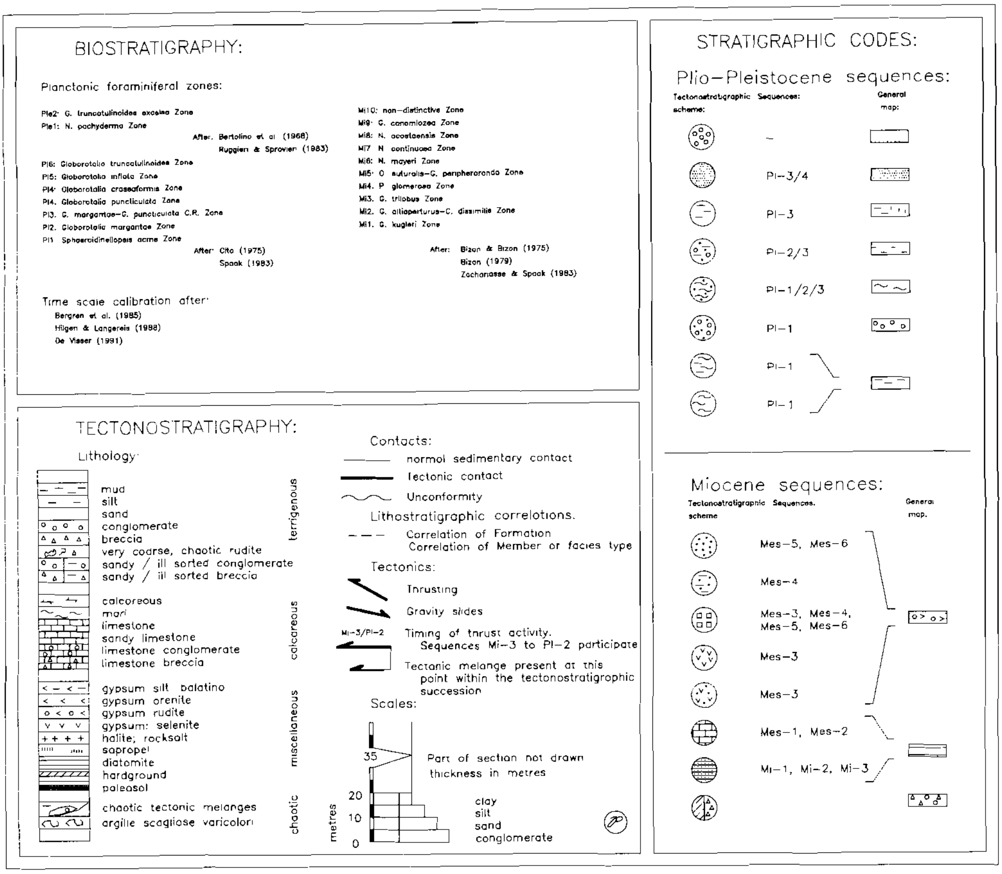


Fig. 7 - Legend for the tectonostratigraphic schemes of fig. 6.

Lower-middle Messinian «Lower Evaporites» sequence (Mes-1 and Mes-2): The base of the first sequence resembles the base of the previously described sequences; the outgrowth of a fan-body in the basin (Scala Coeli Fm in the Ciro-Rossano Area in the north), transgressive sands and marine clays along the margin (Cropani and Loggia Mbs in the central and southern areas). The top of the sequence, however, shows a deviating picture: Along the basin margin, the deposits grade into diatomites followed by dolomitic limestone-rudites («Calcare di Base»; Scavino Fm), whereas in the centre intercalations of sapropelites and diatomites are followed by clastic gypsum, varying from fine-grained balatino-type to coarse grained gypsum arenites (Trabbese Fm). The evaporites locally directly overlie basement, representing the base of the second Messinian sequence. This development reflects the local onset of the Messinian salinity crisis (see for a discussion of comparable facies in Sicily Ogniben, 1957 and Decima *et alii*, 1988). The top of the second sequence shows an upwards fining into carbonate-margin turbidites or carbonate sands with increasing influx of debris-flow material along the margins («lower fines facies» of the Teodore Fm in the Petilia-Mesoraca area; see for facies models McIlreath & James, 1979). Upwards

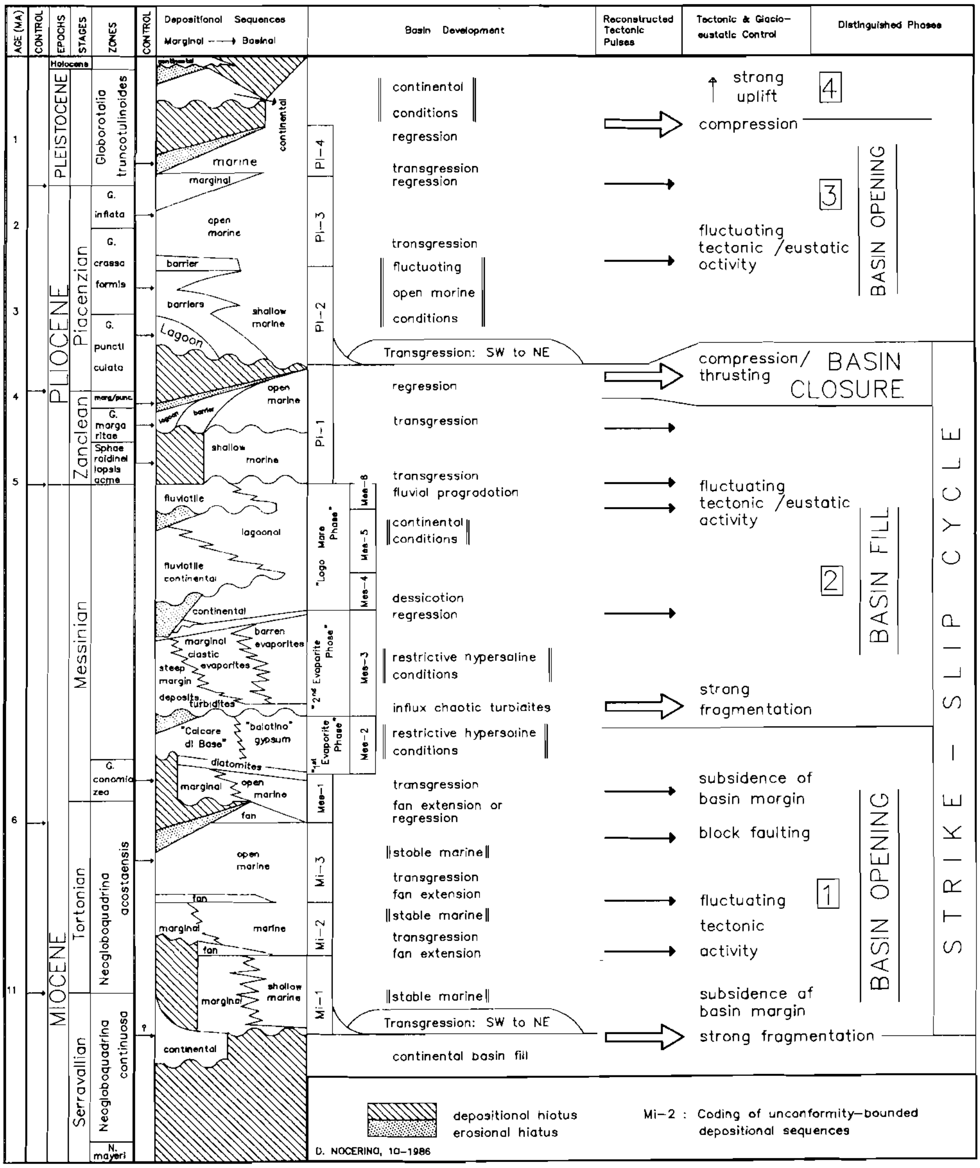


Fig. 8 - Composite synthetic tectonostratigraphic scheme for the basin development of Central and Northern Calabria. Modified from VAN DIJK & OKKES (1988, 1990 and in press.) and VAN DIJK (1991).

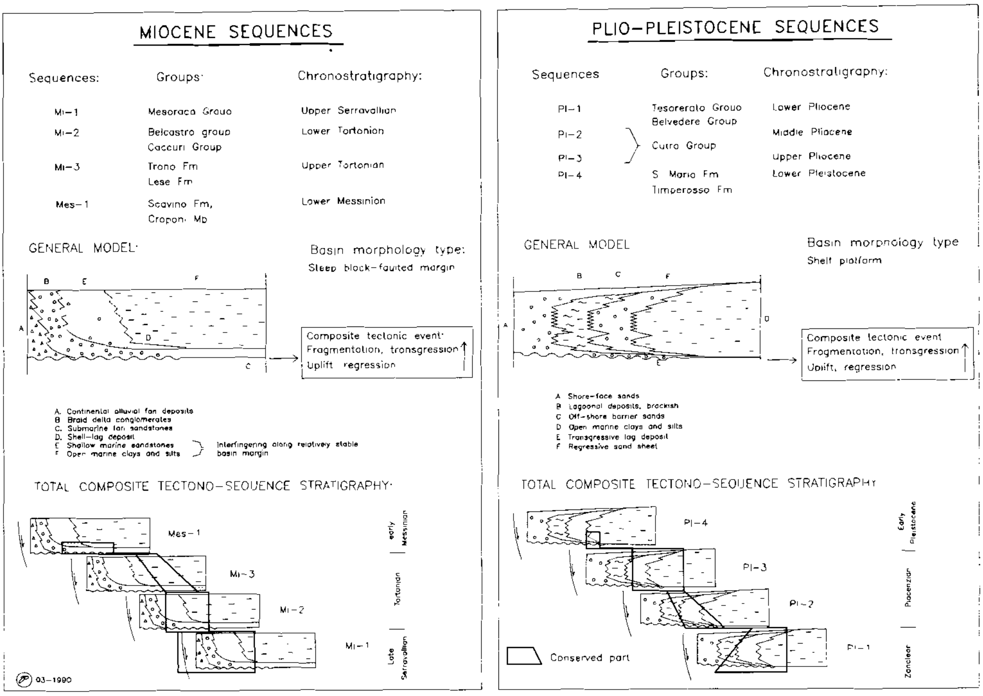


Fig. 9 - Sequence models for the Miocene and Pliocene of the Crotone Basin.

grading into silts and clays with intercalated gypsum turbidite layers occurs in the central area (Coste del Sale Fm).

Middle-upper Messinian «Upper Evaporites» sequence (Mes-3): The base of this sequence locally shows growth faults with a N140 and N090 trend and slide blocks containing lower Messinian deposits, associated with very coarse clastics comprising olistostromes and alluvial fan deposits («middle megabreccia facies» of the Teodoro Fm in the Petilia-Mesoraca area). These deposits are followed by silts and sands with thin limestone-sand intercalations («upper sands/silts facies»), resembling the Colombacci-type lacustrine deposits of the Northern Apennines (SELLI, 1973). In the central area, a thick sequence of clastic gypsum and salts was formed (Coste del Sale Fm; see for facies models the review of basinal evaporites of KENDALL, 1979). In the area north of the Crotone Basin, this sequence is represented by a turbidite succession, resembling the Upper Messinian sequences of the Central Apennines such as the Laga Flysch Fm (SELLI, 1973). This can (also) in the Calabrian case be interpreted as the representation of a depositional system along the active margin of the evaporite basin. The top part of the sequence shows a shallowing with increasing influx of sandy material, followed by a distinct level of gypsum siltstones (Salinella Mb and Cutuchiusa Fm) which is recognizable over a large area (from Belvedere di Spinello in the central area up to Catanzaro in the south). These gypsum silts probably reflect the erosion of older gypsum deposits due to a regional relative sea level lowering, precluding the «Lago Mare» stage.

Upper Messinian «Lago-Mare» sequence (Mes-4 to Mes-6): In the upper Messinian continental deposits we distinguish the following three sequences:

«Lago-Mare sequence 1» (Mes-4): These deposits consist of fluviatile sandstones and hyposaline/brackish laminated fines with dessication cracks (Cortisa Fm; Paternise Fm), directly overlying the uppermost gypsum deposits. Locally continental breccias are present with an unconformity at the base. Of this sequence, we found only remnants with a thickness of at most 15 metres.

«Lago-Mare sequence 2» (Mes-5): This sequence consists of large sheets of conglomerates and sandstones (Carvane Fm) which once probably covered the whole area from Strongoli in the north up to Cropani in the south, although now only remnants are present along major NW-SE trending fault zones. The base shows channel structures which cut into older Messinian sequences down to the lower Messinian «Calcare di Base». We interpret the deposits as braid plain to braid delta deposits (sensu McPherson *et alii*, 1987) reflecting a strong lowering of the base level of erosion and a (partly) dessicated basin.

The material, in literature referred to as «Sicilide» (e.g. Ogniben, 1973) is polymictic with a high abundance of pebbles of Mesozoic rock provenance. Some authors concluded that its origin is more external (S, SE or NE) in a formerly uplifted area (Ogniben, 1973). This conclusion was based on 1) Source rocks do not outcrop in the Sila, 2) The upper Messinian conglomerates show a sequence of polymict to crystalline material (Burton, 1971) reflecting a switch from external to internal source-area (Messinian-Early Pliocene), 3) The Cariatidi thrust mass (Bonfiglio, 1964; Roda, 1965 a) in the North wich comprises Messinian terrains, is transported from NE to SW; if gravitational sliding is the operative emplacement mechanism, the external area is consequently the uplifted section. We do not support any of the listed arguments; 1) Our data indicate a much more complicated stratigraphy of the upper Messinian coarse clastics than the one proposed by the mentioned authors and we even place the clastics with crystalline material, used by Burton (1971) to support his idea, in a position below and not above the Carvane conglomerates, 2) Mesozoic sequences do outcrop in the Sila and furthermore the rest of the source-area may simply be present in subsided terranes in the Tyrrhenian Basin, and 3. We presented a different tectonic model for the transportation of the thrust masses (Van Dijk & Okkes, 1988, 1990) implying that they are back-thrusts to the SW, and were furthermore not displaced in the Messinian but in middle Pliocene times.

Discussions related to this issue regard the intercalations of Argille Scagliose in the Messinian deposits in the central and northern marginal areas which were interpreted by Ogniben (1955), Roda (1964) and Meulenkamp *et alii* (1986) as being sedimentary in origin (Late Tortonian-Early Pliocene olistostromes). We have established that the phenomena related to these chaotic units can be separated into middle Messinian gravitational slides (Costa del Sale Fm; comparable to the middle megabreccia facies of the Teodoro Fm in the southern marginal area) and middle Pliocene thrusts which cut upwards through the stratigraphy (fig. 6).

The top of the sequence shows upward grading into lagoonal fines (Gigli Fm). We interprete this as the reflection of a decrease in the supply of clastic material (by a flattening of the relief). «Lago-Mare sequence 3» (Mes-6): The top of the Messinian comprises a distinct level of fluviatile sandstones and conglomerates (Arvano Fm). In the studied area, the sequence reaches a maximum thickness of 10 metres. To the south of the area, however, much greater thicknesses (up to 50 metres) have been documented, e.g. in the Soverato area in Central Calabria. Along the basin margin (e.g. near Cropani) the deposits overlie basement rocks (Calamo Fm). We concluded that this level reflects a tectonic pulse responsible for the uplift of the source area and increase in supply of clastic material. This tectonic pulse is followed by the regional transgression at the beginning of the Pliocene, which indicates that the events at the Miocene-Pliocene boundary show a picture which is similar to the composite tectonic event described above. Following this concept, the Mes-6 and the Pli-1 sequences can be taken together as one.

Lower Pliocene sequence (Pl-1): The Lower Pliocene sequence consists of fine grained clastics unconformably overlying older deposits (Russomanno Fm, Farago Fm, Tesorerato Fm). It comprises both brackish, lagoonal fines, as well as shallow marine clays («Cavaliere Fm» of Roda, 1964), silts and sandstones. The lowermost (marine) Pliocene (Farago Fm) is only locally present along the southern margin in upthrusted blocks. It must be stressed that the Pliocene clastic deposits which overlie older terrains along the margin in the central area cannot always be placed with certainty at their correct stratigraphic position. The reconstruction is strongly hampered by tectonic complications and by the fact that biostratigraphic assignments cannot always be performed. We named the total package «Baretta Fm»; only in cases of clear stratigraphic position (large sand bodies, biostratigraphic assignments, clear facies relations), specific formation names have been used. The top of the sequence consists of a thick series of sandstones and conglomerates

(Belvedere Fm). The sequence as a whole fits in a general model which we constructed for the successons of the Pliocene-Pleistocene sequences (fig. 9; see below). It reflects a migrating regressive lagoonal-barrier-open marine depositional system.

Upper Pliocene-Lower Pleistocene sequences (Pl-2 to Pl-4): These three open marine sequences (Cutro Group) show, like the Miocene sequences, a standard succession (fig. 9). Each sequence comprises lagoonal, brackish fines («Spartizzo Fm» of RODA, 1964), barrier-island sands (e.g. the Strongoli Fm) and open marine fines (Cutro Fm), showing complex interfingering relations. Differences between the sequences include relative thickness of the various facies and in some cases absence of certain parts due to erosion. The base of each sequence shows fines and sands overlying previous successions (Tortonian, Messinian, Lower Pliocene) and indicating rapid onlap. The top of the sequences consist of relatively thick, littoral sandstones showing a rapid regressive trend (Scandale Fm, San Mauro Fm).

Like in the Miocene sequences, the total repetitive patterns in the Pliocene and Lower Pleistocene seem to reflect the continuing enlargement of the basin with a pulsating onlap. We therefore propose a comparable model as for the Miocene sequences (fig. 9) i.e. the sequences are separated by a composite tectonic event comprising an uplift phase followed by rapid subsidence, although in the Pliocene case the basin evolution seems to be more gradual.

Upper Pleistocene deposits: Along the southern coast (Botricello), masses of debris-flow material comprising Messinian and Pliocene deposits and slide blocks are present, associated with rotational antithetic faulting (Magliacane Fm). We can only tentatively place these phenomena in the middle Pleistocene, as they are overlain by Upper Pleistocene clastics. The Upper Pleistocene continental (braid-plain/lacustrine) and shallow marine (shoreline) deposits (Sellia Fm, Tacina Fm) are present as various terraces and have been well described in the literature (see for a review OGNIBEN, 1973).

The variations in height above sea level been linked to relative sea level fluctuations as well as to small-scale faulting (see also COSENTINO *et alii*, 1989). Near Le Castella, we observed synsedimentary monoclinal folding (also reported by BRONZINI, 1959 in seismic studies nearby) and tapering indicating opening to the NE along NNW-SSE trending faults.

Sub-) Recent deposits: These are recent deposits in river braid-plains, along the sandy coast and as cones and landslides along the margins of the Sila Massif.

BASIN EVOLUTION AND KINEMATICS

Combining the available information on sequence stratigraphy and tectonics, a general basin development scheme can be constructed (fig. 8). The evolution of the basin can be divided into four stages, which are separated by the main tectonic phases. These phases are distinghuished on the basis of the occurrence of features which indicate compressional tectonics and/or the occurence of angular unconformities. 1) Serravallian-early Messinian stage, 2) middle Messinian-Early Pliocene stage with a late Early («middle») Pliocene Basin inversion phase, 3) Late Pliocene-Early Pleistocene opening stage, and 4) Late Pleistocene-Recent uplift stage.

VAN DIJK (1991) proposed the following kinematic model for the evolution of the Crotone Basin (fig. 11): The basin is situated at the intersection of the NW-SE trending thrust system «A» (which is dominant in the area N of the Crotone Basin) and the NE-SW trending thrust system «B» (which is dominant in the area SW of the Crotone Basin). It is bordered in the NE and SW by two major NW-SE trending sinistral oblique crustal shear zones. The Middle Miocene to middle Pliocene development is characterized by a shearing of the area resulting in an evolution from the initial development of small strike-slip basins along wrench-faults to the final inversion of the whole area in the middle Pliocene. Following this kinematic model the first two stages can be linked to the Strike Slip Cycle of MITCHELL & READING (1978): 1) Late Serravallian-early Messinian «Basin Opening Stage», and 2) middle Messinian-Early Pliocene «Basin Fill Stage» with a late Early Pliocene «Basin Closure Stage».

The geohistory diagrams which we processed (figs. 12a and 12b), illustrate the patterns of vertical movements in respectively basin

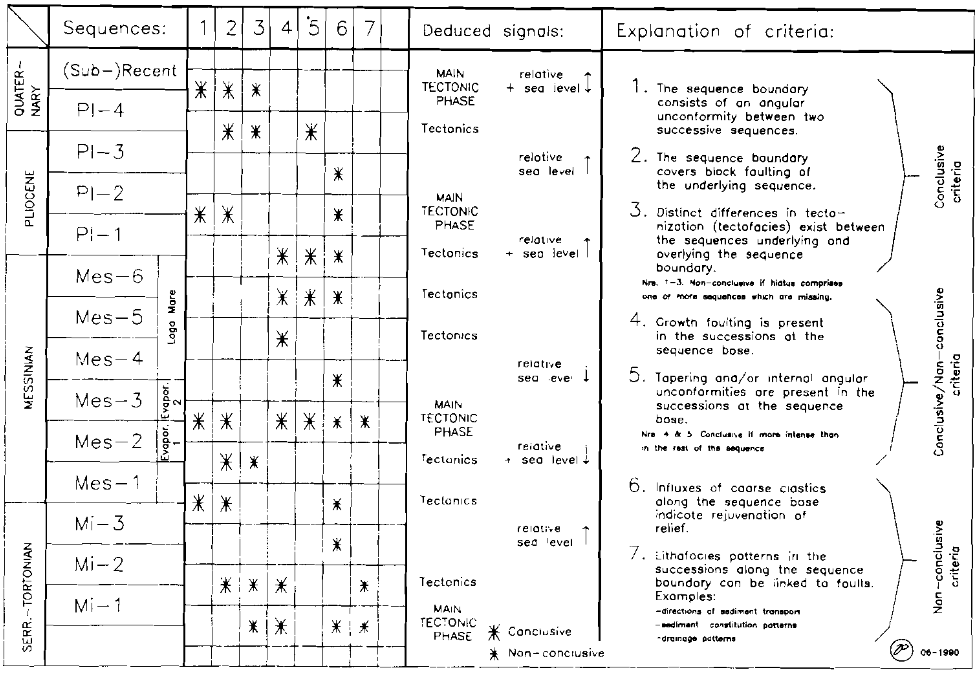


Fig. 10 - Table indicating criteria used in the relativistic analyses of tectonics and sea level fluctuations. The asterix indicate criteria as have been used for recognition of tectonic activity in relation with the sequence boundary. The indication «+ relative sea level» refers to concensus in literature (see text) with respect to the occurence of sea level fluctuations (Messinian salinity crisis. Pleistocene glaciations). The indication «relative sea level» in based on the absence of clear conclusive arguments of tectonic activity (negative proof).

margin and basinal settings. The diagrams show a continuous subsidence from the Serravallian to the Early Pleistocene, interrupted by short phases of high tectonic activity. The characteristic pattern of accelerating subsidence as shown by the diagram of the basin inward setting occurs frequently but not exclusively in foreland basins (compare with diagrams of ALLEN *et alii*, 1986; ARMAGNAC *et alii*, 1988; PIERI & MATTAVELLI, 1986). Notable is the difference in magnitude of vertical movements between the two settings, which illustrates how tectonic mechanisms control the system.

We furthermore present two examples of so-called Time-Snapshot Plots (fig. 13) which display the calculated topography for resp. 10.0 and 3.0 Ma. The two time moments which we choose are interesting because they show two distinct characteristic moments in the evolution of the basin: the first initial development of small strike-slip basins along the Petilia-Sosti fault zone in the south (Late Serravallian-Early Tortonian), and the final stage just after the mid-Pliocene compression phase, when, in the same area, tectonic inversion can be seen, which represents the thrusting of the Miocene-Lower Pliocene deposits towards the southwestern basin margin.

The Messinian regional relative sea level fluctuations seem to overprint the general tectonic evolution. Both the onset as well as the end of the salinity crisis and dessication stages however display the same composite tectonic event as is present in the rest of the tectonostratigraphic record. This argues for a regional control of this composite tectonic event (see further).

The middle Pliocene tectonic phase is reflected by a large-scale tectonic inversion of the basin. The sedimentary cover was folded and thrusted against its margins, which can

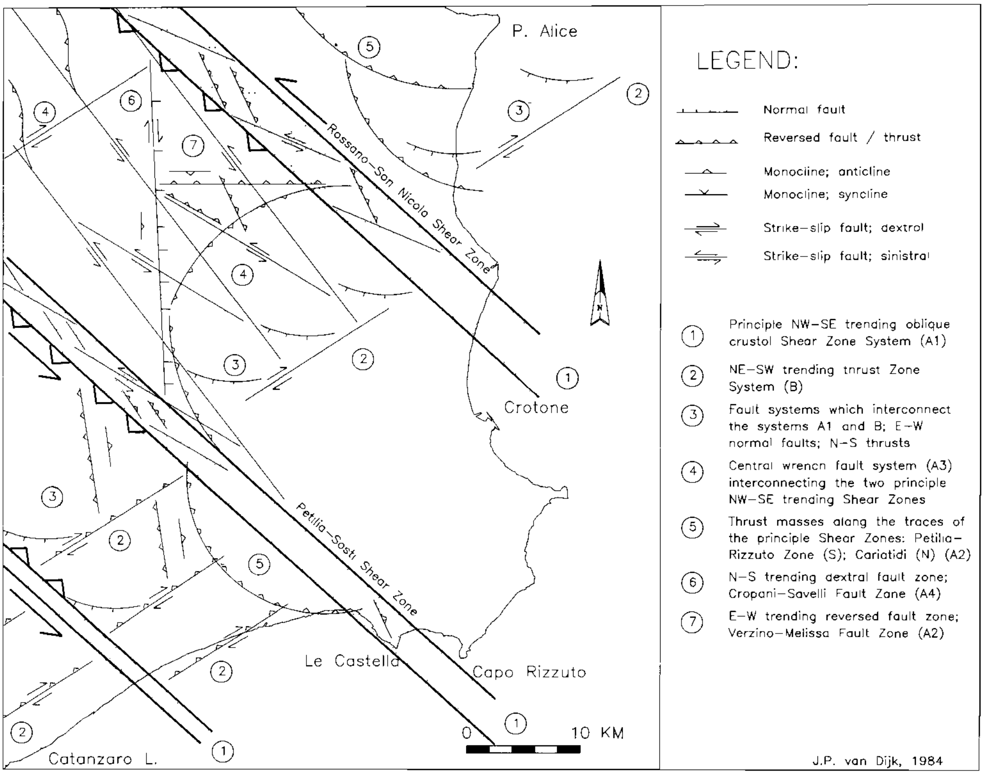


Fig. 11 - Kinematic model for the Late Neogene evolution of the Crotone Basin. From VAN DIJK (1991). For a discussion of the structural data which were used to construct this model, and a differential analyses with existing basin models for the Calabrian Arc, we refer to VAN DIJK & OKKES (1990) and VAN DIJK (1991).

be interpreted as a result of on-going shearing of the area between the large shear zones. VAN DIJK (1991) compared the data from the Crotone Basin with regional data from structural analyses (see for reviews AUROUX *et alii*, 1985; BOUSQUET & PHILIP, 1986) and seismic profiles (ROSSI *et alii*, 1982), which support a regional character of this compression phase, linked to NE-SW shortening, roughly perpendicular to the NW-SE trending oblique sinistral shear zones.

Fig. 12 - Geohistory diagrams of the Crotone Basin. Note the differences in scale between the two diagrams. The diagrams were processed from the composite tectonostratigraphic schemes (maximum thicknesses of formations) of fig. 4. This means that they must be regarded as representative for a whole area, and not, as in the case of a bore hole or land section, for one specific point. The paleobathymetry data are obtained by calibrating the depositional systems as discussed in the text (from lithofacies analyses) to depth zones as available in literature (referred in the text) for these depostional systems. The isostatic loading as has been applied, although it is probably not valid for foreland basins, gives an indication of the maximum influence of the sedimentary loading effect on the tectonic subsidence. The legend (based on Shell, 1976) can be compared to fig. 7b. a) Diagram of the central part of the Crotone Basin. Note that in the diagram the basal coarse clastic deposits have been placed in the Langhian-Serravalian, following the second option (see text). b) Diagram of the Petilia-Policastro-Mesoraca area, along the southwestern margin of the Crotone Basin.

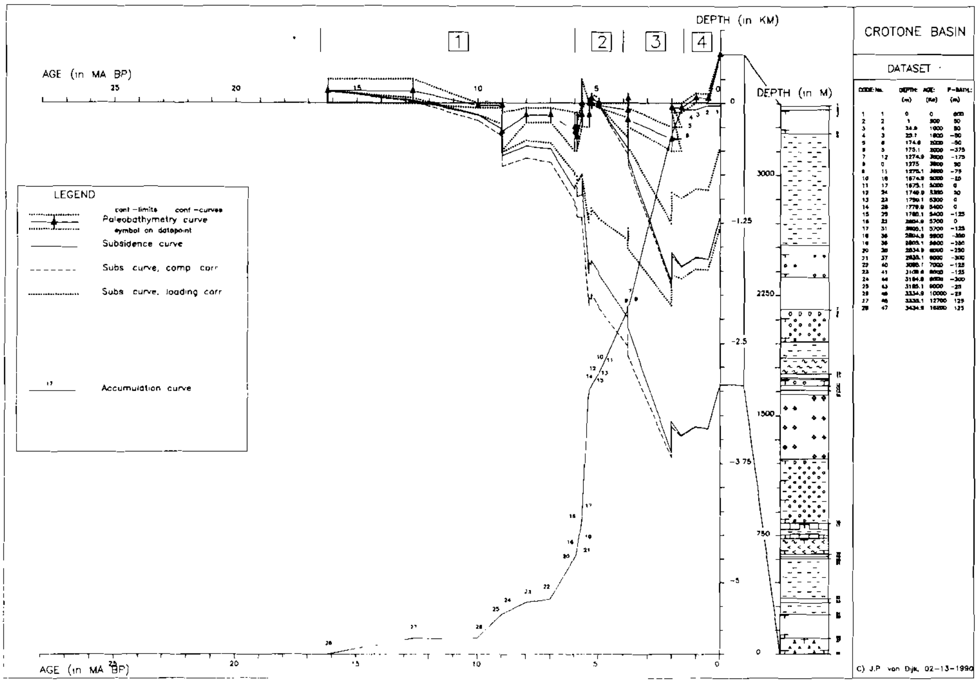


Fig. 12 a

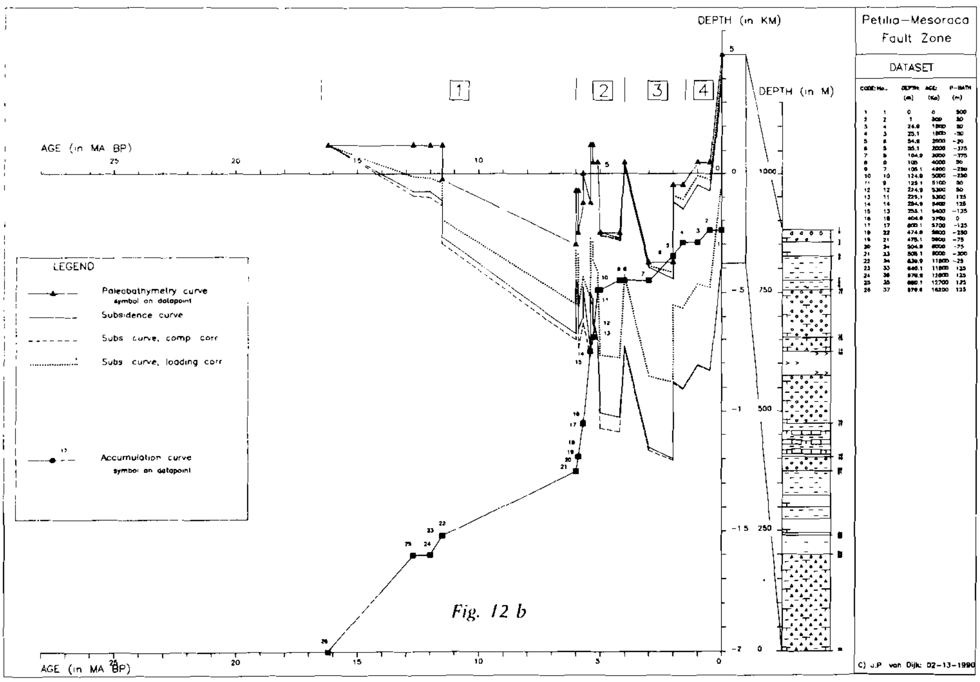


Fig. 12 b

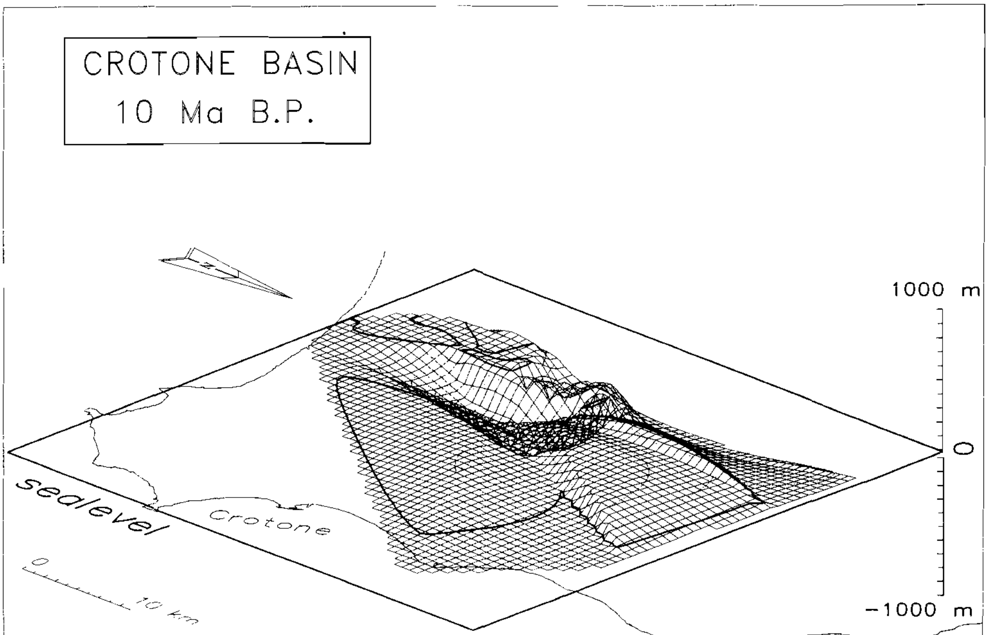


Fig. 13 a

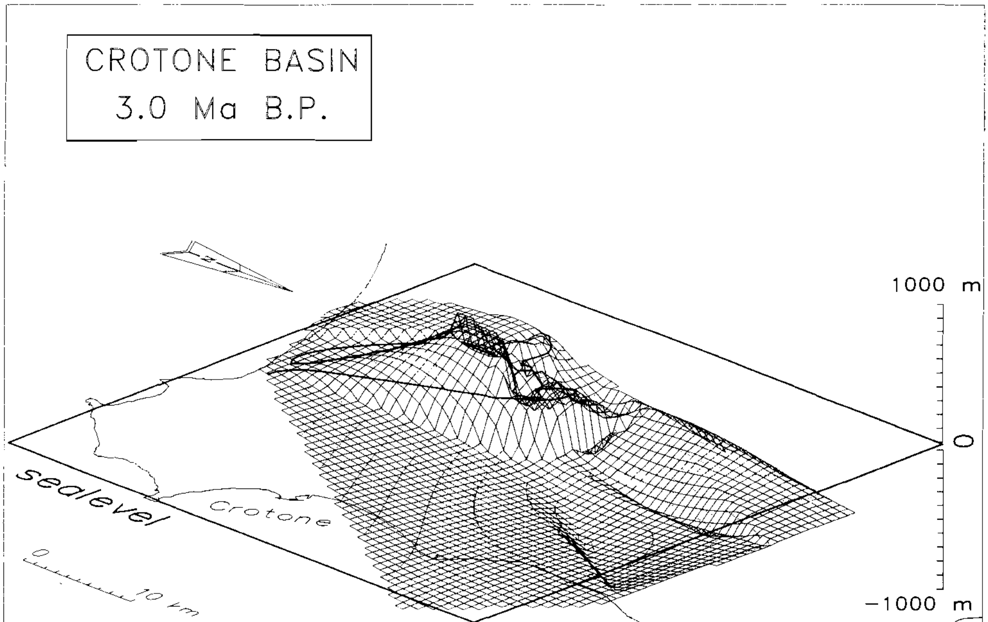


Fig. 13 b

During the Upper Pliocene-Lower Pleistocene stage, repetitive rapid shock-wise subsidence and on-lap occurred, which strongly resembles the Miocene evolution, though it seems to be more gradual (fig. 9). In combination with the large amount of sediment deposited this reflects an ongoing pulsating subsidence (fig. 12a). From middle Pleistocene onwards, the whole area was rapidly uplifted (ca. 0.1-0.5 cm/yr; see fig. 12 and also BIROT, 1980). Tensional fault systems developed as a response to rapid uplift of the Sila Massif.

DISCUSSION

The evolution of the Crotone Basin is closely related to its setting upon the Calabrian accretionary wedge system, developed as a response to the migration to the southeast of the Calabrian Arc (see references in the introduction). VAN DIJK (1991) discussed its development using the mechanism of DAHLEN (1990) and general suggestions of CLOETINGH (1988): The composite tectonic event can be linked to the progressive pulsating growth of the accretionary wedge during stages of migration of the Calabrian Arc to the SE. One such event represents a phase of active thrusting, followed by a phase of restabilization of the wedge morphology by means of progradation of the thrusting. The association of regional sea level fluctuations with local tectonic signals (early Messinian relative lowering, sudden rise at the Miocene/Pliocene boundary) suggests that these fluctuations may be controlled by regional tectonic mechanisms. An important argument in favour of this hypothesis is the fact that the tectonic events, as have they been recognized (fig. 8) can be calibrated with tectonic phases as described for the entire Central Mediterranean system (MEULENKAMP, 1982; PATACCA & SCANDONE, 1989; see for also VAN DIJK & OKKES, in press. and VAN DIJK, 1991). As such, regional tectonics may have triggerred the growth pulses of the accretionary wedge system by temporarily blocking the subduction process or by triggering wedge restabilization.

This development was overprinted by the increase in regional NE-SW stress in the middle Messinian-middle Pliocene and in the middle Pleistocene-Recent phases, which led to resp. basin inversion (middle Pliocene) and rapid uplift of the area (Late Pleistocene-Recent). This last phenomena may have resulted from a process of restabilization of isostatic equilibrium after the rupture of the subducted lithosphere slab in the middle Pleistocene-Recent phase of regional stress (see VAN DIJK & OKKES, 1988, 1990 and in press. VAN DIJK, 1990 and references therein).

As a final exercise, we compared the basin development scheme for the Crotone Basin, extended with information from the rest of the Calabrian realm (fig. 14) with the cycle-cart for global sea level fluctuations (HAQ *et alii*, 1987). From this (preliminary) comparison it can be concluded that the sequences as reconstructed in the Calabrian Arc compare pretty well in both magnitude and timing with third order «eustatic» cycles. This strongly argues for a global tectonic control through fluctuations of intraplate stresses, on both regional tectonics as well as global sea level fluctuations, as put forward by CLOETING (1988 and references therein). Also, major alternating phases of basin inversion and fragmentation (middle Oligocene, late Burdigalian, late Serravallian) separate periods with each a unique general trend of rising or falling sea level (building up or gradual release of intraplate stress in terms of the «Cloetingh model») and coincide with periods of high frequency and large amplitudes of sea level fluctuations. The basin development stages delimited by these phases are comparable in size with the second order cycles.

CONCLUSIONS

The Neogene tectonostratigraphy of the Crotone Basin can be subdivided in a number

Fig. 13 - Preliminary Time-Snapshot Plots «synthetic landscapes») for the Crotone Basin with emphasis on its southern margin. The plots show calculated topography for the indicated moment in time. The thick line represents the coast line. The view-direction is SW. The plots have been processed using the available stratigraphic, lithofacial and biostratigraphic information within the concept of the geometrical and kinematic model for the basin we developped. They where calculated by means of extrapolation in space and time and related surface-fitting between various geohistory diagrams of the composite tectonostratigraphic columns which each represent the development of a part of the basin (see for methodology Van Dijk, in press.). *a*) Time-Snapshot Plot for 10.0 Ma. *b*) Time-Snapshot Plot for 3.0 Ma.

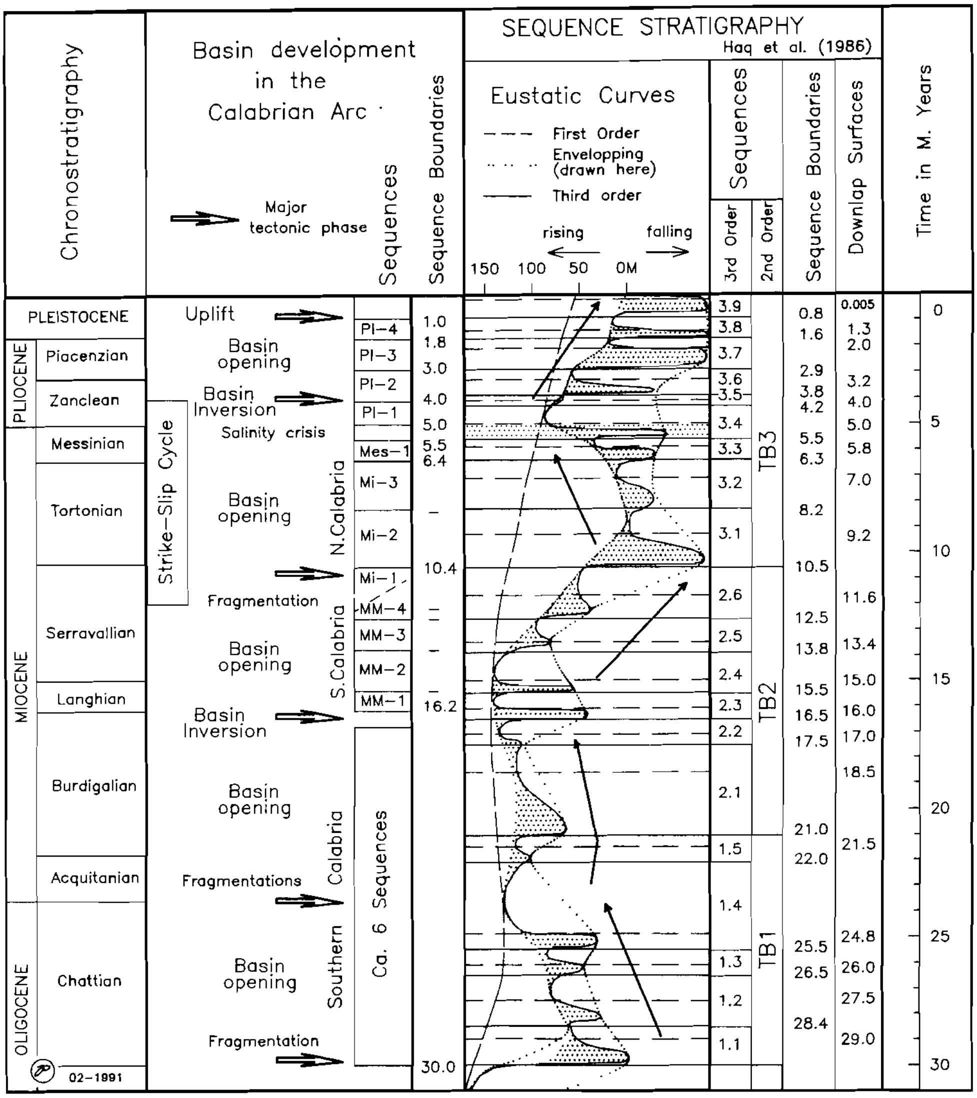


Fig. 14 - Comparison between the basin development in the Calabrian Arc and the cycle-chart for sea level fluctuations of Haq *et alii* (1987; chart of 1986). The basin development for Oligocene-Middle Miocene is modified after Meulenkamp *et alii* (1986). The envelopping curves we draw for the third order curve compare well with the general stress curve of Cloetingh (1988). Within that concept, a sea level drop reflects compressional stress or (sudden) release of tensional stress, and visa versa.

of unconformity-bound depositional sequences. The Late Serravallian-Tortonian and the Pliocene-Early Pleistocene sequences are separated from one another by a composite tectonic event, comprising a phase of uplift and increase of supply of clastic material, shortly afterwards followed by a phase of rapid subsidence and onlap. Both phases are related to tectonic activity along the basin margin.

The evolution of the Crotone Basin can be divided in four stages: 1) Late Serravallian-early Messinian basin opening stage, 2) middle Messinian-Early Pliocene basin fill stage, which ended with a middle Pliocene compression phase with a tectonic inversion of the basin, 3) Late Pliocene-Early Pleistocene opening stage and 4) Late Pleistocene - Recent uplift stage with uplift of the Sila Massif and intense tensional faulting. The first two stages (Late Miocene-Early Pliocene) together reflect the Strike-Slip Cycle of MITCHELL & READING (1978).

The development of the basin was controlled by the local tectonic activity of the accretionary wedge system, overprinted by fluctuations in regional stress. Both local tectonic activity as well as regional relative sea level fluctuations are probably also controlled by regional tectonic mechanisms.

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Basin dynamics and sequence stratigraphy in the Calabrian Arc (Central Mediterranean); records and pathways of the Crotone Basin

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Key words: Central Mediterranean, foreland basins, strike-slip, sequence stratigraphy, Neogene

Abstract

The structural and tectonostratigraphical Late Neogene development of the Crotone Basin is presented, a foreland basin in the accretionary wedge along the external side of the Calabrian Arc (Central Mediterranean). It demonstrates the role of local tectonic activity of the thrust wedge and that of regional relative sea level fluctuations on the formation of unconformity-bound depositional sequences.

The tectonostratigraphic development of the basin can be divided in 4 stages: 1. a Serravalian – early Messinian Stage, characterized by a progressive enlargement of the Basin, 2. a middle Messinian – Early Pliocene Stage, characterized by intense and complex fault movements that were overprinted by the Messinian salinity crisis, 3. an Upper Pliocene – Early Pleistocene Stage, characterized by a pulsating onlap, and 4. a Late Pleistocene – Recent Stage, characterized by strong vertical movements in conjunction with the uplift of the Sila basement Massif. At the end of Stage 2 regional compression during the Mid-Pliocene Phase inverted the basin and thrust its cover towards the margins. A kinematic model is proposed whereby the evolution of the Basin was controlled by oblique sinistral movements along two confining NW-SE trending convergent crustal shear zones. Within this concept, the Middle Miocene – Early Pliocene development (Stages 1 and 2) reflects a strike-slip cycle.

The sequence boundaries that belong to the Stages 1 and 3 are of remarkably similar tectonostratigraphic significance. They reflect a 'composite tectonic event' comprising an uplift/regression pulse, followed by a rapid subsidence/onlap. Each composite tectonic event is here considered to represent one growth pulse in the progressive evolution of the accretionary wedge system, while the middle Messinian – Early Pliocene phases of basin fill and tectonic inversion (Stage 2), and the Late Pleistocene – Recent uplift phase (Stage 4) reflect the increase of regional stress in the Central Mediterranean.

Introduction

In the Central Mediterranean region the Calabrian Arc lies at the junction of three important orogenic systems: the western Mediterranean N. African-Betic Cordilleras system, the Apennine-Alpine system and the eastern Mediterranean Aegean-Dinaride system (Fig. 1). Recently, Van Dijk & Okkes (in press) proposed a new evolutionary model for this area, which addresses aspects of the Late Neogene evolution of these three systems. In that model, the kinematic evolution of the Central

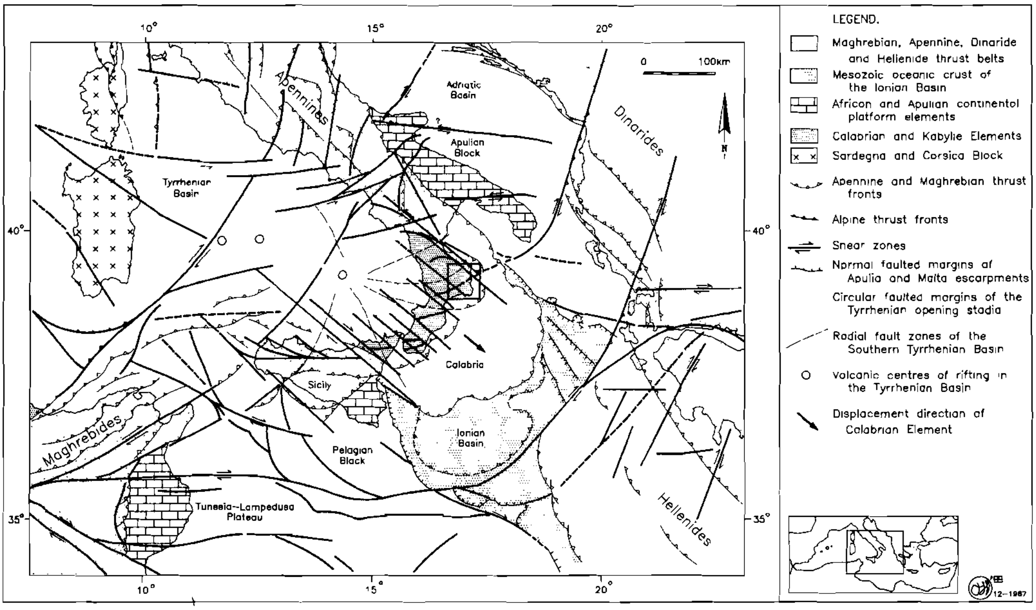

Fig. 1. Calabria in it's Central Mediterranean setting after Van Dijk & Okkes (in press). The inset shows the location of the Crotone Basin.

Mediterranean was characterized by two factors: 1. the sliding of the Calabrian Element* to the SE along a basal mid-crustal detachment zone (due to gravitational instabilities created by slab-pull and asthenosphere doming in the back-arc region), and 2. lateral shear of the area by means of strike-slip movements along large E-W and NE-SW trending trans-Mediterranean shear zones with resulting NE-SW directed shortening. The latter movements were concentrated in distinct phases (L. Burdigalian, middle Pliocene and middle Pleistocene – Recent) in response to increasing regional stress induced by plate reorganizations. The Central Mediterranean appears to be highly interesting for the analysis of the interaction between sea level fluctuations, tectogenesis on various scales and formation of unconformity-bound depositional sequences (see discussions in Vail et al. 1977, Burton et al. 1987, Haq et al. 1987, Sloss 1988, Cloetingh 1988). During the Messinian a drop in sea level and a subsequent sudden rise are thought to have been of global importance (Benson 1984, Müller 1986), and the large-scale tectonic activity of the area can easily be appreciated. This paper discusses these factors within a geokinematic and geodynamic model and describes some aspects of the Neogene evolution of the Crotone Basin, which is situated at the northeastern, external side of the Calabrian Arc (Figs 1 and 2).

Previous studies of the Crotone Basin described the stratigraphy but gave little information on the tectonic setting and development of the Basin (Ogniben 1955, Roda 1964, 1965, Burton 1971, Meulenkamp et al. 1986; for historical references see Ogniben 1973). Recently, some ideas have been expressed concerning the kinematic evolution of the Calabrian basins within the frame of regional models for the Arc: Ghisetti & Vezzani (1981) regarded them as being tensional triangular basins,

* A microplate or amalgamated terrane following the terminology of Irwin 1972, Coney et al. 1980, Schermer et al. 1984, and adapted for the Calabrian Arc by Van Dijk & Okkes 1988, 1990.

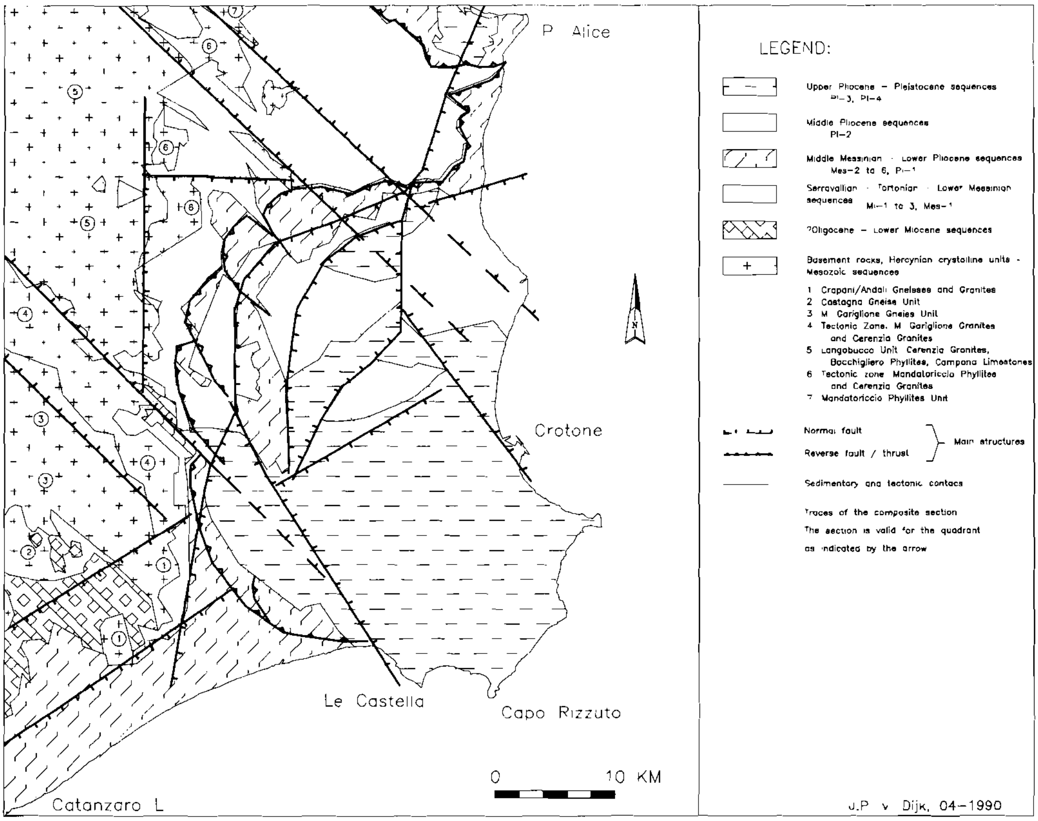

Fig. 2a. Geological sketch map of the Crotone Basin.

whereas Moussat (1983) and Boccaletti et al. (1984) considered them to be pull-apart basins between NE-SW trending shear zones. Van Dijk & Okkes (in press) proposed a different model in which these basins were regarded as oblique (transpressive) piggy-back basins. The present contribution aims to illustrate this last model.

Methods

New data were gathered during a number of field campaigns between 1983 and 1989 in the internal area of the Crotone Basin. This resulted in 1: 25.000 and 1: 10.000 geological maps and stratigraphic schemes supported by biostratigraphic assignments to ca. 100 samples. The results were compared with previously published field studies (see references above and also Selli 1973, Dubois 1976, Guérémy 1976, Gurrieri et al. 1982, Cosentini et al. 1989), seismic sections (Finetti & Morelli 1972, Finetti 1982, Rossi et al. 1982, Pacchiarotti 1984, Pieri & Mattavelli 1986), borehole data (Bronzini 1959, Roda 1965) and satellite photography studies (Biju-Duval et al. 1975). The composite tectonostratigraphic sequences were processed to construct geohistory diagrams using information on biostratigraphy and facies. The software is based on procedures described by Horowitz (1976) and Van Hinte (1978) and reviewed by Guidish et al. (1985). The backstripping algorithms are from Stam et al. (1987).

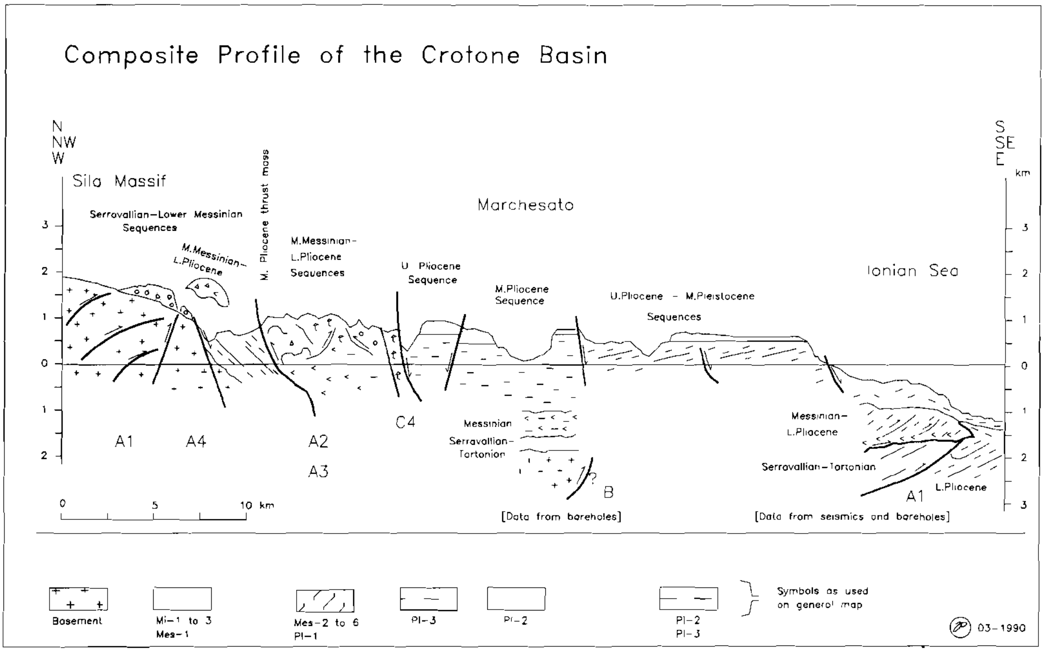

Fig. 2b. Composite cross-section of the Crotone Basin. Fault patterns A1-C4 correspond with the notations of Fig. 3. Note that the section can be read in a N-S, as well as in a W-E or NW-SE sense.

Records: tectonic structure

The recent configuration of the Crotone Basin can be characterized as follows: In plan view (Fig. 2a), the remnants of Miocene to recent terrains are present in a quadrangular area confined to the west by a N-S and to the north by an E-W trending normal fault zone (resp. Cropani-Savelli Fault Zone and Strongoli Fault Zone). The succession comprises three zones, which from inner to outer basin can be recognized both in a W-E as well as in a N-S direction: A. along the margins (N-S and E-W trending fault zones) Middle to Upper Miocene sequences cover the basement and display a monoclinal dip towards the centre of the Basin. B. The central part of the area (Marchesato) comprises Upper Miocene to Lower Pliocene folded and thrust terrains. C. the external area (Crotone Peninsula) in the SE comprises relatively undisturbed Upper Pliocene-Pleistocene sediments.

A schematic cross-section through the Basin (Fig. 2b) shows that the Messinian and Lower Pliocene is folded and thrust towards the N-S and E-W trending faulted basin margins ('pushed up and squeezed out of the basin'), movements which can be linked to a middle Pliocene tectonic phase. The thrust mass is confined along the external SE-side by normal faults with vertical displacements of several hundred metres. Along these faults, tectonic melanges of Messinian sediments with wedges of Lower Pliocene remnants are present. Externally, thrusts have been documented in seismic profiles (e.g. Pacchiarotti 1984), showing overthrusting of Upper Miocene sequences upon Lower Pliocene deposits and decollement of Tortonian and Messinian terrains.

The faults and fault zones present in the area are grouped in systems which in turn can be grouped in a number of patterns (Fig. 3; for terminology see Badgley 1965 and Visser 1980): 1. patterns A and B, a conjugate set of NW-SE and NE-SW trending oblique shear zones and related faults of the Rie-

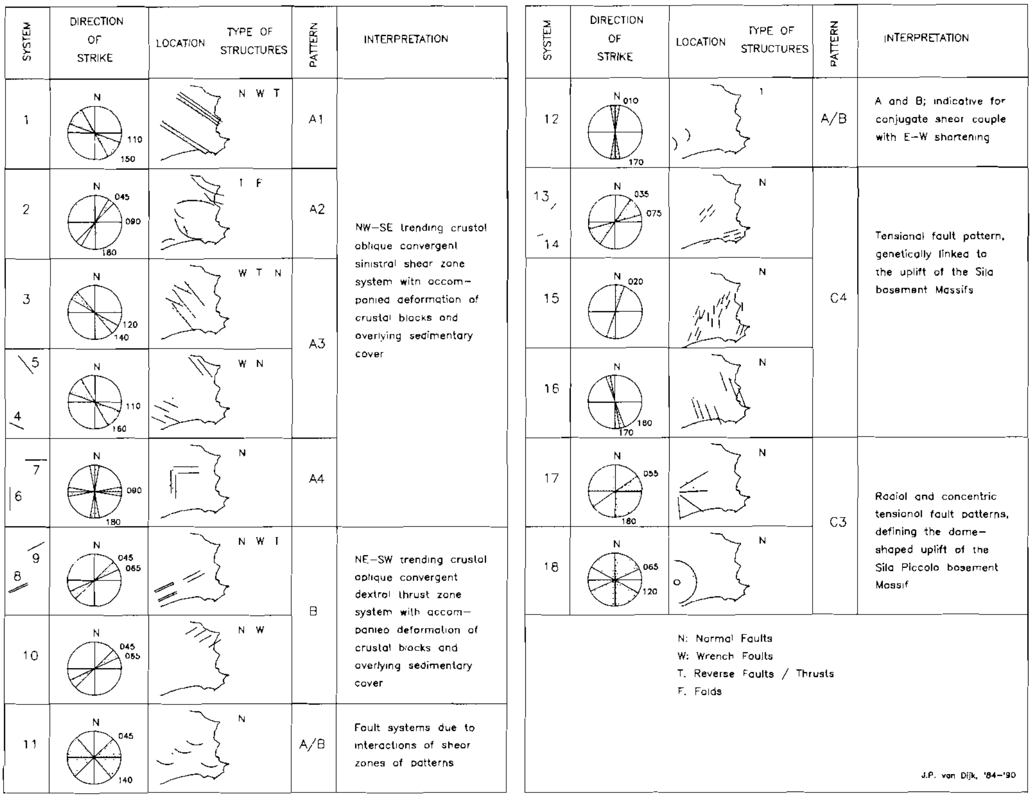

Fig. 3. Fault systems and patterns distinghuished in the Crotone Basin.

del-shear and pull-apart basin type. 2. pattern C, tensional faults that are linked to the Late Pleistocene to Recent uplift of the Sila Massif. Pattern C partly coincides with fault systems of the older patterns A and B.

The interpretation of the patterns A and B as oblique crustal shear zones is based on the Riedel-shear fault patterns (terminology of Cloos 1928, Riedel 1929, Emmons 1969, Tchalenko 1970, Wilcox et al. 1973, Sanderson & Marchini 1984, Sylvester 1988), basement structure (Dubois 1976, Gurrieri et al. 1982) and seismic profiles (see references above). Two major NW-SE fault zones can be recognized (Fig. 2a): the Petilia-Sosti Zone in the SW, and the Rossano-San Nicola Zone in the NE. These NW-SE trending shear zones confine the principle tectonostratigraphic suspect terranes of which the Calabrian Element is constituted.

Records: sequence stratigraphy

The Upper Neogene tectonostratigraphy was reconstructed by mapping the internal parts of the Basin and by sampling key sections for biostratigraphic assignments. A general scheme has been constructed (Fig. 4), in which information from outside the studied area has been included (Catanzaro Area to the SW, Rossano-Cariati Area to the NE).

The tectonostratigraphy can be divided into a number of sequences that are bounded by uncon-

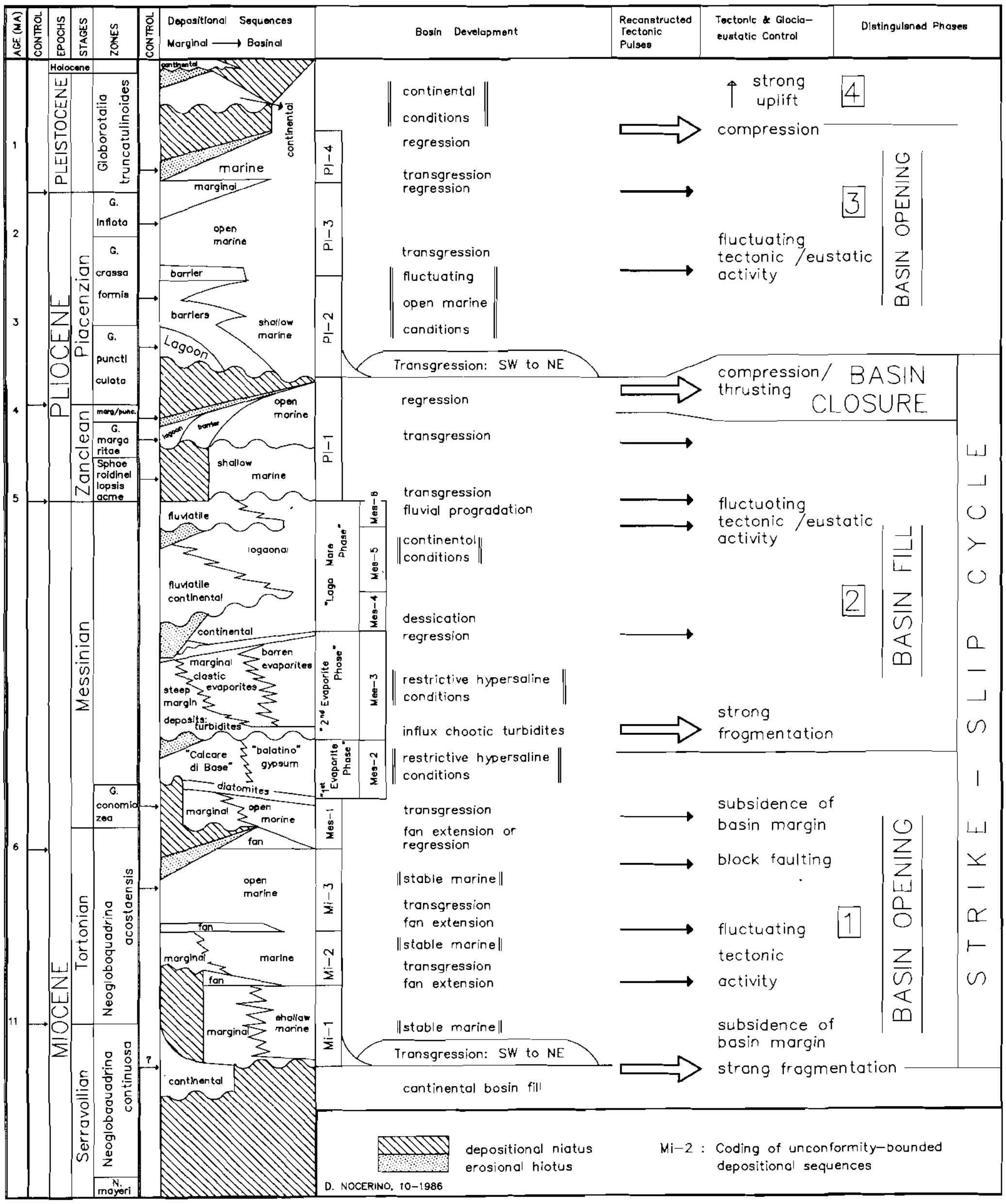

Fig. 4. Composite synthetic tectonostratigraphic scheme for the Central and Northern Calabrian basins. Stages 1, 2, 3 and 4 (see text) are marked.

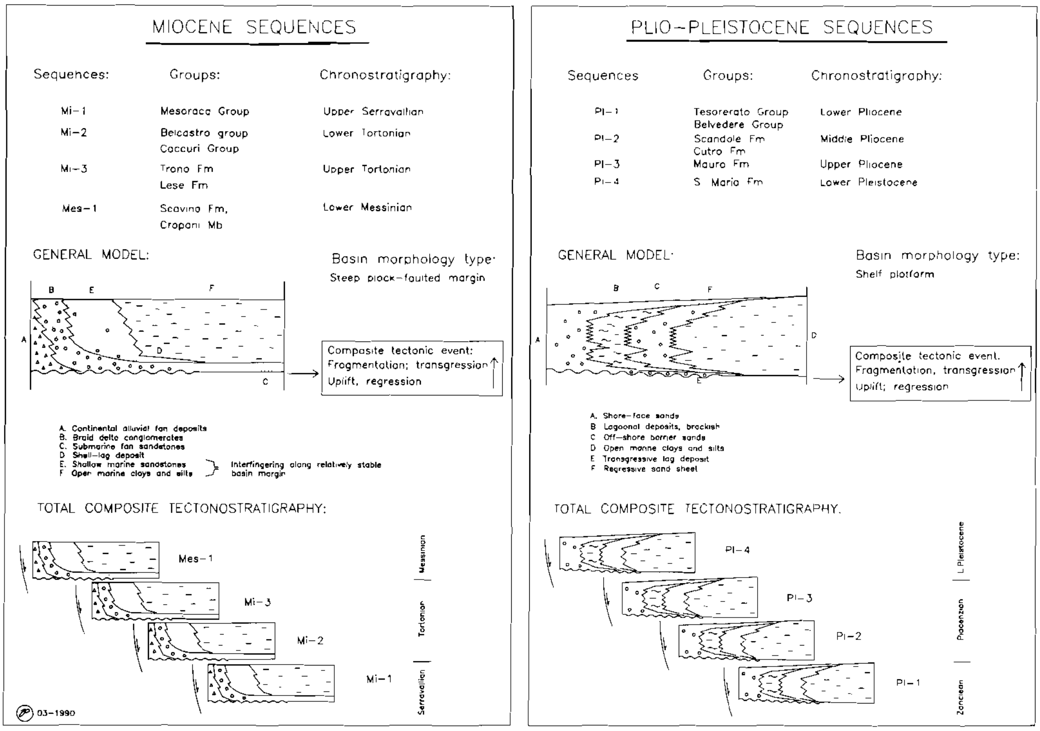

Fig. 5. Sequence models for the Miocene and Pliocene of the Crotone Basin.

formities. The unconformities which separate the Serravallian/Tortonian and Pliocene/Pleistocene sequences seem to record a standard tectonic signal (Fig. 5): the base of each sequence can be interpreted to reflect a small chain of tectonic events which we choose to collectively call a 'composite tectonic event', comprising 1. a phase of uplift and erosion of the basin margin, accompanied by the outgrowth of a submarine fan, and 2. a rapid subsidence and back stepping of the basin margin producing a regional onlap.

In order to be able to detect which sequence boundaries are accompanied by tectonic pulses, we set up a series of criteria which we used for this purpose (Fig. 6; see also Krumbein 1942, Shanmugam 1988 and Embry 1989 for this type of approach). Combining these criteria enabled us to establish the reliability with which sequence boundaries can be linked to tectonic pulses or to relative sea level fluctuations. The latter may still be due to tectonic activity, but then on a larger scale than the studied basin, or to glacio-eustatic activity.

The evolution of the Basin can be divided into four stages (Fig. 4), which are separated by main tectonic phases:

1. a Serravallian – early Messinian Basin Opening Stage,
2. a middle Messinian – Early Pliocene Stage (2a) with high tectonic instability that is overprinted by the Messinian salinity crisis and ends with a middle Pliocene basin inversion Phase (2b),
3. a Late Pliocene – Early Pleistocene Basin Opening Stage, and
4. a Late Pleistocene – Recent Uplift Stage.

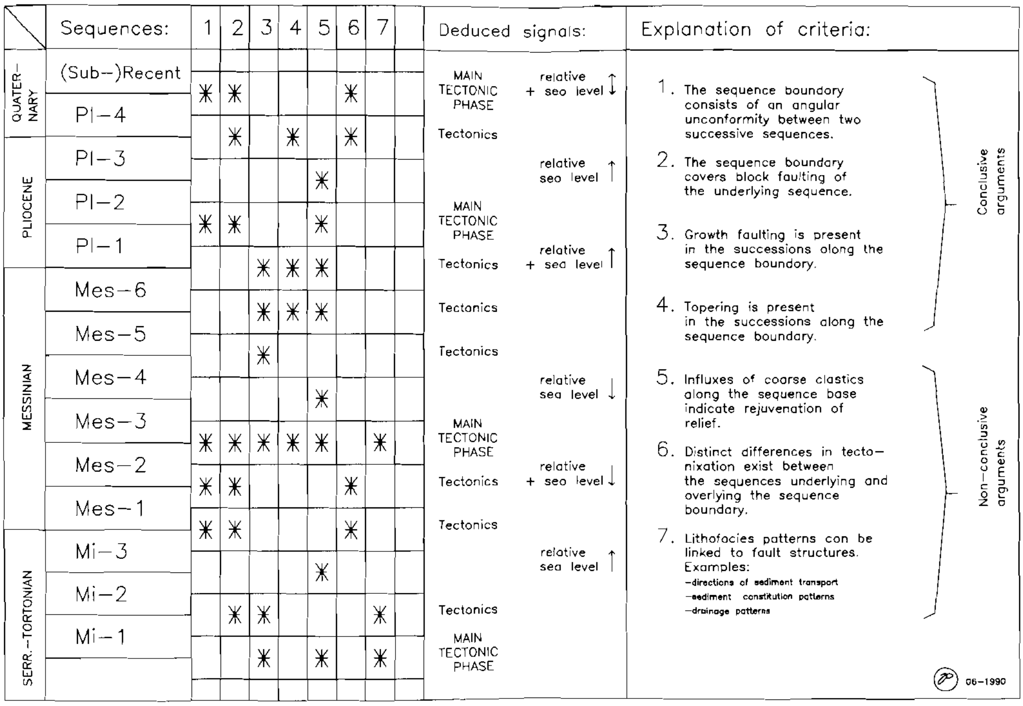

Fig. 6. Scheme of criteria used in the relativistic analyses of tectonics and sea level fluctuations. The asterisks indicate criteria that have been used to establish which signal is represented by the sequence boundary.

Pathways: kinematic basin evolution

We propose the following kinematic model for the evolution of the Crotone Basin (Fig. 7): The Basin is situated at the intersection of the NW-SE trending 'thrust system A' (which is dominant in the area north of the Crotone Basin) and the NE-SW trending 'thrust system B' (which is dominant in the area to the southwest of the Crotone Basin). It is locked between two major NW-SE trending sinistral oblique crustal shear zones, which belong to the oblique thrust system A. The Middle Miocene to middle Pliocene development is characterized by a shearing of the area whereby an evolution from initial small strike-slip basins to a large pull-apart basin finally results in an inversion of the whole area in the middle Pliocene.

Analysis of in situ measurements on small scale deformation phenomena, previously presented for the Calabrian area by Tortorici (1981), Ghisetti & Vezzani (1981) and Moussat (1983), all show a similar pattern of overall tension interrupted by two short periods of compressional deformation in the middle Pliocene and middle Pleistocene. The vectors of maximum shortening for both these periods were placed in the NE-SW quadrant. Although those data were almost exclusively gathered outside the Crotone Basin, and are based on less detailed stratigraphic schemes, they can be used in combination with our tectonostratigraphic framework.

The two geohistory diagrams which we processed (Figs 8a and b), illustrate the vertical movements in respectively basin margin and basinal settings. The diagrams show a continuous subsidence from Serravallian to Early Pleistocene, interrupted by short phases of high tectonic activity. The characteristic pattern of accellerating subsidence as

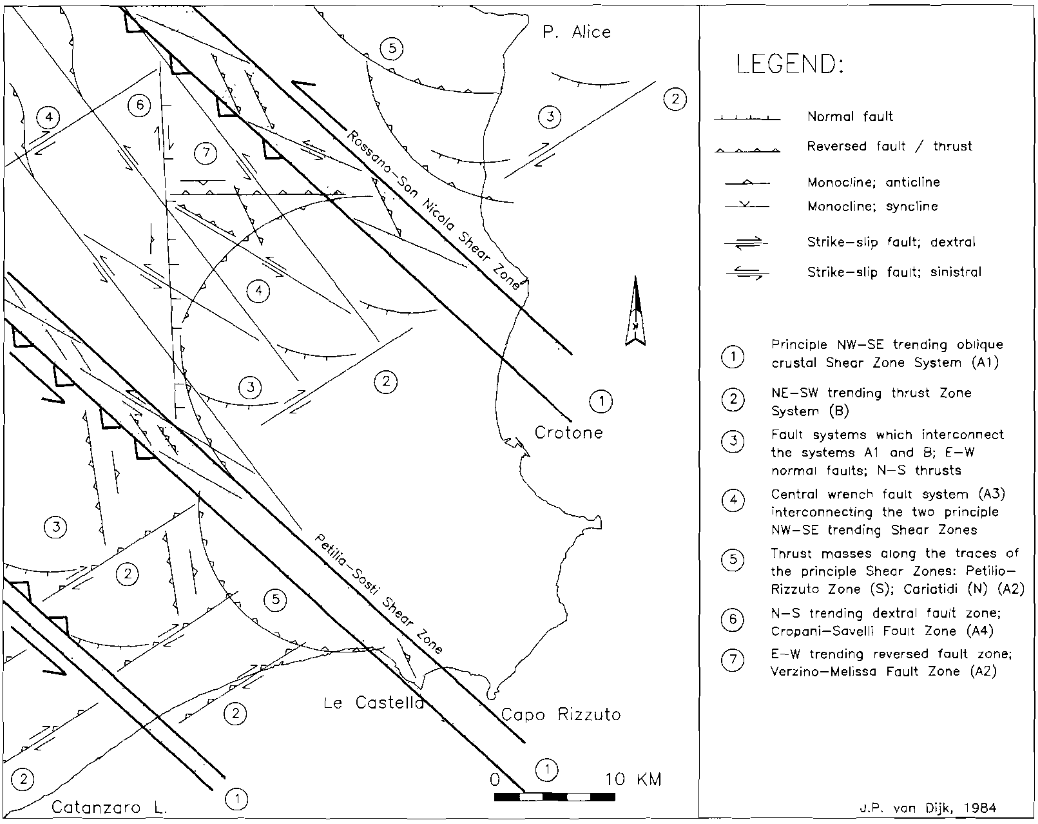

Fig. 7. Kinematic model for the Late Neogene evolution of the Crotone Basin.

shown by the diagram for the basinal setting occurs frequently but not exclusively in foreland basins (compare with diagrams of Allen et al. 1986, Armagnac et al. 1988, Pieri & Mattavelli 1986). The difference in magnitude of vertical movements between the two settings is quite noticeable and supports the idea that tectonic mechanisms control the system (cf. a suggestion by Embry, 1989 for extensional basins).

Using the kinematic model as descriptive concept, the first two of the Stages in basin development as mentioned above can now be linked to the Strike Slip Cycle of Mitchell & Reading (1978) and the basin evolution can be characterized as follows:

1. the Serravallian – early Messinian basin opening stage

In this period, the area started to subside intermittently as a response to lateral movements along the bordering NW-SE trending shear zones. Thus a large sedimentation area was finally formed, limited by the N-S trending Cropani-Savelli Fault zone, which can be regarded as the 'pull-apart margin'. Local sedimentation patterns were determined by N090 trending tensional faults and N120 trending R-shears along this margin. This can be seen as the opening stage of the pull-apart basin.

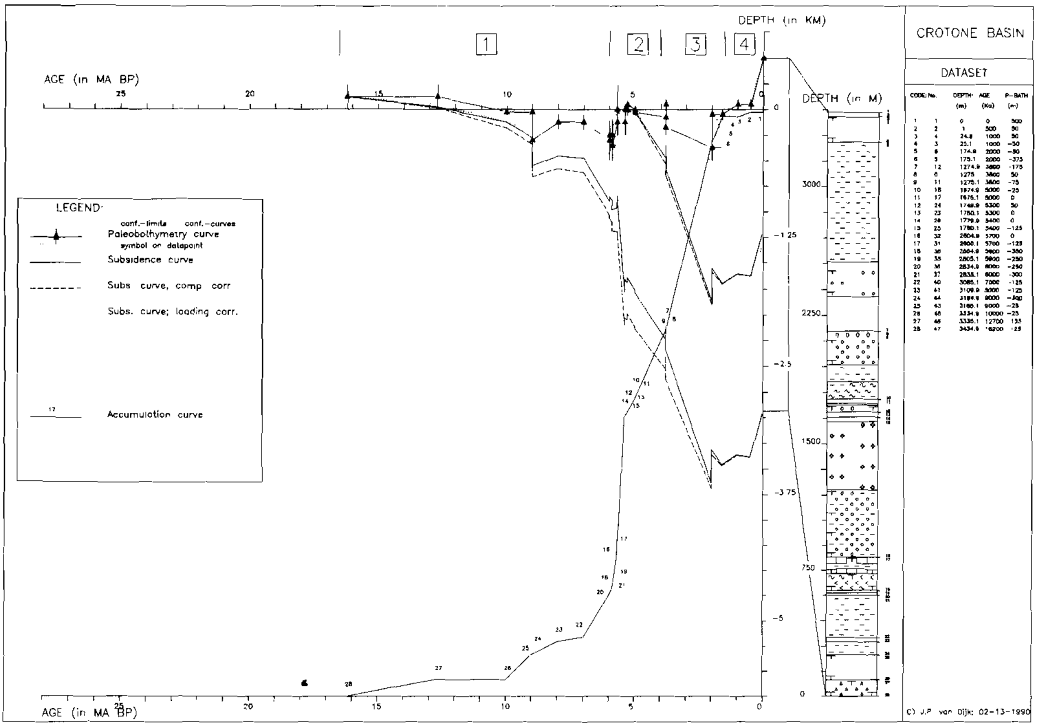

Fig. 8a. Geohistory diagram of the Crotone Basin. Stages 1, 2, 3 and 4 (see text) have been marked.

2a. the middle Messinian – early Pliocene basin fill stage

For this period the subsidence curve (Fig. 8a) shows a dramatic accelleration. During the tectonic phase in the middle Messinian faulting along P-shears and tensional E-W faults in the Petilia-Sosti Shear Zone (basin margin during this period) was very intense. Furthermore, the complex upper Messinian tectonostratigraphic patterns probably also reflect the high tectonic activity along the bordering shear zones. Basin subsidence may partly be due to loading of overlying thick sedimentary sequences (Fig. 8) but after (maximum) correction for that effect a still considerable amount of subsidence remains. We propose to link the subsidence and tectonic activity to folding of the basin floor due to the thrusting along the NW-SE trending crustal shear zones in response to a NE-directed component of regional stress. The regional relative sea level fluctuations of the Messinian salinity crisis, although bounded by tectonic phases, seem to overprint this tectonic evolution.

2b. the middle Pliocene tectonic phase

During this phase, a large-scale tectonic inversion of the basin occurred. The sedimentary cover was folded and thrust against its margins, probably as a result of on-going transpressional shear of the area between the large shear zones. The information based on the on-shore geology alone supplies no evidence for a regional character of the compressive phase. The amount of shortening in the seismic profiles (e.g. Rossi et al. 1982), the regional character of the inversion phenomena and the occurrence of small scale deformation features (see references

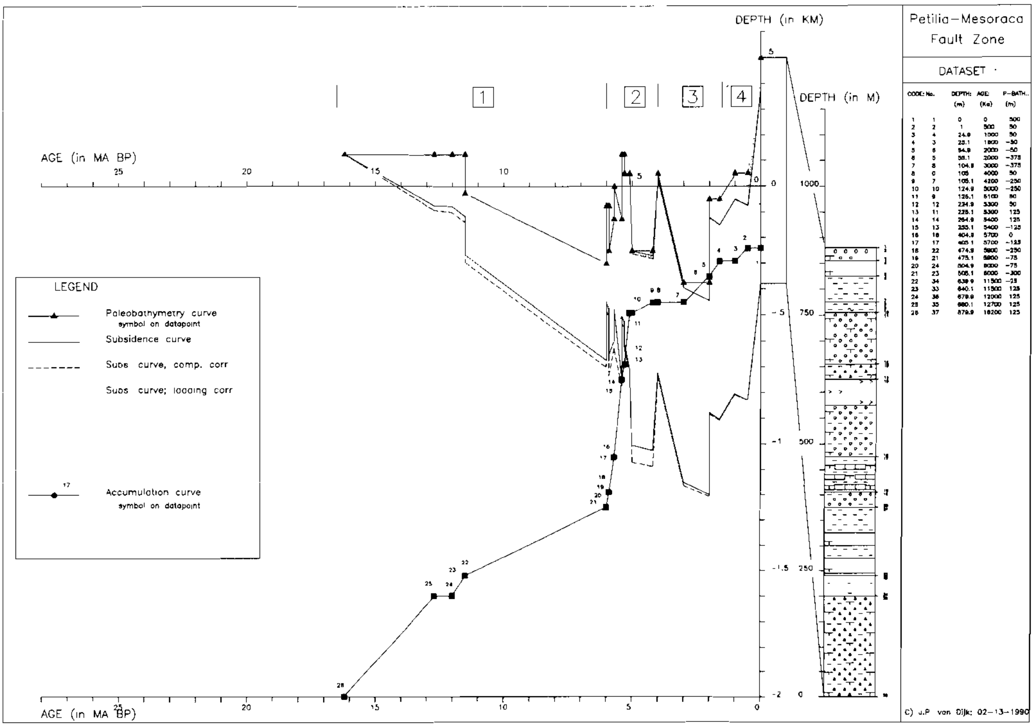

Fig. 8b. Geohistory diagram of the Petilia-Policastro – Mesoraca area, along the SW-margin of the Crotone Basin. Stages 1, 2, 3 and 4 (see text) have been marked. Note the difference in scale between the two diagrams. The legend is based on Shell (1976).

above), however, strongly support the interpretation of a regional middle Pliocene compressive phase linked to NE-SW shortening, roughly perpendicular to the NW-SE trending oblique sinistral shear zones. The mid-Pliocene compressive phase has also been reconstructed from structural analyses elsewhere in the Calabrian Arc and in the southern Apennines. For a discussion and review, we refer to Auroux et al. (1985) and Bousquet & Philip (1986).

3. the late Pliocene to early Pleistocene basin opening stage

During this period, repetitive rapid shock-wise subsidence and onlap occurred which, although more gradually, strongly resembles the Miocene evolution (Fig. 5).

4. the late Pleistocene – recent uplift stage

During this last stage, the whole area was rapidly uplifted. The fault systems of pattern C developed in response to rapid uplift of the Sila Massif. This Stage was also associated with a regional mid-Pleistocene compressive Phase (see references above).

Discussion

The development of the Crotone Basin can be described in the following way:

Stages 1 and 3 can be linked to southeastward

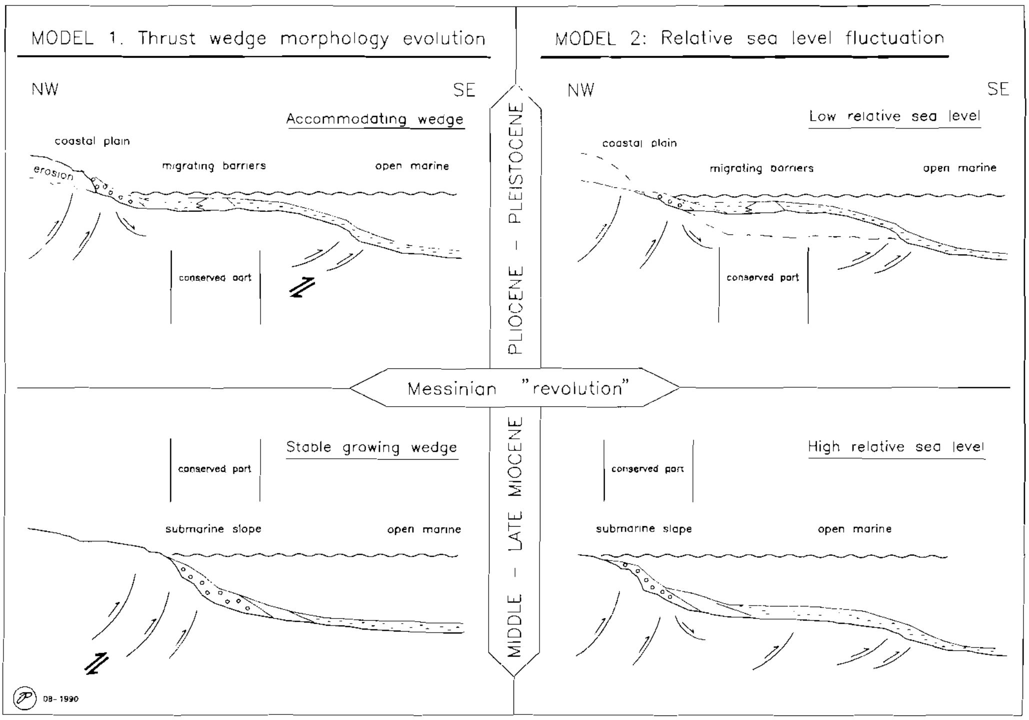

Fig. 9. Two possible models which can be used to explain the principle differences between Miocene and Pliocene development of depositional systems in the Crotone Basin.

pulsating gravitational sliding of the Calabrian Element and accompanied growth of the frontal accretionary wedge. The composite tectonic events which control the sequence stratigraphy development during these Stages (Fig. 5) can be linked to phases of stagnation in Element migration. We believe that each of these events reflects a sudden compressive growth of the accretionary wedge followed by tensional accommodation through restabilization of its taper as was mathematically modelled in a series of papers by Davis et al. (1983), Dahlen et al. (1984) and Dahlen (1990).

This evolution is overprinted by phases of increasing regional compressive stress, of which the middle Messinian – middle Pliocene and the middle Pleistocene – Recent phases are examples. These phases account for the NE-SW compression and inversion of the foreland basins. Furthermore these phases are accompanied by periods of excessive vertical fault movements such as in the Late Pleistocene – Recent, which overprinted all previous formed structures. These taphrogenetic movements were induced by the detachment of subducted lithosphere remnants and subsequent rapid regional isostatic adjustments (see for discussion Van Dijk & Okkes, in press). Externally along the Arc, thrusting activity can be observed in seismic profile MS-25 (Finetti & Morelli 1972) which can be regarded as gravitational spreading (Ogniben 1973) linked to an extensional collapse of the accretionary wedge in response to the rapid uplift of the Arc.

The fundamental difference between the Miocene and Pliocene basin morphology can be explained in one or the other of two ways (Fig. 9). The first model accepts the dominant role of the tectonic thrust wedge morphology evolution. During the Miocene, the basin was situated on a normal growing accretionary wedge. In the Pliocene and Pleistocene, the basin was situated on a large crustal slab with a back-stepping tensional margin, which slid to the SE to restabilize the externally growing accretionary wedge (Van Bemmelen 1976, Platt 1986). The second model assigns a dominant role to erosion/deposition and relative sea level fluctuation in the shaping of the basin morphology. In that case, the tectonic thrust wedge morphology did not necessarily change fundamentally in the latest Miocene.

The association of regional sea level fluctuations with local tectonic signals (early Messinian relative lowering, sudden rise at the Miocene/Pliocene boundary) suggests that these phenomena may both be controlled by regional tectonic mechanisms. Likewise, regional tectonic activity may have controlled the growth pulses of the accretionary wedge by temporarily blocking the subduction process and/or by triggering wedge restabilization. This provides an explanation for the synchronous sequence boundaries in various Mediterranean systems (see also suggestions by Meulenkamp & Hilgen 1986, Cloetingh 1988), despite differences in tectonic setting.

Conclusions

The evolution of the Crotone Basin can be divided in four stages: 1. a Serravallian – early Messinian Tension Stage, 2. a middle Messinian – Early Pliocene Basin Fill Stage, which ended with a middle Pliocene Compression Phase with basin inversion, 3. a Late Pliocene – Early Pleistocene Tension Stage and 4. a Late Pleistocene – Recent uplift Stage with uplift of the Sila Massif and intense tensional faulting. The Late Miocene – Early Pliocene evolution reflects the Strike-Slip Cycle of Mitchell & Reading (1978).

The development of depositional sequences was controlled by the local tectonic activity of the accretionary wedge system, overprinted by the increase in regional stress in the middle Messinian – middle Pliocene and in the middle Pleistocene – Recent Phases. Both local tectonic activity and regional relative sea level fluctuations are probably controlled by regional tectonic mechanisms.

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APPENDIX I

THE GEOLOGY OF CENTRAL CALABRIA

IA. DESCRIPTION OF THE STRUCTURE OF THE STUDIED REGION

The numbers of figures and tables refer to Van Dijk (submitted) (Ch. 1).

NEOGENE SUCCESSIONS

1. Sila Piccola block: Cropani-Simeri Sector

This part consists of two areas, separated by the Albi-Sellia Fault Zone, and bounded to the north by the Sersale Fault Zone. The area bordering the PRFZ has been named the Cropani-Belcastro Subsector. Figure 3a, profile 1 shows a cross section.

The northern part consists of a ca. 300 m. thick sequence of coarse clastics of the Sersale Fm (Oligo-Miocene; Sersale facies), steeply dipping to the south, which contact with the basement rocks of the Sila consists of a low angle thrust plane. This relation can be studied along the Sersale Fault Zone near Sersale and north of the fault zone along the margin of the Sila Piccola. These deposits are confined in the east by the Crocchio Fault Zone, and show a lateral transition to the west into a fine-grained turbidite succession (Ragazzi facies), along the Albi-Sellia Fault Zone. This image strongly suggests a deposition in a Late Oligocene-Early Miocene basin with NW-SE trending margins (Crocchio Fault Zone, Albi-Sellia Fault Zone).

In the south, these successions are unconformably overlain by Late Neogene deposits along the NE-SW trending Tribisina Fault Zone. These consist of remnants of Tortonian Belcastro sands and Messinian Scavino limestones, unconformably overlain by upper Messinian Calamo conglomerates, all dipping steeply to the SSE.

South of the Tribisina Fault Zone, Lower Pliocene clays (Tesorerato Fm) are present, which are unconformably overlain by Pleistocene terraces (Sellia Fm). The Lower Pliocene terrains are intersected by faults with various trends which are difficult to reconstruct due to the homogenous character of the clays. The clay formation itself lies in a para-autochtonous position as can be inferred from the deformation phenomena near its base consisting of numerous sliding surfaces showing slickensides which indicate gliding to the south (e.g. near Tribisina; Fig. 8a).

Remnants of approximately the same sequence outcrop along the N-S trending Sila margin, defined by NNW-SSE to NNE-SSW trending faults. They dip roughly to the east and are intersected by NW-SE and NE-SW trending faults. The area is intersected by the Belcastro Fault, the southeastern margin of the PRFZ. This fault has the character of a normal fault with a downthrown SE-block.

The northern margin of the sector is formed by the intersection of the SW-NE trending complex Sersale Fault Zone and the (S)SE-(N)NW trending Marcedusa Fault Zone. North of this intersection point, a completely different structural and stratigraphic framework has been established.

The eastern margin of the sector near Belcastro is formed by the Umbro Thrust, a N-S trending reverse fault. Within this western boundary of Sector 2, various deformation features have been observed such as folds, cataclasis and foliation in the clays. Large blocks of upper Messinian Carvane conglomerate are present near Lucrezia and Cangiasi, incorporated in the thrust zone as tectonic wedges.

2A. Petilia-Rizzuto Zone: Marcedusa-Botricello Sector; Lucrezia-Arvano-Tenese Subsector

This area comprises strongly disturbed middle Messinian - Lower Pliocene successions. Locally some clays occur which probably belong to the Upper Pliocene Cutro Fm. Several fault systems intersect the area which makes it hard to reconstruct.

The subsector has been defined between the Belcastro Fault Zone and the Umbro Thrust in the east (see above) and the Marcedusa and Condole Fault Zones in the west. The latter two fault zones show a normal character with eastern down-thrown blocks.

Roughly two parts can be distinguished, seperated by the NE-SW trending Tribisina Fault Zone. The northern part comprises middle Messinian evaporites and upper Messinian Carvane conglomerates, intersected by numerous NW-SE trending faults. In the southern part more complete successions occur, intersected by NW-SE, NE-SW, N-S, NNW-SSE and E-W trending faults. The outcropping lithologies are strongly deformed following the chaotic dispersion of dips of the bedding planes up to vertical and overturned, and frequently occuring foliation, cataclasis and locally overthrusting. Figure 3, profiles b and c display a schematic reconstruction of the region. The structures show mainly thrusting to the SE and W to NW and normal faulting along almost all fault directions.

The whole assemblage of thrusts and reverse faults constitutes a fan-shaped pattern on the map, with main NW-SE trending faults and splays with N-S to NE-SW trends. The Umbro Thrust, Belcastro Fault Zone with thrusts near Arvano, and the (N)E-(S)W trending chaotic zone near Steccato (see further) form one large structure which can be interpreted as a large thrust to the (S)W, seemingly intersected by (N)NW-(S)SE faults and thrusts.

2B. Petilia-Rizzuto Zone: Marcedusa-Botricello Sector; Arciere-Steccato Subsector

The exact tectonic setting of this small triangular area can not clearly be established. West of it, the Tacina River plain covers possible contacts with the sediments of the Cutro Fm or the successions of the Lucrezia-Arvano-Tenese Subsector. The eastern margin of the sector is formed by a NW-SE normal fault along which remnants of lower Pliocene sediments occur.

Within the sector, a chaotic association of lithologies occurs belonging to the Messinian Lucrezia evaporites up to lower Pliocene Farago clays. Several overthrusts can be observed in what can best be called a tectonic melange zone. An example outcrops along the eastern river bank of the Tacina near Arciere.

3. Petilia-Rizzuto Zone: Petilia Policastro--Mesoraca Sector

The profile d of Figure 3 gives a schematic picture of the structure of this area. A pretty complex association of ?Late Serravallian to upper Messinian sediments occurs, which can be subdivided in numerous small, mostly wedge-shaped areas each of which displays its own lithostratigraphic composite column. These areas are separated by mainly N120^0, N130^0 and N140^0 trending faults.

East of Mesoraca and near Petilia Policastro, small thrusts have been reconstructed, branching from the main fault structures. The reconstruction of these thrusts is strongly hampered by the fact that they nowadays mainly display a normal fault character. Furthermore, they are dissected by numerous, more recent and often steeper dipping normal faults.

The NW-SE trending faults form a braided fault pattern, dissected by N-S, E-W and N60^0 to N90^0 trending normal faults. This makes that the sector can best be regarded as one complex fault zone, which is confined by (see Fig. 4):

1. The NW-SE trending Arietta Fault Zone along the Fosse Potamo in the S,
2. A number of large NW-SE trending melange zones displaying normal fault character, and N50^0 to N90^0 trending normal faults at the eastern margin of the sector, separating the Miocene and Lower Pliocene from Upper Pliocene clays and sands,
3. The NW-SE trending Demetrio-F. Tacina-Ampollino Fault in the N, and
4. Numerous, ill-defined N-S trending faults along the margin of the Sila, seperating the Miocene rocks from the basement rocks of the Sila.

The eastern margin of the Sector consists of chaotic fault zones and melange zones, interconnected by N50^0 to N90^0 trending normal faults with down-thrown southern blocks. This resulted in a dented character of the eastern Sila margin as it occurs nowadays. Along the melange zones, many thrusts to the (S)W have been observed within Messinian evaporites overthrusting upper Messinian coarse clastics of the Carvane Fm.

The faults occurring in the area clearly fall apart

in the following six groups:
1. N135 trending large faults, along which melanges and thrusts are presents,
2. N120^0 trending, large normal faults,
3. N140^0 trending, small normal faults,
4. N60^0 to N90^0 trending normal faults,
5. N180^0 to N20^{0}0^0 trending small normal faults,
6. N140^0 to N160^0 trending, WSW-vergent thrusts.

4A. Crotone Basin: Caccuri-Roccabernarda Subsector ("Southern marginal Area")

The Central Segment of northern Calabria (Crotone Basin ss.) consists of a number of small NW-SE trending sectors, bounded by N140 to N120 trending fault zones (Neto Fault Zone, Lese Fault Zone). Figure 3, profile e shows a schematic section through the area.
In this Sector, Tortonian sands and clays (Caccuri Fm, Lese Fm) occur, which are covered by a condensed Messinian sequence of Scavino limestones, Coste del Sale fines, and upper Messinian Carvane conglomerates, all dipping to the east. This assemblage is cut by NW-SE trending chaotic fault zones. The eastern part consists of middle Pliocene sands and clays (Baretta Fm; probably Roccobernarda Fm).
Directly east of the Neto Fault Zone, conglomerates and sands of the middle Pliocene Belvedere Fm occur, dipping to the west. These occurences are confined by large N-S to NNE-SSW trending post-middle Pleistocene normal faults.

5A. Crotone Basin: Crotone Subsector

In this large area monotonous successions of Upper Pliocene Cutro clays followed by the Upper Pliocene - Pleistocene Mauro sands occur. The structure of the region can hardly be recognized due to the scarcety of diagnostic levels in the sediments. The large variety in sedimentary dips however points to a reasonal amount of deformation of the deposits. At some places the clays contain numerous small faults and near Marcedusa tensional (N)NE-(S)SW faulting can be observed in the sands of the Mauro Fm.
The successions near Marcedusa can be linked to the central area of the Crotone Basin (Cutro, Crotone, San Mauro; see Van Dijk, 1990).

SILA BASEMENT

The reader is referred to Table 1 and to Figure 1 of this appendix for a schematic subdivisions of basement units in the Sila Piccola as used in the literature.

1. Monte Gariglione Sector

The sector consists of the Monte Gariglione Unit (sensu A. Morelli et al., 1976), containing high-grade metamorphic gneisses with small intercalated lenzes of marbles and 2-mica granodiorites. The unit overthrusts the Castagna gneisses of Sectors 4, 8 and 3 (Amodio-Morelli et al., 1976) and has a fault-bounded western limit with the complex association of metamorphites and intrusiva of Sectors 5 and 7b (Pezzotta et al., 1973, Dubois, 1971, 1976).

2. Cotronei Sector

This sector consists of a large granitic mass, which we choose to call the "Cerenzia Granites", and which is assigned to the Longobucco Unit (sensu Dietrich et al., 1976) by most recent authors. Earlier works such as Ogniben (1973) and Dubois (1971, 1976) assign the granites and the Monte Gariglione Unit together with the units in Sectors 5, 7b and 6b to one and the same unit ("Calabride Complex; Falda di Aspromonte", "Nappe superieure"). There seems to exist enough evidence to support a seperation of the sectors as depicted in Fig. 4 and 8 (Bari school of authors; e.g. Lorenzoni and Zanettin Lorenzoni, 1978, 1982; Zanettin Lorenzoni, 1982; Gurrieri et al., 1981; Lorenzoni et al., 1982). Near Savelli, a N-S trending overthrust to the east of Cerenzia granites over Bocchliero phyllites can be deduced from the profiles of Burton (1962), which coincides with the N-S margin of the Crotone basin.

3. Pentone Sector / 8. Catanzaro Sector

Within this large and extremely complicated area, a nappe pile has been reconstructed by many former workers such as Bonfiglio (1966), Dubois (1971, 1976) and Amodio-Morelli et al. (1976).
From the bottom upwards the nappe sequence consists of (see also Fig. 8):
A. Lowermost Unit ("Unita di Verbicaro", "Unita di S. Donato", "Complesso Panormide", "Appennine range"), only visible in some small win-

dows and consisting of slightly metamorphosed dolomites and basic rocks.

B. Central Unit ("Reventino-Gimigliano Unit"), outcropping in various "horst" structures (Frido - Diamante - Terranova - Reventino - Gimigliano areas), and consisting of serpentinites, metabasites, clays and schists, interpreted as parts of an ophiolitic sequence.

C. "Bagni-Fondachelli Unit": Metasediments upon metapsammites and phyllites.

D. "Castagna Unit": Augengneiss, granites and micaschists.

E. "Pentone Klippen" ("Scisti Varie di Pentone" + "Sorbo granite"): An isolated klippen structure (Bonfiglio, 1966, Lorenzoni and Zanettin-Lorenzoni, 1975) consisting of schists and associated granites, overthrusting both Units C and D and in literature variously assigned to the Monte Gariglione Unit (Amodio-Morelli et al., 1975) or southernly defined "Tiriolo Unit" (Zanettin-Lorenzoni, 1982) or "Galati Unit" (Ogniben, 1973).

The Units B, D and E are named "Alpine Range" by the authors of Bari, while the Units B and C are part of the "Liguride Complex" of Ogniben (1973). Sectors 3 and 8 are separated by the NE-SW trending Fault Zone, an oblique dextral shear zone according to Pezzota et al. (1973).

4. Zagarise Sector

Within this sector a window is present below the Monte Gariglione Unit which shows overthrust contacts between Monte Gariglione Unit and Castagna Unit, associated with lenzes of ?Oligo-Miocene (cf. Dubois, 1976; Pezzota et al., 1971) coarse clastics of the Sersale Fm which display tectonized basal contacts.

5. Lago Ampollino Sector

Within this sector a complex tectonic association of granites and gneisses with various overthrust contacts has best been documented by Gurrieri et al. (1981) and Lorenzoni et al. (1982). It can be regarded as the basal surface trace of the Monte Gariglione Nappe along which various tectonic slices have been preserved and which continues through the Sila to the northwest up to the village Rose.

6a. Pre-Sila Sector; Monte Raga Subsector

In this sector, an association occurs of granites ("Raga Granites") with tectonized ?Oligo-Miocene coarse clastics of the Sersale Fm which steeply dip to the SE. We have studied the relations along the southern margin of the Sersale Fault Zone where zones of cataclasis and tectonized basal contacs of the Sersale Fm can be seen (profile 1 of Fig. 3). Sectors 6a and 6b are separated by the Crocchio Fault Zone, a large normal fault with downthrown southwestern block which delimits the occurences of the Oligo-Miocene Sersale Fm.

6a. Pre-Sila Sector; Fiume Crocchio Subsector

Within this sector metamorphites occur, which we have named "Andali metamorphites" and which are associated with the foliated "Cropani granites" for which no clear relationship with the units occuring in the other sectors has been described so far in literature. They are in contact with the Monte Gariglione gneisses along a steeply dipping, NNW-SSE trending zone of cataclasis (Pezzota et al., 1973). The units (drawn on the map following Lorenzoni et al., 1982) have been given separate names here in order to avoid confusion with the various assignments figuring in the literature (see Table 1).

7a. Sersale Fault Zone: Sersale Subsector

In this area, a number of basement units occurs, which are also present in the surrounding sectors (Andali metamorphites, Monte Gariglione gneisses, Castagna gneisses), and for which no clear relations have been established. Near Sersale, a key section reveals a thrust contact between Sersale clastics and Castagna gneisses, bounded by a steeply dipping cataclasis zone (Fig. 3, profile 1). A NE-SW trending zone of mylonites has been indicated on the maps of Burton (1962) in the region of the village Sersale, which forms the southeastern boundary of the sector. Sectors 7a and 7b are delimited by the NW-SE trending Crocchio Fault Zone, along which a zone of mylonites is indicated on the map of Burton (19-62).

7b. Sersale Fault Zone: Petrona Subsector

This sector has been distinghuished because of its chaotic character and its function as a zone of transition between the Sectors 6 and 1, 4 and 5. Its southern limit can clearly be defined as a normal fault zone, while the northern limit displays various faults and overthrust surfaces. Combining the phenomena as visible in the Sectors 6a, 7a and 4, we have concluded that a flake of the granites with its Oligo-Miocene sedimentary cover has been transported to the north and overthrusted the crystalline units of the Sectors 4 and 7a.

Albi-Sellia Fault Zone

This zone clearly forms a limit between the Sectors 3 and 8 on one hand, and Sectors 4, 7a and 6 on the other. Along the trace of the zone, overthrusting with cataclasis of the Monte Gariglione Unit has occured at the northwestern side, where a NW-SE trending zone of mylonites has been indicated on the maps of Burton (1962) and Pezzota et al. (1973). We have mapped reverse faults and tectonized ?Oligo-Miocene clastics of the Sersale Fm along its southwestern side, in a triangular area in between Sersale Fault Zone and Albi-Sellia Fault Zone, near the village Sellia.

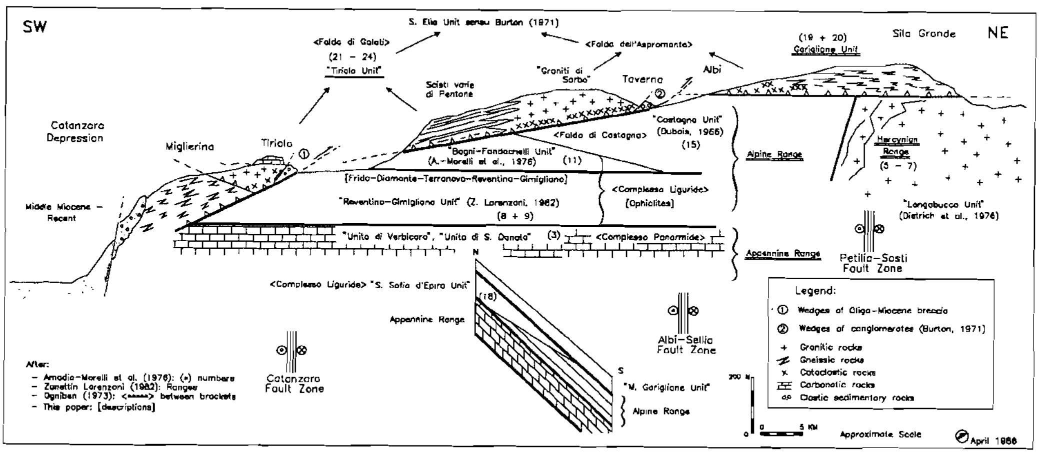


Fig. 1. Scheme for subdivisions used in the literature for the thrust nappe pile of the Sila Piccola. Discontinuities where major fault zones have been defined in this thesis, are indicated in the figure. These are the Catanzaro, Albi-Sellia and Petilia-Sosti Fault Zones.

IB. CROSS SECTIONS THROUGH THE STUDIED REGION (CENTRAL CALABRIA)

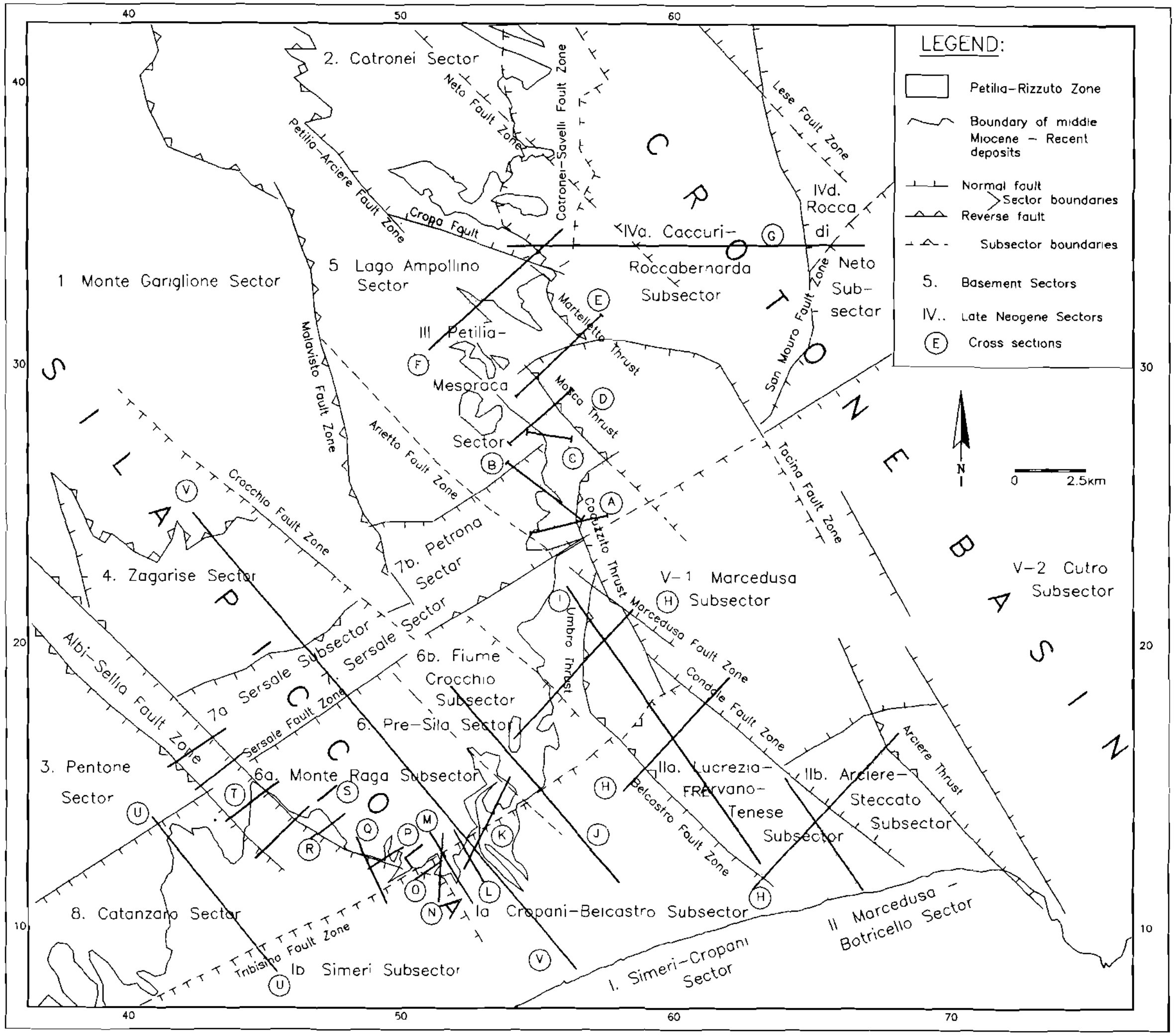
Figure 2 shows the location of the presented cross sections.

The following 22 composite sections are presented:

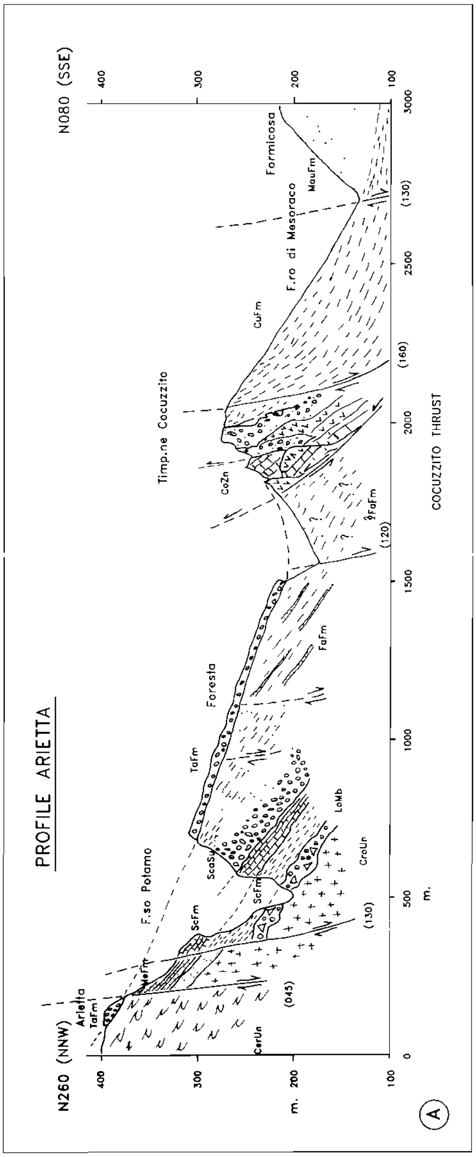
A. Profile Arietta
B. Profile Filippa
C. Profile Mesoraca
D. Profile Campizzi
E. Profile Petilia Policastro
F. Profile Teodoro
G. Profile Roccabernarda
H. Profile Belcastro-Marcedusa
I. Profile Salinella-Botricello
J. Profile Cropani
K. Profile Barveriti
L. Profile Casa Frasillo
M. Profile Raga-Tribisina
N. Profile Raga-Mandile
O. Profile Mandile River; south bank
P. Profile Torrente Uria
Q. Profile Fiume Valle
R. Profile Fiumara
S. Profile Barbara
T. Profile Fiume Simeri
U. Profile Simeri
V. Profile Sersale

Along the base of the figures, the strikes of the main faults are indicated.
The sections are compiled from encountered relations in a broad zone along both sides of the section trace. See Van Dijk (1990) (Ch. 2) for the codations of the stratigraphic units.

Acknowledgements. I thank Dora Nocerino for patiently and carefully drawing the composite profiles and Wil Den Hartog who provided copy-proofs of the drawings.



LEGEND:
Petilia–Rizzuto Zone
Boundary of middle Miocene – Recent deposits
Normal fault
Sector boundaries
Reverse fault
Subsector boundaries
5. Basement Sectors
IV.. Late Neogene Sectors
E Cross sections
0 2.5km
N
1 Monte Gariglione Sector
2. Cotronei Sector
3. Pentone Sector
4. Zagarise Sector
5 Lago Ampollino Sector
6. Pre–Sila Sector
6a. Monte Raga Subsector
6b. Fiume Crocchio Subsector
7a Sersale Subsector
7b. Petrona Sector
Sersale Sector
8. Catanzaro Sector
I. Simeri–Cropani Sector
Ia Cropani–Belcastro Subsector
Ib Simeri Subsector
II Marcedusa – Botricello Sector
IIa. Lucrezia–Frevano–Tenese Subsector
IIb. Arciere–Steccato Subsector
III Petilia–Mesoraca Sector
IVa. Caccuri–Roccabernarda Subsector
IVd. Rocca di Neto Subsector
V–1 Marcedusa Subsector
V–2 Cutro Subsector
SILA PICCOLA
CROTONE BASIN
Neto Fault Zone
Cotronei–Savelli Fault Zone
Lese Fault Zone
Petilia–Arciere Fault Zone
Cropa Fault
Martelletto Thrust
Morca Thrust
San Mauro Fault Zone
Malavisto Fault Zone
Arietto Fault Zone
Crocchio Fault Zone
Tacina Fault Zone
Copuzzito Thrust
Marcedusa Fault Zone
Umbro Thrust
Condole Fault Zone
Albi–Sellia Fault Zone
Sersale Fault Zone
Belcastro Fault Zone
Arciere Thrust
Tribisina Fault Zone
40
50
60
70
10
20
30



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N080 (SSE)
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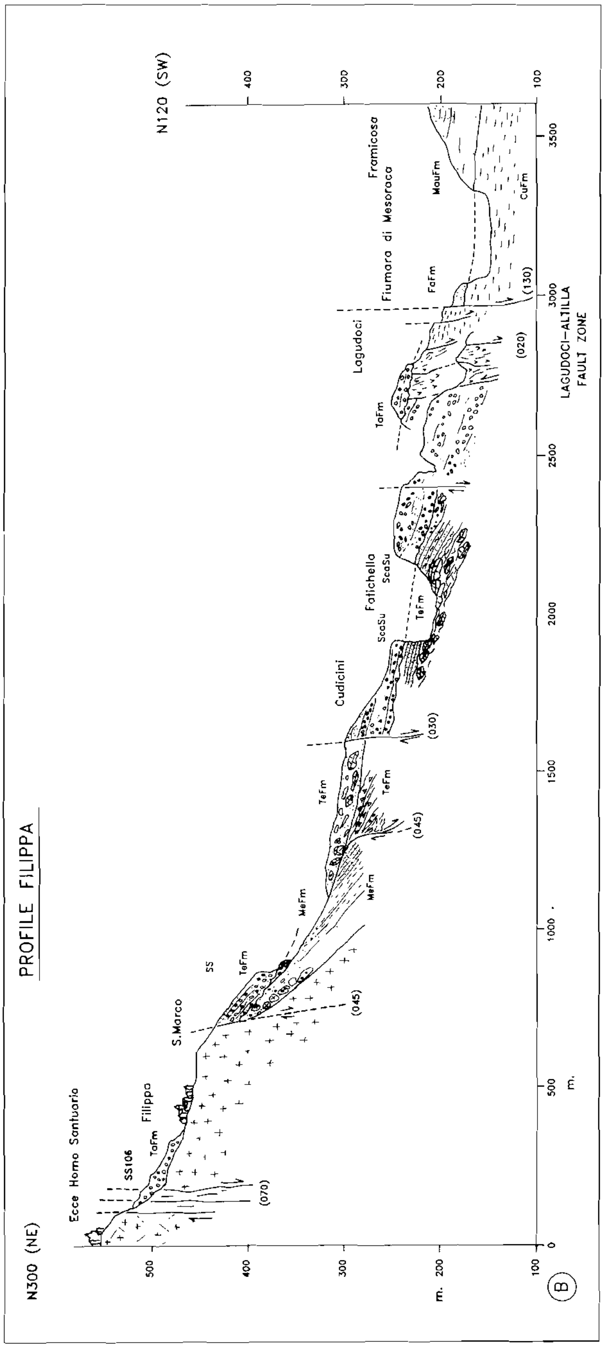
COCUZZITO THRUST
F.so Potamo
Foresta
Timp.ne Cocuzzito
F.ro di Mesoraco
Formicosa
Arietta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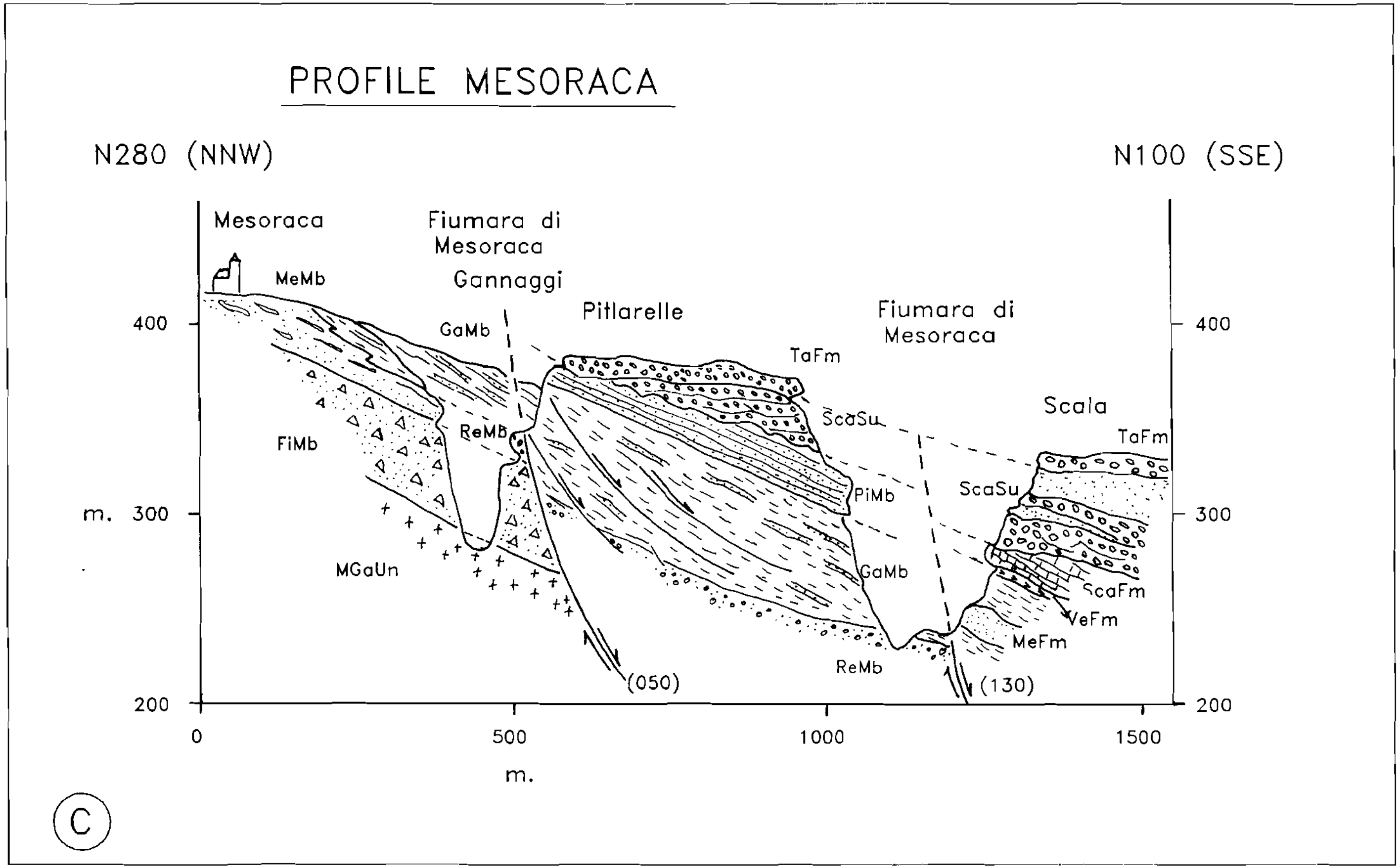
Ecce Homo Santuario
SS106
TaFm
Filippa
S.Marco
SS
TaFm
MeFm
MeFm
TeFm
TeFm
Cudicini
ScaSu
Fatichella
ScaSu
TeFm
TaFm
Lagudoci
Fiumara di Mesoraca
Framicosa
FaFm
MauFm
CuFm
(070)
(045)
(045)
(030)
(020)
(130)
LAGUDOCI-ALTILLA
FAULT ZONE
m.
m.
B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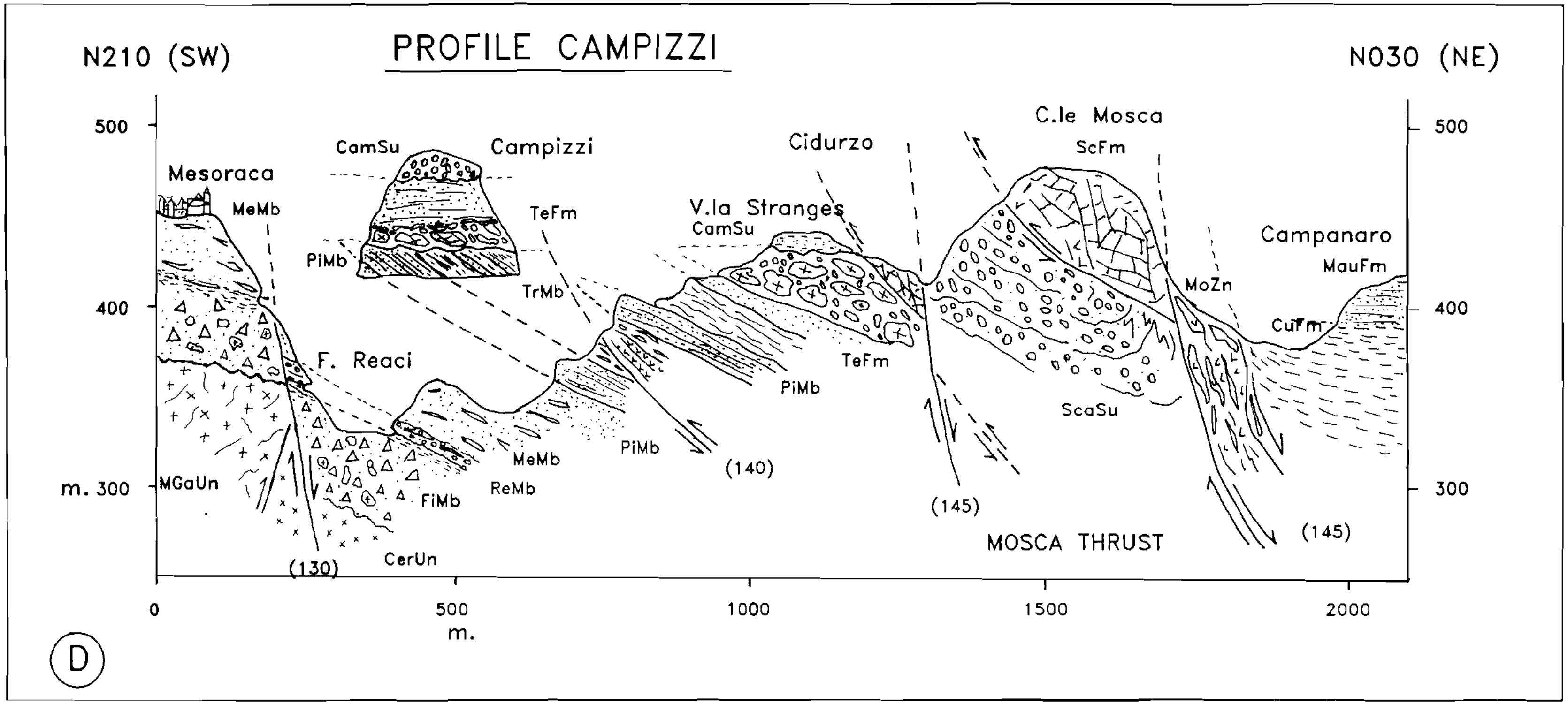
N100 (SSE)
Mesoraca
Fiumara di
Mesoraca
Gannaggi
Pitlarelle
Fiumara di
Mesoraca
Scala
MeMb
GaMb
TaFm
ScaSu
ReMb
FiMb
PiMb
ScaSu
TaFm
MGaUn
GaMb
ScaFm
VeFm
MeFm
ReMb
(050)
(130)
400
300
200
m.
0
500
1000
1500
m.
C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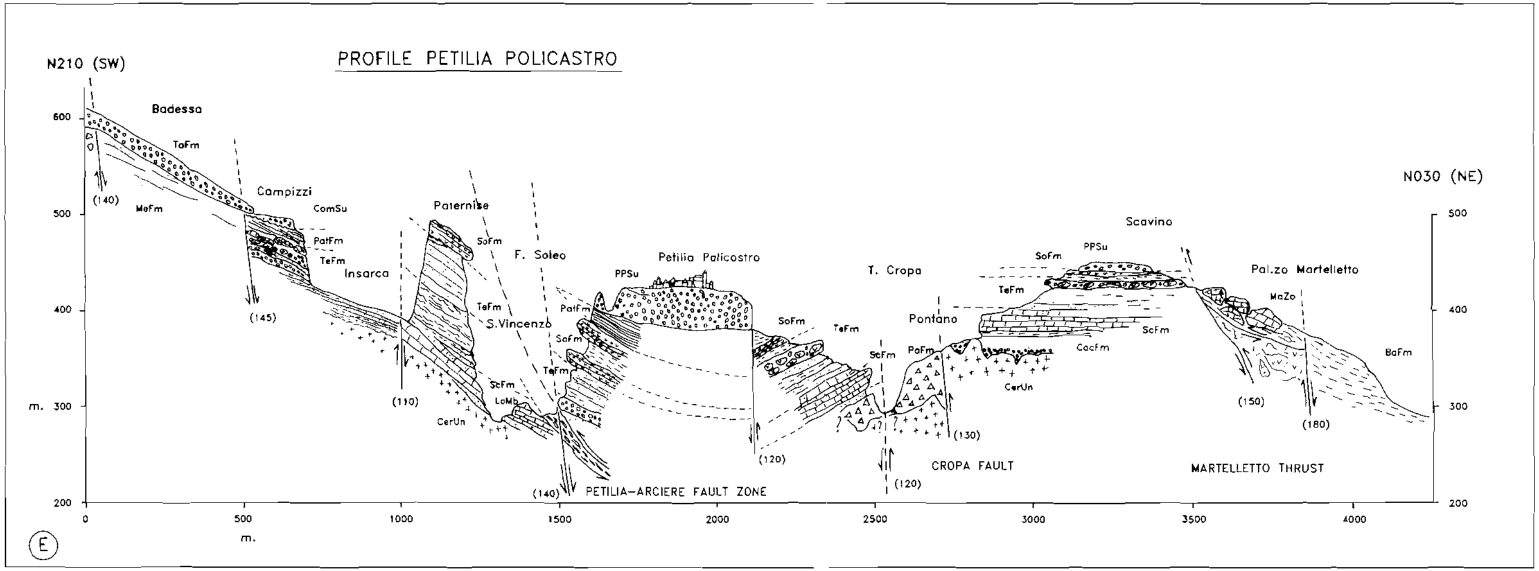
N030 (NE)
500
400
m. 300
500
400
300
Mesoraca
MeMb
CamSu
Campizzi
PiMb
TeFm
TrMb
F. Reaci
MGaUn
FiMb
CerUn
(130)
MeMb
ReMb
PiMb
(140)
Cidurzo
V.la Stranges
CamSu
TeFm
PiMb
(145)
C.le Mosca
ScFm
ScaSu
MOSCA THRUST
MoZn
Campanaro
MauFm
CuFm
(145)
0
500
1000
1500
2000
m.
D



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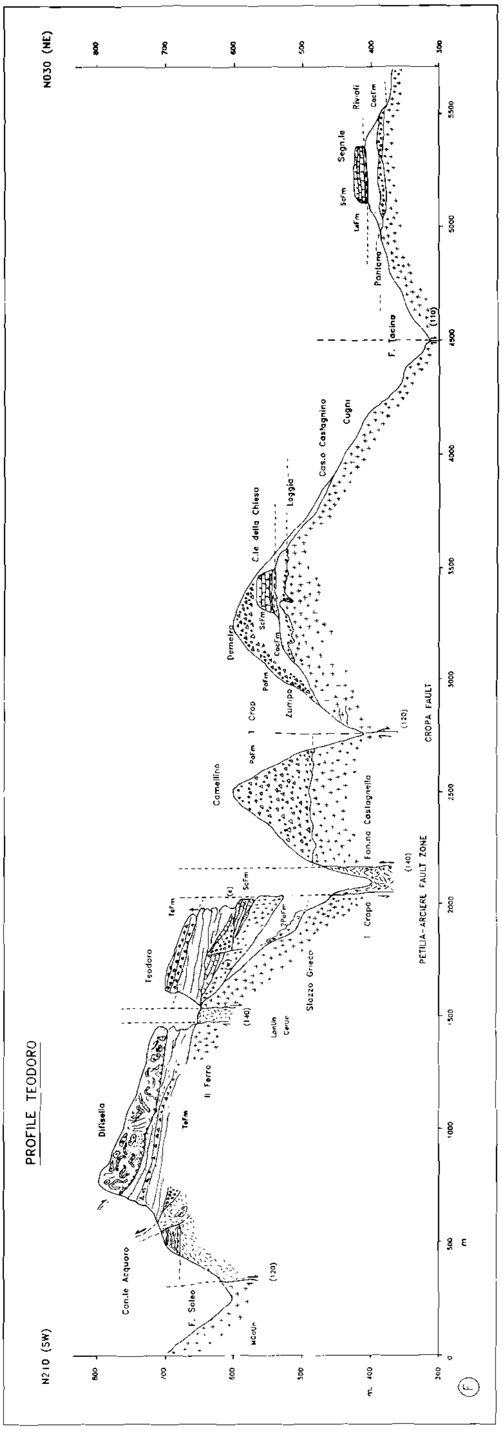
N030 (NE)
Badessa
TaFm
MeFm
Campizzi
ComSu
PatFm
TeFm
Insarca
Paternise
SoFm
F. Soleo
S.Vincenzo
ScFm
LoMb
CerUn
PPSu
Petilia Policastro
T. Cropa
Pontano
PaFm
Scavino
CacFm
Pal.zo Martelletto
MaZo
BaFm
(140)
(145)
(110)
(120)
(130)
(150)
(180)
PETILIA-ARCIERE FAULT ZONE
CROPA FAULT
MARTELLETTO THRUST
m.
E



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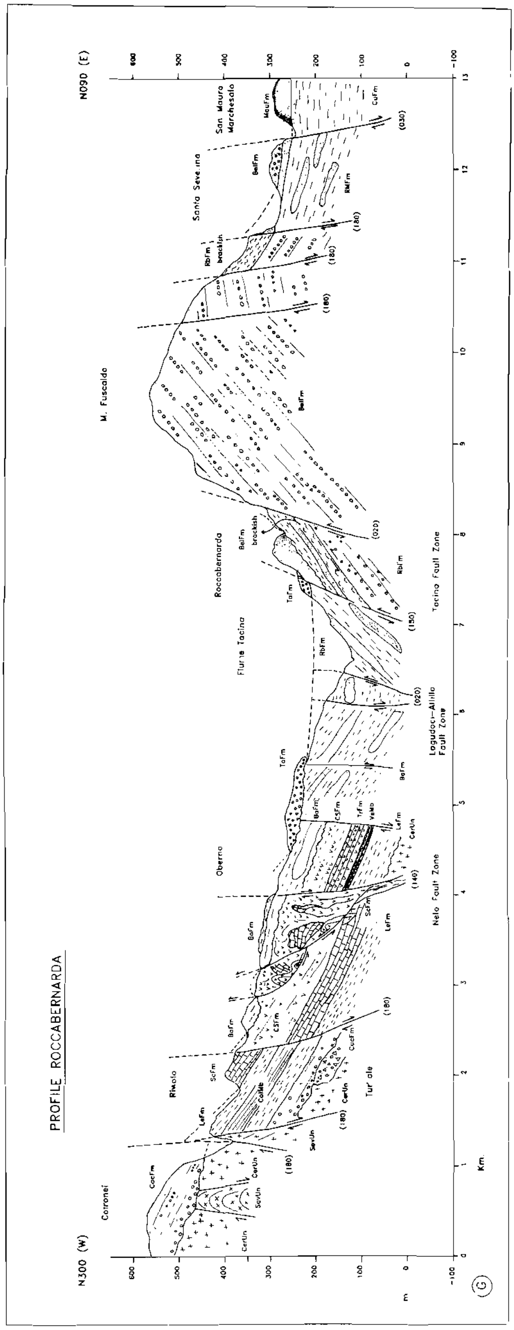
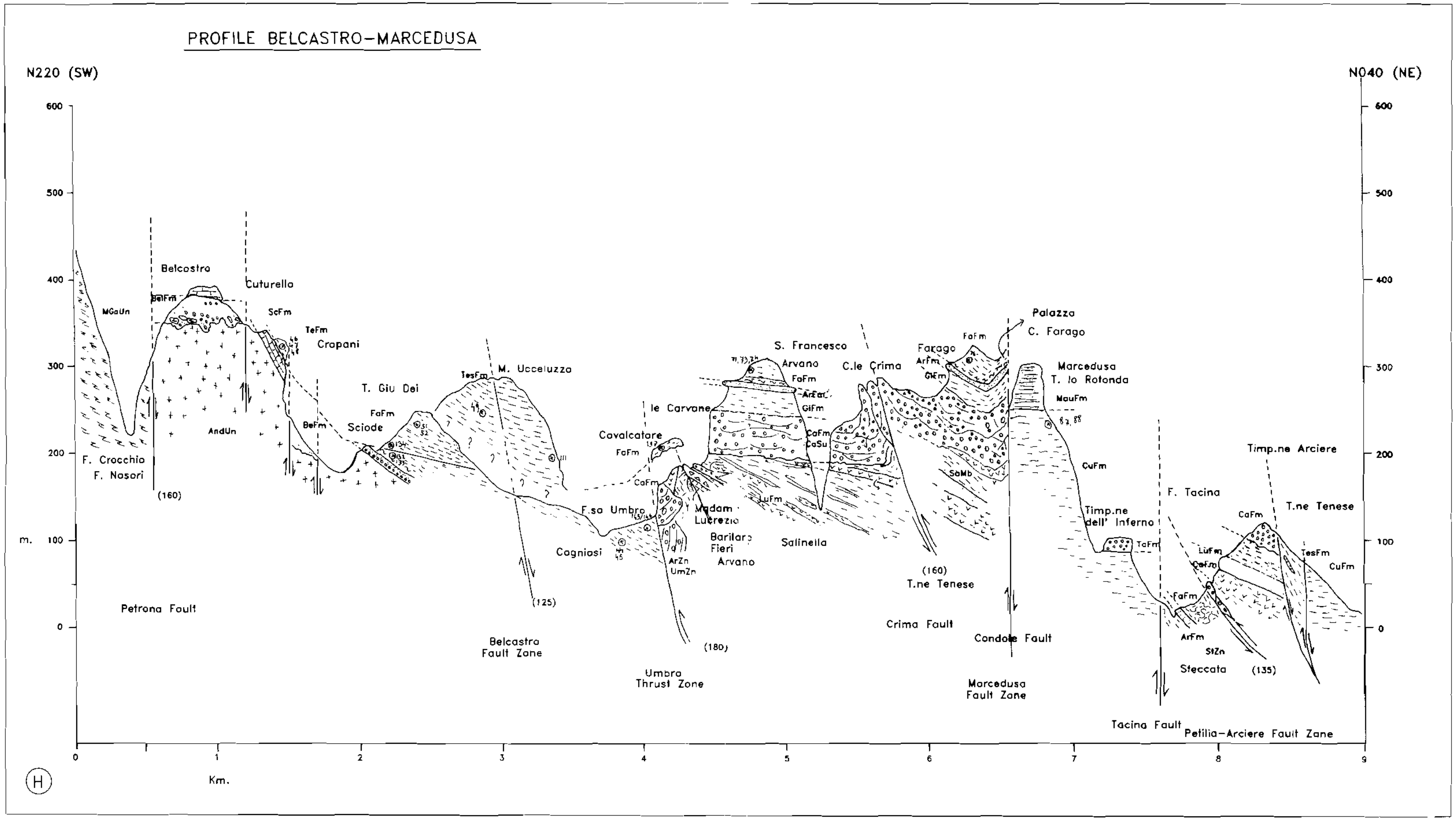
N030 (NE)
Con.le Acquaro
F. Soleo
Difisella
Il Ferro
Teodoro
Slazzo Grieco
I Cropa
PETILIA-ARCIERE FAULT ZONE
Fon.na Castagnella
Camellino
CROPA FAULT
Demetra
Zumpo
C.le della Chiesa
Loggia
Cas.o Castagnino
Cugni
F. Tacina
Pantano
Segn.le



PROFILE ROCCABERNARDA
N300 (W)
N090 (E)
Cotronei
Rivolo
Turrale
Oberno
Fiume Tacina
Roccabernarda
M. Fuscaldo
Santa Severina
San Mauro Marchesato
Nelo Fault Zone
Lagudoci–Altilia Fault Zone
Tacina Fault Zone
Km
m
G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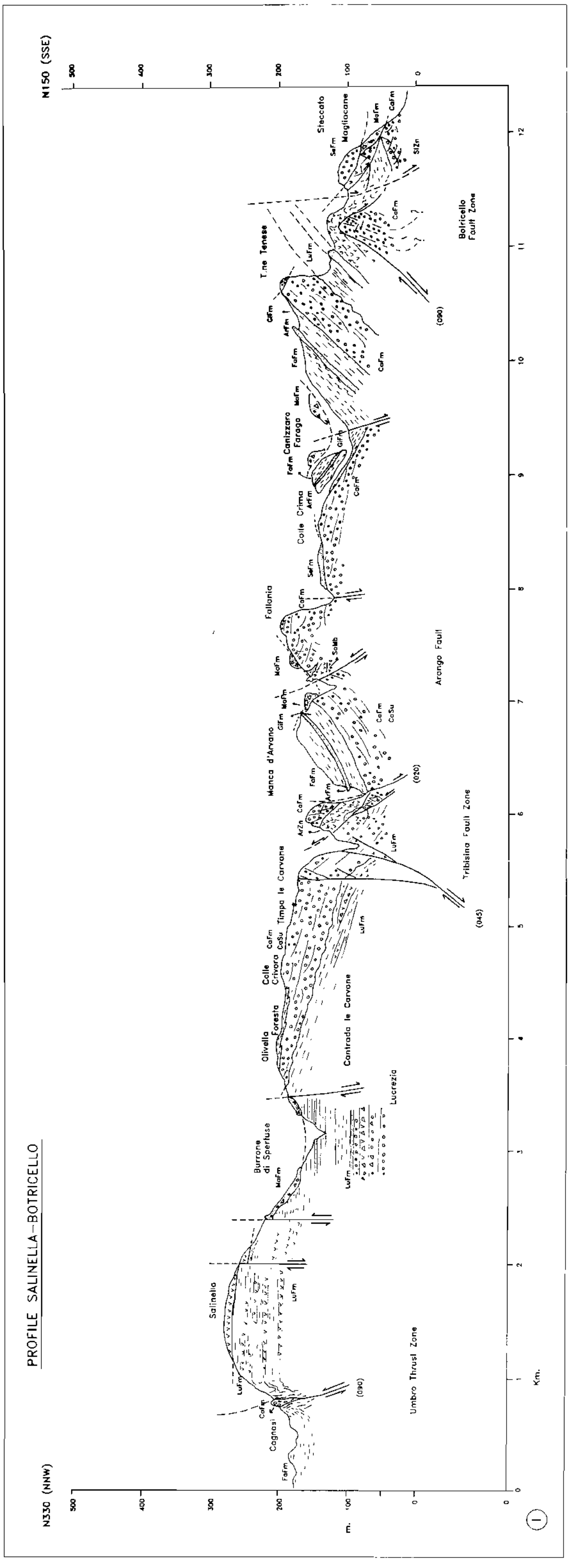
500
400
300
200
100
0
m.
Belcastro
Cuturello
BelFm
ScFm
TeFm
Crapani
MGaUn
AndUn
F. Crocchio
F. Nosori
(160)
Petrona Fault
T. Giu Dei
FaFm
BeFm
Sciode
TesFm
M. Ucceluzzo
(125)
Belcastro
Fault Zone
le Carvone
Cavalcatore
FaFm
CaFm
F.so Umbro
Cogniosi
Madam
Lucrezia
Barilaro
Fieri
Arvano
ArZn
UmZn
(180)
Umbro
Thrust Zone
S. Francesco
Arvano
FaFm
ArFm
GlFm
CaFm
CaSu
LuFm
Salinella
C.le Crima
Farago
ArFm
GlFm
FaFm
SaMb
(160)
T.ne Tenese
Crima Fault
Palazza
C. Farago
Marcedusa
T. lo Rotonda
MauFm
CuFm
Condole Fault
Marcedusa
Fault Zone
Timp.ne
dell' Inferno
TaFm
F. Tacina
Tacina Fault
Timp.ne Arciere
CaFm
T.ne Tenese
LuFm
CaFm
TesFm
CuFm
FaFm
ArFm
StZn
Steccata
(135)
Petilia-Arciere Fault Zone
0
1
2
3
4
5
6
7
8
9
Km.
H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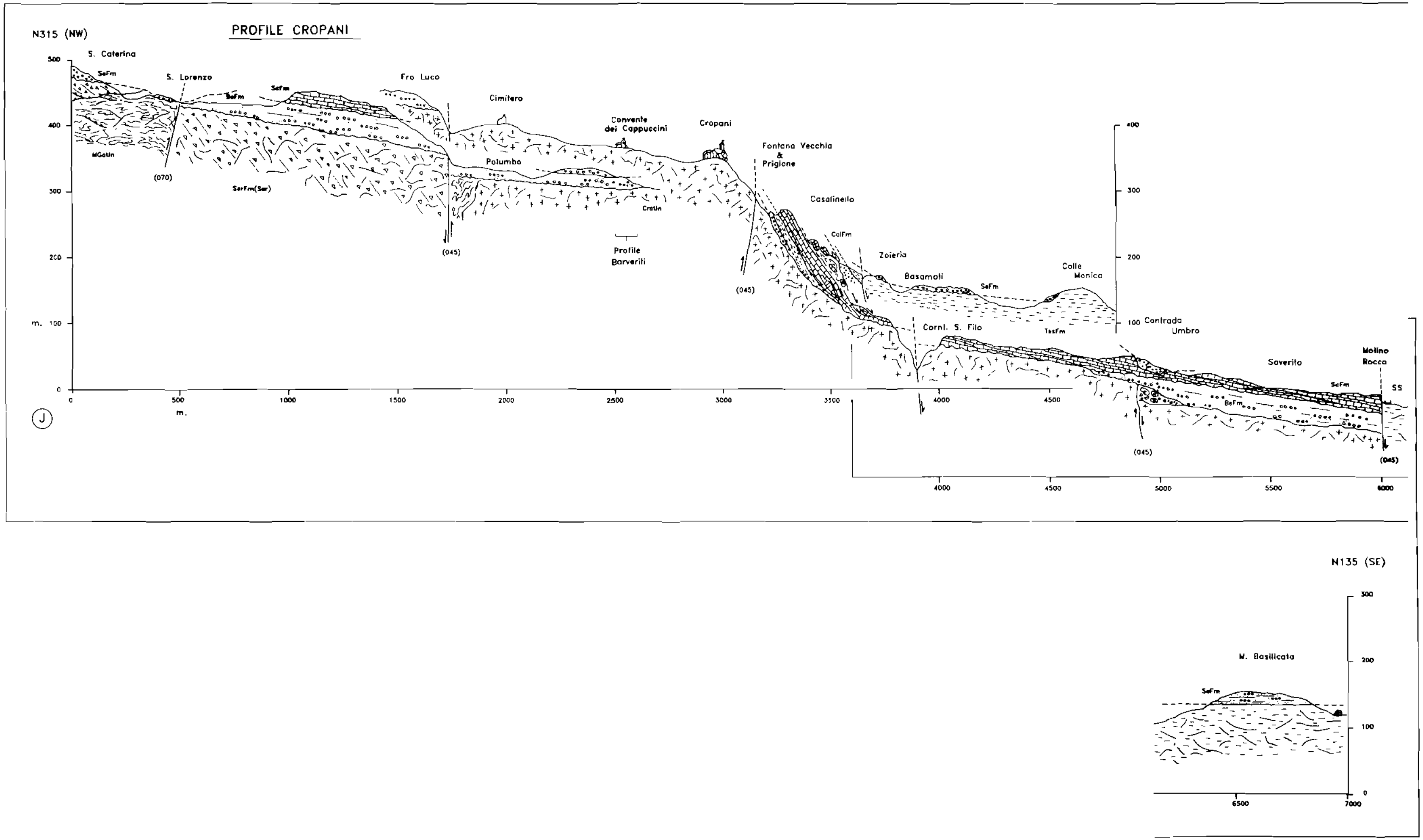
N150 (SSE)
m.
Km.
Cagnasi
Salinella
Burrone di Sperfuse
Lucrezia
Olivella
Foresta
Colle Crivaro
Timpa le Carvone
Contrada le Carvone
Manca d'Arvano
Fallonia
Colle Crima
Canizzaro
Farago
T.ne Tenese
Steccato
Magliacane
Umbro Thrust Zone
Tribisina Fault Zone
Arango Fault
Botricello Fault Zone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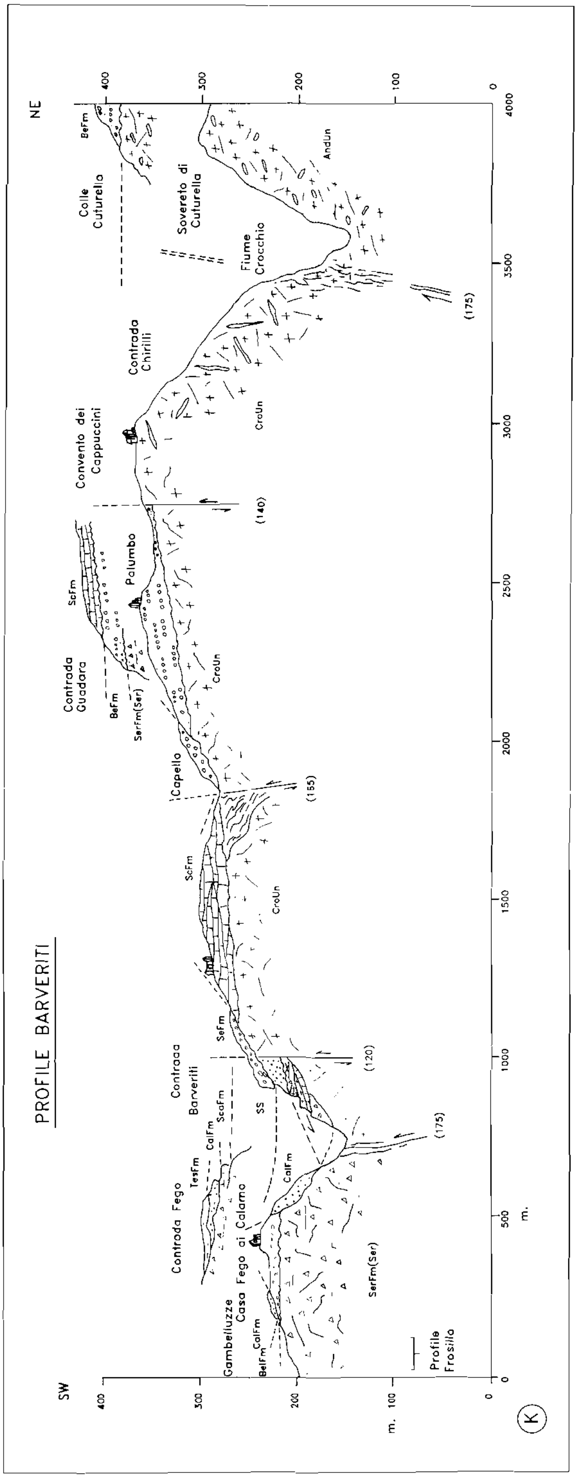
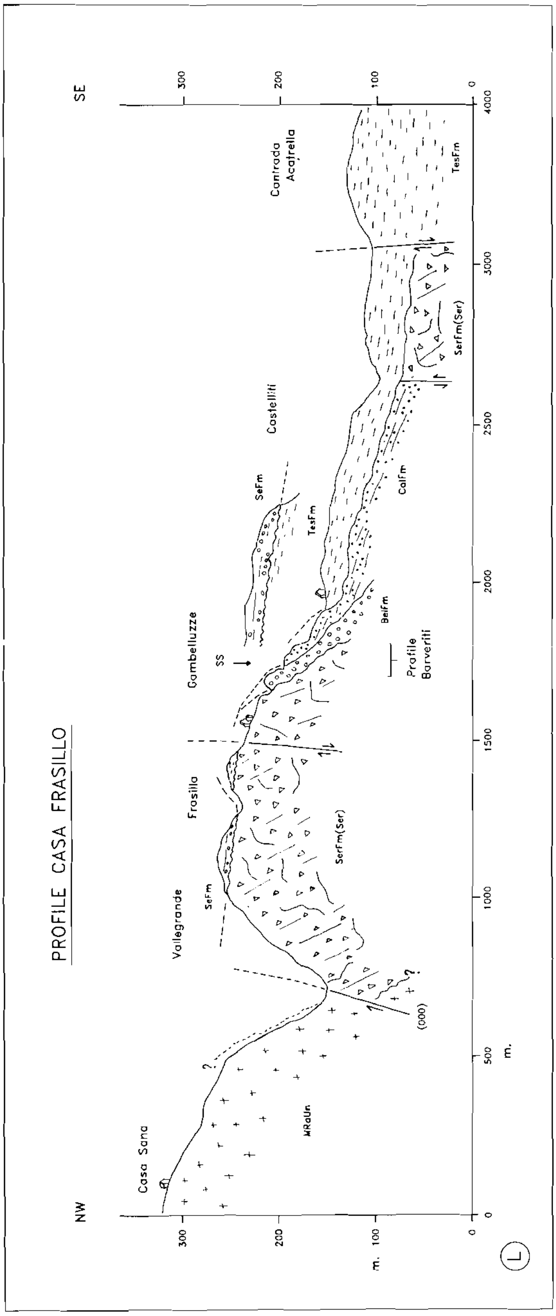
PROFILE CROPANI
S. Caterina
S. Lorenzo
Fra Luco
Cimitero
Convente dei Cappuccini
Cropani
Fontana Vecchia & Prigione
Polumbo
Casalinella
Zoieria
Basamoti
Colle Monica
Contrada Umbro
Profile Barverili
Corni. S. Filo
Saverito
Molino Rocco
SS
SeFm
BeFm
SerFm(Ser)
CalFm
TsFm
(070)
(045)
m.
N135 (SE)
M. Basilicata



PROFILE BARVERITI
SW
NE
Gambelluzze
Casa Fego ai Calamo
Contrada Fego
Contraaa Barveriti
Capello
Contrada Guadara
Palumbo
Convento dei Cappuccini
Contrada Chirilli
Fiume Crocchio
Sovereto di Cuturella
Colle Cuturella
Profile Frosilo
BelFm
CalFm
TesFm
ScaFm
SS
SerFm(Ser)
ScFm
BeFm
CroUn
AndUn
(175)
(120)
(155)
(140)
m.
0
100
200
300
400
500
1000
1500
2000
2500
3000
3500
4000
K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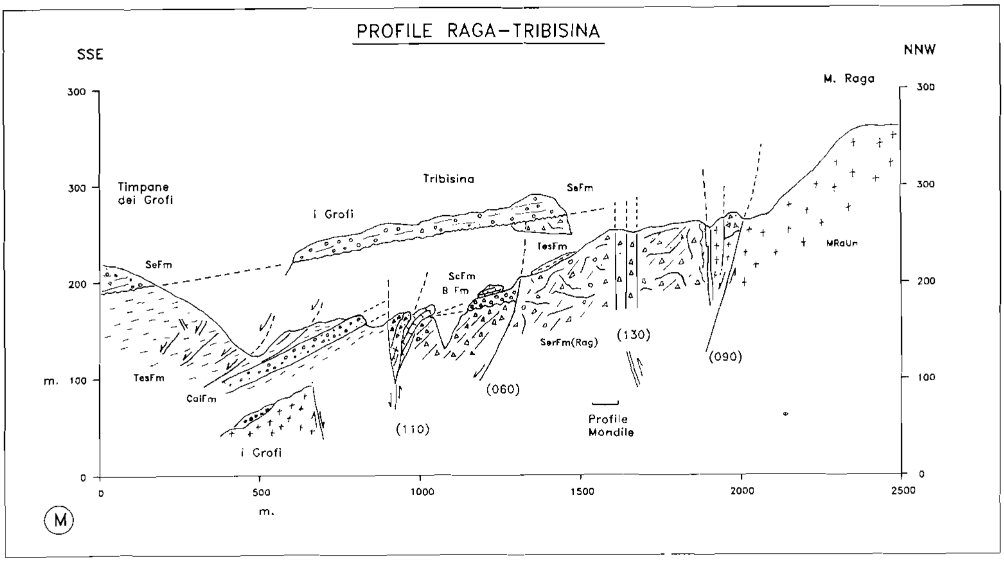
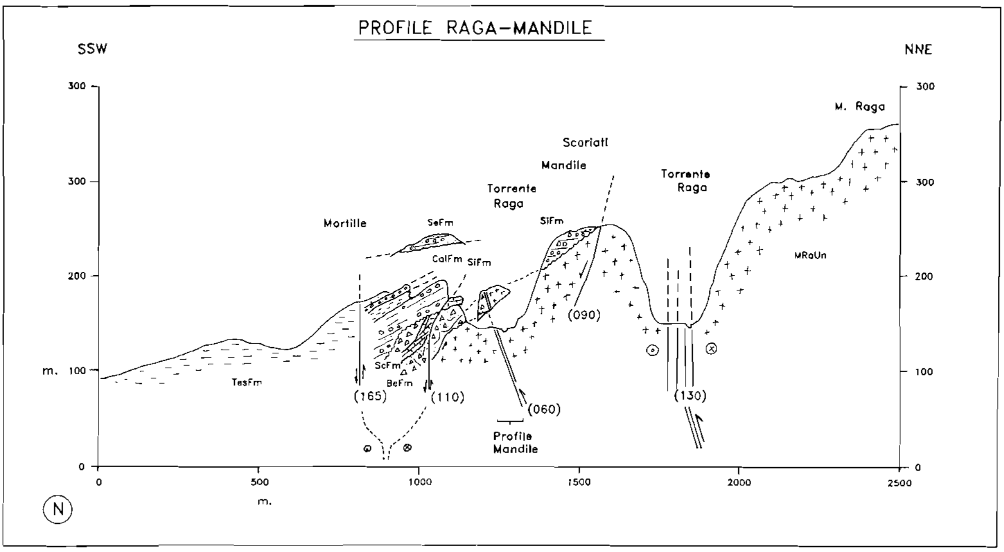
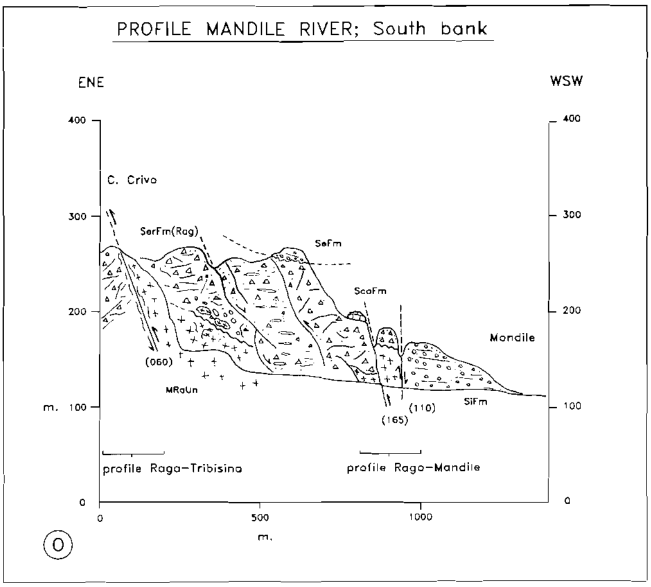
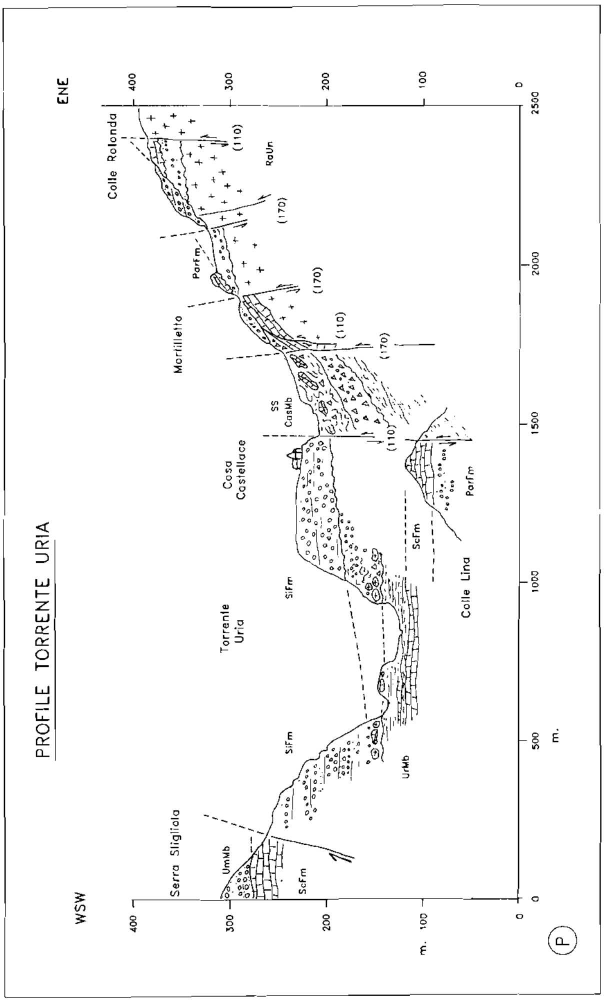
NW
SE
Casa Sana
MRaUn
Vallegrande
SeFm
Frasilla
SerFm(Ser)
(000)
Gambelluzze
SS
Profile Barveriti
BelFm
SeFm
TesFm
CalFm
Castelliti
SerFm(Ser)
Contrada Acatrella
TesFm
m.
L


PROFILE RAGA–TRIBISINA
SSE
NNW
M. Raga
Timpane dei Grofi
Tribisina
i Grofi
SeFm
TesFm
ScFm
B Fm
SerFm(Rag)
TesFm
CalFm
MRaUn
(130)
(090)
(060)
(110)
Profile Mondile
i Grofi
m.
M


PROFILE RAGA–MANDILE
SSW
NNE
M. Raga
Scoriati
Mandile
Torrente Raga
Torrente Raga
Mortille
SeFm
SiFm
CalFm
SiFm
MRaUn
(090)
TesFm
ScFm
BeFm
(165)
(110)
(060)
(130)
Profile Mandile
m.
N


PROFILE MANDILE RIVER; South bank
ENE
WSW
400
300
200
m. 100
0
C. Crivo
SerFm(Rag)
SeFm
ScoFm
Mondile
(060)
MRaUn
(165)
(110)
SiFm
profile Raga-Tribisino
profile Raga-Mandile
0
500
1000
m.
O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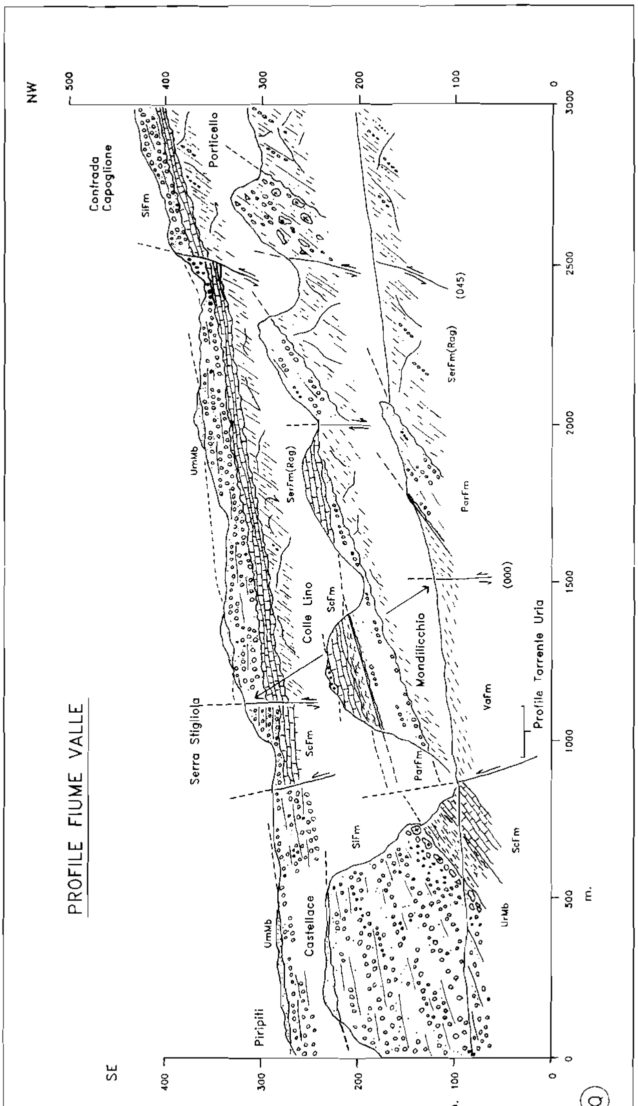
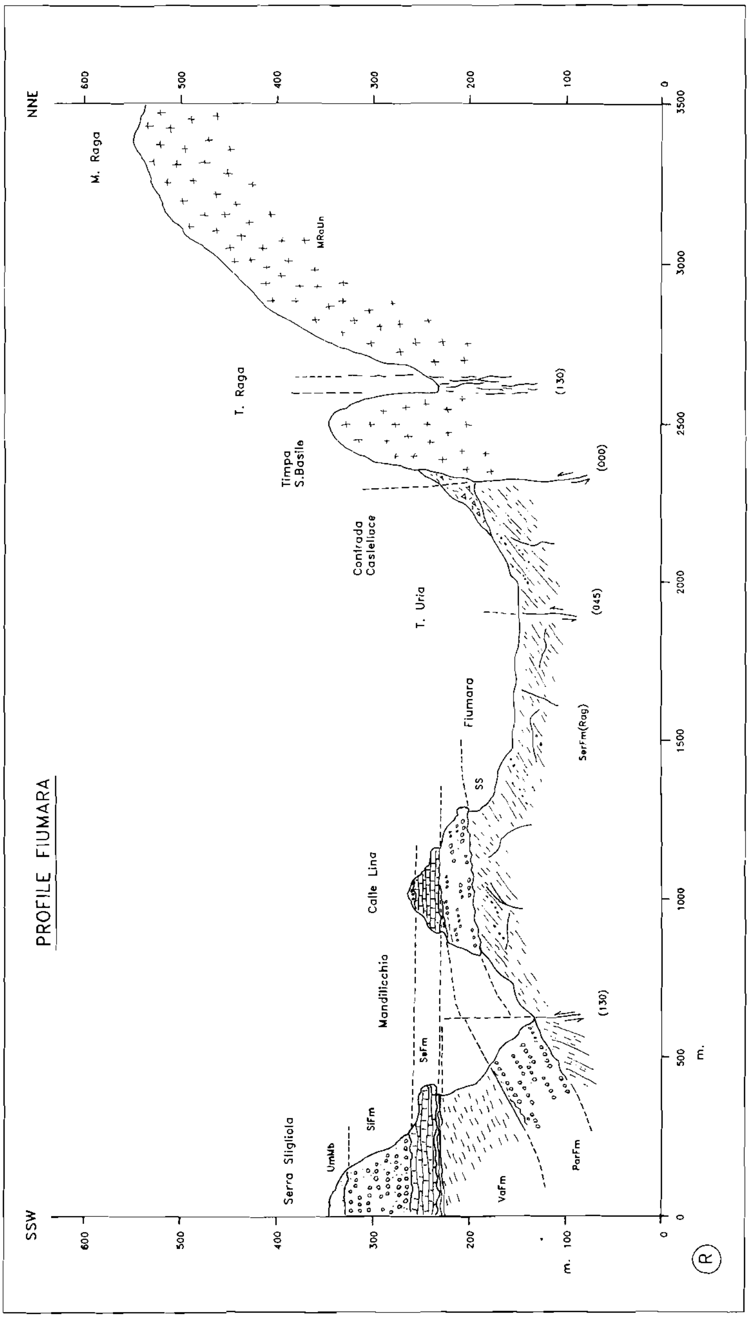
WSW
ENE
Serra Sligliala
Torrente Uria
Casa Castellace
Morfilletto
Colle Rotonda
Colle Lina
UmMb
ScFm
SlFm
UrMb
SS
CasMb
ParFm
RaUn
(110)
(170)
P
m.


PROFILE FIUME VALLE
SE
NW
Piripiti
UmMb
Castellace
Serra Stigliola
ScFm
Colle Lino
SerFm(Rag)
Mandilicchio
ParFm
VaFm
Profile Torrente Urla
(000)
SiFm
UrMb
Contrada Capoglione
Porticello
(045)
m.
a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SSW
NNE
M. Raga
MRaUn
T. Raga
(130)
Timpa S.Basile
(000)
Contrada Castellace
T. Uria
(045)
Fiumara
SerFm(Rag)
SS
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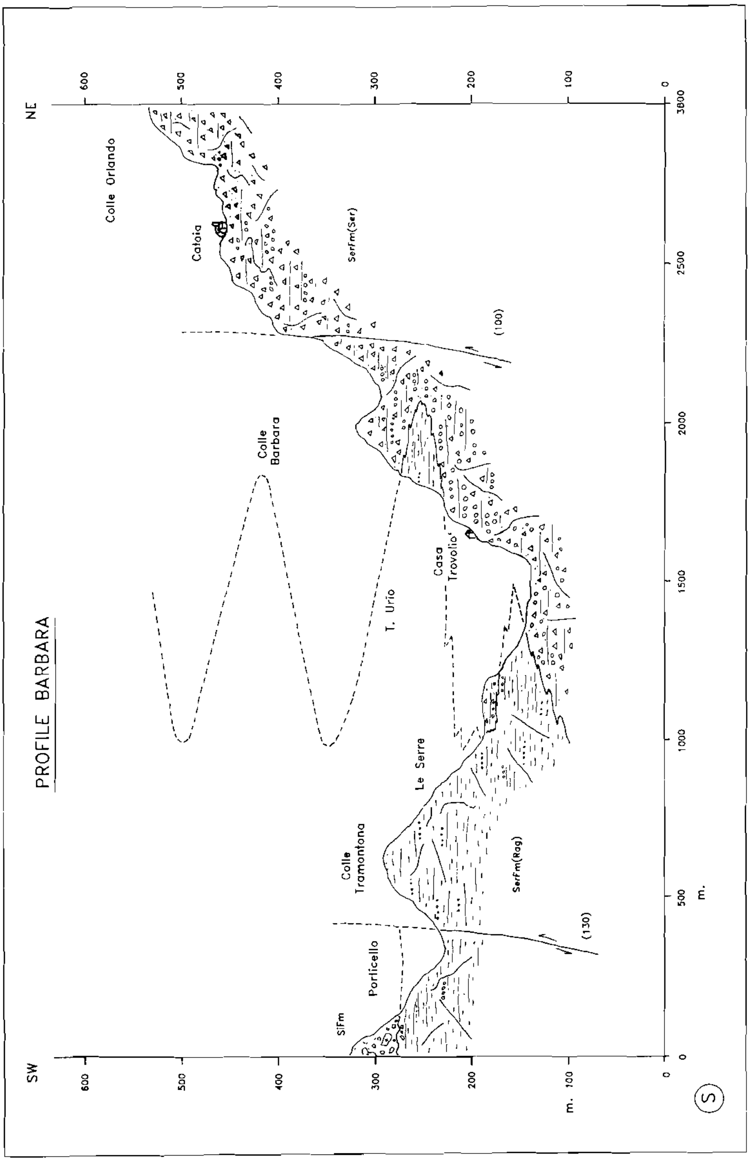
SeFm
(130)
SlFm
UmMb
Serra Sligliola
VaFm
ParFm
m.
R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SW
NE
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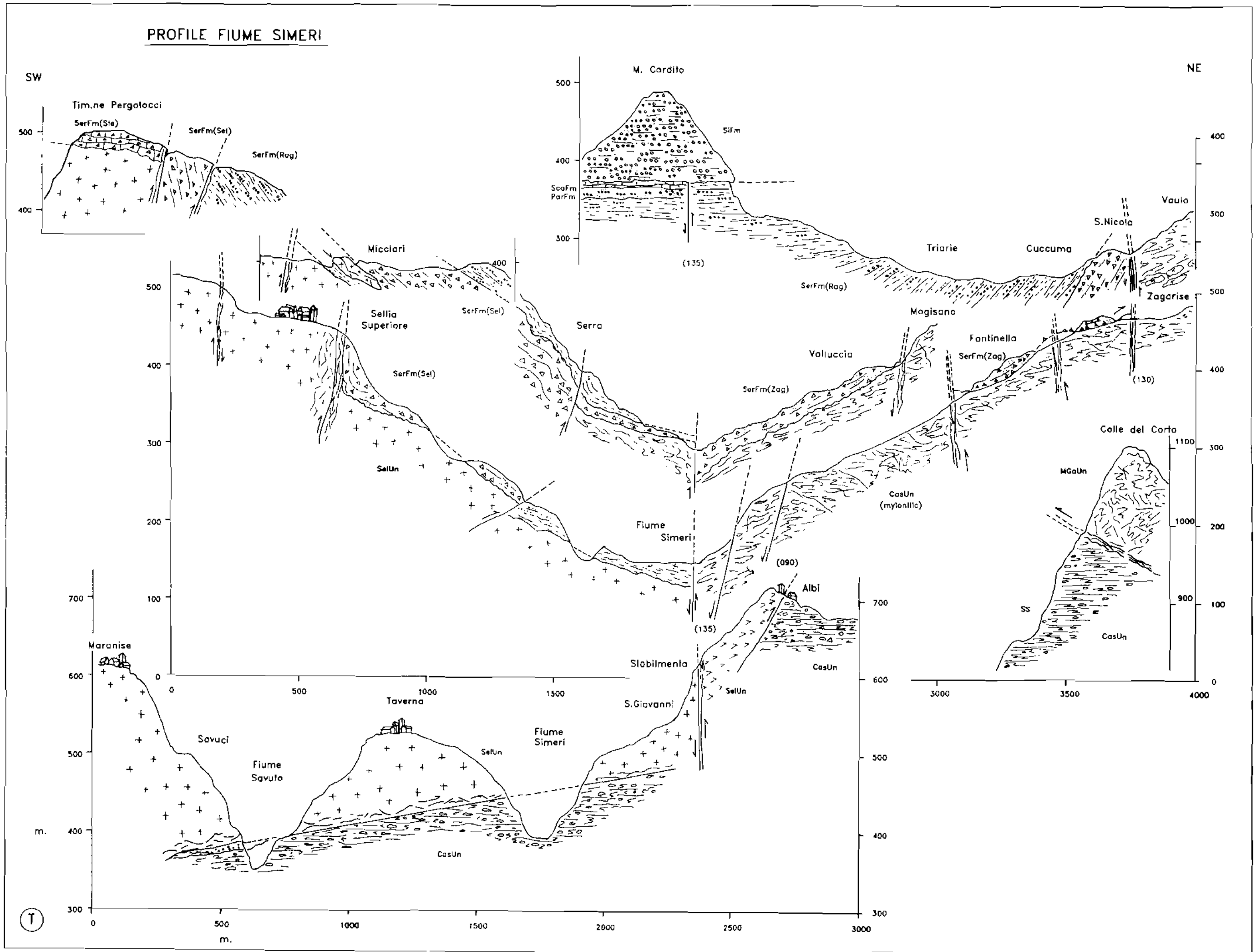
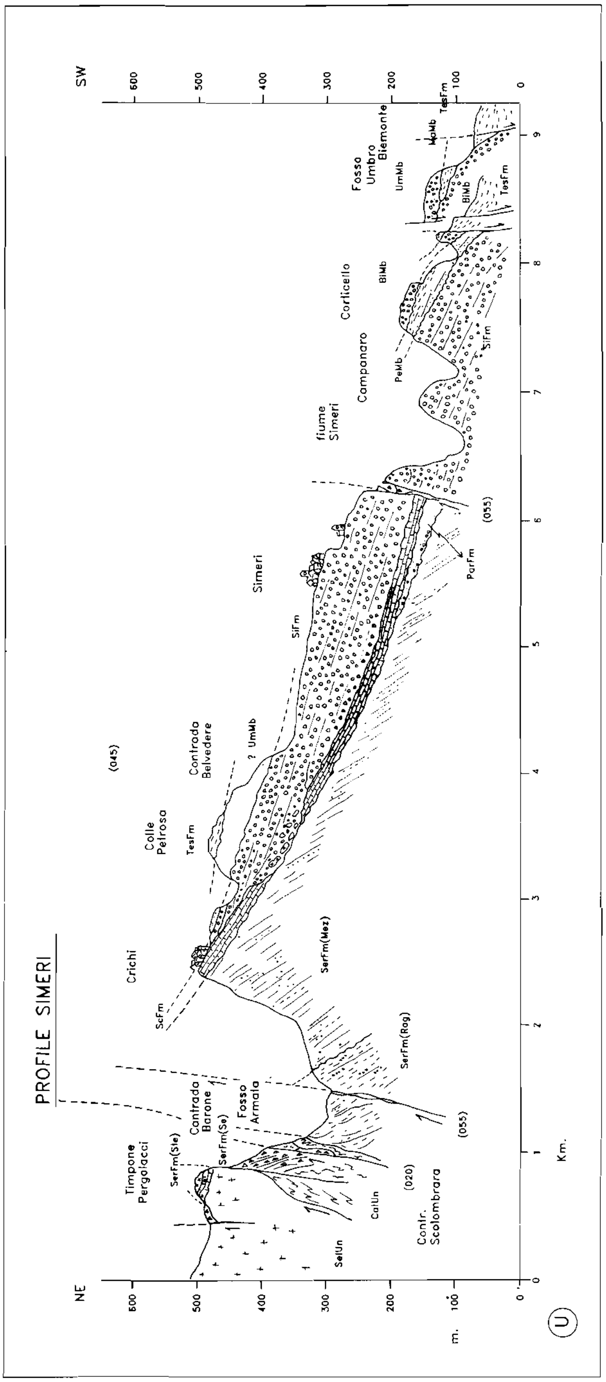
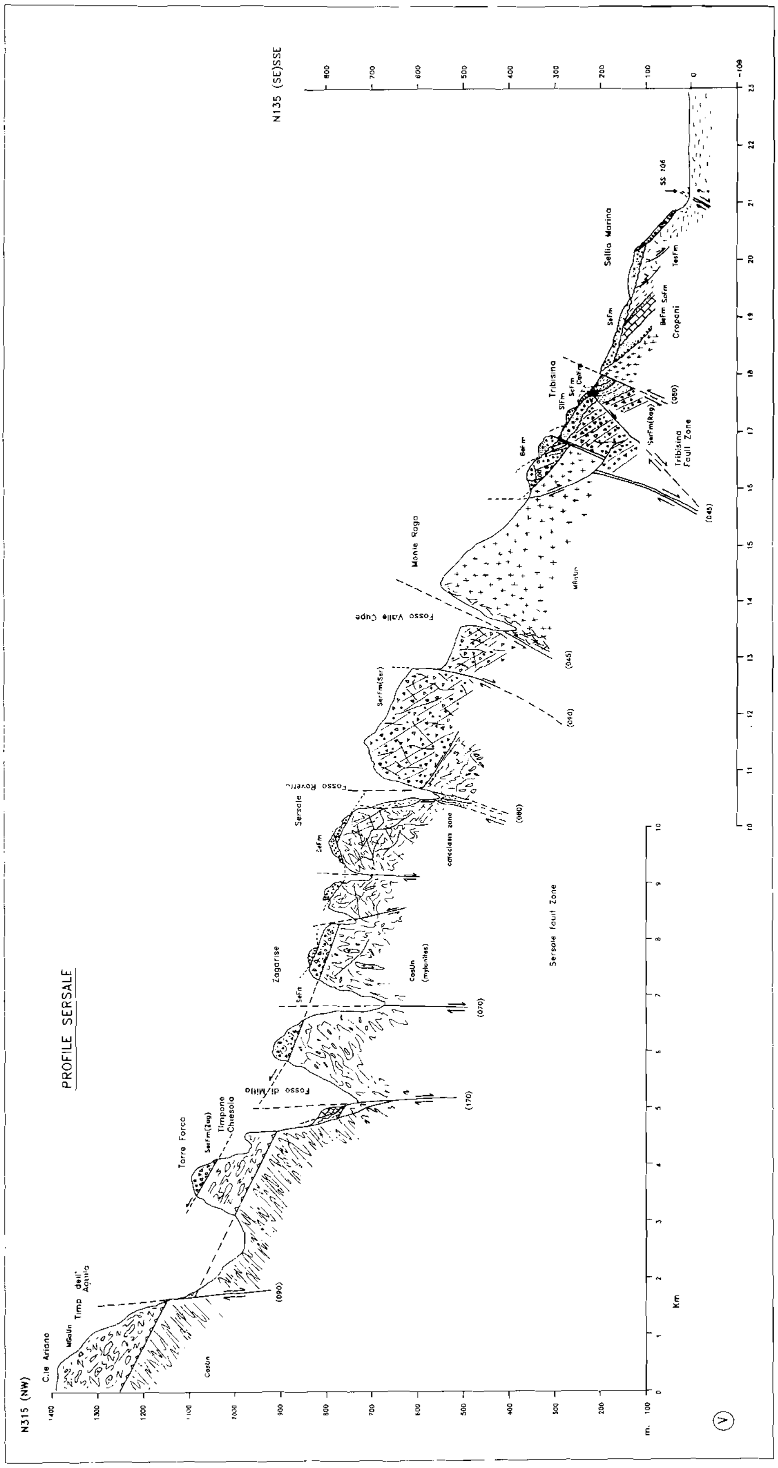
Cataia
SerFm(Ser)
(100)
Colle Barbara
Casa Trovolio
T. Urio
Le Serre
Colle Tramontana
SerFm(Rag)
(130)
Porticello
SiFm
m.


PROFILE FIUME SIMERI
SW
NE
Tim.ne Pergolocci
SerFm(Ste)
SerFm(Sel)
SerFm(Rag)
M. Cardito
SiFm
ScaFm
ParFm
(135)
Triarie
Cuccuma
S.Nicola
Vauia
Micciari
Sellia Superiore
SerFm(Sel)
Serra
Valluccia
Magisano
Fontinella
SerFm(Zag)
Zagarise
(130)
SelUn
Fiume Simeri
CasUn (mylonitic)
(090)
(135)
Albi
Colle del Corto
MGaUn
SS
CasUn
Maranise
Savuci
Fiume Savuto
Taverna
SelUn
Fiume Simeri
S.Giovanni
Slobilmenta
CasUn
m.


PROFILE SIMERI
U
NE
SW
m.
Km.
Timpone Pergolacci
SerFm(Sle)
SerFm(Se)
Contrada Barone
Fosso Armala
SelUn
CalUn
(020)
Contr. Scolombrara
(055)
SerFm(Rag)
ScFm
Crichi
SerFm(Mez)
Colle Pelrosa
TesFm
(045)
Contrada Belvedere
? UmMb
SiFm
Simeri
ParFm
fiume Simeri
Companaro
PeMb
Corticello
BiMb
Fosso Umbro Biemonte
UmMb
MoMb
TesFm
SiFm


PROFILE SERSALE
N315 (NW)
N135 (SE)SSE
C.le Ariano
Timp dell' Aquila
Torre Forca
Timpone Chiesola
Fosso di Millo
Zagarise
Sersale
Fosso Rovetto
Fosso Valle Cupe
Monte Raga
Tribisina
Tribisina Fault Zone
Cropani
Sellia Marina
SS 106
Sersale fault Zone
cataclasis zone
Km
m.
V

PART 2

GEOHISTORY ANALYSIS

Nisida è un' isola,
e nessuno lo sa...

Edoardo Bennato

Janpieter van Dijk, PhD-Thesis, 1992
Department of Geology, Institute for Earth Sciences,
Utrecht University, Budapestlaan 4, 3508 TA Utrecht,
The Netherlands; Tel. (0)30-535122; Fax: (0)30-535030 NL

CHAPTER 4

GEOHISTORY ANALYSIS OF CENTRAL MEDITERRANEAN BASINS:

VERTICAL BASIN KINEMATICS IN THE CALABRIAN ARC

Abstract. A quantitative analysis is presented of vertical motions in the Neogene basins of the Central Mediterranean. The geohistory analysis method, comprising decompaction procedures and loading corrections (backstripping) is being discussed. A comparative analysis of assumptions and used parameters provides insight into the precision of the results obtained.

Geohistory diagrams are generated of the Tyrrhenian back-arc Basin, of Calabrian summit and fore-arc basins, of Sicilian fold-and-thrust-belt basins, and of forleand areas comprising the Iblean block and the Ionian basin. The diagrams show a high variety of subsidence/uplift and accumulation rates, both spatial and temporal. Three specific episodes of high frequency tectonic activity can be recognized in the entire Central Mediterranean area: Early Miocene, Messinian-Early Pliocene, and Pleistocene-Recent.

It is shown that spreading episodes in the Tyrrhenian back-arc area (with a duration of about 1 Ma) alternate with phases of overthrusting in the surrounding thrust-belts. Subsidence curves of the back-arc area show an acceleration of subsidence with individual rates exceeding 500 cm/Ka, which can not be explained by classical rifting models. These accelerations may be the result of repetitive rifting phases, and phases of downwarping. Downwarping, in turn, may contributed to an increase in regional compressive stress, or to an extensional collapse related to plate rupture.

Rates of vertical oscillations are one order of magnitude larger that the possible amount of vertical eustatic sea level variation. This illustrates that tectonic activity is the main factor in the genesis of third-order unconformity-bound depositional sequences.

The "Cloetingh model" of intra-plate stress fluctuations may be applied to explain high amplitudes of basinal and marginal subsidence and uplift patterns in the basins adjacent to the Calabrian Arc. Compression is provided by phases of contraction of the thrust-wedge which may be related to pulses in stagnation of arc migration.

INTRODUCTION

The quantitative analysis of subsidence and uplift histories inferred from stratigraphic sequences, geohistory analysis, has been a major tool in the study of hydrocarbon generations since the early 70's (see for a review Van Hinte, 1978). The method has also been applied in research on both passive and active mar-gins (Sleep, 1971; Watts and Ryan, 1976; Horowitz, 1976; Van Hinte, 1978; Hardebol et al., 1980; Sclater and Christie, 1980; Bond and Kominz, 1984). Thermo-tectonic subsidence curves, obtained from geophysical modeling, can be compared with observed subsidence patterns, cor-rected for sediment loading effects. The latter technique is called "backstripping" (Watts and Ryan, 1976).
The accurate analysis of the amount of vertical motions is of great importance in basin studies for a number of reasons: As mentioned above, the method provides the possibility to compare real datasets with forward tectonophysical models, and it allows to investigate the relations between subsidence and thermal parameters (e.g. Lerche, 1989). Furthermore, the compilation of subsidence curves for different basin kinematic settings may be usefull as a first-order classification of basin-types based on their characteristic subsidence patterns (Pitman and Andrews, 1985; Brenner and McHargue, 1988, p. 368; Kukal, 1990). The integration of detailed structural and stratigraphic studies of basin kinematics with a subsidence

analysis can give insight into the rates and character of various tectonic processes such as tilting, folding, and differential block-faulting (Van Dijk, 1990, 1991; Fortuin and De Smet, 1991; Postma et al., in press.; Meulenkamp et al., submitted). In sequence-stratigraphy analysis, the interactions of sea level, tectonics and sediment supply may be illustrated with geohistory diagrams (Hardenbol et al., 1980; Vail et al., 1990, 1992), whereby, however, greatest caution has to be taken when interpreting the various signals on both small scale and larger (global) scale (e.g. Guidish et al., 1984; Burton et al., 1987; Cloetingh, 1988; Kooi, 1991, p. 158).

Geohistory diagrams will be presented for various Neogene basins in the Central Mediterranean area (Figs. 1, 2). The Calabrian Arc comprises the southern Apennines thrust-belt, the Calabrian block, with the Calabrian Accretionary Wedge, and the Sicilian Maghrebides thrust-belt. A wide variety of basin types is present, ranging from oceanic back-arc basins through fore-arc, intra-arc and summit basins, to foreland basins upon external platform areas. The Neogene evolution of the area is dominated by the migration of the Calabrian Arc to the southeast, coupled with the extension of the Tyrrhenian Basin. Neogene successions of the different basins reflect episodes and pulses of extension and contraction with various durations. Therefore, the comparison of subsidence patterns of the basins can contribute to a better understanding of the kinematic evolution of this complex segment of the late Alpine Mediterranean deformation zone.

METHODOLOGY

The method of geohistory analysis (a term introduced by Van Hinte, 1978) has been developed by Sleep (1971), Perrier and Quiblier (1974), Watts and Ryan (1976), Horowitz (1976) and Van Hinte (1978). It is a one-dimensional method, which restores stratigraphic successions in boreholes or field sections to their original thickness for each time-slice and plots the restored units at their correct burial depth (Van Hinte, 1978; Ungerer et al., 1984 and Guidish et al., 1985; Bessis, 1986; Tacherist, 1991). The method consists of three steps, for each of which a knowledge base must be provided. This knowledge base contains classifications such as zonations, application and correlation rules for these zonations, and algorithms for corrections for compaction and loading with various default parameters to match.

1. The first step consists of plotting the age against depth of deposition for each datapoint of the stratigraphic sequence. Age data are obtained from biostratigraphy, magnetostratigraphy and radiometrical dating. Paleobathymetry is obtained from micropaleontological and paleoecological analyses of foraminifera, and from sedimentological facies analyses. Also seismostratigraphy may be used to infer age-depth estimates.
2. The second step implies the restoration of the lithological units to their original thickness. The burial depth of each layer is then plotted against age, substracting the decompacted thickness from the paleobathymetry. In order to do this, porosity-depth curves for each lithology and algorithms for compaction behaviour versus parameters such as burial depth, age and lithological composition, are needed. For an extensive discussion we refer to Perrier and Quiblier (1974), Watts and Ryan (1976), Sclater and Christie (1980), Bond and Kominz (1984) and Gallagher (1989).
3. In order to compare the age-depth relations with model-curves for the thermo-tectonic subsidence and uplift ("forward models"), corrections can be made for the effect of the loading of the sedimentary rocks on the crust ("backstripping"). The corrections commonly used are based on Airy type isostasy, but flexural (elastic) or visco-elastic (time-dependent) responses are in some cases modeled. For an extensive discussion the reader is referred to papers by Sleep (1971), Horowitz (1976), Watts and Ryan (1976), Falvey and Middleton (1980), Hardenbol et al. (1980), Sclater and Christie (1980) and Bond and Kominz (1984).

In many papers, paleobathymetry estimates are regarded as a correction which is performed in the final stage of the analysis (e.g. Ungerer et al., 1984; Angevine et al., 1990). This is only correct when water loading is not regarded in decompaction procedures and loading corrections. Otherwise, bathymetry should be incorporated in the analysis right from the beginning, as indicated above.

In literature, the terms geohistory analysis and burial history analysis are often confused. If paleobathymetry estimates are not included, diagrams should be termed burial history diagrams (Lerche, 1990). In the cases presented here subsidence rates often by far exceed accumulation rates and, therefore, paleobathymetry estimates are of fundamental importance for the reconstruction of vertical motions.

Erosional and depositional hiatuses have a number of effects on the reconstructed subsidence patterns: In the first place, burial history diagrams always suggest subsidence and never any uplifts, if erosion is not taken into account. Secondly, decompaction corrections are too small, because one of the assumptions is that compaction is an irreversible process, and the weight of the overlying column is considered too small compared to what really has been present. Thirdly, during the time-slice which is not covered by any sedimentary record, uplifts and subsidences are not reconstructed, and calculated (mean) subsidence and accumulation rates may, therefore, be smaller than those that in reality occurred (cf. Kukal, 1990; pp. 35, 28, 122). In the case of accumulation rates, this is a well-known effect for every sedimentary record as beds are always separated by small hiatuses (see references in Appendix II and Friend et al., 1989; Lerche, 1990, p. 18). As such, it would be more appropriate to speak of "preservation" or "conservation rate" in these cases (see the discussion related to the "completeness" factor C of Friend et al., 1989). A method for estimating the amount of removed sediment using vitrinite reflectance data, was presented in a paper of Armagnac et al. (1988).

Paleobathymetry estimates (which is depth relative to local sea level at that time) are plotted relative to a straight horizontal axis of present sea level. Eustatic sea level fluctuations are thus not taken into account, also because we are interested in recognizing them in the diagrams, and it is therefore not recommended to insert eustatic sea level fluctuation curves in advance (like in the analysis of e.g. Vail et al., 1992; their fig. 9). This implies that calculated subsidence curves must be regarded as reflecting "relative tectonic subsidence", which term is congruent with "relative sea level fluctuations". The latter are reconstructed in sequence stratigraphic analysis, where basement depth is regarded as fixed, or where a subsidence trend is envisaged as gradual or as following the trend of a hypothetical model.

We designed a geohistory analysis management system for microcomputers. This system comprises a relational database system for stratigraphic datasets, with tables for biostratigraphical zonations, geochronological units, lithofacies, paleobathymetry zonations, and lithological characteristics (GeohBase). The database is linked with calculation programs for decompaction and (isostatic) loading corrections, geohistory diagram preparation software, and graphical design packages. For the relational database, we used the Dbase-IV package of MicroSoft Ltd. We used the algorithms and software (the packages Depor and Bursub; V. 3.01) for decompaction and loading as published by Stam et al. (1987) and Gradstein and Fearon (1989). Our software for the preparation of the format (DiaGram) for the geohistory diagrams is linked (DXF Format) to the design package AutoCAD (V. 11.1) of Autodesk Ltd.

The geohistory diagrams which are presented contain two diagrams in one, the geohistory diagram proper and the accumulation diagram. The geohistory diagram uses the standard horizontal age-axis and vertical subsidence-depth axis. The accumulation diagram uses the same age-axis, but a different vertical axis, namely the thickness-axis along the right hand side of the figure, along which the sedimentary column is drawn. For the sedimentary column the symbol set of the standard Shell Legend (Shell, 1976) was used, which is indicated in Figure 3. The following curves are depicted in the diagrams:

(a) Paleobathymetry curves. These curves interconnect age-waterdepth datapoints, indicated with triangles.

(b) Subsidence/uplift curves. These curves interconnect age-depth datapoints for a chosen reference level, indicated by circles. In several diagrams, more than one reference level has been processed.

1. Uncorrected subsidence/uplift curves ("Total subsidence curve"). These are obtained by substracting uncorrected sediment thickness from the paleo-bathymetry (solid lines).

2. Decompacted subsidence/uplift curves. These are the same as 1., but corrected for post-depositional compaction (dashed lines).

3. Loading-corrected ("back-stripped") subsidence/uplift curves ("Thermo-tectonic curve"). These are the same as 2., but also corrected for isostatic, Airy-type loading effects (dotted lines).

(c) Burial history curves. These are the same three types of curves as listed under b., but without any information concerning bathymetry. In the diagrams, datapoints are indicated with quadrangles. They are valuable in cases when bathymetry is unknown or stable, like in datasets merely based on seismostratigraphic interpretations. They can be regarded as mirrored accumulation curves.

(d) Accumulation curves. These curves interconnect age-total sediment thickness datapoints, indicated with quadrangles. They are so-called "Bubnoff's curves" (Kukal, 1990; p. 34, cf. Von Bubnoff, 1948), or "Time-level plots" (Friend et al., 1989).

Along the curves, bars are drawn which indicate minimum, maximum and mean estimates for both

age and bathymetry, and which are interconnected by enveloping confidence interval curves. These confidence limits are indicated either along the paleobathymetry or along the subsidence curves. Closed datapoint symbols point to observed data, whereas open symbols indicate interpreted data (interpolated/extrapolated). Not all mentioned curves with confidence intervals are shown for each diagram, because the image would become blurred by too many lines. Furthermore, scales have been choosen in such a way that a maximum of information is visible. Most diagrams use the base of the sedimentary succession as reference level for the subsidence curves. In some diagrams, one or more extra reference levels have been processed.
In the diagrams, many artefacts are visible which are due to the way datapoints are plotted and interconnected. Therefore, only general trends can be regarded as being valid. In the next paragraphs, the various input parameters and correction procedures will be discussed briefly. A relative sensitivity analysis will be outlined, in order to investigate the precision of the methodology as can be obtained at present.

Age estimates

Age estimates were obtained in three different ways:
1. Assignment of biozones to numerical timescales. In general, biozonations are calibrated with magnetostratigraphic scales. The degree of resolution that can be obtained in the Neogene with biostratigraphic zonations ranges from about 0.5 to 2 Ma. Higher resolutions, up to 20 Ka, can be obtained by integrating bio- and cyclostratigraphy with magnetostratigraphy into an astronomical time scale following the methods developed and applied by Hilgen (1991b). Further information and discussion is given in Appendix IIa.
(a) Planctonic foraminifera zonations. The pelagic and hemipelagic deposits in Central Calabria have been sampled, analysed and assigned to Mediterranean biostratigraphic zonations (e.g. Cita, 1975; Spaak, 1983; Zachariasse and Spaak, 1983; Iaccarino et al., 1985).
(b) Nannofossil zonations. For a number of sections, nannofossil data are available from the literature which provide a relative age assignment from nannofossil biozonations (e.g. Driever, 1988; Rio et al., 1990).
2. Radiometrical data. A limited amount of radiometrical age data has been presented in literature for ash-layers and volcanic basalts in the area.
3. Sequence boundaries. Depositional sequences were linked to the numerical timescale by means of biostratigraphy. If the resolution of the sequences is higher than that of the biostratigraphic units, ages of sequence boundaries were assigned by interpolation. This method was applied to the Tortonian and Messinian sequences of the Calabrian fore-arc region.

Paleobathymetry estimates

An important parameter in geohistory analysis is paleobathymetry. In areas which show a relatively high subsidence rate relative to the sedimentation rate, the paleobathymetry estimates-trend tends to dominate the reconstructed subsidence curve, or, in other words, paleobathymetry mirrors subsidence. In areas where accumulation rates can keep pace with subsidence, paleo-depths tends to remain stable. In that case, and if paleodepths are small, burial history diagrams can give satisfactory results. Both of these two end-member are encountered in our study area.
We inferred the paleobathymetry estimates from the stratigraphic successions in three ways:
1. Paleontological data. The best way of obtaining bathymetry estimates is by analysis of the (micro)faunal associations. A number of approaches can be followed: (a) A quantitative method is based on the relation between the numbers of planctonic and benthic foraminifera (P/B ratio; Grimsdale and Van Morkshoven, 1955; Wright, 1977; Van Marle et al., 1987). Corrections for in-faunal benthic elements were proposed by Van der Zwaan et al. (1990). Such P/B data are available for a number of sections in the Central Mediterranean (Verhallen, 1991). The method is summarized in Appendix IIa. (b) Qualitative estimates are based on individual species or on associations of benthic foraminifera. Depth ranges can be found in the literature for a large number of foraminiferal species and associations (e.g. Brolsma, 1978; Meulenkamp and Van der Zwaan, 1990). For a number of sections, such data are available (e.g. Brolsma, 1978; Sprovieri et al., 1990; Verhallen, 1991; De Visser, 1991; p. 182, 183). Also, in some cases data were available from larger invertebrate fossils.
2. Depositional systems. In cases where paleontological data were not available, we had to rely on rough bathymetry estimates based on lithofacies. We compiled a knowledge base which contains lithofacies and depositional system codes (about 1000 lithofacies types and 450 depth

zones), similar to the approach of Enos (1991). The data have been taken from sedimentological manuals and papers. This provides default bathymetry estimates for a large variety of deposits. Examples of the main groups of depth zones used are the following: (a) The general marine zonation of Hedgpeth (1957): Inner sublittoral (0-50 m), Outer sublittoral (50-200 m), Bathyal (200-4000 m), Abyssal (4000-5000 m), Hadal (5000-8000 m), Abysso-pelagic (4000-500 m), Pelagic-Neritic (0-100 m), Epi-pelagic oceanic (0-130 m), Meso-pelagic oceanic (130-1000 m) and Bathy-pelagic oceanic (1000-4000 m), (b) The Mediterranean benthic zonation of Wright (1978) (see also : Neritic (0-200 m), Epi-bathyal (100-1300 m), Meso-bathyal (1000-4000 m), Infra-bathyal (4000-8000 m), (c) Various lithofacies zonations for specific depositional environments which can be calibrated with depth (see e.g. Hardie and Eugster, 1970; Pannekoek, 1973; Bossellini and Winterer, 1975; LoCicero and Catalano, 1976; Schreiber and Decima, 1976; Vai and Ricci Lucchi, 1977; Kendall, 1979a, 1979b; Moore et al., 1979; Walker, 1979; Homewood and Caron, 1982; Tucker, 1982; DeCelles, 1986; Reading, 1986; McPherson et al., 1987): lakes, alluvial systems, deltaic environments, clastic shores, shallow marine clastic systems, clastic slopes, deep sea clastics, shallow marine carbonates, carbonate slopes, pelagic environments and evaporites (basinal, coastal, sabkah), (d) Zonations for specific continental and marine reliefs (e.g. Pannekoek, 1973; Pipkin, 1977; Reading, 1978): e.g. continental margins, deep sea floors, marginal and inland seas.

3. Petrological data. For some successions of boreholes in the Tyrrhenian Sea, paleo-depth estimates were based upon the study of submarine basalts (Kastens et al., 1990). These estimates are based on the vesicularity of the basalts which gives an indication for the depth of submarine deposition.

The precision that can be obtained with the various methods decreases with increasing depth, and uncertainties can, in deep water environments, amount to up to several hundreds of meters. This implies that the reliability of the obtained subsidence curves strongly depends upon the reliability (and the confidence intervals) of the paleobathymetry estimates.

Decompaction procedures

If the subsidence curve is corrected for compaction of the sediments, a so-called "compaction-corrected subsidence curve" is generated. This curve will generally lie deeper than the uncorrected curve, apart from starting point (the reference-level at the time when it constituted the basin floor, i.e. the sediment-water interface) and end-point (present-day location of the reference-level). Computer programs that perform this exercize use the assumption that compaction is an irreversible, mechanical process whereby volume-loss is achieved by reduction of porosity. Therefore, the porosity-depth relation is a measure for the amount of compaction versus depth of burial of the sediment. Porosity-depth relations can directly be derived from porosity measurements along a borehole, or from sonic velocities. Computer programs usually provide a library of porosity-depth relations for various lithologies, based on literature. Some programs permit the declaration of an amount of cementation. The extreme case would be 100% cementation i.e. no compaction. As such, the compaction-corrected subsidence curve gives a maximum value, which is a lower boundary constraint. The decompaction procedures as described in literature are extensively discussed in Appendix IIb.

In our analysis, we used the algorithms and software of Stam et al. (1986) and Gradstein and Fearon (1989), which contain tables with default values. The corrections obtained in this way can be in the order of magnitude of 30-40% of the thickness of the unrestored sedimentary column (generally some tens of meters, but, in some cases, several hundreds of meters).

Loading corrections

In order to estimate the relative contribution of sediment loading to subsidence, a correction must be calculated which has to be substracted from the observed subsidence. This value is usually called "Mantle displacement" (Horowitz, 1976), and the procedure is called "backstripping" (A term introduced by Watts and Ryan, 1976; p. 28). Correcting a subsidence curve for loading will result in a curve which is "shallower" than the uncorrected one, the so-called "thermo-tectonic subsidence curve".

The most simple way of performing the calculation, is assuming Airy-type of isostasy (Airy, 1855). In many cases, however, this assumption is not valid for a number of reasons: The lithosphere will generally show a flexural rigidity (Vening Meinesz, 1930; in Vening Meinesz, 1958) and (visco-)elastic behaviour, especially in foreland areas, where subsidence is strongly influenced by the load of the thrust belt (e.g. Beaumont, 1981). Estimates for flexural loading and (visco-)elastic behaviour are rather difficult to obtain, because they heavily depend on assumptions for the local situation. Another effect is that, in cases regional stresses are present, the amount of deflection depends on the position of the site with respect to present loads (cf. Cloetingh, 1988). This situation is likely to occur along active margins like the one studied here. Nevertheless, the isostatic loading correction gives a maximum value for the amount of sediment loading-induced subsidence. Therefore, it is useful to give this value because the assumptions involved are independent of the local situation and it provides a boundary constraint.

Algorithms for loading corrections are outlined in Appendix IIc. Isostatic correction results in a curve which lies about one-third of the thickness of the restored sedimentary column higher up in the diagram. This curve shows the relative contribution of thermo-tectonic processes to the subsidence of the area.

GEOLOGICAL SETTING

The Neogene evolution of the Central Mediterranean area is characterized by the migration of the Calabrian Arc to the southeast and the opening of the Tyrrhenian back-arc Basin through rifting and spreading (Argand, 1924; Caire (1962, 1973, 1978); Boccaletti and Guazzone, 1972; Rehault et al., 1984; Wezel, 1985; Bousquet and Philip, 1986; Boccaletti et al., 1986; Kastens et al., 1988; Hill and Hayward, 1988; Van Dijk and Okkes, 1988, 1990, 1991; Patacca and Scandone, 1989). Key features in this evolution are rotations and translations of small blocks such as the Sardegna-Corsica and Calabrian block, compression related to the relatively northward displacement of the African Plate, and migrations of the Maghrebian-Apenninic thrust-belt, subduction-related troughs, and foreland bulge(s). Due to a complex interaction of various small microplates, a large variety of basin types is present.

The area can be divided into a number of domains, going from internal to external (Figs. 1 and 2). These are the Tyrrhenian back-arc Basin, the Calabrian block, the Sicilian Maghrebide and the Southern Apennines fold-and-thrust-belts, and the foreland (comprising Iblean block, Ionian Basin and Apulian block). The Calabrian block is separated from the Sicilian thrust-belt by the NW-SE trending Vergilio-Etna Fault Zone (Van Dijk and Okkes, 1991; Taormina Line of A.-Morelli et al., 1976). Along the northeastern side, the Calabrian block is separated from the Southern Apennines by the NW-SE trending "Ciro-Benevento Fault Zone" (comprising numerous branches and fault zones such as the Pollino Line and the Deep Shear Zone of Ghisetti and Vezzani, 1982; "T1" of Moussat, 1983; the Rossano-San Nicola Zone of Meulenkamp et al., 1986; the San Nicola-Campana, Strongoli-Cropalati, and Ciro-Terranova Zone of Van Dijk and Okkes, 1991). The external limit of the Sicilian thrust-belt is chosen along the Gela overthrust. The internal limit of the Calabrian block is chosen along the Eolian volcanic ring. The external limit of the Calabrian block follows the external limit of the Calabrian Accretionary Wedge.

A. Back-arc basins

The Tyrrhenian back-arc Basin can roughly be subdivided into three domains (Kastens et al., 1988): (1) The Sardinia margin or Cornaglia Terrace, which is characterized by a number of N-S trending (half-)grabens, originating from a Late Miocene phase of rifting. (2) The Central and Southern Tyrrhenian oceanic basins, which were formed during the Late Miocene to Pleistocene by oceanic spreading related to the drifting of the Calabrian block to the southeast. The northwestern "rifted" and southeastern "oceanized" areas are separated by the NE-SW trending Central Tyrrhenian Fault (Selli and Fabbri, 1971). They are characterized by high heatflow, and a very thin crust. The Tyrrhenian subbasins are from northwest to southeast: The Magnaghi Basin, the Vavilov Basin, and the Marsili Basin. The latter two are separated by the Issel Ridge, which shows a thicker crust. (3) The southern Tyrrhenian area adjacent to the Calabrian Arc. This area shows a concentric ring of calc-alkaline, Late Pleistocene - Recent volcanous, the Eolian Ring (e.g. the emerged islands of Stromboli, Volcano and Lipari). Still closer to the Calabrian Arc, a concentric ring of intra-arc summit basins is present, which will be described below.

B. Calabrian basins

1. Intra-arc basins and summit basins

Two quasi-concentric rings of basins are present along the internal side of the Calabria block:

(a) Summit Basins (cf Geist et al., 1988). Within the Tyrrhenian basin, adjacent to the margin of Calabria, a set of arc-paralell basins is present which are concentrically grouped around the Eolian volcanic ring, which, in turn, encircles the central Marsili Basin. These basins are, from west

to east: The Cefalu Basin along the northern margin of Sicily (Gruppo Bacini Sedimentari, 1980), the Gioia Basin (Fabbri et al., 1980) and the Paola Basin (Wezel, 1985, Argnani and Trincardi, 1990) along the internal side of Calabria, and the Policastro Basin along the southern Apennines. These basins are well known from seismic surveys. Internally verging (back-)thrusts below the summit basins have been hypothesized by Van Dijk and Okkes (1988, 1990) and by Argnani and Trincardi (1990). Argnani and Trincardi (1990) showed that the Paola Basin was subject to a middle Pleistocene phase of inversion.
(b) Intra-arc basins. Within Calabria, a number of arc-paralell tensional grabens border the Tyrrhenian margin. The main basins are the Crati Graben and the Mesima Graben. Van Dijk and Okkes (1990) hypothesized that these basins may have transtensional margins. In the Southern Apennines, a number of NW-SE trending grabens along the Tyrrhenian internal margin seem to belong to this group of basins (Pollino graben, Tanagro graben). Roure et al. (1988, 1991) and Van Dijk and Okkes (1988, 1990, 1991) hypothesized that the intra-arc basins are bounded by listric tensional faults dipping towards the internal side, the Tyrrhenian Sea.

2. Fore-arc basins

The fore-arc basins are situated upon the internal slope of the Calabrian Accretionary Complex, and can be subdivided into strike-slip, pull-apart, piggy-back, "detached-slab", and "harmonica" basins (Van Dijk, submitted). These are all special types of thrust-belt basins. The on-shore Calabrian basins show a pulsating development from middle Oligocene to Recent, with basin inversions in late Burdigalian, mid-Pliocene and mid-Pleistocene times.
Pull-apart basins (Moussat, 1983; Boccaletti et al., 1984; Van Dijk and Okkes, 1988, 1990, 1991) are present within NW-SE trending segments. Along the boundaries of the segments, within NW-SE trending shear zones, small strike-slip basins are present (Meulenkamp et al., 1986; Van Dijk and Okkes, 1990, 1991). Along the external margin of the arc, the thrust-belt basins can be regarded as piggy-back basins and "harmonica basins" upon the accretionary thrust-wedge (Van Dijk and Okkes, 1988, 1990; Van Dijk, submitted). The Crotone-Spartivento Basin, along the external margin of Calabria, is a typical fore-arc basin. Van Dijk (1990, 1991 and submitted) speculated that the present-day on-shore part of the basin is situated upon a shallow slab, facing the subduction through and detached at a depth of about 2 km ("detached slab basin").

C. Fold-and-thrust-belt basins

The basins within the Sicilian and Southern Apennines fold-and-thrust belt can be regarded as complex piggy-back basins (Giunta, 1985; Roure et al., 1990, 1991). They show an evolution with frequent phases of overthrusting and decollement, during late Early Miocene (18-15 Ma), late Middle - early Late Miocene (10-9 Ma), intra-Messinian (6-5 Ma), mid-Pliocene (4-3 Ma) and mid-Pleistocene (1.5-0.5 Ma) diastrophic phases (Lentini et al., 1987; Patacca and Scandone, 1989). Lentini et al. (1987) and Broquet et al. (1981a) distinghuished a number of sedimentary sequences separated by unconformities, which coincide with the above-mentioned diastrophic phases.

D. Foreland areas

The foreland area of the Calabrian Arc is very heterogeneous, and can be subdivided in a number of small blocks or "microplates" (We refer to the subdivision into microplates although the term refers to an older more rigid plate tectonic concept, which should be abandoned). It comprises the Apulian Platform, which is part of the Adria or Apulia Microplate (Lort, 1971; Dewey et al., 1973; Udias, 1974; Moretti and Royden, 1988). This block is delimited by the Apulian Escarpment, a NW-SE trending fault zone (Charrier et al., 1987). The Calabrian block faces the Ionian Basin, the origin of which is not clear: Many authors postulated a Mesozoic rifting and spreading episode with the formation of a Neotethyan oceanic area ("Mesogea Stage"; see e.g. Biju-Duval et al., 1977; Dercourt et al., 1985; Abbate et al., 1986). Others stated that rifting in the area did not take place until Neogene times (Fabbri et al., 1982; Casero et al., 1984; Mantovani et al., 1990), witnessed by a "Late" phase of foundering. The Ionian Basin is often regarded as a separate "microplate", the Ionian Plate (Dewey et al., 1973) The southern part of the Central Mediterranean is formed by a promontory of the African Plate, the "Ragusa Platform, Ragusa-Malta Plateau, Hyblean Plateau or Iblean Block (e.g. Cogan et al., 1989; Pedley and Grasso, 1991) which may, however, be regarded as part of a separate, continental, "micro-plate", the Messina Plate (Dewey et al., 1973; Jongsma et al., 1985) or Iblean Microplate (Jongsma et al., 1987). The Iblean block is separated from the African Plate by the NW-SE trending Sicily Strait or "Medina wrench", which shows a Pliocene phase of dextral transtensional rifting (Illies, 1969, 1981; Finetti, 1984; Jongsma et al., 1985, 1987; Boccaletti et al., 1987; Cello, 1987; Argnani, 1990). The Iblean block is separated from the Ionian Basin by the NNW-SSE trending Malta Escarpment (Casero et al., 1984; Charrier et al., 1988), which is the southwestern counterpart of the Apulian Escarpment.

GEOHISTORY DIAGRAMS

We used stratigraphic successions from the Calabrian and Sicilian mainland and from the surrounding Tyrrhenian, Pelagian, and Ionian Basins (see Figs. 1 and 2 for locations). These successions comprise field sections, composite stratigraphic columns, boreholes and successions inferred from seismic stratigraphy. The dataset is very heterogeneous, both in a spatial and in a temporal sense and it is based on different sources. The diagrams based on composite columns must be seen as representing the composite subsidence history of an area, showing maximum total thicknesses present. Some datasets are based on the results of analysis of sampled field sections (Central Calabrian data; Van Dijk, 1990, 1991 and in press.). The data concerning the Crotone and Monte Singa sections are based on the analyses of sample material partly published by Verhallen (1990), Hilgen (1991b) and Lourens et al. (1992). Other datasets are extracted from the literature: These comprise ODP Leg 107 boreholes (Kastens et al., 1987, 1990) and also stratigraphic sequences from on-shore geology or seismostratigraphy (e.g. Ogniben, 1973; Caire, 1973, 1978; A.-Morelli et al., 1976; Broquet et al., 1981, Giunta, 1985; Meulenkamp et al., 1986, Rehault et al., 1986, Catalano and D'Argenio, 1990). If only seismic sections are known, the diagrams processed automatically result in burial history diagrams. Nevertheless, in most of these cases, we arbitrarily estimated a general bathymetry trend to investigate a first approximation of the geohistory of the area.

In the following sections, the resulting diagrams (Figs. 4-7) will briefly be discussed. Subsidence and accumulation rates will be expressed in cm/Ka, in order to get an impression of the relative rates for the various areas. These rates are a mean value, as they are averaged for longer episodes. The used timetable with ages for stage and epoch boundaries can be found in Figure 3. For the Messinian interval, an extra curve is drawn in the diagrams (as a dashed line), which reflects the average subsidence filtered for intra-Messinian tectonics and eustatic sea level fluctuations (by simply connecting pre- and post-Messinian levels). It must be noted that a number of artefacts are present in the diagrams, due to the fact that datapoints are plotted in the centre of a confidence interval for age and paleobathymetry zones. This procedure leads to seemingly instantaneous subsidences or uplifts whereas the rates might have been more gradual. However, in many cases, vertical transitions from one facies type into another as observed in the field indeed are fairly abrupt, and do not show indications for large gaps in the sedimentary record. This implies that the rates as inferred from the diagrams may be considered fairly realistic.

A. The Tyrrhenian back-arc Basin (Fig. 4)

In the Tyrrhenian area a number of boreholes were drilled during three Legs of the DSDP and the ODP Programs. These are Leg 13, Site 132 (Sardinia margin), and Leg 42, Site 373 (Vavilov Basin). The results were published in the DSDP Volumes 13 (Ryan, Hsü, et al., 1973) and 42 (Hsü et al., 1978). The data we processed from the Tyrrhenian area (Okkes, 1988; Van Dijk, in press.) are based on ODP Leg 107, which data are published in two ODP Volumes (Kastens et al., 1987, 1990). Age determinations are based on biostratigraphy and magnetostratigraphy, and on a few radiometrical age estimates of basalt deposits. Paleobathymetry estimates are based on inferences from the associations of benthic foraminifera by Sprovieri et al. (1990). Depth estimates for the basalt deposits are extensively discussed in various papers in Kastens et al. (1990).

We processed four boreholes which are located from northeast to southwest: the Sardinia Margin (654), the Magnaghi Basin (652), the Vavilov Basin (651) and the Marsili Basin (650). Tisseau et al. (1989) and Rehault et al. (1990) also showed results of geohistory analysis of the Tyrrhenian Basin. They processed the Sardegna Plateau and the Mangaghi Basin, but could not include the bathymetry constraints of Sprovieri (op. cit.). Their results show simple decelerating "Sclater"-curves (shown in the diagrams of Figs. 4a and 4b), which are not in accordance with the results presented here. In the diagrams, extra curves were drawn for the oceanic spreading interval, showing maximum syn-spreading subsidence rates (see further for an extensive discussion).

The Sardinia Margin; ODP Leg 107; Site 654/DSDP Leg 13; Site 132 (Fig. 4a)

The geohistory diagram of this borehole shows an initial phase related to late Tortonian rifting with rapid subsidence of 86.6 cm/Ka, decelerating to 4.3 cm/Ka. The Messinian salinity crisis is evidenced by a positive peak in the diagram. If this peak is filtered, fluctuations in subsidence, however, remain. After an Early Pliocene stability, the middle Pliocene phase shows an acceleration of subsidence (123.6 cm/Ka), which decelerates in the Late Pliocene-Pleistocene (8.8 cm/Ka). Accumulation rates show a weak trend towards lower values during the Late Miocene-Pliocene interval (maximum of 30.9 cm/Ka; minimum of 3.2 cm/Ka; mean of 6.9 cm/Ka).

The Magnaghi Basin; ODP Leg 107; Site 652 (Fig. 4b)

The diagram for the Magnaghi Basin shows that basaltic crust was covered by evaporitic clays in the Messinian. This was accompanied by an accelerating subsidence, (107.2 cm/Ka), which decelerated in the Early Pliocene (1.7 cm/Ka). From the middle Pliocene onwards, a second phase of accelerated subsidence (64.0 cm/Ka) started, which lasted until Recent (186.6 cm/Ka). The data suggest that drifting and oceanic spreading must have taken place before and during the Messinian. The accumulation curve shows very high rates in the Messinian (63.1 cm/Ka), and low rates in the Plio-Pleistocene interval (3.6 cm/Ka).

The Vavilov Basin; ODP Leg 107; Site 651 (Fig. 4c)

The diagram shows that basaltic flows were intercalated in the sedimentary deposits until about 2.0 Ma (subsidence rate of 13.4 cm/Ka). This was followed by a quasi instantaneous "collapse" accompanied by the coverage of the youngest basalt flows by pelagic deposits. It must be noted that the magnitude of this "collapse" is merely the result of the way bathymetry data concerning the basalts and the overlying deposits are plotted. A rapid phase of subsidence has, anyway, occurred during and shortly after the deposition of the last basalts. The diagram suggests a middle Pleistocene episode of uplift, followed by Late Pleistocene - Recent acceleration of subsidence (23.3 - 715.0 cm/Ka). The accumulation curve shows a staggering increase of accumulation rate (from 14.3 cm/Ka to 56.7 cm/Ka) during the Late Pliocene - Recent, with an exeption for the early middle Pleistocene (2.3 cm/Ka). Comparison with various data regarding the ages of the basalts, and with data from DSDP Site 373 shows that the accretion of basaltic crust in the Vavilov Basin probably took place until 4.0 Ma, and that the basalt flows encountered in this Site belong to a later stage of eruptions (e.g. Kastens et al., 1988; p. 1150).

The Marsili Basin; ODP Leg 107; Site 650 (Fig. 4d)

The diagram for the Marsili Basin suggests a rapid Early Pleistocene foundering (954.1 cm/Ka) when ponded turbidites covered the basaltic basement rocks. After a middle Pleistocene phase of stability, Late Pleistocene - Recent acceleration occurred (13.3 - 186.6 cm/Ka). The accumulation curve shows a staggering increase of subsidence rate from 5.8 cm/Ka to 47.0 cm/Ka (mean of 26.1 cm/Ka). The diagram suggests a Late Pliocene drifting-related spreading of the oceanic basin.

B. Calabrian Basins (Fig. 5)

The Paola summit Basin (Fig. 5a)

The stratigraphic sequence of the Paola Basin was inferred by Finetti and Del Ben (1986) and Argnani and Trincardi (1990) through seismostratigraphic analysis, after discussion of previous interpretations. We processed the geohistory diagram with a first approximation for the paleobathymetry of 1100 m ("depth as if constant"). Middle Pleistocene basin inversion phenomena linked to slumping and sliding were outlined by Argnani and Trincardi (1990). No clear changes in burial rate are appearent from the diagram during this phase. Burial rates vary between 163.5 and 25.5 cm/Ka, and show a gradual deceleration. It must be noted, however, that ages of the seismostratigraphic units were obtained by Argnani and Trincardi (1990) by averaging of the sedimentation rates (mean of 89.5 cm/Ka) over the Plio-Pleistocene, which has automatically smoothed out the burial history curve.

The Amantea Area (Fig. 5b)

The Amantea area is situated along the Tyrrhenian coast of Northern Calabria and forms part of the external margin of the Paola summit Basin. The geology has been described by Ortolani et al. (1979). The area comprises a Middle Miocene to Lower Pliocene succession of sandstones, clays, limestones, evaporites and marls. The Pleistocene tectonic uplift history has been outlined by Sylvester et al. (1987) and Sylvester and Sorriso Valvo (1990). We used the paper of Ortolani et al. (op. cit.) to infer paleobathymetry estimates from the described lithofacies types, using standard zonations.

The diagram shows a Late Miocene episode of increasing subsidence rates, from 3.5 cm/Ka to seemingly instantaneous "collapse", with a mean of 42.9 cm/Ka. This was followed by a Messinian-Early Pliocene uplift phase (80.2 cm/Ka), after which the succession was overthrusted by a granitic unit with a Miocene cover. The subsidence episode shows an average accumulation rate of 10.4 cm/Ka, while the uplift episode shows a rate fluctuating between 23.6 and 2.7 cm/Ka. At present, the area is situated about 500 m above sea level. This means that an average uplift of 5.0 cm/Ka has taken place since 4.5 Ma.

The Capo Milazzo (Fig. 5c)

Capo Milazzo is a peninsula of the Peloritani area in northeastern Sicily. It is situated along the Tyrrhenian margin of the Calabrian block, and shows a very heterogeneous Upper Miocene - Recent succession (Lipparini et al., 1955; Fois, 1990). The geohistory diagram is based on data from Fois (1990), who accurately described the sedimentary-tectonic history of the area. She also gave a fairly detailed description of biofacies and depth of depositional environments (using algae, corals, bryozoa, etc.).

The diagram shows two main subsidence episodes: a Late Miocene, and a Late Pliocene-Pleistocene episode. The first shows subsidence rates varying from 0 to 94.1 cm/Ka with a mean of 15.1 cm/Ka. Accumulation rate shows a mean of 3.2 cm/Ka during this episode. The second subsidence episode shows a mean rate of 34.6 cm/Ka and accumulation rates of about 1.4 cm/Ka. These two episodes are confined by a mid-Pliocene uplift phase (mean rates up to 572.7 cm/Ka), and the Late Pleistocene uplift phase (rates up to 54.9 cm/Ka; accumulation rates of 0.9 cm/Ka).

The Crotone Basin (Fig. 5d)

The Crotone Basin is situated along the external margin of the Calabrian Arc, in the Northern Calabrian area. The tectonostratigraphy of the basin has been extensively discussed by Ogniben (1955), Roda (1964) and Van Dijk (1990, 1991). The basin shows a nearly continuous upper Serravallian to middle Pleistocene succession. For a discussion of used facies models we refer to these publications (see also Steininger et al., 1985; area 23). The composite column for the basin (with maximum thicknesses for the successions; after Van Dijk, 1990) has been processed (valid for the area called "Marchesato"), using default values for paleobathymetry of various depositional systems as recognized from the lithofacies. The paleobathymetry shows moderate variations which are small compared to the amount of subsidence. The area must be regarded as relatively basin inward with respect to Figures 5e-g, and relatively marginal with respect to Figure 5h.

The diagram shows a pulsating subsidence, gradually accelerating from Middle Miocene till middle Pleistocene times. This was followed by rapid uplift. The overall image of accelerating subsidence resulting in a convex upward subsidence curve is typical for foreland basins (Beaumont, 1980, Allen et al., 1986; Angevine et al., 1990). The Crotone Basin may therefore be regarded as a classical example of this kind of development. The subsidence is frequently interrupted by brief pulses of relative uplift, immediately followed by relative subsidence.

The basin evolution can be subdivided into four episodes: 1) Langhian - middle Messinian, with accelerating subsidence and accumulation (subsidence rates 3.5 - 43.3 - 285.8 cm/Ka; mean of 13.9 cm/Ka; accumulation rates 1.1 - 25.9 - 429.6 cm/Ka; mean of 15.5 cm/Ka), 2) middle Messinian - middle Pliocene with rapid subsidence (rates of 30.9 cm/Ka; accumulation rates 32.2 cm/Ka), 3) middle Pliocene - Early Pleistocene with rapid subsidence and accumulation (subsidence 61.8 cm/Ka; accumulation 56.0 cm/Ka), and 4) Early Pleistocene - Recent rapid uplift (rates of 35.7 cm/Ka; mean accumulation rate 1.3 cm/Ka). Episodes 1 and 2, and episodes 3 and 4 are separated by short phases with dramatic increase in subsidence, in middle Tortonian and middle Messinian times, respectively. The middle Pliocene phase of basin inversion, as evidenced by field geology (Roda, 1964; Meulenkamp et al., 1986; Van Dijk, 1990, 1991) had only moderate effects in this basin inward setting, as shown in the diagram by a short uplift pulse.

The Belcastro-Cropani basin margin Area (Fig. 5e)

The Belcastro-Cropani Area was defined by Van Dijk (1990); it is situated along the southwestern margin of the Crotone Basin (at the transition to the NE-SW trending margin of the Calabrian Sila

Massif). It shows an incomplete succession of Upper Miocene-Pleistocene sediments. The data which are used for the diagram are based on lithofacies descriptions by Van Dijk (1990 and submitted).
The diagram shows an initial subsidence phase (subsidence rates of 25.6 cm/Ka, accumulation rates 17.3 cm/Ka), followed by uplift and erosion. The Messinian and the Early Pliocene intervals show decelerating subsidence from 228.6 cm/Ka to 9.3 cm/Ka with an average of 45.0 cm/Ka. Accumulation rates show a mean of 9.3 cm/Ka. This subsidence phase coincides with monoclinal flexure along the basin margin, towards the east and towards the southeast. This was followed by a late Early Pliocene uplift, which resulted in decollement of the Lower Pliocene sediments and sliding of the successions to the southeast, downslope into the Ionian Basin. The diagram shows a rapid Pleistocene uplift of 54.9 cm/Ka, accompanied by an average accumulation rate of 6.5 cm/Ka.

The Petilia-Mesoraca fault zone Area (Fig. 5f)

The geology of the Petilia-Mesoraca area has been described by Van Dijk (1990 and submitted). The area is part of the complex, faulted southeastern margin of the Crotone Basin. The stratigraphy comprises upper Serravallian to Lower Pliocene deposits. Many unconformities are present, which reflect frequent emergence and submergence of the area. For detailed descriptions of stratigraphy and references to facies models, we refer to Van Dijk (1990).
The diagram for the area shows a pulsating development with very high uplift and subsidence rates. This pattern can be viewed in the light of the setting of the area within the sinistral Petilia-Sosti Shear Zone (Van Dijk, submitted). The rapid vertical motions of small fault-bounded blocks are probably related to the lateral displacements along the shear zone. The Middle - Late Miocene shows a linear subsidence with a rate of 5.5 cm/Ka, and accumulation rates of about 3.6 cm/Ka. The Messinian shows acceleration of subsidence to 21.4 cm/Ka and also acceleration of accumulation to 40.7 cm/Ka. The late Early Pliocene shows a seemingly instantaneous uplift of about 200 m. This phase is related to the late Early Pliocene basin inversion phase in the evolution of the Crotone basin. The Late Pliocene shows subsidence with a mean of 23.6 cm/Ka and accumulation rates of about 2.1 - 5.0 cm/Ka. The latest Pliocene - Pleistocene uplift with an average rate of 40.1 cm/Ka (maximum rate of 81.4 cm/Ka) is associated with an average accumulation rate of 2.7 cm/Ka.

The Lucrezia-Magliacane thrust-belt Area (Fig. 5g)

This area has been defined by Van Dijk (1990) and comprises a number of thrust wedges facing the southeastern margin of the Crotone basin, within the Petilia-Rizzuto fault Zone. The thrust belt displays a Messinian-Lower Pliocene succession of evaporites and shallow marine clays and sandstones. The diagram has been constructed using facies descriptions by Van Dijk (1990 and submitted).
The diagram shows an average Messinian subsidence rate of 32.0 cm/Ka, accompanied by an accumulation rate of 20.6 cm/Ka. The Early Pliocene displays pulsating subsidence and uplift with rates of about 60 cm/Ka (uplift and subsidence), accompanied by an accumulation rate of 22.7 cm/Ka. This was followed by a late Early Pliocene rapid uplift, reflecting a phase of basin inversion by thrusting towards the margins (in this area towards the west). The diagram shows a Pleistocene uplift rate of 37.6 cm/Ka with a mean accumulation rate of 2.8 cm/Ka.

The Crotone Peninsula (Fig. 5h)

For references to descriptions of the geology of the Crotone Peninsula we refer to Selli (1975) Cosentino et al. (1989) and Van Dijk (1990). The peninsula can be regarded as the external area of the Crotone Basin, and shows a succession of Upper Pliocene to Lower Pleistocene clays, covered by Upper Pleistocene sandstones presently forming a coastal terrace. Near Crotone, a number of sections are situated, one of which, the Vrica Section, was proposed as Calabrian Stratotype by Selli (1961) and as a Plio-Pleistocene boundary stratotype at the Seventh INQUA Congress in 1965. For this reason, it has been studied in detail and paleobathymetry estimates are available (Verhallen, 1990), based on the methods described by Van der Zwaan et al. (1990), and corrected with depth estimates for specific benthic foraminifera species. The succession, correlations and age-constraints used are based on the descriptions and calibrations to the astronomical timescale of Hilgen (1990), Zijderveld et al. (1991) and Lourens et al. (1992). The information regarding the terrace deposits is based on Cosentino et al. (1989).
Three episodes can be distinghuished from the subsidence and accumulation patterns: The first

episode was characterized by rapid subsidence (82.0 cm/Ka) and rapid accumulation (37.3 cm/Ka). This was followed by an episode of relatively stable conditions, whereby accumulation (24.8 cm/Ka) exceeded subsidence which resulted in a shallowing trend. The third, middle-Late Pleistocene - Recent episode shows a rapid, average uplift with a rate of 51.2 cm/Ka, accompanied by a mean accumulation rate of 21.5 cm/Ka (including the terrace deposits). The accumulation as a whole shows a general decelerating trend. It must be born in mind that the "initial" episode of rapid subsidence is mainly determined by the inference of shallower depositional environments at the base of the Semaforo Section. During this episode, a general onlap occurred along the margins of the Crotone Basin.

The Stilo Block (Fig. 5i)

The Stilo Block is situated as the present-day apex of the Calabrian Arc. The geology has been described by Bonardi et al. (1971), Caire (e.g. 1973), Steininger et al. (1985; area 24), Meulenkamp et al. (1986). Within the area, the Monte Singa Section is situated, which has been studied extensively because of its relatively complete Pliocene-Pleistocene succession of hemipelagic "Trubi" marls followed by "Narbone-type" of clays with sapropel intercalations.

The diagram of Figure 5i1 shows a composite section of the Stilo Block, mainly based on Meulenkamp et al. (1986; based on fieldwork in the area by D. Den Hartog, 1983; E.J. Wijffelman, 1985) (appended with data from R. Huis in 't Veld, 1987). The significance of the upper Burdigalian silexite layer indicated in the succession has been discussed by Wezel (1975) and Lorenz (1984) in a Western Mediterranean context. The authors related this deposit to widespread volcanic activity during this episode. The diagram of Figure 5i2 shows the detailed Pliocene-Pleistocene evolution of the area, based on data from the sections near Monte Singa, as described by Zijderveld et al. (1986; magnetostratigraphy Lower Singa), Zijderveld et al. (1991; magnetostratigraphy Upper Singa), De Ridder (1986; paleobathymetry), Verhallen (1991; paleobathymetry), and Lourens et al. (1992; age).

The composite diagram, Fig. 5i1, shows a staggering subsidence from Middle Oligocene till Recent. Four episodes can be distinghuished: The Late Oligocene subsidence episode (subsidence rate 8.9 cm/Ka; accumulation rate 2.5 cm/Ka), The Early Miocene stable episode (subsidence rate 4.8 cm/Ka; accumulation rate 7.5 cm/Ka), the middle Miocene subsidence episode (subsidence rate 10.0 cm/Ka; accumulation rate 19.6 cm/Ka) and the Pliocene subsidence episode (subsidence rate 8.5 cm/Ka; accumulation rate 6.5 cm/Ka). A number of relatively brief pulses can be distinghuished, which show negative and positive deviations (so-called "Positive pulses" and "Negative Pulses"). These are around 25-23 Ma (subsidence and accumulation both about 29.0 cm/Ka) and around 16-14 Ma (rapid subsidence followed by uplift; both of about 250 m.). Because their magnitude far exceeds the magnitude eustatic sea level fluctuations can cope with (about 100 m.), these pulses can be interpreted as tectonic events. This interpretation is in concordance with field evidence, which also points to tectonic activity during these time intervals (Meulenkamp et al., 1986). The Messinian shows subsidence rates of up to 158.6 cm/Ka and accumulation rates of around 12.8 cm/Ka. The recent uplift rates are around 195.7 cm/Ka with accumulation rates of 6.9 cm/Ka.

The diagram for the Monte Singa sections, Fig. 5i2, shows the detailed Early Pliocene-Pleistocene development. The Early Pliocene was characterized by gradual uplift (12.5 cm/Ka; accumulation rate of 6.9 cm/Ka), followed by a middle Pliocene subsidence. The Late Pliocene shows a gradual subsidence of 6.1 cm/Ka, accompanied by accumulation rates of 8.1 cm/Ka. Pleistocene uplift rates amount to 107.2 cm/Ka with accumulation rates of 20.0 cm/Ka. It must be noted that the high P/B ratios in the Lower Pliocene deposits may be misleading: Nearby, shallow marine sandstones are intercalated in the Trubi marls (Hilgen, pers. comm.), which may indicate that the Early Pliocene flooding occurred over a shallow area, and was accompanied and followed by rapid subsidence. The hiatus present may be due to a mid-Pliocene submarine sliding of parts of the succession to the southeast (J.E. Meulenkamp and F.J. Hilgen, pers. comm.), which may be related to a phase of tilting-related uplift (Meulenkamp et al., 1986).

C. The Sicilian part of the Maghrebide fold-and-thrust Belt (Fig. 6)

The Caltanissetta Basin (Fig. 6a)

The composite column for the northern marginal area of the Caltanissetta Basin was compiled after the data of Marchetti (1956), Ogniben (1957), Flores (1959), Broquet et al. (1981a, 1981b), Meulenkamp et al. (1981), Guerrera et al. (1984), Steininger et al. (1985; area 25), Sestini and Flores (1986), Lentini et al. (1987), Decima et al. (1988), Courme and Mascle (1988a) and Grasso et al. (1990). Bathymetry estimates are based on considerations of these authors and by calibrations to standard lithofacies zonations.

The diagram shows the Neogene development of the basin which started as a rapidly subsiding area in Aquitanian times (33.2 cm/Ka; accumulation rate 9.6 cm/Ka). In Late Burdigalian times, an accelerating subsidence was coupled with overthrusting of the Maghrebian thrust belt (subsidence rate 117.6 cm/Ka). The accretion of the thrust slices is indicated in the diagram as "tectonic accumulation". The episode from 16 to 6 Ma was characterized by continuous subsidence (12.7 cm/Ka; accumulation rate 3.1 cm/Ka). When relative sea level effects are filtered for the Messinian, it is shown that a switch from subsidence to uplift occurred between 6.0 and 4.0 Ma. Late Early Pliocene folding (uplift) was followed by mid-Pliocene onlap (subsidence) which is not indicated in the diagram, as the basinal part of the succession was stacked for the Pliocene. The Late Pliocene-Pleistocene episode is characterized by rapid uplift (28.8 cm/Ka). Accumulation rates are fairly constant (around 4.9 cm/Ka), except for the Messinian, which shows a rate of 68.7 cm/Ka.

The Agrigento Area (Fig. 6b)

The data concerning the Agrigento Area are based on descriptions of Ogniben (1954; "Zona di Passarello", 1957), Magné et al. (1972), Brolsma (1978), Sprovieri (1978), Ruggieri (1985), De Visser (1991) and Hilgen (1991a). In this area, a number of sections is situated which provide a detailed image of the Upper Miocene-Pliocene-Pleistocene development of the area. The Pliocene is well represented in the Capo Bianco, Eraclea Minoa, Capo Rosello, Punta di Maiata, Punta Grande, Lido Rosello and Punta Piccola sections. The Capo Rosello Section has been assigned as the Miocene - Pliocene boundary stratotype (Cita and Gartner, 1973; Cita, 1975). The successions consist of the hemipelagic Trubi marls, followed upwards by the terrigenous clays of the Narbone Formation, and unconformably overlain by the sandstones of the Agrigento Formation. This Pliocene succession overlies the late Messinian continental Arenazzolo clay Formation. Paleobathymetry estimates for the Pliocene are based upon P/B ratios and benthic foraminifera associations. Bathymetry estimates for the Miocene are based on standard facies zonations and general suggestions from the referred literature.

The diagram shows a Late Miocene subsidence episode, with decelerating subsidence (65.1 - 2.6 cm/Ka, with a mean of 15.6 cm/Ka), and an accumulation rate of 33.7 cm/Ka. The Messinian phase shows rapid uplift (93.0 cm/Ka) and rapid accumulation (137.4 cm/Ka). The Pliocene subsidence episode was characterized by a mean subsidence of 29.8 cm/Ka and an accumulation rate of 50 cm/Ka. Pleistocene uplift rates up to 108.3 cm/Ka (mean of 33.2 cm/Ka) were accompanied by an average accumulation rate of 4.4 cm/Ka.

It must be noted that the Pliocene subsidence and rapid Messinian uplift was merely introduced in the diagram by the inference of rather shallow paleodepth estimates for the lowermost Pliocene Trubi deposits (cf. Ogniben, 1954; p. 69; Brolsma, 1978). In case one choses to interpret the Trubi deposits as formed at a considerable depth (as implied by the high P/B ratios) the average Messinian uplift rate becomes considerably less, and continues into the Pliocene.

The Gela Basin (Fig. 6c)

The column for the Gela basin was compiled after Ogniben (1957), Beneo (1957), Rocco (1959a, b). The Gela Basin has been extensively treatened by Sestini and Flores (1986), Lentini et al. (1987) and Novelli et al. (1988). Seismic sections in the Sicilian foretrough region have been described by Argnani (1987). The Gela column comprises the well-known Pleistocene "Gela Nappe" (Beneo, 1957; Ogniben, 1960), whereby Miocene overthrusts Pleistocene terrains, along a major decollement which comprises the Argille Scagliose tectonic melange. Age and bathymetry data are based on data from field sections near San Nicola, Giammoia and Falconara (Romeo, 1969; Colalongo et al., 1979; Van der Zwaan, 1982, 1983; Zachariasse and Spaak, 1983; De Visser, 1991).

The diagram for the upper block is shown in Fig. 6c1. The Middle Miocene is characterized by gradual subsidence (2.6 cm/Ka), accelerating in the Messinian (35.7 cm/Ka), and gradually changing to uplift in the Early Pliocene. The middle-Late Pliocene - Pleistocene episode is characterized by rapid uplift (25.9 cm/Ka). The accumulation rates show a gradual acceleration (from 2.6 cm/Ka to 10.0 cm/Ka), with the exception of a rapid Messinian accumulation (37.3 cm/Ka). The diagram for the footwall (Fig. 6c2) shows a rapid, accelerating Late Pliocene - Pleistocene subsidence (26.8 cm/Ka), accompanied by rapid accumulation (38.5 cm/Ka). The two diagrams together show an image of a gradual overthrusting of the two thrust units, which may have started as early as 4.0 Ma.

D. The foreland area (Fig. 7)

The Iblean Block (Fig. 7a)

The composite column for the Iblean Block ("Ragusa Platform") was compiled after data from Kafka and Kirkbridge (1959), Grasso and Lentini (1982), Steininger et al. (1985; area 26), Schramm and Livraga (1986), Courme and Mascle (1988b), Cogan et al. (1989), Pedley and Grasso (1991) and Wildenborg (1991).
The diagram shows a stable Early Miocene episode (accumulation rate 1.0 cm/Ka), followed by rapid subsidence (65.1 cm/Ka; accumulation rate 2.4 cm/Ka). The Middle Miocene was characterized by a gradual change from subsidence (9.6 cm/Ka) to uplift (5.3 cm/Ka), with an average accumulation rate of 2.4 cm/Ka. This was followed by a second phase of rapid subsidence during the Messinian (35.7 cm/Ka) showing high accumulation rates (15.4 cm/Ka). The Pliocene to Recent episode shows gradual uplift (16.8 cm/Ka) and an average accumulation rate of 3.1 cm/Ka.

The Maltese Islands (Fig. 7b)

The column for Malta was compiled after data from Felix (1973), Theodoridis (1984), Drooger (1985), Pedley and Bennet (1985), Pedley and Grasso (1985), Steiniger et al. (1985; area 136) and De Visser (1990). Paleobathymetry estimates were given by some of these authors, based on associations of benthic foraminifera, P/B ratios and lithofacies. The classical lithostratigraphical subdivision of Malta ("Lower Coralline limestone", "Globigerina limestone", "Blue clay", "Greensand", "Upper Corallina Limestone") is indicated in the diagram.
The diagram shows a Late Oligocene - Middle Miocene episode with gradually accelerating subsidence (1.0 - 5.8 cm/Ka, average of 2.0 cm/Ka) and a mean accumulation rate of 1.2 cm/Ka. The subsidence was interrupted by brief positive pulses with rapid relative uplifts of up to 100 m. Drooger (1985) and Pedley and Bennet (1985) showed that these pulses are coupled with tectonic activity, which interrupted pelagic sedimentation and during which phosphorite pebble beds and hiatuses were generated. The Middle Miocene episode was characterized by rapid accumulation of clastic blue clays, coupled with rapid subsidence. The Late Miocene subsidence episode shows a mean subsidence rate of 1.7 cm/Ka and an accumulation rate of 1.7 cm/Ka. These two subsidence episodes were separated by a rapid mid-Miocene uplift of about 175 m. If uplift started immediately after the deposition of the Upper Coralline Limestone the mean Late Tortonian - Recent uplift would be 6.0 cm/Ka.

The Ionian Basin (Fig. 7d)

The column for the Ionian bathyal plain was processed using the seismostratigraphic interpretation of Finetti and Del Ben (1986). The burial history diagram is appended with a first approximation for bathymetry using standard zonations. Some data are available for the Pliocene through DSDP Leg 13, site 125 (Cobblestone area of the Mediterranean Ridge; Ryan, Hsü et al., 1973), and DSDP Leg 42, site 374 (Hsü et al., 1978; compiled by Steininger et al., 1985; area 139).
The diagram suggests a gradual burial with a rate of 3.0 cm/Ka during Mesozoic and Paleogene times, mirroring the accumulation rate (The depth is taken as constant). This was followed by a Neogene acceleration in burial, with a mean rate of 21.7 cm/Ka. Accumulation rates for the Neogene show a mean value of 21.7 cm/Ka.

SYNTHESIS OF THE DATA

In view of the large variety in basin types within the Calabrian Arc, it can be appreciated that the subsidence patterns show a large variation from basin to basin, and, also, within the various subbasins. Furthermore, it must be noted that vertical movements of the basins probably, to a large extend, reflect the temporal variation in horizontal mobility of the region. Therefore, the subsidence histories must be viewed within the perspective of horizontal kinematics of the area, in order to understand their meaning.

Patterns and magnitudes of subsidence/uplift and accumulation

The individual diagrams show a number of specific subsidence/uplift patterns, which components can be grouped into episodes (time-slices larger than 1 Ma) and pulses (time-slices smaller then 1 Ma), given the resolution of the biostratigraphic scales used in the study (0.2 - 2 Ma). The components can be subdivided as follows:

(1) Episodes:
(a) Stable episodes: Subsidence and uplift oscillate around a specific depth value.
(b) Linear or gradual subsidence (b1) or uplift (b2) trends.
(c) Gradual acceleration or deceleration of subsidence or uplift (4 types).
(2) Pulses:
(a) "Composite pulses": Pulses or peaks superimposed on a continuing trend of the types described under heading (1). Two types exist: Positive pulses (PP), comprising sudden uplift followed by sudden collapse, or negative pulses (NP), comprising sudden collapse followed by sudden uplift.
(b) "Events": Sudden acceleration of subsidence, "downwarping", "foundering" or "collapse" (b1) or sudden acceleration of uplift or "inversion" (b2).
(c) "Composite events": Combination of a composite pulse (type a), superimposed on a collapse or inversion event (type b).

All these components are present in the patterns shown by the diagrams and may be linked to specific types of basin generating kinematic processes, and tectonic events within the migrating arc. The tectonic composite events, pulses and composite pulses interrupt longer periods of more gradual subsidence/uplift, creating an image of a spasmodic or "jerkey" evolution (cf. Bloom and Yonekura, 1985; Van Dijk, 1990, 1991; Fortuin and De Smet, 1991).

The subsidence/uplift and accumulation rates as observed in the Central Mediterranean may be compared to rates as known from other settings. Sadler (1981), Anders et al. (1987), and Kukal (1990) gave extensive reviews and compilations of subsidence rates and accumulation rates.

According to Kukal (his. fig. 24), subsidence rates along continental margins vary between 1 and 50 cm/Ka (maxima up to 500 cm/ka), while uplift rates amount to 100 cm/Ka. Recent vertical crustal motions show rates up to 500 cm/Ka (maxima of 1000 cm/Ka), while seismotectonic movements amount between 100 and 5000 cm/Ka (maxima of 8000 cm/Ka). The results of the present analysis show that subsidence rates are in the range as descibed by Kukal, but uplift rates can be much higher.

Accumulation rates as calculated for the Central Mediterranean can be compared with the overview of Kukal (op. cit., his figs. 57 and 61). He showed that an enormous variety exists between different depositional environments, and also that ancient rates (up to 300 cm/Ka) are generally lower than rates that have come forward from the study of modern environments (up to 10.000 cm/Ka). Orogenic sediments are shown to exhibit rates between 0.4 and 20 cm/Ka. If we consider the hereby studied successions as syn-orogenic, the present study shows that the latter values can be much higher, and that rates up to 200-300 cm/Ka may occur. Such rates were considered to be confined to post-orogenic Molasse-type of sediments by Kukal (op. cit.), following Spencer (1974).

Temporal patterns

The data on subsidence/uplift and accumulation rates have been compiled in Figure 8. Three specific episodes with increased tectonic activity can be recognized, which had a regional impact:

The Late Oligocene-Early Miocene episode shows positive tectonic pulses in Calabria, overthrusting and accelerating subsidence along the Sicilian fold-and-thrust belt, a downwarping of the Ragusa foreland, and positive pulses on Malta. The episode came to a close with a major phase of shortening in late Burdigalian time. This phase shows overthrusting of the Maghrebian thrust sheets to the southeast and major shortening in Calabria and the Southern Apennines. The Western Mediterranean must be regarded as the back-arc area during the Late Oligocene-Early Miocene. As no data were analysed for this area, the picture for this episode is relatively incomplete.

The Messinian-Early Pliocene episode generally shows very high accumulation rates, and many rapid uplift-subsidence composite pulses. By interconnecting pre-Messinian and post-Messinian levels, the effect of both tectonics and eustatics is filtered, and the overall tectonic effect for the Messinian remains. Acceleration of subsidence is observed in many areas. Superimposed on this tectonic evolution is the Messinian sea level fluctuation, which express itself as a positive peak in the diagrams, and intra-Messinian tectonics.

As emphasized by Kukal (1990; p. 38), "*It is common knowledge that the rate of subsidence of the Mediterranean sea floor is not just an academic problem, but that it is of great importance for the final solution of the problem of dessication of the sea at the boundary between the Miocene and Pliocene.*". It would, of course, be interesting to try to establish the magnitude of the eustatic signal as filtered from the diagram. As expected, this magnitude shows large variations from region to region, which mirrors both Messinian topography and differential intra-

Messinian subsidence rates. Maximum flooding heights amount up to one thousend metres, but these values are obtained from southern Calabrian fore-arc areas, where rapid subsidence may have been associated with the flooding. Furthermore, subsidence rates comparable with near-instantaneous flooding rates can without any problem be envisaged in this highly active area. All these considerations make it difficult to establish with any certainty the magnitude of the eustatic sea level fluctuation in the Central Mediterranean area.

End-member solutions can be investigated through a reasoning in the line of Hsü (1985). In that paper, Hsü tried to argue for a deep basin generation of the basinal evaporites, assuming subsidence rates will not have exceeded 10 cm/Ka. In that way, basinal evaporites with a thickness of about 2.5 km must have been deposited in a basin with a minimum depth of 2.4 km, whatever the water depth in the basin was (assuming a length of 0.5 Ma for the deposition of the evaporites). In the first place, Hsü's reasoning implies that the basin, in case of minumum depth, in the end was almost completely filled with evaporite which then leads to a moderate transgression and not to a Zanclean deluge. Secondly, the present study shows that the choise for subsidence rates is much wider, so that Hsü's assumptions are not valid. This leads to two end-member models for the Messinian evolution in the Calabrian fore-arc area (Fig. 9). In both end-members, pre-Messinian (Late Tortonian) and Early Pliocene basin depths are set at large values (800-1500 m). The enigmatic episode comprises early Messinian up till earliest Pliocene. Also, in both solutions, rapid intra-Messinian accumulation of the evaporites must be taken into account (-1500 m in the Crotone Basin; -750 m in Sicily; see also CNR, 1983). Scenario 1 envisages a low Messinian subsidence rate, so that rapid accumulation results in a shallow basin. A small sea level drop, of glacial magnitudes (50-100 m) is than enough to create a dessicated basin. After a Zanclean sea level rise, however, rapid earliest Pliocene subsidence is "needed" in the model to end up with a mid-Pliocene deep basin. Scenario 2 envisages Messinian acceleration of subsidence, which keeps pace with rapid Messinian accumulation. In this way, the basin floor depth does not change, and a sea level drop of over 800 m can be expected to have occurred. In that way, after the Zanclean deluge, a deep water-filled basin is present from earliest Pliocene onwards. The difference between the two scenarios is, thus, the timing of the rapid subsidence: intra-Messinian or earliest Pliocene. In fact, the consequence of interpreting the Trubi deposits as shallow water, is that scenario 2 is accepted. Anyway, because the effects of intra-Messinian tectonics have considerably blurred the image, the choise between the scenarios or the construction of a golden mean is still practically impossible.

The middle Pleistocene - Recent episode is characterized by rapid uplift in all areas, with maximum mean values up to 100 cm/Ka (individual values in parts of the diagrams exceed 250 cm/Ka). The Tyrrhenian Basin, where spreading has ceased, shows a collapse, with mean subsidence rates of up to 200-700 cm/Ka.

Spatial patterns

For the different areas, characteristic patterns are the following:

A. Back-arc area (Fig. 8c). At first sight, the subsidence curves for the Tyrrhenian back-arc Basin do not seem to fit into classical models for rifting and oceanic spreading. These models predict decelerating, so-called "Slater" curves (e.g. Parsons and Sclater, 1977) which are concave upward, related to a linear relation between square root of the age and subsidence depth of the oceanic crust (e.g. the outcome of Rehault et al., 1990). The Tyrrhenian basins are much younger (~2 - 6 Ma) than the timescales involved in the Sclater models, and, furthermore, the spreading process in the Tyrrhenian basins did not take place orthogonal to a neat rift axis, as envisaged in the classical oceanic spreading models, but rather in a concentric way around a central spreading centre. Therefore, it it not surprising that the Tyrrhenian curves do not match with the Sclater curves.

Tyrrhenian subsidence curves show convex upward overall shapes, and high average subsidence rates: Sardinia 40 cm/Ka, Magnaghi 70 cm/Ka, Vavilov 100 cm/Ka and Marsili 100 cm/Ka. Several relations may be responsible for this pattern: Firstly, Late Pliocene acceleration of subsidence as observed on the Sardinia Margin may be related to a second phase of rifting, coupled with spreading in the Vavilov Basin, more to the southeast. Bathymetry constraints for the Magnaghi Basin permit to envisage a 6-4 Ma and a 3.5-2 Ma concave upward "rifting" type of curve, which may then be coupled with spreading in the Vavilov and Marsili Basins, repectively. The same holds for the relation between post-spreading subsidence in the Vavilov Basin and the spreading in the Marsili Basin. Secondly, rapid post-spreading subsidence is also observed in all curves, after spreading has ceased in the Marsili Basin. The overall value of this "late foundering" or "collapse" seems to decrease from northeast to southwest; Minimum values amount 1875 m. in the Magnaghi Basin, 1625 m. in the Vavilov Basin and 750 m in the Marsili Basin. Thirdly, syn-spreading subsidence rates are difficult to calculate, because of poor control on the episodes of spreading. There seems to be a difference in depth of oceanic crust emplacement between the Magnaghi Basin on one hand (<500 m.), and Vavilov and the Marsili Basin on the other (<2500 m). The relations between the subsidence patterns as outlined above, suggest spreading episodes with a duration of about 1 Ma for each basin. This implies maximum syn-spreading subsidence rates for the Vavilov Basin (spreading between 5 and 4 Ma) and the Marsili Basin (spreading between 3 and 2 Ma) of 250 cm/Ka (2500 m/1Ma). It seems to be more realistic, however, to envisage a deepening trend to the southeast in initial depth of emplacement (especially if rift-phases have preceeded spreading). This implies a possible decreasing trend in syn-spreading subsidence rate when going to the southeast (especially if older spreading episodes where longer). Considering maximum syn-spreading subsidence rates calculated above (250 cm/Ka), a post-2 Ma acceleration, however, still remains. Fourthly, the bathymetry constraints suggest that rapid subsidence directly followed the last basalt flows in the Marsili Basin (around 2 Ma). This may also have been the case in the other basins, but the data do not permit to test this assumption.

The reader is also referred to the discussion by Kastens et al. (1988), Kukal (1990) and Sengör (1990) on the high overall Tyrrhenian subsidence rates. Kastens et al. (1988) discussed the Tyrrhenian opening and concluded that, compared to other back-arc areas, relatively slow horizontal opening rates (70 km in 2 Ma; 3.5 cm/yr) are accompanied by relatively high mean subsidence rates (70 cm/Ka). The real opening rate may, however, be much higher if during downwarping phases the spreading has ceased, which seems to have been the case. For example, the reconstruction of Van Dijk (submitted) shows a shortening for the Marsili Basin of about 60 km, which may have taken place between 3 and 2 Ma ago. This results in an opening rate of 6 cm/Ka, which is more compatible with rates observed in other back-arc basins. Kukal (1990; p. 38) concluded that subsidence rates in the Tyrrhenian basin must have exceeded 100 cm/Ka. Sengör (1990; pp. 70-71) came to the conclusion that the mean subsidence rate must have been about 200 cm/Ka. He assumed, however, that rifting and spreading started 2 Ma ago at a depth of 0 m, thus over-emphasizing the mean subsidence rates, which somewhat accentuates the discussion. Kastens et al. and Sengör mentioned the works of Hayes (1983, 1984) and Kobayashi (1984) who showed that eastern Pacific marginal back-arc basins also show initial subsidence rates (up to 188 cm/Ka) which are larger than those observed in open-ocean sea oceanic crust (25 cm/Ka). Individual subsidence rates observed in the Tyrrhenian Basin, however, exceed even these high values. Royden and Sclater (1981) showed subsidence curves of Carpathian back-arc basins. These curves also show linear subsidence and high average rates of up to 100 cm/Ka. The authors explained this high subsidence rate as a thermal effect of superimposed additional heat sources.

Summarizing, the following can be stated: Short spreading episodes with a duration of 1 Ma (?7-6 Ma, 5-4 Ma and 3-2 Ma) show a trend of increasing horizontal spreading rates and decreasing syn-spreading subsidence rates to the southeast. Rifting and spreading episodes are accompanied by rapidly accelerating subsidence ("foundering") in more internal basins where spreading has already ceased. Cessation of spreading may have been followed by a short phase of rapid subsidence or "collapse". The post-2 Ma episode shows an anomalous acceleration of subsidence in all basins, increasing towards the northeast. The overall result of these processes is that the back-arc basins show average convex upward subsidence curves, and anomalously high average subsidence rates (up to 100 cm/Ka) and individual rates up to 950 cm/Ka which are somewhat higher than the highest rates observed in other back-arc basins such as the eastern Pacific marginal basins.

B. Calabrian Basins (Figs. 8d and 8e). A general characteristic of the basins bordering the arc is the following: Areas directly next to the emerged arc show accelerating subsidence and large amounts of netto subsidence up to several kilometres (Paola Basin, Crotone Basin). Within these basins, middle Pliocene inversions can be seen in the, at present on-shore terrains (Amantea Area along the Paola Basin, Lucrezia-Magliacane Area and Marchesato Area of the Crotone Basin), while mid-Pleistocene inversions are evidenced in seismic profiles from the off-shore basins (Paola Basin, Squillace Gulf) (Argnani and Trincardi, 1990). Areas which are more distant from the arc are stable or show moderate subsidence rates

(Crotone Peninsula, Stilo Block; and, on a larger scale, Marsili back-arc Basin and Crotone-Spartivento Basin, off-shore along the Ionian side of Calabria) and generally remain fairly stable. In these areas, deposits like the hemipelagic Lower Pliocene Trubi marls were formed. Superimposed on this evolution are numerous positive composite tectonic pulses, especially evident in marginal regions. The Calabrian Arc massifs and bordering areas show high uplift and subsidence rates of about 200 cm/Ka.

C. Fold-and-thrust-belt basins (Fig. 8f). The Sicilian Basins show classical alternations of acceleration followed by overthrusting, and stability accompanied by gradual accumulation. All basins show a gradual uplift which started inbetween 6 and 4 Ma ago. The gradual regression to the south (e.g. Lentini et al., 1987) reflected this general uplift. At least four major phases of overthrusting were associated with this uplift (late Early Pliocene; 4 Ma, early Late Pliocene; 3 Ma, Pliocene-Pleistocene boundary interval; 1.6 Ma, middle Pleistocene; 1 Ma).

D. Foreland areas (Fig. 8g). The diagrams for the Ragusa and Malta foreland areas show very different images: The Ragusa Platform seems to react on overthrusting in the Maghrebides by downwarping, whereas the Malta area shows positive composite pulses during the same phases. This complex behaviour may be related to the large variety of crustal properties in the region, and to the important role of strike-slip tectonics during foreland deformation.

IMPLICATIONS AND DISCUSSION

Depositional sequences: Tectonics and sea-level

The origin of depositional sequences and their bounding unconformities along active margins may be predominantly related to tectonic mechanisms (Cloetingh, 1988; Gelati and Gnaccolini, 1988; Van Dijk, 1990, 1991; various papers in Macdonald, 1991; Postma and Fortuin, in press.). Our data provide a number of arguments in favour of this hypothesis:

Embry (1989) and Van Dijk (1990, 1991) stated that conclusive evidence can be obtained by comparing marginal and basinal subsidence rates, which should show clear differences. The data concerning the Calabrian fore-arc areas as presented in this paper are in accordance with this statement: marginal tectonic pulses (e.g. Fig. 5e; Belcastro-Cropani marginal Area and Fig. 5f; Petilia-Mesoraca fault zone Area) clearly show higher amplitudes than their basinal counterparts (Fig. 5d; Crotone Basin).

The data presented clearly show, that subsidence and uplift rates are one order of magnitude larger than a eustatic signal can cope with. Guidish et al. (1984), Burton et al. (1987) and Cathles and Hallam (1991) showed that glacial fluctuations can provide up to 100 metres of eustatic sea level changes. Many pulses shown here far exceed this value, and can therefore be related to tectonic mechanisms.

These conclusions are supported by field data which are available in some areas (Crotone basin: Van Dijk, 1990, 1991; Stilo Block: Meulenkamp et al., 1986; Malta: Drooger, 1985; Pedley and Bennet, 1985). These data clearly show that tectonic activity occurred during the genesis of unconformities which bound the principal depositional sequences.

Basin kinematics and stress-field

According to Cloetingh et al. (1985) and Cloetingh (1988) changes in intra-plate stress regime have considerable effects on vertical movements along basin margins. Their quantitative models showed that during phases with changes towards increased compressive stress, uplifts occur along basin margins, whereas basin centres rapidly subside, due to the effect of sedimentary loads present. These marginal areas become highly accentuated relative to areas which are distant from the basin. The model may also be applied to foreland basins, as outlined by Cloetingh (1988). The subsidence and uplift patterns as reconstructed for the basins adjacent to Calabria seem to plead in favour of this view: They show, as predicted by the "Cloetingh model", high amplitudes within marginal areas (Amantea Area, Capo Milazzo Area, Belcastro-Cropani Area, Petilia-Mesoraca Area) and in basin centres (Paola Basin, Crotone Basin), whereas the relatively distant areas (Marsili back-arc Basin, Crotone-Spartivento Basin) remain relatively stable (see the previous section). Another reason for the fact that the external fore-arc areas remain relatively stable, is that they are situated upon detached slabs, more or less defined, which face the subduction trough (Van Dijk, 1990, 1991). These slabs are related to restabilization of the taper angle of the Coulomb thrust wedge (Platt, 1986; cf. Dahlen, 1990).

In the case of the Calabrian Arc, the compressive stress field is provided in two ways (Van Dijk, in press.): (1) Pulses in the horizontal displacement of the Calabrian lithosphere element, a supracrustal slab or "scholle" (sensu Sylvester, 1988),

create short pulses of accretion (wedge contraction; uplift, out-of-sequence thrusting, and back-thrusting) followed by tensional restabilization (subsidence, onlaps, tensional faulting). (2) The regional stress field shows a number of distinct phases of increasing compressive stress: Early Miocene, Messinian-mid Pliocene, and Early-middle Pleistocene (see for a review Philip, 1987). Van Dijk (in press., and submitted) discussed how short pulses of regional compressive stress provoked collision of the migrating supracrustal slab with the foreland, which process was responsible for short pulses of thrust-wedge accretion and restabilization.
Beaumont (1981), Cloetingh (1988) and Flemmings and Jordan (1989) presented models for the interaction between active margin tectonics, vertical motions and facies progradation in foreland basins. Their models differ in both lithosphere behaviour and time scale. Some of the data presented here can be compared to the outcome of these quantitative models. The forward models did not provide any insight into the evolution of fore-arc basins nor did they model back-arc basin development. Therefore, only the relation between thrust-belt migration, overall foreland basin shape and foreland (flexural bulge) evolution can be investigated. As evident from the present study, pulses of thrusting in the fold-and-thrust-belt seem to coincide with downwarping of the Iblean block, which may have constituted a foreland bulge. This is consistent with the refered forward models, but does not provide insight into the relations between regional stress, bulge migration and used assumptions regarding crustal properties.

Geodynamic implications

Phases of cessation of spreading and possibly collapse in the back-arc basin coincide with phases of contraction and overthrusting in the Apennines (see also Van Dijk, in press.). The post-2 Ma episode shows a rapid acceleration of subsidence (foundering) and collapse. These features may be explained in two different ways: They may represent an extensional collapse, related to the rupture and detachment of the subducted lithosphere (Van Dijk and Okkes, 1990, 1991). It may also be related to a synclinal downbending or downwarping under the influence of an increase in regional compressive stress (Van Dijk and Okkes, op. cit.; cf. Kooi, 1991). This phenomenon has been observed in the North Sea area, and also in other Mediterranean basins such as the Gulf of Lyon (Kooi, 1991; Kooi et al., 1992).

The rapid middle Pleistocene uplift of the Calabrian Arc is coupled with the accelerating subsidence ("collapse") of the Tyrrhenian back arc Basin during this episode. As extensively argued by Van Dijk and Okkes (op. cit.), these phenomena can be linked to the rupture and detachment of the subducted lithosphere following a phase of increasing regional compressive stress during the Early - middle Pleistocene. The rapid uplift of the Calabrian Arc can than be explained in terms of a rapid rebound of the non-detached lithosphere remnants (cf. Wortel and Spakman, in press.).
The Neogene acceleration of subsidence of the Ionian Basin may be explained in two different ways: It may be a loading response to the advancing Calabrian Arc as envisaged in the models of e.g. Beaumont (1981). Mantovani et al. (1990), however, stated that the late phase of foundering of the Ionian basin (as evident from onlaps observed in seismic profiles; e.g. Fabbri et al., 1982) was due to a late rifting of the basin, linked to the anti-clockwise rotation of the Adria Plate. These two processes may also be mutually related.

Comparison with other areas

The results from the Calabrian Arc can be compared with some results from studies of the Indonesian Arc (Fortuin, De Smet c.s.), the Taiwan region (Lundberg and Dorsey, 1988) and the Carpathian Arc (Royden and Sclater; see above). None of these studies, however, shows a complete overview of back-arc, intra-arc, fore-arc and foreland regions as in the present study.
Fortuin et al. (1988), Sumosusastro et al. (1989), De Smet et al. (1989), De Smet et al., (1990), Fortuin et al. (1990) and Fortuin and De Smet (1991) published subsidence diagrams of the Indonesian region. In this area, the same pattern of longer episodes of subsidence interrupted by short, spasmodic pulses of uplift (with a 0.1-1.0 Ma duration) emerges. Also, a rapid post-early Quaternary uplift has taken place of the same order of magnitude as the uplift present in the Calabrian Arc. Fortuin and De Smet (1991) discussed their results in the light of the interaction between eustatics and tectonics. They concluded the following: The tectonic activity dominates the development of sedimentary sequences along the active margin of the arc, perturbated by third and higher-order eustatic fluctuations. Tectonic oscillations in a vertical sense, are one order of magnitude larger than eustatic cycles. In time, however, they are of the same order of magnitude as third-order cycles. The relative vertical motions

show an irregular pattern in space, especially related to tectonic processes like open folding and tilting. This makes the eustatic signal very hard to recognize. These general conclusions are in accordance with the results obtained from the Calabrian basins.

Another case study is the work of Lundberg and Dorsey (1988) in the southeast Asian Taiwan region. They observed similar accelerations of subsidence in summit basins, from 80 to 510 cm/Ka, as can be observed in the diagrams of Calabria. The authors related this phenomenon to the loading of the back-thrusted arc by collision. This mechanism can be compared with the ideas of Van Dijk and Okkes (1988, 1990, 1991) and of Argnani and Trincardi (1990) concerning the mid-Pleistocene compressional folding of the summit basins along the internal side of the Calabrian Arc, such as the Paola Basin.

Very interesting is the observation that post-middle Pleistocene uplifts with a mean rate of up to 250 cm/Ka occur along the Indonesian Arc, and with rates exceeding 500 cm/Ka in the Taiwan area. This phenomenon is comparable to what is observed in the Calabrian Arc, which is the more interesting because along the Indonesian Arc, lithosphere rupture and split is postulated as well (Price and Audley-Charles, 1987).

CONCLUSIONS

The Central Mediterranean Area shows highly variable subsidence/uplift and accumulation rates, both spatial and temporal. Specific components that can be recognized in the diagrams comprise episodes (longer than 1 Ma) showing gradual, linear, accelerating and decelerating subsidence, and pulses (1 Ma and shorter) showing combinations of sudden acceleration, uplift (inversion) or subsidence (collapse). Specific episodes of high frequency tectonic activity in the entire Central Mediterranean area can be recognized in the Early Miocene, Messinian-Early Pliocene, and Pleistocene-Recent. These episodes show collapses, inversions, composite tectonic pulses and accelerations in accumulation rates.

Spreading episodes in the Tyrrhenian back-arc area (7-6, 5-4 and 3-2 Ma) alternate with phases of overthrusting in the surrounding Apennines (intra-Messinian; 5.5 Ma, mid-Pliocene; 4-3 Ma, Pleistocene; 1-0.7 Ma). The pattern of overall subsidence curves for the various subbasins in the back-arc area shows an acceleration of subsidence which may be due to repetitive rifting, short phases of collapse and late post-2 Ma foundering. Individual subsidence rates amount up to 950 cm/Ka and mean rates of up to 100 cm/Ka occur. These rates are higher than observed in other back-arc basins, and can not be explained by classical rifting models. Rapid foundering and collapse may be linked to downwarping under the influence of increasing regional stress, or to an extensional collapse related to plate rupture.

The rates of vertical motions during short tectonic pulses along basin margins are considerably higher than subsidence rates in more basinal areas. These oscillations are one order of magnitude larger that the possible amount of vertical eustatic sea level variation. This illustrates that tectonic activity is the main factor in the genesis of third-order unconformity-bound depositional sequences.

The "Cloetingh model" of intra-plate stress fluctuations may be applied to explain high amplitudes of basinal and marginal subsidence and uplift patterns in the basins adjacent to the Calabrian Arc. Compression is provided by pulses in stagnation of arc migration, which are also associated with pulses of contraction of the thrust-wedge.

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FIGURE CAPTIONS

Figure 1.
Terrane map of the Central Mediterranean with principle geological features.
The locations of the stratigraphic sequences used in our analysis are indicated.
Modified after Van Dijk and Okkes (1991).

Figure 2.
Map of the main Neogene Basins in Calabria. Indicated are the areas for which we processed the stratigraphic sequences.
Modified after Van Dijk and Okkes (1991).

Figure 3.
The legend for the lithological columns of the Figures 4-7 (based on Shell, 1976).
The timescale as used in the present paper.

Figure 4.
Geohistory diagrams of the Tyrrhenian back-arc Basin

a. Geohistory diagram of the Sardinia Margin
b. Geohistory diagram of the Magnaghi Basin
c. Geohistory diagram of the Vavilov Basin
d. Geohistory diagram of the Marsili Basin

Figure 5.
Geohistory diagrams of Calabrian Basins; summit, intra-arc and fore-arc basins

a. Burial history diagram of the Paola summit Basin
b. Geohistory diagram of the Amantea Area
c. Geohistory diagram of the Capo Milazzo
d. Geohistory diagram of the Crotone Basin
e. Geohistory diagram of the Belcastro-Cropani basin margin Area
f. Geohistory diagram of the Petilia-Mesoraca fault zone Area
g. Geohistory diagram of the Lucrezia-Magliacane thrust-belt Area
h. Geohistory diagram of the Crotone Peninsula
i. Geohistory diagrams of the Stilo Block
    i1. Diagram of the Stilo Block
    i2. Diagram of the Monte Singa Area

Figure 6.
Geohistory Diagrams of Sicilian Maghrebide fold-and-thrust-belt basins

a. Geohistory diagram of the Caltanissetta Basin
b. Geohistory diagram for the Agrigento Area
c. Geohistory diagram of the Gela Basin
    c1. Diagram of the Gela Basin; Upper Block
    c2. Diagram of the Gela Basin; Lower Block

Figure 7.
Geohistory diagrams of the Iblean and Ionian foreland area

a. Geohistory diagram of the Iblean Block
b. Geohistory diagram of the Maltese Islands
c. Burial history diagram of the Ionian Basin

Figure 8.
Compilation of Neogene subsidence and accumulation rates in the Central Mediterranean.
The individual curves indicated in the diagrams a and b represent ranges of subsidence and accumulations for the different areas (enveloping curves of the diagrams c-g). The individual curves drawn in the diagrams c-g represent rates calculated from the individual diagrams of Figures 4-7. The peaks up to 1000 cm/Ka in de diagrams represent near instantaneous subsidence/uplifts, which are often artefacts of the way points are plotted. In reality, these peaks represent "very rapid" subsidence/uplift rates.
Note that the southern Calabrian fore-arc Stilo Block has been compiled with composite diagram for the Sicilian thrust-belt basins (Fig. 8f). This is done because both contain data pertinent to the Oligocene-Early Miocene timeslice. The diagram for the Monte Singa Area has been compiled with the other Calabrian fore-arc areas (Fig. 8e), as these diagrams all regard the Late Miocene-Pliocene evolution of Calabria.

a. Composite diagram of subsidence/uplift rates for all areas
b. Composite diagram of accumulation rates for all areas

c. Composite diagram of the Tyrrhenian back-arc basins
d. Composite diagram of the summit and intra-arc basins in Calabria
e. Composite diagram of the fore-arc basins in Calabria
f. Composite diagram of the thrust-belt basins in Sicily and of the Stilo block (S. Calabria)
g. Composite diagram of the Pelagian and Ionian foreland areas

Figure 9.
End-member scenarios for the overall Messinian evolution of the fore-arc area.
Note that the Messinian sea level fluctuation has been modeled as a gradual fall and rapid rise. Subsidence has been taken as if linear for the 6-5 Ma interval.
It must be emphasized that these scenarios are purely hypothetical, since two distinct sea level drops and an intra-Messinian tectonic phase are known to have occurred, and since Messinian facies and thus accumulation rates are very heterogeneous. The scenarios merely serve to show the total, overall effect of the Messinian crisis.

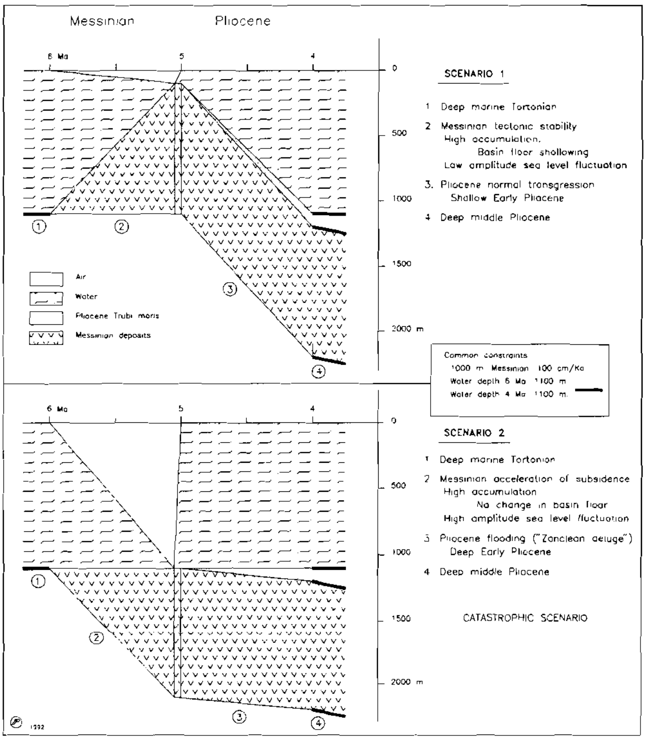


Fig. 9

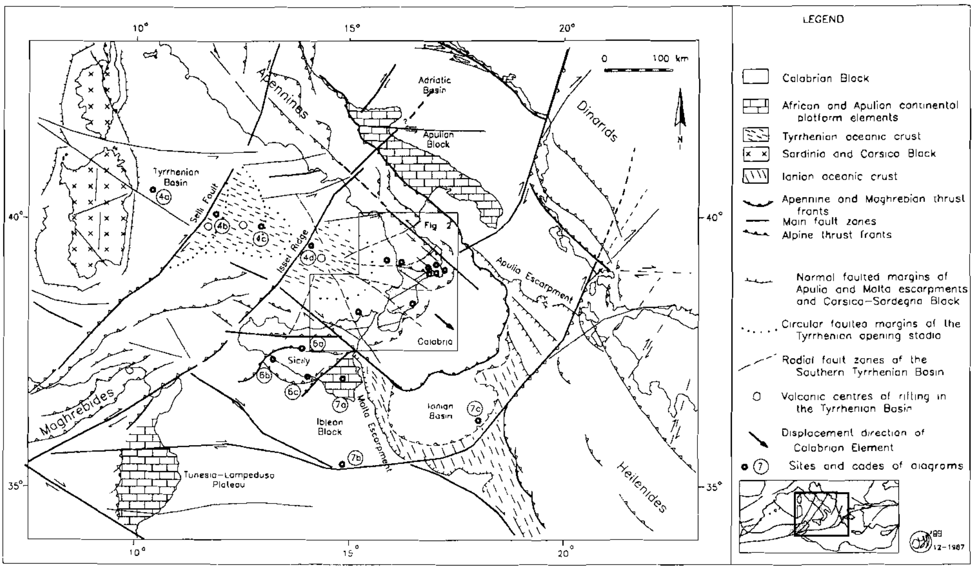

LEGEND
Calabrian Block
African and Apulian continental platform elements
Tyrrhenian oceanic crust
Sardinia and Corsica Block
Ionian oceanic crust
Apennine and Maghrebian thrust fronts
Main fault zones
Alpine thrust fronts
Normal faulted margins of Apulia and Malta escarpments and Corsica-Sardegna Block
Circular faulted margins of the Tyrrhenian opening stadia
Radial fault zones of the Southern Tyrrhenian Basin
Volcanic centres of rifting in the Tyrrhenian Basin
Displacement direction of Calabrian Element
Sites and codes of diagrams
0 100 km
Apennines
Adriatic Basin
Apulian Block
Dinarids
Tyrrhenian Basin
Selli Fault
Issel Ridge
Fig 2
Apulia Escarpment
Calabria
Sicily
Maghrebides
Ibleon Block
Malta Escarpment
Ionian Basin
Tunesia-Lampedusa Plateau
Hellenides
4a
4b
4c
4d
6a
6b
6c
7a
7b
7c
10°
15°
20°
35°
40°
12-1987

Fig. 1

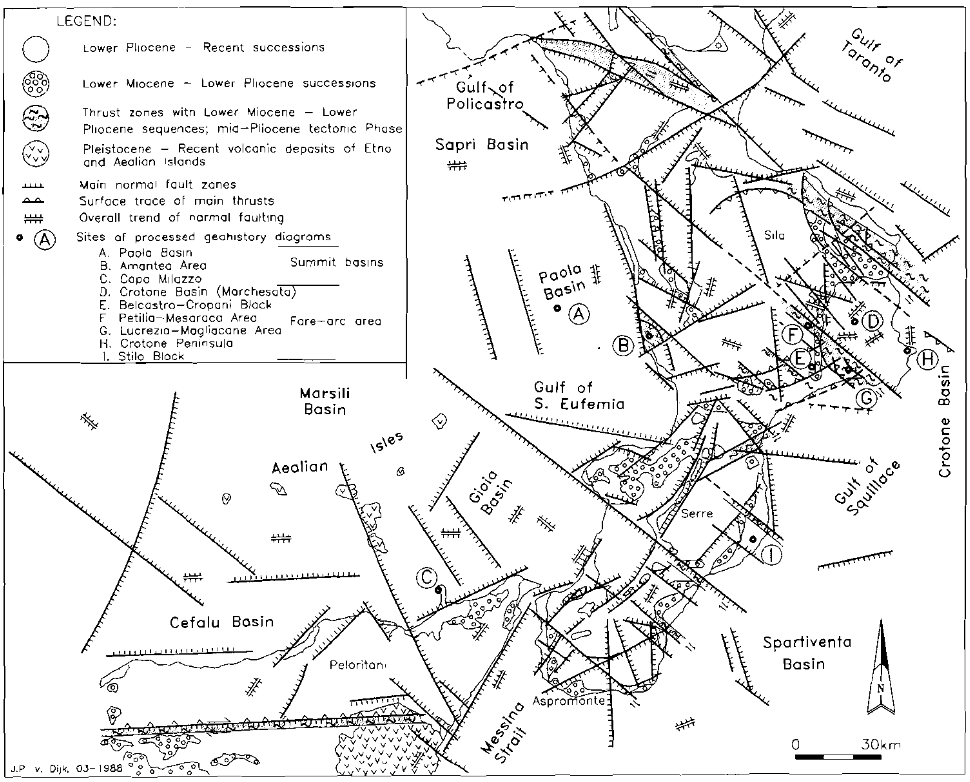

LEGEND:
Lower Pliocene - Recent successions
Lower Miocene - Lower Pliocene successions
Thrust zones with Lower Miocene - Lower Pliocene sequences; mid-Pliocene tectonic Phase
Pleistocene - Recent volcanic deposits of Etna and Aeolian Islands
Main normal fault zones
Surface trace of main thrusts
Overall trend of normal faulting
Sites of processed geohistory diagrams
A. Paola Basin
B. Amantea Area
C. Capo Milazzo
D. Crotone Basin (Marchesato)
E. Belcastro-Cropani Block
F. Petilia-Mesaraca Area
G. Lucrezia-Magliacane Area
H. Crotone Peninsula
I. Stilo Block
Summit basins
Fore-arc area
Gulf of Taranto
Gulf of Policastro
Sapri Basin
Sila
Paola Basin
Gulf of S. Eufemia
Marsili Basin
Aeolian Isles
Gioia Basin
Gulf of Squillace
Crotone Basin
Serre
Cefalu Basin
Peloritani
Aspromonte
Messina Strait
Spartiventa Basin
N
0 30km
J.P. v. Dijk, 03-1988

Fig. 2

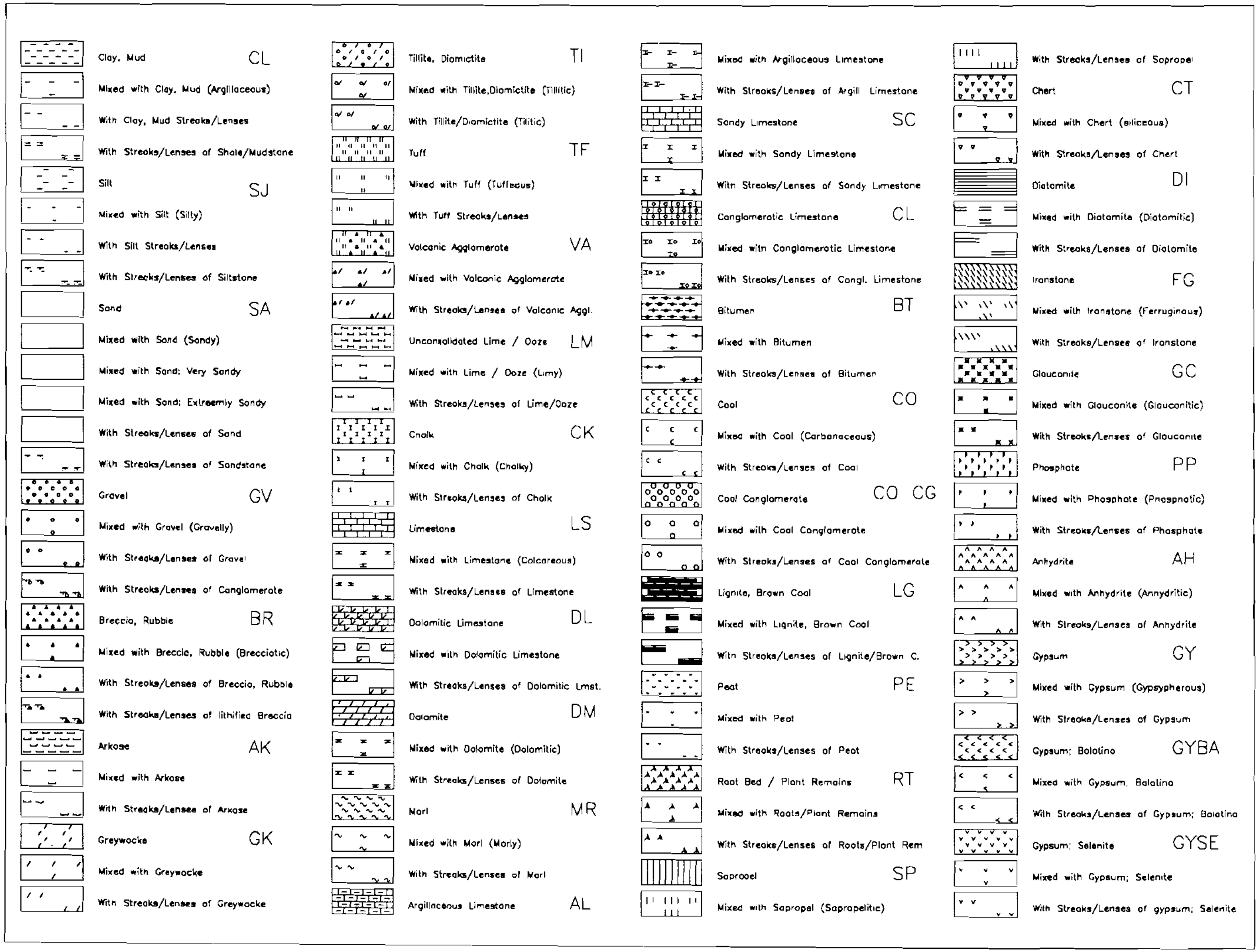

Clay, Mud CL
Mixed with Clay, Mud (Argillaceous)
With Clay, Mud Streaks/Lenses
With Streaks/Lenses of Shale/Mudstone
Silt SJ
Mixed with Silt (Silty)
With Silt Streaks/Lenses
With Streaks/Lenses of Siltstone
Sand SA
Mixed with Sand (Sandy)
Mixed with Sand: Very Sandy
Mixed with Sand: Extreemly Sandy
With Streaks/Lenses of Sand
With Streaks/Lenses of Sandstone
Gravel GV
Mixed with Gravel (Gravelly)
With Streaks/Lenses of Gravel
With Streaks/Lenses of Conglomerate
Breccia, Rubble BR
Mixed with Breccia, Rubble (Brecciatic)
With Streaks/Lenses of Breccia, Rubble
With Streaks/Lenses of lithified Breccia
Arkose AK
Mixed with Arkose
With Streaks/Lenses of Arkose
Greywacke GK
Mixed with Greywacke
With Streaks/Lenses of Greywacke
Tillite, Diamictite TI
Mixed with Tillite,Diamictite (Tillitic)
With Tillite/Diamictite (Tillitic)
Tuff TF
Mixed with Tuff (Tuffaous)
With Tuff Streaks/Lenses
Volcanic Agglomerate VA
Mixed with Volcanic Agglomerate
With Streaks/Lenses of Volcanic Aggl.
Unconsolidated Lime / Ooze LM
Mixed with Lime / Ooze (Limy)
With Streaks/Lenses of Lime/Ooze
Chalk CK
Mixed with Chalk (Chalky)
With Streaks/Lenses of Chalk
Limestone LS
Mixed with Limestone (Calcareous)
With Streaks/Lenses of Limestone
Dolomitic Limestone DL
Mixed with Dolomitic Limestone
With Streaks/Lenses of Dolomitic Lmst.
Dolomite DM
Mixed with Dolomite (Dolomitic)
With Streaks/Lenses of Dolomite
Marl MR
Mixed with Marl (Marly)
With Streaks/Lenses of Marl
Argillaceous Limestone AL
Mixed with Argillaceous Limestone
With Streaks/Lenses of Argill Limestone
Sandy Limestone SC
Mixed with Sandy Limestone
With Streaks/Lenses of Sandy Limestone
Conglomeratic Limestone CL
Mixed with Conglomeratic Limestone
With Streaks/Lenses of Congl. Limestone
Bitumen BT
Mixed with Bitumen
With Streaks/Lenses of Bitumen
Coal CO
Mixed with Coal (Carbonaceous)
With Streaks/Lenses of Coal
Coal Conglomerate CO CG
Mixed with Coal Conglomerate
With Streaks/Lenses of Coal Conglomerate
Lignite, Brown Coal LG
Mixed with Lignite, Brown Coal
With Streaks/Lenses of Lignite/Brown C.
Peat PE
Mixed with Peat
With Streaks/Lenses of Peat
Root Bed / Plant Remains RT
Mixed with Roots/Plant Remains
With Streaks/Lenses of Roots/Plant Rem
Sapropel SP
Mixed with Sapropel (Sapropelitic)
With Streaks/Lenses of Sapropel
Chert CT
Mixed with Chert (siliceous)
With Streaks/Lenses of Chert
Diatomite DI
Mixed with Diatomite (Diatomitic)
With Streaks/Lenses of Diatomite
Ironstone FG
Mixed with Ironstone (Ferruginous)
With Streaks/Lenses of Ironstone
Glauconite GC
Mixed with Glauconite (Glauconitic)
With Streaks/Lenses of Glauconite
Phosphate PP
Mixed with Phosphate (Phosphatic)
With Streaks/Lenses of Phosphate
Anhydrite AH
Mixed with Anhydrite (Anhydritic)
With Streaks/Lenses of Anhydrite
Gypsum GY
Mixed with Gypsum (Gypsypherous)
With Streaks/Lenses of Gypsum
Gypsum; Balatino GYBA
Mixed with Gypsum, Balatino
With Streaks/Lenses of Gypsum; Balatino
Gypsum; Selenite GYSE
Mixed with Gypsum; Selenite
With Streaks/Lenses of gypsum; Selenite

Fig. 3

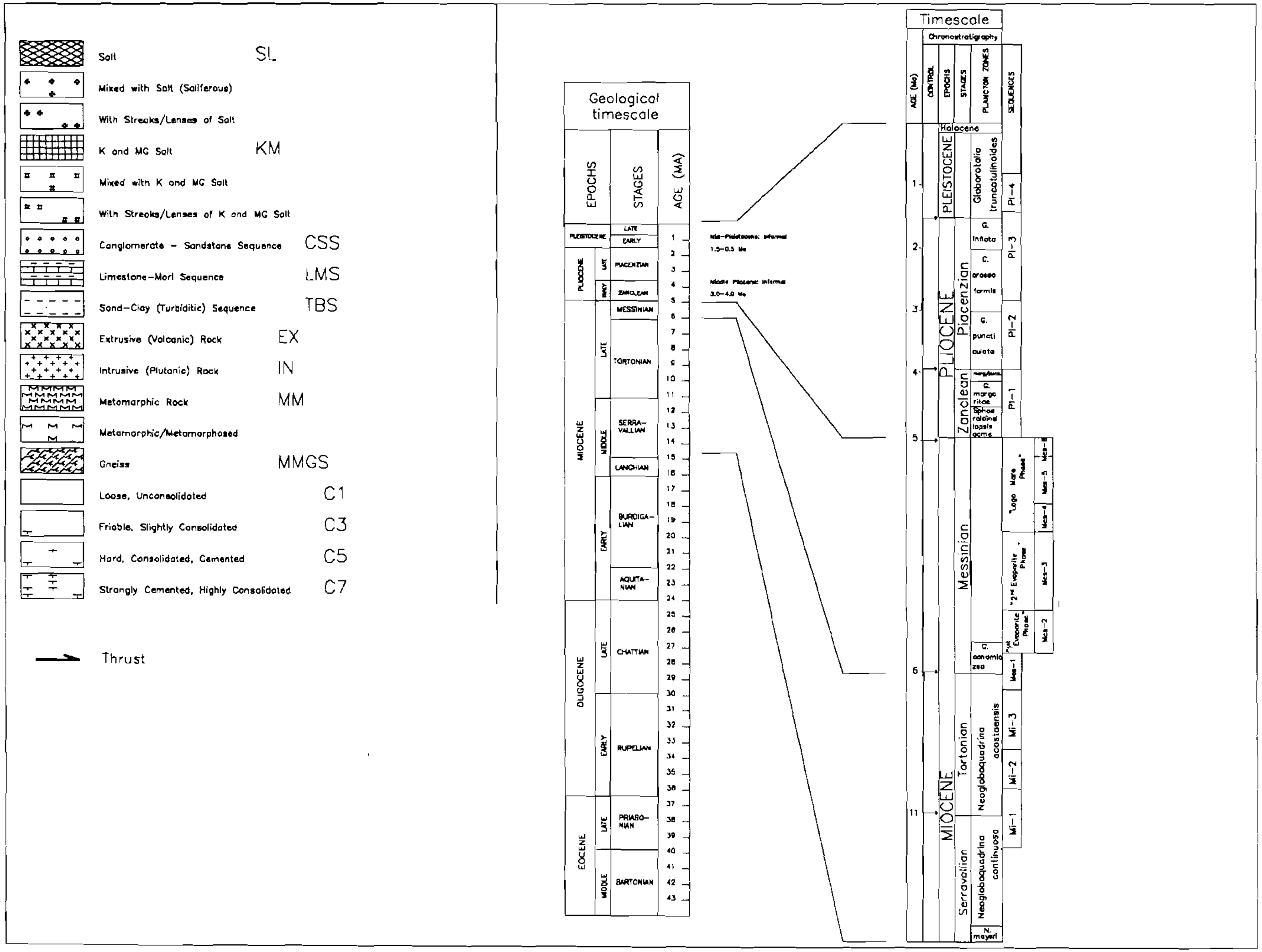
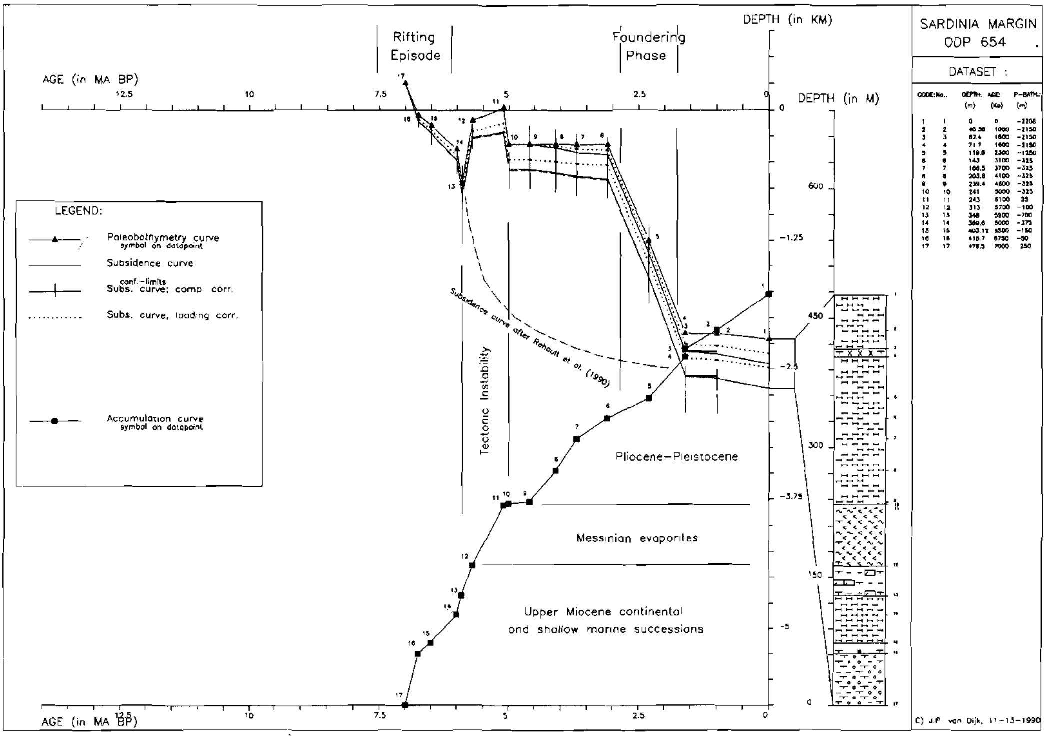

Salt SL
Mixed with Salt (Saliferous)
With Streaks/Lenses of Salt
K and MG Salt KM
Mixed with K and MG Salt
With Streaks/Lenses of K and MG Salt
Conglomerate - Sandstone Sequence CSS
Limestone-Marl Sequence LMS
Sand-Clay (Turbiditic) Sequence TBS
Extrusive (Volcanic) Rock EX
Intrusive (Plutonic) Rock IN
Metamorphic Rock MM
Metamorphic/Metamorphosed
Gneiss MMGS
Loose, Unconsolidated C1
Friable, Slightly Consolidated C3
Hard, Consolidated, Cemented C5
Strongly Cemented, Highly Consolidated C7
Thrust
Geological timescale
EPOCHS
STAGES
AGE (MA)
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
LATE
EARLY
MIDDLE
PIACENZIAN
ZANCLEAN
MESSINIAN
TORTONIAN
SERRA-VALLIAN
LANGHIAN
BURDIGA-LIAN
AQUITA-NIAN
CHATTIAN
RUPELIAN
PRIABO-NIAN
BARTONIAN
Timescale
Chronostratigraphy
AGE (Ma)
CONTROL
EPOCHS
STAGES
PLANCTON ZONES
SEQUENCES
Holocene
PLEISTOCENE
PLIOCENE
MIOCENE
Piacenzian
Zanclean
Messinian
Tortonian
Serravallian
Globorotalia truncatulinoides
G. inflata
G. crassaformis
G. puncticulata
Sphaeroidinellopsis acme
G. conomiozea
Neogloboquadrina acostaensis
Neogloboquadrina continuosa
N. mayeri
Pl-4
Pl-3
Pl-2
Pl-1
"Lago Mare Phase"
"2nd Evaporite Phase"
1st Evaporite Phase
Mes-1
Mes-2
Mes-3
Mes-4
Mes-5
Mi-3
Mi-2
Mi-1

Fig. 4a


SARDINIA MARGIN
ODP 654
DATASET :
Rifting Episode
Foundering Phase
AGE (in MA BP)
DEPTH (in KM)
DEPTH (in M)
LEGEND:
Paleobathymetry curve symbol on datapoint
Subsidence curve
Subs. curve; comp corr. conf.-limits
Subs. curve, loading corr.
Accumulation curve symbol on datapoint
Tectonic Instability
Subsidence curve after Rehault et al. (1990)
Pliocene–Pleistocene
Messinian evaporites
Upper Miocene continental and shallow marine successions
C) J.P. van Dijk, 11-13-1990

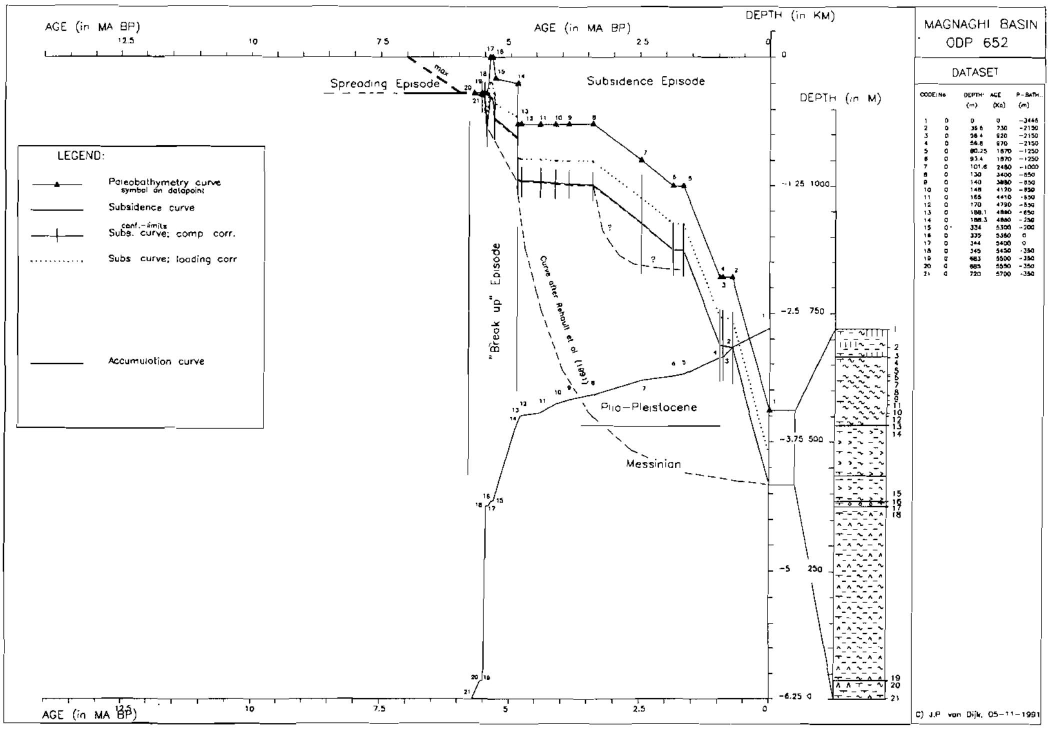
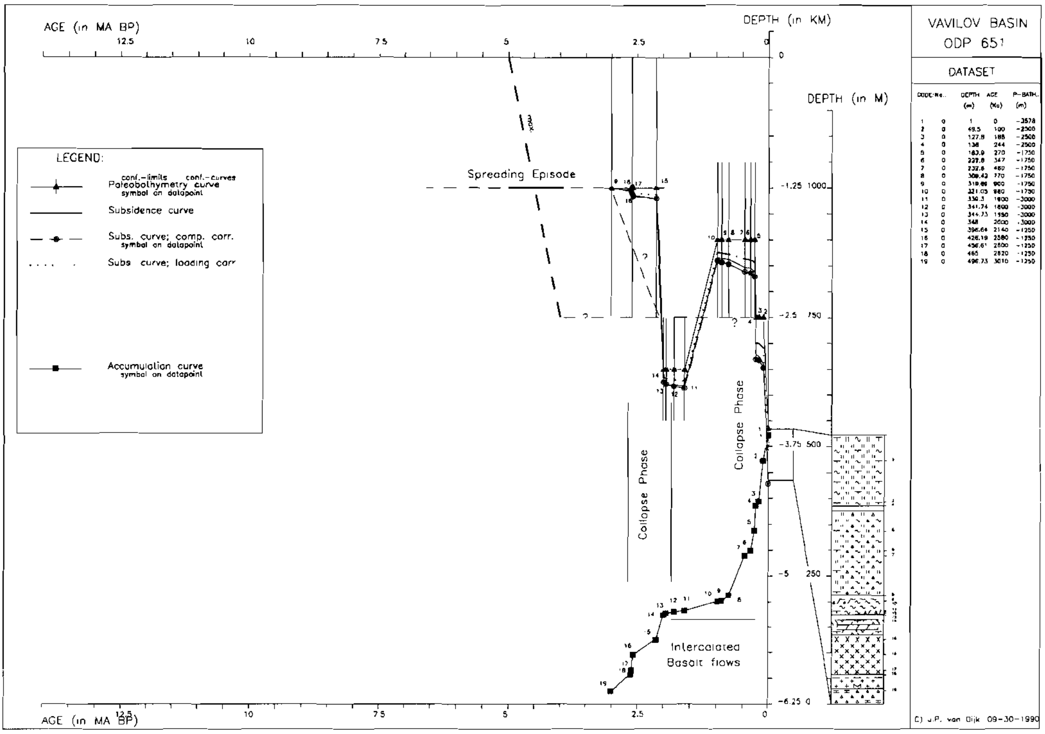

MAGNAGHI BASIN
ODP 652
DATASET
AGE (in MA BP)
DEPTH (in KM)
DEPTH (in M)
Spreading Episode
max
Subsidence Episode
LEGEND:
Paleobathymetry curve symbol on datapoint
Subsidence curve
Subs. curve; comp corr. conf.-limits
Subs curve; loading corr
Accumulation curve
"Break up" Episode
Curve after Rehault et al. (1991)
Plio–Pleistocene
Messinian
C) J.P. van Dijk, 05-11-1991

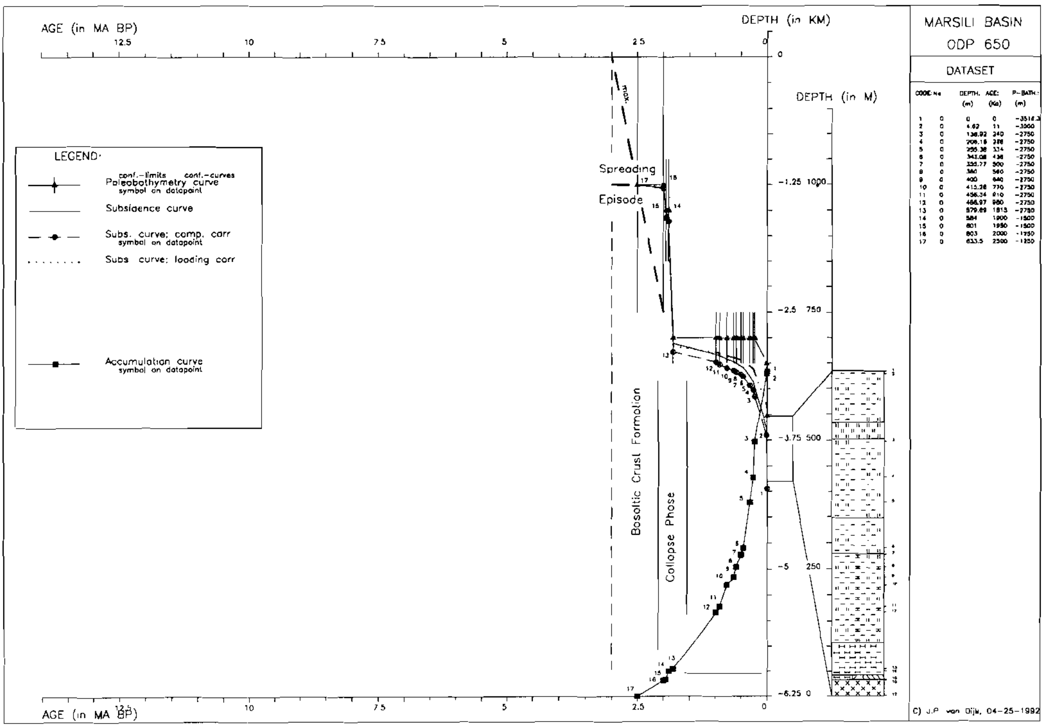
Fig. 4b

Fig. 4c



DATASET

CODE:	No.	DEPTH (m)	AGE (Ka)	P-BATH. (m)
1	0	1	0	-3578
2	0	49.5	100	-2500
3	0	127.8	188	-2500
4	0	138	244	-2500
5	0	183.9	270	-1750
6	0	227.8	347	-1750
7	0	232.6	460	-1750
8	0	308.42	770	-1750
9	0	319.88	900	-1750
10	0	321.05	980	-1750
11	0	339.3	1600	-3000
12	0	341.74	1800	-3000
13	0	344.73	1950	-3000
14	0	348	2000	-3000
15	0	396.64	2140	-1250
16	0	426.19	2580	-1250
17	0	456.61	2600	-1250
18	0	465	2820	-1250
19	0	496.73	3010	-1250

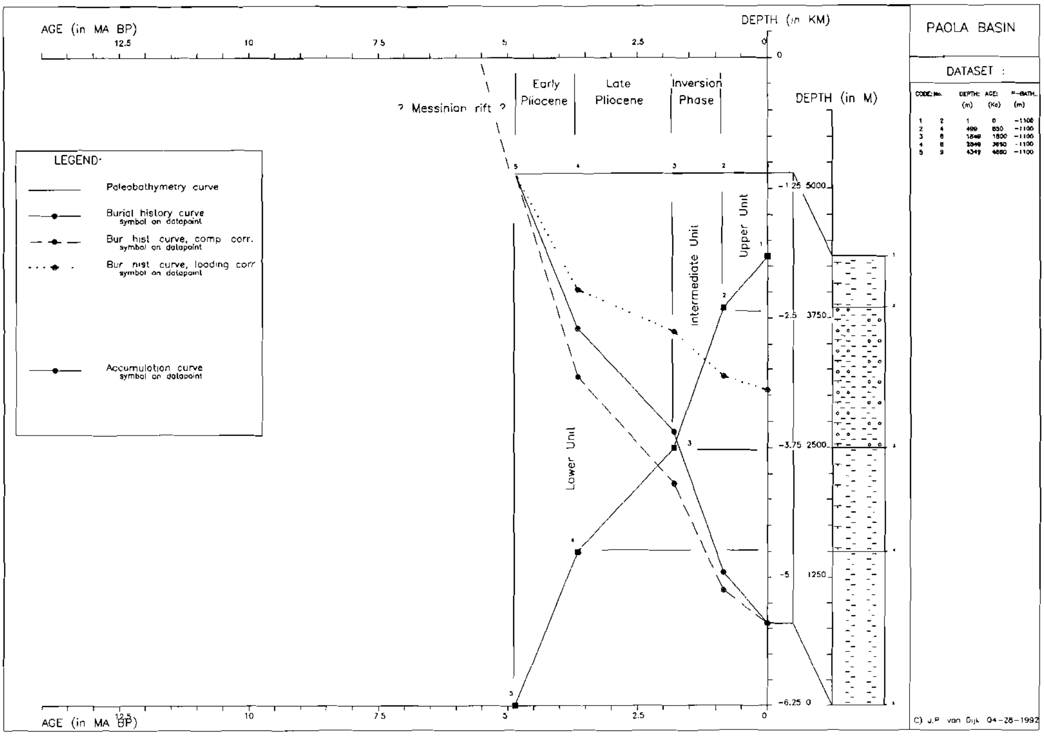


DATASET

CODE:	No	DEPTH. (m)	AGE: (Ka)	P-BATH.: (m)
1	0	0	0	-3516.3
2	0	4.62	11	-3000
3	0	138.92	240	-2750
4	0	206.18	288	-2750
5	0	255.38	334	-2750
6	0	343.08	438	-2750
7	0	356.77	500	-2750
8	0	360	560	-2750
9	0	400	640	-2750
10	0	415.28	770	-2750
11	0	456.34	810	-2750
12	0	486.97	980	-2750
13	0	579.89	1813	-2750
14	0	584	1900	-1500
15	0	601	1950	-1500
16	0	603	2000	-1250
17	0	633.5	2500	-1250

Fig. 4d

Fig. 5a


AGE (in MA BP)
12.5
10
7.5
5
2.5
0
DEPTH (in KM)
DEPTH (in M)
? Messinian rift ?
Early Pliocene
Late Pliocene
Inversion Phase
LEGEND:
Paleobathymetry curve
Burial history curve symbol on datapoint
Bur. hist. curve, comp. corr. symbol on datapoint
Bur. hist. curve, loading corr. symbol on datapoint
Accumulation curve symbol on datapoint
Lower Unit
Intermediate Unit
Upper Unit
-1.25 5000
-2.5 3750
-3.75 2500
-5 1250
-6.25 0
PAOLA BASIN
DATASET :
CODE: No. DEPTH: (m) AGE: (Ka) P-BATH. (m)
1 2 1 0 -1100
2 4 499 850 -1100
3 6 1849 1800 -1100
4 8 2849 3850 -1100
5 9 4349 4800 -1100
C) J.P. van Dijk 04-28-1992

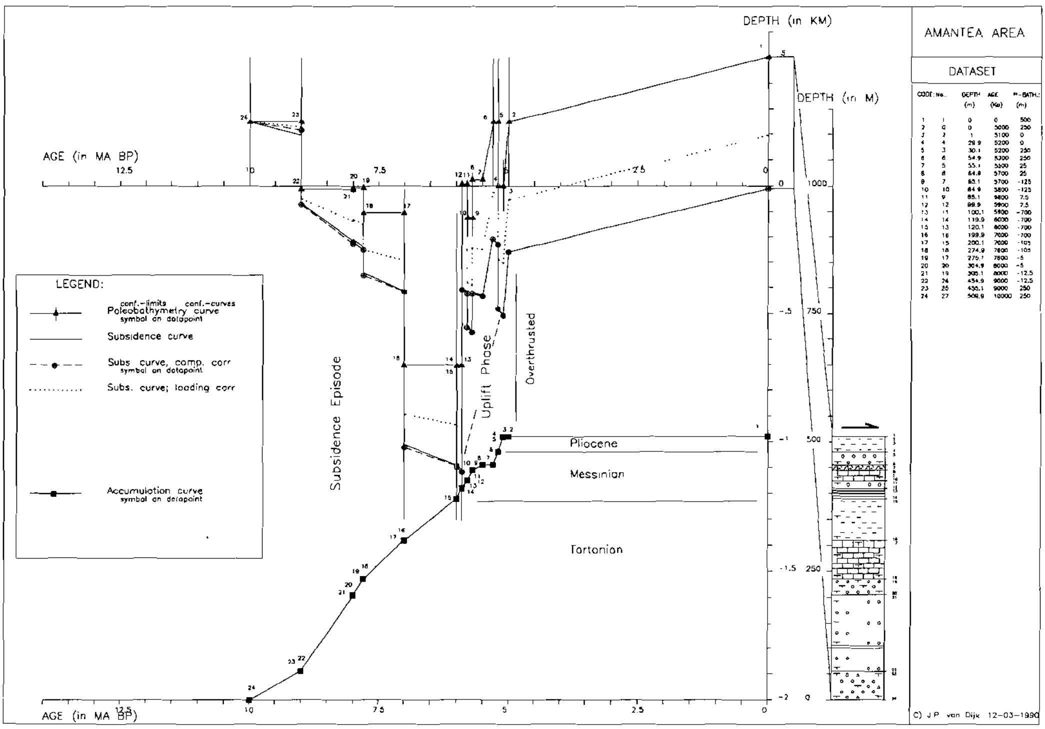
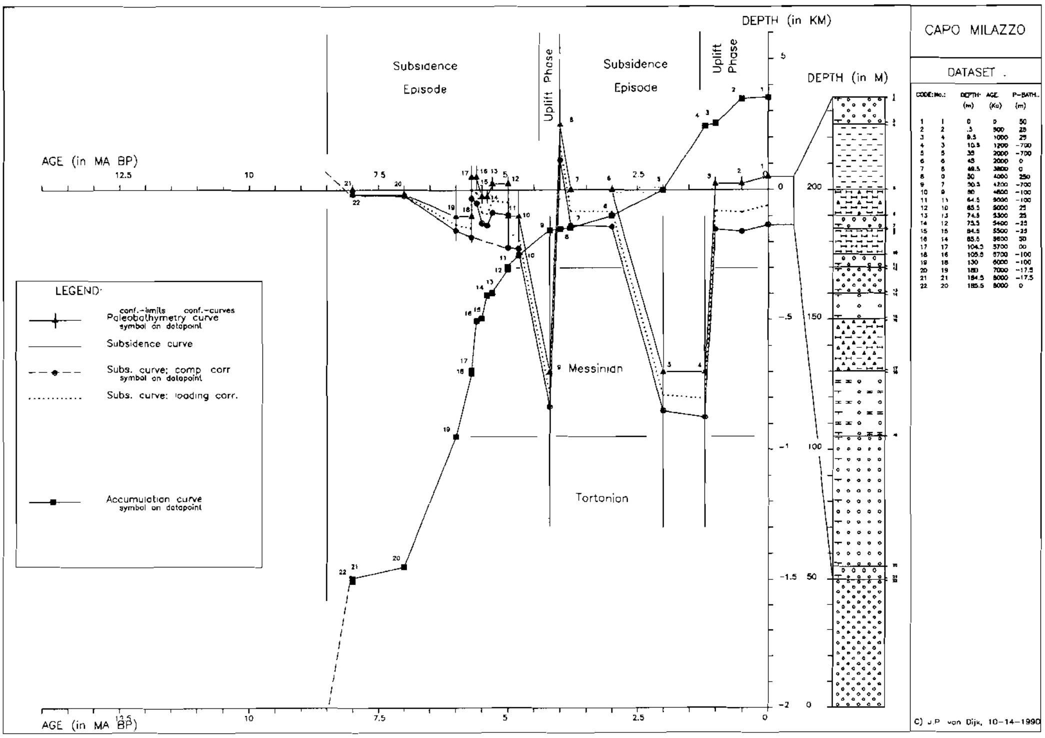
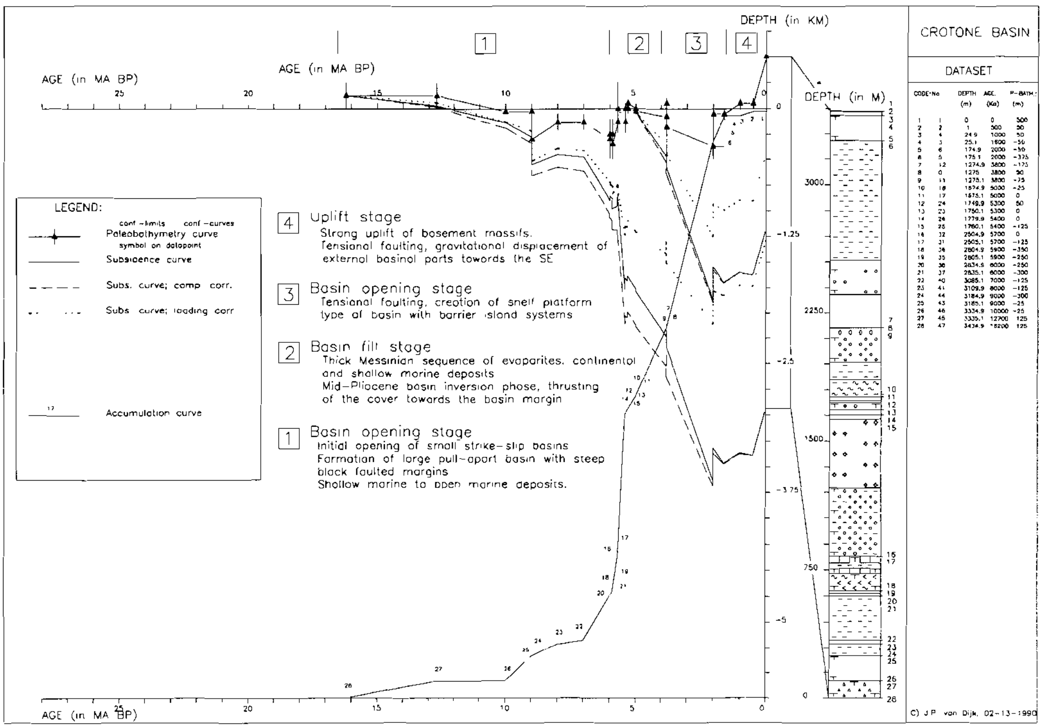

DEPTH (in KM)
DEPTH (in M)
AGE (in MA BP)
12.5
10
7.5
5
2.5
0
LEGEND:
conf.-limits conf.-curves
Paleobathymetry curve symbol on datapoint
Subsidence curve
Subs. curve, comp. corr. symbol on datapoint
Subs. curve; loading corr.
Accumulation curve symbol on datapoint
Subsidence Episode
Uplift Phase
Overthrusted
Pliocene
Messinian
Tortonian
1000
-.5 750
-1 500
-1.5 250
-2 0
AMANTEA AREA
DATASET
CODE: No. DEPTH (m) AGE (Ka) P-BATH. (m)
1 1 0 0 500
2 4 0 5000 250
3 2 1 5100 0
4 4 29.9 5200 0
5 3 30.1 5200 250
6 6 54.9 5300 250
7 5 55.1 5500 25
8 8 64.9 5700 25
9 7 65.1 5700 -125
10 10 84.9 5800 -125
11 9 85.1 5800 7.5
12 12 99.9 5900 7.5
13 11 100.1 5900 -700
14 14 119.9 6000 -700
15 13 120.1 6000 -700
16 16 199.9 7000 -700
17 15 200.1 7000 -105
18 18 274.9 7800 -105
19 17 275.1 7800 -5
20 20 304.9 8000 -5
21 19 305.1 8000 -12.5
22 24 454.9 9000 -12.5
23 25 455.1 9000 250
24 27 509.9 10000 250
C) J.P. van Dijk 12-03-1990

Fig. 5b

Fig. 5c



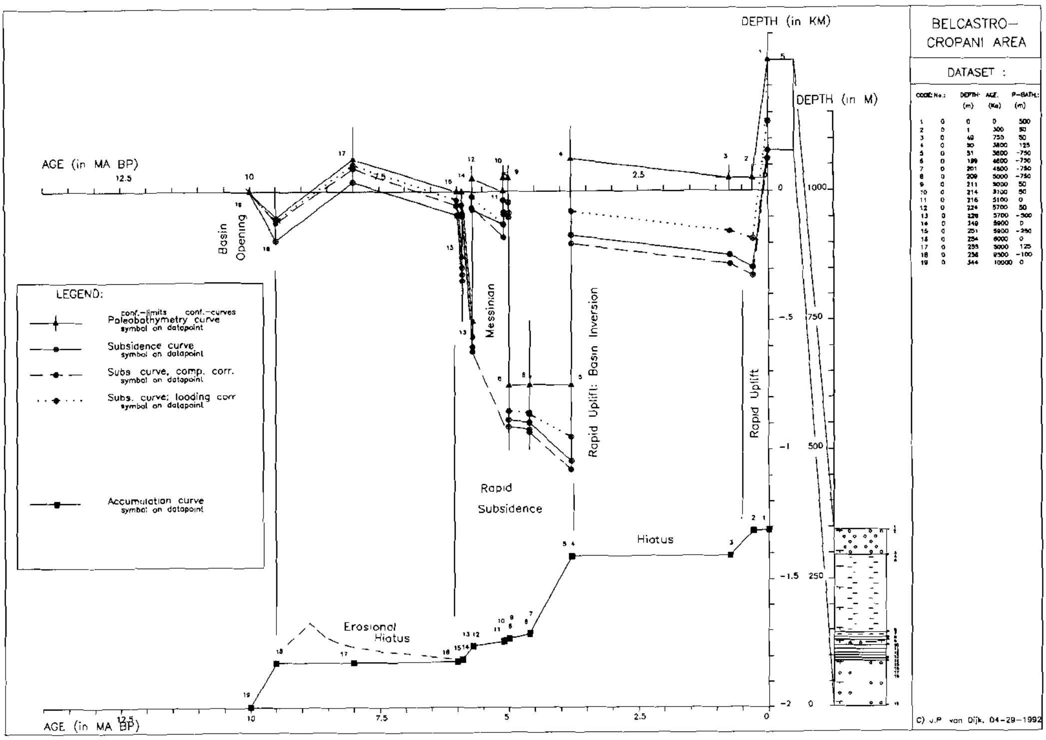
CODE:	No.:	DEPTH (m)	AGE (Ka)	P-BATH. (m)
1	1	0	0	50
2	2	.3	500	25
3	4	9.5	1000	25
4	3	10.5	1200	-700
5	5	35	2000	-700
6	6	45	2000	0
7	8	48.5	3800	0
8	0	50	4000	250
9	7	50.5	4200	-700
10	9	60	4600	-100
11	11	64.5	5000	-100
12	10	65.5	5000	25
13	13	74.5	5300	25
14	12	75.5	5400	-25
15	15	84.5	5500	-25
16	14	85.5	5600	50
17	17	104.5	5700	00
18	16	105.5	5700	-100
19	18	130	6000	-100
20	19	180	7000	-17.5
21	21	184.5	8000	-17.5
22	20	185.5	8000	0



CODE	No	DEPTH (m)	AGE (Ka)	P-BATH. (m)
1	1	0	0	500
2	2	1	500	50
3	4	24.9	1000	50
4	3	25.1	1600	-50
5	6	174.9	2000	-50
6	5	175.1	2000	-375
7	12	1274.9	3800	-125
8	0	1275	3800	50
9	11	1275.1	3800	-75
10	18	1674.9	5000	-25
11	17	1675.1	5000	0
12	24	1749.9	5300	50
13	23	1750.1	5300	0
14	26	1779.9	5400	0
15	25	1780.1	5400	-125
16	32	2504.9	5700	0
17	31	2505.1	5700	-125
18	34	2804.9	5900	-350
19	35	2805.1	5900	-250
20	36	2834.9	6000	-250
21	37	2835.1	6000	-300
22	40	3085.1	7000	-125
23	41	3109.9	8000	-125
24	44	3184.9	9000	-300
25	43	3185.1	9000	-25
26	46	3334.9	10000	-25
27	45	3335.1	12700	125
28	47	3434.9	15200	125

Fig. 5d

Fig. 5e


BELCASTRO–
CROPANI AREA
DATASET :
CODE: No.: DEPTH: (m) AGE. (Ka) P–BATH.: (m)
1 0 0 0 500
2 0 1 300 50
3 0 49 750 50
4 0 50 3800 125
5 0 51 3800 -750
6 0 199 4600 -750
7 0 201 4800 -750
8 0 209 5000 -750
9 0 211 5000 50
10 0 214 5100 50
11 0 216 5100 0
12 0 224 5700 50
13 0 226 5700 -500
14 0 249 5900 0
15 0 251 5900 -250
16 0 254 6000 0
17 0 255 8000 125
18 0 256 9500 -100
19 0 344 10000 0
DEPTH (in KM)
DEPTH (in M)
AGE (in MA BP)
Basin Opening
Messinian
Rapid Uplift: Basin Inversion
Rapid Uplift
Rapid Subsidence
Hiatus
Erosional Hiatus
LEGEND:
conf.–limits conf.–curves
Paleobathymetry curve
symbol on datapoint
Subsidence curve
symbol on datapoint
Subs. curve, comp. corr.
symbol on datapoint
Subs. curve; loading corr
symbol on datapoint
Accumulation curve
symbol on datapoint
C) J.P. van Dijk, 04-29-1992

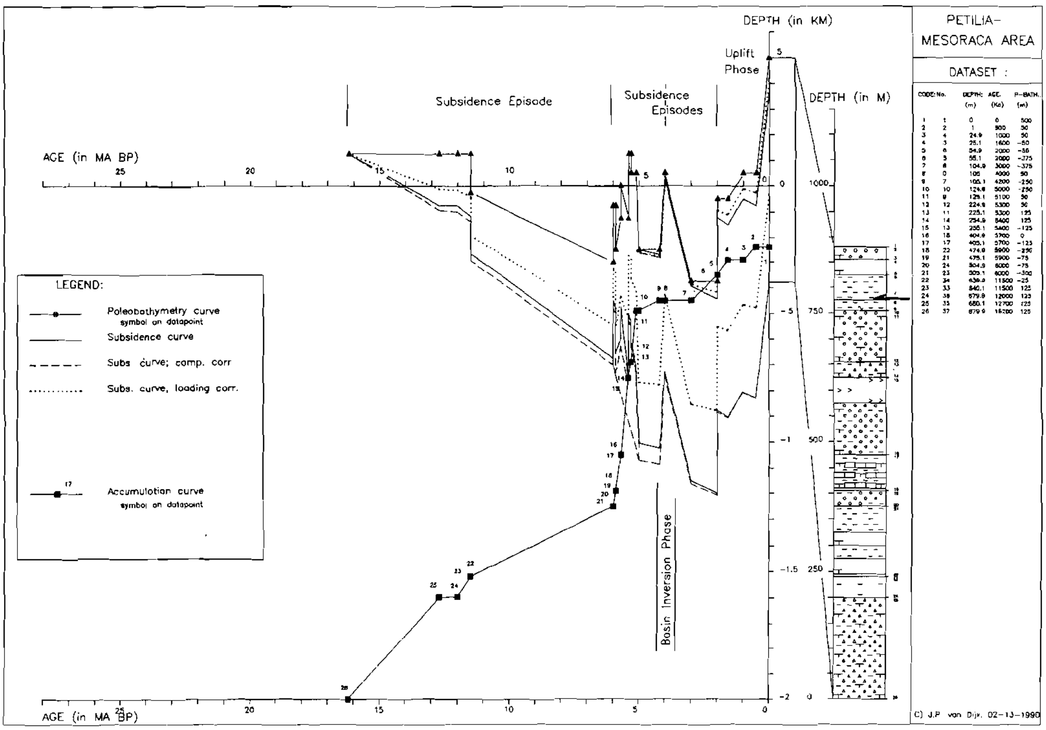
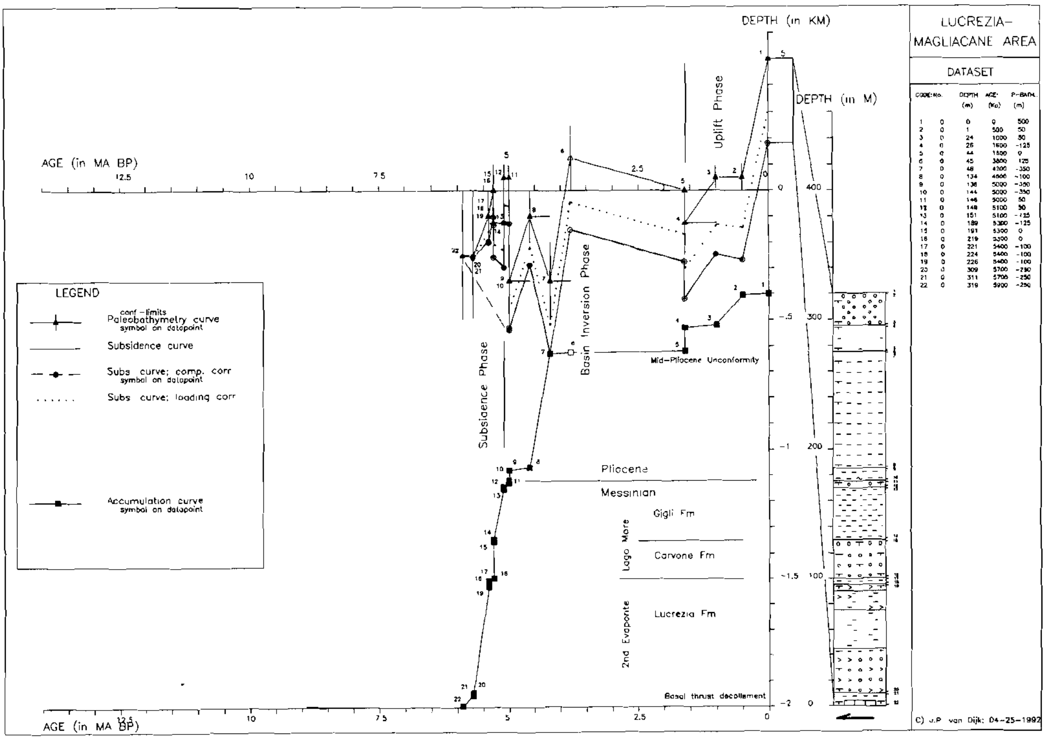

PETILIA–
MESORACA AREA
DATASET :
CODE: No. DEPTH: (m) AGE. (Ka) P–BATH. (m)
1 1 0 0 500
2 2 1 500 50
3 4 24.9 1000 50
4 3 25.1 1600 -50
5 6 54.9 2000 -50
6 5 55.1 2000 -375
7 6 104.9 3000 -375
8 0 105 4000 50
9 7 105.1 4200 -250
10 10 124.9 5000 -250
11 9 125.1 5100 50
12 12 224.9 5300 50
13 11 225.1 5300 125
14 14 254.9 5400 125
15 13 255.1 5400 -125
16 18 404.9 5700 0
17 17 405.1 5700 -125
18 22 474.9 5900 -250
19 21 475.1 5900 -75
20 24 504.9 6000 -75
21 23 505.1 6000 -300
22 34 639.9 11500 -25
23 33 640.1 11500 125
24 38 679.9 12000 125
25 35 680.1 12700 125
26 37 679.9 16200 125
DEPTH (in KM)
DEPTH (in M)
AGE (in MA BP)
Uplift Phase
Subsidence Episode
Subsidence Episodes
Basin Inversion Phase
LEGEND:
Paleobathymetry curve
symbol on datapoint
Subsidence curve
Subs curve; comp. corr
Subs. curve, loading corr.
Accumulation curve
symbol on datapoint
C) J.P. van Dijk, 02-13-1990

Fig. 5f

Fig. 5g


LUCREZIA–MAGLIACANE AREA
DATASET
DEPTH (in KM)
DEPTH (in M)
AGE (in MA BP)
LEGEND
Paleobathymetry curve
Subsidence curve
Subs. curve; comp. corr
Subs. curve; loading corr
Accumulation curve
Uplift Phase
Basin Inversion Phase
Subsidence Phase
Mid–Pliocene Unconformity
Pliocene
Messinian
Lago Mare
Gigli Fm
Carvone Fm
2nd Evaporite
Lucrezia Fm
Basal thrust decollement
C) J.P. van Dijk; 04-25-1992

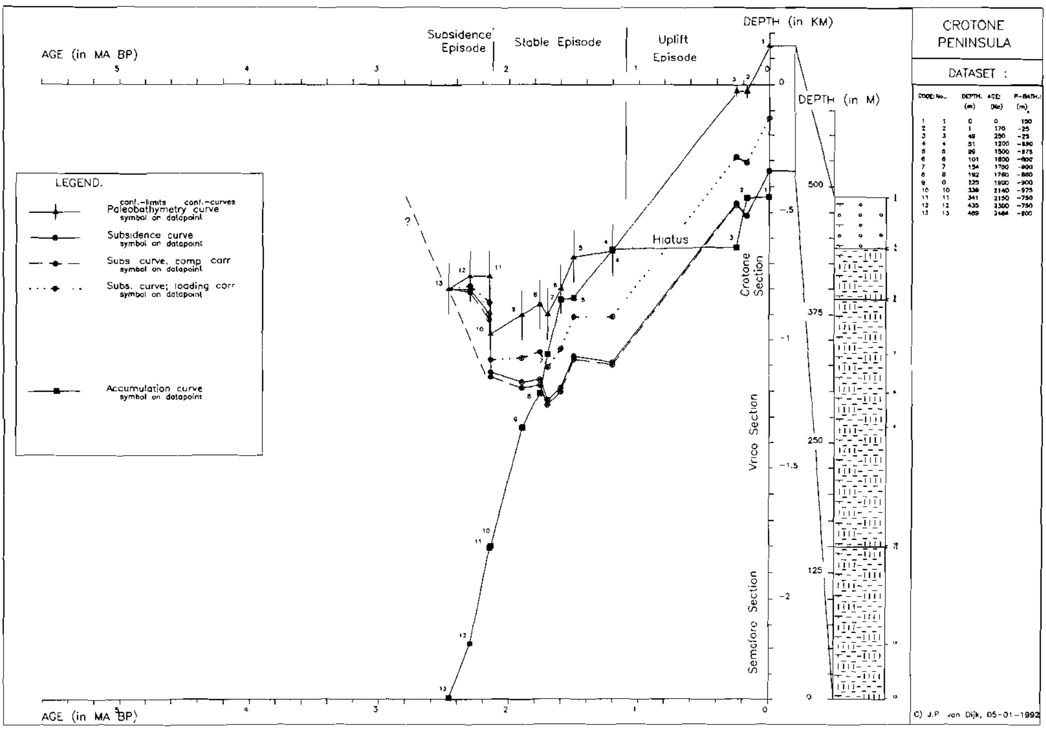
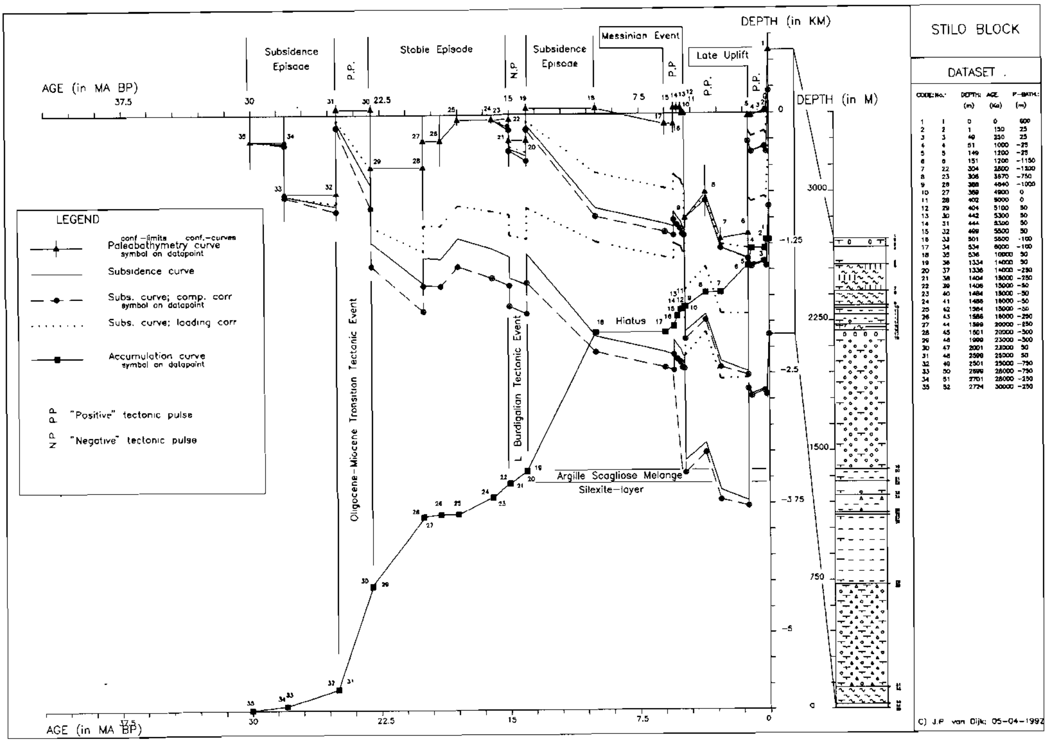

CROTONE PENINSULA
DATASET :
DEPTH (in KM)
DEPTH (in M)
AGE (in MA BP)
Subsidence Episode
Stable Episode
Uplift Episode
LEGEND.
Paleobathymetry curve
Subsidence curve
Subs. curve, comp. corr
Subs. curve; loading corr
Accumulation curve
Hiatus
Crotone Section
Vrica Section
Semeloro Section
C) J.P. van Dijk, 05-01-1992

Fig. 5h


STILO BLOCK
DATASET
DEPTH (in KM)
DEPTH (in M)
AGE (in MA BP)
Subsidence Episode
P.P.
Stable Episode
N.P.
Subsidence Episode
Messinian Event
Late Uplift
LEGEND
Paleobathymetry curve
Subsidence curve
Subs. curve; comp. corr
Subs. curve; loading corr
Accumulation curve
"Positive" tectonic pulse
"Negative" tectonic pulse
Oligocene-Miocene Transition Tectonic Event
L. Burdigalian Tectonic Event
Hiatus
Argille Scagliose Melange
Silexite-layer
C) J.P. van Dijk; 05-04-1992

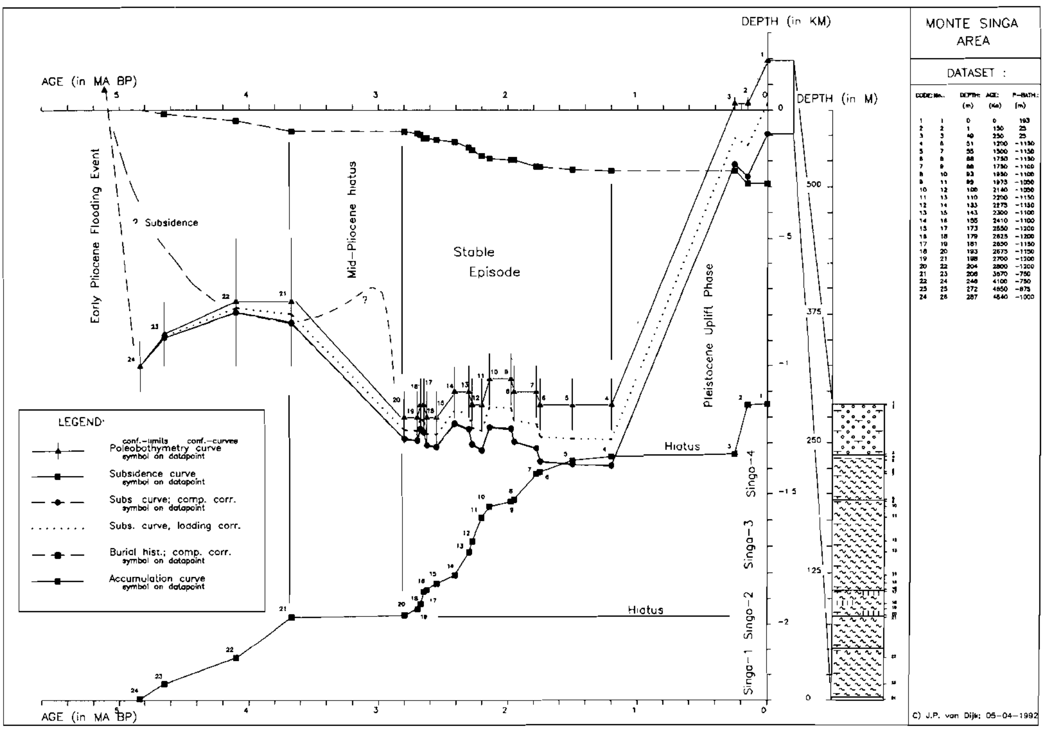
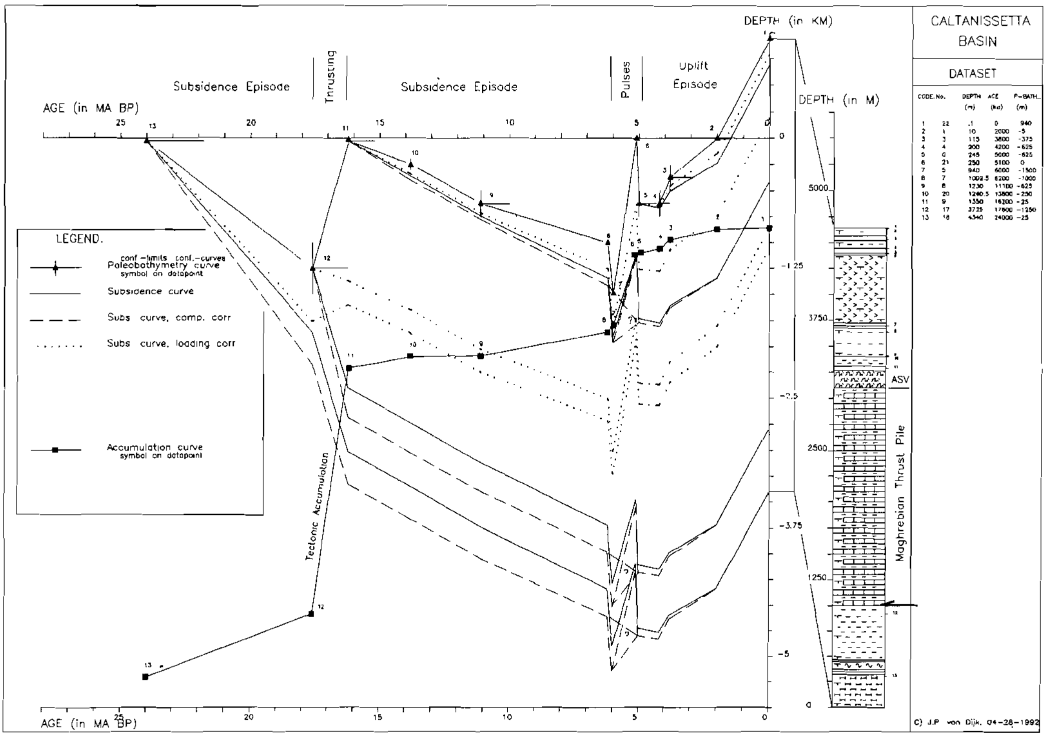

MONTE SINGA AREA
DATASET :
DEPTH (in KM)
DEPTH (in M)
AGE (in MA BP)
Early Pliocene Flooding Event
? Subsidence
Mid-Pliocene hiatus
Stable Episode
Pleistocene Uplift Phase
Hiatus
Singa-1
Singa-2
Singa-3
Singa-4
LEGEND
Paleobathymetry curve
Subsidence curve
Subs curve; comp. corr.
Subs. curve, loading corr.
Burial hist.; comp. corr.
Accumulation curve
C) J.P. van Dijk; 05-04-1992

Fig. 6a


CALTANISSETTA
BASIN
DATASET
DEPTH (in KM)
DEPTH (in M)
AGE (in MA BP)
Subsidence Episode
Thrusting
Subsidence Episode
Pulses
Uplift
Episode
LEGEND.
Paleobathymetry curve
Subsidence curve
Subs curve, comp. corr
Subs curve, loading corr
Accumulation curve
Tectonic Accumulation
ASV
Maghrebian Thrust Pile
C) J.P. van Dijk, 04-28-1992

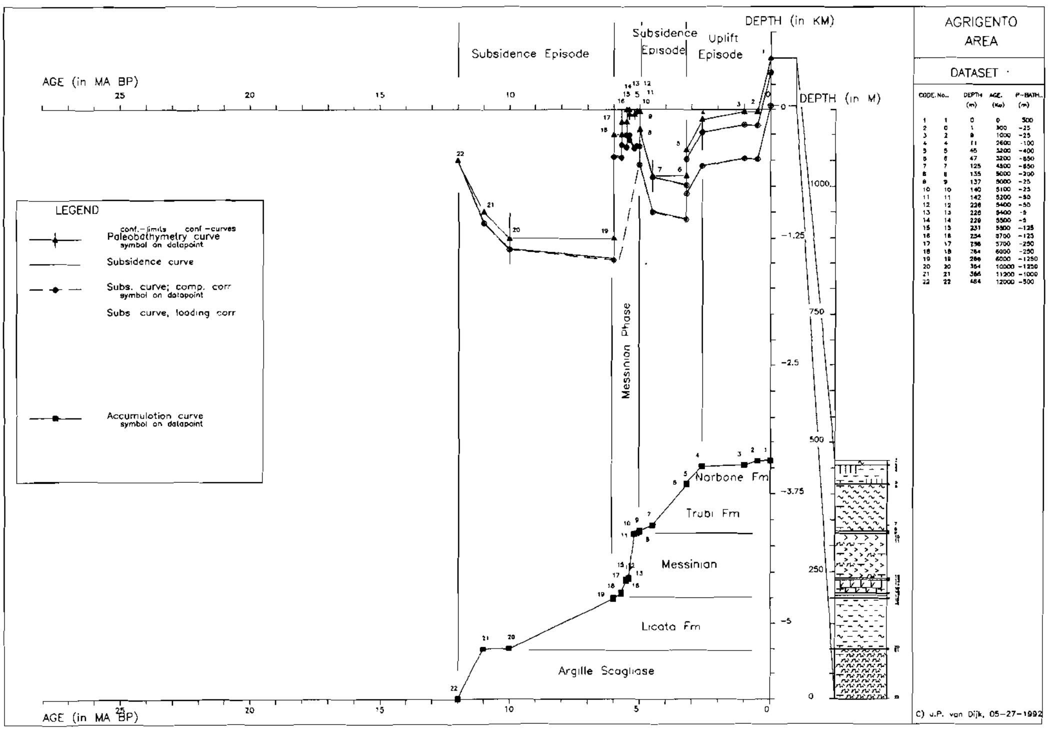
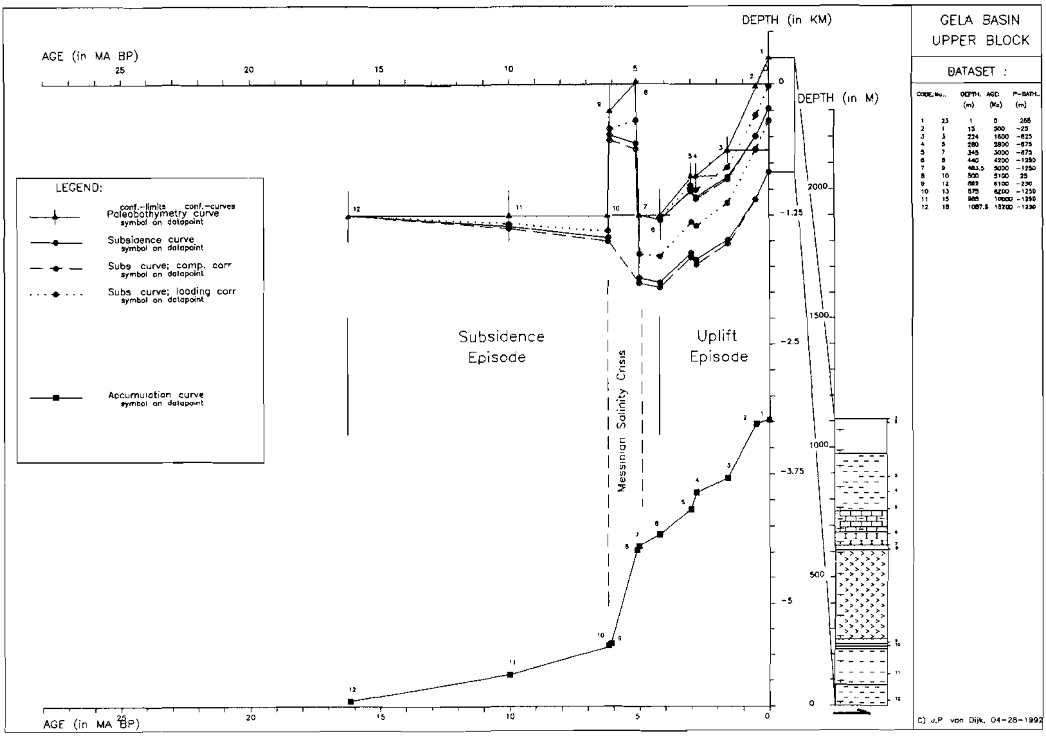
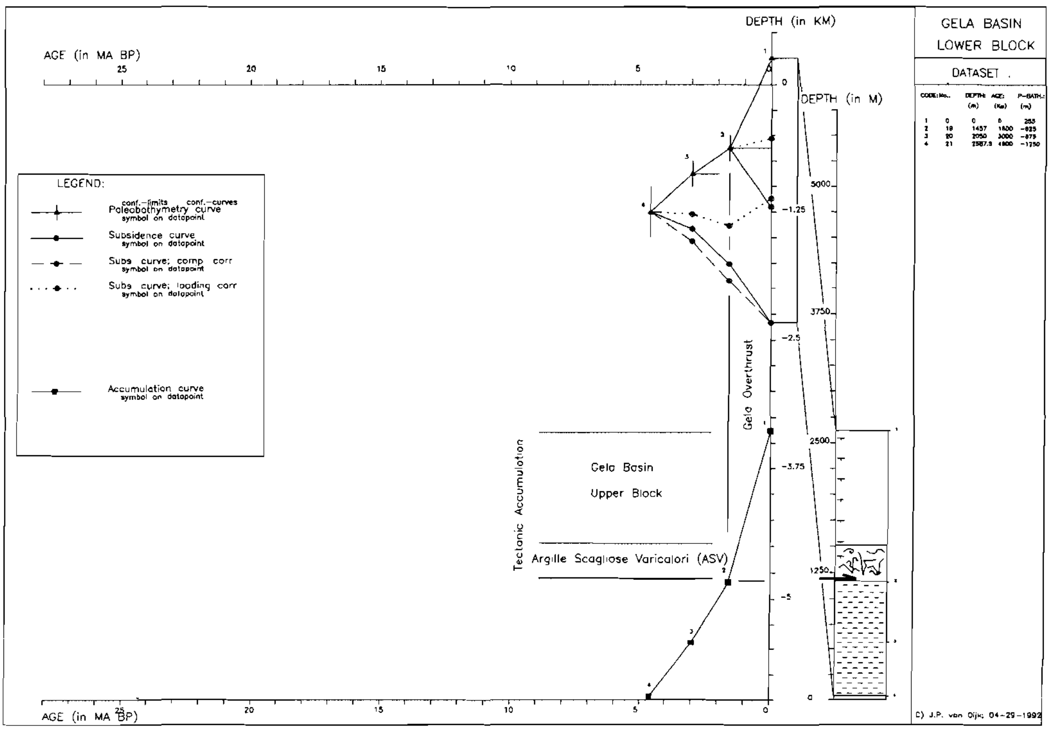

AGRIGENTO
AREA
DATASET
DEPTH (in KM)
DEPTH (in M)
AGE (in MA BP)
Subsidence Episode
Subsidence
Episode
Uplift
Episode
LEGEND
Paleobathymetry curve
Subsidence curve
Subs. curve; comp. corr
Subs curve, loading corr
Accumulation curve
Messinian Phase
Norbone Fm
Trubi Fm
Messinian
Licata Fm
Argille Scagliose
C) J.P. van Dijk, 05-27-1992

Fig. 6b

Fig. 6c

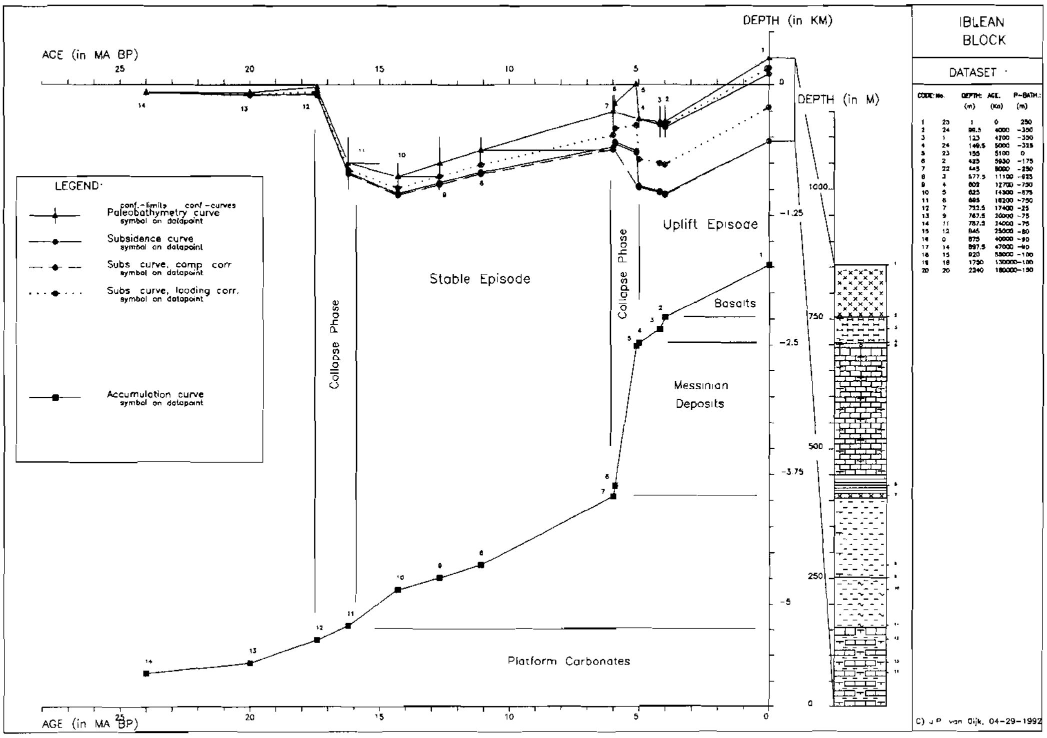


DEPTH (in KM)
AGE (in MA BP)
DEPTH (in M)
GELA BASIN
UPPER BLOCK
DATASET :
CODE: No.. DEPTH (m) AGE (Ka) P-BATH.. (m)
LEGEND:
conf.-limits conf.-curves
Paleobathymetry curve
symbol on datapoint
Subsidence curve
symbol on datapoint
Subs curve; comp. corr
symbol on datapoint
Subs curve; loading corr
symbol on datapoint
Accumulation curve
symbol on datapoint
Subsidence Episode
Messinian Salinity Crisis
Uplift Episode
C) J.P. van Dijk, 04-28-1992



DEPTH (in KM)
AGE (in MA BP)
DEPTH (in M)
GELA BASIN
LOWER BLOCK
DATASET .
CODE: No.. DEPTH (m) AGE (Ka) P-BATH.: (m)
LEGEND:
conf.-limits conf.-curves
Paleobathymetry curve
symbol on datapoint
Subsidence curve
symbol on datapoint
Subs curve; comp corr
symbol on datapoint
Subs curve; loading corr
symbol on datapoint
Accumulation curve
symbol on datapoint
Gela Overthrust
Tectonic Accumulation
Gela Basin
Upper Block
Argille Scagliose Varicolori (ASV)
C) J.P. van Dijk; 04-29-1992

Fig. 7a


DEPTH (in KM)
AGE (in MA BP)
DEPTH (in M)
IBLEAN
BLOCK
DATASET
CODE No. DEPTH (m) AGE (Ka) P-BATH. (m)
LEGEND
conf.-limits conf.-curves
Paleobathymetry curve symbol on datapoint
Subsidence curve symbol on datapoint
Subs. curve, comp. corr. symbol on datapoint
Subs. curve, loading corr. symbol on datapoint
Accumulation curve symbol on datapoint
Collapse Phase
Stable Episode
Collapse Phase
Uplift Episode
Basalts
Messinian
Deposits
Platform Carbonates
C) J.P. van Dijk, 04-29-1992

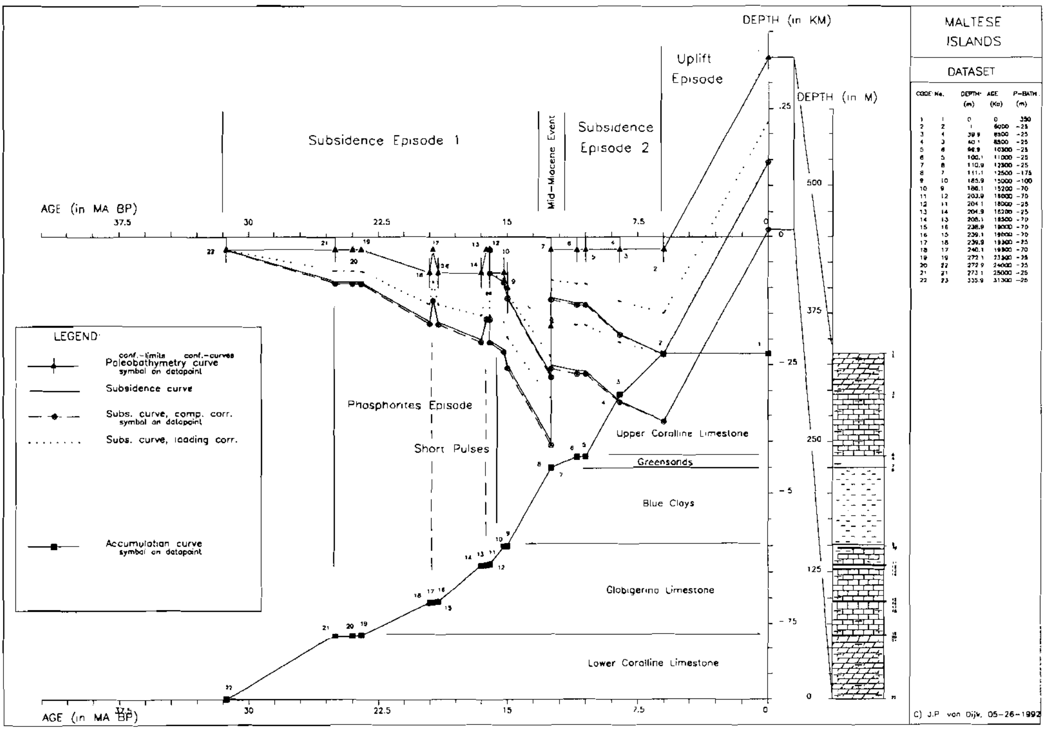
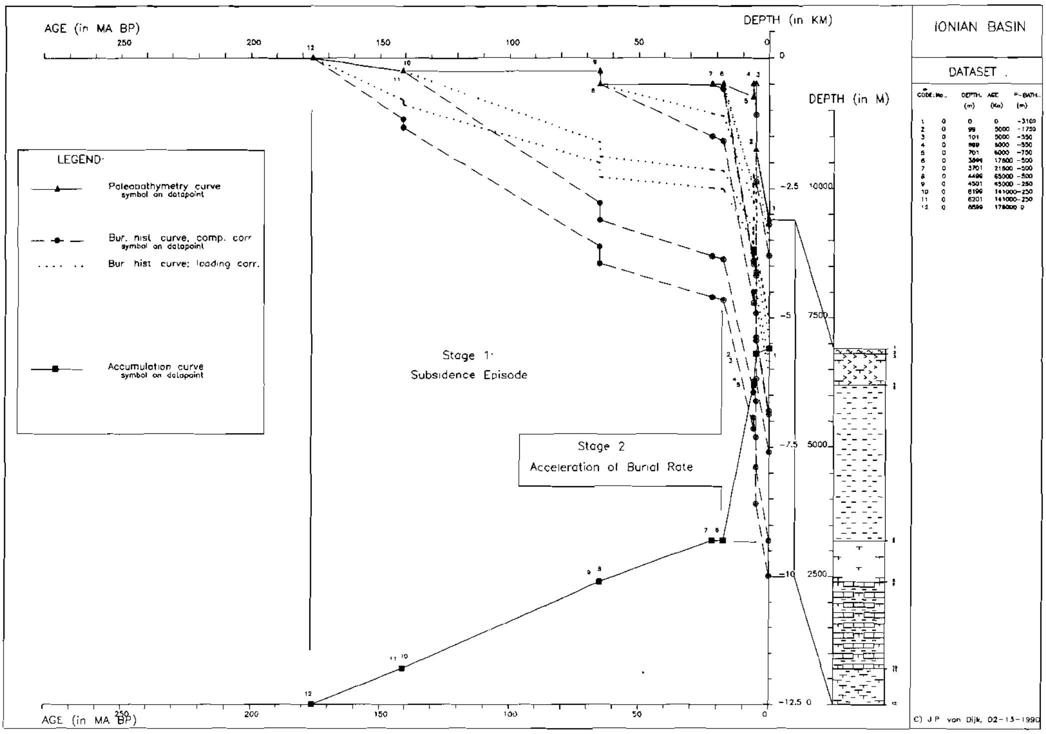

DEPTH (in KM)
MALTESE
ISLANDS
DATASET
CODE No. DEPTH (m) AGE (Ka) P-BATH. (m)
Uplift
Episode
DEPTH (in M)
Subsidence Episode 1
Mid-Miocene Event
Subsidence
Episode 2
AGE (in MA BP)
LEGEND
conf.-limits conf.-curves
Paleobathymetry curve symbol on datapoint
Subsidence curve
Subs. curve, comp. corr. symbol on datapoint
Subs. curve, loading corr.
Accumulation curve symbol on datapoint
Phosphorites Episode
Short Pulses
Upper Coralline Limestone
Greensands
Blue Clays
Globigerina Limestone
Lower Coralline Limestone
C) J.P. van Dijk, 05-26-1992

Fig. 7b

Fig. 7c


AGE (in MA BP)
DEPTH (in KM)
DEPTH (in M)
IONIAN BASIN
DATASET .
CODE: No.. DEPTH. (m) AGE (Ka) P-BATH.. (m)
LEGEND
Paleobathymetry curve symbol on datapoint
Bur. hist. curve, comp. corr symbol on datapoint
Bur. hist. curve; loading corr.
Accumulation curve symbol on datapoint
Stage 1 Subsidence Episode
Stage 2 Acceleration of Burial Rate
C) J.P. van Dijk, 02-13-1990

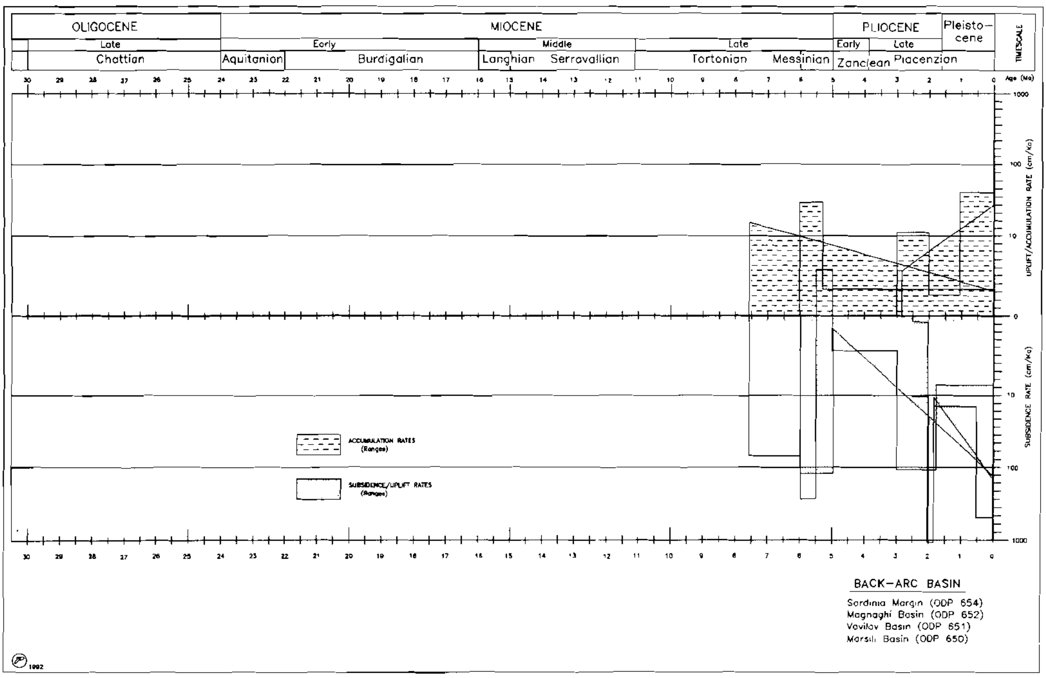
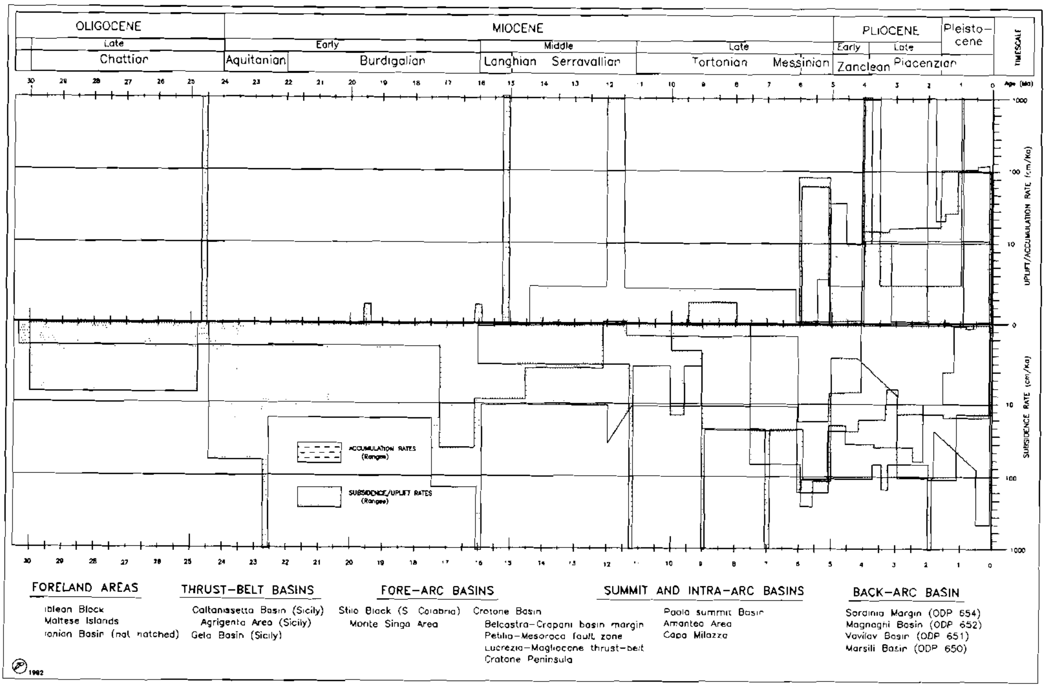
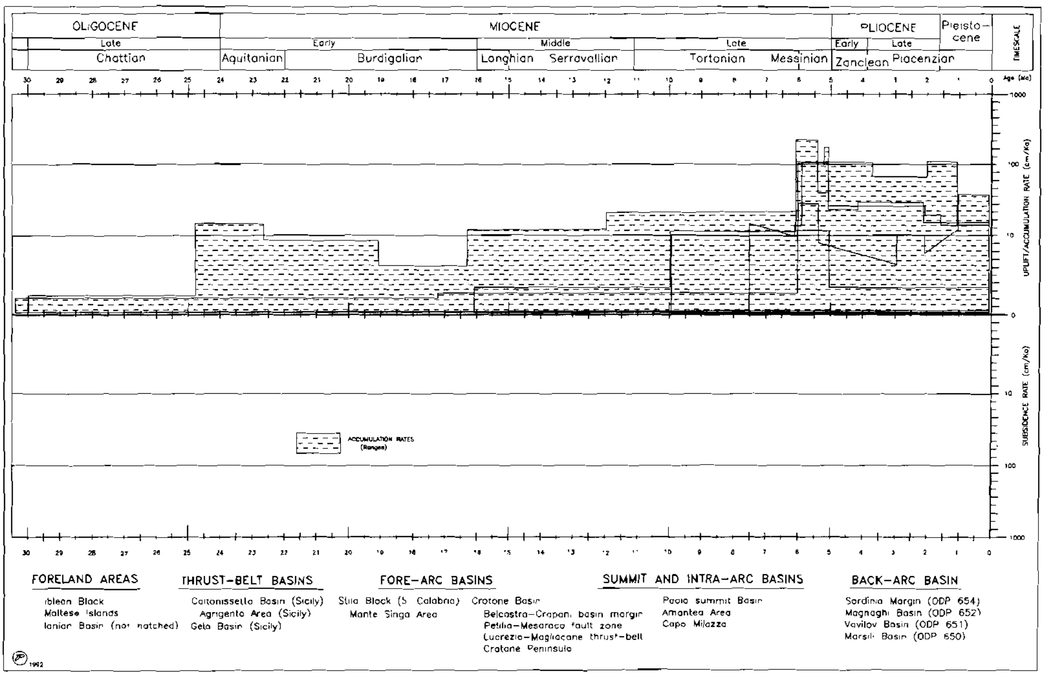

OLIGOCENE
MIOCENE
PLIOCENE
Pleisto-cene
Late
Early
Middle
Late
Early
Late
Chattian
Aquitanian
Burdigalian
Langhian
Serravallian
Tortonian
Messinian
Zanclean
Piacenzian
TIMESCALE
Age (Ma)
UPLIFT/ACCUMULATION RATE (cm/Ka)
SUBSIDENCE RATE (cm/Ka)
ACCUMULATION RATES (Ranges)
SUBSIDENCE/UPLIFT RATES (Ranges)
BACK-ARC BASIN
Sardinia Margin (ODP 654)
Magnaghi Basin (ODP 652)
Vavilov Basin (ODP 651)
Marsili Basin (ODP 650)
1992

Fig. 8c

Fig. 8a



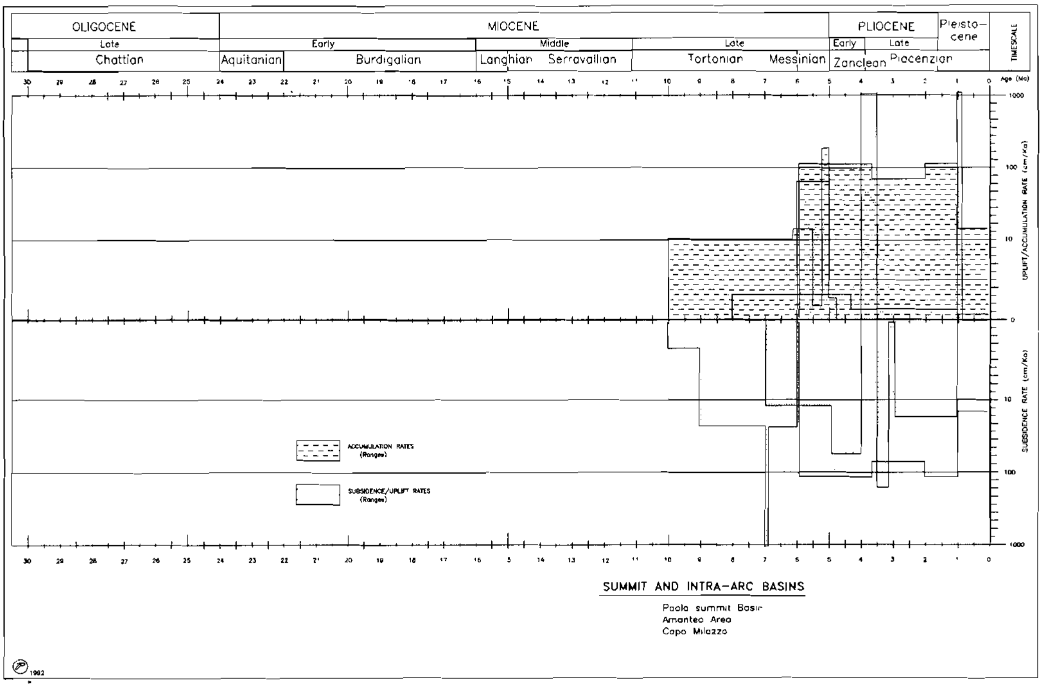
OLIGOCENE
MIOCENE
PLIOCENE
Pleisto-cene
Late
Early
Middle
Late
Early
Late
Chattian
Aquitanian
Burdigalian
Langhian
Serravallian
Tortonian
Messinian
Zanclean
Piacenzian
TIMESCALE
Age (Ma)
UPLIFT/ACCUMULATION RATE (cm/Ka)
SUBSIDENCE RATE (cm/Ka)
ACCUMULATION RATES (Ranges)
SUBSIDENCE/UPLIFT RATES (Ranges)
FORELAND AREAS
Iblean Block
Maltese Islands
Ionian Basin (not hatched)
THRUST-BELT BASINS
Caltanissetta Basin (Sicily)
Agrigento Area (Sicily)
Gela Basin (Sicily)
FORE-ARC BASINS
Stilo Block (S Calabria)
Monte Singa Area
Crotone Basin
Belcastro-Crapani basin margin
Petilia-Mesoraca fault zone
Lucrezia-Magliocane thrust-belt
Crotone Peninsula
SUMMIT AND INTRA-ARC BASINS
Paola summit Basin
Amantea Area
Capo Milazzo
BACK-ARC BASIN
Sardinia Margin (ODP 654)
Magnaghi Basin (ODP 652)
Vavilov Basin (ODP 651)
Marsili Basin (ODP 650)
1992



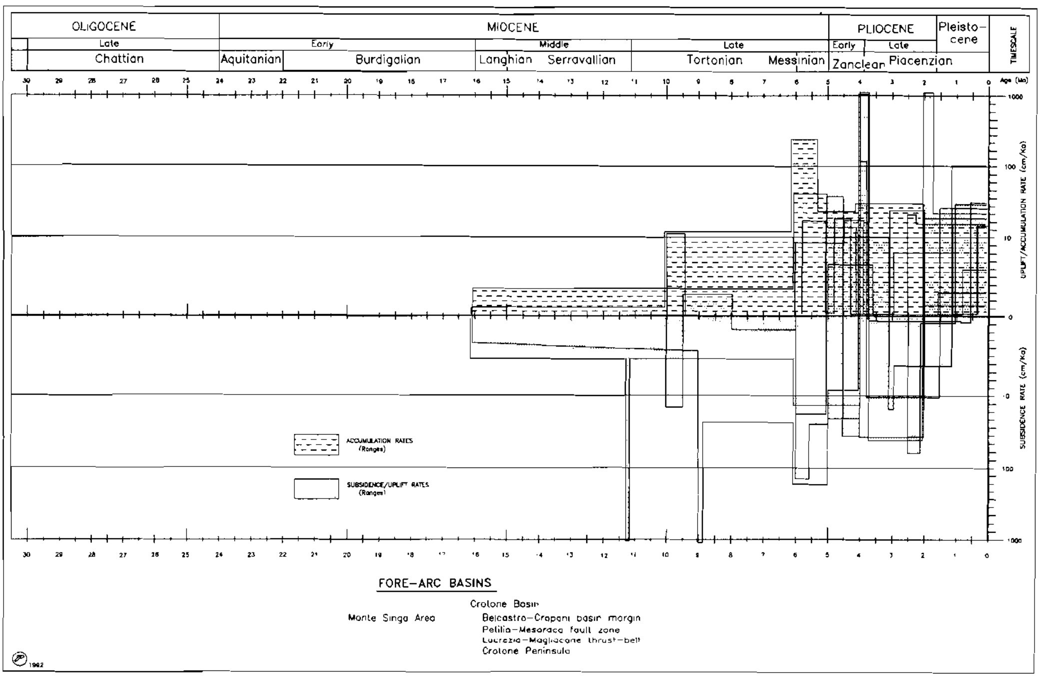
OLIGOCENE
MIOCENE
PLIOCENE
Pleisto-cene
Late
Early
Middle
Late
Early
Late
Chattian
Aquitanian
Burdigalian
Langhian
Serravallian
Tortonian
Messinian
Zanclean
Piacenzian
TIMESCALE
Age (Ma)
UPLIFT/ACCUMULATION RATE (cm/Ka)
SUBSIDENCE RATE (cm/Ka)
ACCUMULATION RATES (Ranges)
FORELAND AREAS
Iblean Block
Maltese Islands
Ionian Basin (not hatched)
THRUST-BELT BASINS
Caltanissetta Basin (Sicily)
Agrigento Area (Sicily)
Gela Basin (Sicily)
FORE-ARC BASINS
Stilo Block (S Calabria)
Monte Singa Area
Crotone Basin
Belcastro-Crapani basin margin
Petilia-Mesoraca fault zone
Lucrezia-Magliocane thrust-belt
Crotone Peninsula
SUMMIT AND INTRA-ARC BASINS
Paola summit Basin
Amantea Area
Capo Milazzo
BACK-ARC BASIN
Sardinia Margin (ODP 654)
Magnaghi Basin (ODP 652)
Vavilov Basin (ODP 651)
Marsili Basin (ODP 650)
1992

Fig. 8b

Fig. 8d



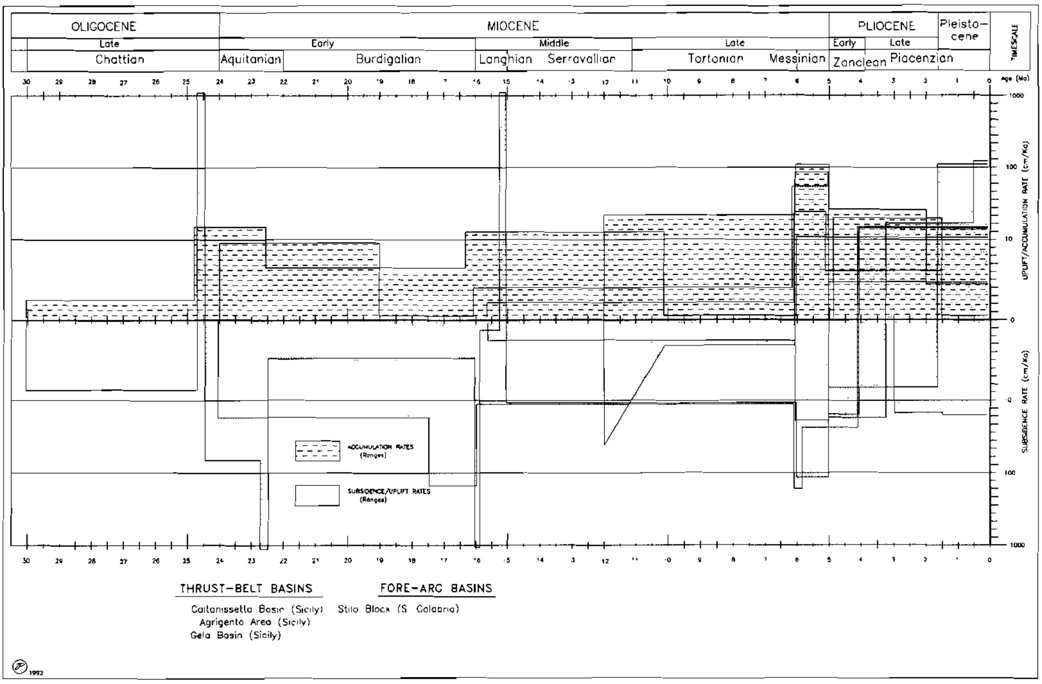
OLIGOCENE
MIOCENE
PLIOCENE
Pleisto-cene
Late
Early
Middle
Late
Early
Late
Chattian
Aquitanian
Burdigalian
Langhian
Serravallian
Tortonian
Messinian
Zanclean
Piacenzian
TIMESCALE
Age (Ma)
UPLIFT/ACCUMULATION RATE (cm/Ka)
SUBSIDENCE RATE (cm/Ka)
ACCUMULATION RATES (Ranges)
SUBSIDENCE/UPLIFT RATES (Ranges)
SUMMIT AND INTRA-ARC BASINS
Paola summit Basin
Amanteo Area
Capo Milazzo
1982



OLIGOCENE
MIOCENE
PLIOCENE
Pleisto-cene
Late
Early
Middle
Late
Early
Late
Chattian
Aquitanian
Burdigalian
Langhian
Serravallian
Tortonian
Messinian
Zanclean
Piacenzian
TIMESCALE
Age (Ma)
UPLIFT/ACCUMULATION RATE (cm/Ka)
SUBSIDENCE RATE (cm/Ka)
ACCUMULATION RATES (Ranges)
SUBSIDENCE/UPLIFT RATES (Ranges)
FORE-ARC BASINS
Crotone Basin
Monte Singa Area
Belcastro-Crapani basin margin
Petilia-Mesoraca fault zone
Lucrezia-Magliacane thrust-belt
Crotone Peninsula
1982

Fig. 8e

Fig. 8f


OLIGOCENE
MIOCENE
PLIOCENE
Pleistocene
Late
Early
Middle
Late
Early
Late
Chattian
Aquitanian
Burdigalian
Langhian
Serravallian
Tortonian
Messinian
Zanclean
Piacenzian
TIMESCALE
Age (Ma)
UPLIFT/ACCUMULATION RATE (cm/Ka)
SUBSIDENCE RATE (cm/Ka)
ACCUMULATION RATES (Ranges)
SUBSIDENCE/UPLIFT RATES (Ranges)
THRUST-BELT BASINS
Caltanissetta Basin (Sicily)
Agrigento Area (Sicily)
Gela Basin (Sicily)
FORE-ARC BASINS
Stilo Block (S. Calabria)
1992

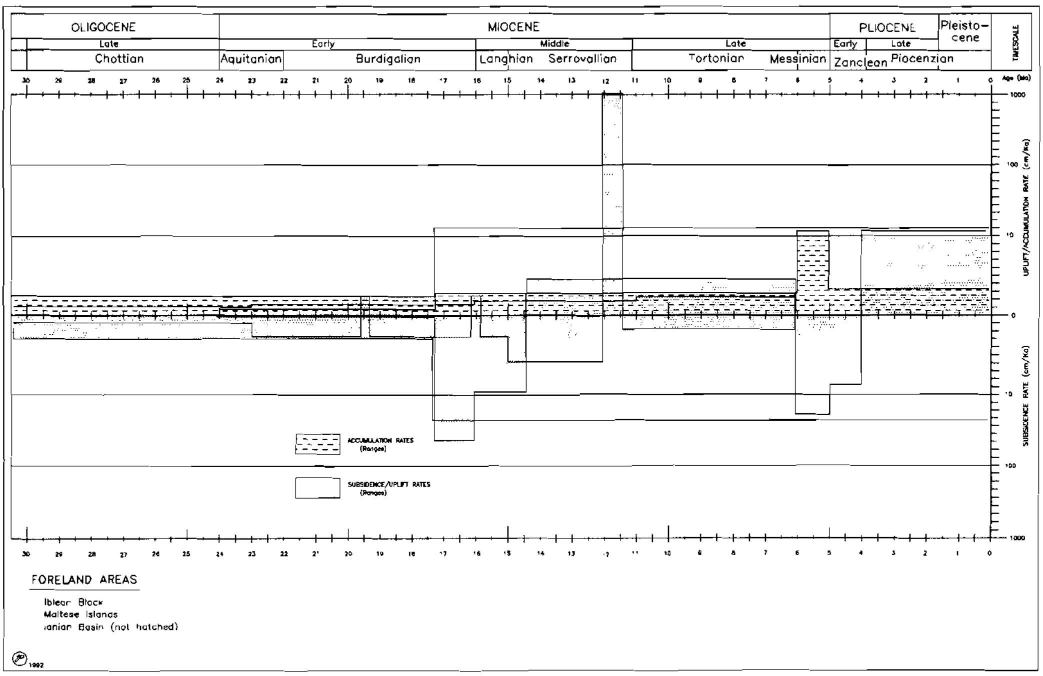

OLIGOCENE
MIOCENE
PLIOCENE
Pleistocene
Late
Early
Middle
Late
Early
Late
Chattian
Aquitanian
Burdigalian
Langhian
Serravallian
Tortonian
Messinian
Zanclean
Piacenzian
TIMESCALE
Age (Ma)
UPLIFT/ACCUMULATION RATE (cm/Ka)
SUBSIDENCE RATE (cm/Ka)
ACCUMULATION RATES (Ranges)
SUBSIDENCE/UPLIFT RATES (Ranges)
FORELAND AREAS
Iblean Block
Maltese Islands
Ionian Basin (not hatched)
1992

Fig. 8g

Janpieter van Dijk, PhD-Thesis, 1992
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Utrecht University, Budapestlaan 4, 3508 TA Utrecht,
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CHAPTER 5

THREE-DIMENSIONAL QUANTITATIVE RESTORATION OF CENTRAL MEDITERRANEAN NEOGENE BASINS; THE DYNAMIC GEOHISTORY APPROACH

Preprint from: Van Dijk, J.P. (1993); Three-dimensional quantitative restoration of central Mediterranean Neogene basins. In: Spencer, A.M. (Ed.); Generation, accumulation and production of Europe's hydrocarbons III. Special publication of the European Association of Petroleum Geologists No. 3, Springer-Verlag, Heidelberg, pp. 000-000.

Abstract. Three-dimensional computer-aided reconstructions of the Neogene development of the Central Mediterranean are presented from the Tyrrhenian back-arc basin and the Crotone fore-arc basin. The method developed consists of extrapolating data provided by geohistory analyses within a kinematic frame obtained by terrane analyses, balancing cross-sections and paleomagnetism. Two presentation methods are discussed. Time-Snapshot Plots show a restoration of paleo-landscapes and subsurface geology. Dynamic Geohistory Plots which we introduce in this paper, show the development in time of a transect through the area. They can be used to illustrate and investigate the effects of phases in basin evolution in both stratigraphic as well as tectonic senses. The results from the Central Mediterranean illustrate the effects of local thrust wedge dynamics and (Messinian) sea level fluctations. Two processes alternated. Local pulsating migration to the southeast of the Calabrian Arc was interrupted by regional stress phases related to plate reorganizations, which result in shortening in the Apennines and the cessation of back-arc rifting followed by large isostatic vertical movements. These conclusions place important constraints to numerical tectonophysical forward models, regarding the spatial and temporal distribution of vertical movements and the relative importance of processes such as passive subduction and intraplate stresses.

1. INTRODUCTION

The kinematic development of the Apennine-Maghrebide System (fig. 1) over the past 10 Million years was characterized by large horizontal mobility (see balanced cross-sections of Balley et al., 1986; Hill and Hayward, 1988; Endignoux et al., 1989; Sage et al., 1991). Many geodynamic mechanisms have been invoted as oceanization, active versus passive subduction, asthenospheric doming and various types of collisional processes (see for a review Van Dijk and Okkes, 1990, 1991). Understanding the timing and magnitude of crustal movements is fundamental in order to evaluate geodynamic hypotheses. As a result of the ODP Leg 107, drilling at six sites in the Tyrrhenian back-arc Basin (Kastens et al., 1987, 1990), the timing of the opening of the basin and formation of its oceanic crust is well known and can be compared with the phases of overthrusting in the surrounding orogenic systems. Two models for this comparison have been suggested. In one, thrusting in the Apennines and Sicilian Maghrebides coincided with phases of stretching and rifting of the Tyrrhenian back-arc basin (Moussat, 1983; followed by most authors). Recently, we suggested an alternative model in which (local) Tyrrhenian stretching episodes related to migration of the Calabrian Arc alternate with (regional) Apennine/Maghrebian thrusting phases (Van Dijk and Okkes, 1988, 1990, 1991). This last model has important implications for the relative contribution of local processes (slab pull, asthenosphere doming) and regional processes (intraplate stress; plate reorganization; global shear) to the dynamics of the region. It implies that the latter process interrupts and restabilizes the former, and therefore controls the local basin dynamics which are related to back-arc thermal dynamics and passive subduction along the arc.

Examples of two groups of basins will be presented in this paper. The Tyrrhenian back-arc basin is documented through drilling and seismic surveys. The Sicilian, Calabrian and Southern Apennines foreland basins are mainly documented through field work. In the first, basic questions in tectonophysical modelling concern the type of stretching model or subduction zone model and related processus and parameters which can be applied (fault kinematics, lithosphere properties, heat flow). Channell and Marechal (1989), Wang et al. (1989) and Cogan et al. (1989) presented the results of modelling exercises of this type for the Central Mediterranean. The second case regards basin kinematics in a setting with combinations of (oblique) strike-slip and thrust wedge dynamics. Hereby, processes such as sedimentation-deposition balance, compactional behaviour, fluid flow, overpressure and heat flow play a key role. An example of a small-scaled conceptual model for the southern Sicilian Gela area was presented by Novelli et al. (1987). We present the geological data processing, which provides the constraints for the tectonophysical modelling exersizes. The results of forward modelling are usually confronted with and tested against the geological model in its final, recent stage. We chose to develop a method which provides the possibility to perform this feed-back in every stage of the development of the basin.

In order to do so, geological data need to be translated into a quantitative format which is compatible with the output of forward tectonophysical modelling; in other words, the development through time of all three dimensions of past basin geometry must be constructed. This has always been one of the most challenging goals in Earth Sciences. Analyses of sedimentary basins, plate tectonic restorations, and paleogeographic reconstructions have tried to reach it by means of widely varying techniques. In this paper, a working method will be presented which ties these fields together, resulting in a quantified four-dimensional image of the development of a part of the Earth's crust. One of the main problems encountered is the incompleteness of the information, spatial as well as stratigraphic. Two approaches can be followed. The first consists of a three-dimensional restoration of the geometric and stratigraphic units as a whole. Although three-dimensional forward modelling of sedimentary basins is at an advanced stage (Welte and Yalçin, 1985; Tetzlaff and Harbaugh, 1989; Bayer et al., 1990; Tipper, 1990; Grigo et al., 1991), no solutions for the 3-D reconstruction problem have been presented yet. The mathematics for the structural balancing of three-dimensional kinematics have not yet been developed (see for a review of balancing techniques Woodward et al., 1991). The essentially two-dimensional reconstructions of fluid flow, thermal properties and compaction (e.g. Lerche, 1989) have not yet been extended to three dimensions. We therefore chose an approach which uses the one-dimensional geohistory method as a basis. A framework based on balanced cross-sections, plate kinematics and terrane analyses, serves as a basis for extrapolations of the various restored sequences in order to obtain a complete three-dimensional image. "Time-Snapshot Plots" (three-dimensional paleo-surfaces) represent topography ("synthetic landscapes"). A new method -the "Dynamic Geohistory Plot"- shows the time-space development of a sedimentary basin. Examples will be shown of topography as well as of layers in the subsurface.

2. STORAGE AND CALCULATION METHODS

Methods dealing with quantitative reconstructions of the geological record ("backward modelling") at present only deal with one or two of the three dimensions we are interested in (fig. 2). In balancing cross-sections, one horizontal and one vertical dimension is restored, whereas paleomagnetic analyses treat two horizontal components of kinematics. While the geohistory analysis method provides an absolute value along the (vertical) depth axis (Z), balancing cross-sections provides a depth value which is only relative. Thus, the only way of obtaining a complete reconstruction is to tie the results of these methods together. Therefore, our working method (figure 3) starts with the setting-up of a relational database in two parts. A stratigraphic part focusses on the vertical components and a kinematic part contains the horizontal components of movement. A geometrical classification ties these two parts together. Our database is constructed with the Dbase-4 package of MicroSoft Ltd. and contains general litho-, bio- and chrono-stratigraphic classifications, boreholes and field sections, and a bathymetry classification scheme.

The method of geohistory analysis has been developed by Sleep (1971), Perrier and Quiblier (1974), Watts and Steckler (1976), Horowitz (1976) and Van Hinte (1978). It is a one-dimensional method, which restores stratigraphic successions in boreholes or field sections to their original thickness for each time-slice and plots the restored units at their correct burial depth (Van Hinte, 1978; Ungerer et al., 1984 and Guidish et al., 1985). The method consists of three steps, for each of which a knowledge base must be provided. This knowledge base contains classifications such as zonations, application and correlation rules for these zonations, and restoration algorithms with various default parameters to match.

1. The first step consists of plotting the age against depth of deposition for each datapoint of the stratigraphic sequence. Age data are obtained from biostratigraphy, magnetostratigraphy and radiometrical dating. Paleobathymetry is obtained with micropaleontological and paleoecological analyses of foraminifera, and sedimentological facies analyses. Also, seismostratigraphy may be used to infer age-depth estimates.

2. The second step implies the restoration of the lithological units to their original thickness. The burial depth of each layer can in this way be plotted against age, substracting the decompacted thickness from the paleobathymetry. For this, porosity-depth curves for each lithology and algorithms for compaction behaviour versus parameters such as burial depth, age and composition, are needed. For an extensive discussion we refer to Perrier and Quiblier (1974), Watts and Ryan (1976), Sclater and Christie (1980), Bond and Kominz (1984) and Gallagher (1989).

3. In order to compare the age-depth relations to model-curves for the thermo-tectonic subsidence and uplift ("forward models"), corrections can be applied for the effect of the loading of the sedimentary rocks on the crust ("backstripping"). The most used corrections are based on Airy type isostasy, flexural (elastic) or visco-elastic (time-dependent) responses. For a full discussion we refer to Sleep (1971), Horowitz (1976), Watts and Ryan (1976), Falvey and Middleton (1980), Sclater and Christie (1980) and Bond and Kominz (1984).

For the decompaction and (isostatic) loading corrections, we use the algorithms and software published by Stam et al. (1987) and Gradstein and Fearon (1989). The method provides age(X)-depth(Z) values in the database for each chosen layer of the stratigraphic sequence. Our software for the preparation of the format for the geohistory diagrams is linked to the design package AutoCAD of Autodesk Ltd., well known in industrial and architectural design.

The geometric framework for the analyses is obtained as follows. The area of interest is divided into a number of sectors, each represented by a unique stratigraphic sequence known from field-analyses or boreholes. The sector boundaries are defined by tectonic elements, thrusts/reverse faults and normal faults, known from field mapping and seismic sections. Each sector is defined by a minimum number of X-Y points along the boundaries necessary to distinguish the sector from its neighbours. This method of dividing an area in tectonic sectors or blocks with each their unique tectono-sedimentary development shows affinity with the method of suspect tectonostratigraphic allochtonous terrane analysis and the orogenic collage concept. Although "terrane" may be a superfluous term -see for a critical review Sengör (1990)- we prefer to use it as a descriptive concept because it covers best the definition as needed in our computerized analyses. Our approach is similar to the one described by Ross and Scotese (1988) in their retrotectonic analysis of the Central American region.

The kinematic framework is constructed by means of regional plate-tectonic schemes, and local balanced cross-sections and paleomagnetic information. This provides X-Y positions for each point of each sector at a minimum number of fixed ages necessary to describe the displacement path of the sector. Consumption along convergent margins and creation of new sectors in areas of ocean-crust formation can be taken into account.

After combining the geohistory, geometric and kinematic information into one relational database, it becomes possible to perform interpolations in time and space of the depth-values. Groups of X-Y-Z pairs are compiled which define a certain layer in the (sub)surface or the topography itself as it was present at a certain time.

Algorithms which calculate meshes using these spatial datapoints are finally used to obtain a spatial surface grid. These methods can, however, effect the result in an important way (Tipper, 1977; Schaeber, 1988; Fisher and Wales, 1990; Srivastava and Mallet, 1990; Pflug et al., 1990): Faults may be smoothed out or accentuated, and non-existing topographic features may be created due to interpolation and overshoot when smoothing in between datapoints. One should therefore take care that artefacts are recognized and, if possible, avoided (see for example fig. 9 which is shown in it's non-corrected form to illustrate these effects). The algorithms chosen for the kriging and spline fitting procedures (cubic, bezier, nurbs) and the subsequent calculations of rectangular or triangular meshes, use factors such as the weighting of nearby and more distant points, which determine the smoothness vs. angularity and the texture of the reconstructed elements. This is often a matter of taste and depends heavily on the knowledge and processes involved in the creation of these geological elements and landscapes.

Our software for the interpolations and compilations of datapoints is linked to the AutoCAD design package V.10.0 of Autodesk Ltd. and the applications QuickSurf of Schreiber Instruments, Inc., and AutoShade rendering package of Autodesk Ltd., which fulfill the basic needs of our analyses.

3. PRESENTATION METHODS

We have developed two presentation methods for the four-dimensional datasets:

3.1. Time-Snapshot Plot. This plot shows a three-dimensional surface which represents topography at a certain time, a quantitative counterpart of the conventional paleogeographic maps ("synthetic paleo-landscapes"). Also, the shape of a selected buried layer characterized by a certain age or lithology can be shown at any moment in time. The plot and accompanying contour maps can be used as a basis for the reconstruction of paleo-landscapes, but can also provide data such as volume estimates of paleo-subsurface geology or specific water budgets of the basin.

3.2. Dynamic Geohistory Plot. This plot shows the development in time of one specified (seismic) section or transect through the area (fig. 4) (Okkes, 1988; Van Dijk, 1990). As such, the three-dimensional diagram contains one depth axis (Z), one time axis (X), and one distance axis (Y). The age (X) - and depth (Z) axes are directly compatible with the axes of a geohistory diagram, and the plot can therefore simply be described as a number of geohistory diagrams, placed along side each other and interpolated in the distance (Y) direction (fig. 4b). In the same way, the plot can be regarded as a series of transects through an area, stacked in the age (X) direction (fig. 4c). A complication, however, is that values along the distance (Y) axis are calculated in a specific way. For each time-slice, the position of the sectors on the map is calculated, a line is generated which connects the sectors, and cumulative distances along this "section-trace" are calculated. The total variations of the length of this section-trace through time therefore show stretching and shortening along the transect, which is especially illustrative for the horizontal mobility of the region.

On the horizontal (X-Y) plane of the diagram, a so-called "time-trace map" is plotted, which shows a net of the "section-traces" (lines which each interconnect the positions of the sectors in the distance (Y) direction for one moment in time), and the "time-traces" (lines which each interconnect the position of one sector in the age (X) direction). This map shows a clear image of the periods of shortening and stretching of the area along the transect (see below for an example; fig. 13b).

Examples from literature which show affinity with this "transect approach" are the reconstruction of the Neogene margin of the Lyon Gulf (Ungerer et al., 1984), the reconstruction of the South Mozambique Graben (Lerche, 1990) and the (qualitative) resource assesment model for a part of the geothermal region of northern California (Burns, 1990). These methods however only show a series of reconstructed transects without a continuous interpolation and furthermore do not account for the relative horizontal movement of parts of the section.

In the approach of Lerche (1990), the horizontal mobility is simulated by redrilling the section with pseudowells after each step of restoration. In our model, wells or pseudowells which cross a fault are treated in a different way. The hanging wall is simply regarded as being (tectonic) accumulation/accretion for the footwall (and vice versa), and we therefore create separate geohistory diagrams for each part of the section. This is done because in our case, large-scale overthrusting must be taken into account.

The Dynamic Geohistory Plot and accompanying contour maps can be used to illustrate phases of tectonic activity or sea level fluctuations. Another example of the usage of the Plot is in paleo-oceanographic investigations were it shows the potential of water-flow through a seaway passage, which depth in time can easily be read from the diagram. The Plot also gives the possibility to predict the stratigraphy for areas not yet covered by data.

Instead of depth below sea level, the values of alternative parameters can be plotted against the depth-axis of the Time-Snapshot and Dynamic Geohistory Plots. Examples are accumulation rate, subsidence-uplift rate and thermal parameters. The diagram can then be used to compare with tectonophysical forward models which predict the development through time along the transect.

4. DATA AND RESULTS

4.1 The Crotone Basin

The Crotone Basin has been chosen as an example on a relatively small scale. The basin is situated along the external side of the Calabrian Arc, upon the accretionary wedge system (fig. 5). It can be regarded as an oblique piggy-back basin locked between two sinistral convergent crustal shear zones (Van Dijk and Okkes, 1988; Van Dijk, 1990, 1991). We used data from field mapping, seismic sections, boreholes, satellite photography and aeromagnetics. The evolution of the basin shows a typical development of the Strike-slip Cycle from a tensional pull-apart type of basin in the Tortonian - early Messinian to a stage of basin inversion in the late Messinian - middle Pliocene (fig. 6). The development of numerous unconformities along the basin margins are related to tectonic pulses of the accretionary thrust wedge dynamics.

The Time-Snapshot Plot for 10.0 Ma (fig. 7a) shows small basins with a NW-SE trend, representing the initial opening along Riedel shear fractures within the sinistral, NW-SE trending Petilia-Rizzuto shear zone, which confines the (later developed) Crotone basin along the southwest. The Time-Snapshot Plot for 3.0 Ma (fig. 7) shows a large central basinal area, confined along the southwest by a NW-SE trending margin. Along this margin, topographic highs are visible, representing upthrusted terrains, which belong to the former small strike-slip basins (previous figure). These backthrusts are the result of the regional compression phase in middle Pliocene times. Furthermore, the Plot for 10.0 Ma illustrates topological artefacts which were created by the computerized gridding method. Topographic ridges seem to cross the basin floor, but are not real: they were created by smoothing of the data towards the extremes of the dataset.

The Dynamic Geohistory Plot along the same, southern basin margin for the basement subsidence (fig. 8), shows a remarkable feature. Uplift and subsidence pulses along the basin margin become extinct towards the basin centre. This illustrates the tectonic origin of the unconformities and is fundamental for the understanding of the processes which create the depositional sequences.

4.2 The Tyrrhenian Basin

The analysis of the Tyrrhenian back-arc basin uses the results of the ODP Leg 107 cores (fig. 9), which provide biostratigraphy, magnetostratigraphy and paleobathymetry information (Kastens et al., 1987, 1990). Furthermore, we used sequence-stratigraphy for on-shore geology and seismic stratigraphy for the off-shore parts (fig. 9; see for a review Van Dijk, 1990, 1991; Van Dijk and Okkes, 1991). The considerations of Van Dijk and Okkes (1991) have been taken as a basis for the kinematic framework for the past 16 million years (fig. 10). This framework is based on the interaction of two processes: (a) A pulsating gravitational displacement of the Calabrian Element, a supracrustal lithosphere slab, to the SE, with accompanying rotative expulsion of thrust sheets in an oroclinal fashion and (b) Translation to the NE of the whole system, with bending-related rotation of large blocks related to phases of NE-SW compression in the Early Miocene (16.0 Ma), mid-Pliocene (4.0-3.0 Ma), and mid-Pleistocene (1.0-0.5 Ma) times.

The stratigraphic sequences which were processed all lie on an approximately N100 trending transect through the area, which is the mean vector of opening of the back-arc basin (fig. 1). One example of a geohistory diagram for the boreholes in the Tyrrhenian sea, for the Magnaghi Basin (fig. 11), hows some features which are typical: An initial phase of rifting, accompanied by large sedimentation and subsidence-rates, followed by a phase of pulsating, accelerating subsidence. The magnitudes of subsidence do not fit any of the existing models for rifting, which suggests that the Tyrrhenian back-arc basin opening was governed by a special type of interaction of different processes.

Figure 12 shows a compilation of the paleobathymetry and subsidence/uplift curves, extracted from the total set of diagrams used in the analysis. The relative amounts of the vertical component of movements of the different settings in the system can be seen. These are largest in the areas adjacent to the arc, and intermediate in the back-arc region.

The Dynamic Geohistory Plot for the topography along this transect (fig. 13a) shows phases of regional shortening (middle Pliocene, middle Pleistocene-Recent), expressed by general uplift and shallowing. The Messinian sea level fluctuation between 6.0 and 5.0 Ma shows a pattern which is comparable with the expression of the phases of compression; a temporal increase in landmass, which is in this case due to the sea level lowering. Three major phases of subsidence are shown: Late Tortonian, Early Pliocene, and Late Pliocene. Also, a middle Pleistocene-Recent collapse is clear. The time-trace map (fig. 13b) shows the periods of stretching along the transect, which result from the kinematic model used. The contour plot (fig. 13c) shows an alternating forward and backward displacement of the land-area, which is evidenced by an undulating bend. This bend contains some gaps, due to missing information from the area directly NW of the recent arc. The undulations reflect the pulsating displacement of the Calabrian supracrustal slab to the southeast (Van Dijk and Okkes, 1990). We distinghuish two phases: During long episodes of slab migration, underplating along the thrust wedge occurred. The migration was interrupted by short pulses of accretion along the wedge and related basin inversion. This resulted in uplift of the arc with increase and migration of the emerged area.

A summary of data which concern rotations, thrusting and unconformities in the surrounding orogenic belt (figs. 12b and 13c) reveals that subsidence pulses in the Tyrrhenian Basin alternate with phases of thrusting, rotation and the creation of unconformities in the surrounding Apennines. Furthermore, phases of accelerating subsidence in the Tyrrhenian Basin (Okkes, 1988), which are related to the ceasing of rifting and the onset of sedimentation on the newly created basaltic crust, coincide or just predate the contractional phases in the Apennines. Sartori (in Kastens et al., 1990), in his qualitative analysis of the ODP borehole data, also observed the accelarated subsidence (Okkes, 1988; Van Dijk and Okkes, 1988, 1990, 1991). His model, however, related the relative long phases of back-arc rifting to progressive thrusting in the Apennines and the short, interrupting phases to restabilization with mainly vertical tectonics creating the unconformities. The data presented here support the second kinematic model discussed in the introduction: The translation of the arc to the southeast, the opening of the back-arc basin and the progressive evolution of transpressive thrust-wedge (piggy-back) basins in the Apennines were related to the gravitational migration of the Calabrian Element. The migration was interrupted by short periods of regional compression, which lead to contractional tectonics in the surrounding orogenic belts. These short phases of regional compressive stress blocked the roll-back process. Collision of the migrating slab with the foreland bulge provoked thrust wedge accretion and related initial basin margin uplift and tilting. Subsequent restabilization of the Coulomb wedge resulted in tensional faulting, subsidence and onlap. This complex process created major unconformities along the external fore-arc basin margins (Van Dijk, 1990, 1991). What remains is the search for mechanisms which explain the collapse of the back-arc basin during these stress phases. Two possible explanations are contractional synclinal downbending, and a collapse due to rupture of subducted lithosphere and the sinking of a detached fragment (see for a discussion Van Dijk and Okkes, 1988, 1990, 1991).

5. CONCLUSIONS

The working method presented provides an effective way of combining all the available data on one specific area into a quantified space-time frame. By means of the Time-Snapshot Plot and the Dynamic Geohistory Plot, insight can be obtained in the four-dimensional development of a sedimentary basin. Through extrapolations, incompatibilities in the datasets can be detected, and predictions can be made for areas from which data are missing. Furthermore, the representation methods give the opportunity to manipulate available geological data in a way that they can be compared to predictions from tectonophysical models, in all four dimensions.

The examples from the Crotone Basin illustrate features of basin inversion tectonics on the scale of a small thrust-wedge basin. The Dynamic Geohistory Plot from the Central Mediterranean shows how the combination of various datasets supports the model of alternating back-arc basin opening and orogenic contraction, which can be explained by an interchange between local subduction-related processes and phases of regional compressive stress.

Acklowledgements. I greatly acknowledge the stimulating coöperation with Dr. F.W.M. Okkes during the early stages of the development of the system for three-dimensional restorations. The valuable suggestions of Dr. F.W. Hilgen, Prof. J.E. Meulenkamp, Dr. G.J. Van der Zwaan and Dr. W.J. Zachariasse have been of great importance. An earlier version of the manuscript has been critically reviewed by Prof. J.E. Meulenkamp and Dr. G.J. Van der Zwaan. The assistance of Dr. P. Sjoerdsma and R. Van Dam during the development of computer programs is highly appreciated. Special thanks are due to D. Nocerino and T. Van Hinte for their assistance with the computer graphics.

FIGURE CAPTIONS

Figure 1.
a. Geological map of the Central Mediterranean with the location of the Crotone Basin (rectangle) and the investigated transect through the Tyrrhenian Basin (double line). Modified after Van Dijk and Okkes (1990, 1991).

Figure 2.
Restoration methods in the Earth Sciences and the spatial dimensions treated.

Figure 3.
Flow chart for four-dimensional restoration of sedimentary basins. The system has been installed on a small network of microcomputers, making use of commercial, user-friendly software packages for database management and graphical design where possible.

Figure 4.
(a) Dynamic Geohistory Plot showing the development of topography through time of a NE-SW section along the margin of a tensional basin. The hatched areas show the profile of the topography at the beginning and end (Recent) of the chosen time-slice. A transgression from NE to SW is evidenced by the trace of the coastline through time. Also, two distinct phases of stretching are indicated by rapid increase in length of the transect.
(b) The Dynamic Geohistory Plot, reduced to a series of geohistory diagrams.
In this way, a well-constrained seismic section can be processed to produce an image of it's development in time, using pseudo-wells if necessary (see also Lerche, 1990 for this 2D approach). Also, a series of tectonostratigraphic columns from field analyses combined with borehole data, of which the exact basin shape is unknown, can be restored.
(c) The Dynamic Geohistory Plot, sliced to give a series of transects.
This can then give clues to basin type along the section and various tectonophysical parameters involved. Thus, the approach adds one (time) dimension to the synthetic seismic section of Van Hinte (1983). The paleo-traces on the map follow a line which interconnects the paleo-position of the terranes and is not necessarily straight (fig. a).

Figure 5.
Geological sketch-map and composite profile of the Crotone Basin. From Van Dijk (1990).
Note that the section can be read in a N-S, as well as in an E-W or NW-SE sense. The basin is situated upon a slab, detached at a depth of circa 2 km. This slab, facing the subduction trough, accomodates for the increase in the taper angle of the Coulomb wedge.

Figure 6.
Geohistory Diagram of the Crotone Basin. Modified after Van Dijk (1990, 1991). Two reference-levels have been processed: Base of the section (late Burdigalian; 16.2 Ma) and the base of the Pliocene (5.0 Ma). Accuracy intervals have been indicated along the paleobathymetry curve.

Figure 7.
Time-Snapshot Plots of the topography ("synthetic landscapes") of the Crotone Basin.
The thick line represents the intersection of the topography grid with the sea level, i.e. the coastline. The majority of the data used are situated near the southern margin of the basin. Note the small computer-generated peninsula in the centre of the Plot for 3.0 Ma (...).

Figure 8.
Dynamic Geohistory Plot of the Crotone Basin.
The subsurface reference-level chosen is the top of the basement, i.e. the base of the Tortonian (10 Ma), along a SW-NE transect of the southern basin margin. Note that the observed ridges representing pulses in subsidence are not artefacts like in figure 7b, but are created by real interpolation between pulses of various magnitude.

Figure 9.
Terrane map of the Central Mediterranean indicating the data used in our analyses. Based on Van Dijk and Okkes (1990, 1991).

Figure 10.
Kinematic model for the Neogene development of the Central Mediterranean. Slightly modified after Van Dijk & Okkes (1988, 1990, 1991). The model is the basis for the kinematics of the terranes used in our analyses.

Figure 11. Geohistory diagram of the Central Tyrrhenian Magnaghi Basin ("terrane 4"), based on data from ODP Site 652 (Leg 107) (Kastens et al., 1990). The data of Sprovieri et al. (in Kastens et al., 1990) were followed for the paleobathymetry estimates. Vertical bars along the subsidence/uplift curve indicate accuracy intervals. See figure 6 for a legend.

Figure 12.
Compilation of paleobathymetry and subsidence/uplift curves for the Central Mediterranean.
The diagram is a side view of the Dynamic Geohistory Plot. The surface grid has been omitted. The Plot shows the curves of the individual geohistory diagrams (paleobathymetry and subsidence curves) as used in the analysis.

Figure 13.
(a) Dynamic Geohistory Plot of the Central Mediterranean, showing the topography along a NW-SE section, for the time-slice 10 Ma to recent.
Geohistory diagrams (paleobathymetry) of the individual stratigraphic columns and boreholes used are plotted along the grid. They show the control points used for the gridding procedure. These control points are represented by 3D balls, cubes and tetraeders fixed to the grid in virtual computer space.
(b) Time-trace map of the Dynamic Geohistory Plot.
The plot illustrates how shortening and stretching along the transect, as implied by the kinematic model used, has been incorporated in the analysis. The irregular spacing of the transect lines is due to the fact that for every datapoint one transect is calculated and datapoints are irregularly spaced. The density of the spacing thus shows the coverage of data used for each timeslice.
(c) Contour map of the Dynamic Geohistory Plot.
The raw computer output has been edited interactively, and data are appended concerning rotations and phases of thrusting as known from the Apennines and Sicilian Maghrebides and datings of volcanic deposits from the Tyrrhenian back-arc basin (see text for reference). Furthermore, landmasses have been interpolated where they appear to be missing due to extrapolations during the gridding procedures. An intriguing feature is the prediction of a mid-Messinian erosion phase in the central Tyrrhenian Sea (Issel Basin), which has indeed been observed in seismic profiles.
(d) Geographical location map of the processed transect.

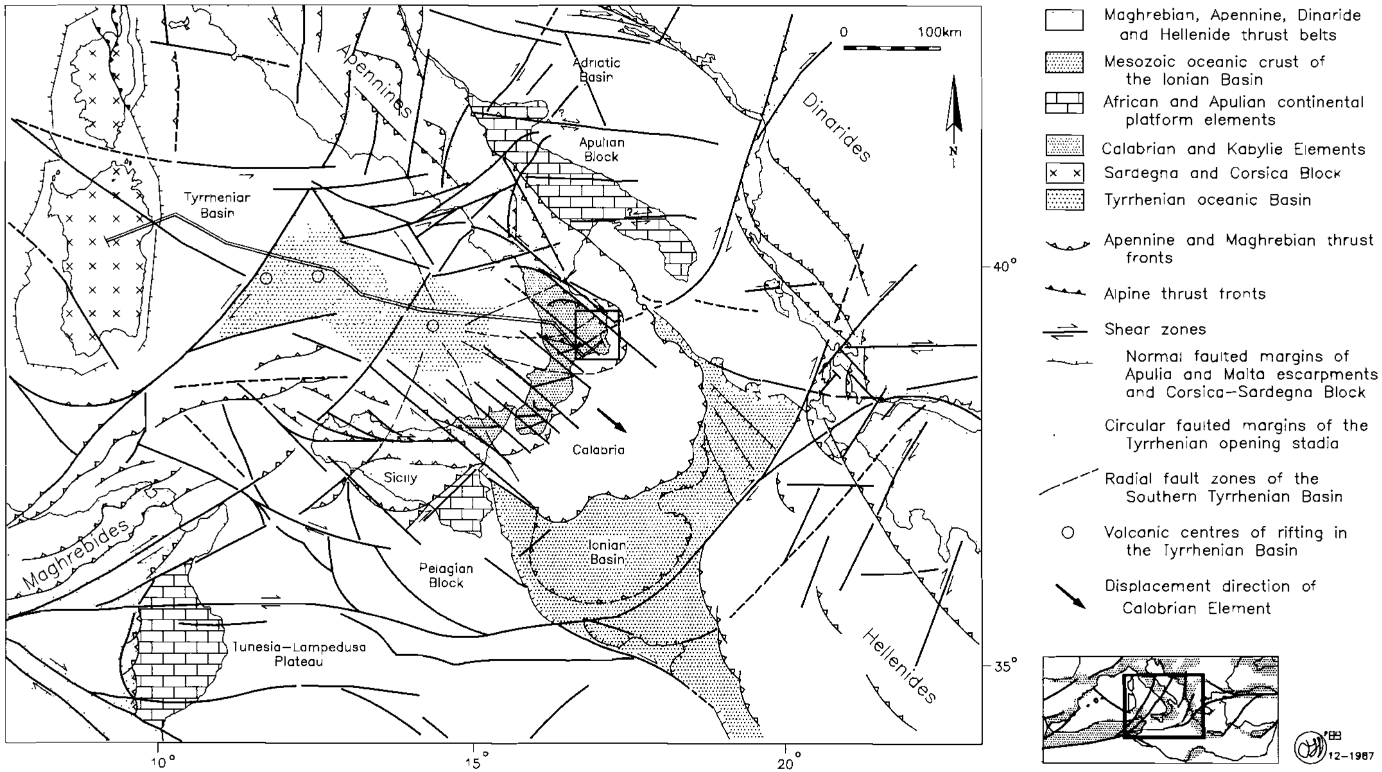
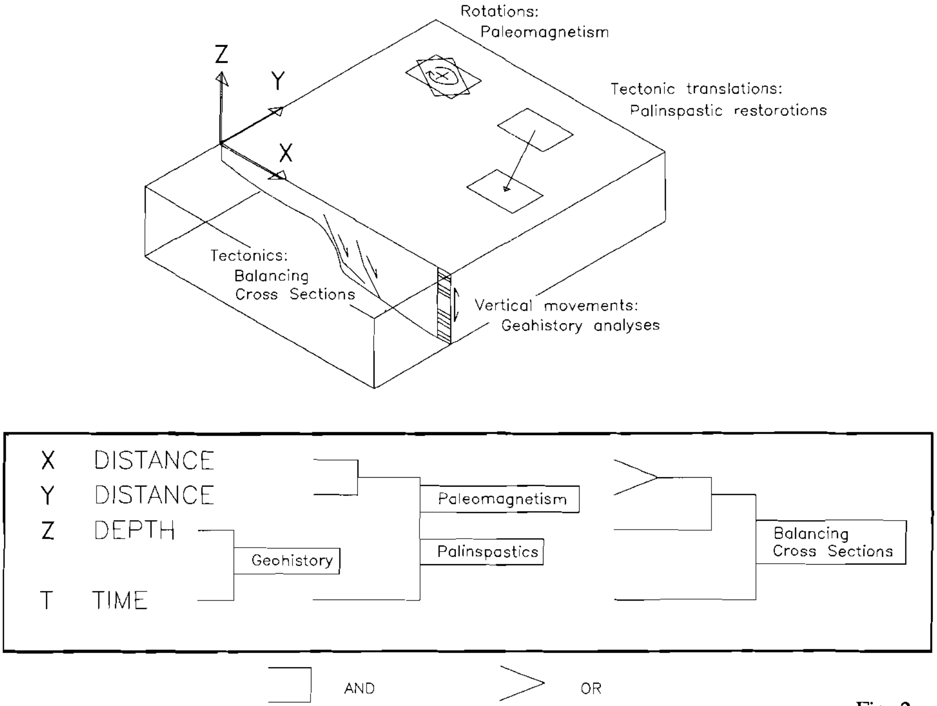
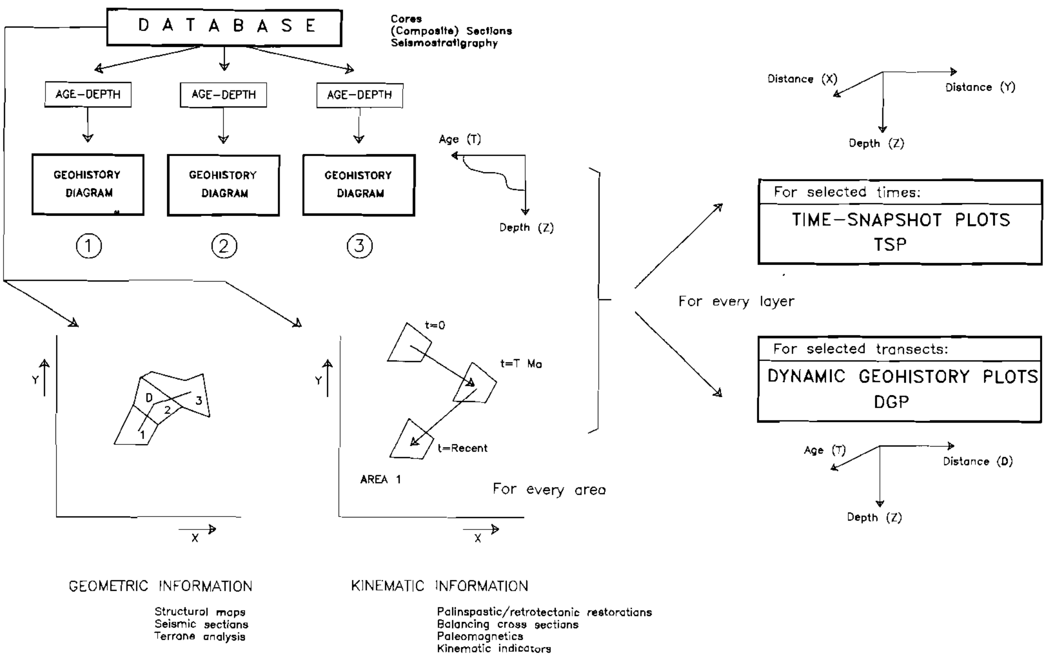

Adriatic Basin
Apulian Block
Apennines
Dinarides
Tyrrhenian Basin
Calabria
Sicily
Ionian Basin
Pelagian Block
Maghrebides
Tunesia–Lampedusa Plateau
Hellenides
0 100km
N
40°
35°
10°
15°
20°
Maghrebian, Apennine, Dinaride and Hellenide thrust belts
Mesozoic oceanic crust of the Ionian Basin
African and Apulian continental platform elements
Calabrian and Kabylie Elements
Sardegna and Corsica Block
Tyrrhenian oceanic Basin
Apennine and Maghrebian thrust fronts
Alpine thrust fronts
Shear zones
Normal faulted margins of Apulia and Malta escarpments and Corsica–Sardegna Block
Circular faulted margins of the Tyrrhenian opening stadia
Radial fault zones of the Southern Tyrrhenian Basin
Volcanic centres of rifting in the Tyrrhenian Basin
Displacement direction of Calabrian Element
12–1987

Fig. 1



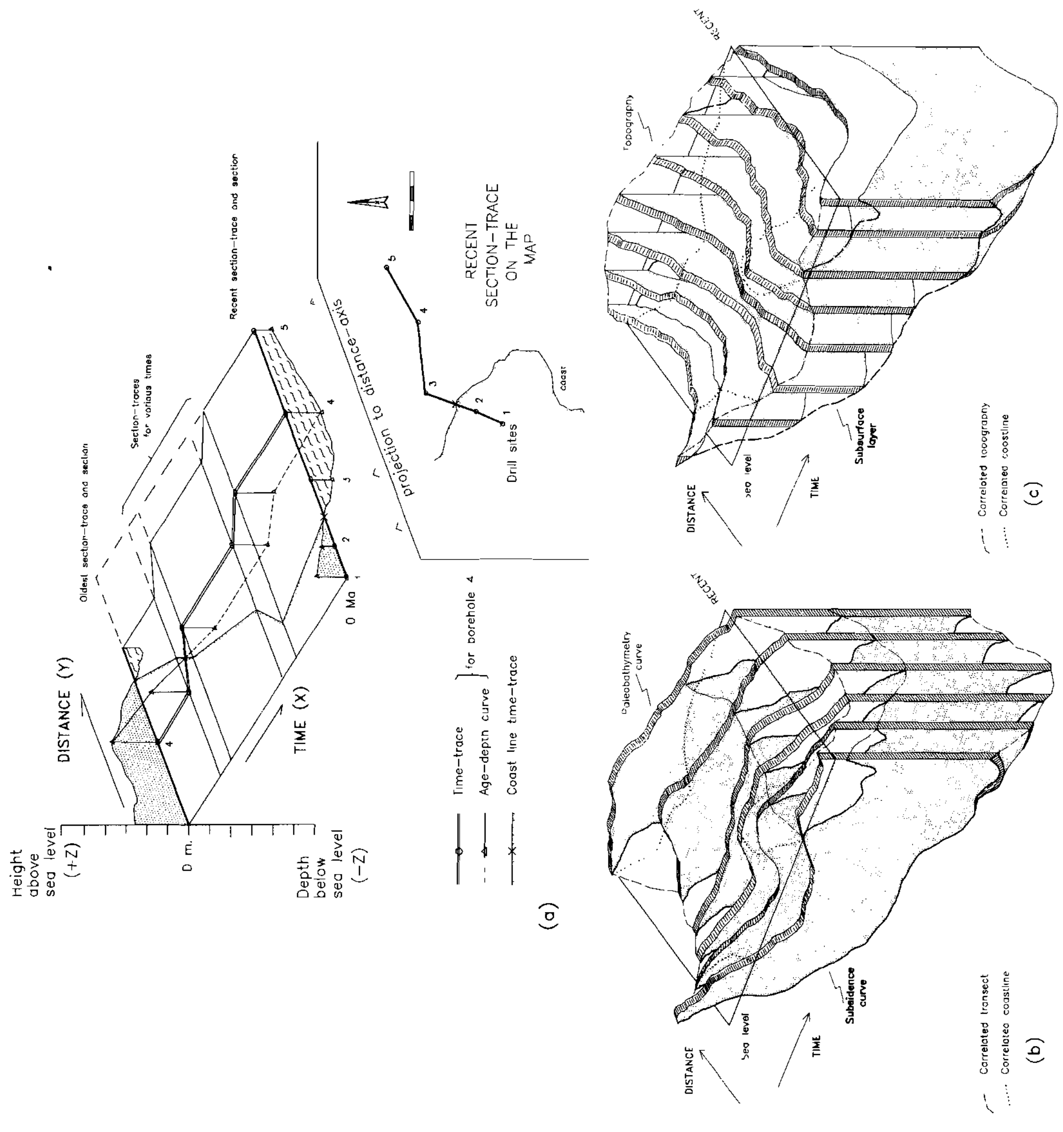
Rotations:
Paleomagnetism
Z
Y
X
Tectonic translations:
Palinspastic restorotions
Tectonics:
Balancing
Cross Sections
Vertical movements:
Geohistory analyses
X DISTANCE
Y DISTANCE
Z DEPTH
T TIME
Geohistory
Paleomagnetism
Palinspastics
Balancing
Cross Sections
AND
OR

Fig. 2



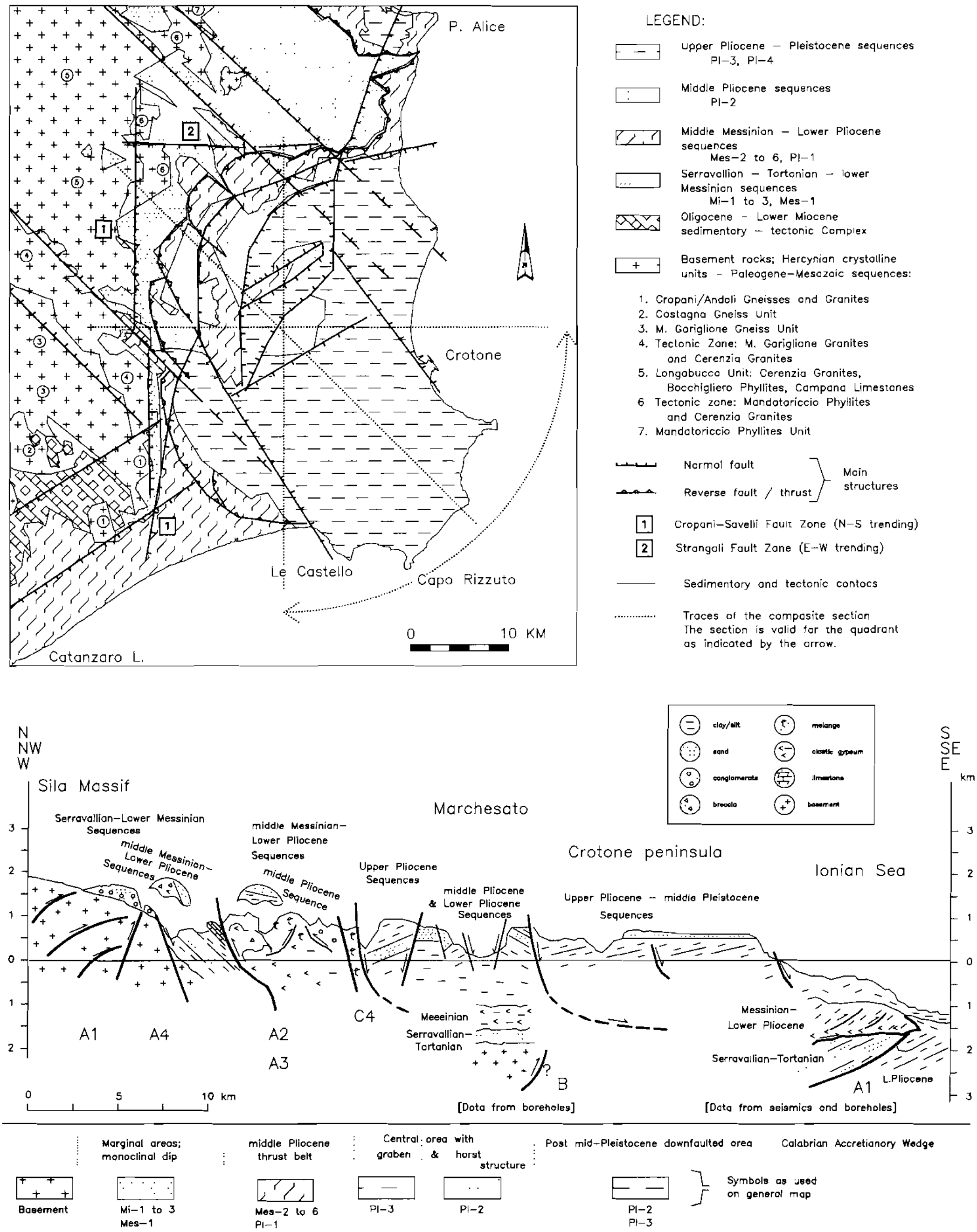
D A T A B A S E
Cores
(Composite) Sections
Seismostratigraphy
AGE-DEPTH
AGE-DEPTH
AGE-DEPTH
GEOHISTORY DIAGRAM
GEOHISTORY DIAGRAM
GEOHISTORY DIAGRAM
1
2
3
Age (T)
Depth (Z)
Distance (X)
Distance (Y)
Depth (Z)
For selected times:
TIME-SNAPSHOT PLOTS
TSP
For every layer
For selected transects:
DYNAMIC GEOHISTORY PLOTS
DGP
Age (T)
Distance (D)
Depth (Z)
Y
X
D
1
2
3
t=0
t=T Ma
t=Recent
AREA 1
For every area
GEOMETRIC INFORMATION
Structural maps
Seismic sections
Terrane analysis
KINEMATIC INFORMATION
Palinspastic/retrotectonic restorations
Balancing cross sections
Paleomagnetics
Kinematic indicators

Fig. 3



Height above sea level (+Z)
0 m.
Depth below sea level (−Z)
DISTANCE (Y)
TIME (X)
Oldest section-trace and section
Section-traces for various times
Recent section-trace and section
0 Ma
Time-trace
Age-depth curve
Coast line time-trace
for borehole 4
(a)
projection to distance-axis
Drill sites
coast
RECENT SECTION-TRACE ON THE MAP
DISTANCE
Sea level
TIME
Subsidence curve
Palaeobathymetry curve
RECENT
Correlated transect
Correlated coastline
(b)
Topography
Subsurface layer
Correlated topography
(c)

Fig. 4



P. Alice
Crotone
Le Castello
Capo Rizzuto
Catanzaro L.
0 10 KM
LEGEND:
Upper Pliocene – Pleistocene sequences
Pl-3, Pl-4
Middle Pliocene sequences
Pl-2
Middle Messinian – Lower Pliocene sequences
Mes-2 to 6, Pl-1
Serravallian – Tortonian – lower Messinian sequences
Mi-1 to 3, Mes-1
Oligocene – Lower Miocene sedimentary – tectonic Complex
Basement rocks; Hercynian crystalline units - Paleogene-Mesozoic sequences:
1. Cropani/Andali Gneisses and Granites
2. Costagna Gneiss Unit
3. M. Gariglione Gneiss Unit
4. Tectonic Zone: M. Gariglione Granites and Cerenzia Granites
5. Longobucco Unit: Cerenzia Granites, Bocchigliero Phyllites, Campana Limestones
6 Tectonic zone: Mandatoriccio Phyllites and Cerenzia Granites
7. Mandatoriccio Phyllites Unit
Normal fault
Reverse fault / thrust
Main structures
Cropani–Savelli Fault Zone (N–S trending)
Strongoli Fault Zone (E–W trending)
Sedimentary and tectonic contacts
Traces of the composite section
The section is valid for the quadrant as indicated by the arrow.
clay/silt
sand
conglomerate
breccia
melange
clastic gypsum
limestone
basement
N
NW
W
S
SE
E
km
Sila Massif
Marchesato
Crotone peninsula
Ionian Sea
Serravallian–Lower Messinian Sequences
middle Messinian–Lower Pliocene Sequences
middle Pliocene Sequence
Upper Pliocene Sequences
middle Pliocene & Lower Pliocene Sequences
Upper Pliocene – middle Pleistocene Sequences
A1
A4
A2
A3
C4
Messinian
Serravallian–Tortonian
B
Messinian–Lower Pliocene
L.Pliocene
0 5 10 km
[Data from boreholes]
[Data from seismics and boreholes]
Marginal areas; monoclinal dip
middle Pliocene thrust belt
Central area with graben & horst structure
Post mid-Pleistocene downfaulted area
Calabrian Accretionary Wedge
Basement
Mi-1 to 3
Mes-1
Mes-2 to 6
Pl-1
Pl-3
Pl-2
Pl-2
Pl-3
Symbols as used on general map

Fig. 5

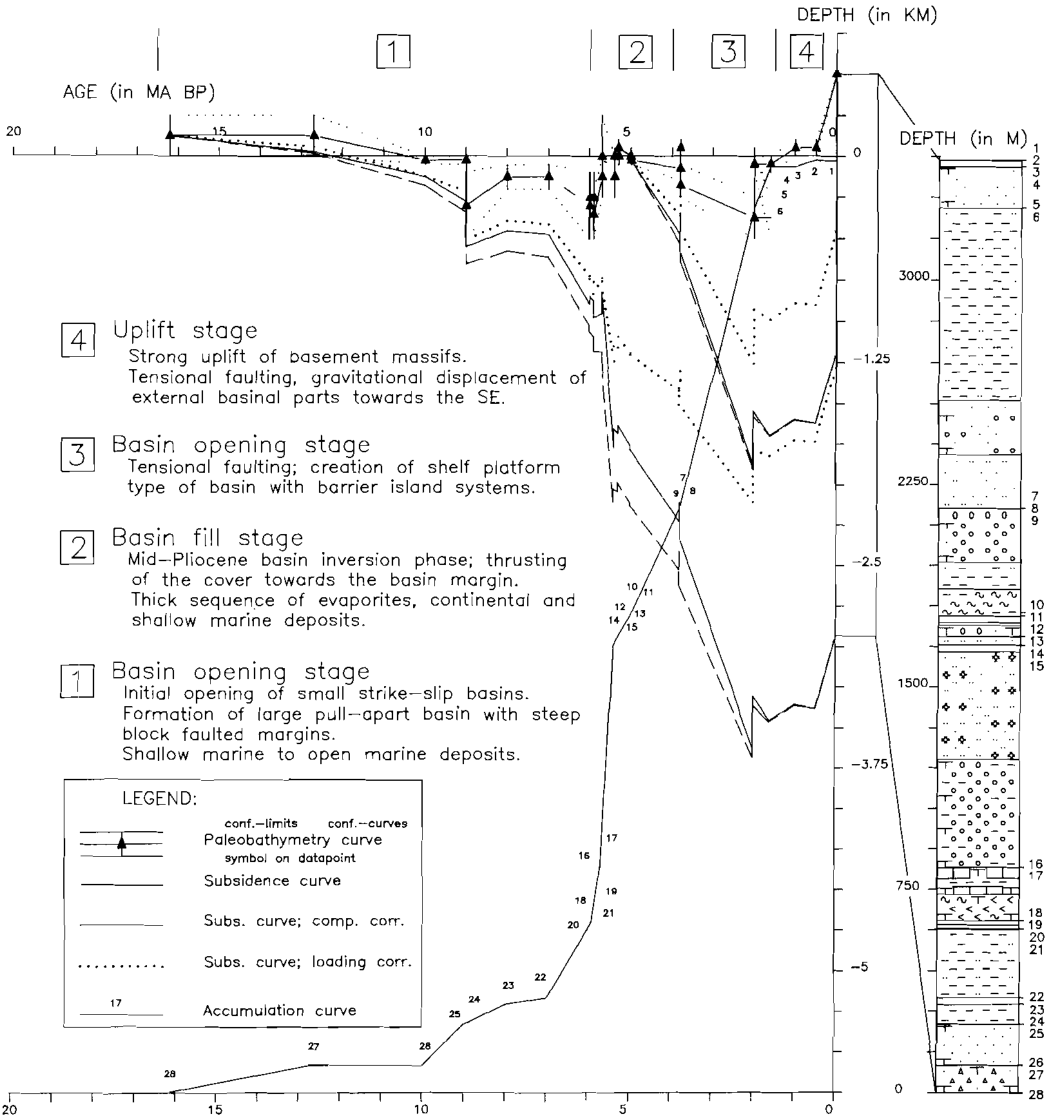

DEPTH (in KM)
1
2
3
4
AGE (in MA BP)
DEPTH (in M)
4 Uplift stage
Strong uplift of basement massifs.
Tensional faulting, gravitational displacement of external basinal parts towards the SE.
3 Basin opening stage
Tensional faulting; creation of shelf platform type of basin with barrier island systems.
2 Basin fill stage
Mid-Pliocene basin inversion phase; thrusting of the cover towards the basin margin.
Thick sequence of evaporites, continental and shallow marine deposits.
1 Basin opening stage
Initial opening of small strike-slip basins.
Formation of large pull-apart basin with steep block faulted margins.
Shallow marine to open marine deposits.
LEGEND:
conf.-limits
conf.-curves
Paleobathymetry curve
symbol on datapoint
Subsidence curve
Subs. curve; comp. corr.
Subs. curve; loading corr.
Accumulation curve
0
-1.25
-2.5
-3.75
-5
3000
2250
1500
750
0
20
15
10
5
0

Fig. 6

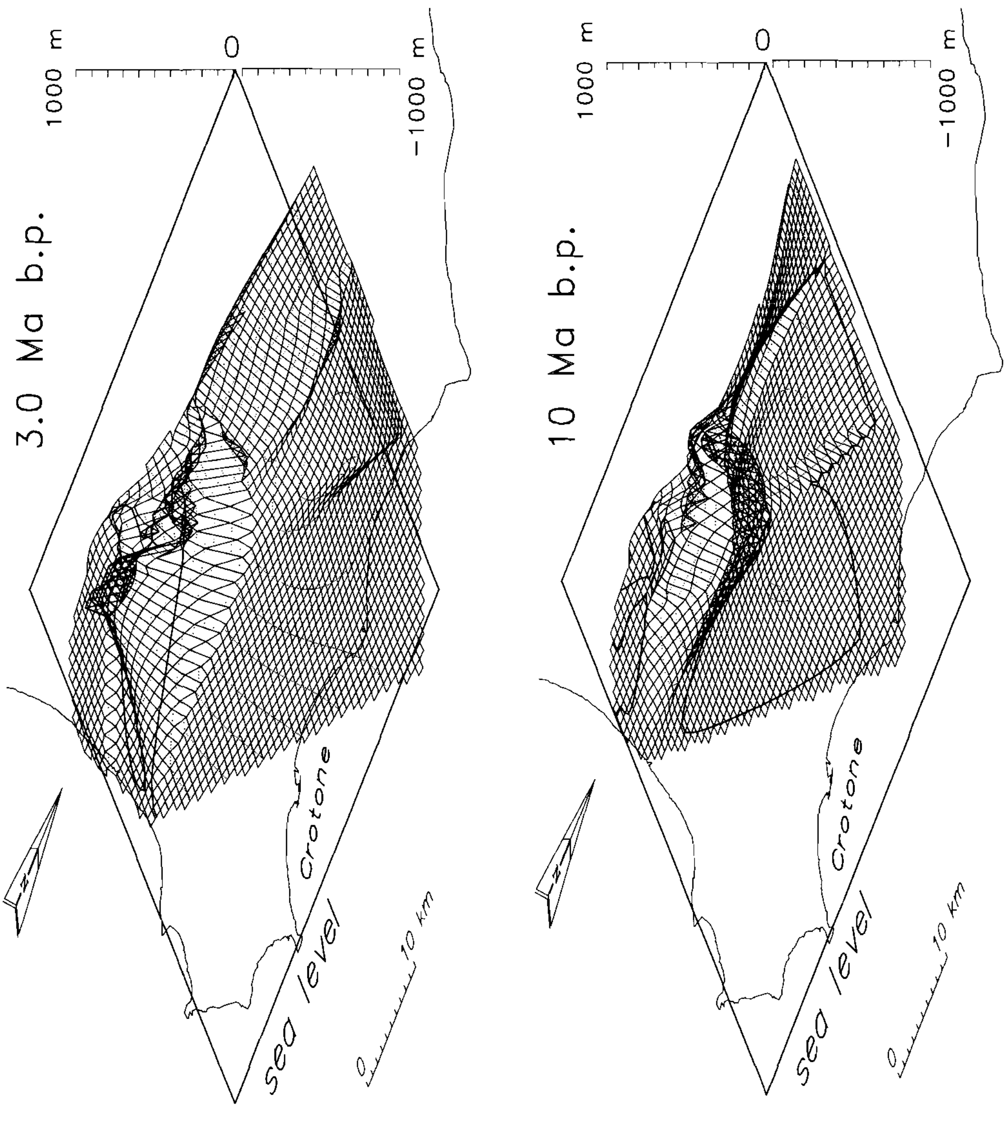

3.0 Ma b.p.
1000 m
0
-1000 m
sea level
Crotone
0
10 km
N
10 Ma b.p.
1000 m
0
-1000 m
sea level
Crotone
0
10 km
N

Fig. 7

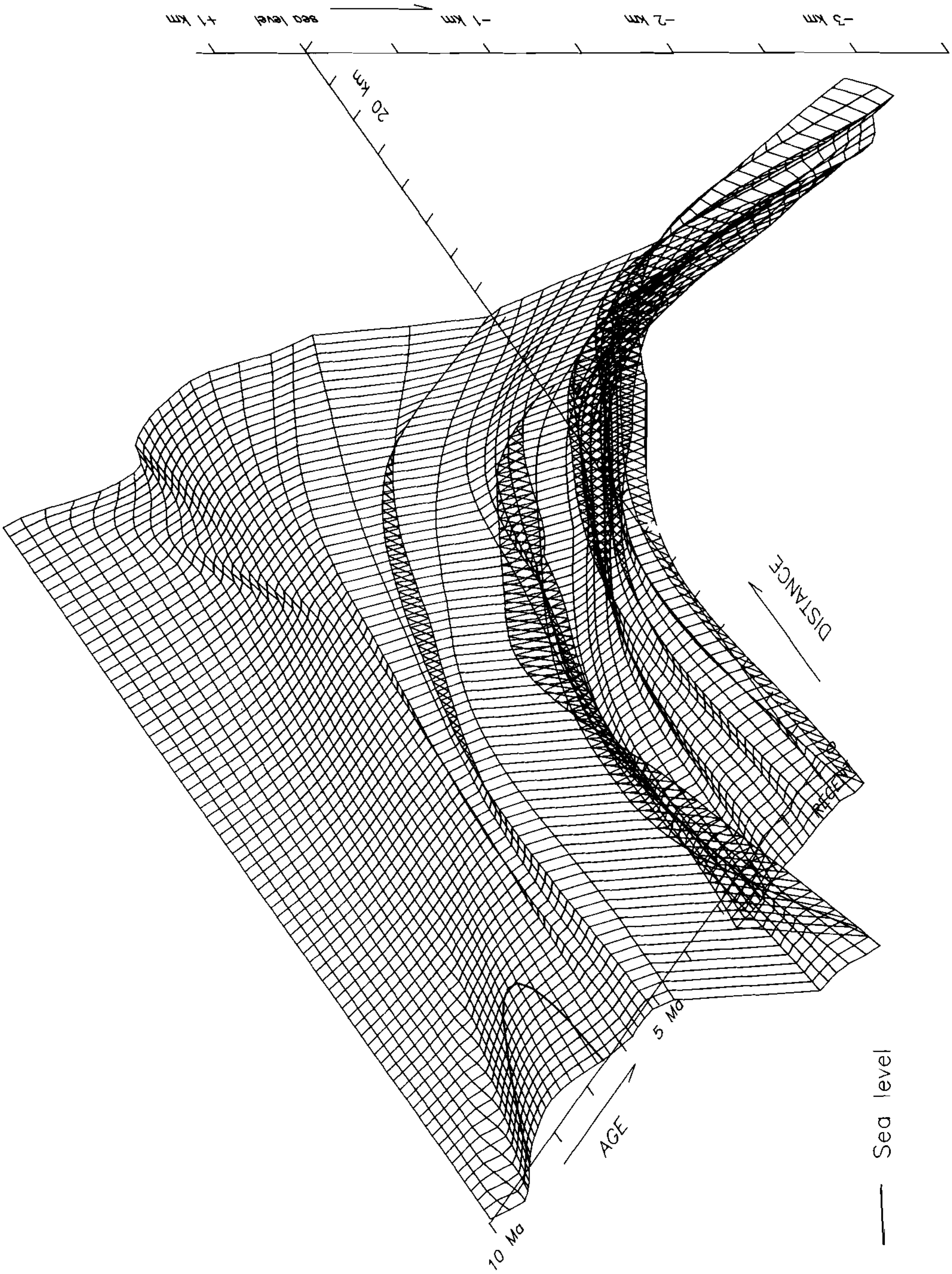

+1 km
sea level
-1 km
-2 km
-3 km
20 km
DISTANCE
5 Ma
10 Ma
AGE
Sea level

Fig. 8

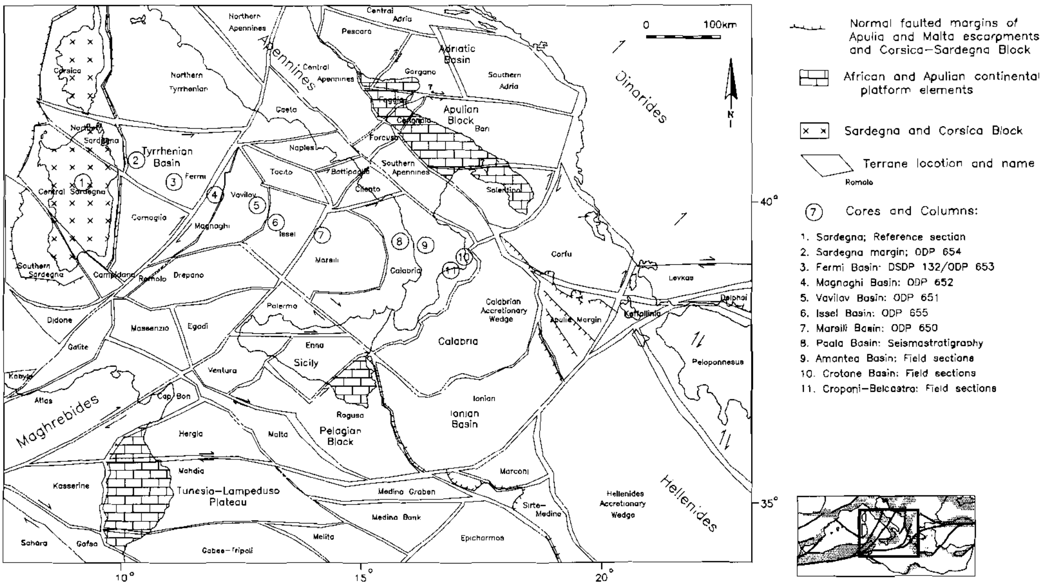

Normal faulted margins of Apulia and Malta escarpments and Corsica–Sardegna Block
African and Apulian continental platform elements
Sardegna and Corsica Block
Terrane location and name
Romolo
Cores and Columns:
1. Sardegna; Reference section
2. Sardegna margin; ODP 654
3. Fermi Basin: DSDP 132/ODP 653
4. Magnaghi Basin: ODP 652
5. Vavilov Basin: ODP 651
6. Issel Basin: ODP 655
7. Marsili Basin: ODP 650
8. Paola Basin: Seismostratigraphy
9. Amantea Basin: Field sections
10. Crotone Basin: Field sections
11. Croponi–Belcastro: Field sections
0 100km
Northern Apennines
Apennines
Central Adria
Pescara
Adriatic Basin
Dinarides
Northern Tyrrhenian
Central Apennines
Gargano
Southern Adria
Apulian Block
Bari
Tyrrhenian Basin
Fermi
Gaeta
Naples
Foggia
Forcusa
Southern Apennines
Salentino
Vavilov
Tocito
Battipaglia
Cilento
Central Sardegna
Carnaglia
Magnaghi
Issel
Marsili
Calabria
Corfu
Southern Sardegna
Campidano
Romolo
Drepano
Levkas
Delphoi
Calabrian Accretionary Wedge
Apulia Margin
Kefallinia
Didone
Massenzio
Egadi
Palermo
Enna
Calabria
Galite
Sicily
Peloponnesus
Kabylia
Ventura
Atlas
Cap Bon
Ionian
Maghrebides
Ragusa
Ionian Basin
Pelagian Block
Hergla
Malta
Mahdia
Marconi
Kasserine
Tunesia–Lampeduso Plateau
Medina Graben
Hellenides Accretionary Wedge
Hellenides
Sirte–Medina
Medina Bank
Sahara
Gafsa
Melita
Epicharmos
Gabes–Tripoli
40°
35°
10°
15°
20°

Fig. 9

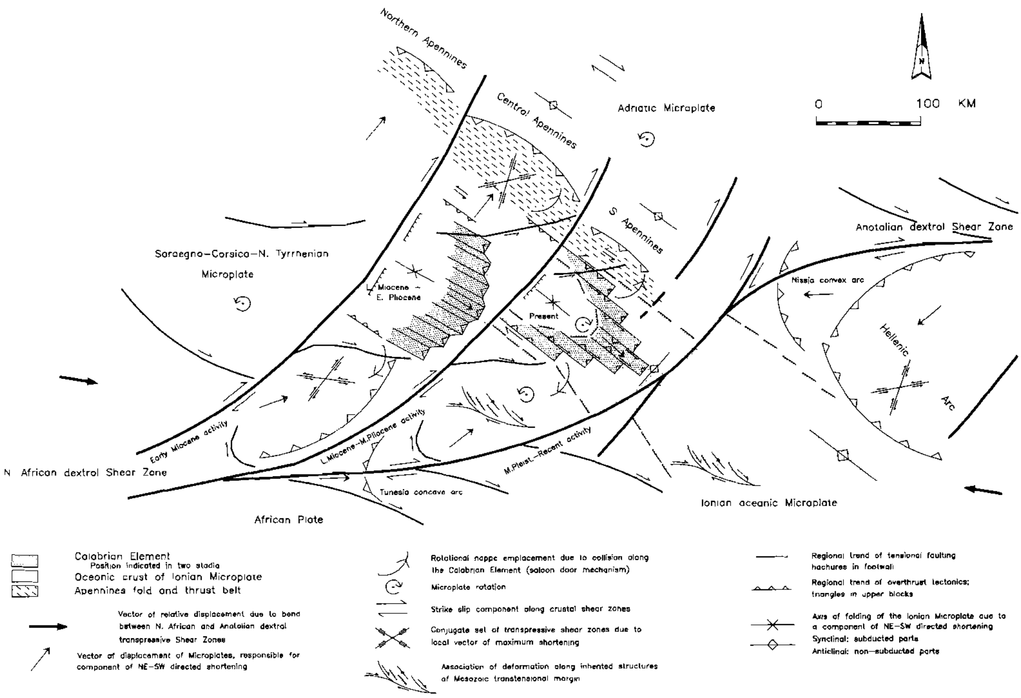

Northern Apennines
Central Apennines
Adriatic Microplate
0 100 KM
S Apennines
Anatolian dextral Shear Zone
Saraegno–Corsica–N. Tyrrhenian Microplate
Miocene – E. Pliocene
Present
Nissia convex arc
Hellenic Arc
Early Miocene activity
L.Miocene–M.Pliocene activity
M.Pleist.–Recent activity
N African dextral Shear Zone
Tunesia concave arc
Ionian oceanic Microplate
African Plate
Calabrian Element
Position indicated in two stadia
Oceanic crust of Ionian Microplate
Apennines fold and thrust belt
Vector of relative displacement due to bend between N. African and Anatolian dextral transpressive Shear Zones
Vector of displacement of Microplates, responsible for component of NE–SW directed shortening
Rotational nappe emplacement due to collision along the Calabrian Element (saloon door mechanism)
Microplate rotation
Strike slip component along crustal shear zones
Conjugate set of transpressive shear zones due to local vector of maximum shortening
Association of deformation along inherited structures of Mesozoic transtensional margin
Regional trend of tensional faulting hachures in footwall
Regional trend of overthrust tectonics; triangles in upper blocks
Axis of folding of the Ionian Microplate due to a component of NE–SW directed shortening
Synclinal: subducted parts
Anticlinal: non-subducted parts

Fig. 10

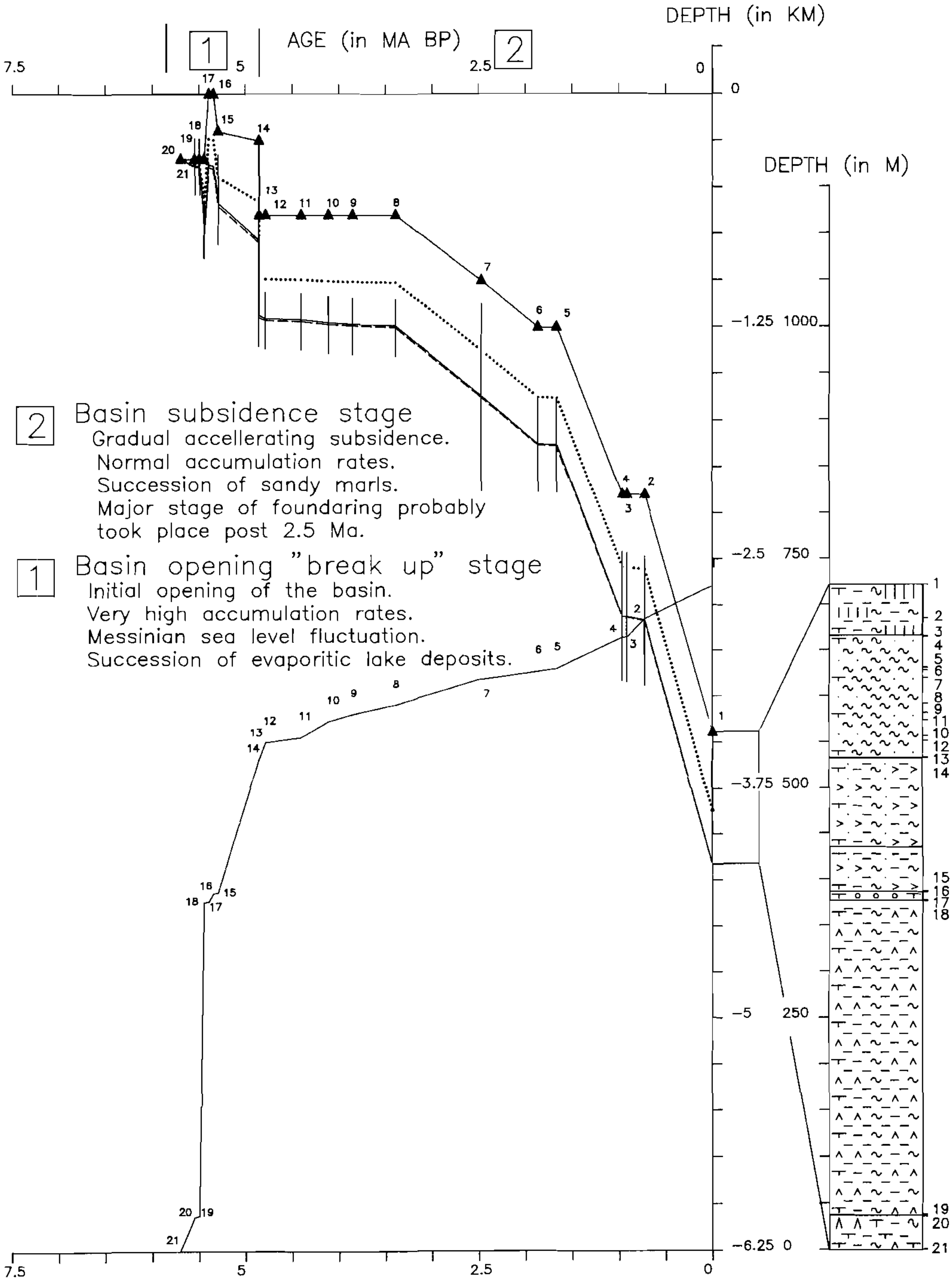

DEPTH (in KM)
AGE (in MA BP)
DEPTH (in M)
2
Basin subsidence stage
Gradual accellerating subsidence.
Normal accumulation rates.
Succession of sandy marls.
Major stage of foundaring probably
took place post 2.5 Ma.
1
Basin opening "break up" stage
Initial opening of the basin.
Very high accumulation rates.
Messinian sea level fluctuation.
Succession of evaporitic lake deposits.

Fig. 11

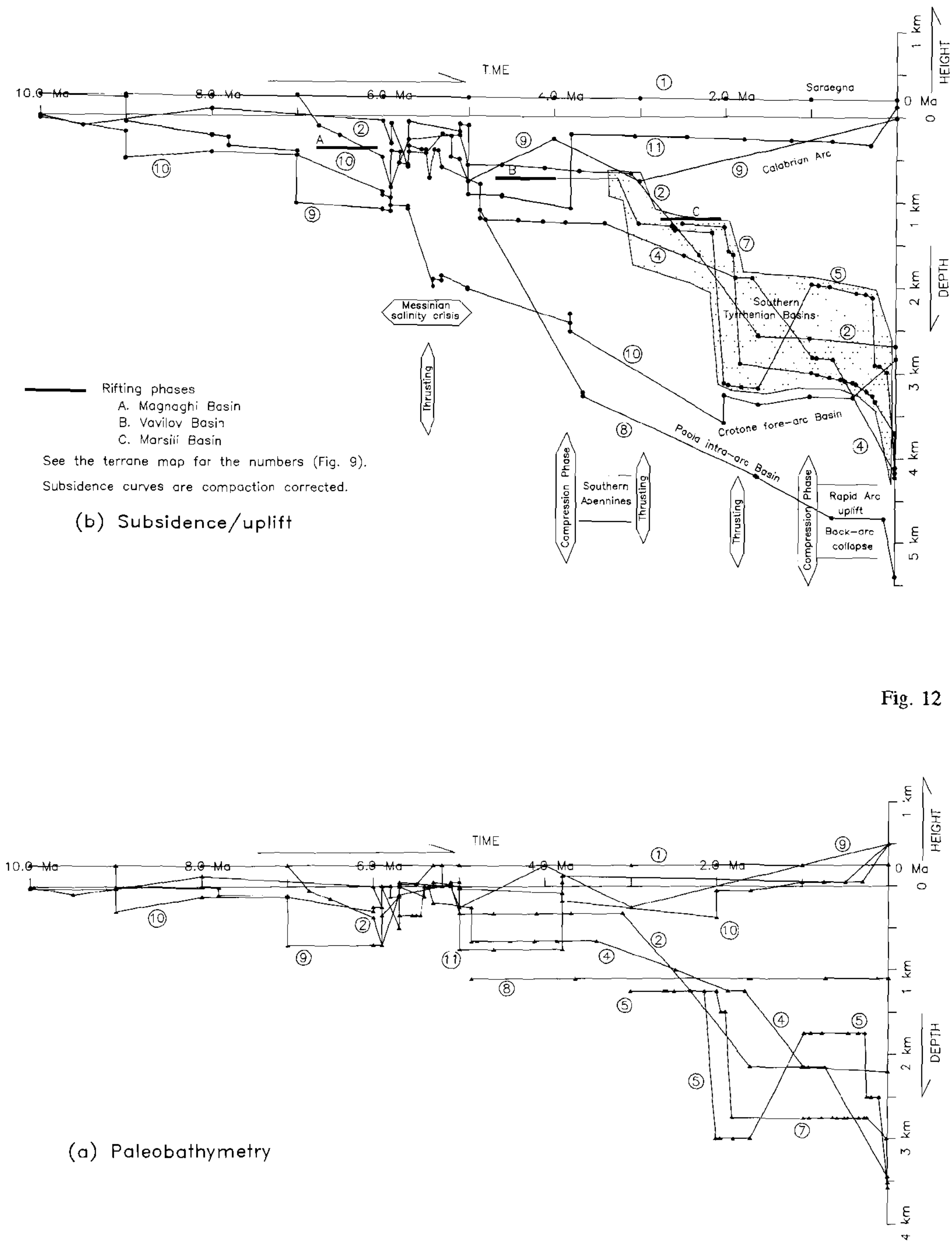
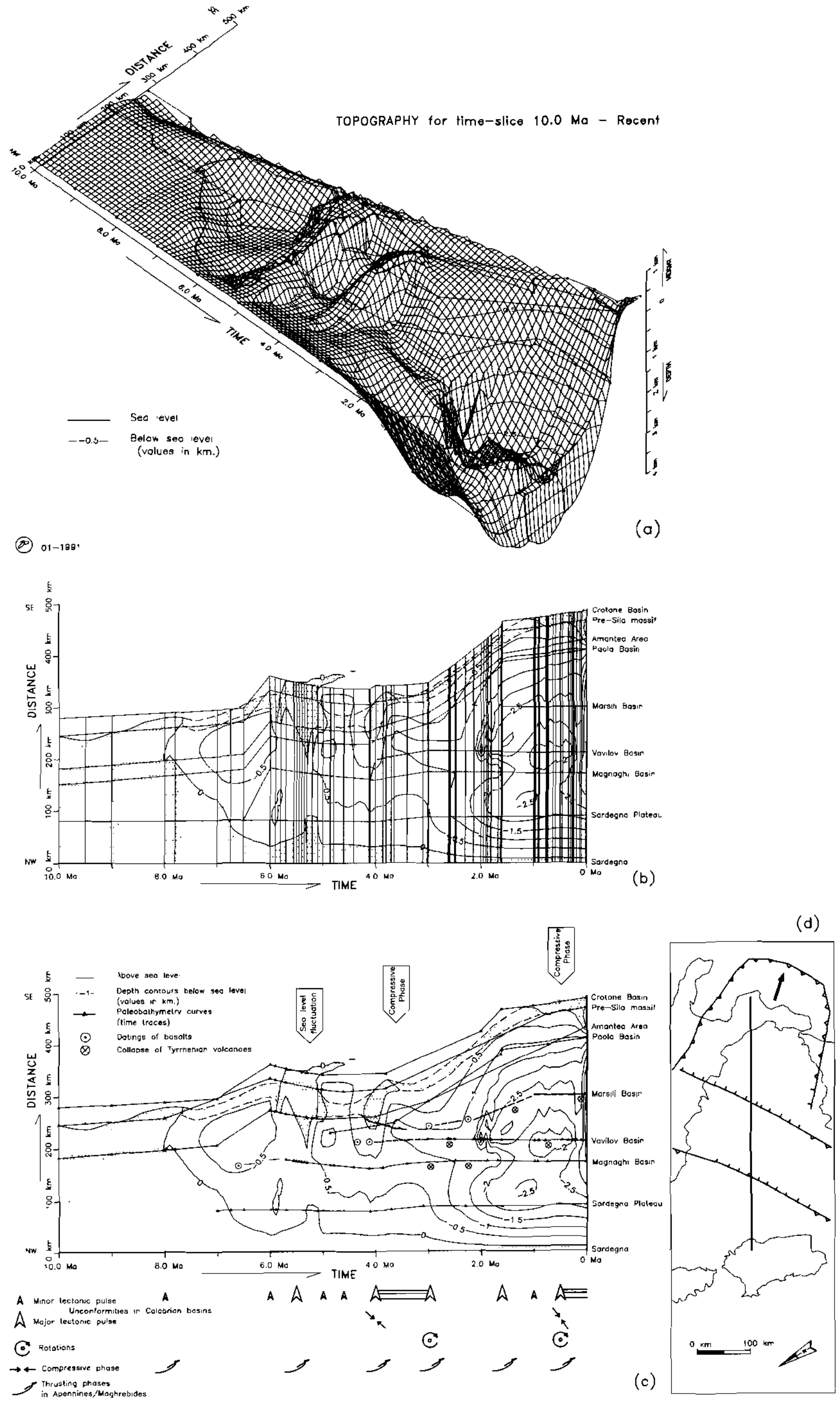

TIME
10.0 Ma
8.0 Ma
6.0 Ma
4.0 Ma
2.0 Ma
0 Ma
Sardegna
Calabrian Arc
Southern Tyrrhenian Basins
Messinian salinity crisis
Thrusting
Compression Phase
Southern Apennines
Crotone fore-arc Basin
Paola intra-arc Basin
Rapid Arc uplift
Back-arc collapse
HEIGHT
DEPTH
1 km
0
1 km
2 km
3 km
4 km
5 km
Rifting phases
A. Magnaghi Basin
B. Vavilov Basin
C. Marsili Basin
See the terrane map for the numbers (Fig. 9).
Subsidence curves are compaction corrected.
(b) Subsidence/uplift
TIME
10.0 Ma
8.0 Ma
6.0 Ma
4.0 Ma
2.0 Ma
0 Ma
HEIGHT
DEPTH
1 km
0
1 km
2 km
3 km
4 km
(a) Paleobathymetry

Fig. 12



TOPOGRAPHY for time-slice 10.0 Ma – Recent
DISTANCE
300 km
400 km
500 km
TIME
8.0 Ma
6.0 Ma
4.0 Ma
2.0 Ma
Sea level
Below sea level (values in km.)
(a)
SE
NW
Crotone Basin
Pre-Sila massif
Amantea Area
Paola Basin
Marsili Basin
Vavilov Basin
Magnaghi Basin
Sardegna Plateau
Sardegna
10.0 Ma
0 Ma
(b)
Above sea level
Depth contours below sea level (values in km.)
Paleobathymetry curves (time traces)
Datings of basalts
Collapse of Tyrrhenian volcanoes
Sea level fluctuation
Compressive Phase
Minor tectonic pulse
Unconformities in Calabrian basins
Major tectonic pulse
Rotations
Compressive phase
Thrusting phases in Apennines/Maghrebides
(c)
(d)
0 km
100 km

Fig. 13

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APPENDIX II

SOME REMARKS REGARDING QUANTITATIVE STRATIGRAPHIC METHODS

Reviews regarding quantitative methodology in stratigraphic analysis can be found in Agterberg and Gradstein (1988) and Maples and West (1992). It is beyond the scope of this summary to discuss the various quantitative methodologies available. We will focuss on bathymetry and age estimation, and compaction and loading correction, only comprising the part which has been used in the present study.
Stratigraphic datasets do not give any direct information on the parameters we are interested in, and therefore, calibrations with quantitative scales have to be performed. Within a computerized database, as was used in the present study, this can be done through look-up tables and comparisons between results from different approaches. For the present study, a number of these tables was constructed in cases they were not available in used programs. Kukal (1990) gave an extensive review of quantitative sedimentological and stratigraphic parameters. An interesting paper of Enos (1991) lists an enormous amount of quantative data on stratigraphic parameters such as accumulation rates, periodicity of sedimentation, denudation and erosion, and compaction and cementation.

IIA. QUANTITATIVE AGE-DEPTH ESTIMATIONS

A well-known method of obtaining paleobathymetry estimates for deeper water deposits, is based on the ratio between the numbers of planctonic and benthic foraminifera as present in a sample (Grimsdale and Van Morkhoven, 1955). It appears, however, that this factor heavily depends on local conditions in the basin. Wright (1977) and Van Marle et al. (1987) established an equation which describes the relation between planctonic foraminifera and depth:

$$PP = a + (b \ln(D)) \qquad (1)$$

wereby

PP = Percentage of planctonic foraminifera
a, b = Function parameters which are characteristic for a certain region
D = Depth (m)

Recently, Van der Zwaan et al. (1990) proposed that the percentage of planctonic foraminifera relates to depth according to the following equation:

$$J(z) = k * (PP / (z/100)) \qquad (2)$$

whereby

J(z) = The amount of organic matter present at depth z
z = Depth
k = A function parameter
PP = Percentage of planctonic foraminifera in the assemblage

They furthermore proposed to correct the total amount of benthic foraminifera with the number of in-fauna elements, i.e. foraminifera from which it is known that they lived below the sediment-water interface, within the sediment. These are substracted from the amount of benthic foraminifera, which increases the percentage of planctonic foraminifera (PP) and thus the depth. This means that if no data are present for in-benthic species, the paleo-depth estimates will be an upper limit.
The authors processed a large amount of data from the Gulf of Mexico, Gulf of California and from the Adriatic Sea, and correcting for the in-benthic species, they derived at the following, area-independent relationship:

$$\mathrm{Ln}(D) = 3.58718 + 0.03534 * PP \qquad (1a)$$

whereby

D = Depth (m)
PP = Percentage of planctonic foraminifera

This equation can be used to derive at bathymetry estimates in a large variety of regions.
A small computer program allows to infer depth estimates and also accuracy-intervals for samples when percentage of planctonic and percentage of benthic foraminifera (corrected for in-fauna elements) are provided.

The geohistory is used in order to reveal patterns in relative subsidence, or relative sea level fluctuations. The amount of eustatic sea level is, therefore, not introduced into the database in advance, and will thus show up as a component of relative subsidence.
An important factor often not discussed is the effect of gravitational anomalies which affects sea level through the shape of the geoide. As this shape in unknown for past situations, there is no possible way of revealing this factor. Therefore, local sea level is, in every sense, the only reference axis in the diagrams.

Age estimates can be obtained by calibrations with existing scales. We used the Berggren et al. (1985) timescale for deposits older then 6 Ma. For younger deposits, the timescale of Hilgen (1991 and references therein) was used.
As we are interesting in the interplay between tectonics, sea level and sediment supply, the timing of tectonic activity is fundamental. Because this tectonic activity in the Mediterranean region may be linked to movements of large plates and sea floor spreading rates, the usage of time scales which introduce arbitrarily ages through extrapolation between calibration points in magnetic anomaly patterns may in some way introduce circular reasoning into basin analysis procedures. The timescales of Berggren et al. (1985) and especially Harland et al. (1982; we refer to their remarks on p. 69) are to a certain extend loaded with the effect of sea floor spreading rate extrapolations. This effect probably influences the results of timing and magnitudes of subsidence in two ways: (1) Extrapolations between calibrations assuming constant spreading rates will tend to smooth out tectonically related events, and (2) At the calibration points used, artificial events and possible kinks in subsidence curves may tend to occur. Therefore, timescales based on independent mechanisms such as the one constructed by Hilgen (e.g. 1991) can be regarded as much more reliable.

IIB. DECOMPACTION PROCEDURES; a brief outline

Introduction

Possible procedures concerning decompaction of sediment will be discussed. These procedures are used in the geohistory analysis method, to determine the past thicknesses of various sedimentary packages, or in other words, to restore sediments to their original thickness. Furthermore, the densities of the sediments must be calculated, which values are needed for the "loading correction".
The decompaction correction can be as large as 30-40% of the thickness of the packages concerned, and can therefore considerably alter the shape of subsidence curves.

The various methods are all based on the following assumptions:

1. Compaction basically takes place as a result of porosity/void space decrease.
2. The porosity decrease leads to expulsion of water.
3. Solid grain mass/volume remains equal.
4. The compaction process is a mechanical one.
5. Compaction is an irreversible process.

Thus, it is assumed that no cementation or diagenesis has taken place. Furthermore, during erosion episodes, no decompaction takes place. The effect is, that of hiatusses occur in the section, decompaction procedures tend to underestimate the decompacted thickness.
Cementation reduces the amount of compaction, so that in restoration procedures the value calculated for decompaction is a maximum one, and the minimum restored value ("cementation case") is equal to the present-day thickness.

The only factor which thus determines the amount of compaction is loading of the overlying sedimentary column (gravitational compaction). In order to calculate the thickness of a certain layer of sediment, the load of the overlying column must therefore be determined. This automatically leads to the conclusion that the calculations must be performed from top to bottom.
The load of the overlying column is determined by its density, so that the porosity of the packages must be calculated (see the assumptions above). To do so, a porosity-depth relation must be used.

In the following discussion, only these derivates which are needed for the decompaction procedures will be discussed, without refering to other mathematical considerations concerning the processes involved. The methods as described have basically been developed by Perrier and Quiblier (1974), Van Hinte (1978) and Sclater & Christie (1980).

The letter indices of the symbols used follow the following conventions:

t = At a certain moment in time
p = At present
z = At depth z below top of core
0 = At depth 0 below top of core
o = Original
i = Initial
r = Restored
w = Water
s = Solid grains
' = Values for restored situations

In calculations, the following data can be used:

Solid-grain density for sandstones: 2.65 g/cm^3
shales: 2.72
limestones: 2.71
Average water density: 1.04 g/cm^3
Mantle density: 3.30 g/cm^3

<u>Unit, burial depth, porosity</u>

In equations, the thickness (T) of a segment or unit is calculated between the top at depth z1 and the bottom at depth z2:

$T = (z2 - z1)$

To treat segments of a stratigraphic succession, a parameter is introduced called "Burial Depth of a unit" (below the top of the column). This value is defined as follows:

BD = "Thickness of the column overlying the unit"
BDp = Present day burial depth of a unit
BDt = Burial depth of a unit at a certain moment t
BDo = Burial depth of a unit at the top of the column = 0

A unit sediment is constituted of one part water (Tw; void space, w), and one part solid matter (Ts; Ss; solid sediment, Tn; Netto thickness, sg;solid grains, s).
The relations between total thickness of the column and water and solid grains are:

Total thickness = solid matter + water
T = Ts + Tw

T = [(1 - P) * T] + [P * T]

T = Thickness
P = Porosity (0<P<1)
S = Solidity (0<S<1)

P + S = 1

P * T = Tw   and   S * T = Ts

Establishing the porosity-depth relation

1) A present-day porosity-depth relation is plotted for each lithology.
These data can be obtained from well-logs or from dry bulk density and wet bulk density measurements.
2) A curve is fitted through the points, and a mathematical function is defined.

If no porosity-depth values are known, arbitrarily chosen functions can be used for each type of lithology. Computer programs often contain a library of lithologies and related function parameters. These mostly are phenomenological models, i.e. empirical functions.

The assumption used is that this porosity-depth relation has always been this way, so that restoration of the thickness of a unit means shifting it along the curve.
This assumption also comprises the fact that the column as observed is completely compacted under its own weight; it is "stable". Gretener and Labute (1969) (referred in Okkes, 1988) describe a quantitative model for the percentage of compaction verses the thickness of the unit. In general, there is no time lag-effect included in the models.

In literature, most used is an exponential function for the porosity-depth relation. Linear, parabolical and hyperbolical functions are also known (Baldwin & Butler, 1985).

Exponential

This is the most used relation, with the general form:

$$Pz = Po * e^{-c * z} \qquad (1)$$

where 0<=Po<1 and 0<=c

Pz = Porosity at a depth z below the top of column
Po = Porosity at the top of the column (Porosity at the moment of deposition)

This value can be measured, or extrapolated from a fitted curve for a buried unit.
c = Function parameter (constant) c>0 (This parameter is often called "betha".)
z = Depth below the top of the column
The porosity approaches an asymptote of 0 as depth approaches infinity.
In order to use this equation, Po and c must be known.
The equation is based on the work of Athy (1930a) and Hedberg (1936) (references in Lerche, 1990).
Values for Po and c can be found in Sclater and Christie (1980, table AIa), Bond & Kominz (1984), and Angevine et al. (1991).

Some values are:	Po	c (m^{-1})
Sandstones:	0.38 - 0.50	0.5 - 2.7 * 10^{-4}
Shales:	0.50 - 0.80	1.65 - 5.0 * 10^{-4}
Carbonates:	0.50 - 0.80	7.0 * 10^{-4}

If c becomes larger, the compaction versus depth becomes larger.

Baldwin & Butler (1985) solved the equation for burial depth, obtaining:

$$z = c1 * \ln [c2 / Pz]$$

In which c1=3.70 and c2=0.49 for shales.

Reciprocal

The general form of this equation is:

$$P(z) = 1 / (c1 + c2*z) \qquad (1a)$$

where c1>1 and c2>0
and P(0) = 1/c1

Horowitz (1976): $Pz = 1 / \{1 + (0.0001 * z)\}$

Falvey & Middleton (1981): $1/Pz = (1/Po) + (c * z)$

These curves define hyperbolic relations, where the porosity approaches an asymptote of 0 as depth approaches infinity.

Linear

A well known work by Steckler & Watts (1978) uses linear relations. We refer to this work for the used function parameters. The general form is:

$$P(z) = Po - c*z \qquad (1b)$$

where P(z) = 0 if (Po/c <= z)
0<=Po<1 and 0<=c

If c=0, than porosity is constant with depth; this means no compaction or in other words cementation.

Power Law

Baldwin & Butler (1985) argue for a power-law function (parabolic function) describing the porosity-depth relation, rather than an exponential relation.
The general form of this equation is:

$$BD = BD_{max} * S^{alpha}$$

BD = Burial Depth
S = Solidity (= 1 - P)
BD_{max} = "Maximum Burial Depth"; this is a constant
alpha = A function parameter

They give two equations which can describe the porosity-depth relations of shales:

<200 m: Normally compacted: $BD = 6.02 * S^{6.35}$: "Baldwin-Butler equation"
>200 m: Undercompacted & overpressured: $BD = 15 * S^{8}$: "Dickinson equation"

On Log-Log paper, this function plots as a straight line.
Baldwin & Butler stated that the exponential relation can probably best be applied to sandstones, while the power-law relation best fits the data for shales.

Written as a porosity-depth function, this equation results in:

$$P(z) = 1 - c1*(z^{c2}) \qquad (1c)$$

where $P(z) = 0$ if $(c1^{(-1/c2)} = 0)$
and $c1>0$ and $0<c2<1$

<u>Present thickness, original thickness, initial thickness and restored thickness</u>

Present Thickness of a unit (PT) is, of course, the thickness of the unit at the moment that the column is described, i.e. the measured data.

The Original Thickness of a unit (OT) means the state in which the unit has not undergone any compaction. Its mean porosity is than the porosity at the time of deposition, as can be measured at the top of the stratigraphic section, or calculated from extrapolation of a fitted curve to the top of the section. This value represents a maximum for the thickness of the unit. Thus, this is the value which is exclusive of syn-depositional compaction.

The Initial Thickness of a unit (IT) is the state in which the unit has been compacted under its own weight i.e. below a burial depth BD_0 (=0). This thickness is valid for units which top is situated at the top of the column. For the uppermost unit at present day, this is equal to the Present Tickness (PT). During calculations, this thickness is regarded as a special type of restored thickness (RT; see below).

The Restored Thickness of a unit (RT) is the state at a certain moment in time, when a part of the overlying column was not yet deposited. This thickness is generally larger than the present thickness.

Because the solid matter part of the unit does not change during compaction, the following general relation is always valid:

$$T_{t-1} = \frac{(1 - P_t) * T_t}{(1 - P_{t-1})} \qquad (2)$$

T_t = Thickness of the unit at a moment t, buried at a depth BDt
This is the value you are looking for.
T_{t-1} = Thickness of the unit at a moment t-1, buried at a depth BDt-1
P_t = Mean porosity of the unit at a moment t, buried at a depth BDt
P_{t-1} = Mean porosity of the unit at a moment t-1, buried at depth BDt-1

The following specific form of this equation is often used (v. Hinte, 1978):

$$T_o = \frac{(1 - P_p) * T_p}{(1 - P_o)} \qquad (2a)$$

To = Thickness of the unit in uncompacted state; Original thickness (OT)
It is the thickness of the unit, if it should not have been compacted at all.
Tp = Present thickness of the unit (PT), which is known
Po = Mean porosity of the unit in uncompacted state
This is the same value as P_0 in equation (1) and it is known
Pp = Mean present day porosity of the unit
This needs to be calculated using equation (1)

A parameter which is often used is the so-called "compaction factor" or "compaction number" D (see Perrier & Quiblier, 1974 for references). It is calculated as follows:

D = IT / RT = Ti / Tt

Carbonates (the ooze-chalk-limestone system) display a relation like:
(Moore, 1969)

$$H_{ooze} = \frac{(1 - P_{limestone})}{(1 - P_{ooze})} * H_{limestone} \qquad (2b)$$

H_{ooze} = Initial thickness of uncompacted ooze interval: to be calculated
$H_{limestone}$ = Present thickness of limestone derived from ooze
P_{ooze} = Original porosity of ooze (ca. 80%)
$P_{limestone}$ = Porosity of limestone (ca. 40%)

Schlanger & Douglas (1974) state that:

Burial depth 0-200 m: Ooze (P = 80%) compacts to chalk (P = 65%)
Burial depth 200-1000 m: Chalk compacts to limestone (P = 40 %)
For both stages, the equation (2b) holds; in the first stage, $_{limestone}$ would become $_{chalk}$.

Using this (semi-quantitative) model, a decompaction value can easily be obtained.

Calculating the original thickness (OT)

Equations (1) and (2a) are both needed to restore a unit to its original thickness. What is known are the following values:

Tp = Thickness at present
BDp = Present day burial depth of the unit
c = Porosity-depth function constant
P_0 = Porosity at the top of the column; porosity at the moment of deposition

The porosity for a unit at present is calculated for the middle of the unit (burial depth), and is stated to be valid for the entire unit. For this purpose, equation (1) is used.
This results in:

Pz = Porosity at present = Pp

For a unit at the top of the column, this is the porosity in a state of compaction under its own weight. For a buried unit, it is of course the porosity of the unit at burial depth BDp.

Furthermore, using equation (2a), the Original Thickness of the unit can be calculated from Tp, Pp and Po (=Po):

To = see equation (2a) = OT (Original Thickness)

Calculating the initial thickness (IT)

From the porosity-value Pp for the present situation, it can easily be calculated how much solid sediment is present in the unit. This value is called the Net Thickness (Ts). From the definition of thickness and porosity, it follows that:

$$Ts = (1 - Pp) * Tp \qquad (3)$$

Gretener and Labute (1969) gave a graphical representation for shales between initial thickness and solid sediment thickness. From this graph, the initial thickness can be read.

Perrier & Quiblier (1974) presented easy-to-use diagrams for shales and sandstones. Using Present Thickness and Burial Depth of a certain layer, the Initial Thickness can be read from the diagram. This diagram is based on their calculation method as described below. Note that for the top unit, Present thickness equals Initial thickness!

Calculating a restored thickness (RT)

Perrier and Quiblier (1974) gave a graphical representation of the relations between Initial Thickness (IT), Thickness at a certain moment t (Tt), which they call "Present Thickness" and Burial Depth at that same moment in time (BDt), for shales and sandstones. Using Initial Thickness as calculated, and burial depth as obtained from restored thicknesses of overlying units, the diagrams can be used to obtain the "present" thickness for the moment in time desired.

Calculating the restored thickness takes more time. For this purpose, a number of mathematical derivations must be given. The following approaches can be found in literature:

a) Perrier & Quiblier (1974) / Horowitz (1976) / Sclater & Christie (1980) method
b) Falvey & Middleton (1981) method
c) Angevine et al. (1990) "Correct" method

Exponential relations like equation (1) for the porosity-depth relation are mostly used, although also hyperbolic or linear relations occur.
Furthermore, in all three methods, the following relation for the solid matter volume of a buried unit related to depth and porosity is used:

$$Ts = {}_{z1}[]^{z2} (1 - P(z))\, dz \qquad (4a)$$

$$Tp = {}_{z1}[]^{z2} P(z)\, dz \qquad (4b)$$

[] stands for the integral symbol

Combining with equation (1) these equations can be solved as:
(Sclater & Christie)

$$Ts = (z2 - z1) - (Po / c) * (\exp(-c*z1) - \exp(-c*z2)) \qquad (5a)$$
$$Tw = (Po/c) * (\exp(-c*z1) - \exp(-c*z2)) \qquad (5b)$$

$$Ts' = Ts \qquad (5c)$$
$$Tw' = (Po/c) * (\exp(-c*z1') - \exp(-c*z2')) \qquad (5d)$$

Ts = Netto Thickness = Thickness of solid sediment part of the column
Tw = Thickness of water part for the present situation
Tw' = Thickness of water part for the restored situation
z1 = Top of buried layer at present
z2 = Base of buried layer at present
z1' = Top of buried layer for the restored situation
z2' = Base of buried layer for the restored situation

Combining with equation (1a) the solution is:
(Falvey & Middleton)

$$Ts = (z2 - z1) - (1/c) \ln \{ (1/Po + c*z2) / (1/Po + c*z1) \} \quad (6)$$

If this Ts value is known, which is valid for present as well as past situations, the past situation must be considered:
(We continue only with the approach a))

Combining past and present, equation (2) results in:

$$(z2' - z1') = Ts + Tw' \qquad (7)$$

From a combination of the equations (5d) and (7), z2' can be isolated, as z1' is known from restoration of previous layers, resulting in:

$$\underline{z2' + (Po/c)*\exp(-c*z2')} - (z2-z1) - (Po/c) + (Po/c)*(\exp(-c*z1)-\exp(-c*z2) = 0 \qquad (8)$$

If z1', Po, c, z1 and z2 are filled in, an equation results, from which z2' can numerically be solved from the part which is underlined.

The calulation method of Angevine et al. (1990) (their "correct method") is somewhat different, as it uses a finite difference approximation algorithm to obtain a thickness value. We refer to this text for further explanation.

The approach of Falvey & Middleton (1981) may be considered as being more correct, because it calculates the amount of compaction due to the load of the overlying mass, which constitution varies according to the material present. The other methods regard the overlying mass as being constituted of the same material as the unit which is being restored, so that the porosity-depth curve can be used.

Perrier & Quiblier (1974; their Figure 4) also presented a method to avoid this problem. It consists of a restoration for the syndepositional time-slice of the section being considered. After that, the sediment thickness in time is extrapolated to the present thickness to obtain the compacted values for the post depositional period, for which in that way no porosity-depth curve is being used.

The approach of Doligez et al., (1986), Bethke (1989) and Wendebourg & Ulmer (1992) use transient pore pressure calculations, assuming that compaction is a function of effective stress (hydrostatic and lithostatic pressures) during burial. The authors use empirical models to determine the porosity loss during pressure increase.

Petersen (1991) gave an interesting review of decompaction methodology, distinguishing between syn- and post-depositional compaction, and the effect of erosion.

It must be noted that, although decompaction as a whole is a reverse modelling procedure, the syn-depositional part of the calculations in fact is a small forward modelling exersize.

C. Restoration of an entire column

The flow-chart will be described for the decompaction as can also be performed manually.
When a lithological column must be decompacted, the following data must be registered:

1. Thicknesses of present lithologies
2. Type of present lithologies
3. If possible, porosity-depth values for the whole column.
   From these values, empirical curves can be fitted.
   If no data are present, The following must be arbitrarily assigned:
   a. Type of function (usually exponential)
   b. function parameters:
      - porosity at time of deposition
      - c constant
   If no functions can be assigned, the tables of Perrier & Quiblier (1974) can be applied, although they are only valid for shales and sandstones.

A table is used to fill in the values obtained during the restoration of the column (Van Hinte, 1978).

1. First, present thicknesses and lithology-characteristics are filled in the left side of the table. (C, Po, and grain densities)
2. The following step is to calculate the porosities of the present-day situation (e.g. equation 1).
This is done using the procedure described above in the paragraph on calculating the Original thicknesses. Original thicknesses of all the units are then calculated (equation 2) and filled in.
Furthermore, netto thicknesses can be calculated from original thicknesses using Po values (equation 3).

3. Initial thicknesses of all the units are calculated and filled in on the right side of all the rows. These are the restored thicknesses for all the uppermost units for each moment in time. Used is the procedure described above. Porosity values are also calculated and filled in.
Calculations of initial thicknesses can be avoided by using the graphs of Perrier & Quiblier, from which initial thicknesses can be read.

4. The following part of the procedure comprises the calculation of (porosities and) thicknesses for all the units for all moments in time. To do so, for each moment, the column is calculated from top to bottom. In that way, burial depths are always known.
-The correct way to do this is to calculate for small slices of each lithology the syndepositional restored thicknesses, using the appropriate porosity-depth relations. For the post-depositional period, an extrapolation can than be performed, plotting restored thicknesses against time, and extrapolating this to the present thickness. The extrapolation type (linear, exponential, etc.) is arbitrarily (their Figure 4).-
The tables of Perrier & Quiblier can be used to obtain restored ("present") thicknesses in an easy way.

5. The last step comprises the cumulative sediment thickness calculations, which are needed for loading compaction calculations. These data are filled in at the bottom of the table, for each moment in time.

6. The Mantle Displacement values can at this stage also be calculated. Netto thicknesses as calculated in step 2. are used.

IIC. LOADING CORRECTION PROCEDURE

Generally, an Airy-model of isostasy is used in basin modelling, which assumes that the weight of water, sediment and lithosphere are in Archimedes equilibrium with the asthenosphere (Airy, 1855). It assumes that the lithosphere has no lateral strength and reacts to a point load as water to a float; the load simply sinks into the mantle and floats onto it. The following equation shows the relation between Mantle displacement due to sediment loading and amount and density of the sediment load (Stoneley, 1969; Bomford, 1971, p. 441;

Horowitz, 1976):

$$MD = \frac{D_s - D_w}{D_m - D_w} * Ss = 0.3457\ Ss$$

whereby

MD = Mantle Displacement (m)
Ss = Thickness of solid sediment (m) = Thickness of sediment * Solidity
D_s = Density of solid sediment (ca 2.7 g/cm^3)
D_m = Density of mantle material (ca 3.3 g/cm^3)
D_w = Density of water (ca 1.03 g/cm^3)

A more sophisticated model, the flexural loading model, however, assumes that the crust has a certain lateral strength (Vening Meinesz, 1930). This model is represented by flexure of an elastic plate overlying an inviscid fluid. This inviscid fluid corresponds to the, poorly defined, hotter (lower) portion of the lithosphere and the asthenosphere. The following equation describes the relation between crustal strength and plate flexure (Turcotte & Schubert, 1982; Ranelli, 1987; Angevine et al., 1990):

$$V^2 * (D * V^2 * w) = P - (D_m - D_s) * g$$

whereby

D = Flexural rigidity of the plate (Newton times square meter; Nm^2)
    D varies from 10^{21} to 10^{25} N*m)
w = Vertical deflection of the crust (m)
P = Vertical load per unit area (Pa)
D_m = Density of mantle material (ca 3.3 g/cm^3)
D_s = Density of the sediment (solid plus void) ca   g/cm ^{3})
g = acceleration of gravity (m/s^2)

The flexural regidity D describes the mechanical strength of the plate as follows (Walcott, 1970):

$$D = \frac{E * (EET)^3}{12 * (1 - v^2)}$$

whereby

E = Young's modulus (7 * 10^{10} n/m^2)
EET = Effective plate thickness (m)
v = Poisson's ratio (0.25)

EET seems to be independent of the age of the load and may be related to the thermal structure of the lithosphere - hot lithosphere has a small EET, cool lithosphere a large one (Watts et al., 1982). This again may be related to an isotherm at a certain depth.

In order to solve these equations numerically, a finite-difference routine is acquired, either for a one-dimensional line or rectangular load (Turcotte & Schubert, 1982; Zoetemeijer et al., 1990; Angevine et al., 1990) or for a bi-dimensional block load (Wendebourg & Ulmer, 1992). Turcotte & Schubert (1982) and Angevine et al. (1990) describe simple algorithmic solutions for the finite-difference calculations. Wendebourg & Ulmer showed two alternative means of treating boundary conditions for elastic plates; one with a plate in between two fixed walls (semi-infinite) and one with a plate lying upon two walls (infinite).
Generally, immediate response of the crust to the load is assumed, so that the time-steps between cal-

culations automatically become the response-time of the loading.

Both isostatic and flexural loading models run into trouble in subduction zone areas, where lateral stresses are high, and tectonic loads are often very young (Angevine et al., 1990; p. 37). Anyway, the isostatic loading correction provides a maximum value for which may be corrected, and implies little and very straightforward assumptions. Therefore, the best strategy for reverse modeling exercizes (backstripping) is to apply isostatic loading correction to provide a boundary constraint before going into more sophisticated modeling. As discussed by Angevine et al. (1990; p. 55-56), however, it should be kept in mind that as foreland basins can be considered flexural compensations of mountain belt loads, Airy backstripping provides tectonic subsidence were none has ("yet") occurred.

PART 3

IMPLICATIONS: STRUCTURE, KINEMATICS AND GEODYNAMICS OF THE CENTRAL MEDITERRANEAN

CHAPTER 6
Neogene stratigraphy and kinematics of Calabrian Basins;
implications for the geodynamics of the Central Mediterranean.
Reprint from: Van Dijk & Okkes (1991); Tectonophysics, Vol. 196, pp. 23-60.

APPENDIX 3
Some remarks on the kinematics and geodynamics of the Central Mediterranean.

Procul recedant somnia,
et noctium fantasmata.

Tectonophysics, 196 (1991) 23–60
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Neogene tectonostratigraphy and kinematics of Calabrian basins; implications for the geodynamics of the Central Mediterranean

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ABSTRACT

Van Dijk, J.P. and Okkes, F.W.M., 1991. Neogene tectonostratigraphy and kinematics of Calabrian basins: implications for the geodynamics of the Central Mediterranean. *Tectonophysics*, 196: 23–60

A new structural model for the Calabrian Arc (Southern Italy) is presented, based on a systematic analysis of basin kinematics combined with a review of the literature on basement structure.

Three tectonic patterns can be distinguished: (A) NW–SE trending oblique thrust zones, determining a set of N130 trending segments, (B) SW–NE to E–W trending thrust zones, and (C) radial and concentric tensional fault systems in the southern Tyrrhenian back-arc area. These faults, combined with dome-shaped uplift centres determine the actual arc. Patterns A and B can be regarded as the on-shore representation of the Calabrian accretionary-wedge system.

The kinematics of various types of basins such as piggy-back, pull-apart and complex-oblique-strike-slip basins are connected to these patterns. The patterns A and B can be linked to the Middle Miocene–Early Pliocene development of oblique, convergent crustal shear zones ("strike-slip cycle"), whereas pattern C can be linked to the Pleistocene collapse of the Southern Tyrrhenian basin and concentric uplift of the arc.

Our structural model has considerable implications for the understanding of the kinematic evolution of the Central Mediterranean. We propose a model in which the evolution is characterized by an alternation of the translation of the Calabrian lithosphere element either to the southeast (gravitationally) or to the northeast (compression).

Combining (a) our analyses of basin evolution, (b) the structural model and (c) some considerations concerning kinematics of the Central Mediterranean, with the geodynamic mechanisms as proposed in literature, we present a model which consists of a geodynamic cycle comprising the following three stages: (1) a tension stage with back-arc basin opening related to the diapiric inflow of asthenosphere material and roll-back of the subducted Ionian slab, resulting in gravitational displacement of the Calabrian Element to the southeast, (2) a transpression stage with oblique overthrusting towards the northeast upon the Southern Apennines, and (3) a compression stage with NE–SW compression due to oblique dextral shear along the North African margin, plate rupture/lithosphere split and back-arc basin collapse.

Introduction

The structural development of the Central Mediterranean arc-shaped orogenic belt (Fig. 1) is one of the main problems in palinspastic reconstructions of the Western Mediterranean. Of particular interest is the Calabrian Arc, which links the WSW trending North African–Sicilian Maghrebides to the NW–SE trending Italian Apennines. Various models have been presented to describe the kinematic evolution of the Calabrian Arc. These models can be grouped as follows:

(A) *Primary arc models*: These models postulate that the Calabrian Arc is the result of the overthrusting of one single "Calabrian Block or Microplate" to the southeast upon the Ionian part of the African Plate (Argand, 1924; Caire, 1970; Boccaletti and Guazzone, 1972; Alvarez et al., 1974; Görler and Giese, 1978).

(B) *Secondary arc models*: These models postulate that the origin of the arc-shape is due to a differential displacement of the various parts of which the arc is composed. Four types of models can be further distinghuished (Table 1): transla-

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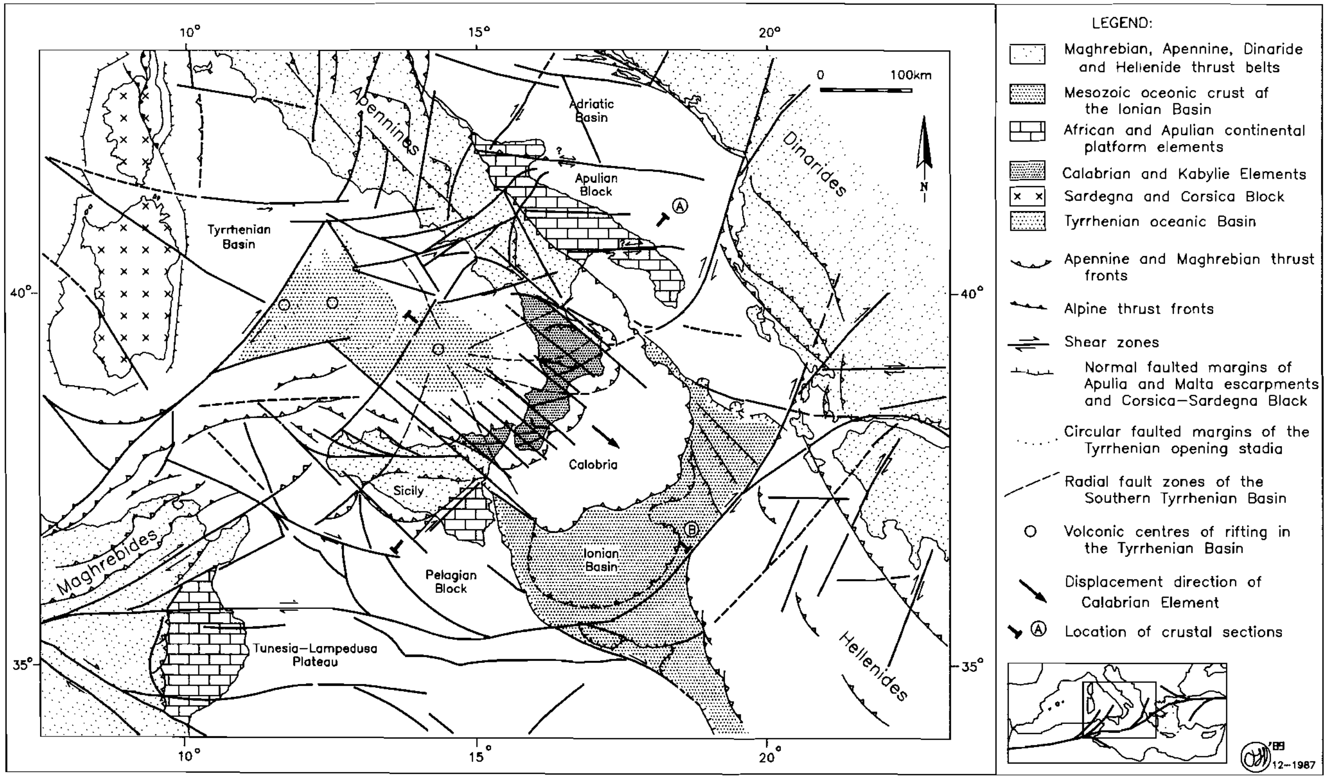
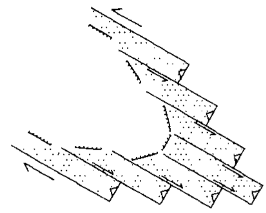
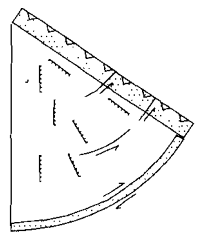
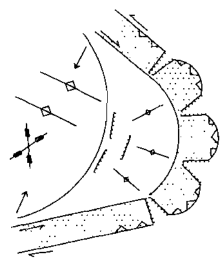
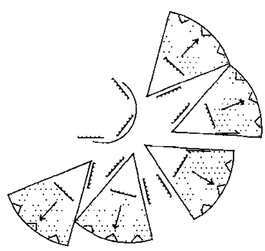


Fig. 1. Schematic structural map of the Central Mediterranean. The configurations in the Calabrian area based on our analyses. The area outside Calabria was compiled and modified after: Cohen (1980), Gasparini et al. (1982), Fabbri et al. (1982), Moussat (1983), Ciaranfi et al. (1983), Wezel (1981, 1985), Boccaletti et al. (1984), Jongsma et al. (1985), Finetti and Del Ben (1986), Auroux et al. (1985, 1987), Argnani et al. (1987), Cello (1987), Ben-Avraham et al. (1987), Locardi (1988) and Lavecchia (1988).

TABLE 1

Secondary kinematic models for the Calabrian Arc as have been described in literature

1. TRANSLATION MODELS Moussat (1983) Auroux et al. (1985, 1987) Meulenkamp et al. (1986) Dewey et al. (1989)	
2. SPHENOCHASM MODELS Carey (1958, 1986) Vagt et al. (1971) Gidon (1974) Locardi et al. (1976) Caire (1979) Scandone (1979, 1982) Boccaletti et al. (1982, 1984, 1986) Bouillin (1984) Selli (1985) Mantovani et al. (1985) Dewey et al. (1989)	
3. BENDING MODELS Ghisetti & Vezzoni (1982a, 1982b) Ghisetti et al. (1982) Van der Linden (1985) Luanga (1988)	
4. RADIAL DRIFT MODELS Dubois (1976) Wezel (1981, 1985) Finetti & Del Ben (1986)	

LEGEND:

- Thrusting; triangles in upper block
- Normal faulting; dashes in down-faulted block
- Strike-slip faulting; dextral
- Strike-slip faulting; sinistral
- Folding axis
- Movement direction of blocks

N

0 50 KM

J.P. van Dijk, 11-1988

TABLE 2

Geodynamic mechanisms for the Central Mediterranean as have been postulated in literature

Local Mechanisms	Vertical forces dominate. Resulting structures are symmetrical.	**SLAB–PULL PROCESSES** Model after: Elsasser (1971); Van Bemmelen (1972) See also: Van Bemmelen (1974, 1976) Ritsema (1979) Malinverno and Ryan (1986) Description: Due to sinking of the underthrusting lithosphere and resulting outward migration of the subduction zone (roll–back), the Calabrian Arc actively overrides the Ionian Plate.	Kinematic Models: Translation Models Radial Drift Models
		MANTLE PROCESSES Model after: Van Bemmelen (1969, 1976) See also: Wezel (1981, 1985) Selli (1985) Locardi (1986) Luongo (1988) Channel & Mareschal (1989) Description: The (interaction of) mantle processes such as metasomatism, wedge flow and diapiric uplift, resulted in active back–arc spreading and possibly mantle–lithosphere delamination. Some authors describe radial nappe shedding from a central height.	Kinematic Models: Radial Drift Models Sphenochasm Models Bending Models
Regional Mechanisms	Horizontal forces dominate. Resulting structures are assymetrical.	**COLLISION PROCESSES** Model after: Gzovsky (1959); Pavoni (1961) Suggested by: Caire (1973) See also: Brunn (1976) Tapponnier (1977) Boccaletti et al. (1982, 1984) Mantovani et al. (1985) Description: Frontal collision along the N–margin of the African Plate resulted in a regmatic shear zone pattern, lateral expulsion of blocks (micro–push arcs), and/or the opening of mega–tension fissures (sphenochasms).	Kinematic Models: Bending Models Spenochasm models
		MEGA–SHEAR PROCESSES Model after: Carey (1958, 1986); sinistral shear Ritsema (1969); dextral shear See also: Hsu(1977) Caire (1978, 1979) Neeve and Hall (1982) Mantovani et al. (1985) Weijermars (1987) Description: Mega–shear between the African and European Plates is responsible for the lateral compression of the Central Mediterronean Area.	Kinematic Models: Bending Models Spenochasm models

J.P. van Dijk, 1989

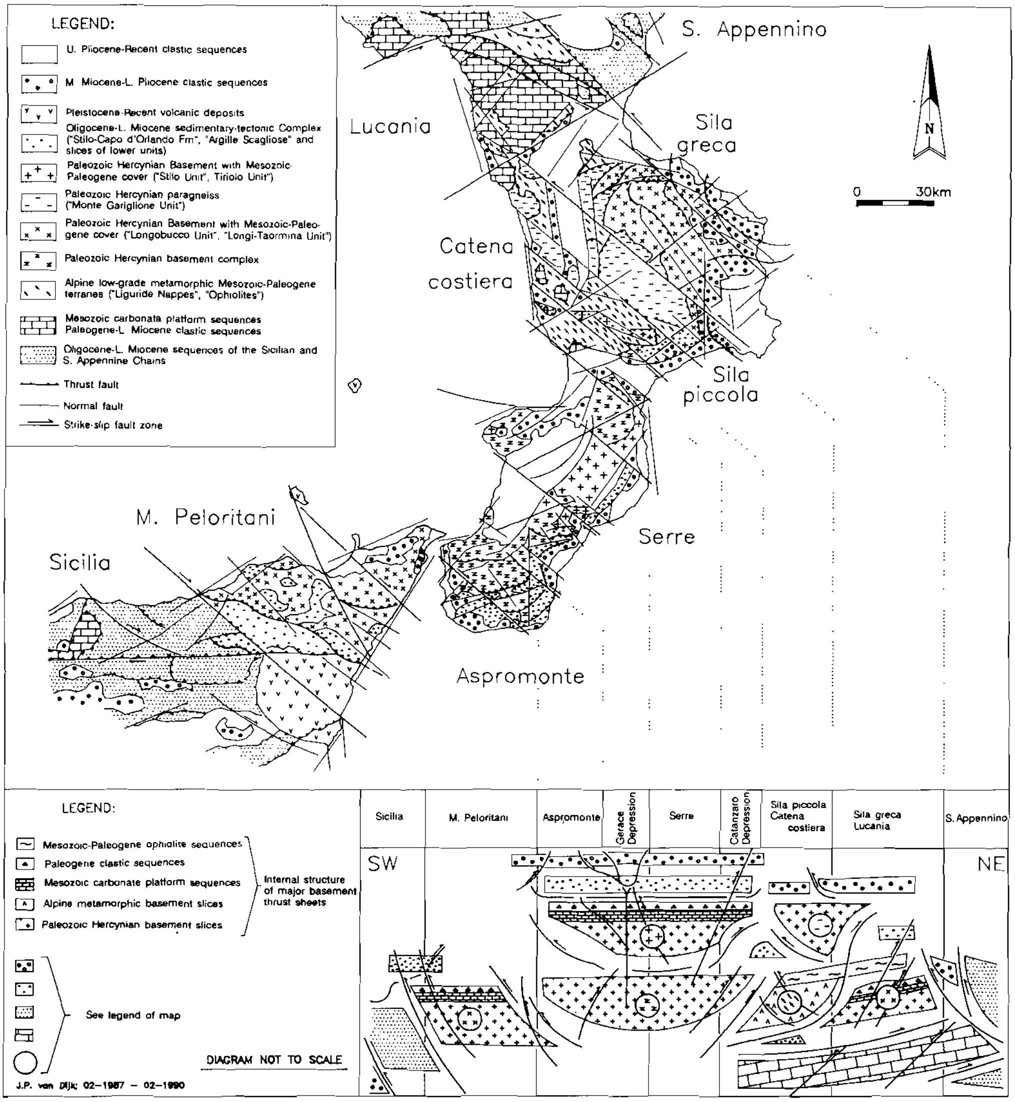


Fig. 2. Geological map and structural diagram of the basement of Calabria. For the sake of clarity, only principle structural relationships have been depicted. Compiled and reinterpreted after new data of the authors (see text) and Ogniben (1973), Dubois (1976), Grandjacquet and Mascle (1978), Lorenzoni et al. (1983), Bonardi et al. (1984), Teale and Young (1987) and Bouillin et al. (1988).

pp. 27–28

TABLE 3

Data concerning the principle fault zones of the Calabrian Arc from literature and our own mapping as have been combined and analysed in the construction of the presented geometrical and kinematic model for the Calabrian Element. Only the minimum amount of references necessary for the identification of the character of the zones has been included

STRUCTURAL ELEMENTS		GEOMETRY				KINEMATICS
		BASINS:	BASEMENT:	SEISMIC LINES:	VARIOUS:	INDICATORS & TIMING:
(A) NW–SE TRENDING OBLIQUE SHEAR ZONES	1 Vergilio – Etna Zone	8(MB)	2(OT) 6(OT) 7(OT) 13(OT)		6(BZ) 7(MA)	9(LS):Sd
	2. Capo d'Orlando Zone		2(OT) 6(OT) 7(OT) 13(OT)	2:R 8(IC)	7(MA)	2(FS):Sd
	3. Milazzo Zone		6(OT)	1:N 2:R	4(HC) 7(MA,RT)	
	4. Condofuri Zone	2(FM,TS) 5(FM) 6(FM)	12(OT)	1:N 2:R	4(AL) 7(MA)	7(ST):N(L.PII–Ple) 10(LS):Sd(MI–PII)
	5. Scilla Zone	2(FM,TS)	14(NC)	1:N 2:R	4(HC) 7(RT)	6(LS):N 10(LS):Sd(MI–PII)
	6 Capo Vaticano - Riace Zone	2(FM,TS)	6(NC) 7(NC) 12(NC)	1:N 2:R 8(IC)	7(MA)	7(ST):N(L.PII–Ple) 3(FT):Sa(Tor–E.PII) 6(LS):N 9(LS):Sd 10(LS):Sd(MI–PII)
	7. Assi Zone	2(FM,TS)	18(FZ)			10(LS):Sd(MI–PII)
	8. Soverato – Lamezia Zone	1(FM,TB,TS) 2(FM,TS)	15(OT) 3(OT) 18(OT) 9(NC)		7(RT)	7(ST):N(L.PII–Ple) 10(LS):Sd(MI–PII) 1(DS):Sa(Tort–M.PII)
	9. Cotanzaro – Amontea Zone	1(FM,TB,TS) 2(FM,TS) *	15(ST,NC) 4(NC) 5(ST) 17(ST) 18(ST) 15(OT)	8(IC)	2(AL) 7(MA)	3(FT):Sa(Tor–E.PII) 9(LS):Sd 1(DS):Sa(Tort–M.PII)
	10. Albi – Cosenza Zone	1(FM,TB,TS)	7(OT) 5(OT) 15(OT)	3(MO)	2(AL) 7(MA)	1(DS):Sa(Tort–M.PII)
	11. Petilia – Sosti Zone	1(FM,TB,TS) 2(FM,TB,TS) 7(FM) *	15(OT) 5(NC,FZ) 8(NC) 10(ST,NC) *	3(MO)	1(ML) 7(MA,RT) 4(AL) *	2(FS):Sa(R) 10(LS):Sa(MI–PII) 9(LS):Sd 1(DS):Sa(Tort–M.PII) *
	12 San Nicola - Campana Zone	1(FM,TB,TS) 2(FM,TB,TS)	11(NC) 1(ST)	4:R	7(MA,RT)	10(LS):Sa(MI–PII) 9(LS):Sd 1(DS):Sa(Tort–M.PII)
	13 Strongoli – Cropalati Zone	1(FM,TB,TS) 2(FM,TS)	1(ST) 11(OT)		7(RT)	1(DS):Sa(Tort–M.PII) 10(LS):Sa(MI–PII) 3(FT):Sa(Tor–E.PII)
	14. Ciro – Terranova Zone	1(FM,TS) 2(FM,TS)	1(ST) 21(OT) 4(OT)		7(RT)	9(LS):Sd 11(ST):R(L.MI–R)
(B) NE–SW TRENDING THRUST ZONES	B1 Africo Zone	2(FM,TS)	6(OT) 12(OT) 2(OT) 20(OT)		3(ML) 7(MA) 4(AL)	
	B2. Vaticano - Soverato Zone	1(FM,TS)	7(OT) 16(OT) 22(NC) 9(NC)			1(DS):Sd(Tort–M.PII) 9(LS):Sd(A,P)
	B3. Tribisina Zone	1(FM,TS)	1(ST)		1(ML) 2(AL) 7(MA)	1(DS):Sd(Tort–M.PII)
	B4. Sersale Zone	1(FM,TS) 2(FM,TS)	1(ST) 7(NC)		1(ML) 2(AL) 7(MA)	10(LS):Sd(MI–PII)
(C) RADIAL & CONCENTRIC S. TYRRHENIAN FAULTS	A. Cefalu Fault Zone	8(MB)		8(IC)	7(MA)	8(DI,LS):N
	B. Volcano Fault Zone	8(MB)		1:N 8(IC)	4(AL) 7(MA)	7(ST):Sd(M.PII) 7(ST):N(PII–Ple) 8(LS):Sd
	C. Capo Vaticano Fault Zone	1(FM,TS) 8(MB)		1:N 8(IC)	7(MA)	7(ST):Sd(M.PII) 7(ST):N(PII–Ple)
	D Vibo Valentia Fault Zone	2(FM,TS) 8(MB)		1:N	2(AL) 7(MA)	
	E. Savuto Fault Zone	8(MB)		1:N	1(HC) 7(MA) 2(AL)	
	F. Sangineto Fault Zone	7(FM) 8(MB)	7(NC,OT) 15(OT) 4(NC)	1:N 6(IC)	7(MA)	7(ST):Sd 5(LS):Sd(E.PII)
(D) MAGHREBIAN & APENNINE OBLIQUE THRUST ZONES	D1. Mt. Kumeta – Alcantaro Zone		4(OT) 6(OT)		7(MA)	7(ST):Sd,R(L.PII–Ple) 12(DI,ST):Sd.R(E.MI–PII)
	D2. Costelbuono Zone		6(OT)		7(MA)	
	D3. Taormina Zone		2(OT) 6(OT) 7(OT) 13(OT)		7(RT)	6(LS):Sd(M.PII) 9(LS):Sd
	D4. Acri – Caloveto Zone		5(OT) 23(OT)			7(ST):Sd(M.PII) 3(FT):Sa(Tor–Mes,M.Ple)
	D5 Pollino Zone	7(FM)	15(OT) 4(OT) 21(OT)		7(RT) 5(HC)	11(ST):Sa(E.MI–Tor) 11(ST):Sd,R(Mes–Ple) 3(FT):Sa(Tort–E.PII)

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TABLE 3 (continued)

Legend to Table 3:

BASINS:

FM: Faulted basin margins/hingelines
TB: Mid-Pliocene thrust belt
TS: Tectonostratigraphic break
MB: Morphological break

1. Our mapping (1983–1989)
2. Meulenkamp et al. (1986)
3. Burton (1971)
4. Roda (1964)
5. Bousquet et al. (1980)
6. Tortorici (1981)
7. Lanzafame & Tortorici (1981)
8. Barrier (1984); Barrier et al. (1987)
9. Wezel (1985)

BASEMENT:

OT: Overthrust trace
NC: Break in Nappe Pile constitution
FZ: Fault Zones: mylonites, kataklasis
ST: Small scaled thrusting

1. Our mapping (1983–1989)
2. Meulenkamp et al. (1986)
3. Burton (1971)
4. Caire (1970)
5. Dubois (1970, 1976)
6. Ogniben (1973)
7. Amodio-Morelli et al. (1976)
8. Lorenzoni et al. (1983)
9. Zanettin-Lorenzoni (1982)
10. Gurrieri et al. (1982)
11. Lorenzoni et al. (1978)
12. Bonardi et al. (1984)
13. Wezel (1975)
14. Lorenzoni & Z.Lorenzoni (1980)
15. Grandjacquet et al. (1961)
16. Borsi et al. (1976)
17. Ortolani et al. (1979)
18. Lorenzoni & Z. Lorenzoni (1975)
20. Bouillin et al. (1985, 1988)
21. Grandjacquet & Mascle (1978)
22. Boccaletti et al. (1984)
23. Zuffa & De Rosa (1978)

SEISMIC PROFILES:

MD: Break in Moho-depth

1. Barone et al. (1982)
2. Makris et al. (1986)
3. Goerler & Giese (1978)
4. Pacchiorotti (1984)

VARIOUS:

SATELLITE PHOTOGRAPHY:
AL: Alined lineaments
HC: High concentrotion of small lineaments
ML: Main linemant

1. Byu-Duval et ol. (1975)
2. Bodechtel & Muenzer (1978)
3. Bottari et al. (1982)
4. Bottari et al. (1986)
5. Auroux et al. (1985, 1987)

SEISMICITY:
BZ: Break in geometry of Benioff Zone
IC: Trend in isodepth contour of seismicity

6. Gasparini et al. (1982)
8. Wezel (1985)

MAGNETIC ANOMALIES:
MA: Magnetic anomaly maxima alignment
RT: Regional trend in anomaly contours

7. AGIP (1984)

KINEMATIC INDICATORS:

FT: Mesoscopic faulting & Strike combined
ST: Striations
DS: Statistics of distribution of strikes
LS: Large-scale considerations
DI: Mapped displacements
FS: Fault plane solution of seismicity

1. Our mapping (1983-1989)
2. Gasparini et al. (1982)
3. Moussat (1983)
4. Tortorici (1981)
5. Lanzafame & Tortorici (1981)
6. Amodio-Morelli et al. (1976)
7. Ghisetti & Vezzani (1981)
8. Wezel (1985)
9. Boccaletti et al. (1984)
10. Meulenkamp et al. (1986)
11. Ghisetti & Vezzani (1982 c)
12. Ghisetti & Vezzani (1984)

TIMING:

Pz: Paleozoic
Mz: Mesozoic
Pal: Paleocene
E: Eocene
Oli: Oligocene
Mi: Miocene
Bur: Burdigalian
Lan: Langhian
Srv: Serrovalian
Tor: Tortonian
Mes: Messinian
Pli: Pliocene
Ple: Pleistocene
Ho: Holocene
R: Recent

E: Early
M: Middle
L: Late
Pr: Pre-
Po: Post-

H: Hercynian
A: Alpine (M.Cretaceous-L.Eocene)
P: Apennine (Oligocene-Recent)

GENERAL:

N: Normal faults
R: Reverse faults/thrusts
S: Strike-slip faults
Sd: dextral slip
Ss: sinistral slip
F: Folding

*: Illustrated in this paper

J.P. v. Dijk & A. Meertens; 1987–1990

tion models, sphenochasm models, bending models and radial drift models.

The kinematic models have been used in literature to support various hypotheses concerning the geodynamic mechanisms for the evolution of the area (Table 2). Therefore, conclusive structural evidence concerning the kinematic models can be regarded as crucial in resolving basic questions regarding the geodynamics of the Central Mediterranean.

Fault zones intersecting the Calabrian Arc appear to play a widely different role in all models. In the translation models the NW–SE trending fault zones are considered to be a set of parallel vertical shear zones, sinistral in the northeast and dextral in the southwest of the arc. A point of discussion concerns the orientation of the major shear zones which varies from N120 (Moussat, 1983) to N140 (Meulenkamp et al., 1986). The translation models, however, cannot account for the observed amount of shortening in the Southern Apennines. The sphenochasm models focus on this aspect and put more emphasis on E–W to SW–NE trending fault zones. These are regarded as dextral shear zones displacing the northern parts of the arc relatively to the east. The bending models and radial drift models postulate (trans)tension along the radial and tension along

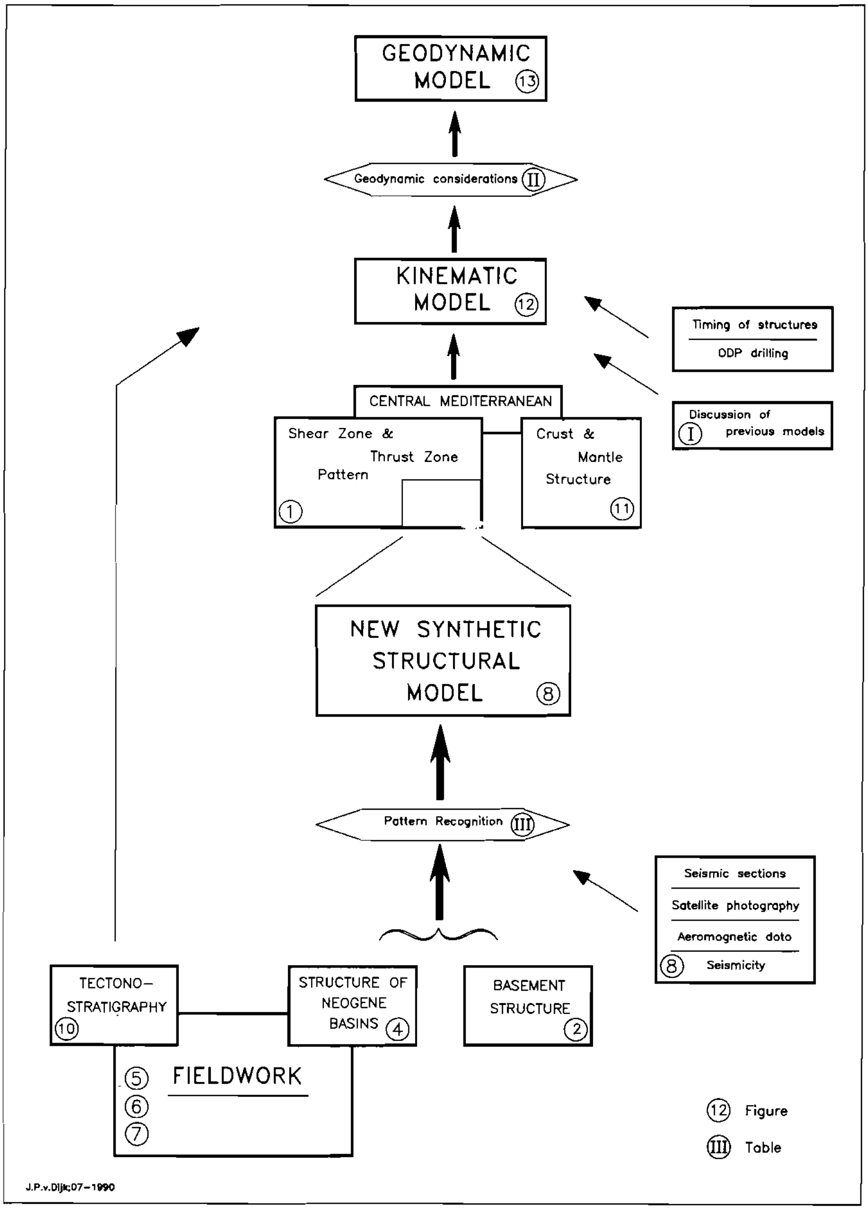


Fig. 3. Flow diagram showing the line of reasoning followed in the paper and relative position of the figures and the tables presented.

the concentric fault patterns within the Southern Tyrrhenian area. To solve these apparent contradictions, we studied the Neogene terrains of the Calabrian Arc. New data will be presented from Central and Northern Calabria.

The line of reasoning followed in the present paper and the role of various presented data and figures are shown in Fig. 3. We combined the datasets on Neogene basin kinematics with data from the literature on the structure of the basement (Fig. 2), with evidence from deep seismic profiles and with satellite photographic studies into a new structural synthesis and subsequently a related kinematic model. Finally, implications for the geodynamics of the Central Mediterranean are discussed.

New data and methods

The new data we collected during seven field campaigns from 1983 to 1989 resulted in 1 : 25,000 and 1 : 10,000 maps of Central and Northern Calabria (unpublished, and summarized in Fig. 4). These maps, based on about 3000 outcrops, are supported by aerial photography and by about 500 samples which have been analysed for planctonic foraminifers and structural data (fault planes, bedding planes, striations). Furthermore,

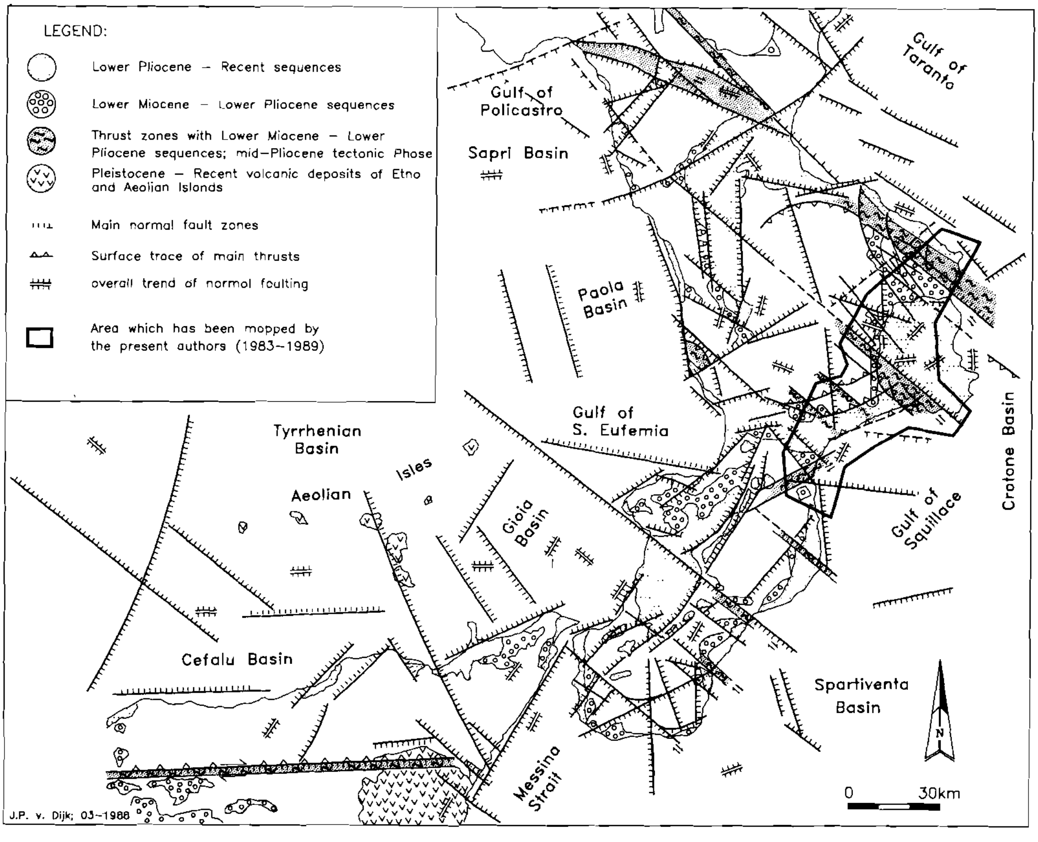


Fig. 4. Geological map of the Neogene of Calabria. Indicated is the area which has been mapped by the authors. Data outside this area have been compiled after Ghisetti and Vezzani (1981), Tortorici (1981), Barone et al. (1982), Moussat (1983), Pacchiarotti (1984), Barrier et al. (1987), Makris et al. (1986), Meulenkamp et al. (1986), Auroux et al. (1985, 1987).

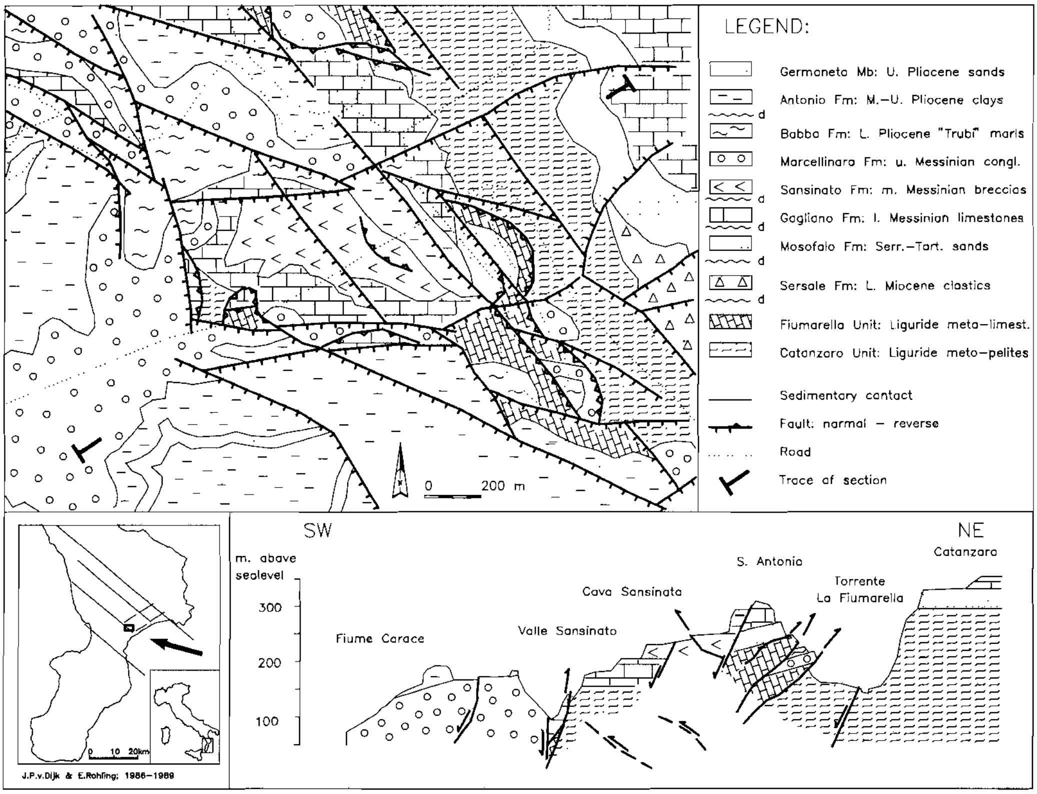


Fig. 5. Geological map and structural section of the Catanzaro area in the central part of Calabria. The figure shows thrusting towards the basin margin (NE) and inferred basement thrusting towards the southwest along N120 and N145 trending faults in which Serravallian–Lower Pliocene ("Trubi marls") as well as basement rocks have been incorporated. These configurations are typical for the Calabrian shear zones and have been interpreted by the present authors as asymmetrical positive flower structures.

we used unpublished maps of the external part of Calabria as have been summarized by Meulenkamp et al. (1986). Figures 5, 6, 7 and 10 are exclusively based on the results of our field analyses. More details have been presented in Van Dijk and Okkes (1990), Van Dijk (1991), Van Dijk (in press.) and forthcoming papers.

The structure of the arc

In general, the terrains which constitute the Calabrian Arc can be divided in two parts: (1) "The Basement", consisting of a complex of crystalline Paleozoic Hercynian thrust sheets with Mesozoic–Paleogene cover, and a complex of Oligocene–Lower Miocene terrains and (2) Middle–Upper Miocene, Pliocene and Quaternary terrains, consisting of a number of sequences which unconformably overly the basement.

Basement structure

The various descriptive models and explanatory hypotheses concerning the Calabrian basement will not be discussed in detail (for a short review, we refer to Van Dijk and Okkes, in press). Our own data combined with a systematic review of the available data in literature (see references in Table 3), suggests the picture which has been presented in Fig. 2. Along the northeast and southwest, the Calabrian terranes overthrust the Sicilian Maghrebides and Southern Apennines which comprise

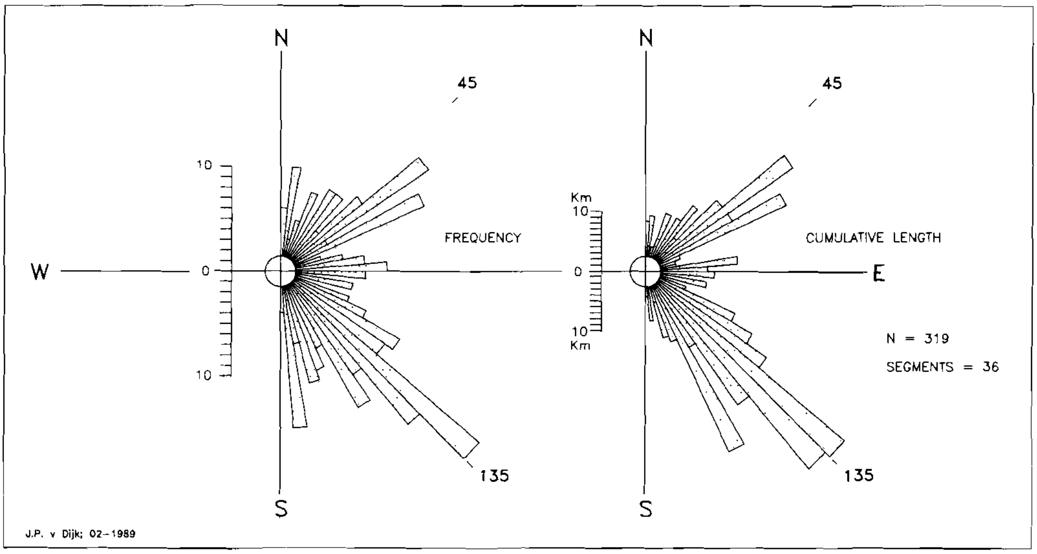


Fig. 6. Rose diagram of frequency and cumulative length of faults which have been mapped in the area of the Petilia–Rizzuto fault zone in Central Calabria. The diagram shows maxima in N130 and N045 directions and furthermore secondary maxima in N140 and N120 directions and N090 and N180 directions.

Oligocene–Lower Miocene terrains and Mesozoic carbonate platform elements.

The southwestern (Monte Peloritani) and northeastern (Sila Greca) sides of the Calabrian basement complex are composed of a pile of thrust nappes with an external vergence, in literature often referred to as "African" and "Apennine vergence" respectively. These units consist of granitic/metamorphic Paleozoic, Hercynian basement nappes, covered with Mesozoic–Paleogene-(?)Lower Miocene sediments.

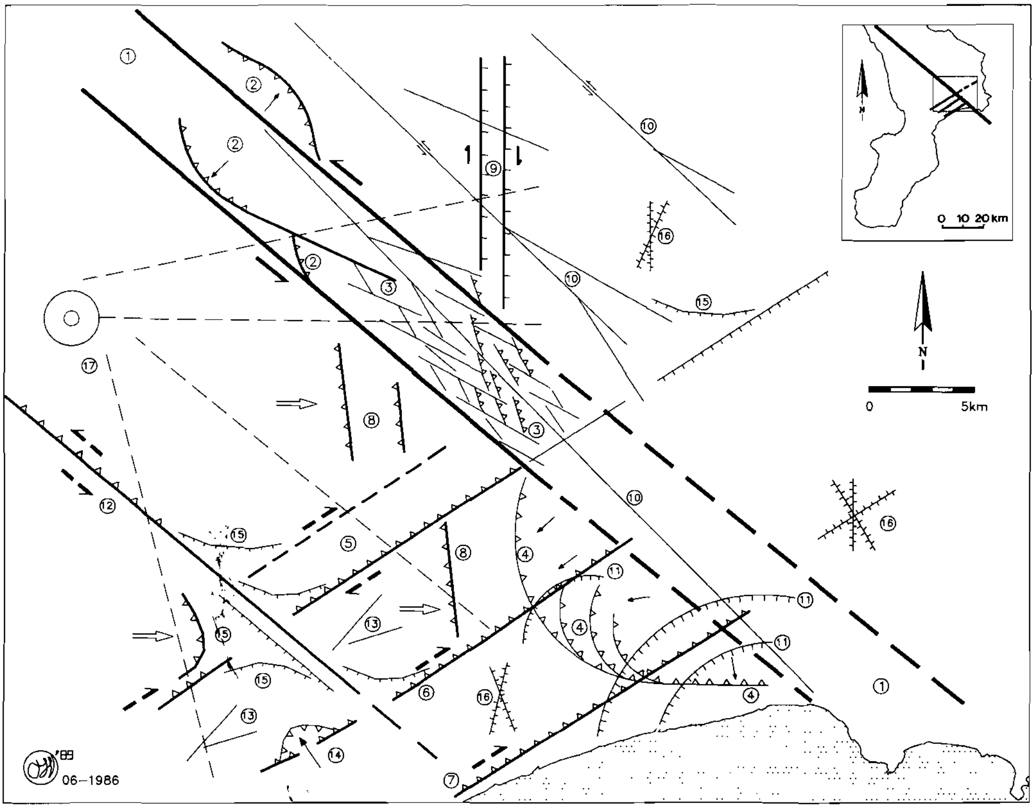
The central part of the arc (Sila Piccola, Serre, Aspromonte) can be regarded as a large klippe which overlays the above described thrust pile along two major boundaries: The Petilia-Sosti Line in the northeast (Fig. 9a; no. *11*) and the Condofuri Line in the southwest (Fig. 9a; no. *4*). The lowermost units consist of a number of thrust sheets with a so called "European vergence". These comprise low-grade Alpine (Eocene) metamorphic units (Mesozoic–Paleogene "Liguride" ophiolite sequences) and "Panormide" carbonate platform elements, and slices of metamorphic basement and Oligocene–Lower Miocene terrains. The uppermost thrust sheets consist of Paleozoie Hercynian granites and gneisses.

Along the frontal, southeastern side (Sila Piccola, Serre Aspromonte) the central klippe is obliquely overlain by the "Stilo Unit/Tiriolo Unit" along, e.g., the Capo Vaticano–Soverato fault zone (Fig. 9a; *B2*). The structure of this unit is essentially the same as the lowermost units along the northeastern and southwestern sides of the arc. Closely related to this unit, Oligocene–Lower Miocene allochthonous terrains with slices of basement are present along the central external southeastern side of the arc.

Along NW–SE trending fault zones thrust-wedges are present which comprise both basement and Middle Miocene–Lower Pliocene sequences.

Evidently, this picture highly simplifies the real basement structure but represents a good working model for further reasoning. Remarkable are the following points: (1) The central units of the arc which contain slices of Oligo-Miocene sequences show an increase in complexity towards the northeast. (2) The wedges wich incorporate Middle Miocene–Lower Pliocene sequences increase in size towards the northeast. (3) The basement complex can be separated into NW–SE trending segments which each show their own characteristic sequence of thrust sheets.

The entire Calabrian basement complex can be regarded as an amalgamation of suspect allochthonous terranes (terminology of Irwin, 1972; Coney et al., 1980; Schermer et al., 1984, proposed for the Calabrian Arc by Van Dijk and Okkes, 1988 and in press.), accreted in Late Eocene, Early Miocene and late Early Pliocene times. This com-



Legend:

1. N130 trending surface trace of the sinistral Petilia – Sosti Shear Zone
2. Basement flower structures along the trace of the Shear Zone (Age unknown)
3. Fault pattern within the Fault Zone:
   N120 trending Riedel faults
   N140 trending P-structures
   N160 trending thrusts
   N060 trending anti-Riedel faults and
   N090 trending tensional faults
   have not been depicted
4. Large flower structures in Neogene deposits covering the Fault Zone as occurring in the SW
5. Surface trace of the dextral Sereale Fault Zone
6. Surface trace of the Tribisina Fault Zone
7. Surface trace of the Batricello Fault Zone
8. N175 trending steeply dipping basement thrusts
9. N–S trending propably dextral boundary of the Crotone Basin (Related Reidel pattern structures have been omitted.)
10. N140 trending wrench faults in the Central Segment:
    Petilia–Arciera Fault Zone
    Neto Fault Zone
    Lese Fault Zone
    with N120 and N180 branching faults in the sedimentary cover
11. Rotational tensional antithetic faults along the trace of the SE–verging thrusts resulting in chaotic terranes
12. N130 trending trace of the oblique sinistral Albi – Cosenza Shear Zone
13. Riedel pattern structures in between the dextral shear zones
14. Backthrusting along the trace of the dextral thrust zones
15. Fault systems as present in the areas of intersection of the two main oblique thrust systems:
    – E–W trending normal faults
    – N–S trending thrusts and reverse faults
16. Main Pleistocene – Recent conjugate tensional fault patterns and trends of large tensional fault zones
17. Centre of the Pleistocene Sila Piccola dome–shaped uplift with inferred radial fault pattern

Fig. 7. Model for the structural configurations in the Petilia–Rizzuto shear zone of Central Calabria. The model is based on 1 : 25,000 and 1 : 10,000 mapping of the area (see Fig. 4).

plex has travelled to the southeast during the Neogene as one large allochthonous element.

Neogene and Quaternary terrains

For details concerning stratigraphy, tectonics, satellite photography and the analyses of small-scaled structures, we refer to the extensive reviews and discussions which are mentioned in Table 3 and to Van Dijk (in press.). Figure 4 summarizes our data and the information from the literature. The following patterns of basin controlling faults and fault zones can be recognized in the southern Tyrrhenian Basin and Calabrian Arc:

(A) NW–SE trending fault zones, which determine a set of N130 trending segments. Within and along these segments, the following two fault systems are developed:

(A1) large N110–N150 orientated wrench faults, N–S and E–W trending transtensional (intra-arc) and transpressional (external) faults within the segments. These faults confine small strike-slip and pull-apart basins.

(A2) Chaotic thrust zones/wrench faults along the boundaries of the segments (Riedel shear set; positive flower structures; see Fig. 5). These faults confine small-scale strike-slip basins. The segment boundaries as a whole define pull-apart basins on a larger scale within the segments. On a 1 : 25,000 map-scale, N120 and N140 faults dominate the structural pattern, whereas on the scale of satellite photography (1 : 1,000,000) N130 trending lineaments tend to be conspicuous (see Table 3 and Figs. 4, 5, 6 and 7).

(B) SW–NE trending fault zones. The trend of these fault zones gradually changes from NE–SW in the north to E–W in the south. The fault zones define the margins (growth faulting, hingelines) of small basins along the external side of the arc.

(C) Radial and concentric fault systems in the southern Tyrrhenian back-arc Basin. Three fault systems can be distinguished:

(C1) Radial tensional fault zones intersecting the entire arc and constituting a fan-shaped Southern Tyrrhenian pattern. These faults confine a set of triangular segments which together constitute the semi-circular Southern Tyrrhenian Basin.

(C2) Concentric tensional faults along the internal, Tyrrhenian side of the arc. These faults dominate the recent morphology of the actual arc.

(C3) Radial and concentric faults belonging to dome-shaped uplifted massives within the arc.

A new structural model

We interpret the NW–SE and NE–SW trending fault zones of patterns A and B as oblique thrust zones. This conclusion is based on the comparitative analyses of the available information on Neogene basin kinematics, basement structures and additional information such as satellite photography, aeromagnetics and seismic lines. The principle features of our set of data have been added as Table 3. An example of the comparitative analyses has been depicted in Fig. 8. Basically, a combination of four arguments has led us to our conclusion:

(1) The trend and spacing of the fault zones compares well with the trend and spacing of thrusts as visible on seismic profiles along the external side of the arc, and are in some cases in a direct line with these structures. For pattern A this applies to the seismic lines along the northeast side of the arc (Gulf of Taranto) such as MS-25 of Finetti and Morelli (1973), the profiles of Cello et al. (1981) and the seismic lines in the southwest part of the accretionary-wedge of Makris et al. (1986). For pattern B, we refer to the profiles of Rossi and Sartori (1981) and line MS-60 of Finetti (1981, 1982) and Finetti and Del Ben (1986).

(2) Comparing the data on the structure basement as described above with the Neogene fault zones we concluded that these zones coincide with breaks in composition of the nappe pile (Fig. 2). These breaks in the crystalline basement are in fact large overthrust zones, characterized by cataclasis and mylonites. This indicates that neotectonic shearing of the arc principally occurred along (pre-existing) basement thrusts and fracture zones.

(3) In the areas where the fault zones intersect (e.g. Fig. 7), tectonic stacking has occurred which is in agreement with the combination of the vergence of the thrust zones as implied by arguments

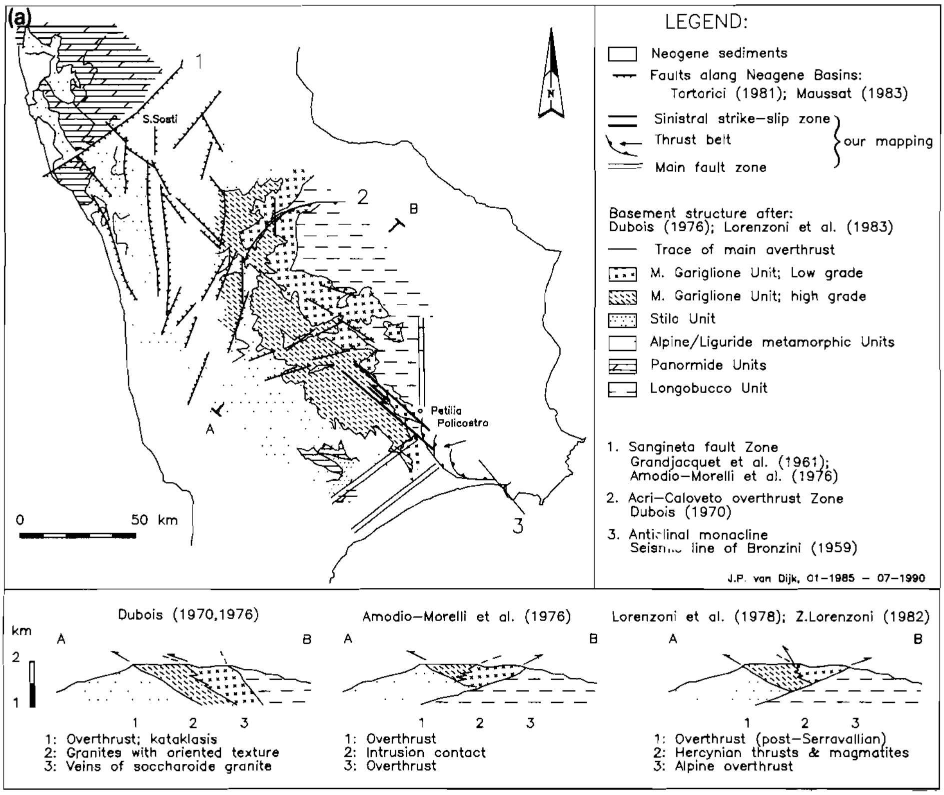


Fig. 8. (a) Compilation of geological data concerning the Petilia–Sosti fault zone in Northern Calabria. The figure shows how basement structure and the structure of the Neogene basins coincide and give an indication of the deeper structure of the fault zone. The offset of the low grade and high-grade parts of the Monte Gariglione Unit along the strike of the fault zone indicates a sinistral shear which is in accordance with our analyses of the Neogene character of the shear zone in the southeastern part of the area. (b) Satellite lineament plot and contour map of aeromagnetic anomalies in the area of the Petilia–Sosti fault zone in Northern Calabria. The trace of the fault zone coincides with a high density of satellite lineaments as well as with a regional trend in magnetic anomaly contours and maxima.

(1) and (2) and the strike-slip character as inferred from the basin kinematics.

(4) The position of principle basins and heights is in agreement with these positions as implied by the interpreted vergence of the thrust zones. Also, the hinge-line character of many fault zones can be related to their thrust activity.

The interpretation of patterns A and B as two intersecting thrust systems implies that the principle basins along the external side of the arc can be regarded as piggy-back basins (sensu Ori and Friend, 1984; proposed for the Calabrian basins by Van Dijk and Okkes, 1988). The two tectonic patterns are in fact the on-shore continuity of the accretionary-wedge system along the external side of the arc. An example of the interaction of faults belonging to the three patterns is shown in Fig. 7.

Taking all available information into account, the following (hypothetical) synthetic structural model has been developed (Fig. 9): The Calabrian Arc can be divided into N130 trending segments, separated by oblique shear zones (pattern A). These zones (widths of 5–10 km) are defined by either NE- or SE-verging basement thrusts. Within these shear/thrust zones, complex Riedel fault sets and basement thrusts are present (Fig. 7).

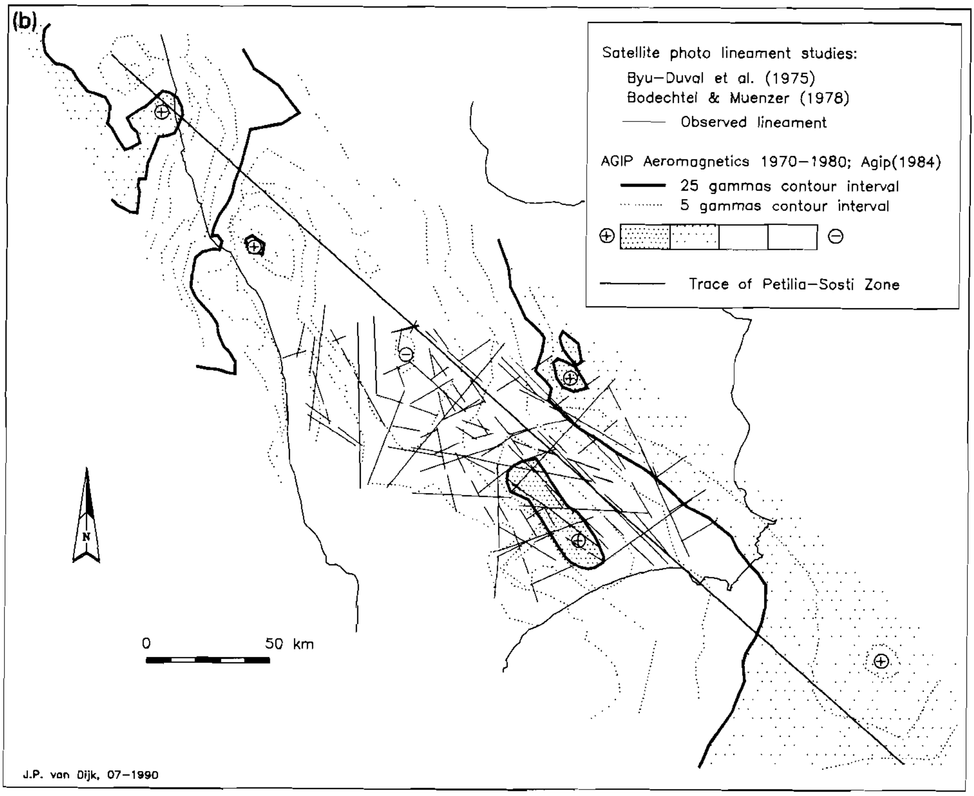


Fig. 8 (continued).

Each segment between the shear zones displays its own characteristic nappe pile geometry (Fig. 2) and is intersected by large N110–120 and/or N140–150 trending basement wrench faults (fault system A1). Blocks between opposite verging thrusts form heights (Sila Piccola, Aspromonte, Serre) whereas blocks between facing thrusts form depressions (Catanzaro depression and Gerace depression). Blocks between equal verging thrusts form intermediate areas (Sila Grande–Greca, Peloritani) (Fig. 9b-A).

Remarkable is that the principal wrench fault orientation (fault system A1) in the Peloritani and Aspromonte blocks is N140 whereas the Catanzaro depression, Sila Piccola block and Sila Grande block are mainly intersected by N120 trending wrench faults. This is related to a change in differential movement of the segments, from dextral in the southern part to sinistral in the northern part of the arc. The Serre block forms the central segment of which the shearing direction is unclear.

Intersected and displaced by this thrust system, a SE-verging second thrust system has developed (pattern B). This second system defines a vector of basin opening to the southeast in the course of the Neogene (Fig. 9b-B–D). Back-thrusting of Neogene deposits along this system has occurred, also visible on the seismic section MS-60. The Serre block (Fig. 9b-C) is a comparable feature though on a larger scale. The internal ENE–WSW trending internal margin of this block has been described as a dextral wrench zone and as a SE-verging thrust (Table 3). Probably, the Serre block was (back-)thrusted to the north-northwest along this dextral zone with related tilting to the south-southeast. Pattern A continues in the Southern

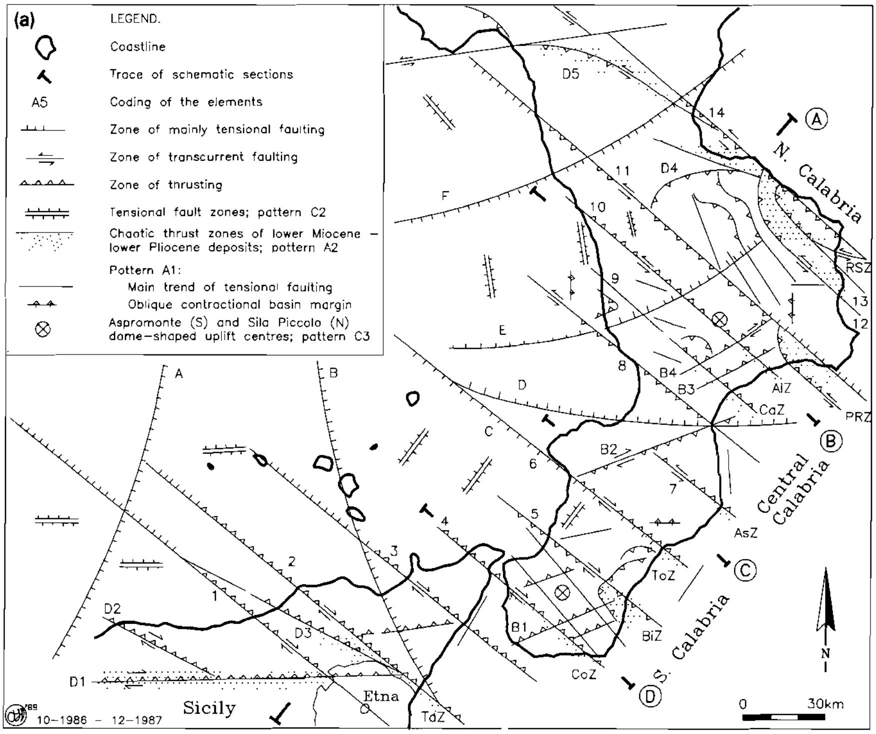


Fig. 9. (a) Schematic structural map showing the main Neogene tectonic elements of the Calabrian Arc. (b) Schematic cross-sections of the Calabrian Arc. Note the differences in scale between sections below and above sealevel.

Apennines thrust belt which displays a NW–SE trending oblique sinistral character. In the same way, pattern B continues in the Sicilian Maghrebides thrust belt, which displays an E–W trending oblique dextral character. Pattern C overprints the two thrust systems A and B. The continuation of these structures into the Calabrian Arc partly coincides with the boundaries of the NW–SE trending segments (Fig. 9a).

Models for the crustal structure of parts of the Calabrian Arc based on deep seismic sections as presented Görler and Giese (1978), Finetti and Del Ben (1986), Scandone (1979) and Cello et al. (1981), fit well into the new geometric model for the two intersecting thrust systems. The "mushroom-structure" of the isobaths of recent seismicity in the Southern Tyrrhenian as described by Wezel (1985), neatly corresponds with the tectonic pattern C.

Evolution of the arc

The following generalized flow-chart for the development of the basement can be deduced (see references in Table 3; and caption of Fig. 2):

Trias–middle Cretaceous: Development of a NW–SE trending passive continental margin opening to the northeast which was probably dextral transtensional (see, e.g., Bouillin, 1984; Santantonio and Teale, 1987; Teale and Young, 1987). Note that the directions evidently relate to the recent orientation of the structures.

Middle Cretaceous–Late Eocene: Destruction of the continental margin and related Piemonte–Liguride–Ionian oceanic basin with associated Alpine metamorphism and ophiolite nappe emplacement related to "Europe-vergent" thrusting in a northwestward dipping subduction zone (see, e.g., De Roever, 1972; Dubois, 1976).

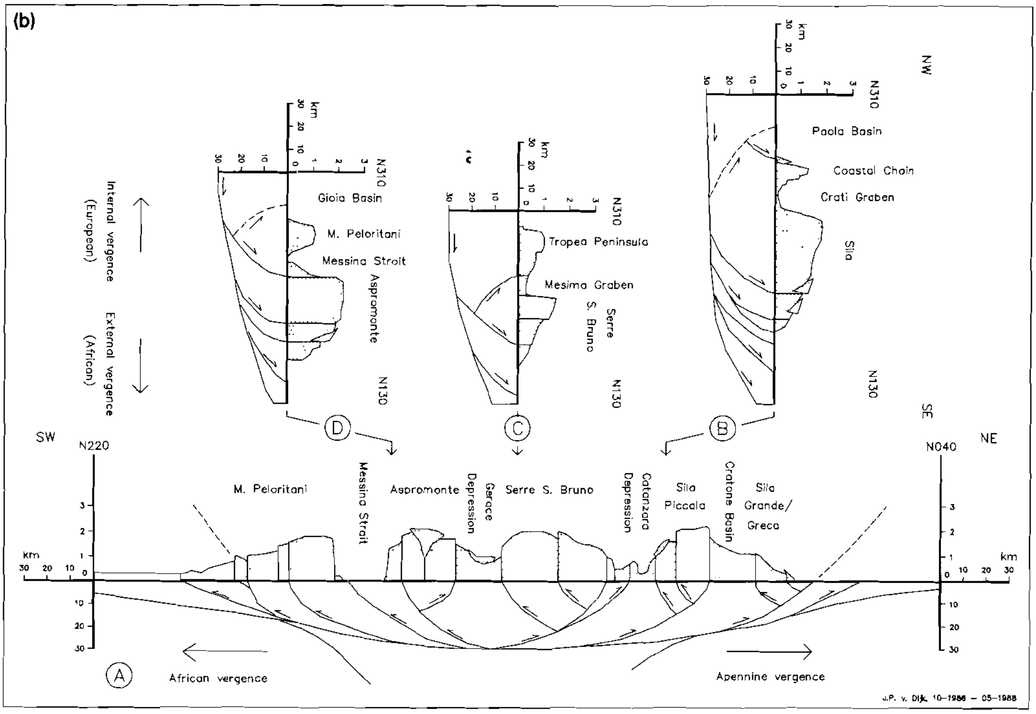


Fig. 9 (continued).

Oligocene–Late Burdigalian: We interpret the available data analogous to the model for the Middle–Late Neogene as described below in more detail. Basin development during this period was essentially controlled by progressive thrusting to the southeast along thrusts of pattern B with associated deposition of clastic sequences in piggy-back basins, laterally confined by the NW–SE trending fault zones of pattern A. These deposits are the continental and shallow marine basin margin equivalents of the "Argille Varicolori" and "Numidian Flysch" basins of Sicily and the Southern Apennines (see Durand Delga, 1980 for a review), and not a post-orogenic molasse ("Stilo-Capo D'Orlando Fm") as is usually stated in literature (Bonardi et al., 1980; Giunta, 1985). The southern part of the sequences may have an intra-arc or back-arc basin origin (cf. the statements of Durand Delga, 1988 for parts of the Algerian sequences; see fault system A1). This follows from (a) the description of Platt and Compagnoni (1990) of Late Oligocene metamorphism and N–S stretching related to uplift of the Aspromonte basement which indicates that the basins where created by extensional faulting, and (b) similarity between Late Oligocene–Lower Miocene tectonostratigraphic development of the Southern Calabrian basins and the Sardinian (intra-arc) rift basins (Cherchi and Montadert, 1982), which where probably interconnected (see further). In Late Burdigalian times, these sequences were incorporated in compressional thrusting and gravitational sliding to the southeast and related back-thrusting to the northwest (Meulenkamp et al., 1986; Van Dijk and Okkes, 1990), which is probably related to a major shortening phase in Sicily. Traces of Burdigalian overthrusting are also detected in Northern Calabria by Dietrich (1976), reflecting a SW–NE directed component of shortening related to a major shortening phase in the

Apennines (see also Fig. 2). The Late Oligocene–Early Miocene development is related to the opening of the Western Mediterranean rift Basin and rotation of the Sardinia–Corsica block in the final stage (see Rehault et al., 1985 and references therein).

Neogene: "Late" phases of basement thrusting (Ortolani et al., 1979; Zanettin-Lorenzoni, 1982) along the major shear zones can be placed in the late Early Pliocene (Van Dijk and Okkes, 1990; see Figs. 2 and 5).

We subdivided the Langhian–Recent tectonostratigraphy in a number of unconformity-bound depositional sequences, which resulted in a general scheme for the Neogene development of the Calabrian basins (Fig. 10, Table 3; see also Van Dijk, in press). The comparison of this development scheme with data from ODP and seismic surveys in the Tyrrhenian (reviewed by Moussat, 1983 and Kastens et a]., 1988) and Ionian basins (reviewed by Finetti and Del Ben, 1986) and with the basin development in Sicily and the Apennines (reviewed by Pattaca and Scandone, 1989) results in the following flow chart:

After an onlapping phase in the *Late Burdigalian–Langhian*, the subsequent *Serravallian–Early Pliocene* basin development along the major fault zones of pattern A can be divided into three stages: a basin opening stage, a basin fill stage and a basin closure stage. This development mirrors the strike-slip cycle sensu Mitchell and Reading (1978) and Reading (1980) (see Fig. 10). During these stages, the NW–SE running shear zones controlled the development of complex pull-apart basins which are mainly half grabens with sediment supply along the steep margins confined by the shear zones (system A2, see also brief remarks on this matter by Moussat, 1983; Boccaletti and Dainelli, 1982; Meulenkamp et al., 1986 and Tortorici, 1981 and a detailed description by Van Dijk, 1991). Oblique contractional and extensional pull-apart margins (system A1) delimited the external basins and the intra-arc basins respectively (Figs. 7 and 9a). Within each of the NW–SE trending segments, a unique set of wrench faults with characteristic orientation developed (system A1). These orientations show divergences up to 15° from the main N130 trend. Along the NE–SW trending external side of the arc, the faults of pattern B determined the development of piggy-back basins. The basin development along the two intersecting thrust zone systems shows affinity with the piggy-back basin models of Ricci-Lucchi 1986) for the Northern Apennines and models for inversion of half grabens reviewed by Graciansky et al. (1988) for the Western Alps and by Watson et al. (1987) for China. The activity of patterns A and B coincide with the Late Serravallian–Early Pliocene opening of the Northern and Central Tyrrhenian Basin. We postulate a Langhian–Serravallian phase of rifting in the southwestern Tyrrhenian area (see further). In the Late Serravallian and middle Messinian, this development was interrupted by short phases of uplift and tilting, erosion and subsequent onlaps. These phases can be correlated with thrusting phases which led to the development and destruction of foreland basins in the Central and Southern Apennines (e.g. the Early Miocene Irpinian Basin and the Messinian Laga Basin).

During the *late Early Pliocene*, the Calabrian basins were subsequently deformed and inverted by convergent shearing along the above mentioned wrench faults. The expression of this late Early Pliocene phase of shortening can be found as chaotic zones of oblique back-thrusts along the traces of all shear zones (system A2). We are able to prove that basement was involved in the late Early Pliocene thrusting in some areas (see above). We also observed oblique back-thrusts along the faults of pattern B. This compressive phase coincides with a major phase of shortening in the Apennines and in Sicily.

The *Middle Pliocene–Late Pliocene* phase was characterized by rapid subsidence of the Calabrian basins and compressional thrusting in the outer arc region, called the "Calabrian Ridge" (Rossi and Sartori, 1980; Finetti, 1981, 1982). During this period, the Southern Tyrrhenian Basin opened, which implies a rapid southeastward migration of the Calabrian Arc. The combination of internal tensional faulting and external compressive thrusting during this period can be explained by assuming that the southeastward displacement of the arc and resulting growth of the thrust wedge created an instability which was compensated by tensional

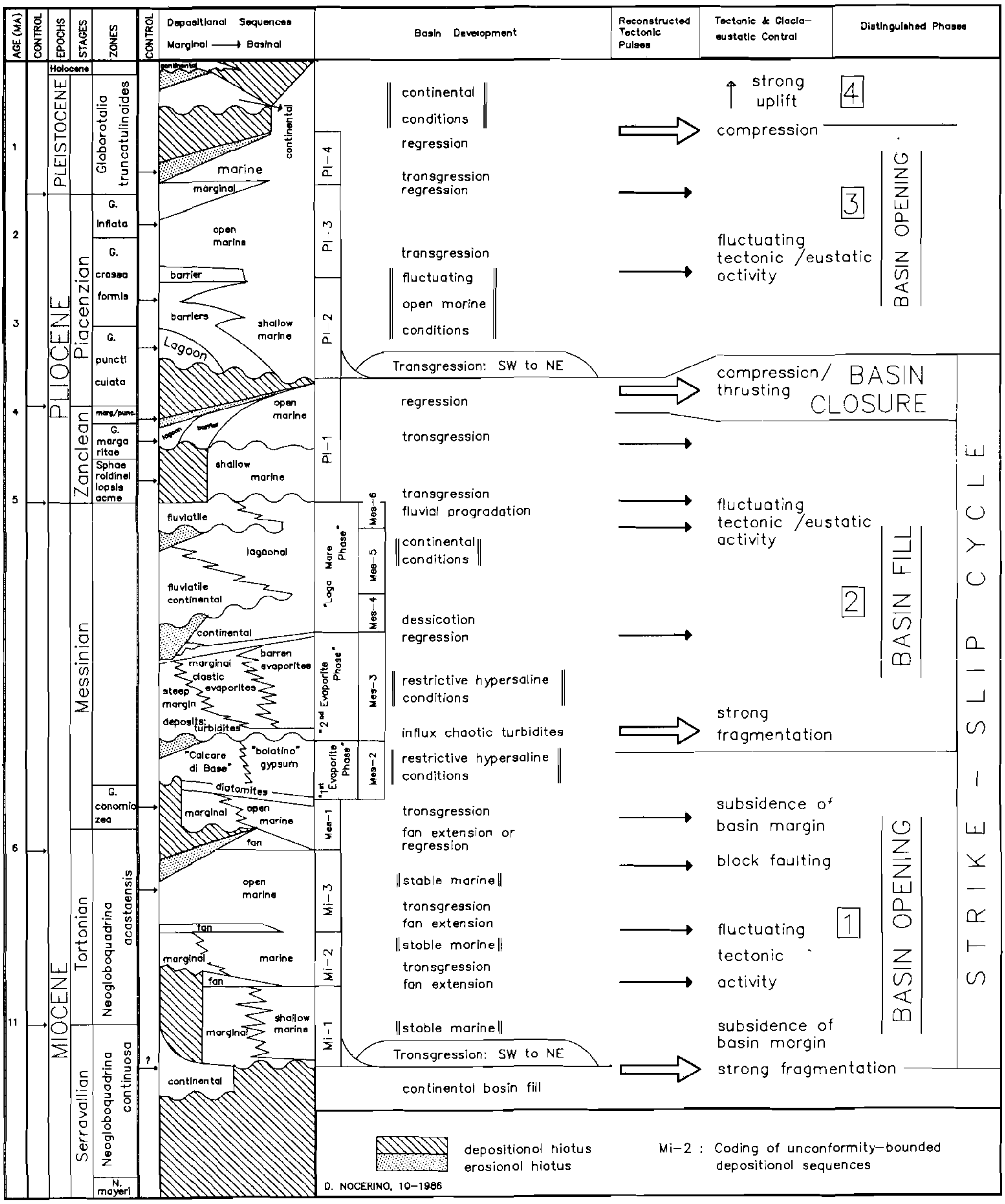


Fig. 10. Synthetic diagram for the Neogene basin development of Central Calabria, based on fieldwork performed in the central part of Calabria (see Fig. 4).

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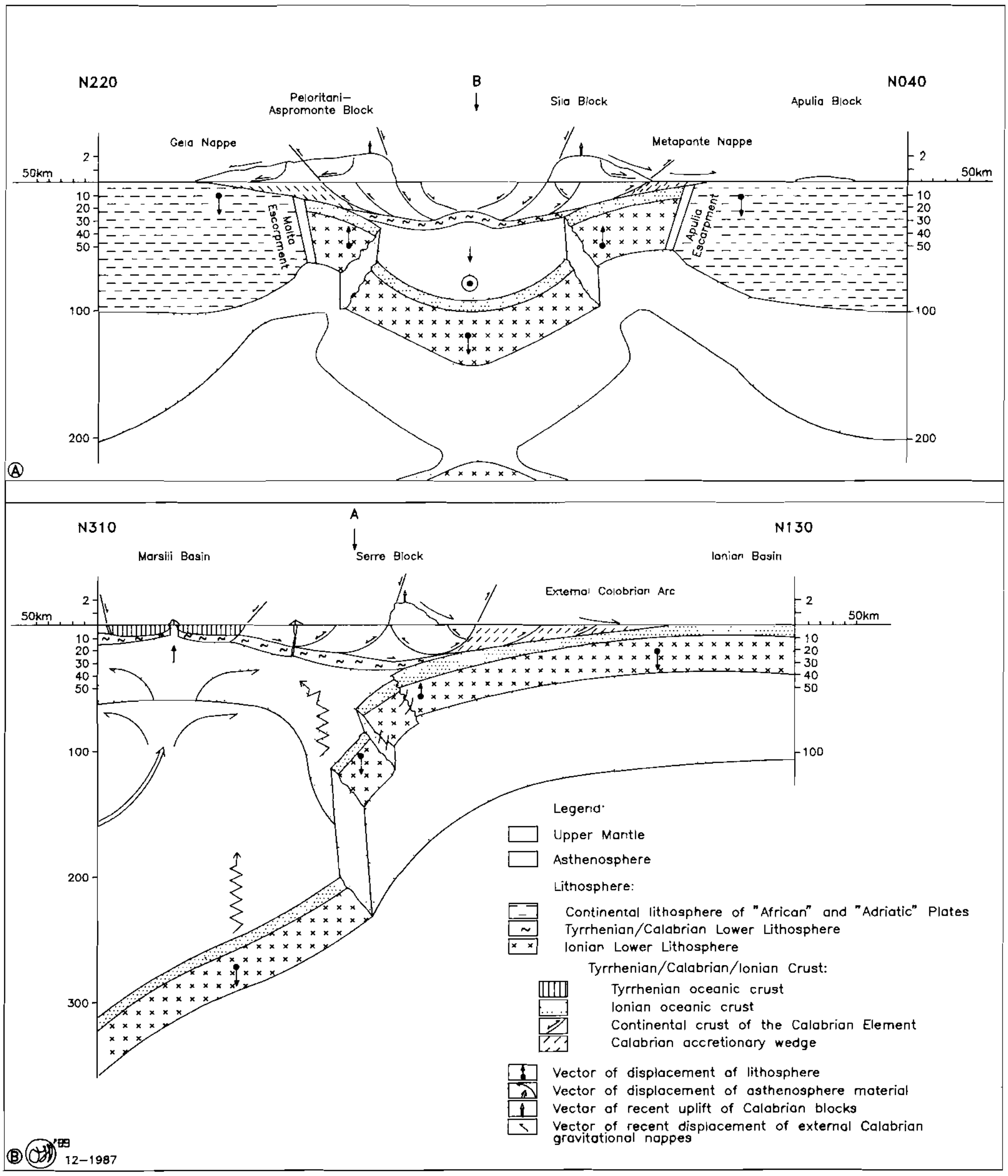

Fig. 11. Synthetic sections of the Central Mediterranean region, based on seismicity, seismic tomography and deep seismic profiles. Compiled and modified after Petersmitt (1956), Cassinis et al. (1969), Ritsema (1969, 1979), Caputo and Postpischl (1973), Giese and Morelli (1975), Van Bemmelen (1978), Schütte (1978), Görler and Giese (1978), Giese and Reutter (1978), Roeder (1978), Cassinis et al (1979), Cello et al. (1981), Giese et al. (1982), Horvath and Berckhemer (1982), Ghisetti and Vezzani (1982a), Mantovani (1982), Mantovani et al. (1985), Finetti and Del Ben (1986), Spakman (1986), Rapolla (1986), Anderson and Jackson (1987), Cello and Nur (1988) and Moretti and Royden (1988).

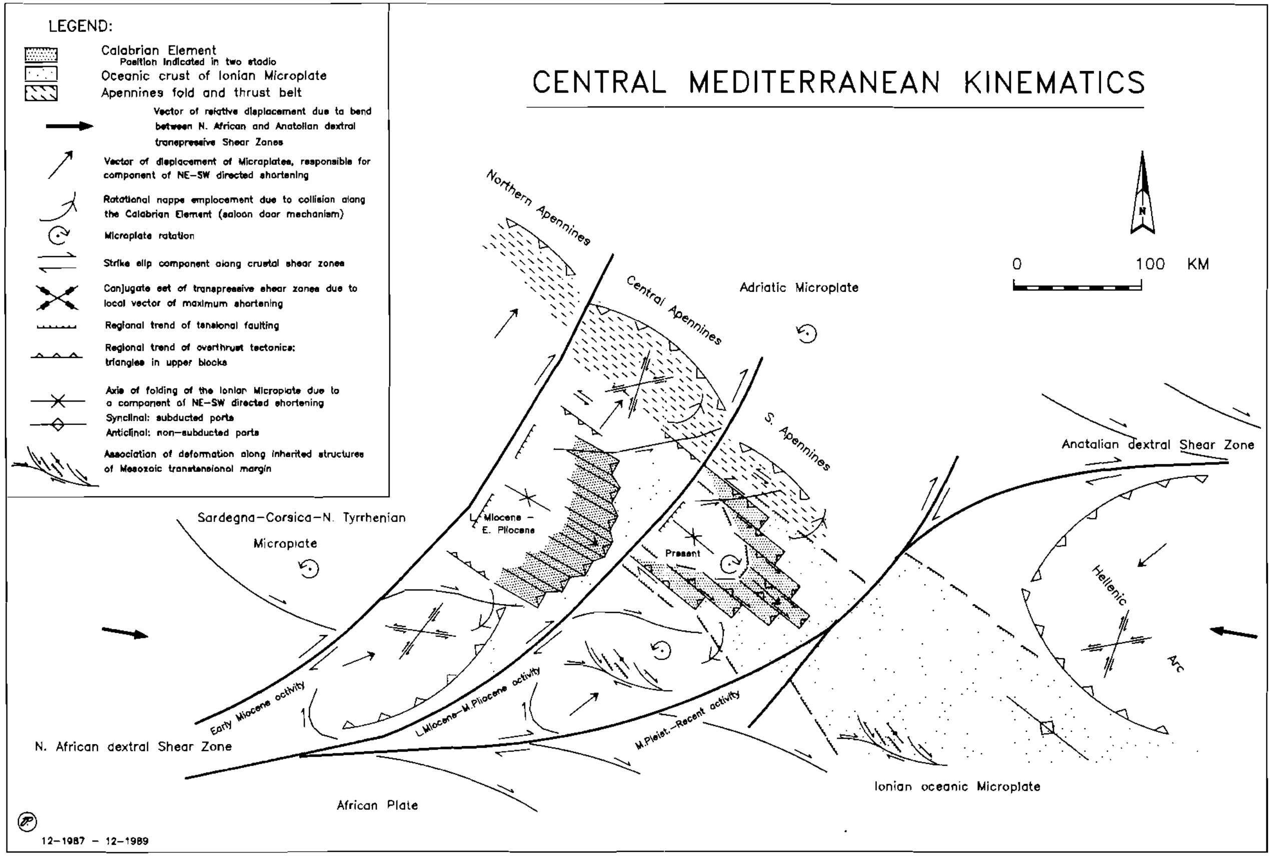

Fig. 12. Kinematic model for the Neogene Central Mediterranean development. Notable is the eastward shift of the activity of the dextral shear zones, in which each shear zone reaches its maximum activity in one of the distinghuished compression stages. The model implies a restoration of the position of the Calabrian Element between Sardinia and Tunesia (see also Bouillin, 1984; Bouillin et al., 1988; Van Dijk and Okkes, 1988, in press.; Pattacca and Scandone, 1989; Dewey et al., 1989), which confirms the older hypothesis of Argand (1924) and contradicts the common view of an original position east of Sardinia. The model furthermore implies a post-Early Miocene clockwise rotation of the Calabrian Element as inferred from the dextral NE-SW trending shear zones. These considerations fit well with the data on a NW-SE (restored) opening of the Oligocene-Early Miocene basins (see text). Pattern B in the Calabrian Element seems to represent a disrupted scar of the southeastern extension of the NW-SE trending "Paul Fallot Fault" (Durand Delga, 1980), which runs from Barcelona to the south of Sardinia. The NE-SW trending slices confined by the shear zones coincide with the segments of the subducted slab along the Apennines as also independently suggested by Royden et al. (1987). This feature may be inherited from a Mesozoic segmentation of the Piemonte-Ligunde-Ionian Ocean in which the shear zones acted as transform faults. The model is compatible with the Neogene WNW-directed vector of relative displacement of the African continent (predicted or deduced by the authors mentioned in Table 2; confirmed by Dewey et al., 1989; see also Van Dijk and Okkes, 1988 and in press, and references therein). The premordial Mesozoic fracture pattern mentioned in the legend can be found in, e.g., Ouali et al. (1986).

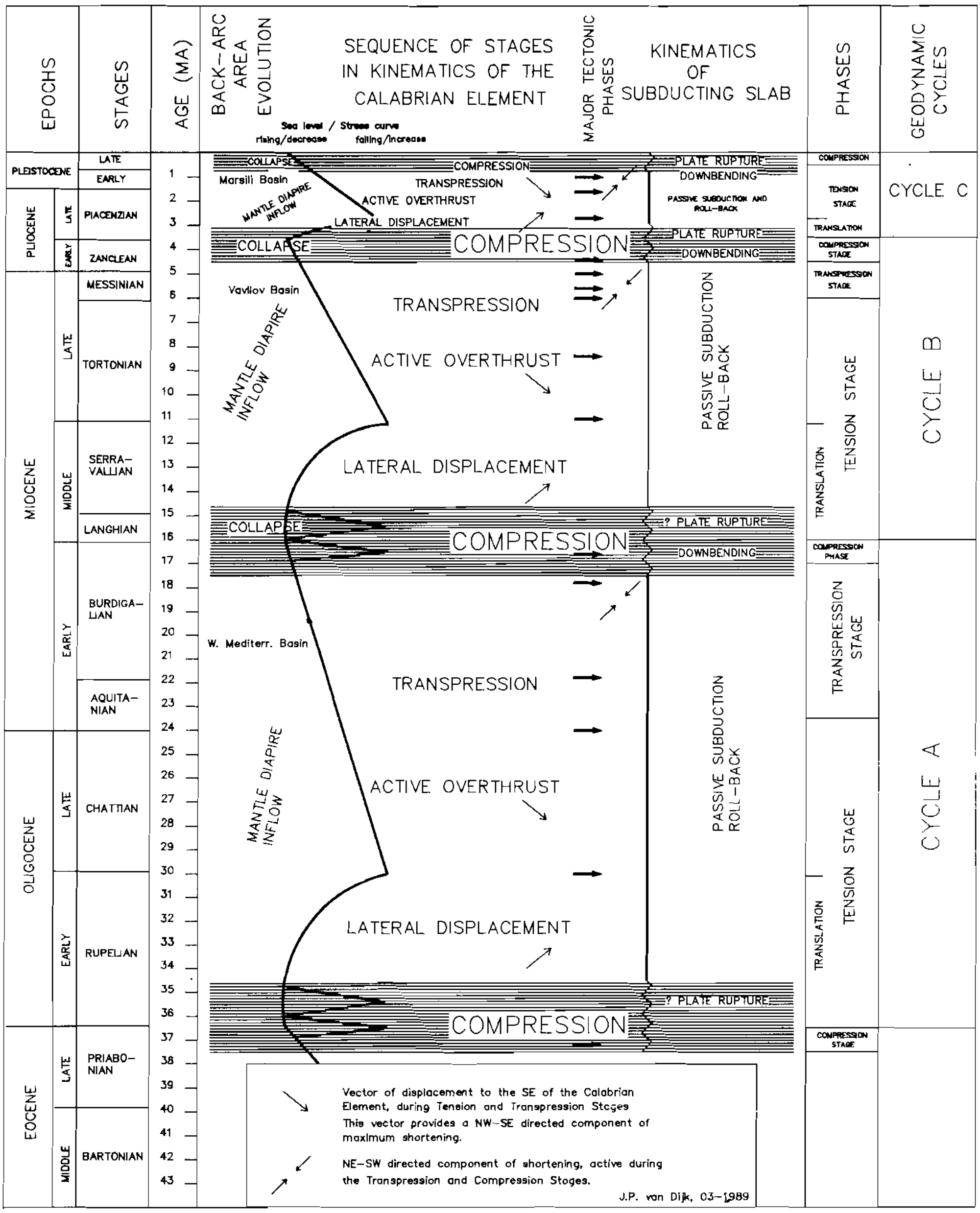

Fig. 13. Diagram for the Neogene geodynamic evolution of the Central Mediterranean. Compiled after our analyses of the Calabrian basins (Fig. 10), Durand Delga (1980, 1988), Meulenkamp et al. (1986), Bousquet and Philip (1986) and Kastens et al. (1988). The induced phases of increased stress are characterized by abnormal sedimentation patterns (silexites, evaporites), a complex sequence stratigraphy, extreme subsidence and uplift rates, the frequent occurence of rapid transgression events and high volcanic activity. These phenomena are linked to pulses of overthrust tectonics, rapid rotations of small microplates, lithosphere rupture and subduction polarity reversal, and related extensional collapse of back-arc basin and accretionary-wedge, induced by global plate reorganizations.

listric faulting (qualitative model of Van Bemmelen, 1976, quantitative model of Platt, 1986; see discussion in Van Dijk, 1991).

During the *Pleistocene*, the concentric faults of system C2 and dome-shaped uplift centres dominate the recent geomorphology of the Calabrian area and the Southern Tyrrhenian Basin. This phase was characterized by extreme uplift of the Calabrian massives of up to 1400 m (Birot, 1981). Large allochthonous slabs/olistostromes were transported to the external side of the arc, of which the Metaponte "Nappe" in the northeast (Ogniben, 1969; Finetti and Morelli, 1973) and the Gela "Nappe" in the southwest (Beneo, 1957; Ogniben, 1960) are the best examples. In the middle Pleistocene, a compressive phase has been documented for the Southern Apennines (Ghisetti and Vezzani, 1981; Gars, 1983). We conclude that pattern C is the result of the post-middle Pleistocene collapse of the Southern Tyrrhenian which immediately followed after a regional compressive phase.

Central Mediterranean kinematics

The translation models mentioned in the introduction, match with the activity of patterns A and B (Serravallian–Early Pliocene), although the authors which favour these models have erroneously used wrench faults of the Riedel shear pattern (N120 and N140) as indicative for the main shearing directions. The pattern C obviously has been over-emphasized in the bending and radial drift models. Faults belonging to Pattern B have been used in the sphenochasm models to explain the opening of the Tyrrhenian Sphenochasm. This will be discussed further on.

We have considered the following striking features (see Figs. 1 and 11) in our model for the kinematics of the Central Mediterranean (Fig. 12):

The Neogene development of the Calabrian Arc has been controlled by two intersecting thrust systems with NE–SW and NW–SE directed shortening (tectonic patterns A and B). Main present-day morphological features in the Southern Tyrrhenian area display an intersection of radial and concentric structures (tectonic pattern C), overprinting the patterns A and B.

The Calabrian Block can be seen as an isolated, "boat-shaped" element, overriding Apulian, Ionian and Pelagian blocks (Fig. 11). We propose to call this lithosphere fragment the "Calabrian Element". The configuration is essentially asymmetric, which is the result of an increase in shortening to the northeast due to oblique movement of this Calabrian Element and a related transpressive regime along the Southern Apennines.

Stress analyses on small-scale deformation features in the Calabrian Arc revealed a pattern of overall tension interrupted by short periods of compressional deformation in the middle Pliocene and middle Pleistocene. The vectors of maximum shortening for both these periods were placed in the NE–SW quadrant (Tortorici, 1981; Ghisetti and Vezzani, 1981; Moussat, 1983; reviewed by Auroux et al., 1985 and Bousquet and Philip, 1986).

The opening of the Tyrrhenian Basin and the path of translation of the Calabrian Element can be deduced from the pattern of rifting centres (possibly linked to the position of core complexes). These centres are seemingly aligned along a N110–N120 directed axis which Moussat (1983) in his translation model interpreted as the result of a displacement of the Calabrian Arc in a N120 direction. We believe, however, that this displacement to the southeast has taken place in a N130 direction (pattern A). Rifting centres are located between N130 and N045 trending fault zones which probably are surface traces of large-scale oblique crustal detachments (Fig. 1). The N045 fault zones can be linked to a vector of displacement to the northeast related to overthrusting in the Southern Apennines. We conclude that the vector of displacement of the Calabrian Element has alternated in time: either N045 or N130. This resulted in an overall N120 direction of opening of the Tyrrhenian Basin.

The shear zone pattern dissecting the Central Mediterranean consists of three sets of dextral fault zones: E–W, NW–SE and SW–NE (Fig. 1). We regard the latter set as horsetail splays which interconnect the Western and Eastern Mediterranean E–W trending shear zones. The activity of this dextral system provided the NE–SW directed component of shortening which resulted in the

N045 directed vector of displacement of the Calabrian Element.

The ENE–WSW trending sinistral and NNE–SSW trending dextral wrench faults within the Apennines may be a conjugate set, related to the ENE–WSW transpression caused by the displacement of the Calabrian Element. The tectonic pattern B in the Calabrian Arc displays locally also an ENE–WSW trend but shows a dextral sense of translation. We interpret these faults as a disrupted scar of a previously continuous fault zone belonging to the above mentioned set of dextral horsetail splays (see also caption of Fig. 12).

Geodynamics

We propose a new synthetic model for the geodynamic evolution of the Central Mediterranean in which the above-mentioned kinematic and geodynamic mechanisms (Table 2) are incorporated as follows (Figs. 12 and 13):

(1) The activity of the NE–SW and E–W trending dextral shear zones within the Central Mediterranean as described resulted in a NE–SW directed component of compression. Due to this compression the Ionian lithosphere below the Calabrian Arc was bended downwards (see Fig. 7a and Mantovani, 1982).

(2) The resulting disturbance in equilibrium initiated two processes:

(a) Flow of mantle material filled the "flattened cone"-shape between the Ionian lithosphere slab and Tyrrhenian lithosphere and resulted in mantle–lithosphere or lower–upper lithosphere delamination (cf. suggestions for the Northern Apennines of Reutter, 1979, Reutter et al., 1980 and Kutorskoy et al., 1986; and for the Calabrian Arc of Van Dijk and Okkes, 1988; modeled by Channel and Mareschal, 1989). This was accompanied by mantle metasomatism and resulted in a diapiric uplift of the back-arc area. We refer to the references in Table 2 and also to Oxburgh and Turcotte (1970), Karig (1971), Van Bemmelen (1972), Keen (1985), Uyeda (1986) and Laubscher (1988) for suggestions and reviews concerning mantle processes in back-arc regions.

(b) Slab-pull and roll-back of the subducted Ionian slab resulted in subsidence of the Calabrian Element (see references in Table 2 and also Wortel and Cloetingh, 1986).

The kinematic concequences of these two processes are initial back-arc area uplift which may have resulted in subsequent diapiric spreading, crustal exhumation and gravitational radial "superficial" nappe shedding. The combination of the processes 2a and 2b may have created enough inclination to initiate the gravitational migration of a subcrustal slab (the Calabrian Element) to the southeast, on top of a detachment zone between the lower and upper crust (kinematic model of Van Bemmelen, 1974; applied by Van Dijk and Okkes, 1987, 1988; modeled by Wang et al., 1989, and adapted for the Aegean Arc by Meulenkamp et al., 1988). The process was accompanied by Tyrrhenian extension through rotational dissymetrical graben formation with a steep margin at the Sardinian side and a compressional margin along the Calabrian Arc (see elaboration by Kastens et al., 1988). Within the accretionary-wedge, the displacement process was associated with frontal collision resulting in lateral rotational expulsion of "nappe flakes" to the east (Southern Apennines; anti-clockwise) and to the south (Sicily; clockwise) comparable to the opening of saloon doors (micro push-arcs), as follows from the paleomagnetic data and palinspastic reconstructions (e.g. Caire, 1970; Scandone et al., 1974; Grandjacquet and Mascle, 1978; Channell et al., 1979; Hill and Hayward, 1988; Incoronato and Nardi, 1989). Furthermore, the central segments of the Calabrian Element logically move faster than the lateral segments, because of higher cumulative velocities.

(3) Renewed increase in regional stress resulted in the following:

(a) Detachment of the lithosphere slab is followed by large isostatic adjustments in the whole region. The existence of a disrupted slab below the Tyrrhenian Basin was evidenced by Görler and Giese (1978) and Spakman (1986). Due to the slab rupture detachment the upper, non-detached parts of the lithosphere rapidly "bounce upwards" which results in an extremely rapid uplift of the overlaying blocks, whereas relatively uplifted external platform areas subside (see also the discussion in Sorel et al., 1988 for the Aegean Arc).

These movements result in gravitational transport of large slabs/olistostromes to the external side (see Fig. 11). This model of an extensional collapse of the accretionary-wedge mirrors the process of "vertical uplift and lateral spreading" as discussed by Ogniben (1969, p. 680).

(b) In our opinion, the extensional collapse of the mantle diapire in the back-arc region (Wezel, 1985; see also Weijermars, 1985 for a review of the Alboran Arc) can be related to the slab rupture and the sinking of the distacked part of the slab (a suggestion of Van Dijk and Okkes, 1988; successfully adapted and elaborated for the Alboran Arc by Platt and Vissers, 1989). The back-arc basin collapse is accompanied by rapid uplift of it's margins, especially at the external part of the rapidly subsiding wedge-shaped segments (tectonic pattern C), which shaped the recent morphology of the arc.

We hypothesize that the slab detachment may eventually lead to a subduction polarity reversal (as has been postulated for the Late Eocene compressive phase), lithospheric split (a crustal doubling in Northern Calabria was evidenced by Görler and Giese, 1978; see Fig. 11), and finally uplift, exhumation and/or subduction of the crust of the Tyrhenian back-arc basin. Comparable features in the Neogene Pacific and Indonesian arcs can be found in Oxburgh (1972) and Price and Audley-Charles (1987).

The suggested scenario consists of the following geodynamic cycle (Fig. 13): (1) tension stage (processes 2a and 2b; gravitational displacement and active overthrusting to the southeast/inflow of asthenosphere diapire and back-arc basin opening), (2) transpression stage, and (3) compression phase (processes 1, 3a and 3b; NE–SW compression and displacement to the northeast/plate rupture and lithosphere split/collapse of asthenosphere diapire and back-arc basin collapse). A sequence of these geodynamic cycles results in an undulatory evolution which shows affinity with older concepts of undation and oscillation tectonics (Haarmann, 1930; Van Bemmelen, 1933, 1978; Umbgrove, 1946; recently adapted and elaborated by Wezel, 1988).

Combining the accurate timing of the tectonic activity of the various fault patterns (see above), with the available knowledge on the evolution of the Central Mediterranean from literature, we postulate the following flow chart (Fig. 13): The first recognizable, *Late Eocene–Early Miocene* cycle, closed by a *Late Burdigalian* compression phase, can be linked to the opening of the Western Mediterranean Basin and the rotational displacement of the Sardinia–Corsica block. This was followed by the *Langhian–Serravallian* translation phase and the *Tortonian–Early Pliocene* strike-slip cycle (Fig. 10), which together coincide with one geodynamic cycle: The *Langhian–middle Messinian* southeastward movement of the Calabrian Element, related to the opening of the Central Tyrrhenian Basin, was overprinted by a NE–SW directed component of compression in the *middle Messinian–late Early Pliocene*, and closed by the regional *middle Pliocene* compression phase. The third cycle starts with the *Late Pliocene* continuation of the southeastward movement of the Calabrian Element with related opening of the Southern Tyrrhenian Basin. A *Late Pliocene–Pleistocene* increase in NE–SW compression in the Central Mediterranean probably triggered the lithosphere rupture and diapire collapse. Arguments in favour of this hypothesis are the documented regional Mediterranean middle Pleistocene compression phase (see above and especially the discussion in Bousquet and Philip, 1986), recent coeval seismicity patterns in Italian and Aegean regions (see e.g. Mantovani et al., 1987), the link between recent seismicity and the fault pattern C, and the accellerating subsidence in the Southern Tyrrhenian Basin (Okkes, 1988). The latter can be related to both the back-arc area collapse as well as the downbending of the Tyrrhenian oceanic lithosphere due to an increase in regional stress.

We postulate that these two processes (3a and 3b) also played a role after the middle Pliocene shortening phase, of which the detached lithosphere slab below the Tyrrhenian Basin (Fig. 11 b) bears witness.

Conclusions

We propose a new synthetic structural model for the Calabrian Arc based on the interaction of two thrust zone systems overprinted by a radial/concentric tensional fault pattern. The geodynamic evolution of the Central Mediterranean is believed to display a geodynamic cycle which comprizes an interplay of NE–SW compression, diapiric rise, and roll-back and detachment of lithosphere remnants and results in gravitational displacement of the Calabrian Element to the southeast on top of a basal detachment zone. The geodynamic scenario can be constrained by a chronostratigraphic frame which results in the recognition of three cycles in the Neogene, confined by the Late Eocene, Late Burdigalian, middle Pliocene and middle Pleistocene–Recent compression phases.

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APPENDIX III

ADDITIONAL REMARKS ON THE KINEMATICS AND GEODYNAMICS OF THE CENTRAL MEDITERRANEAN

CENTRAL MEDITERRANEAN KINEMATICS

The kinematics of the Central Mediterranean displays some particular interesting aspects which have been used as key features for a new model for the Neogene kinematic evolution, outlined by Van Dijk and Okkes (1988, 1990, 1991) (Ch. 6) and updated by Van Dijk (in press.) (Ch. 5). The main elements of this model are:

A new structural model

The new structural model for the Calabrian Arc has considerable implications for the understanding of the kinematic evolution of the Central Mediterranean. It implies that shortening to the northeast as well as to the southeast has been large both in the Southern Apennines and in the Calabrian block itself. These constraints are placed by palinspastic reconstructions listed by Van Dijk (in press.) (Ch. 5). Models which show only displacement to the southeast (e.g. the Translation Models of Moussat, 1983 and Rehault et al., 1986), or only to the east-northeast (e.g. the Sphenochasm models of various authors) can not provide a sufficient amount of shortening. The combination of Calabrian basin evolution (Pt. 1) and subsidence histories of Central Mediterranean basins (Pt. 2) provides the timing of the displacement.

A set of ransversal fault zones

A fan-shaped pattern, or horsetail set of strike-slip zones is recognized, which consists of E-W to NE-SW trending fault zones, which are both dextral and sinistral. The individual elements of this system are from NW to SE: The Annaba-La Galite-Central Tyrrhenian-Anzio-Ortona/Ancona Fault Zone, the Tunis-Egadi-Issel Ridge-Napoli-Gargano-Dubrovnic Fault Zone, the Egadi-Monte Kumeta-Alcantara-Otranto-Scutari-Pec Fault Zone, and the Gabes-Melita-Medina-Kefallinia Fault Zone. All these faults branch off from the major "Great Fundamental Fault" which separates the Atlas from the Sahara Shield (e.g. De Sitter, 1956; p. 463). This fault has also been called "Agadir Fault Zone" (e.g. Ziegler, 1984) or "South Atlas Fault", and regained importance through the work of Weijermars (1987a) who also assigned it as the northern boundary of the African Plate. Parts of this system have been described in literature as strike-slip transtensional and transpressional fault zones by many different authors.

The NE-SW trending transversal fault zones were already present in the works of Beneo (1950, 1951) who also recognized that they were "anteriore al ricoprimento". Aubouin (1960, 1965) indicated them in the Hellenides and Dinarides as trending orthogonal to his isopic zones. Ogniben (1969, 1973) indicated a number of NE-SW running fault zones, which played a key-role in the transversal segmentation of Apennines and Dinarides. The fault zones also play a key role in the works of Caire (1961, 1970, 1975). During the 1970s and 1980s, emphasis was laid upon the southeastward migration of the Calabrian Arc in the light of Plate Tectonics, and the role of the NE-SW trending fault zones was not appreciated any more. Still, some reference was made to them as fault structures became evident from seismic surveys:

Vercellino and Rigo (1970; their figure 1) indicated a major fault zone dissecting the southern Apennines and following the Issel Ridge.

Selli and Fabbri (1971) defined the NE-SW trending "Central Tyrrhenian Fault", which runs from the Sardinian Channel in the southeast to the

Italian coast near Anzio.
Alvarez et al. (1974, 1976) indicated the "Anzio-La Galite Scarp" in the central Tyrrhenian area as a major tensional boundary within the Tyrrhenian back-arc region. The structure is identical to the Central Fault of Selli and Fabbri (1971).
Horvath and Channell (1977) depicted a major fault zone in the Gargano-Dubrovnik area.
Rogers and Cluff (1979) indicated the boundary of the African Plate along the northern Sicilian E-W trending fault zone, continuing in a northeastern direction somewhere southeast of Calabria. This is similar to later suggestions of Gealy (1988; see below).
Ghisetti (1981) and Ghisetti and Vezzani (1979, 1981, 1982a, b) showed that along the northern Sicilian mountain chain, a major dextral shear zone is present. They named this structure the Monte Kumeta-Alcantara Line.
Ghisetti and Vezzani (1982a, b) indicated a major dextral fault zone between the Central and the Southern Apennines.
Boccaletti et al. (1984) indicated sinistral shear along a hypothetical NE-SW trending fault zone in the area of the External Calabrian Ridge.
Rehault et al. (1984, 1987) indicate that dextral slip along the Annaba-Ancona Fault Zone occurred in Early Miocene times, establishing the boundary of the Northern Apennines.
Ziegler (1984), in his model for the European Hercynian orogenesis showed that a complex set of E-W to NE-SW trending, mainly dextral fault zones was already active in the Paleozoic.
Boccaletti et al. (1985) depicted a set of strike-slip zones between Naples and Gargano. In the light of their general regmatic scheme, they assign a sinistral shear to these zones.
Jongsma et al. (1985, 1987) indicated a major boundary between the African and "Messina" plates, following the Gabes - Medina fault Zone. They argued in favour of a former continuity with the North Anatolian Fault Zone across the Hellenic Arc, and indicated the Kefallinia Fault Zone as a branch wich delimits the Adria Plate.
Finetti (1986) and Fedi and Rapolla (1988, 1990) indicated dextral rotational slip along a major fault zone south of the Salentino Peninsula along the strait of Otranto, based on aeromagnetic evidence.
On the Neotectonic Map of Italy (Bartolini, 1986), sinistral shear was indicated along large fault zones separating the Central and the Southern Apennines.
Anderson and Jackson (1987) argued for a possible boundary between the Adria Plate and the African Plate along the Strait of Otranto, where a weak present-day seismicity occurs.
Gealy (1988) stated that the Scutari-Pec lineament was a major boundary within the (Liguride-Piemonte) Tethys ocean, which divided the passive margin into two major segments. He hypothesized a continuity of the northern Sicilian M. Kumeta - Alcantara fault zone with the Scutari-Pec Lineament. The boundary at present shows an oblique overthrusting and determines the boundary between Dinarides and Hellenides.
Dewey et al. (1989) indicated sinistral slip along a major NE-SW trending fault zone which was situated along southern Spain, trending southeast of the Sardo-Corsica block up to Genova. The activity was placed in the the Oligocene - Early Miocene interval, comparable to the models of Rehault et al. (op. cit.), but with a different sense of displacement.
Serri (1990) showed that the volcanic belt wich extends along the Tyrrhenian side of the Apennines can be divided into 2 provinces; the Roman and the Campanian, separated by the "Campanian lithosphere boundary", wich is situated in the area of the Napoli-Gargano Fault Zone.
From the deep seismic tomographic profiles of Spakman (1990; his fig. 4), it became evident that a major crustal-mantle boundary exists between the Central and the Southern Apennines, which shows a steep dip towards the southeast. The Napoli-Dubrovnik Fault Zone seems to be the surface expression of this major ("Great Fundamental" sensu De Sitter, 1956) boundary.
Westaway (1990) argued that the Gargano-Dubrovnik seismic belt shows a recent sinistral shear, which accounts for the differences in rate of extension between northern and southern Apennines. In the light of the model presented here, this larger rate can be explained by differences in uplift rate between the two areas.
The "Vening-Meinesz Ridge" depicted on the International Tectonic Map of Europe (IGC, 1984) follows the central segment of the Gabes-Melita-Medina-Kefallinia Fault Zone.
Recent work of Mascle and Martin (1990) shows that comparable features may also be present in the Aegean Arc.

The transversal fault lines are inherited from transform faults dissecting the Tethyan ocean and dividing it into segments (Aubouin and Dercourt, 1975; Winterer and Bossellini, 1981; Gealy, 1988; Dercourt et al., 1990). As is generally assumed, the break-up of the Tethys ocean was characterized by a number of parallel isopic zones resulting in platform areas alternating with basinal areas. These are areas with normal and

with thinned continental crust along the passive margin, respectively. Orthogonal to these "ribbons", the isopic zones were dissected by transform fault zones, which define jumps in isopic zone constitution.
The transversal fault zones define a number of small "microplates" between the stable African and European Plates, such as the northern Adria, the southern Adria (Apulian), the Ionian and the Iblean blocks. Furthermore, they delimit a continental "bridge" in between two Neotethys areas: The northern Liguride-Piemonte ocean and the southern Ionian-eastern Mediterranean oceanized basin. The area where continental crust may have continued between the African and Adria Plates, is situated along a broad, NE-SW trending zone, extending from northern Tunesia to the Adriatic Basin, and possibly continuing into the Central Pannonian Basin (Van Dijk and Okkes, 1991; inset of their fig. 1). The reconstructions of the Western Mediterranean of D'Argenio et al. (1980), Coutelle and Delteil (1989) and Dewey et al. (1989), in fact, show the possibility of this "Trans-Mediterranean", NE-SW trending continental "bridge", interconnecting Southern Apennine (Adriatic) and Sicilian Maghrebian (Iblean) platform areas. The Annaba-La Galite-Central Tyrrhenian-Anzio-Ortona/Ancona Fault Zone and the Tunis-Egadi-Issel Ridge-Napoli-Gargano-Dubrovnic Fault Zone delimit this broad fault zone in the Central Mediterranean, which comprises numerous E-W and NNE-SSW trending major fault zones. The "Trans-Mediterranean bridge" may be regarded as the former eastern continuity of the "Alboran block" (Andrieux et al., 1971; Bouillin et al., 1986; Weijermars, 1987), which is a mobile belt that lay inbetween the African and the Iberian-European plates in the Western Mediterranean.
Because the transform faults define breaks in subduction rate and thus in the overthrust velocity of the fold-and-thrust-belt, tensional faulted boundaries within the back-arc area tend to be in-line with the transform faults, and can be regarded as scars. It can be appreciated that the lateral (NW to SE) propagation of the rupture of the subducted slab (cf. Wortel, 1992; Wortel and Spakman, in press.) will be interrupted by these transversal boundaries. On the other hand, along the external, southeastern side of the Calabrian Arc, the rupture will preferably happen along these weak, faulted lines.
The concept advocated here that ancient fault zones can be recognized along mobile "hinge" zones, through platforms areas and also within back-arc crust, shows affinity with the mechanism of "New Basement Tectonics" in which long-lived ancient fault zones are continuously re-used in plate tectonics (cf. Moody, 1966; Gay, 1973; Bryan, 1986; Woodcock, 1986) (*"once a crack, always a crack"*; Bryan, 1986, p. 105).

WNE-ESE trending transtensional faults

A second pattern of strike-slip fault zones which plays an important role in the proposed kinematic model, is a set of WNE-ESE trending fault zones which transect the Central Mediterranean in the area between Sicily and Africa. These fault zones are part of a large alignment of dextral transtensional faults along a broad, extensive zone dissecting the entire Mediterranean from Barcelona up to Cairo (Van Dijk and Okkes, 1988, 1990). The different parts of this fault system have been described in literature, and a dextral trend has repeatedly been assigned to the different segments. Examples are the "Paul Fallot fault" (Durand-Delga, 1980) transecting the Western Mediterranean Basin, the Sicily Rift Zone or "Medina wrench" (see for references Ch. 4), the southeastern boundary of the Ionian plate (Dewey et al., 1973; Van Dijk and Okkes, 1988, 1990; King et al., 1991), and a set of dextral transtensional features along the Libyan-Egyptian coast (Ben-Avraham et al., 1987).
This fault pattern also seems to be inherited from Mesozoic passive margin features as apparent from work in Tunesia by e.g. Caire (1975b) and Ouali et al. (1986). The Barcelona-Cairo fault zone and the near-parallel Tornquist fault zone, together seem to confine the "European Plate" (cf. Caire, 1975b; Boccaletti et al., 1984b; Van Dijk and Okkes, 1988, 1990).

Implications of the kinematic model

The presented kinematic model implies a WNW-directed relative movement of the African Plate in Neogene times, and a related dextral transpressive regime along the North African boundary zone. It must be noted that this assumption (see for historical references the review in Ch. 6; Van Dijk and Okkes, 1991, and also Boccaletti and Guazzone, 1975; Mattauer et al., 1977; Letouzey and Trémolière, 1980) has long been neglected. This is because plate reconstructions based on Atlantic spreading patterns (see for recent reviews Livermore and Smith, 1985; Klitford and Schouten, 1986; Savostin et al., 1986; Srivastava, 1986; Srivastava et al., 1990) generally infer a N to NNW direction of relative movement, and some authors even prefer a NE-directed vector (e.g. Mantovani et al., 1985, 1990). Only in some recent papers (Neev and Hall, 1982; Weijermars, 1987; Van Dijk and Okkes, 1988, 1990, 1991; Dewey et al., 1989; Doglioni, 1990, 1991, 1992; Laubscher, 1990; Mladenovic and Stefanovic, 1990; Doglioni et al., 1991) the assumption of a WNW-directed vector has been revived, supported by recent seismicity patterns which indicate dextral slip along the North African boundary zone (Ritsema, 1969; Udías, 1982).

As outlined by Mantovani et al. (1990), the relative direction of African movement in the Central Mediterranean is determined by the position of the rotational axis of the African continent; A slight shift of this axis to the north may induce a locally more northeasterly directed movement. Differential spreading rates between northern and central Atlantic ocean relate to the position of this axis. Recent analysis of the Atlantic spreading patterns (Pollitz, 1991) and of volcanic activity along Central Atlantic transform faults (e.g. Araña and Ortiz, 1992; see their fig. 15) indicate that spreading velocities were fluctuating during the Neogene. This may implie that during the Neogene, the relative movement of the African Plate in the Central Mediterranean has fluctuated between NE, N and NW. Speculating further upon this implication, it could well be that during Translation Stages (Ch. 6; Van Dijk and Okkes, 1991; see further), the relative African vector in the Central Mediterranean was directed NE (relative spreading rate higher in the southern Atlantic), whereas during Tension Stages, the vector was directed WNW (relative spreading rate higher in the northern Atlantic), which would fit into the different displacement patterns as apparent from the kinematic model.

The proposed kinematic model shows an evolution which is characterized by an alternation of the translation of the Calabria lithosphere Element either to the SE (Tension Stages; gravitationally) or to the NE (Translation Stages; compression, linked to oroclinal bending). The restoration of the Calabrian Element in Early Miocene times (16 Ma), just after the late Burdigalian phase of compression, is of fundamental importance. There are two possible positions: along the northeastern margin of Sardinia (Caire, 1964, 1970, 1975; Alvarez et al., 1974, 1976; Boccaletti and Guazzone, 1972; Rehault et al., 1986) or a more western position, between Sardinia and the coast of Tunisia or even more to the west (Argand, 1924; Görler and Giese, 1978; Van Dijk and Okkes, 1988, 1990; Pattaca and Scandone, 1989). This second option was followed in the presented analysis, as it is a consequence of the kinematic considerations used.

The kinematic model shows affinity with the models of Caire (1979; various orogenic belts), Ziegler (1984; Hercynian orogenesis) and Sengör (1990; Iranian Belt). It seems to be part of a new generation of kinematic models for the Tethyan collisional Mountain Belt. Characteristics of this type of model are combinations of large strike-slip movements (cf. Woodcock, 1986), complex interactions of small deforming "microplates", and rotational expulsive tectonics along major transpressive collisional boundaries.

CENTRAL MEDITERRANEAN GEODYNAMICS

The arc migration model

The southeastward displacement of the Calabrian Arc is related to the interplay of two processes: Passive subduction due to gravitational sinking of the relict Ionian oceanic slab and related roll-back and retreat of the hinge zone (Van Bemmelen, 1974; Ritsema, 1979; Moussat, 1983; Malinverno and Ryan, 1984; Kastens et al., 1988; Pattacca and Scandone, 1989; De Jonge and Wortel, 1990), and asthenosphere inflow, upwelling and convection in the back-arc region (Van Bemmelen, 1969; Locardi, 1986; Channell and Marechal, 1989). In this study, it is hypothesized that these two processes resulted in a gravitational displacement of the Calabrian lithosphere Element, a detached supracrustal slab or "Scholle" (cf. Sylvester, 1988), to the southeast (cf. Van Bemmelen, 1974; Horvath et al., 1981; see Ch. 6; Van Dijk and Okkes, 1988, 1990, 1991; Wang et al., 1989).

The model basically finds its roots in the work of Van Bemmelen (1969, 1972, 1974, 1978), and, as stated by Horvath and Berckhemer (1981; p. 397) *"actually, explicit or not, this is the germ of many other more recent models"*. He combined back-arc diapirism, passive subduction and the sliding of lithosphere slivers as a reflection of lateral spreading under the influence of gravity. This approach found its way into modern literature along a number of different roads: (1) In the papers of Elsasser (1971), Chase (1978), Molnar and Atwater (1978), Uyeda and Kanamori (1979), Wu (1978) and Dewey (1980) (see for a review Weissel, 1981, Jarrard, 1986, and Sengör, 1990), the mechanism of back-arc extension through "roll-back" and retreat of the subduction-hinge zone, was developed. This mechanism was instantly applied to the Mediterranean Arcs by Van Bemmelen (1974), Le Pichon (1979) and Ritsema (1979), and further elaborated by Angelier and Le Pichon (1981), Horvath et al. (1981), Moussat (1983), Malinverno and Ryan (1984), and many others. These authors envisaged the back-arc stretching as a simple thinning of the lithosphere. (2) Meanwhile, a number of authors continued to emphasize the role of asthenosphere inflow (e.g. Reutter, 1979; Horvath et al., 1981), convection (Channel and Marechal, 1989) and updoming (e.g. Makris, 1977; Wezel, 1981, 1985; Selli, 1985; Locardi, 1986) in the Mediterranean back-arc regions, actively (cf. the older models of Van Bemmelen) or passively related to slab penetration in the asthenosphere, to "roll-back" or "delamination" processes, or simply to the back-arc stretching itself. (3) Inspired by Van Bemmelens spreading or "mushrooming" model (Berckhemer, 1977; Makris, 1977), Horvath et al. (1981) and Horvath and Berckhemer (1982) developed a model for the Mediterranean arcs which envisages the sliding of lithosphere slivers following Alpine continental collison as a reflection of orogenic spreading. This mechanism was subsequently termed "orogenic collapse" by Dewey (1988a), who combined it with the Himalayan collapse models of Houseman et al. (1981). (4) The models developed by Wernicke (1981, 1985), Wernicke and Burchfiel (1982) and Lister et al. (1984, 1991), finally, provided the general acceptance of the mechanics of low angle supracrustal detachments, and described their relation with core complexes. These mechanisms were subsequently applied to back-arc region stretching by Lister et al. (1984) and Meulenkamp et al. (1988) in the Aegean Arc, and by Van Dijk and Okkes (1987, 1988, 1990, 1991) and Kastens et al. (1988) in the Calabrian Arc.

In this study, all four approaches are combined into one synthetic model, which envisages that the interaction of roll-back and back-arc diapirism provided the gravitational instability which provoked the southeastward migration of the supracrustal Calabrian Element.

The role of the inter-plate stress field

Superimposed on these relatively endogenic, arc-related mechanisms, is a regional compression, created by the transpressive movement of the African Plate relative to the European Plate, which was directed NW, N to NE (see above). This also generated a complex shear zone system, which temporarily resulted in a NE-SW directed compressive axis in the Central Mediterranean. In the present study, it is hypothesized that the temporal variation in compressional and extensional stresses was a major controlling factor and determined the nature of various episodes and phases in the evolution of the Calabrian Arc (see also similar suggestions by e.g. Mercier, 1981 for the Aegean Arc, and Sharaskin et al., 1981 for the Philippine Arcs, and reviews by Jarrard, 1986a, b). Regional compressive stress provoked buckling of the subducted lithosphere and thus the increasing rapid inflow of hot asthenosphere below the back-arc region by suction, in the same way as the suction through passive roll-back by "shear at the top of the downgoing slab" (Jarrard, 1986b, p. 93, cf. Reutter, 1979; Uyeda and Kanamori, 1979).

Slab detachment

Another important element is the occurrence of a (partly) detached slab below the arc. The presence was already deduced by Görler and Giese (1978) from seismicity patterns and confirmed by Spakman (1988, 1990), although not all authors agree (Anderson and Jackson, 1987). Consequences of slab rupture and detachment in the Mediterranean region in terms of vertical motions were speculated upon by Görler and Giese (1978; Calabrian Arc), Royden et al. (1983; Carpathian Arcs), Sorel (1988; Aegean Arc), Spakman et al. (1988; Aegean Arc), Van Dijk and Okkes (1988, 1990, 1991; Calabrian Arc), Platt and Vissers (1989; Alboran Arc), Wortel and Spakman (1990 and in press; Aegean and Calabrian Arcs), De Jong (1991; Alboran Arc) and Meijer and Wortel (1992; Aegean Arc). In this study (Ch. 6; Van Dijk and Okkes, 1988, 1990, 1991) it is hypothesized that during phases of compressive stress, slab rupture was provoked by synclinal downbending of the subducted lithosphere. Elastic rebound or "snapback" (a term introduced by Cathles and Hallam, 1991) of the non-detached remnants provoked extreemly rapid uplift of the overlying arc-segments, reflected by an extensional collapse of the thrust-wedge. Rapid sinking of the detached slab, or "lithosphere blob" (cf. Houseman et al., 1981) is reflected by collapse of the back-arc basin.

This mechanism differs from the "blob detachment mechanism" as proposed by Houseman et al. (1981), and as applied by Platt and Vissers (1989) to the Alboran Arc (see also Sengör, 1990; p. 123, 126), for two reasons: (1) The latter models refer to processes during the very early stage of initiation of arc migration, and are thus equivalent to the orogenic spreading model of Horvath et al. (1981) and Horvath and Berckhemer (1982) as outlined above. (2) Our suggestion is deterministic and mechanical, linking the triggering of blob-detachment to culminations of inter-plate compression.

Geodynamic cycles and periodicity

The accurate analyses of basin evolution has permitted to place the various geodynamic processes and mechanisms in a geological time-frame, combining them with the new Calabrian structural model and with considerations concerning kinematics of the Central Mediterranean. A model is presented which consists of a geodynamic cycle comprising four stages (Van Dijk and Okkes, 1989, 1991):

(1) A Translation Stage, with northeastern displacement and bending of the arc, and overthrusting in the southern Apennines, reflected by progressive development of thrust-wedge basins. In the Calabrian area, this phase is characterized by condenced shallow water successions.

(2) A Tension Stage with back-arc basin opening related to the diapiric inflow of asthenosphere material and roll-back of the subducted Ionian slab, resulting in gravitational displacement of the Calabrian Element to the SE. In Calabria, this episode was characterized by basin openings and progressive fragmentation, and pulsating subsidence.

(3) A Transpression Stage with oblique overthrusting towards the E upon the Southern Apennines. The Calabrian basins show accelerating subsidence, high accumulation rates and complex high-frequency sequences during this episode.

(4) A Compression Stage with NE-SW compression due to oblique dextral shear along the North African margin, plate rupture/lithosphere split and back-arc basin collapse. In Calabria, this episode was characterized by major basin inversion and back-shear motions along the accretionary wedge.

In the post-Eocene evolution of the Central Mediterranean, three cycles can be recognized: Cycle A: Oligocene - late Burdigalian, Cycle B: Langhian - late Early Pliocene and Cycle C: Late Pliocene - Recent. Remarkable is the regularity of the cycles, their shortening in duration in the coarse of time, and the fact that they are composed of respectively 3, 2 and 1 relatively stable episodes with a duration of 4 Million years, separated by episodes of 2 Million years of increased tectonic activity. This periodicity vindicates and specifies the periodicity of 6 Ma as recognized by Meulenkamp (1982) in the Mediterranean region. The Late Miocene-Recent evolution shows a periodicity of about 2 Ma, showing spreading (tension; arc migration) episodes, alternating with episodes comprising phases of overthrusting (compression; stagnations of migration), both with a duration of about 1 Ma. Geodynamic cyclicity has been recognized by various authors in different areas. Examples of geodynamic cycles which show affinity with the hereby proposed cycle are the Stages of Görler and Giese (1978), the Subduction Cycle of Kobayashi (1983), and the cycle of Sorel et al. (1988).

The evolution of the Alps fold-and-thrust belt, summerized by Laubscher (1990), reflects the kinematic evolution of the Adriatic Plate. From the Alpine kinematics, Laubscher deduced a three-staged displacement path of the Adria Plate. The three stages compare remarkably well with the three geodynamic cycles for the Central Mediterranean. This provides other evidence for the regional, Alpine character of this evolution. The Late Eocene phase compares with the "Pyrenean", "Levantine-Pontide", "Alpine backfolding", or "Ligurian" Phase, the late Early Miocene phase compares with the "Styrian" Phase, while the mid-Pliocene phase compares with the "Tuscan" Phase.

SYNTHESIS AND DISCUSSION

SYNTHESIS AND DISCUSSION

The various elements presented in this thesis can be related to one another (Fig. 1) through their implications for the role of tectonics in the genesis of depositional sequences. In the next chapters, the most important conclusions with respect to these elements will be outlined.

TECTONOSTRATIGRAPHY AND SEQUENCE STRATIGRAPHY

A high-resolution stratigraphic framework has been constructed for the Middle Miocene - Recent evolution of the Central Calabrian fore-arc area, which can be regarded as unique for the Apennines (Fig. 2). A large number of unconformities has been recognized along the basin margins. This has made it possible to set up a detailed sequence-stratigraphic framework for the area. Fourteen unconformity-bound depositional sequences have been distinghuished (Ch. 2; Van Dijk, 1990).

Phenomena reflecting syn-depositional tectonics have been studied in great detail (Ch. 1; Van Dijk, submitted) and a list of criteria has been set up (Ch. 2; Van Dijk, 1991). The use of this list has made it possible to establish which unconformity can be linked to tectonic pulses, and as such, the depositional sequences could be characterized in terms of relative sea level fluctuations.

A "Composite Tectonic Event" has been defined (Chs. 2 and 3; Van Dijk, 1990, 1991) which is probably characteristic for fore-arc regions. This composite event comprises a pulse of uplift, block faulting and erosion along the basin margin and accompanied outgrowth of clastic wedges into the basin, immediately followed by tensional faulting and related onlap along the basin margin.

TECTONICS

The transition from northern to southern Calabria shows a trend in time from northwest to southeast: The continental Oligo-Miocene successions in the study area (reclassified in the present study) show a NW-SE trending basin margin along the Crocchio Fault Zone near Cropani. The middle Messinian deposits show a southern Calabrian affinity (characterized by huge coarse clastic fan-delta deposits) up till the Albi-Sellia Fault Zone, and the Lower Pliocene hemipelagic marl (Trubi) facies occurs up to somewhat northeast of Catanzaro along the Siano-Giulivetto Fault Zone. This general picture indicates that the stratigraphic limit between northern and southern Calabria was formed by the Sila Piccola "block". The depocentre shift to the southwest is highly suggestive for a northeast directed accretion of terrains which fits in the structural model presented for the Calabrian Arc (see further). According to this model, the Catanzaro depression can be regarded as a synclinal downbended basin, locked between two facing oblique intra-arc thrust zones (see below).

The limit between northern and southern Calabria within the basement follows the SW-NE trending northwestern limit of the "Stilo Unit". This thrust unit is disrupted and incorporated in the "Oligo-Miocene Complex" (Ch. 6; Van Dijk & Okkes, 1988, 1990, 1991). This is a newly defined tectonic unit, comprising a "tectonic mixture" of Crystalline basement, Mesozoic-Lower Miocene cover and Argille Scagliose Varicolori. According to the presented structural model for the arc, this represents the most northwesterly situated, deepest and wedge-shaped element of a series of (dextrally) oblique backthrusts, which are characteristic for the southern Calabrian segment and the Pre-Sila area. The elements comprising this unit were tectonized in late Burdigalian times, possibly up to late Serravallian times. The basal terrigenous deposits in the Central Calabrian study area can be regarded as continental (lacustrine, alluvial fan and fan-delta) basin marginal deposits of the Late Oligocene-Early Miocene, Austroalpine "Numidian Basin".

The various faults, fault zones and thrust

zones dissecting the area have been subdivided into a number of systems (Ch. 3; Van Dijk, 1991). These systems fall apart in two basic patterns:
The first pattern comprises a conjugate set of NW-SE ("A") and NE-SW ("B") trending fault zones, which can be interpreted as a set of sinistral and dextral shear zones, respectively. These shear zones are the surface expression of large oblique thrust zones, comparable to the structures as visible in seismic sections in the offshore accretionary wedge. Large N-S and E-W trending (trans)tensional faults and reverse fault zones can be regarded as secondary features linked to this conjugate system.
The second pattern comprises tensional fault systems such as a set of large radial faults within the rapidly uplifted Sila Piccola, and a number of large tensional faults along the margins of the quasi-circular dome-shaped massif (which has also been recognized on satellite images). NNW-SSE and NNE-SSW trending tensional fault patterns within the Crotone Basin also fall within this second pattern. The faults belonging to these systems overprint all previous faults and the activity can therefore be placed in the post-middle Pleistocene.

One of the most important features that have come forward from the present study, are the basin inversion phenomena. Thrust zones appear to be present along all major NW-SE trending oblique fault zones. These thrusts show major detachments along Messinian evaporite levels. The inversion phenomena are also observed along secondary N-S and E-W trending fault zones. These inversion phenomena can be dated as late Early Pliocene.
The back-thrust belt continues along the northern margin of the Crotone Basin where Argille Scagliose melanges act as decollement levels. The back-thrust belt as a whole shows that the Miocene-Lower Pliocene was popped-up and squeezed out of the basin during the mid-Pliocene basin inversion phase.
Along the northern margin of northern Calabria (along the coast of the Taranto Gulf), thrusts facing the basin margin are also present. Within this thrust system, known as the "Cariatidi" or "Crotonidi", Argille Scagliose levels are also present. In literature, these were viewed as gravitational sliding features, and were often placed in the Late Miocene. The present study has illustrated that they can be viewed in the same light as the thrust belts in the southern part of northern Calabria, and that they are phenomena linked to a major mid-Pliocene basin inversion phase. As such, the interpretation fits well with the interpretation of the seismic profile through the Taranto Gulf of Cello and Nur (1988, their fig. 2), which also shows back-thrusts in the Neogene. Grandjacquet and Mascle (1978) were the first to use the term back-thrust for these terrains. As shown by the present study, the structures that are displayed in the area fit into the presented model for a sinistrally transpressive shear zone within a fore-arc thrust-belt as developed for the Petilia-Rizzuto Zone. In this case, they are related to the sinistrally transpressive Rossano-San Nicola shear zone.

BASIN KINEMATICS

The following kinematic basin models have been applied to and/or newly developed for the Calabrian Basins (Ch. 1; Van Dijk, submitted):

1. Oblique, thin-skinned pull-apart basins
The Crotone basin can be regarded as the best example of this basin type. It is locked between two NW-SE trending shear zones, each of which shows oblique convergent displacement. The basin is created by a pull-apart between these shear zones, and probably detached at a depth of a few km. The E-W and N-S trending bounding fault zones show transtensional displacements, developing into transpressional movements. Tensional faulting occurred along NE-SW trending, anti-Riedel faults. This basin model shows affinity with the thin-skinned intra-thrust belt basin model of Royden (1985) for the Vienna basin.

2. Strike-slip basins
Classical small strike-slip basins have developed within the NW-SE trending shear zones (cf. Sylvester, 1988). Rapid uplift and subsidence of small wedge-shaped blocks characterize the evolution of these basins. Transtensional as well as transpressional features can be recognized.

3. Harmonica basins
The areas along the Sila Piccola show a development which is mainly controlled by a nearly orthogonal conjugate set of oblique fault zones. The result is, that fault zones do not displace one another and that the deformation takes place in the areas in between the fault zones. The model shows affinity with the pure-shear model of Reading (1978). Transcurrent movements along the fault zones resulted in areas of tension and areas of contraction. The tensional areas, defined by listric faults, act as depocentres, while the

contractional areas show thrust stacks and are uplifted and eroded. Along the NW-SE trending fault zones, both sediment transport and deposition were concentrated. A peculiar feature of these areas is, that both the NW-SE and the NE-SW trending fault zones show an oblique convergent character. This results in an image whereby both along a NE-SW and along a NW-SE section, a half-graben shape can be recognized.

4. Detached slab basins
During its Late Pliocene - Early Pleistocene development, the Crotone basin was situated on a shallow slab, detached at a depth of about 2 km. This thin thrust slab, facing the subduction trough, can be regarded as an accomodation phenomenon of the accretionary wedge. It helped to maintain the critical taper of the migrating thrust-wedge. The existence of this special basin type in subduction arcs was hypothesized by Van Bemmelen (1976), Platt (1986) and also by Geist et al. (1988).

5. Intra-arc sheared synclinal basins
The Catanzaro depression is situated between two major NW-SE trending transversal shear zones. The basin shows a half-graben shape, with a steep margin along the Sila Piccola. Along both sides, the margins show a progressive flexure towards the basin axis. These margins are confined by N100-N120 trending Riedel shear faults. It is postulated that the basin originated as a synclinal downbending of the crust between two sinistral convergent intra-arc shear zones.

The basin evolution of the northern Calabrian basins from late Serravallian onward shows the following stages:
A. Strike-slip cycle: late Serravallian - Early Pliocene (11.0 - 4.0 Ma)
1. Tension stage (Basin opening): late Serravallian - middle Messinian (11.0 - 5.5 Ma)
2. Transpression stage (Basin fill): middle Messinian - Early Pliocene (5.5 - 4.0 Ma)
3. Compression phase (Basin closure; basin inversion): middle Pliocene (4.0 Ma)
B. Extension episode: Late Pliocene - Early Pleistocene (4.0 - 1.0 Ma)
C. Collapse phase: middle Pleistocene - Recent (1.0 - 0.0 Ma)
During these four stages, the basins of the studied area have passed through a number of episodes, each characterized by a special type of basin. The Crotone Basin has developed from a thin-skinned pull-apart basin (stage A) to a detached slab basin (stage B). The Sila Piccola Area has developed from a series of harmonica basins (stage A) to a detached slab basin (stage B). The Catanzaro depression shows a continuous development of an intra-arc synclinal basin.

All these basins are special types of supra-complex fore-arc basins, which implies that their development is basically controlled by the dynamics of the thrust-wedge. A typical feature is the fact that the basins have been inverted several times. These inversions can be regarded as back-shear motions along the thrust-wedge, and also show up in experimental models (Malaveille, 1984; Byrne et al., 1988). The inversions have occurred in various directions along the variously trending basin margins. As a general picture, the basin contence was popped-up and squeezed out of the basin. In seismic profiles along the internal and external Calabrian margins, comparable features appear to be present in the middle Pleistocene (e.g. Trincardi and Argnani, 1990). This provides evidence that the reconstructions from on-shore geology for older phases are plausible. The inversions of the Calabrian basins have occurred in late Burdigalian, middle Pliocene, and middle Pleistocene times.

The tectonostratigraphic succession can be subdivided into a number of unconformity-bound depositional sequences. The tectonostratigraphic significances of the sequence boundaries are remarkably similar: they reflect a "composite tectonic event" comprising an uplift/regression pulse, followed by a rapid subsidence/onlap (see above).
This recurrent signal can be linked to the dynamics of the accretionary complex (Ch. 3; Van Dijk, 1991), as has come forward from mathematical models presented in literature (e.g. Davis, 1990). Each composite event represents one pulse in the progressive evolution of the accretionary wedge system. Accretion and wedge-thickening results in out-of-sequence thrusting, reflected by tilting, regression and basin margin uplift. These events are followed by restabilization of the taper of the Coulomb wedge by in-sequence thrusting along its toe. This is reflected by tensional faulting and subsidence along the basin margin and rapid onlap.
The evolution of the area thus reflects the pulsating advancement of the thrust-wedge by means of an alternation of long episodes of underthrusting, and interrupting, short pulses of contraction and extension.

DYNAMIC GEOHISTORY ANALYSIS

A computerized geohistory analysis system has been designed, with relational database, calculation and presentation programs. Subsidence patterns of the various basin types within the Calabrian Arc (summit basins, fore-arc basins and thrust-belt basins) are compared to subsidence diagrams for the Iblean, Maltese and Ionian foreland areas and Tyrrhenian back-arc basins (Ch. 4).
Three-dimensional computer-aided reconstructions of the Neogene development of the Central Mediterranean are presented for the Tyrrhenian back-arc basin and the Crotone fore-arc Basin (Ch. 5; Van Dijk, in press.). The method developed consists of extrapolating data provided by geohistory analyses within a kinematic frame obtained by terrane analyses, balancing cross-sections and paleomagnetism. Two presentation methods are discussed. Time-Snapshot Plots show a restoration of paleo-landscapes and subsurface geology. Dynamic Geohistory Plots which we introduce in this study, show the development in time of a transect through the area. They can be used to illustrate and investigate the effects of phases in basin evolution in both a stratigraphic and a tectonic sense.

The results of the dynamic geohistory analysis have led to the following conclusions (Ch. 4):
The Central Mediterranean basins show large varieties in subsidence/uplift and accumulation rates, both spatial and temporal. Specific components that can be recognized in the diagrams comprise episodes (longer than 1 Ma) showing gradual, linear, accelerating and decelerating subsidence, and pulses (1 Ma and shorter) showing combinations of sudden acceleration, uplift (inversion) or subsidence (collapse). Tectonic pulses as reconstructed from the fore-arc area can be recognized in the entire Central Mediterranean area, and appear to be synchronous.
Specific episodes of high-frequency tectonic activity can be recognized in the Early Miocene, Late Miocene (Messinian) - Early Pliocene, and Pleistocene - Recent. These episodes show collapses, inversions, composite tectonic pulses and accelerations in accumulation rates.
Spreading episodes in the Tyrrhenian back-arc area alternate with phases of overthrusting in the surrounding thrust-belts. This is in conflict with the current believes regarding the kinematics of the Calabrian Arc. Subsidence curves of the back-arc area show an acceleration of subsidence with rates exceeding 500 cm/Ka, which can not be explained by classical rifting models. This implies that the characteristic pattern of accelerating subsidence is not restricted to foreland areas. It is shown in the Messinian of the Calabrian fore-arc basins, and in the Late Pliocene and Pleistocene of the Tyrrhenian back-arc Basin. Phases of foundering and collapse may be explained by downwarping under the influence of increasing regional stress, or due to an extensional collapse related to plate rupture (see further).
Rates of vertical oscillations vary considerably between basin marginal and basinal areas, and are one order of magnitude higher that the possible amount of eustatic sea level variation. This illustrates that tectonic activity is the main factor in the genesis of third-order unconformity-bound depositional sequences.
The "Cloetingh model" of intra-plate stress fluctuations may be applied to explain high amplitudes of basinal and marginal subsidence and uplift patterns in the basins adjacent to the Calabrian Arc. Compression is provided by phases of contraction of the thrust-wedge which may be related to pulses in stagnation of arc migration.

A NEW STRUCTURAL MODEL FOR THE CALABRIAN ARC

A new structural model for the Calabrian Arc is presented, based on the systematic analysis of basin evolution combined with a review of the literature on basement structure and seismic sections (Ch. 6; Van Dijk and Okkes, 1988, 1990, 1991).
Three tectonic patterns can be distinguished: (A) NW-SE trending oblique thrust zones, determining a set of N130 trending segments, (B) SW-NE to E-W trending thrust zones, and (C) Radial and concentric tensional fault systems in the southern Tyrrhenian back-arc area. These faults, combined with dome-shaped uplift centers determine the actual arc. Patterns A and B can be regarded as the on-shore representation of the Calabrian accretionary-wedge system.
The kinematics of the various types of thrust-wedge basins are connected to these patterns. The patterns A and B can be linked to the Middle Miocene - Early Pliocene development of oblique, convergent crustal shear zones ("strike-slip cycle"), whereas pattern C can be linked to the Pleistocene collapse of the southern Tyrrhenian Basin and extensional collapse with rapid uplift of the arc.

The conjugate set of oblique shear zones indicates an E-W directed axis of effective compressive stress. This is in agreement with the results of small-scale measurements which were presented in literature (e.g. Moussat, 1983). In order to explain this (local) effective stress axis, the interference of three components is proposed (Ch. 1; Van Dijk, submitted):

A) Strike-slip dynamics: Differential displacement of the two arc segments, during which the more centrally positioned segment moved relatively faster, created a sinistral shear with a local ENE-WSW directed compressive stress (cf. Sanderson and Marchini, 1984; Naylor et al., 1986).

B) Thrust-wedge dynamics: NW-SE extension prevailed during phases of subcretion/underplating/underthrusting along the thrust-wedge (terminology after Scholl et al., 1980; Moore and Sample, 1986; Platt, 1986; Brown and Westbrook, 1988). NW-SE directed compressive stress was active during phases of thrust wedge accretion. This axis is responsible for transtension along the shear zone. Locally generated body forces, originating from pressure gradients due to gravity and acting normal to the trend of the wedge (cf. Platt et al., 1989) are responsible for a continuously acting radial compressive stress (NW-SE to NE-SW through E-W).

C) Regional stress field: The regional stress has two components: (1) A relative NW-N-NE directed movement of the African Plate (see further) provided a component of compressive stress opposite to (NW) and orthogonal to (NE) the direction of arc migration. (2) NE-SW directed stress was generated by microplate interactions in the Central Mediterranean area (see further).

The existence of the NE-directed component of compressive stress (axis C) is well known from the Central Mediterranean (cf. Philip, 1987). At present, this stress field also seems to be active (Riuscetti and Schick, in Schick, 1978). This component of the compressive regional stress probably increased in late Burdigalian, mid-Pliocene and mid-Pleistocene times.

Axes A and B are endogenic, whereas axis C is exogenic with respect to the subduction arc. The interference of the three components A, B and C led to an E-W directed effective compressive stress in the northern, and a N-S directed effective compressive stress in the southern part of the Calabrian Arc.

CENTRAL MEDITERRANEAN KINEMATICS

The kinematics of the Central Mediterranean display some particularly interesting aspects which have been used as key features for a new model for the Neogene kinematic evolution, outlined by Van Dijk and Okkes (1988, 1990, 1991) (Ch. 6) and updated by Van Dijk (in press.) (Ch. 5, App. 3). The main elements of this model are:

The new structural model for the Calabrian Arc (see above) has important implications for the understanding of the kinematic evolution of the Central Mediterranean. It implies that shortening to the northeast as well as to the southeast has been considerable both in the Southern Apennines and in the Calabrian block itself. The combination of Calabrian basin evolution (Part 1) and subsidence history of Central Mediterranean basins (Part 2) provides the framework for the timing of the displacements.

A fan-shaped pattern, or horsetail set of strike-slip zones is recognized, which consists of E-W to NE-SW trending fault zones, both dextral and sinistral. The individual elements of this system are from NW to SE: The Annaba-La Galite-Central Tyrrhenian-Anzio-Ortona/Ancona Fault Zone, the Tunis-Egadi-Issel Ridge-Napoli-Gargano-Dubrovnic Fault Zone, the Egadi-Monte Kumeta-Alcantara-Otranto-Scutari-Pec Fault Zone, and the Gabes-Melita-Medina-Kefallinia Fault Zone. Parts of this system have been described in literature as strike-slip transtensional and transpressional fault zones by many different authors.

The NE-SW trending transversal fault lines are inherited from transform faults dissecting the Tethyan ocean and dividing it into segments, orthogonal to the isopic zones. The area where continental crust may have been continuous between the African and Adria Plates, is situated along a broad, NE-SW trending zone, extending from northern Tunesia to the Adriatic Basin, and probably continuing into the Central Pannonian Basin (Van Dijk and Okkes, 1990; inset of their fig. 1). This "Trans-Mediterranean", NE-SW trending continental "bridge", interconnected the Southern Apennine (Adriatic) and Sicilian Maghrebian (Iblean) platform areas, and was delimited-by the NE-SW transversal faults.

Because the transform faults may be supposed to define breaks in subduction rate and thus in the overthrust velocity of the fold-and-thrust-belt, tensional faulted boundaries within the back-arc area tend to be in-line with the transform faults, and can be regarded as scars. It may be argued that the propagation of the rupture of the subducted slab (cf. Wortel, 1992; Wortel and Spakman, in press.) will be interrupted by the transversal boundaries. On the other hand, along the external, southeastern side of the Calabrian Arc, the rupture will preferably happen along these weak, faulted lines.

A second pattern of strike-slip fault zones which plays an important role in the proposed kinematic model, is a set of WNW-ESE trending fault zones which transect the Central Mediterranean in the area between Sicily and Africa. These fault zones are part of a large alignment of dextral transtensional faults along a broad, extensive zone dissecting the entire Mediterranean from Barcelona up to Cairo (Van Dijk and Okkes, 1988, 1990). The different parts of this fault system have been described in literature, and a dextral trend has been assigned to the different segments. This fault pattern seems also to be inherited from Mesozoic passive margin features as apparent from work in Tunesia by e.g. Ouali et al. (1986).

During the Neogene, the relative movement of the African Plate in the Central Mediterranean has fluctuated between NE, N and NW. It could well be that during Translation Stages (see below), the relative African vector in the Central Mediterranean was directed NE (relative spreading rate higher in the southern Atlantic), whereas during Tension Stages, the vector was directed WNW (relative spreading rate higher in the northern Atlantic), which fits into the different displacement patterns as apparent from the kinematic model.

The proposed kinematic model is characterized by an alternation of the translation of the Calabrian lithosphere Element either to the SE (Tension Stages; gravitationally) or to the NE (Translation Stages; compression, linked to oroclinal bending). The restoration of the Calabrian Element in Early Miocene times (16 Ma), just after the late Burdigalian phase of compression, results in a position south of Sardinia, which revives earlier models (e.g. Argand, 1916).

The kinematic model is part of a new generation of kinematic models for the Tethyan collisional Mountain Belt (cf. Ziegler, 1984; Sengör, 1990), characterized by combinations of large strike-slip movements, complex interactions of small "microplates", and rotational expulsive tectonics along major transpressive collisional boundaries.

CENTRAL MEDITERRANEAN GEODYNAMICS

The southeastward displacement of the Calabrian Arc is most likely related to the interplay of two processes (Ch. 6, App. 3): Passive subduction due to gravitational sinking of the relict Ionian oceanic slab and related roll-back and retreat of the hinge zone (Van Bemmelen, 1974; Ritsema, 1979; Moussat, 1983; Malinverno and Ryan, 1984; Kastens et al., 1988; Pattacca and Scandone, 1989; De Jonge and Wortel, 1990), and asthenosphere inflow, upwelling and convection in the back-arc region (Van Bemmelen, 1969; Locardi, 1986; Channell and Marechal, 1989). In this study, it is hypothesized that these two processes resulted in a gravitational displacement of the Calabrian lithosphere Element, a detached supracrustal slab or "Scholle" (cf. Sylvester, 1988), to the southeast (cf. Van Bemmelen, 1974; Horvath et al., 1981; Van Dijk and Okkes, 1988, 1990, 1991; Wang et al., 1989).

Superimposed on these relatively endogenic, arc-related mechanisms, is a regional compression, created by the transpressive movement of the African Plate relative to the European Plate. This generated a component of a NE-SW directed compressive axis in the Central Mediterranean. In the present study, it is hypothesized that the temporal variation in compressional and extensional stresses was a major controlling factor and determined the nature of various successive steps (episodes and pulses) in the evolution of the Calabrian Arc.

Another important element is the occurrence of a (partly) detached slab below the arc (Görler and Giese, 1978; Spakman, 1988, 1990). In this study (Ch. 6; Van Dijk and Okkes, 1988, 1990, 1991) it is hypothesized that during phases of compressive stress, slab rupture was provoked by synclinal downbending of the subducted lithosphere. Elastic rebound (Wortel and Spakman, 1990 and in press.) or "snapback" (sensu Cathles and Hallam, 1991) of the non-detached remnants provoked extremely rapid uplift of the overlying arc-segments, reflected by an extensional collapse of the thrust-wedge. Rapid sinking of the detached slab, or "lithosphere blob" (cf.

Houseman et al., 1981) is reflected by collapse of the back-arc basin.

The accurate analyses of basin evolution has permitted to place the various geodynamic processes and mechanisms in a geological time-frame, combining them with the new Calabrian structural model and with considerations concerning kinematics of the Central Mediterranean. A model is presented which consists of a geodynamic cycle comprising the following stages (Fig. 2):
(1) A Translation Stage, with northeastern displacement and bending of the arc.
(2) A Tension Stage with back-arc basin opening and arc migration to the southeast.
(3) A Transpression Stage with oblique overthrusting towards the E.
(4) A Compression Stage with NE-SW compression due to oblique dextral shear along the North African margin, plate rupture/lithosphere split and back-arc basin collapse.
In the post-Eocene evolution of the Central Mediterranean, three cycles can be recognized: Cycle A: Oligocene - late Burdigalian, Cycle B: Langhian - late Early Pliocene and Cycle C: Late Pliocene - Recent. Remarkable is the regularity of the cycles, their shortening in duration in the coarse of time, and the fact that they are composed of 3, 2 and 1, episodes of 6(4+2) Million years. The Late Miocene-Recent evolution shows a periodicity of about 2(1+1) Ma (App. 3).

THE STRESS-TRANSMISSION MECHANISM

According to the "Cloetingh-model" (e.g. Cloetingh, 1988) both third and second-order fluctuations in relative sea level can be related to fluctuations in intra-plate stress. The following calibrations between second-order and third-order sequences in the Calabrian Arc and the sea level curve of Vail and Haq c.s. of the "Exxon Group" (e.g. Haq et al., 1990) support this view:
(A) The tectonically-controlled sequences in the Calabrian basins are comparable in timing with the third-order, unconformity-bound depositional sequences of the global charts of Vail and Haq c.s.
(B) The geodynamic cycles in the Central Mediterranean correlate with second-order trends in sea level rise and fall: The transition from the Translation Stage (1; sea level fall; compressional trend) to the Tension Stage (2; sea level rise; tensional trend) is characterized by fragmentations, basin formation and major onlaps. The transition from the Tension Stage (2; sea level rise; tensional trend) to the Transpressional Stage (3; high frequency sea level oscillations; many tectonic pulses) is characterized by acceleration of subsidence, high accumulation rates and high frequency of tectonic pulses. The final switch from the Transpression Stage to the Compression Stage (4; switch from rising to falling sea level; switch to compressional stress trend) is characterized by basin inversions, uplifts and the creation of major angular unconformities.

A new mechanism is presented, the so-called "Stress-transmission mechanism", to explain the supposed link between inter-plate stress and third- and second-order depositional sequences within the thrust-belt:
In the subduction arc, thrust-wedge dynamics will depend on the relative velocities of the roll-back of the subduction hinge zone (V_{rb}), and the displacement of the supracrustal slab (V_{sl}) (cf. Dewey, 1980; see for a discussion Jarrard, 1986a). It is proposed that small fluctuations in the regional inter-plate stress field (axis C) mainly controlled the thrust-wedge dynamics (axis B) in the following way:
Small pulses in compressive regional stress had two effects: 1. It added a component of velocity to the subducting plate, opposite to the roll-back (V_{rb}<) and/or 2. It generated a stress component orthogonal to the subduction direction, so that it temporarily blocked the roll-back process (V_{rb}->0). Both these effects provoked phases in thrust-wedge growth ($V_{sl}>V_{rb}$). This resulted in so-called "composite tectonic events" of uplift/regression (thrust-wedge contraction and accretion) rapidly followed by fragmentation (subsidence)-/onlap (thrust-wedge extension and restabilization of the wedge taper).
It is hereby suggested that short compressive pulses were probably dominated by effect 1, whereas larger scale stress fluctuations are related to effect 2. The Switch from tensional to compressive trends resulted in basin inversion through backshear motions (Fig. 2).
The importance of mechanical coupling between the two plates along convergent plate margins was earlier stressed by Mercier (1981) and De Jong (1990) (see also a discussion by Jarrard, 1986a, b). The hereby proposed mechanism seems to provide a satisfactory explanation for the spatial and temporal link between regional tectonics and pulses which control the genesis of third- and second-order depositional sequences along active plate margins. It forms part of the group of "tectono-eustatic" mechanisms advocated by e.g.

Pitman (1978), Cloetingh (1988) and Cathles and Hallam (1991).

Returning to a well-known poultry controversy, however, we must not forget that regional (e.g. glacio-) eustatic sea level fluctuations may have provoked tectonic activity. Two mechanisms have been proposed in the literature for this "eustato-tectonic" activity: Le Pichon (1984) calculated that a considerable drop in sea level may provoke the overthrusting of basin margins over the basin floor. This is the result of isostatic restabilization after the unloading of the water. Le Pichon proposed that this mechanism may be applied to the margins of the Mediterranean Basin during the Messinian dessication event which may have shown a drop of the sea level of about 2 km. Van den Berg (1989) showed that a eustatic sea level drop may provoke thrust-wedge restabilization through spreading, as subaerial wedges can have a steeper top slope than submarine wedges (cf. the models of e.g. Davis et al., 1983 and Dahlen, 1990). Both these eustato-tectonic mechanisms had the same effect and may have been responsible for the infra-Messinian tectonic phase observed along the Mediterranean fold-and-thrust belts.

Furthermore, following Sengör (1992), two major objections can be made against the synchroneity of the recognized diastrophic phases: (1) The resolution of the analysis is determined by the resolution of the used biostratigraphic frame, which is 0.5-2 Ma. Remarkably, the present study indeed recognizes one or more diastrophic events within each biozone. Possibly, different onlap events have, in fact, been taken together due to a lack of precision; (2) Sequence boundaries as recognized in the field are often assumed to be synchronous, which mirrors the "law of orogenic synchroneity" of Stille (1922; in Sengör, 1992, p. 440). Only if the events can be dated by means of stratigraphical methods of a higher resolution than the event-recurrency itself, their synchroneity can be tested. Sengör (1992, p. 450-458) showed that, even in a simple case of a continuously though spasmodically growing accretionary wedge (cf. Platt, 1988), depositional sequences created by various individual shortening-pulses can not be distinghuished by biostratigraphy "*unless the top of the wedge rises above sea level*" (p. 457). This is exactly the case in the present study, which than again turns the argument in favour of the presented synthesis.

GLOBAL SYNCHRONEITY AND EPISODICITY

The question wether regional relative sea level fluctuations and tectonic activity can be related to major global changes and epeirogeny has been discussed at least since early this century (Haug, 1900, 1907; Suess, 1906; Stille, 1922, 1924; Shepard, 1923; Grabau, 1934; Umgrove, 1946; Gilluly, 1949, 1950; Stille, 1950a, 1950b). This has given rise to a major controversy (also called the "Stille/Gilluly controversy"), whether or not regional and global synchronous phases, pulses and episodes of orogeny, related to global regressions and epeirogeny (Ellenberger, 1976) can be identified (see further Gould, 1965; Trümpy, 1973, 1982, 1984; Austin, 1978; Williams, 1981; Meulenkamp, 1982; Schwan, 1985, 1986). Interesting recent discussions related to this subject are in search for quantitative models which may describe global tectonic pulses (Hays, 1983; Hallam, 1984; Miall, 1984, Ch. 4; Parkinson and Summerhayes, 1985; Ayrton, 1987; Burton et al., 1987; Sheridan, 1987, p. 71; Sengör, 1990, pp. 21-25, 32-45, 161-167; Cathles and Hallam, 1991; Kooi, 1991, pp. 77, 78, 142; Cloetingh and Kooi, 1992). This has resulted in a number of suggestions for both qualitative and quantitative tectonic mechanisms to account for the global synchroneity of relative sea level fluctuations, which do not seem to be mutually exclusive:

Cloetingh and co-workers (Cloetingh et al., 1985; Cloetingh, 1988; Kooi, 1991) introduced the concept of world-wide intra-plate stress reorganizations, causing regional tensional or compressional stress as a major cause for third-order relative sea level changes. Cathles and Hallam (1991) described how stress-induced changes in plate-density may cause global regressions and transgressions.

Global stress-field reorganizations may find their source in processes which are inherent to the kinematics of plate-tectonics (e.g. motion over hot-spots of Burke and Dewey, 1973; membrane tectonics of Turcotte, 1974; plate boundary reorganizations of Dewey, 1988b).

Other suggestions envisage deformation mechanisms which act on a global scale. These are generally inspired upon spatial or temporal (or both) regularities in the distribution of global strain. Many types of regular patterns have been recognized and described for more than a century, and only a few are at present still outlined in the literature. Amongst these are the verticalistic pattern of Earth radius fluctuation (various authors), and a number of horizontalistic patterns. This last group comprises rhegmatic and other types of shear patterns (e.g. Dana, 1847; Hobbs, 1911; Sonder, 1938, 1947; Vening Meinesz, 1947; Boutakoff, 1952; Brock, 1956, 1957; Moody and Hill, 1956; Moody, 1966; Sonder, 1956; O'Driscoll, 1980; Wezel, 1988), global tectonic whirls or undulations (Wunderlich, 1964; Caire, 1979; Neeve and Hall, 1982; Doglioni, 1990, 1991, 1992), global shear (Carey, 1986), relative westward drift of the lithosphere (e.g. Bostrom, 1971; Nelson and Temple, 1972; Knopoff and Leeds, 1972; Moore, 1973; Doglioni, 1990, 1991, 1992) and global torsion (Van Dijk and Okkes, 1988, 1990; cf. previous models of e.g. Jardetzky, 1929, 1930, 1951, 1954, 1958; Rance 1967, 1968, 1969; Williams and Austin, 1973 and Austin and Williams, 1978). Another global deformation pattern is the change in the shape of the geoid by polar wander (e.g. Vening Meinesz, 1947; Jardetzky, 1962; Creer, 1975 and Mörner, 1983). In a number of papers, Sabadini and co-workers developed a global deformation theory closely related to those earlier ideas (e.g. Sabatini and Peltier, 1981; Sabatini et al., 1982, 1990; Sabadini and Yuen, 1989; Ricard et al., 1991). This theory suggests that polar wander might explain global (tectonic; sea level) changes through changes in the shape of the geoid and related membrane tectonics.

Suggestions for geodynamic mechanisms to account for global deformation can be subdivided into two groups:

The first group is in search of internal (thermal) sources such as episodic hot-spot activity or "bursts" of radial heat flow (e.g. Rice and Fairbridge, 1975; Ellenberger, 1976; Sheridan, 1987; Sloss, 1976, 1991), mantle convection reorganizations (e.g. Sutton, 1963; Fitch and Miller, 1965; Turcotte and Burke, 1978; Officer and Drake, 1985; Gurnis, 1991), or secular cooling of the Earth (e.g. Solomon, 1987). Some authors calculated that polar wander may be generated by glaciations (Sabadini and Peltier, 1981; Sabadini et al., 1982) or by mantle convection instabilities (Sabadini et al., 1982; Sabadini and Yuen, 1989: Ricard et al., 1991).

The second group stresses the contribution of earth rotation processes to global deformation, which is a mechanical, and more controversial mechanism (see for historical notes Jacoby, 1981). Machado (1967), Steiner (1967), Steiner and Grillmar (1973) and Whyte (1977) (recently adapted by Wezel, 1988) envisaged variations of the radius and rotational spin of the Earth as a major factor in global deformation cycles. Other authors hypothesized upon the role of differential rotation of parts of the lithosphere, mantle and core through internal phase and density changes (e.g. Austin and Williams, 1978). Recently, some authors suggested that the "Chandler wobble" effect of the earth spin axis (see for a review Wahr, 1988) by e.g. polar wander may produce quasi-periodicity (Van Alstine, 1981; in Sabatini et al., 1982) and/or spatial regularity (undulating asthenosphere flow; Doglioni, 1990) in global deformation.

Irrespective of these deviating ideas, many observations on global plate reorganizations, hiatuses, and unconformities seem to speak in favour of global synchroneity of tectonic activity and relative sea level fluctuations. For example, recent papers by Dewey et al. (1989), Pollitz (1988, 1991) and Harbert (1991) have shown that switches in direction and rate of spreading of Pacific and Atlantic areas have occured at 20, 15, 9, and 6-3 Ma ago, possibly associated with global plate reorganizations. Harbert convincingly showed that between 4 and 3 Ma, major orogenic activity occurred along the Californian coastal region, related to changes in Pacific spreading patterns. Major changes in Pan-Pacific biogeographical evolution, related to plate tectonic evolution, were demonstrated by Tsuchi (1990) to have occurred at 16-15, 6, and 3 Ma. Hayes (1984; his fig. 4) already showed that major phases of southeast Asian plate reorganisation occurred during the Early Oligocene (38-32 Ma) and the Middle Miocene (17-11 Ma) (see also Sharaskin et al., 1981). Global phases of increased explosive volcanic activity have been indicated by various authors (compiled by Rampino, 1991, p. 14) at 40, 20, 16-14, 11-8, 6-5-3-2.5, and 0.5 Ma ago, which phases seem to coincide with major glaciations, pulses in plate motion and sea level changes. Moore et al. (1978) described various distinct temporal patterns in the occurrences of hiatuses in the record of marine sediments. Pronounced maxima in hiatus occurence were noted in the 39-37, 18-17, 12-10 and 4-3 Ma intervals. Cloetingh et al. (1990) recognized a major N. Atlantic plate reorganization which started 1.9-1.6 Ma ago, possibly related to a Late Neogene "phase of intensive global compressional tectonics".

All these phases and episodes coincide with main diastrophic phases and stages described here for the Central Mediterranean. As discussed by Rampino (1991), the lack of sufficient accuracy makes it difficult to establish any cause-and-effect relationship at this scale, although many authors claim to be able to (e.g. Sabatini and Peltier, 1981; Sabatini et al., 1982; Rampino, 1991; Cloetingh, 1991; p. 272). All these data and their apparent consistency, make it tempting indead to envisage that global geodynamic pulses have occurred. Sengör (1992), in his hail for uniformitarianism, convincingly showed that, when various continuously deforming processes interact at different scales, each of which shows episodic, spasmodic strain, synchronous global pulses can not be expected to occur. This approach, on the other hand, also confirms earlier reconciliations of Lyell's uniformitarian doctrine (e.g. Le Conte, 1895; Barrell, 1917; Williams, 1981) that "*gradual evolution ..., but not at uniform rate*" characterized most processes. As such, the reasoning of Sengör can be interpreted in favour of global synchronous pulses, because global continuous deformation processes (like the ones listed above) can also be expected to show spasmodic behaviour.

The question wether or not global tectonic signals (if they exist) show some kind of (pseudo- or quasi-)periodic, cyclic or other temporal regularity, should be tackled separately as it is not implicit to global synchronism. Reviews by Williams (1981), Meulenkamp (1982), Chaloner and Hallam (1989), Kukal (1990, p. 208), Sharpton et al. (1990) give an enormous amount of evidence for the existence of regional and global (pseudo-) periodicity of orogeny on various timescales, although the topic is controversial (Einsele et al., 1991; Sengör, 1992). A number of large-scale "megacycles" have been recognized, where the smallest cycle comprises 33±3 Ma. The largest duration of small scale cycles (such as Milankovitch cycles) is 1 Ma. In the scale of third- and second-order cycles, no references exist to a regular cyclicity. The present study emphasizes periodicities of (2nd-order) 6(4+2) Ma and of (3rd-order) 2(1+1) Ma, whereas, on the other hand, a decrease in duration of (2nd-order) geodynamic cycles (18-12-6 Ma) is also clear. The latter phenomenon may partly explain why it is difficult to recognize an orogenic periodicity of this scale. The presence of periodicities in orogenesis itself makes it tempting to envisage an influence of astronomical cyclicity (e.g. orbital and rotational parameters) on geodynamic processes.

The search for global synchronism of episodes and pulses, and the tendency to recognize periods and cycles is closely related to the so-called "Catastrophism", "Fixistic" or "Kober-Stille" Schools of though (cf. Argand, 1924; Newell, 1967; Van Bemmelen, 1974; Sengör, 1990; p. 22), as it seaks for global determinism and regularism. At first glance, this seems to be in conflict with other modern currents in Sciences which view Nature as a constantly dynamically, brownian and chaotically developing system. Examples are the hypercollisional tectonics, orogenic collage and allochtonous tectonostratigraphic terrane Schools which are more in correspondence to the "Uniformitarian", "Mobilistic" or "Wegener-Argand" Schools. It must be born in mind that "*harmony of apparent chaos is fractal geometry*" (Hsü, 1992), and, therefore, regular patterns may be expected to occur anyhow. Altogether, the schism outlined above seems to be rather redundant and convulsive. A possible synthesis envisages long episodes which, instead of being characterized by stasis, show a gradual development and a continuous deformation, interrupted by short catastrophic pulses of diastrophism (cf. Gould, 1965; Austin, 1978; Williams, 1981). These pulses might be related to both irregular global spasms, and geodynamic cycles and periodicities of a possible astronomical nature.

FIGURE CAPTIONS

Figure 1.
Flow-chart of the elements presented in this thesis and their mutual relations.

Figure 2.
Synthetic diagram showing the relations between Neogene Calabrian fore-arc basin kinematics and tectonic sequence stratigraphy, global relative sea level fluctuations and geodynamic cycles in the Central Mediterranean.

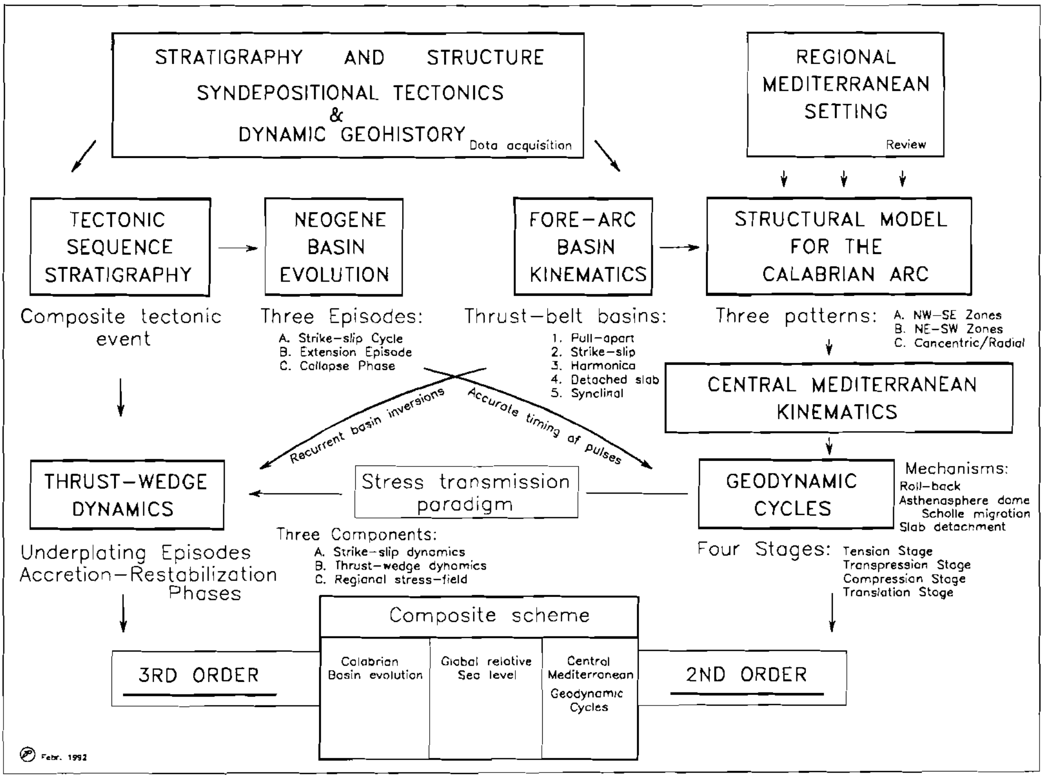
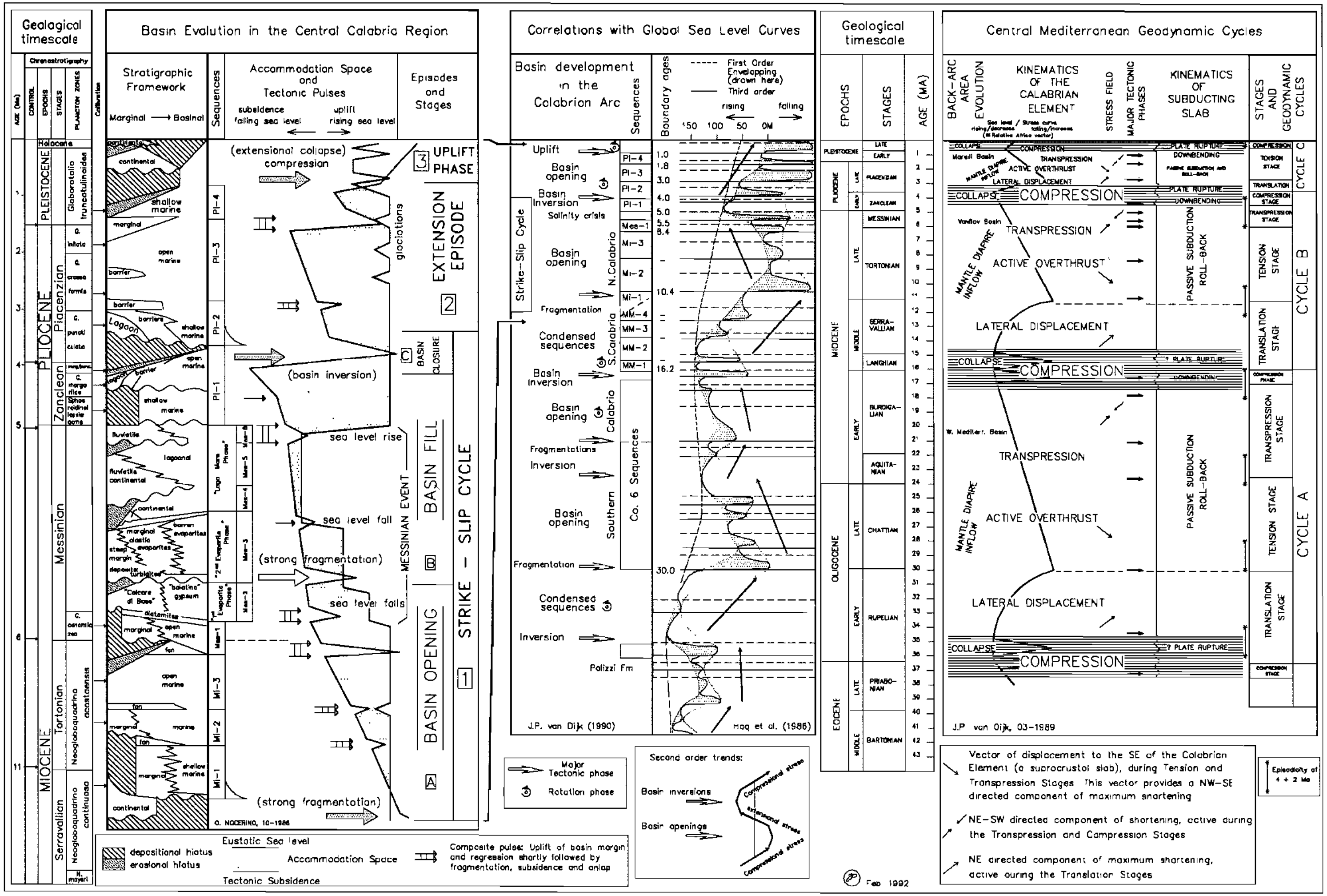

STRATIGRAPHY AND STRUCTURE
SYNDEPOSITIONAL TECTONICS
&
DYNAMIC GEOHISTORY
Data acquisition
REGIONAL MEDITERRANEAN SETTING
Review
TECTONIC SEQUENCE STRATIGRAPHY
NEOGENE BASIN EVOLUTION
FORE-ARC BASIN KINEMATICS
STRUCTURAL MODEL FOR THE CALABRIAN ARC
Composite tectonic event
Three Episodes:
A. Strike-slip Cycle
B. Extension Episode
C. Collapse Phase
Thrust-belt basins:
1. Pull-apart
2. Strike-slip
3. Harmonica
4. Detached slab
5. Synclinal
Three patterns:
A. NW-SE Zones
B. NE-SW Zones
C. Concentric/Radial
CENTRAL MEDITERRANEAN KINEMATICS
Recurrent basin inversions
Accurate timing of pulses
THRUST-WEDGE DYNAMICS
Stress transmission paradigm
GEODYNAMIC CYCLES
Mechanisms:
Roll-back
Asthenosphere dome
Scholle migration
Slab detachment
Underplating Episodes
Accretion-Restabilization Phases
Three Components:
A. Strike-slip dynamics
B. Thrust-wedge dynamics
C. Regional stress-field
Four Stages:
Tension Stage
Transpression Stage
Compression Stage
Translation Stage
Composite scheme
Calabrian Basin evolution
Global relative Sea level
Central Mediterranean
Geodynamic Cycles
3RD ORDER
2ND ORDER
Febr. 1992

Fig. 1



Geological timescale
Basin Evolution in the Central Calabria Region
Stratigraphic Framework
Marginal → Basinal
Sequences
Accommodation Space and Tectonic Pulses
subsidence falling sea level
uplift rising sea level
Episodes and Stages
UPLIFT PHASE
EXTENSION EPISODE
BASIN CLOSURE
BASIN FILL
BASIN OPENING
STRIKE - SLIP CYCLE
MESSINIAN EVENT
glaciations
(extensional collapse) compression
(basin inversion)
sea level rise
sea level fall
(strong fragmentation)
sea level falls
G. NOCERINO, 10-1986
Correlations with Global Sea Level Curves
Basin development in the Calabrian Arc
Boundary ages
First Order Enveloping (drawn here)
Third order
rising
falling
Uplift
Basin opening
Basin Inversion
Salinity crisis
Fragmentation
Condensed sequences
Inversion
Strike-Slip Cycle
N.Calabria
S.Calabria
Southern Calabria
Ca. 6 Sequences
Palizzi Fm
J.P. van Dijk (1990)
Haq et al. (1986)
Geological timescale
EPOCHS
STAGES
AGE (MA)
Central Mediterranean Geodynamic Cycles
BACK-ARC AREA EVOLUTION
KINEMATICS OF THE CALABRIAN ELEMENT
STRESS FIELD
MAJOR TECTONIC PHASES
KINEMATICS OF SUBDUCTING SLAB
STAGES AND GEODYNAMIC CYCLES
COLLAPSE
COMPRESSION
TRANSPRESSION
ACTIVE OVERTHRUST
LATERAL DISPLACEMENT
MANTLE DIAPIRE INFLOW
PASSIVE SUBDUCTION ROLL-BACK
PLATE RUPTURE
DOWNBENDING
TENSION STAGE
TRANSLATION STAGE
TRANSPRESSION STAGE
CYCLE A
CYCLE B
CYCLE C
J.P. van Dijk, 03-1989
depositional hiatus
erosional hiatus
Eustatic Sea level
Accommodation Space
Tectonic Subsidence
Composite pulse: Uplift of basin margin and regression shortly followed by fragmentation, subsidence and onlap
Major Tectonic phase
Rotation phase
Second order trends:
Basin inversions
Basin openings
compressional stress
extensional stress
Fep 1992
Vector of displacement to the SE of the Calabrian Element (a supracrustal slab), during Tension and Transpression Stages. This vector provides a NW-SE directed component of maximum shortening
NE-SW directed component of shortening, active during the Transpression and Compression Stages
NE directed component of maximum shortening, active during the Translation Stages
Episodicity of 4 ± 2 Ma

Fig. 2

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