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Neotectonic rotations in the Calabrian Arc; implications for a Pliocene–Recent geodynamic scenario for the Central Mediterranean

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Abstract

Recently, new data have been presented which imply that major block rotations took place in the Central Mediterranean during the Pleistocene, between 1.0 and 0.7 Ma. Kinematic solutions for the spatial and temporal distribution of rotational data in the Central Mediterranean such as oroclinal bending of the Calabrian Arc and rotation of the Adria Plate are being discussed. Phases of neotectonic rotations appear to be confined to distinct phases of contractions and compressive interplate stress. We present a model in which the middle Pleistocene rotations are caused by a distribution of deformation in the Central Mediterranean through strike-slip motions along a number of major shear zones which define a free boundary between the African and the Adria Plates. One of the main features is the Trans-Mediterranean Mobile Zone, which separates areas with opposite rotations. The timing of the rotations is compared to the evolution of volcanism, basin development, subsidence and uplift patterns, contractional tectonics and seismicity patterns. From this comparison we hypothesize that the Late Pliocene–Recent geodynamic evolution of the Central Mediterranean comprises the following three episodes: (1) A Late Pliocene arc migration episode shows drifting of the Calabrian block and spreading of the back-arc basin without the associated oroclinal rotations that were previously assumed in literature. (2) An Early Pleistocene contraction episode shows a gradual increase of compressive interplate stress, and culminates in a middle Pleistocene "stress release phase" which is associated with block rotations, transpressional tectonics and a rupturing of the subducted slab. (3) A Late Pleistocene–Recent restabilisation episode is characterized by rapid isostatic adjustments, with extensional collapse of the Apennine thrust-wedge and the Tyrrhenian back-arc area related to rebound of non-detached lithosphere remnants and sinking into the mantle of the detached slab.

1. Introduction

Following the early proposals of Argand (1924), Carey (1958) and Caire (1962) which were based on geological considerations, after the advent of Plate Tectonics it has become generally accepted that the Neogene evolution of the Central Mediterranean (Fig. 1) is dominated by the migration of the Calabrian Arc to the southeast, overriding the northern margin of the African Plate and its Mediterranean promontories (Ménard, 1967, Ritsema, 1969; Ryan et al., 1970,

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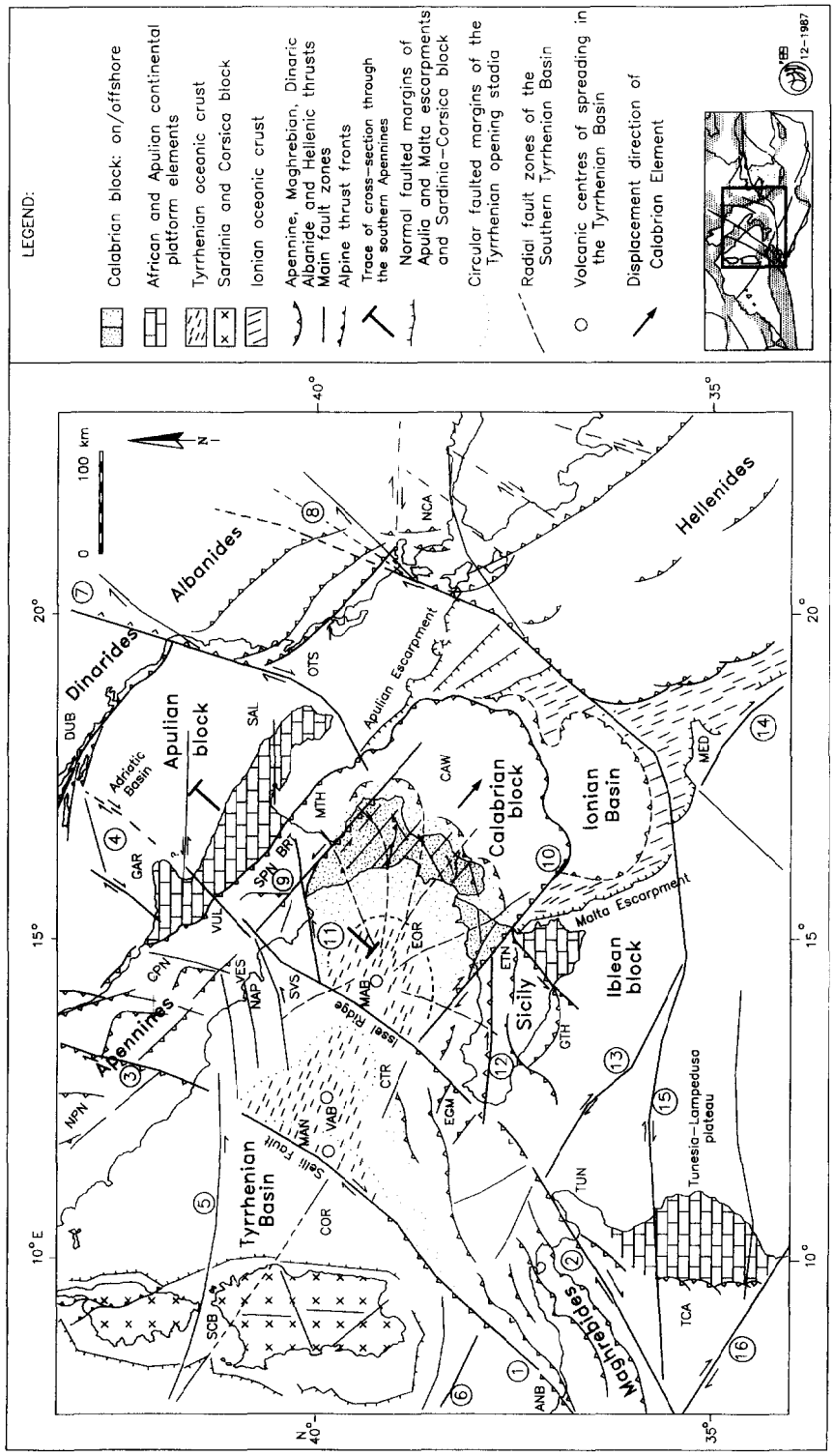
LEGEND:
Calabrian block: on/offshore
African and Apulian continental platform elements
Tyrrhenian oceanic crust
Sardinia and Corsica block
Ionian oceanic crust
Apennine, Maghrebian, Dinaric Albanide, and Hellenic thrusts
Main fault zones
Alpine thrust fronts
Trace of cross-section through the southern Apennines
Normal faulted margins of Apulia and Malta escarpments and Sardinia–Corsica block
Circular faulted margins of the Tyrrhenian opening stadia
Radial fault zones of the Southern Tyrrhenian Basin
Volcanic centres of spreading in the Tyrrhenian Basin
Displacement direction of Calabrian Element
12–1987
Dinarides
Albanides
Hellenides
Apennines
Magrebides
Apulian block
Adriatic Basin
Calabrian block
Ionian Basin
Iblean block
Sicily
Tyrrhenian Basin
Apulian Escarpment
Malta Escarpment
Sardinia
Tunesia–Lampedusa plateau
Sesia Fault
Issel Ridge
0 100 km
N
10° E
15°
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35°
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Morelli, 1970; Vogt et al., 1971; Boccaletti and Guazzone, 1972; Barberi et al., 1973,1974; Caire, 1973,1978; Boccaletti and Guazzone, 1975 and many others). In this paper, we will use the term Calabrian Arc for the geographical domain comprising three main tectonic elements: The southern Apennines fold-and-thrust-belt in the north, the Calabrian block in the centre and the Sicilian Maghrebides fold-and-thrust belt in the south, separated by main, "fundamental" obliquely convergent thrust zones. We will define a number of present-day, tectonically defined, fault bounded domains which are referred to as "blocks", a term which is explicitly genetically undefined and intended to be purely descriptive. Key features of the Neogene evolution of the Central Mediterranean are rotations and translations of small blocks, compression related to the relatively northward displacement of the African Plate, and outward migrations of the Maghrebian and Apenninic thrust-belts, subduction-related foreland basins or "foredeep troughs", and foreland bulges. The foreland area of the Calabrian Arc is formed by the Apulian block, which is part of the Adriatic Plate, the Iblean block, which is an extension of the African Plate, and the Ionian Basin, which separates the two foreland blocks. The Tyrrhenian oceanized basin is regarded as the marginal back-arc basin.

During the last decades, a wide range of models has been proposed in order to explain the observed tectonic rotations in the Central Mediterranean region (Fig. 2). These models include rotation models for the independent motion of the Adria microplate, and orocline models for the Calabrian Arc. It is of fundamental importance to recognize the implications of these theoretical models. Important aspects are the temporal distribution of rotational events, and their spatial relations: The models differ in symmetry of rotation patterns and distribution of strain through transcurrent movements and overthrusting. They also differ with respect to the temporal relation between rotations, arc migration and back-arc spreading; in some models these features alternate, whereas in others they are linked. Consequently, the tectonic rotation is envisaged by some authors as being a gradual process, whereas others regard it as a sudden event (a diastrophic phenomenon) with a short duration. In order to be able to find the mechanism which may have caused the rotations, spatial as well as temporal aspects of the evolution of the Central Mediterranean have to be considered in combination. Therefore, it is crucial to establish the precise timing and location of tectonic rotations.

In our previous work (Van Dijk and Okkes, 1988,1990,1991; Van Dijk, 1990,1991,1992, 1993,1994) we have introduced a number of new concepts regarding the tectonics of the Central Mediterranean: The importance of the interrela-

Fig. 1. Location of areas and data in the Central Mediterranean as discussed in the text (map modified after Van Dijk, 1992). Legend (see also Fig. 4): Main fault zones: 1. Annaba–La Galite Fault Zone; 2. Tunis–Egadi Fault Zone; 3. Anzio–Ancona Fault Zone; 4. Napoli–Gargano–Dubrovnik Fault Zone; 5. 41st Parallel–Circeo–Vulture Fault Zone; 6. Paul Fallot Fault Zone; 7. Otranto–Scutari–Pec Fault Zone; 8. Kefallinia Fault Zone; 9. Cirò–Benevento Fault Zone; 10. Vergilio–Etna Fault Zone; 11. Pollino Fault Zone; 12. M. Kumeta–Alkantara Fault Zone; 13. Sicily Channel Fault Zone; 14. Sirte Fault Zone; 15. Gabes–Melita–Medina Fault Zone; 16. Gafsa Fault Zone

Locations: *DUB* Dubrovnik; *ANB* Annaba; *NAP* Naples; *TUN* Tunis; *OTS* Otranto Strait

Geological units: *SCB*; Sardinia–Corsica block; *CAW* Calabrian Accretionary Wedge; *SVS* Sele Valley Sphenochasm (Locardi, 1986)

Seamounts: *EGM* Egadi Seamount; *MED* Medina Seamount

Escarpments: *APE* Apulian Escarpment; *MAE* Malta Escarpment

Foreland blocks: *GAR* Gargano area; *SAL* Salentino area

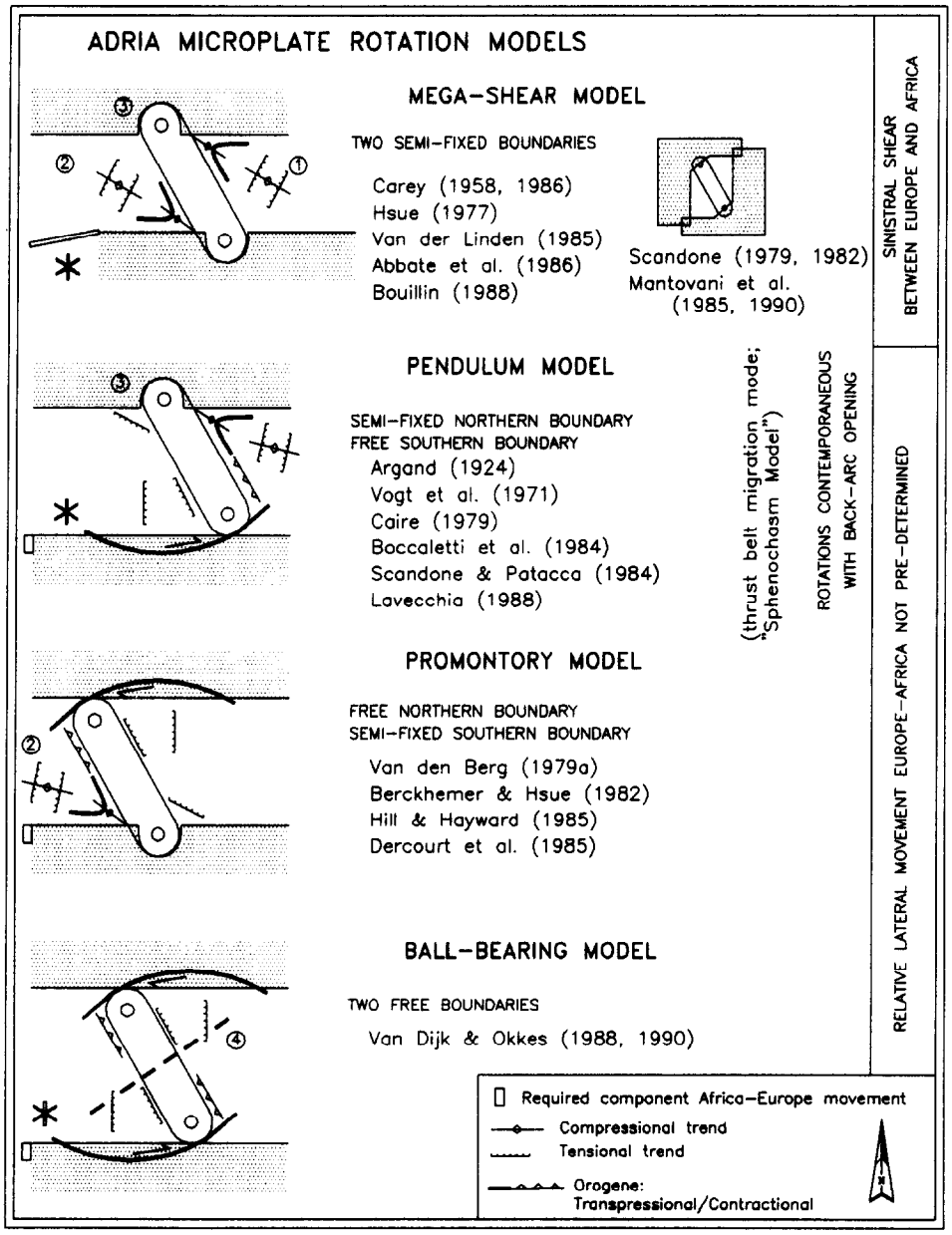
Volcanic areas: *ETN* Etna; *VES* Vesuvio; *CFC* Campo Flegrei Caldera (Napoli) (e.g. Dvorak and Mastrolorenzo, 1992); *VUL* Vulture; *EOR* Eolian Ring; *CTR* Central Tyrrhenian volcanic Ring (Anchise, Anceste, Albatros, Ustica)

Apennines: *NPN* Northern Apennines; *CPN* Central Apennines; *SPN* Southern Apennines; *BRT* Bradanic Trough; *GHT* Gela thrust; *MTH* Metaponto thrust

Small arcs: *NCA* Nissia convex arc; *TCA* Tunesia convex arc

Tyrrhenian back-arc area: *COR* Cornaglia Terrace; *MAN* Magnaghi Basin; *VAB* Vavilov Basin; *MAB* Marsili Basin

tion between transpressional shear, basement thrusting and thin-skinned thrust tectonics, and the widespread occurence of both thick- and thin-skinned backshear motions in the Calabrian thrust belt were extensively illustrated with numerous field examples. New models for the relation between regional interplate stress field fluctuations, thrust wedge pulses (rapid alternations of underplating, accretion, inversion and extensional collapse) and tectonic sequence stratigraphy were proposed. Another important feature is that we view the thrust belt as a pile of relatively



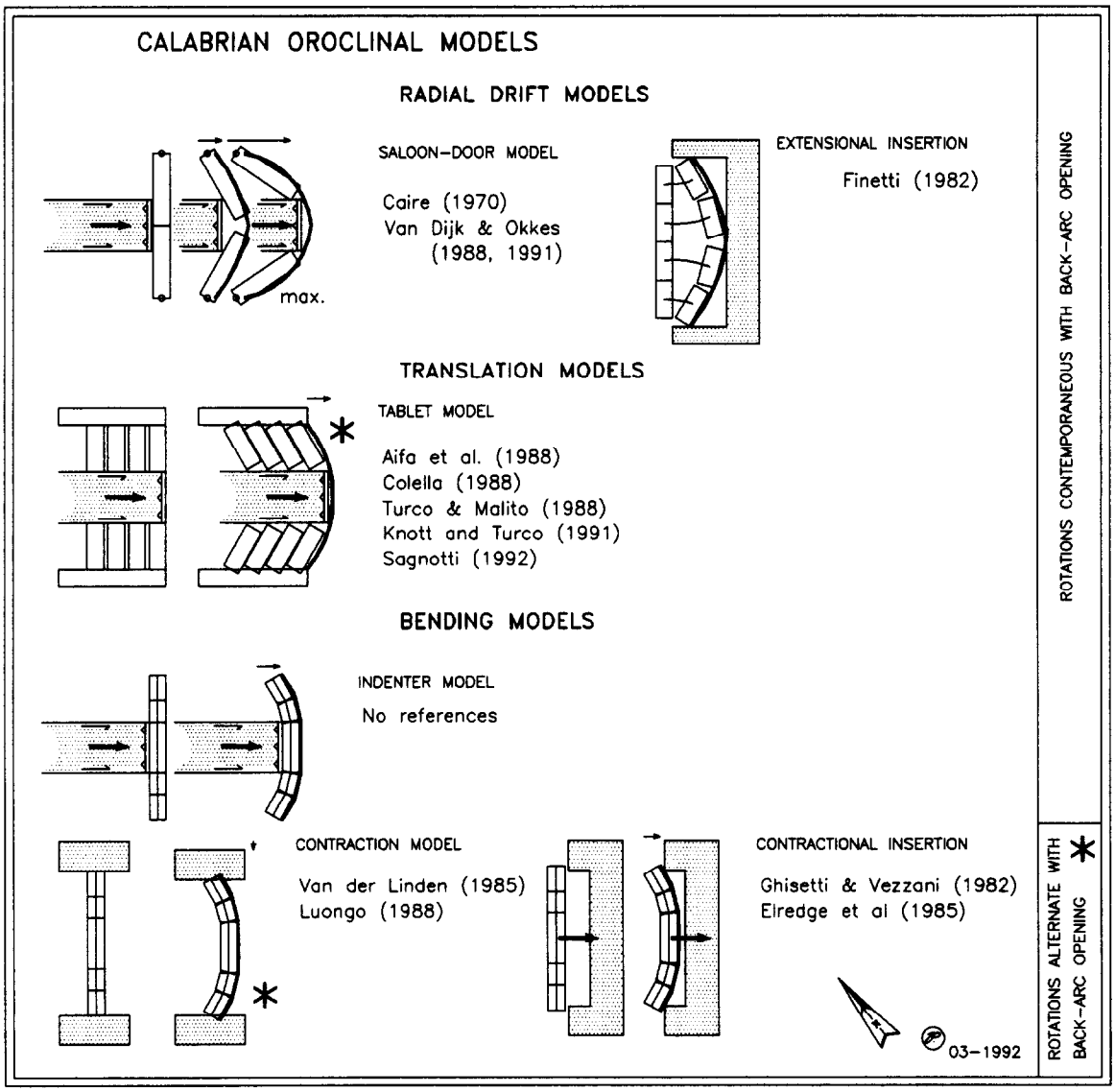


Fig. 2 (continued).

Fig. 2. Kinematic models proposed in literature. The asterisks indicate aspects of the models supported by the present paper as being active during the Pleistocene rotation phase: Sinistral transpression between the African and the European Plate, Dextral transcurrent displacements along a free southern boundary in the Central Mediterranean, counterclockwise rotating thrust panels in the southern Apennines, dextral rotation of crustal blocks through contractional bending of the Calabrian Arc, and an alternation of episodes of arc migration with episodes of contractions and rotations. (a) Kinematic models for the independent rotation of the Adria Microplate as proposed in literature. The numbers 1 to 4 are explained in the text. Consequences of the rotations for the minimum magnitudes of displacements are indicated. Note that we classified the kinematic models according to their spatial relationships, independently of the timing as envisaged by the various authors. (b) Kinematic models for the rotations within a peri-Tyrrhenian orocline as proposed in literature. A tectonic rotation of 30° is depicted. Mentioned are authors which proposed to apply the mechanisms to the Calabrian Arc, and not the original proposals for these kinematic models. Bending models of the indenter type have not yet been proposed for the Tyrrhenian area. It must be noted that the oroclinal models are special cases of kinematic model types as distinghuished by e.g. Van Dijk and Okkes (1990,1991), each of which is not necessarily associated with rotations.

thin thrust sheets and duplex structures, deformed by high-angle fundamental transpressive shear zones which separate the diverse terranes and generated small scaled ("out-of-sequence") thrusting in various directions. We emphasized the inheritance of Mesozoic and possibly older structural grains, (re)activated during Tethyan rifting (e.g. transform faults; cf. Aubouin and Dercourt, 1975 for the Dinarides) and subsequently re-used during Alpine and Apennine orogenesis, which establish fundamental borders and segmentations of the subduction slab and thrust belts. Furthermore, we proposed an integrated kinematic geodynamic scenario for the Kaenozoic evolution of the Central Mediterranean, characterized by an alternation of episodes of passive subduction and arc migration, and phases of compression, bending and thust belt and back-arc basin collapse, related to detachment of the stressed subducted slab. In the present paper, all these concept will briefly be discussed were necessary.

Recently, the results of a research project into the Miocene, Pliocene and Pleistocene successions of Sicily, Calabria and the southern Apennines, conducted at the Paleomagnetic Laboratry "Fort Hoofdijk" (Utrecht) have become available (e.g. Scheepers et al., 1990,1991,1993,1994,submitted; Scheepers, 1992,1994; Scheepers and Langereis, 1993,1994,in press). During this research, which combined the use of high resolution stratigraphic frameworks with paleomagnetic data acquisition, it has become clear that a major phase of block rotations occurred during the middle Pleistocene time interval. This youngest rotation phase has important implications for the reconstruction of the timing of the rotation of the Adria Plate, as will be discussed further on. Therefore, this event has to be considered first in any modern retrotectonic analysis.

We present a review of previously proposed rotational models and of available geological and geophysical data concerning the Plio–Pleistocene evolution of the Central Mediterranean. Furthermore, the implications of the rotational data for the Plio–Pleistocene geodynamics of the Central Mediterranean will be investigated and a new geodynamic framework will be presented.

2. Geological structure and evolution of the Central Mediterranean

The geological history of the Central Mediterranean can be subdivided as follows (Boccaletti et al., 1984; Rehault et al., 1984; Hill and Hayward, 1985; Wezel, 1985; Bousquet and Philip, 1986; Kastens et al., 1987; Van Dijk and Okkes, 1988,1990,1991; Patacca and Scandone, 1989; Alvarez, 1991): During the Triassic–Middle Cretaceous "Mesogea Stage" of Neo-Tethyan rifting, small oceanic basins were created 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 Plates (We refer to the subdivision into microplates for descriptive purposes, although the term refers to an older more rigid plate tectonic concept, which should be abandoned; see e.g. Jackson and McKenzie, 1984). During the Middle Cretaceous–Late Eocene stage the Ligurian oceanic Basin was subducted towards the northwest below the European Plate along an active margin between Gibraltar and the Alps. The Oligocene–Early Miocene episode was characterized by drifting of small "microplate" fragments such as the Sardinia–Corsican, 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 present-day Central Mediterranean area can be divided, on the largest scale, into three domains, going from internal to external (Fig. 1). These are the Tyrrhenian back-arc Basin, the Calabrian Arc (comprising the Sicilian Maghrebide thrust-belt, the Calabrian block and the southern Apennines thrust-belt), and the foreland (comprising the Iblean block, Ionian Basin and Apulian block). Numerous large fault zones separate and intersect the principle domains, dividing them in a number of segments which we prefer to call "blocks". The available literature concerning these fault zones, depicted and codi-

fied in Fig. 1, is extensively discussed in Van Dijk and Okkes (1991) and Van Dijk (1992). The codifications and numbers of Fig. 1 will be referred to in the whole text.

The Calabrian block is separated from the Sicilian thrust-belt by the NW–SE trending *Vergilio–Etna Fault Zone (10)* (Van Dijk and Okkes, 1991; comprising the Taormina Line of Amodio-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" (9)*. This Fault Zone was described by Beneo (1951), Grandjacquet (1962), D'Argenio (1966), Caire (1978), Moussat (1983), Ghisetti (1984) and Catalano et al. (1993) as a major wrench fault zone, by Caire (1962,1970) and Bousquet (1972) Bousquet (1973) as a major overthrust and by Van Dijk and Okkes (1988,1990,1991) and Van Dijk (1992) as a sinistral, obliquely convergent thrust zone (their "pattern D"). This Fault Zone comprised numerous branches and Fault Zones such as the Pollino Fault Zone (cf. D'Argenio, 1966 and Ghisetti, 1984), the "Deep Shear Zone" of Ghisetti and Vezzani (1982a,b), "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). As will be discussed further on, one of the main branches, the *Pollino Fault Zone (11)*, plays a key-role in the kinematic model proposed in this paper. The external limit of the Sicilian thrust-belt is situated offshore along the Gela overthrust (GTH). The internal limit of the Calabrian block is located along the Eolian volcanic ring (EOR) in the Tyrrhenian Basin, while the external limit of the Calabrian block follows the external limit of the Calabrian accretionary thrust wedge offshore. The external limit of the southern Apennines follows the Bradano trough onshore (BTH).

2.1. The Tyrrhenian back-arc Basin

The Tyrrhenian Basin can roughly be subdivided into three domains (e.g. Kastens et al., 1987, Kastens et al., 1990): The Sardinia margin, the Central Tyrrhenian (Vavilov) Basin (VAB) and the Southern Tyrrhenian (Marsili) Basin (MAB). The Sardinia margin (or Cornaglia Terrace) is characterized by a number of N–S trending (half-) grabens, originating from a phase of rifting which started during the Late Miocene. The Central and Southern Tyrrhenian oceanic basins were formed during the Late Miocene to Pleistocene by spreading related to the drifting of the Calabrian block to the southeast. These basins are characterized by high heatflow (with maximum values up to 156 mWm^{-2}; DellaVedova et al., 1984), a very thin crust (a minimum lithosphere thickness of 30 km. and a minimum Moho depth of 10 km.; Panza et al., 1980; Boccaletti et al., 1984). The northwestern "rifted" and southeastern "oceanised" areas are separated by the NE–SW trending "Raimondo Selli Line" (Finetti and Del Ben, 1986) (the "Central Tyrrhenian Fault" or "Anzio–La Galite Scarp" of Selli and Fabbri, 1971 and Alvarez et al., 1974, respectively). We refer to this feature as the *Selli Fault Zone* (Fig. 1). The Tyrrhenian oceanic subbasins are from northwest to southeast: The Magnaghi Basin (MAN), the Vavilov Basin (VAB) and the Marsili Basin (MAB). The latter two are separated by the NE–SW trending *Issel Ridge* (Fig. 1), which shows a thicker crust (Moho between 15 and 20 km). The southeastern Tyrrhenian, situated adjacent to the Calabrian Arc, shows a concentric ring of calc-alkaline, Late Pleistocene–Recent volcanoes, the Eolian Ring (EOR) (e.g. the emerged islands of Stromboli, Volcano and Lipari). Still closer to the Calabrian Arc, a concentric ring of intra-arc summit basins (see further) is present which will be described below. Extensive analyses of subsidence and spreading data regarding the Tyrrhenian basins (from ODP boreholes in Kastens et al., 1987,1990) and comparison with the evolution of the surrounding thrust-belts were presented by Sartori (1990) and Van Dijk (1992,1993).

2.2. The Calabrian block

The Calabrian block (comprising from N to S the Sila, Serre, Aspromonte and Peloritani blocks) is the highest structural element of the Calabrian Arc, overlying the southern Apennines and Sicil-

ian Maghrebides fold-and-thrust belts (Caire, 1962,1978; Ogniben, 1973; Amodio-Morelli et al., 1976; Van Dijk, 1992). It is constituted of a complex pile of thrust sheets comprising Paleozoic basement and Mesozoic to Lower Miocene cover, intersected by numerous oblique transcurrent fault systems. Recently, we introduced some important new features concerning the geology of the Calabrian Arc in literature such as the interrelation between transpressional shear, basement thrusting and thin-skinned thrust tectonics, and the widespread occurence of both thick- and thin-skinned backshear motions (Van Dijk and Okkes, 1988,1990,1991; Van Dijk, 1990,1991,1992). The following Neogene basin types occur within the Calabrian block, from internal to external (WNW–ESE):

Summit Basins (cf Geist et al., 1988). Along the margin of the Tyrrhenian Basin, adjacent to Calabria, a set of arc-parallel basins is present which are concentrically grouped around the Eolian volcanic ring, which, in turn, encircles the Marsili Basin. These basins are, from west to northeast: 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, showing several kilometres of Miocene–Recent deposits, are well known from seismic surveys although deep wells are missing. Internally verging (back-)thrusts beneath the summit basins have been hypothesized by Van Dijk and Okkes (1988,1990) and by Argnani and Trincardi (1990). The latter authors hypothesized that the Paola Basin was subject to a middle Pleistocene phase of basin inversion.

Intra-arc basins. On-shore Calabria, a number of arc-parallel (trans)tensional basins border the Tyrrhenian margin filled with several hundred metres of Upper Miocene–Recent deposits. The main basins of this type are the Crati Graben and the Mesima Graben. Moussat (1983), Colella (1988) and Van Dijk and Okkes (1988,1990) hypothesized that these basins have transtensional margins. In the southern Apennines, a number of NW–SE trending Late Pliocene–Pleistocene grabens along the Tyrrhenian internal margin seem to belong to this group of basins (Pollino graben, Tanagro graben, Agri graben). Baggioni-Lippmann (1981), Roure et al. (1990,, 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, Tyrrhenian side. Possibly, the low angle portions of these normal faults reported outcropping in the southern Appennines (e.g. D'Argenio et al., 1986), are uplifted and eroded parts of these systems of listric normal faults (sensu Gibbs, 1984), which might partly be reactivated overthrusts. Up till now, there is no evidence of large scale extension along these faults (sensu e.g. Buck, 1993; Wernicke and Burchfiel, 1982).

Fore-arc basins. The fore-arc basins are situated upon the internal slope of the Calabrian accretionary thrust wedge, and are of various types (strike-slip, pull-apart, piggy-back, "detached-slab" and "harmonica" basins; see Van Dijk, 1994). These are all special types of thrust-belt basins showing several kilometres of Neogene deposits. The on-shore Calabrian fore-arc 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 Calabria, 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, 1994). The Crotone–Spartivento Basin, along the external margin of Calabria, is a typical fore-arc basin (Rossi and Sartori, 1981; Van Dijk, 1990,1991,1994). The latter author speculated that the present-day onshore part of this basin is situated upon a shallow slab, facing the subduction through and detached at a depth of about 2 km ("detached slab basin").

Rotational data concerning the Calabrian block (Table 2) from the crystalline basement and its

Mesozoic cover show that the Calabrian basement nappes have rotated 100–135° counterclockwise since Late Jurassic times (e.g. Manzoni, 1975,1979; Manzoni and Vigliotti, 1983). Our investigations (Scheepers et al., 1990,1991,1994,submitted) have revealed that a major phase of 15° clockwise rotation has occurred in the Calabrian area in middle Pleistocene times (between 0.5 and 0.7 Ma). Furthermore, our data indicate that the Calabrian block remained stable from Early Pliocene up to Early Pleistocene times. Data concerning Upper Miocene deposits show that clockwise rotations rotations must have occurred during Messinian times. Furthermore, a major counterclockwise rotation was detected for the Early to Middle Miocene interval (Scheepers, 1994). In the literature, it has been hypothesized that rotations in Calabria may be linked to basin openings through transcurrent movements along the major NW–SE trending shear zones and related secondary wrench faults (Colella, 1988; Turco and Malito, 1988; Knott and Turco, 1991). In that case, counterclockwise rotations are expected to have occurred in northern Calabria (Fig. 2), and gradual rotations should have occurred throughout the Late Miocene–Early Pleistocene, none of which is sustained by our data. In fact, the widespread evidence for syndepositional transcurrent motions in Calabria and in the adjacent thrust belts throughout the Miocene and Pliocene connected with basin openings, as presented in literature (see for reviews Moussat, 1983; Van Dijk and Okkes, 1990,1991 and Hippolyte, 1992, see for opposite views Patacca et al., 1992), is in itself not an evidence for contemporaneous rotations. Our data show that the rotations are linked to major basin modifying tectonic pulses induced by regional stress field fluctuations, called "composite tectonic events".

2.3. *Apennines and Maghrebides fold-and-thrust-belts*

The Apennines and Maghrebides thrust-belts are constituted of numerous thrust sheets which

Table 1
Summary of paleomagnetic results from the southern Apennines and the Apulian foreland. N = number of contributions to the mean direction, D(tc) = declination, I(tc) = inclination, k = precision parameter. Further: CL platform = Campania–Lucana platform, LN basin = Lagonegro Basin, AC platform = Abruzzi–Campania platform.

N	D	I	k	locality/unit	age	reference
Apulian Unit						
4 sites	324.4	36.0	480	Gargano peninsula	Cretaceous	Channell and Tarling (1976)
17 sites	335.0	37.8	31	Gargano peninsula	late Cretaceous	Channell (1977)
21 sites	327.7	38.2	56	Gargano peninsula	late Cretaceous	Van den Berg (1983)
3 studies	329.0	37.4	328	Gargano peninsula	Cretaceous	(above)
5 areas	359.8	56.3	491	Apulian Unit	early Pleistocene	Scheepers (1992)
Bradano Unit						
6 areas	359.8	56.2	610	Foggia–Matera zone	early Pleistocene	Scheepers and Langereis (1993)
Southern Appennines, external part						
5 sites	322.4	28.2	120	Campia (matese Mt.)	Cretaceous	Channell and Tarling (1976)
1 site	322.2	30.9		Maggiore (AC platform)	Late Cretaceous	Catalano et al. (1976)
9 sites	326.0	42.0	44	Monte Maiella	Cretaceous	Jackson (1990)
3 areas	323.4	33.7	116	External part	Cretaceous	(above)
13 sites	337.8	56.1	111	Sant' Arcangelo basin	early Pleistocene	Sagnotti (1992)
4 sites	351.3	56.1	144	Éboli–Rotonda zone	middle/late Pleisto	Scheepers and Langereis (1993)
20 sites	336.0	58.4	76	Foggia–Matera zone	early Pleistocene	Scheepers and Langereis (1993)
8 sites	320.8	52.4	159	Salerno–Éboli–Calvello zone	Late Mio–middle Plio	Scheepers and Langereis (1993)
Southern Apennines, internal part						
3 sites	285.8	54.1	48	Capri (CL platform)	late Cretaceous	Catalano et al. (1976)
5 sites	286.6	44.5	21	Mt. Cervicro (CL platform)	late Cretaceous	Manzoni (1975)
113 samples	248.0	30.4	21	Pescopagnano (LN basin)	Cretaceous	Incoronato (1983)
3 areas	271.1	44.6	16	Internal part	Cretaceous	(above)

comprise Mesozoic–Paleogene deposits in basinal (e.g. Lagonegro, Imerese) or carbonate platform (e.g. Campano–Lucano, Abrruzzi–Campania, Panormide platforms), incorporated foreland basin deposits (e.g. Sicilide and Numidian successions) and thrust belt basin deposits (e.g. S. Arcangelo and Caltanisetta basins). Paleogeographic reconstructions result in an originally NE–SW trending belt of alternating platforms and basins along the northern margin of the African Plate. Recently, a new interpretation of seismic data has revealed an involvement of the Apulian Plate in the deformations in the southern Apennines (Mostardini and Merlini, 1988). The thrust belts are dissected by numerous transpressional Fault Zones on various scales (Caire, 1973). The main orogen-parallel elements, the *Ciro–Benevento Fault Zone (9)* and the *M. Kumeta–Alcantara Fault Zone (12)*, were originally interpreted as the traces of the main over-

Table 2
Summary of paleomagnetic results from Sicily and the Calabrian block. See caption of Table 1. Further: in the references: [A] refers to Schult (1973,1976), Barberi et al. (1974), Gregor et al. (1975) and Grasso et al. (1983); [B] refers to Grasso et al. (1983) and Besse et al. (1984); [C] refers to Barberi et al. (1974), Gregor et al. (1975), Grasso et al. (1983) and Besse et al. (1984). See also Aifa et al., 1988; Tauxe et al., 1983 and Watkins et al., 1975 for the Calabrian Area

N	*D*	*I*	*k*	locality/unit	age	reference
Ragusa platform						
4 studies	347.1	27.4	195	Ragusa platform	late Cretaceous	More references [A: see caption]
3 Localities	353.9	44.3	98	Ragusa platform	Eocene–Miocene	More references [B; see caption]
4 studies	351.6	53.1	141	Ragusa platform	Pliocene	More references [C; see caption]
5 sites	339.8	51.8	164	Ragusa platform	early Pleistocene	Scheepers and Langereis (1993)
Gela–Catania foredeep						
2 areas	13.0	53.7	155	Gela–Sam Nicola zone	early Pleistocene	Scheepers and Langereis (1993)
Caltanissatta basin						
32 levels	24.5	42.2	122	Rosello (upper part)	late Pliocene	Scheepers and Langereis (1993)
10 intervals	34.2	46.4	1212	Rossello (lower part)	early Pliocene	Scheepers and Langereis (1993)
Northern Sicilian chain						
8 localities	90.9	30.1	16	Panormide platform	late Cretaceous	Channell et al. (1990)
3 sites	116.3	36.1	13	Imerse basin	late Cretaceous	Channell et al. (1980)
3 localities	35.6	42.2	15	Trapanese Sceamounts	late Cretaceous	Channell et al. (1990)
3 localities	99.9	41.3	146	Sicanian basin	late Cretaceous	Channell et al. (1990)
2 localities	33.3	37.1		Internal Saccense platform	late Cretaceous	Channell et al. (1990)
5 sites	71.4	52.9	18	Petralia superiore	late Miocene	Scheepers and Langereis (1993)
2 sections	8.4	54.1		Buonfornello	early Pliocene	Scheepers and Langereis (1993)
Calabro–Peloritan block						
2 localities	18.9	51.3		Crotone basin	late Miocene	Scheepers et al. (1993)
1 locality	8.3	38.0		Tyrrhenian coast Northern part	late Miocene	Scheepers et al. (1993)
4 localities	11.3	41.9	180	Ionia coast Southern part	early Miocene	Scheepers et al. (1993)
4 localities	16.4	51.4	173	Tyrrhenian coast Southern part	early Pliocene	Scheepers et al. (1993)
3 localities	24.5	48.4	96	Crati basin	late Mio–early Pleisto	Scheepers et al. (1993)
4 localities	10.5	51.1	120	Crotone basin	late Plio–early Pleisto	Scheepers et al. (1993)
4 Localities	13.2	48.3	231	Southern part	Early Pleistocene	Scheepers et al. (1993)
4 localities	2.8	54.2	368	cover Calabro–Peloritan block	middle Pleistocene	Scheepers et al. (1993)
22 localities	14.6	48.8	88	cover Calabro–Peloritan block	late Mio–early Pleisto	(above)

thrusts (Caire, 1962; Mostardini and Merlini, 1988). Subsequently, Moussat (1983) presented a model in which they were viewed as subvertical strike-slip Fault Zones, dissecting the whole lithosphere. Ghisetti and Vezzani (1982a,b,1984) and Ghisetti (1984) added obliqueness to the movement along these fundamental Fault Zones, while Van Dijk and Okkes (1988,1990,1991) presented a model in which the majority of the Fault Zones were interpreted as obliquely convergent thrust zones and their surface expressions (their "pattern D").

The Neogene basins within the Sicilian Maghrebides and Southern Apennines can be regarded as oblique thrust-belt basins such as thin-skinned pull-apart basins and piggy-back basins. 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 (Giunta, 1985; Lentini et al., 1987; Patacca and Scandone, 1989; Roure et al., 1990,1991; Patacca et al., 1992). Lentini et al. (1987) and Broquet et al. (1981) distinghuished a number of sedimentary sequences separated by unconformities, the latter coinciding with the above-mentioned diastrophic phases.

Rotational data concerning the fold-and-thrust belts (Tables 1 and 2) show a symmetrical, "oroclinal" pattern with regard to paleomagnetic directions: clockwise rotations in Sicily, and counterclockwise rotations in the southern Apennines (e.g. D'Argenio et al., 1980; Incoronato and Nardi, 1990). This has led many authors to speculate upon a possible bending of an originally straight zone (Ghisetti and Vezzani, 1982a,b; Van der Linden, 1985), or a relation between arc migration and rotations (Caire, 1970; Van Dijk and Okkes, 1990,1991; saloon-door model). The rotations, on the other hand also show a surprising asymmetrical pattern: In the Sicilian thrust-belt, rotations gradually increase with the age of the successions, which indicates that many pulses of deformation connected with tectonic rotations have occurred (e.g. Channell et al., 1980; Oldow et al., 1990), whereas the southern Apennines show a different pattern: Cretaceous rocks in the internal thrust sheets of the belt show rotations between 75 and 110° (mean of 89°) counterclockwise, while Cretaceous rocks in the external part show rotations that fluctuate between 20 and 40° counterclockwise (mean of 37°) (Scheepers et al., 1993; Scheepers and Langereis, in press).

Our studies on Neogene deposits in thrust-belt basins have shown that the Pliocene deposits of the Caltanisetta Basin have rotated 34° clockwise since Early Pliocene times (Scheepers et al., 1990; Scheepers and Langereis, 1993). It appears that 5–10° of this rotation took place at approximately 3 Ma, while at least 24° of this rotation must have occurred afterwards. The results of our studies in the southern Apennines indicate a smaller rotation for Lower Pleistocene rocks (24°) relative to Upper Miocene to middle Pliocene rocks (39°) (Scheepers et al., 1993; Scheepers and Langereis, in press). The similarity in amount of rotations detected in the Cretaceous rocks of the external Apennines and the Neogene deposits (noted by Scheepers et al., 1990; Sagnotti, 1992 and Scheepers et al., 1993) implies that there is (at present) no indication for any tectonic rotations of the external thrust sheets of the southern Apennines between the Cretaceous and the latest Miocene.

2.4. The foreland areas

The foreland area of the Calabrian Arc is very heterogeneous, and can be subdivided into a number of small blocks or "microplates". These are the Iblean block which can be regarded as a promontory of the African Plate, the Adria block, which once was possibly continuous with the previous one, and the Ionian basin in between.

The Adria block. The Adria (or Apulia) Microplate was first recognized as a separate plate on the basis of present day seismicity patterns (Lort, 1971; McKenzie, 1972; Dewey et al., 1973; Udias, 1974; Moretti and Royden, 1988). Its motion independent of the African Plate must have occurred from at least the middle Tertiary onwards (Van den Berg, 1979a,b,1983; Van den Berg and Zijderveld, 1982). The Apulian block is the southern part of the Adria Plate. The north-

ern Adria block and the Apulian block differ in lithosphere structure: A change in crustal and lithosphere thickness respectively from about 25–36 and 70 km in the north to about 35–40 and 110 km in the south (Nicolich, 1981; Calcagnile and Panza, 1981) takes place along the *Napoli–Gargano–Dubrovnik Fault Zone (4)* (cf. Van Dijk, 1992; see Fig. 1). This ca 150 km wide zone is characterized by a weak present-day seismicity (e.g. Westaway, 1991), NE–SW and E–W trending dextral transcurrent faults, and a broad basement elevation which is associated with E–W anticlinal structures. The Gargano peninsula, an uplifted block, is situated within this Fault Zone. The onshore part of the Apulian block extends to the south into the Salentino peninsula. Foreland platform areas are exposed in the Gargano area (GAR) and in the Murge and Salentino areas (SAL), covered with Pliocene–Pleistocene deposits. The Apulian block is delimited along the southwest by the Apulian Escarpment (APM), a NW–SE trending Fault Zone, showing both Mesozoic and Neogene extensional faulting (In: Charrier et al., 1987).

Paleomagnetic investigations revealed the following (Table 1): The Gargano area rotated 30° counterclockwise since the Early Tertiary (Channell and Tarling, 1976; Channell, 1977; Van den Berg, 1983). It has been stated that the Salentino area possibly shows a clockwise rotation of 25° since the Eo–Oligocene (Tozzi et al., 1988). This lead to many speculations with regard to a possible decoupling of the Salentino and Gargano areas, at least during part of the Late Tertiary, probably along the *Napoli–Gargano–Dubrovnik Fault Zone (4)*. These data, however, have shown to be not significant (Bazhenov and Shipunov, 1991). Furthermore, our data showed that the Gargano and Salentino areas did not rotate in Late Pliocene–Pleistocene times (Scheepers, 1992).

The Iblean block. 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 Sicilian Plate (McKenzie, 1972), the Messina Plate (Dewey et al., 1973; Jongsma et al., 1985) or the Iblean Microplate (Jongsma et al., 1987). The Iblean block is separated from the African Plate by the NW–SE trending Sicily Strait, the *Sicily Channel Fault Zone (13)*, and the "Medina wrench", part of the *Gabes–Melita–Medina Fault Zone (15)*, which show a Pliocene phase of dextral transtensional rifting (Illies, 1969,1981; Finetti, 1984; Jongsma et al., 1985,1987; Boccaletti et al., 1987a; Cello, 1987; Argnani, 1990). The Iblean block is separated from the Ionian Basin by the NNW–SSE trending Malta Escarpment (MAE) (Casero et al., 1984; Charrier et al., 1988), which is the southwestern counterpart of the Apulian Escarpment (APM).

Rotational data (Table 2) indicate that the Iblean block has rotated about 70° counterclockwise, 15° of which took place in middle Pliocene times (Besse et al., 1984). This rotation is generally regarded as being related to the dextral transtensional rifting in the Sicily Strait of the same age.

The Ionian Basin. The Ionian Basin lies between the southern Adria block and the Iblean block. It is delimited along the north by the Apulian Escarpment (APM) and along the south by the Malta Escarpment (MAE). The basin shows an anomalous crustal structure, as evidenced by gravity and seismic data. A high positive Bouguer anomaly (up to 300 mgal; Morelli et al., 1975) is ascribed to a thinned continental crust, to high-density intruded magmas and to the cooling of mantle material. Furthermore, there is a low heat flow and crustal thickness ranges from 17 to 20 km (Hinz, 1974). The Ionian Basin is often regarded as a separate "microplate", the Ionian Plate (McKenzie, 1972; Dewey et al., 1973; King et al., 1993).

The data regarding this area are very poor and have led to conflicting opinions on its origin (see below): 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., 1986; 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; Manto-

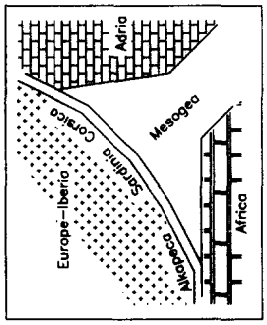
vani et al., 1990), witnessed by a "Late" phase of foundering. This discussion is of fundamental importance, as it directly concerns the original geometry of the Adria Plate and its successive deformation history (Fig. 3).

2.5. The original (Mesozoic) configuration of the northern boundary of the African Plate

In the recent literature, the decoupling zone between the African Plate and the Adria Plate is located at various places which are situated along major E–W to NE–SW trending fault zones dissecting the Central Mediterranean (Fig. 1). On a larger scale, all these Fault Zones are part of a horsetail set of transcurrent faults, constituting a mobile belt between the relatively stable African and European Plates (e.g. Scandone, 1982; Ziegler, 1984; Van Dijk and Okkes, 1990). They acted as former tranform faults of the Neotethyan ("Mesogea"; Jurassic–Cretaceous) ocean (Winterer and Bosellini, 1981; Gealy, 1988; Dercourt et al., 1986). Subsequently, they were major zones of weakness during the Alpine orogeny determining segments of the thrust belt enhanced by segemtns in the subducting Adria foreland (cf. Aubouin and Dercourt, 1975; proposed for the Apennines by Van Dijk and Okkes, 1991, captions of their fig. 12; see for an extensive discussion Van Dijk, 1992). In honour of a number of great geologists, whose names are partly already associated with these Fault Zones, we propose to call the fundamental zones as follows: The *Selli Zone*, comprising the *Annaba–La Galite Fault Zone(1)*, the *Selli Fault* and the *Anzio–Ancona Fault Zone (3)* (In: De Wijkerslooth, 1934; Selli and Fabbri, 1971; Kastens et al., 1987), the *Beneo Zone*, comprising the *Tunis–Egadi Fault Zone (2)*, the *Issel Ridge* and continuing into the *Napoli–Gargano–Dubrovnik Fault Zone (4)* (Beneo, 1951; Ortolani and Pagliuca, 1988; Westaway et al., 1989; Favali et al., 1990; Westaway, 1990), the *Aubouin Zone*, comprising the *M. Kumeta–Alkantara Fault Zone (12)* and *Otranto–Scutari–Pec Fault Zone (7)* (D'Ingeo et al., 1980; Anderson and Jackson, 1987a; Anderson, 1987; Marton, 1987; Gealy, 1988), and the *Vening-Meinesz Zone*, comprising the *Gabes–Melita–Medina Fault Zone (15)* and *Kefallinia Fault Zone (8)* (Dewey et al., 1973; IGC, 1984; Jongsma et al., 1985,1987).

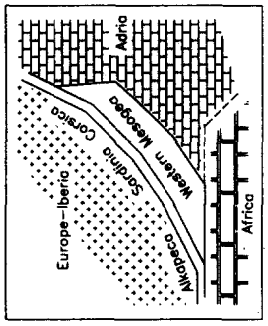
These major Fault Zones define a number of the small "microplates" recognized between the stable African and European Plates described above, such as the northern Adria, the southern Adria (Apulian block), the Ionian Basin and the Iblean blocks. Furthermore, the *Beneo Zone* is part of the southern boundary of a continental "bridge" in between two Neotethys areas (see below): The western Liguride–Piemonte ocean and the central Ionian–eastern Mediterranean oceanised basin.

There is considerable dispute in the literature regarding the original configuration of these small "Mesogean" oceanic basins. The existence of the western and eastern segments of the Mesozoic Tethys is not questioned. In the west, the formation of the Bay of Biscay was connected with the rotation of Iberia. In the northwest, the Liguride–Piemonte Ocean is at present consumed and partly obducted in the Apennines. The eastern branch of the Neothethys, the Taurus Ocean, is at present consumed and partly obducted in the Taurus Range. The existence of the central segment of the Mesogea (eastern Mediterranean, Ionian Sea, and possibly subducted oceanic areas below the Calabrian arc and Tyrrhenian Sea) is, however, debated (Abbate et al., 1986). The following opinions regarding the Ionian crust can be distinghuished in literature (Fig. 3). It is commonly assumed that an Ionian Mesogea ocean extended up to the present-day Gulf of Lyon and is practically completely consumed by subduction (Argand, 1924; Boccaletti and Guazzone, 1975; Alvarez, 1972, 1976, 1991; Görler and Giese, 1978; Finetti, 1982; Malinverno and Ryan, 1984). As field evidence accumulated, it has become clear that (thinned) continental crust continued between Tunis–Sicily and the Adria block, below the present-day Tyrrhenian Basin (Caire, 1962,1964; Haccard et al., 1972; Scandone et al., 1974; Amodio-Morelli et al., 1976; Grandjacquet and Mascle, 1978; Scandone, 1979, 1982). This deduction is based on the clear resemblence between Mesozoic platforms and basins and the Paleocene–Early Miocene foredeep "flysch" deposits in the southern Apennines and Sicilian



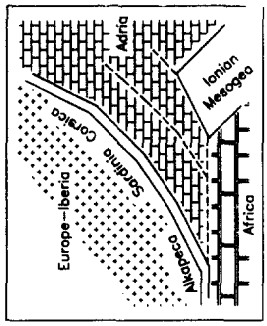
Continuous Mesogea remnant

cf. Glangeaud (1956)
Alvarez et al. (1974, 1976)
Biju–Duval et al. (1977)
Goerler and Giese (1978)
Finetti (1982)
Malinverno and Ryan (1984)
Dercourt et al. (1986)
Hill and Hayward (1988)
Alvarez (1991)



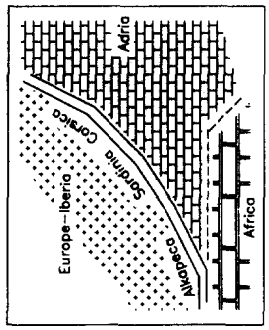
No Central Mesogea remnant

D'Argenio et al. (1980)
Channell and Marechal (1989)



Only Central Mesogea remnant

Scandone et al. (1975)
Scandone (1982)
Balla (1987)
Bouillin (1984)

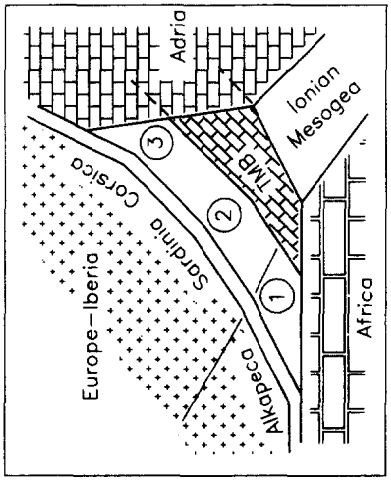


No Western–Central Mesogea remnant

Argand (1924)
Carey (1958)
Caire (1964, 1978)
Scandone et al. (1974)
Boccaletti et al. (1982)
Mantovani (1982)
Mantovani et al. (1985, 1992)

Separated Western–Eastern Mesogea remnants

cf. Coutelle & Deteil (1989)
Dewey et al. (1989)
Van Dijk (1992)
This paper



Western Mesogea remnants:
1. Maghrebide–Sicilide Basin
2. Liguride–Sicilide Basin
3. Piemonte–Liguride Basin

TMB: Trans–Mediterranean Bridge

Maghrebides. Based on this evidence, several authors sustain that the extension of the Ionian Basin is a Neogene feature and that a Central Mediterranean Mesogea has never existed (Carey, 1958,1986; Mantovani, 1982; Mantovani et al., 1985,1992). This extension was then possibly related to post-middle Miocene anti-clockwise rotation of the Adria Plate. The Ionian Basin has, indeed, suffered a major phase of foundering in Pliocene–Recent times, possibly related to a spenochasm-type of opening which was governed by sinistral shear zones within the southwestern part of the Calabrian Accretionary Wedge (Fabbri et al., 1982; Casero et al., 1984; Gresta et al., 1990). Three main constraints can be established: (1) The thrust-belt terranes are displaced over about 200 km, and are pealed-off from a crust which was situated in the present-day Vavilov area. (2) The petrology of volcanogenic products argues in favour of a subducted oceanic crust below the Calabrian Arc (e.g. Serri, 1990). (3) Data on the Malta Escarpment and the Apulian Escarpment (In: Charrier et al., 1987 and Charrier et al., 1988) clearly indicate a Jurassic–Cretaceous rifting of the Ionian sector, apart from a Neogene foundering. Taking these three features into account, it must be concluded that the ambiguous area, where continental crust may have continued between African and Adria Plate, 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 (cf. Coutelle and Delteil, 1989; see Van Dijk and Okkes, 1988,1990; Dewey et al., 1989; inset of Fig. 1) We propose to call this "continental bridge" the "*Trans-Mediterranean Mobile Zone*" (see also Van Dijk, 1992). The *Selli Zone (1–3)* and the *Beneo Zone (2–4)* delimit this broad zone in the Central Mediterranean, which comprises numerous E–W and NNE–SSW trending major Fault Zones. The Trans-Mediterranean zone separates dextral rotated blocks to the southeast of it from sinistral rotated blocks northwest of it (see further). It furthermore comprises the Central Apennines (CPN), which separate the two other major Apenninic arcs, the northern (NPN) and the southern (SPN) Appenines (cf. Royden et al., 1987; see Van Dijk and Okkes, 1988,1990; Patacca and Scandone, 1989). Its cover and slices of its basement are now present in the thrust sheets of the Calabrian Arc as "Apenninic Platform Units" (Apennines), Stilo–Tiriolo–Serre Units (Tyrrhenian vergent units in Calabria; see Van Dijk, 1994), and Panormide Platorm Units (Sicily).

3. Previously proposed rotational models

During the last decades, many solutions have been presented which incorporate the data on the tectonic rotations which have occurred in the Central Mediterranean area. These solutions can roughly be divided into the following four groups: (1) The Adria Plate rotated together with the African Plate, being a promontory, in Mesozoic times (continent scale; > 1000 km). (2) The Adria Plate rotated as an independent microplate, decoupled from the Africa Plate (microplate scale; 100–1000 km). (3) The rotations originated from the formation of a "peri-Tyrrhenian orocline", related to the migration to the southeast of the Calabrian Arc and the opening of the Tyrrhenian Basin (thrust-belt scale; 10–100 km). (4) Theoretically, a fourth solution can be put forward: the observed rotations could also be due to rotational gravitational sliding of superficial slabs along the external margin of the orogen, which are known

Fig. 3. Proposals for reconstructions of the Central Mediterranean for Late Eocene–middle Oligocene times, immediately prior to the rotational migration of the Sardinia–Corsica block and connected opening of the Western Mediterranean basin. Note that the major part of the western Mesogea was already consumed ; most authors agree on that subject. Alkapeca (ALboran–KAbyle–PEloritani–CAlabria) is the alias name of the reconstructed southern margin of the Iberia block (cf. e.g. Bouillin, 1984). The reconstruction favoured in the present paper is the lowermost one. The position of the Lagonegro–Imerese Basin is much debated in literature (see for an extensive discussion Sgrosso, 1994). An external position can be in agreement with our reconstruction, which does, altogether, not depend on this specific detail.

to be present in the Central Mediterranean (slab scale; 1–50 km; e.g. Van Dijk, 1994).

The models of Group 2 (Adria microplate rotation), in turn, can be subdivided into four end-members (Fig. 2): The Mega-shear Model explains the rotation of the Adria microplate as the result of sinistral shear between the European and the African Plates. The Pendulum Model envisages the Adriatic rotations as an expression of the opening of the Tyrrhenian sphenochasm. The Promontory Model regards the Adriatic Plate as a deformed promontory of Africa which has rotated as an effect of collision with the European margin. The Ball-bearing Model shows two free boundaries and a rotating Adria Plate in between transpressive plates. Combinations of these models have also been proposed in order to resolve specific space problems (see below). Two rotation poles have been indicated in literature: The Malta pole in the south and the Elba, Genova or Torino pole in the north. The Ball-bearing Model implies a central pole within the Central Apennines. The so-called "fixed boundaries" show tensional, sphenochasm-like features (cf. Carey, 1958) along one side, and transpressional thrusting along the other.

Each of these models is, to some extent, not compatible with observed structures (see the numbers in Fig. 2a): The Mega-shear Model predicts a symmetry which is not observed (1). Oroclinal bending in the Mega-shear and Promontory Models does not resolve the sphenochasm opening of the Tyrrhenian Sea (2). Mega-shear and Pendulum Models imply stretching in the western Alps (3). The Ball-bearing Model implies a symmetry within the Mediterranean which is not observed (4). These problems can be solved by combining aspects of different models. For example, Lavecchia (1988) and Mantovani et al. (1990) combine the Mega-shear Model with a slight Pendulum effect. Furthermore, Mega-shear and Pendulum Models generally encompass a northern dextral intrusion or indentation along the Alps which is characteristic of the Promontory models (e.g. Scandone, 1979, 1982). Also, extra features were introduced, such as arc migration to the southeast to provide an extra stretching within the Tyrrhenian area, transpressive movements of the two bounding plates to provide shortening in the western Alps, or a releasing bend geometry within the sinistral transcurrent African–European Plates margin, and inherited non-symmetry to explain the asymmetrical structure. A common mistake, however, is that Pendulum kinematics are an incontestable consequence of mega-shear tectonics (e.g. Lavecchia, 1988; Mantovani et al., 1990). The location of tension depends on the distribution of rheology, and location of (long-lived) ruptures; e.g. sphenochasmic opening of the Tyrrhenian Basin can only be achieved by a special type of releasing bend (see Fig. 2a). An alternative suggestion by Lavecchia (1988) envisages ball-bearing type rotations of parts of the Apennines and Adria, in-between E–W trending shear zones (cf. the oroclinal model of Nelson and Jones, 1987).

The models of Group 3 (thrust-belt rotation), in turn, can be subdivided in three end-members with different subtypes (Fig. 2b): (1) Radial Drift Models envisage rotations of small panels as radially translated blocks in various ways (pushed; saloon-door models, or sucked). (2) Translation Models envisage rotation of blocks in-between parallel-sliding corridors (tablet models). (3) Bending Models relate the rotations observed to bending of an originally straight continental ribbon, in various fashions (pushed, inserted or compressed). The differences between the various models concern the relations between rotations, back-arc rifting and regional compression induced by Africa–Europe (trans)pression. Contemporaneous or alternating relations between these processes have been proposed or deduced from the models (Fig. 2b). The comparison between the timing of rotations and the mentioned processes may, therefore, provide important clues with regard to the discrimination between the proposed models.

4. The Plio–Pleistocene evolution

4.1. Available data concerning timing and amount of rotations

The timing of the independent Adria rotation has been rejuvenated ever more in the literature

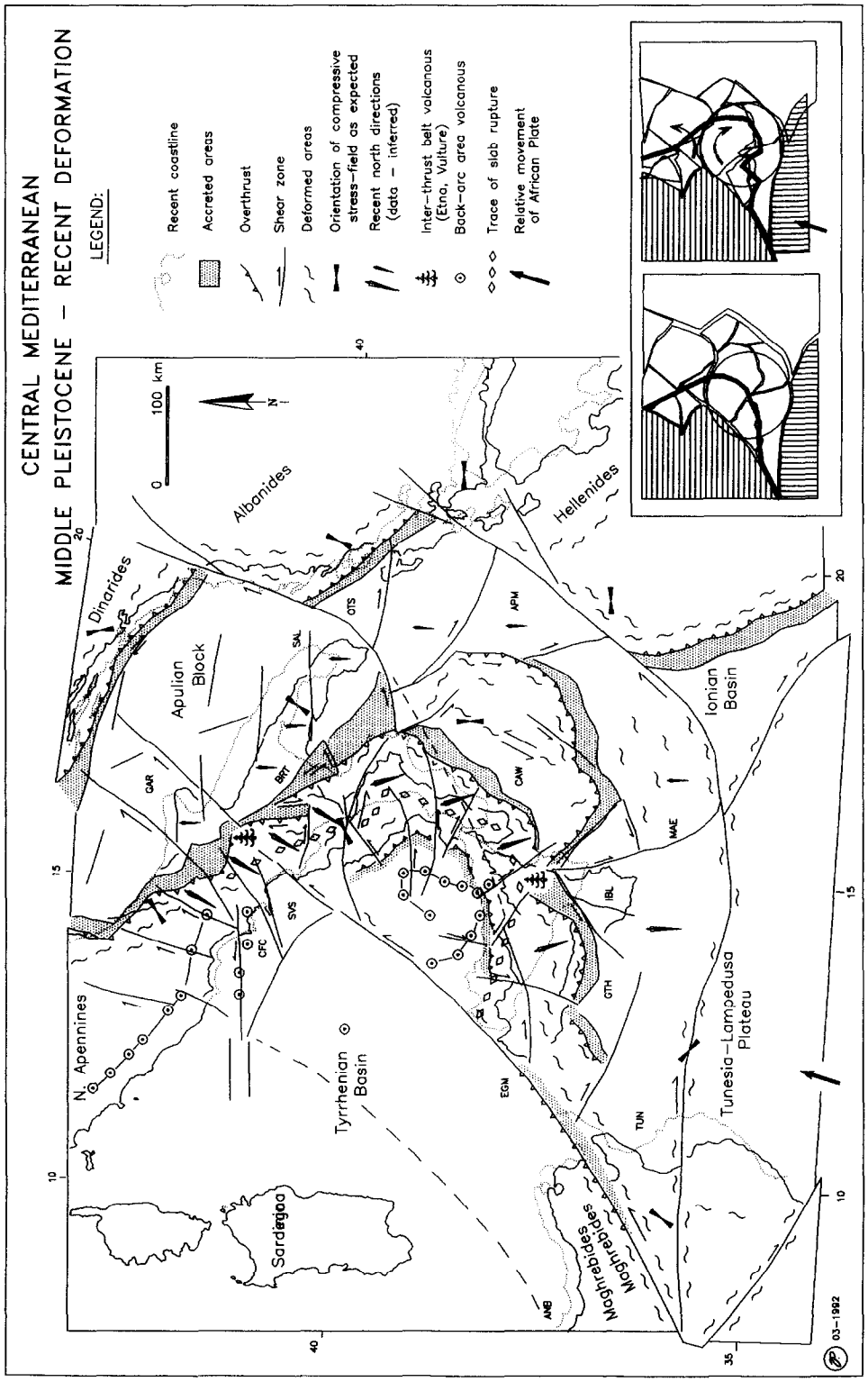
In Fig. 5, a possible solution for option 1 has been depicted. The solution was obtained by means of a 2D mass-balance exercise with a trial-and-error procedure. The constraints are the rotation data as discussed above, limited shortenings along the orogenic belt (Finetti and Morelli, 1973; Rossi and Sartori, 1981; Ambrosetti et al., 1983), and strike-slip faulting along many fault zones within the area as also known from literature (although data on Pleistocene displacements are scanty). The main constraint in this exercise is large-scale sinistral shear between Calabria and the southern Apennines, along the *Pollino Fault Zone (11)*. Fig. 5 illustrates that, basically, the rotation can be resolved by distributed strain within the Central Mediterranean area, with a small NNE directed relative displacement of the African Plate without any large-scale lateral offset. The consequences are the following: Sinistral shear has taken place along the southern part and dextral shear along the northern part of the *Beneo Fault Zone (2–4)*. The Calabrian Accretionary Wedge is characterized by NE–SW sinistral transpression. The Apulian block is deformed internally by dextral displacements along antithetic shear zones. The rotation axis of the Calabrian–Sicily block is situated in the Etna/Stromboli/Messina area. The outline of the rotated block defines a large ball-bearing in between the *Pollino Fault Zone (11)* and the *Gabes–Melita–Medina Fault Zone (15)*. It must be noted that a similar quasi-circular morphotectonic feature was already noted by Van Bemmelen (1976) who imagined it to be the surface expression of an asthenosphere dome or blister. The northern half of this ball has rotated in a seesaw fashion whereby the Iblean block, being a small continental promontory, acted as the hingeline. The whole ball-bearing shows a rolling movement along its southern, and a slipping movement along its northern boundary. The Central Mediterranean is decoupled from the African Plate along E–W to NE–SW trending strike-slip Fault Zones, which is in support of the Pendulum or the Ball-bearing Models.

4.3. Temporal distribution

The chronological framework which comprises the rotations, should acount for the following features (Fig. 6):

Volcanism. The available information regarding the volcanism in the Central Mediterranean indicates that the activity can be divided in three main episodes: A Late Pliocene–earliest Pleistocene episode of activity, and a Late Pleistocene–Recent episode of activity, separated by an late Early Pleistocene quiescence episode (Savelli, 1984). The Late Pliocene–earliest Pleistocene episode was characterized by a normal combination of alkaline basaltic volcanism and calc-alkaline volcanic arc products in the back-arc region, and alkaline volcanism in the Iblean foreland area and in Sardinia. This points to an overall tensional regime and a "classical" southern Tyrrhenian subduction system. The Late Pleistocene–Recent episode was characterized by intra-thrust-belt volcanism in the southern Apen-

Fig. 4. Chronological chart concerning rotations of the tectonic elements in the Central Mediterranean. The data as summarized in Tables 1 and 2 are plotted at their geochronological positions. Note the timescale changes at 10 and 20 Ma. The assymmetrical pattern of rotations in the whole system can be noted comparing the rotations of Sicilian and of southern Apennnines thrust sheets. The middle Miocene rotations of the Calabrian segments (Scheepers, 1994) show an increase of both age and amount of rotation from NE to SW. This feature is in agreement with the fact that contractions show an increase from SW to NE due to a displacement to the NE of the Calabrian Element ("Translation Stage of Geodynamic Cycle B" of Van Dijk and Okkes, 1990). The data suggest the following: The Calabrian Element showed a position similar to the Sardo-Corsican block in the Oligocene, from which it detached in the Early Miocene, rotating counterclockwise during middle Miocene times. At the moment, it can not be established whether Middle–Late Miocene rotations are related to oroclinal or to whole block rotation events. The coincidence between the middle Tortonian rotational and regional tectonic event suggests, anyhow, a link between events of regional stress fluctuations and block rotations, similar to the late Burdigalian and the Pliocene–Pleistocene events. It can be noted that Plio–Pleistocene clockwise rotations occurred when Calabria, drifting towards the southeast, crossed the Trans-Mediterranean Mobile Zone. The second order stress curve and geodynamic episodes depicted in the right column are from Van Dijk (1992).


CENTRAL MEDITERRANEAN
MIDDLE PLEISTOCENE – RECENT DEFORMATION
LEGEND:
Recent coastline
Accreted areas
Overthrust
Shear zone
Deformed areas
Orientation of compressive stress-field as expected
Recent north directions (data – interred)
Inter-thrust belt volcanous (Etna, Vulture)
Back-arc area volcanous
Trace of slab rupture
Relative movement of African Plate
0
100 km
N
Albanides
Hellenides
Dinarides
Apulian Block
Ionian Basin
Tyrrhenian Basin
N. Apennines
Sardegna
Tunesia–Lampedusa Plateau
Maghrebides
GAR
BRT
SAL
OTS
APM
CAW
MAE
IBL
GTH
TUN
EGN
ANB
SVS
CFC
03-1992

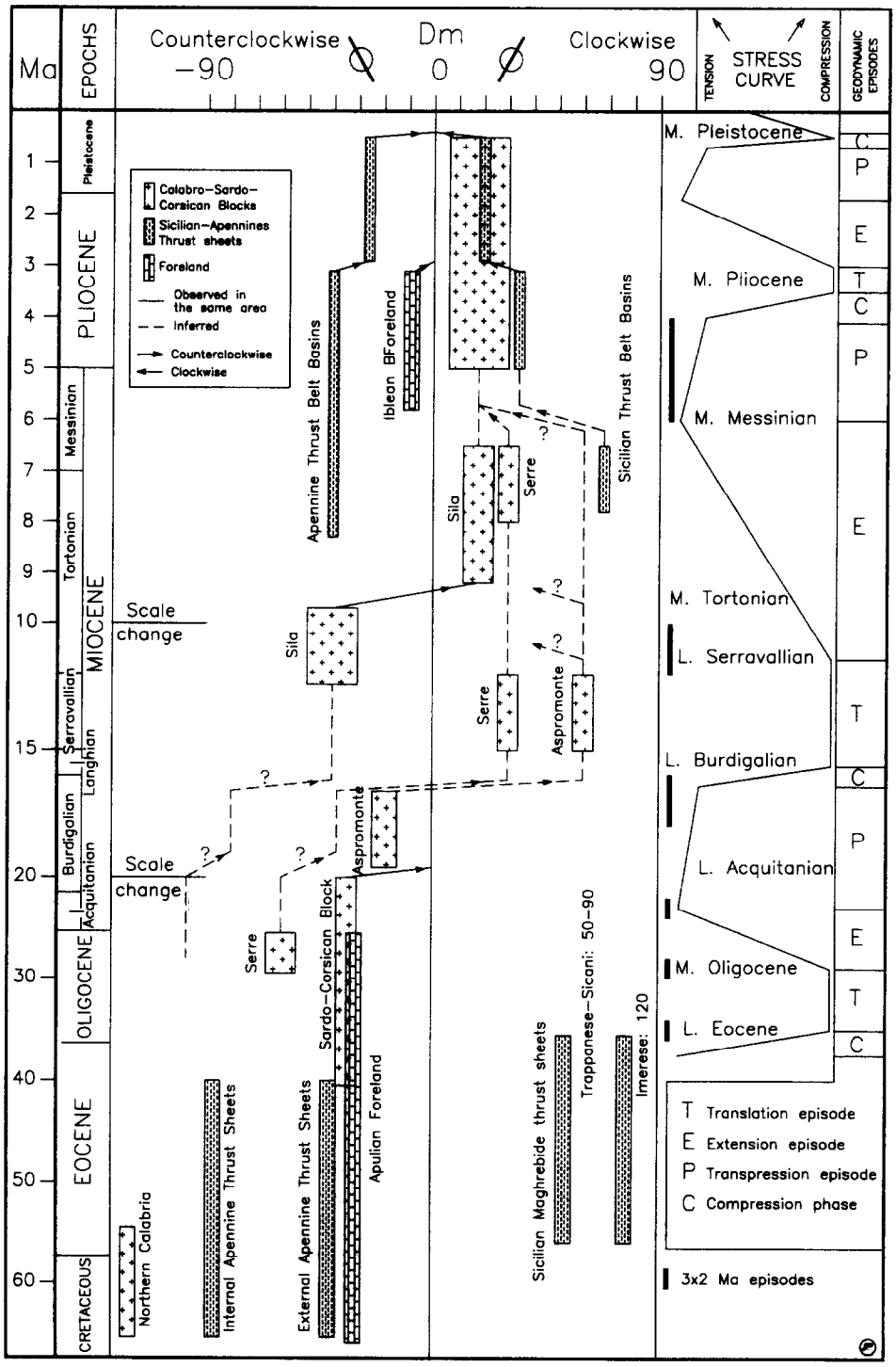
of the last decades: Dewey et al. (1973) and Biju-Duval et al. (1977) envisaged a Mesozoic (middle Jurassic–middle Cretaceous) rotation, related to the opening of the Ionian Mesogea. Van den Berg (1983) claimed a post-Early Tertiary rotation of about 30°, Lowrie (1986) placed a 15° rotation in the Late Tertiary, Mantovani et al. (1985,1990) claimed an age of post-middle Miocene for a rotation of 20°, while Anderson and Jackson (1987a,b) claimed that according to recent seismicity patterns, the rotation is still continuing.

Summarizing, the available data regarding Neogene rotations in the Central Mediterranean are the following (Tables 1 and 2; Fig. 4): The mean direction for the Cretaceous rocks from the Gargano foreland block implies a post-Oligocene 31° counter-clockwise rotation (Channell and Tarling, 1976; Channell, 1977; Channell et al., 1979; Van den Berg, 1983). Our new data reveal that no rotation has occurred in the Gargano and Salentino areas in the Pleistocene interval (Scheepers, 1992). All the paleomagnetic data from the Cretaceous rocks of the southern Apennines thrust-belt imply a considerable counterclockwise rotation (89° in the internal part, 37° in the external part). Our results give amounts of rotation for Upper Neogene sediments similar to the external thrust sheets, of which 24° took place in mid-Pleistocene times (see Scheepers et al., 1993 for a complete overview of these data). This may suggest that these terrains behaved as one coherent block or set of blocks in Pleistocene times. The Calabrian block rotated counterclockwise during the Early–Middle Miocene. Possibly, the first clockwise rotations occurred during Messinian times. In the middle Pleistocene, the Calabrian block has rotated 15° clockwise (Scheepers, 1990; Scheepers et al., 1994,submitted). The data for the Sicilian basins indicate a mid-Pliocene rotational phase (5–10° clockwise) and a remaining Late Pliocene–Pleistocene 24° clockwise rotation, which may also have taken place in mid-Pleistocene times. Furthermore, data of the Iblean block indicate that this area has rotated 15° counterclockwise during the Pliocene but remained stable in the Late Pliocene–Pleistocene (Grasso et al., 1983; Aifa et al., 1988). It can be noted (Fig. 4) that, generally, rotations have occurred during episodes of switching of the second order interplate stress field from compressive to extensional and vice versa, accompanied by numerous tectonic pulses.

These data together imply that in the middle Pleistocene, a major decoupling existed between clockwise rotating Calabria and Sicily on the one hand, and the counterclockwise rotating southern Apennines on the other, which were both decoupled from the stable foreland areas. We propose to place the boundary between the "Calabro-Sicilian block" and the southern Apennines along the NW–SE trending *Pollino Fault Zone (11)*, which is known to have been active as a transpressive shear zone in mid-Pleistocene times (Bousquet, 1972; Moussat, 1983; Ghisetti, 1984).

4.2. Spatial distribution

The rotations in the southern Apennines thrust-belt and those in the Apulian foreland have thus taken place in different time intervals and the two regions were decoupled in mid-Pleistocene times. The rotations in the southern Apennines thrust-belt can be envisaged in two different ways. Firstly, as a number of fault-bounded tablets, ball-bearings or irregular blocks within a regime of sinistral shear, bounded by dextral antithetic shears (option 1). Secondly, as a relatively coherent block around a pole situated within the area (option 2) (cf. Nur et al., 1986; Nelson and Jones, 1987). The latter option would create much more space problems than option 1, which may, therefore, be preferred as a working hypothesis (see also Jackson and McKenzie, 1984, their fig. 33). In option 1, the fact that the amount of clockwise rotation of the different areas appears to be between 20° to 40° might be explained by the criteria of Nur et al. (1986). These criteria show that the range of rotation lies within the predicted range of permissible fault rotations in a stationary stress regime. Possibly, the faults which delimit the rotating "tablets" could be NNW–SSE and NNE–SSW trending dextral faults intersecting the Southern Apennines thrust-belt as suggested by several authors (see e.g. Caire, 1975; his fig. 12).

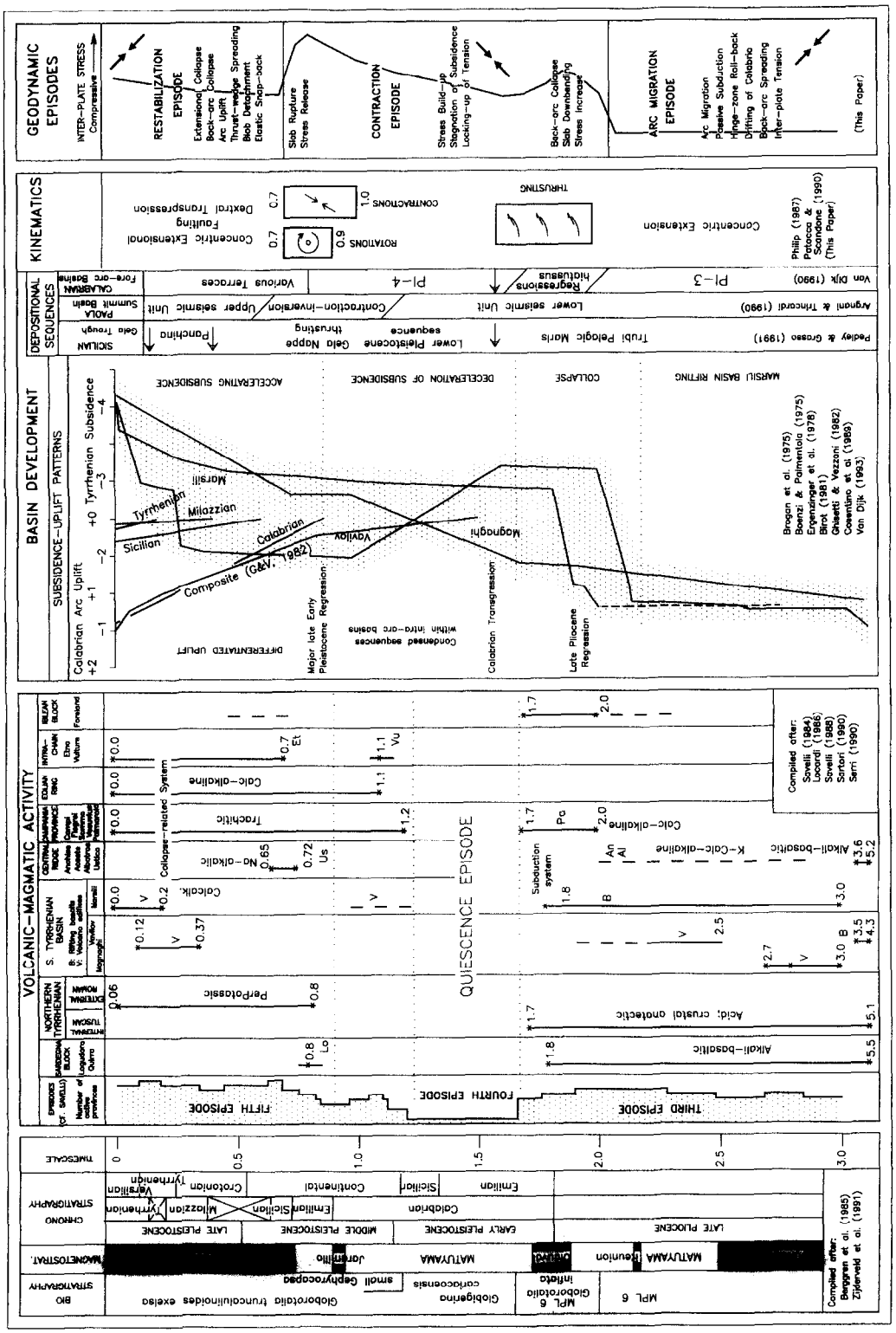

Ma
EPOCHS
Counterclockwise
−90
Dm
0
Clockwise
90
TENSION
STRESS CURVE
COMPRESSION
GEODYNAMIC EPISODES
Pleistocene
PLIOCENE
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Acquitanian
MIOCENE
OLIGOCENE
EOCENE
CRETACEOUS
Calabro–Sardo–Corsican Blocks
Sicilian–Apennines Thrust sheets
Foreland
Observed in the same area
Inferred
Counterclockwise
Clockwise
Scale change
Scale change
Apennine Thrust Belt Basins
Iblean BForeland
Sicilian Thrust Belt Basins
Sila
Serre
Aspromonte
Northern Calabria
Internal Apennine Thrust Sheets
External Apennine Thrust Sheets
Sardo–Corsican Block
Apulian Foreland
Sicilian Maghrebide thrust sheets
Trapponese–Siciani: 50–90
Imerese: 120
M. Pleistocene
M. Pliocene
M. Messinian
M. Tortonian
L. Serravallian
L. Burdigalian
L. Acquitanian
M. Oligocene
L. Eocene
T Translation episode
E Extension episode
P Transpression episode
C Compression phase
3x2 Ma episodes

nines (Campania province) and Sicily (Etna), and calc-alkaline volcanism of the Eolian ring. The products of the back-arc region show a calc-alkaline mix, with an anomalous wide compositional variation, which can best be explained by the addition of fluids from metasomatism of the subducted oceanic slab (Barberi et al., 1973,1974; Beccaluva et al., 1982; Savelli, 1988; Serri, 1990). It was hypothesized (Beccaluva et al., 1982,1989; Mantovani et al., 1985,1990 and Savelli, 1988) that this process may be explained by deformation (e.g. downbending, torsion, segmentation, lateral stretching) and/or passive sinking into the asthenosphere of a fragment of the ruptured subducted slab (cf. Ritsema, 1972).

Tyrrhenian oceanization and subsidence. The available information regarding the Tyrrhenian back-arc basin (ODP Leg 107; Kastens et al., 1987,1990; Van Dijk, 1992,1993) shows that the spreading of the Marsili Basin occured during Late Pliocene times. At the end of the Pliocene, the spreading ceased and the basaltic ocean floor was covered by Late Pliocene pelagic muds. The whole Tyrrhenian basin collapsed at the Plio–Pleistocene transition showing a pattern of accelerating subsidence. The Early Pleistocene was characterized by stagnation of subsidence and possibly even a slight uplift in the central Tyrrhenian Vavilov Basin. In the Late Pleistocene–Recent episode, a second phase of accelerated subsidence and collapse has occurred, and the basin subsided to the present-day basement depth of about 4 km.

Calabrian Basins. Data regarding the basin evolution in the Calabrian Arc are the following: Late Pliocene and Early Pleistocene successions show normal subsidence patterns and fluctuating open marine conditions. At the Pliocene–Pleistocene transition, the occurence of hiatussus, influx of clastic material and local rapid shallowing sequences indicate a relative sea level fall. This was followed by an Early Pleistocene relative rise. The middle Pleistocene to Recent episode is characterized by rapid accelerating uplift of deposits of Calabrian and even younger age (Birot, 1939,1980; Pannekoek, 1969; Demangeot, 1972; Brogan et al., 1975; Boenzi and Palmentola, 1975; Ergenzinger et al., 1978; Ghisetti and Vezzani, 1982a,b; Cosentino et al., 1989). Uplift rates in the southern Apennines, Calabria and Sicily amount up to 0.1–0.5 cm/yr, and Plio–Pleistocene erosion surfaces can nowadays be found at heights of up to 1500 m. The rapid uplifts occur from Palermo in the southwest all along the Calabrian Arc up to Naples in the north. The highest rates are documented in the Aspromonte–Peloritani area and along the Sila Piccola–Monte Pollino areas (in Calabria). In the southeastern Tyrrhenian, middle Pleistocene inversion phenomena have been documented in summit basins (Argnani and Trincardi, 1990), while in the forearc areas huge submarine slides have occurred, associated with or shortly following compressive overthrusting [Gela Nappe (GTH) and Metaponto Nappe (MTH); Beneo, 1957; Ogniben, 1960; Ogniben, 1969; Finetti and Morelli, 1973; Argnani,

Fig. 5. Hypothetical palinspastic reconstruction for the Early Pleistocene Central Mediterranean, and deformation pattern of the middle Pleistocene–Recent episode. See for legend Fig. 1. The small inset in the lower right corner shows a cartoon of the depicted deformation. The main blocks are outlined. Note that boundaries of the main blocks compare reasonably well with those predicted by Rapolla (1986) and Fedi and Rapolla (1988,1990) on the basis of aeromagnetic anomalies. The deformation of the eastern area, the Dinarides, Albanides and Hellenides, has not been worked-out. The depicted shortenings are a consequence of the model and were probably distributed in this whole area. E–W faults within the Apulian block are known from Finetti (1982), Funiciello et al. (1988), Ortolani and Pagliuca (1988) and Lavecchia (1988). Within the Calabrian block, sinistral shear along NW–SE trending shear zones and transtension along a symmetrical radial set of Fault Zones accounts for the internal deformation of the area. Internal backshear motion within the southern Tyrrhenian back-arc area, as postulated by various authors (Van Dijk and Okkes, 1988,1990; Argnani and Trincardi, 1990) is also described by the model. The sinistral shear along NE–SW faults within Calabrian Accretionary Wedge which is a consequence of our model, has been hypothesized by Fabbri et al. (1982), Boccaletti et al. (1984) and Westaway (1990). The deformation of the Ionian Basin consists of an increased rotation towards the northeast, and a rotational tension (sphenochasmic opening sensu Fabbri et al., 1982; Mantovani et al., 1985,1990; Gresta et al., 1990). The deformation is governed by small displacements along a radial set of Fault Zones in the area of the present-day Apulian Escarpment, of which the Otranto–Scutari–Pec Fault Zone is the northermost one.


GEODYNAMIC EPISODES
INTER-PLATE STRESS
Compressive
RESTABILIZATION EPISODE
Extensional Collapse
Back-arc Collapse
Arc Uplift
Thrust-wedge Spreading
Blob Detachment
Elastic Snap-back
Slab Rupture
Stress Release
CONTRACTION EPISODE
Stress Build-up
Stagnation of Subsidence
Locking-up of Tension
Back-arc Collapse
Slab Downbending
Stress Increase
ARC MIGRATION EPISODE
Arc Migration
Passive Subduction
Hinge-zone Roll-back
Drifting of Calabria
Back-arc Spreading
Inter-plate Tension
(This Paper)
KINEMATICS
Concentric Extensional Faulting
Dextral Transpression
CONTRACTIONS
ROTATIONS
THRUSTING
Concentric Extension
Philip (1987)
Patacca & Scandone (1990)
(This Paper)
DEPOSITIONAL SEQUENCES
Fore-arc Basins
CALABRIAN
Summit Basin
PAOLA
Gela Trough
SICILIAN
Various Terraces
Pl-4
Upper seismic Unit
Contraction-Inversion
Pancilina
Regressions
Pl-3
Lower seismic Unit
Lower Pleistocene sequence
Gela Nappe thrusting
Truppi Pelagic Marls
Van Dijk (1990)
Argnani & Trincardi (1990)
Pedley & Grasso (1991)
BASIN DEVELOPMENT
SUBSIDENCE–UPLIFT PATTERNS
Calabrian Arc Uplift
+2 +1 −1 −2 +0 −3 −4
Tyrrhenian Subsidence
ACCELERATING SUBSIDENCE
DECELERATION OF SUBSIDENCE
COLLAPSE
MARSILI BASIN RIFTING
DIFFERENTIATED UPLIFT
Marsili
Tyrrhenian
Milazzian
Sicilian
Calabrian
Composite (G&V, 1982)
Vavilov
Magnaghi
Major late Early Pleistocene Regression
Condensed sequences within intra-arc basins
Calabrian Transgression
Late Pliocene Regression
Brogan et al. (1975)
Bonnzi & Palmentola (1975)
Engenzinger et al. (1978)
Blint (1981)
Ghisetti & Vezzani (1982)
Cosentino et al (1989)
Van Dijk (1993)
VOLCANIC–MAGMATIC ACTIVITY
EPISODES (Cf. SAVELLI)
Number of eruptive phases
SARDINIAN BLOCK
Logudoro Quirra
NORTHERN TYRRHENIAN
INTERNAL TUSCAN
EXTERNAL ROMAN
S. TYRRHENIAN BASIN
Magnaghi
Vavilov
Marsili
CENTRAL RIDGE
Anchise
Adamo
Alicudi
Lisca
CAMPANIAN PROVINCE
EOLIAN RING
INTRA-CHAIN
Ebro
Vulture
IBLEAN BLOCK
Foreland
Collapse-related System
Calc-alkaline
Tracchitic
Na-alkalic
Calcalk.
Perpotassic
Alkali-basaltic
Acid; crustal anatectic
Subduction system
Calc-alkaline
K-Calc-alkaline
Alkali-basaltic
QUIESCENCE EPISODE
FIFTH EPISODE
FOURTH EPISODE
THIRD EPISODE
Compiled after: Savelli (1984) Locardi (1986) Savelli (1988) Santoni (1990) Serri (1990)
TIME SCALE
0 0.5 1.0 1.5 2.0 2.5 3.0
CHRONO STRATIGRAPHY
LATE PLEISTOCENE
MIDDLE PLEISTOCENE
EARLY PLEISTOCENE
LATE PLIOCENE
Vargilian
Tyrrhenian
Milazzian
Sicilian
Emilian
Calabrian
Crotonian
Continental
Sicilian
Emilian
MAGNETOSTRAT.
MATUYAMA
Jaramillo
small Gephyrocapsa
Olduvai
MATUYAMA
Reunion
Gauss
BIO STRATIGRAPHY
Globorotalia truncatulinoides exelsa
Globigerina cariacoensis
MPL 6
Globorotalia inflata
MPL 6
Compiled after: Berggren et al. (1985) Zijderveld et al. (1991)

1987; Trincardi and Argnani, 1990]. Van Dijk (1990,1992,1994) discussed the origin of these slabs in the light of restabilization tectonics of an oversteepened thrust wedge.

Structural data. The combination of stratigraphic and tectonic analyses of meso- and microstructures (Bousquet, 1972,1973; Philip and Tortorici, 1980; Tortorici, 1981; Gars, 1983; Moussat, 1983; Auroux, 1984; Barrier, 1984; Chabellard, 1984; Ghisetti, 1984; Auroux et al., 1987; Bousquet and Lanzafame, 1986; Bousquet et al., 1987; Barrier et al., 1987; Philip, 1987; Hippolyte, 1992) has revealed that the Late Pliocene–Recent evolution of the Calabrian Arc can be subdivided in three episodes: Late Pliocene–Early Pleistocene, middle Pleistocene, and Late Pleistocene–Recent.

The Late Pliocene–Early Pleistocene episode was characterized by extensional structures which rotated with the curvature of the arc; the direction of maximum extension was perpendicular to the convergence of the arc (Philip, 1987). This can be interpreted as the reflection of a migration of the arc and accompanied opening by spreading of the Tyrrhenian back-arc Basin. Extension within the Apennines and absence of thrust-wedge contraction during arc migration can be explained as a restabilization phenomenon while underthrusting/underplating occurs below the accretionary wedge (Van Dijk, 1990, 1992,1994). The transition from underplating of the Apulian platfrom below the southern Apennines to the development of an imbricate duplex structure below the southern Apennines which also dissected the already underthrusted Apulian Platform carbonates (Bousquet, 1973) was hypothesized by Cello et al. (1990) on the basis of an extrapolation of similar structures in the central Apennines (Cello et al., 1987), and a reinterpretation of regional seismic sections presented by Mostardini and Merlini (1988) (Inner Apulian Belt of Cello et al., 1990; see also the discussion in Patacca et al., 1992). Considering the southeastward nature of the displacement of the arc, common sense tells that these structures were transpressive and probably showed transtensive tectonics near the surface along the Tyrrhenian side (perityrrhenian summit basins and intra-arc basins), and transpressive tectonics along the external side of the arc (the opening of the S. Arcangelo Basin as extensively described by Hippolyte, 1992 was, therefore, probably related to transpressive tectonics). The first pulses of uplift registered in the Upper Pliocene–Lower Pleistocene sequences may thus be related to a deep-seeted start of accretion.

Contraction phenomena are documented in the Lower Pleistocene successions which indicate that a major compressional phase took place in mid-Pleistocene times, very well constrained between 1.0 Ma and 0.7 Ma (Selli, 1962; Roda, 1964; Bousquet, 1972,1973; Philip and Tortorici, 1980; Auroux, 1984; Bousquet and Philip, 1986). During this phase a number of reverse faults and folds were (re)activated within the Bradano trough, the southern Apennines thrust-belt and along the NW–SE trending *Pollino Fault Zone (11)* (Bousquet, 1972; Moussat, 1983; Auroux et al., 1987; Ghisetti and Vezzani, 1982a,b; Ghisetti, 1984). The general axis of compression as deduced from microtectonic analysis is directed (N)NE–(S)SW. This was confirmed by magnetic fabric analysis (Scheepers and Langereis, in press.). Recent studies in the northern Apennines revealed that in that area, pulses of NE–SW compression have also occurred during the middle Pleistocene, followed by NW–SE extension (Boccaletti et al., 1987b; Martelli et al., 1989;

Fig. 6. Temporal relations for various geodynamic features in the Pleistocene Central Mediterranean. Note that the volcanic edifices in the Tyrrhenian area become active after the main spreading stages. This initially led to some confusion about the timing of back arc spreading, which, as some authors claimed, seemed to be younger. Note the first short episode following the quiescence episode, which we indicated separately. This can be interpreted as the start of extensional rupturing along various Fault Zones, ringing in the contractional phase. The basin development schemes are relatively inaccurate because they are based on seismostratigraphy or linked to biozonations, and, therefore, they are outlined with oblique lines. The arrows in the column for depositional sequences indicate the timing of major transgressions.

Bettini et al., 1990). Ambrosetti et al. (1983) showed a relatively modest post–Late Pliocene displacement of the Apennines thrust sheets towards the external side of about 10–15 km. Part of the contractional movement may have been taken up by out-of-sequence thrusting by accentuation of the aforementioned deep thrust stack, testified by the uplift of the central axis of the southern Apennines which already started during the Early Pleistocene (Bousquet, 1972; see Cello et al., 1990 and Patacca et al., 1992). The characteristics of the Late Pleistocene–Recent episode are mainly derived from seismotectonic analyses described below.

Seismicity. Present-day seismicity shows that no active subduction is taking place (McKenzie, 1972; Gasparini et al., 1982; Giardimi and Velona, 1991). Two types of seismicity occur: The first are

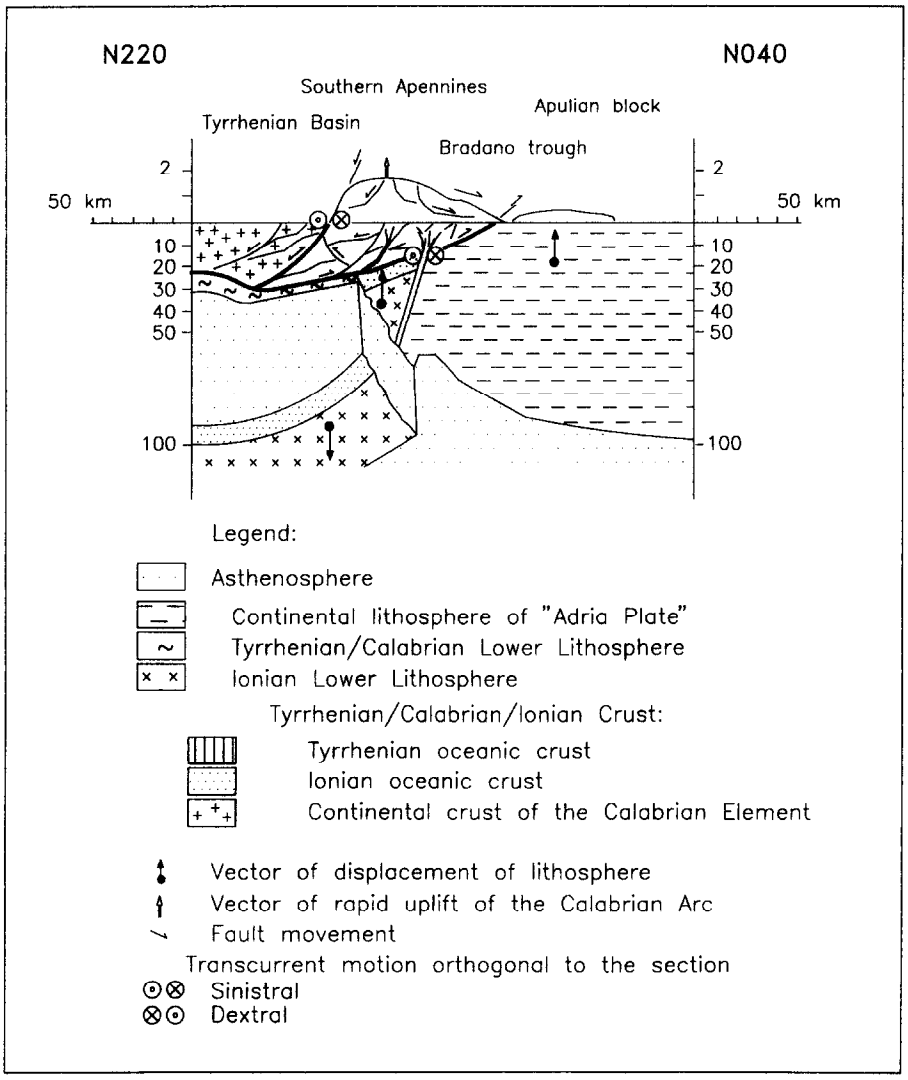


Fig. 7. Model for the relation between slab rupture and tensional faulting in the Calabrian Arc in the post-middle Pleistocene after Van Dijk and Okkes (1988,1990,1991). Geological section modified after Mostardini and Merlini (1988), Cello et al. (1990), Van Dijk and Okkes (1990,1991) and Roure et al. (1991). Note the vertical exaggeration of the section above sea level.

deep shocks down to a depth of 450 km (Peterschmitt, 1956; Caputo et al., 1970,1972; Ritsema, 1972,1979; Papazachos, 1973; Gasparini et al., 1982; Anderson and Jackson, 1987b), which can be linked to the active deformation of remnants of the subducted slab, which may be bended (Mantovani et al., 1985) and ruptured and detached (Ritsema, 1972; Giese and Morelli, 1978; Spakman, 1988). The pattern of shallow seismicity in the back-arc region indicates that it is linked to a vertical collapse, governed by concentric and radial fault patterns (Wezel, 1985). The shallow seismicity shows the following features (Ritsema, 1969; Riuscetti and Schick, 1975; Schick, 1978; Barbano et al., 1978; Westaway, 1991): In Calabria, three types of shallow stress release occur: NW–SE tension, NE–SW compression and E–W sinistral faulting. The southern Apennines show NE–SW tension, and Sicily is dominated by N–S directed compression. E–W dextral trancurrent faulting dominates the North African area. Three basic patterns arise from this activity: Concentric tension around the arc, NE–SW compression and related E–W transcurrent sinistral motions, and dextral shear along the E–W north-African and WNW–ESE Tunesia–Libya boundary zones.

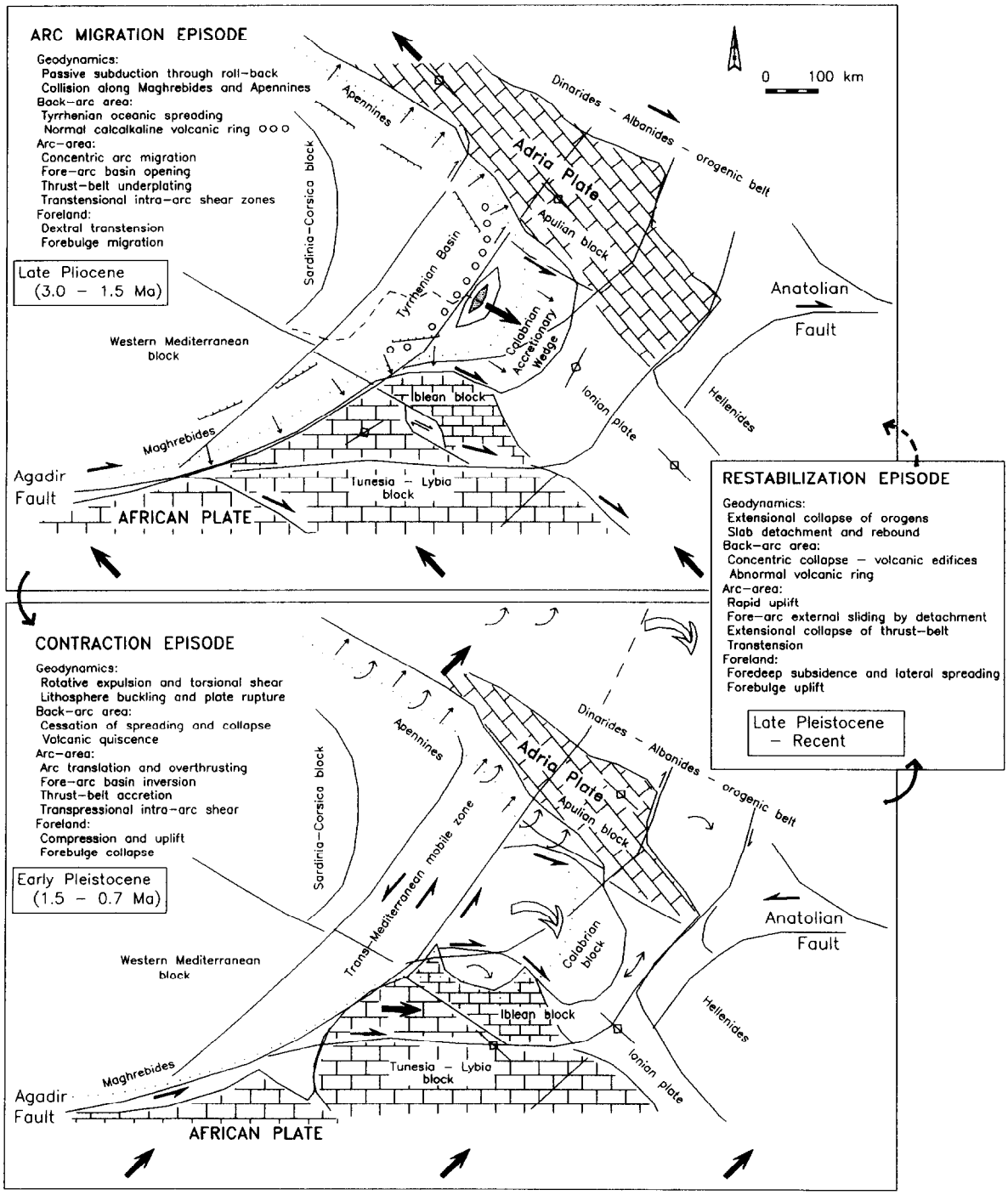
The patterns of Present seismicity in the southern Apennines point to active normal faulting along a NW–SE trending Fault Zone which follows the about 1300 m high mountain crest (Westaway and Jackson, 1984,1987; Westaway, 1987; Boschi et al., 1990; Funiciello et al., 1990). The character of Pleistocene–Holocene tensional faulting shows downfaulting to the northeast (Campania and Basilicata earthquakes of 1962 and 1980; Westaway and Jackson, op. cit.) and to the southwest (Roure et al., 1991). The hinge zone of this tension follows the above-mentioned recently active fault scarp. It coincides with the sudden transition from continental crust with a double Moho reflector to oceanic crust, which is concentric around the arc, also recognizable in gravity anomaly patterns (e.g. Geist et al., 1988). This zone was interpreted as a contractional, "deep shear zone" by Ghisetti and Vezzani (1982a,b), and as the extensional scar of the torn slab by Patacca and Scandone (1989) following Spakman (1988) (see also Wortel and Spakman, 1992). Following the proposal of Van Dijk and Okkes (1988,1990,1991), however, this hinge line is the surface expression of the scar of a rebouncing non-detached lithosphere remnant (Fig. 7). The tensional listric faulting can be regarded as a restabilization or collapse phenomenon, accommodating for an oversteepening of the thrust wedge.

4.4. Geodynamic mechanisms

Before introducing a geodynamic scenario to integrate all the individual spatial and temporal kinematic elements, a few remarks must be made concerning geodynamic mechanisms proposed in literature. The following remarks are based upon the extensive reviews of Van Dijk and Okkes (1990,1991) and Van Dijk (1992):

Arc Migration. Although various authors place emphasis on different processes, it is generally agreed upon in literature that the arc migration process was driven by a combination of two mechanisms: passive subduction due to gravitational sinking of the relict Ionian oceanic lithosphere slab and related roll-back and retreat of the subduction hinge zone (Van Bemmelen, 1972; Ritsema, 1979; Horvath et al., 1981; Moussat, 1983; Malinverno and Ryan, 1984; Van Dijk and Okkes, 1988,1990; Patacca and Scandone, 1989; De Jonge and Wortel, 1990; Royden, 1993), and asthenosphere inflow, upwelling and convection in the back-arc region (Van Bemmelen, 1969; Locardi, 1986; Van Dijk and Okkes, 1988,1990; 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; Van Dijk and Okkes, 1988,1991; Wang et al., 1989).

NW–SE compression. NW–SE compression and the subsequent deformations (cf. Caire, 1962,1964; see further) were considered as the principle driving force in the central Mediterranean geodynamics by Mantovani et al. (1985, 1992) and succesfully modelled by Kruse and Royden (1994). In our work, however, we hypothesized that these phenomena were linked to spe-


ARC MIGRATION EPISODE
Geodynamics:
Passive subduction through roll-back
Collision along Maghrebides and Apennines
Back-arc area:
Tyrrhenian oceanic spreading
Normal calcalkaline volcanic ring
Arc-area:
Concentric arc migration
Fore-arc basin opening
Thrust-belt underplating
Transtensional intra-arc shear zones
Foreland:
Dextral transtension
Forebulge migration
Late Pliocene
(3.0 – 1.5 Ma)
0 100 km
Apennines
Dinarides – Albanides – orogenic belt
Adria Plate
Apulian block
Sardinia-Corsica block
Tyrrhenian Basin
Calabrian Accretionary Wedge
Anatolian Fault
Western Mediterranean block
Iblean block
Ionian plate
Hellenides
Maghrebides
Agadir Fault
Tunesia – Lybia block
AFRICAN PLATE
RESTABILIZATION EPISODE
Geodynamics:
Extensional collapse of orogens
Slab detachment and rebound
Back-arc area:
Concentric collapse – volcanic edifices
Abnormal volcanic ring
Arc-area:
Rapid uplift
Fore-arc external sliding by detachment
Extensional collapse of thrust-belt
Transtension
Foreland:
Foredeep subsidence and lateral spreading
Forebulge uplift
Late Pleistocene
– Recent
CONTRACTION EPISODE
Geodynamics:
Rotative expulsion and torsional shear
Lithosphere buckling and plate rupture
Back-arc area:
Cessation of spreading and collapse
Volcanic quiescence
Arc-area:
Arc translation and overthrusting
Fore-arc basin inversion
Thrust-belt accretion
Transpressional intra-arc shear
Foreland:
Compression and uplift
Forebulge collapse
Early Pleistocene
(1.5 – 0.7 Ma)
Apennines
Dinarides – Albanides – orogenic belt
Adria Plate
Apulian block
Sardinia-Corsica block
Trans-Mediterranean mobile zone
Calabrian block
Anatolian Fault
Western Mediterranean block
Iblean block
Hellenides
Ionian plate
Maghrebides
Tunesia – Lybia block
Agadir Fault
AFRICAN PLATE

cific phases (Van Dijk and Okkes, 1990,1991) interrupting the arc migration process. Consequence of this interplate stress were downwarping or flexural downbending of the subducted slab (lithosphere buckling) below the back-arc basin, and upwarping of the flexural bulge along the subduction hinge zone. The origin of this component of the interplate stress field may be sought in a NE directed relative movement of the African Plate (Mantovani et al., op. cit.; Van Dijk and Okkes, 1988,1991). The driving force may be sought in Atlantic spreading, slab pull along Mediterranean subduction zones, mantle convection flow, or even in global deformational processes (see for a review Van Dijk, 1992). It should, however, be born in mind that the existence of the stress field itself does not provide any exclusive evidence for neither of these hypotheses.

Slab detachment. The presence of a (partly) detached slab below the Calabrian Arc was deduced from seismicity patterns by Ritsema (1972), and confermed by Spakman (1988). Possible consequences of slab rupture and detachment in terms of vertical motions were speculated upon by Giese and Görler (1978), Spakman (1988), Van Dijk and Okkes (1988,1991) and Wortel and Spakman (1992). Van Dijk and Okkes (1990,1991) claimed to be able to give a timing for the slab detachment, placing it in the middle Pleistocene. They speculated upon previous slab detachments during Late Eocene, Early Miocene and middle Pliocene phases, all triggerred by interplate compressive events during phases of switching from regional extensional to compressional stress. They also proposed a link between extensional collapse of the back arc basin due to sinking into the mantle of the detached lithosphere remnant or "blob", and of the thrust wedge as a consequence of rapid isostatic adjustments related to elastic rebouncing (or "snap-back" in an opposite sense to as the term was introduced by Cathles and Hallam, 1991) of non-detached lithosphere remnants. Furthermore, they proposed that the lithosphere rupture and split may have led and may lead to subduction polarity reversals. These new hypotheses have gained a wide acceptence during the last decennium and many authors provided extra support from seismological studies (Luongo et al., 1991; Milano et al., 1994), field data sets (Cinque et al., 1993; Hippolyte et al., 1994), and tectonophysical forward modeling (Kruse and Royden, 1994).

4.5. A geodynamic scenario

Altogether, the most recent major block rotations appear to be confined to distinct phases in the middle Pliocene and middle Pleistocene. Both phases show an oroclinal bending of the arc, with an axis within the Calabrian block and along the Pollino Fault Zone, respectively (suggesting a shifting to the northeast). Both phases are related to cessation of Tyrrhenian spreading and a jump of the spreading axis to the southeast. To integrate all the individual spatial and temporal kinematic elements discussed above into one model, we propose a geodynamic scenario which consists of the following three episodes (Figs. 6 and 8):

Fig. 8. Schematic kinematic reconstruction of the Late Pliocene – Recent evolution of the Central Mediterranean. The model is based on considerations discussed in Van Dijk and Okkes (1988,1990,1991) and Van Dijk (1992). It shows affinity with various aspects of proposals of Caire (1979), Rehault et al. (1984), Mantovani et al. (1985,1992) and Dewey et al. (1989). Transpressive dextral displacements along the Agadir Fault Zone (cf. De Sitter, 1956; Rod, 1962; Weijermars, 1987,1993; Ferrari and Tibaldi, 1992) and the Anatolian Fault Zone (Ketin, 1948; Pavoni, 1961a) play a key role during the arc migration episodes. Note the transtensional movements along the NW–SE trending Barcelona–Cairo Fault Zone within the Sicily Strait area (Van Dijk and Okkes, 1990; Van Dijk, 1992; see also inset of Fig. 1), another long-lived fundamental fault zone which may find its southeastern extension across the Sinai in the Najd Fault System (cf. Brown and Jackson, 1960; Moore, 1979; Stern, 1985) within the Arabian Shield. The Albanide–Hellenide and Carpathian rotation patterns (see e.g. Marton, 1987; Speranza et al., 1982) did not necessary originate during the middle Pleistocene. They are depicted for comparison and in order to show the symmetry which exists along the "Trans-Mediterranean Mobile Zone". The dashed lines shows the displacement path of Calabria from Early Miocene onwards, due to alternations of arc migration and contraction episodes. The Recent restabilization episode seems to be at the transition from the Early Pleistocene contraction episode to a possible future migration episode with arc displacement to the SSE.

The Late Pliocene *arc migration episode* was characterized by migration of the Calabrian Arc to the southeast with the drifting of the Calabrian block, and accompanied opening (by spreading) of the southeastern Tyrrhenian Marsili Basin. These processes were probably associated with large-scale underplating of partly rootless thrust sheets.They were (surprisingly) not accompanied by any oroclinal-type of rotation, as previously assumed by various authors (the Radial Drift and Translation Models in Fig. 2). The absense of rotations may be explained as follows: The arc migration episode was characterized by an overall stable NW–SE inter-plate stress, with no compressive stress component orthogonal to the arc, which may have favoured a "free sliding" along the margins of the arc. For the same reason, the Pendulum Models can also be excluded as a satisfactory explanation of the tectonic rotations.

The Early Pleistocene *contraction episode* started at the Pliocene–Pleistocene transition, with the onset of regional inter-plate compressive stress, probably as a result of an increasing of the approaching velocity and/or a change in relative direction of the African and European Plates. This initially resulted in a phase of accretion in the Apennines. The compression also led to a cessation of spreading in the back-arc basin, and, possibly, an onset of flexural downbending of the subducted slab (lithosphere buckling), shown by the acceleration of subsidence in the back-arc basin. The compressive stress state may initially also have led to an episode of quiescence in volcanic activity by the locking-up of tensional features. Furthermore, uplift of the thrust belt and foreland basin areas may be expected due to an accentuation of the upwarping of the flexural bulge along the subduction hinge zone. The continuation of the inter-plate stress increase culminated in the regional middle Pleistocene contraction phase. During this relatively short phase oroclinal-type of block rotations, transpression along major shear zones and basin inversions along the internal as well as the external side of the Calabrian Arc accomodated the contraction in the Central Mediterranean. We hypothesize that the major phase of contraction resulted in a rupturing of the stressed slab (lithosphere split) and, thus, a sudden, explosive release and, consequently, relaxation of compressive stress.

During the Late Pleistocene to Recent *restablization episode*, detached remnants of the ruptured slab started to sink into the asthenosphere, whereas non-detached remnants rapidly unbended and elastically bounced upwards. As a result of these processes, extensional phenomena related to isostatic restabilisations occurred (Fig. 6). Rapid uplift of the non-volcanic arc, concentric collapse of the back-arc basin, and extensional faulting along both sides of the hinge zone above the lithosphere rupture scar reflect this process. The pattern of tensional faulting mirrors an extensional collapse of the oversteepened Apenninic thrust wedge. Compressional phenomena continued to dominate in Sicily, probably related to a dextral transpressive regime along the north African Plate boundary, as evident from present-day seismicity, possibly reflecting a renewed installation of a stable NW–SE directed regional interplate stress.

5. Discussion

The proposals in the present paper refer to a number of items which require a short discussion:

NE–SW compressive stress. The existence of a NE–SW directed compression was hypothesized for the first time by Caire (1962, 1964) on the basis of geological observations. A premise of this assumption is that the amount and the geometry of the overthrusting, observed along both sides of the Calabria Arc, can not be explained by simple lateral ramping related to southeastward migration of the Calabrian block (Van Dijk and Okkes, 1990). This is because restored cross-sections perpendicular to the strike of the orogen result in an overlap as was also observed by D'Argenio et al. (1980). The latter authors offered an alternative explanation for this overlap in the form of rotating thrust sheets on both sides of the arc (cf. Caire, 1970), called saloon-door mechanism by Van Dijk and Okkes (1990). The existence of NE–SW compression was also confirmed by seismo-tectonic analysis (Riuscetti and Schick, 1975; Schick, 1978; Barbano et al., 1978) and

microstructural analysis (e.g. Bousquet, 1972; Gars, 1983; Moussat, 1983). Early Tertiary and middle Pliocene reconstructed principle stress axes show an E–W trend (e.g. Dubois, 1976; Moussat, 1983). Corrected for Plio–Pleistocene clockwise rotations, these directions of compression would originally also have been NE–SW. Consequently correcting the strike of the main Calabrian transcurrent Fault Zones (N130–135; active during the Late Miocene–Early Pliocene) for the late rotations, these become near-parallel to the *Pollino Fault Zone* (N120).

Expulsion tectonics. The kinematic expulsion model used to explain the rotative movements during the contraction episode was introduced in geology by Gzovsky (1959) and Pavoni (1961b) and applied to the Central Mediterranean by Caire (1973). Later on, this model, advocated by Brunn (1976) and Tapponier (1977) in a more general context, was also applied by Moussat (1983), Van Dijk and Okkes (1988,1991) and Mantovani et al. (1992). In recent literature (see for an extensive review Van Dijk, 1992), some authors prefer this mechanism as the main driving force for the migration of the Calabrian Arc and the opening of the Tyrrhenian Basin (op. cit.), while others invoke slab pull as the main mechanism (see e.g. Malinverno and Ryan, 1984; Royden, 1993). In the present paper, we illustrate how the dominance of these mechanisms may have alternated in time (cf. Van Dijk and Okkes, 1991).

African Plate Motion. The NE–SW stress direction may be directly related to NE-directed motion of the African Plate (as sustained by Mantovani, 1982; Mantovani et al., 1992), or to microplate interactions through transcurrent motions. Van Dijk and Okkes (1988,1990,1991) and Van Dijk (1992,1993) developed a model in which two processes have alternated in time: southeastward drift of the Calabrian block and back-arc spreading during tension stages, and NE-ward translation and rotative extrusion towards the northeast of small blocks such as the Calabrian block during compression stages. On a larger scale, this alternation can be connected with an alternation of relative NW-ward (dextral) and NE-ward (sinistral) transpression between the African and European Plates related to (but not necessarily caused by) variations in relative spreading rate between the northern and the central Atlantic, as outlined by Van Dijk (1992; p. 248 and his fig. 2; see Fig. 4, right column). Thus, various episodes were dominated by specific geodynamic factors: arc migration through passive subduction, regional inter-plate compressive stress and rotative extrusion tectonics, and extensional collapse by slab rupture and detachment. The fact that rapid stress release seems to be associated with regional deformations and a switch in direction of relative motion of the African Plate, may provide a clue to a mechanism whereby the plate driving forces are considerably influenced by the dynamics along the Mediterranean subduction zones, as was also suggested by the geodynamic scenario of Van Dijk and Okkes (1990,1991), in which collisions of small continental fragments determined the timing of geodynamic cycles.

Pleistocene revolution. A Pleistocene global compressional phase was hypothesized by Van Dijk and Okkes (1988,1990) and Cloetingh et al. (1990). Following the concept of Bourcart (1962) of a "Pliocene revolution", we may speak of a "Pleistocene revolution", considering the important geodynamic implications of the mid-Pleistocene phase. Three of these episodes can be recognized in the latest stage of the evolution of the Central Mediterranean (see also Van Dijk, 1992): a Messinian (ca 5–6 Ma), a middle Pliocene (ca 4–3 Ma), and an Early Pleistocene (ca 2–1 Ma) "revolution". It must be noted that other authors indicated "Global Revolutionary Changes" during mid-Pleistocene times in other, much different branches of Earth Sciences such as major impact events (e.g. Glass, 1990). Suggestions do even exist for major changes in the evolutionary pattern of Man around 500 Ma (Leakey and Lewin, 1977, pp. 125–136) when the final antropological and cultural transition occurred from Homo erectus to Homo sapiens.

The Adria Plate. The consequences of the presented analysis and review for the rotational evolution of the Adria Plate are the following: The thrust-belt terranes of the southern Apennines have rotated in middle Pleistocene times, de-

tached from a continental area interconnecting Adria and African Plates, the Trans-Mediterranean Mobile Zone. Measurements in the thrust-belt, therefore, do not directly reflect rotations of an indepented Adria "microplate". At most, they contain a component of distortion of the Trans-Mediterranean zone, previous of the Neogene deformation, which may amount up to 15° counterclockwise. The decoupling between the African and Adria Plates is transmitted through a broad dextral transtensional zone within the Ionian Basin, and through dextral and sinistral transpressional motions along E–W to NE–SW trending transversal Fault Zones. Furthermore, it must be born in mind that the described horsetail set of E–W to NE–SW trending transcurrent Fault Zones may have provided the necessary decoupling of the Adria Plate from the African Plate during its independent rotation, and that original NW–SE trending Neotethyan rift margins may at present show an E–W trend.

Extensional collapse. Numerous papers that were issued during the last decennia proposed models incorporating extensional collapse of the Central Mediterranean thrust belts during the Kaenozoicum. These collapse models find their origin in Van Bemmelen's (e.g. 1972) orogenic mushrooming concepts (see discussion in Horvath et al., 1981). The extensional collapse models can esssentially be devided into three groups (Van Dijk, 1992; pp. 248–250): One group of models views the post-Eocene evolution of the Central Mediterranean as a gradual thick-skinned extensional collapse following the formation and overthickening of the Cretaceous–Late Eocene Alpine, partly collisional thrust wedge (cf. Horvath et al., 1981; Houseman et. al., 1981 and Dewey, 1988). The applicability of this model, which tries to explain the arc migration, was questioned by Sengör (1990, pp. 123, 126), who focussed on the problem of the formation of the back-arc basin. During the late eighties, models were proposed which incorporated episodes of large scaled extension of the thrust wedge deduced from the analysis of Middle Oligocene–Recent basin tectonics (Van Dijk and Okkes, 1988,1990,1991; Van Dijk, 1990,1991,1992,1994), inspired on dynamic thrust wedge models of developed in literature (Van Bemmelen, 1976; Davis et al., 1983; Platt, 1986; Dahlen, 1990). The applicability of these models were readily confermed by data from basement tectonics and fission tracks (Platt and Compagnoni, 1990; Thompson, 1994). This lead to the second group of models which views the thrust wedge collapse as a long post-contractional (post-collisional) episode of thrust wedge extension during still-stand of subduction (Wallis et al., 1993, Thompson, 1994 and many others), applied mainly to the Middle Oligocene–Early Miocene extensional episode (cf. Van Dijk and Okkes, 1988,1990,1991). We, however, prefer a third model which views 2 types of thrust wedge collapse: (1) The first type envisages a recurrent collapse phenomenon of a much shorter duration, immediately following third-order thrust wedge accretion pulses. We view the extensional episodes as related to passive subduction and rapid arc migration (altogether in a context of thick-skinned extension as envisaged by the first group of models which on a larger time scale could, of course, be viewed as a collapse of the Alpine orogen), during which short pulses of thrust wedge restabilization and collapse occured (Van Dijk, 1990,1992,1994) due to pulsating thrust wedge growth as a response to regional stress field fluctuations. (2) The "real" (second order and also of a short duration) extensional collapses might be related, as illustrated in the present paper, to rupturing of the detached slab, rapid rebouncing of non-detached remnants, and are probably accompanied by back-arc basin collapse (Early–Middle Oligocene, Early Miocene, early Late Pliocene and Late Pleistocene extensional collapses proposed by Van Dijk and Okkes, 1990, 1991).

6. Conclusions

Between 1.0 and 0.7 Ma ago, large-scale tectonic block rotations occurred in the Central Mediterranean, associated with contractional tectonics in the areas surrounding the Calabrian Arc. These phenomena were linked to the culmination and sudden release of inter-plate compressive stress, which had been built up during the Early Pleistocene contraction episode, as a result

of N- to NE-ward Europe–Africa collision. The total picture shows a cissor-like, rotative extrusion of the Calabro-Sicilian block around an axis located in the Etna–Messina Strait area. The block rotations accomodated for distribution of strain along a complex, free tectonic boundary along the southern margin of the Central Mediterranean. The phase of contractions and rotations was associated with rupture of the subducted oceanic slab, suggesting that this process was rapid, mechanical and temporally determined. The preceding Late Pliocene arc migration episode of back-arc spreading and southeastward arc migration was not associated with any oroclinal rotations. The third, Late Pleistocene–Recent restabilization episode was characterized by isostatic restabilization through extensional collapse of the area. This occurred in an overall dextral transpressive regime. The extensional collapse is manifested by rapid uplift of the non-volcanic arc above rebouncing non-detached lithosphere remnants and collapse of the Tyrrhenian back-arc basin.

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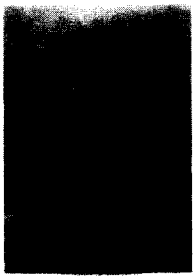

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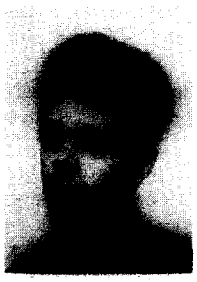

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