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No. 30

DETACHMENT TECTONICS IN THE CENTRAL APENNINES, ITALY

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STELLINGEN

Behorende bij het proefschrift:

"Detachment tectonics in the Central Apennines, Italy".

A. Koopman (1983)

1. Ricci Lucchi's correlatie van SE aangevoerde turbidietbanken, die voorkomen in verschillende tektonische compartimenten van de Noordelijke Apennijnen, met de door hem bij Gubbio beschreven Contessa gidslaag, is aanvechtbaar.

   Ricci Lucchi, F., 1981 - The Miocene marnoso - arenacea turbidites, Romagna and Umbria Apennines. Excursion Guide-book, 2nd Eur. Reg. Meeting, I.A.S., Bologna: 229-303.

2. Binnen de externe Noordelijke Apennijnen moet het op grond van overprint relaties onderscheiden en correleren van afzonderlijke deformatiefasen ten sterkste worden ontraden.

3. Een SW waartse subductie van de continentale Insubrisch - Apulische plaat onder een Corsicaans - Sardijnse plaat als verklaring voor de Oligocene - Neogene deformatie in de Apennijnen, is hoogst aanvechtbaar.

   Civetta, L., Orsi, G. & Scandone, P., 1978 - Eastwards migration of the Tuscan anatectic magmatism due to anticlockwise rotation of the Apennines. Nature 276: 604-605.

   Scandone, P., 1979 - Origin of the Tyrrhenian Sea and Calabrian Arc. Boll. Soc. Geol. It. 98: 27-34.

4. Bij het tekenen van een dwarsdoorsnede door de lithosfeer, in de orde van grootte van 2 platen, moet er rekening mee worden gehouden dat de aarde niet plat is; bovendien dient niet over het hoofd te worden gezien dat overhogen van zo'n profiel de helling van een subductie zone beinvloedt.

   Cloetingh, S., 1982 - Evolution of passive continental margins and initiation of subduction zones. Geol. Ultraiectina 29, fig. 1.1., p. 12.

5. Het gebruik van de term "anticrack" voor een drukoplossingsvlak verdient geen navolging.

   Fletcher, R.C. & Pollard, D.D., 1981 - Anticrack model for pressure solution surfaces. Geology 9: 419-424.

6. Kligfield's bewering dat "de Oligocene tot Recente flysch bekkens van Toscane en Umbrie in belangrijke mate ongedeformeerd zijn" is onjuist.

   Kligfield, R., 1979 - The Northern Apennines as a collisional orogen. Am. Journal of Science, 279: 676-691.

7. De methodieken die gebruikt worden bij het extrapoleren van geochronologische gegevens naar biostratigrafische events, zijn aanvechtbaar en leiden slechts tot schijnbare nauwkeurigheid.

Haq, B.U. - Jurassic to Recent nannofossil biochronology: an updata. Benmark volume of nannofossil biostratigraphy (in press).

Bukry, D., 1975 - Coccolith and sillicoflagellate stratigraphy, north - western Pacific Ocean, DSDP Leg 32. Init. Repts. DSDP, 32: 667-701.

8. Dezelfde auteurs die de Abruzzi nog steeds als autochthoon weergeven, beschikken over boorgegevens waaruit telkenmale verdubbelingen van het sedimentpakket blijkt.

Parotto, M. & Praturlon, A., 1975 - Geological summary of the Central Apennines. In: Structural Model of Italy. Quaderni de La Ricerca Scientifica 90: 257-311.

Parotto, M., 1980 - Apennin central. In: Introduction à la géologie générale d'Italie. 26e Congrès géologique international: 33-37.

9. De structuur van de Hercynische Ardennen wordt in sterke mate bepaald door décollement, en kan derhalve worden gekarakteriseerd als "thin-skinned".

10. Vooral door de inadequate hulpprogramma's van de Italiaanse overheid verworden relatief lichte, enkele seconden durende aardschokken in de Centrale Apennijnen tot jarenlang aanhoudende rampen voor de autochthone bevolking.

11. Het is aanbevelenswaardig de Monti Sibillini tot nationaal park te verklaren.

12. Gezien het feit dat ook in de toekomst de werkzaamheden van een geoloog grotendeels achter bureaus, computer terminals en op laboratoria zullen plaatsvinden moet een grote plaats voor geologisch veldwerk in het onderwijsprogramma gehandhaafd blijven.

13. Politieke partijen met tegenwind denken vooruit te komen door als laverende schepen tussen links en rechts overstag te gaan.

DETACHMENT TECTONICS IN THE CENTRAL APENNINES, ITALY

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN
DE WISKUNDE EN NATUURWETENSCHAPPEN AAN
DE RIJKSUNIVERSITEIT TE UTRECHT, OP GEZAG VAN
DE RECTOR MAGNIFICUS PROF. DR. O. J. DE JONG,
VOLGENS BESLUIT VAN HET COLLEGE VAN DECANEN
IN HET OPENBAAR TE VERDEDIGEN OP WOENSDAG
13 APRIL 1983 DES NAMIDDAGS TE 4.15 UUR

DOOR

ANTONY KOOPMAN

GEBOREN OP 28 MAART 1954 TE HOLTEN

1983
OFFSETDRUKKERIJ KANTERS B.V., ALBLASSERDAM

PROMOTOR: PROF. DR. E. TEN HAAF

Aan Marie-Anne en Annelies

Aan mijn ouders

CONTENTS

VOORWOORD

Bij de voltooiing van mijn proefschrift wil ik graag mijn dank zeggen aan allen, die gedurende mijn studiejaren aan de Rijksuniversiteit te Utrecht hebben bijgedragen tot mijn wetenschappelijke vorming, en aan de totstandkoming van mijn proefschrift.

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Mijn promotor, Prof.Dr. E. ten Haaf ben ik zeer erkentelijk: ik dank hem voor zijn positieve kritiek, die voor mij van het grootste belang is geweest. Zijn waardevolle suggesties en niet aflatende aanmoedigingen, zowel als zijn gave voor het geschreven woord hebben ertoe bijgedragen dat dit proefschrift tot stand kwam, en presentabel werd.

Dr. Kees van den Ende ben ik grote dank verschuldigd; voor zijn gezelschap gedurende een aantal tochten in het veld, en voor de introductie in de eerste jaars veldwerk gebieden in Umbrie en Marche, waar ik vier zomers onder zijn enthousiaste leiding veel kennis mocht opdoen van de geologie in dit deel van de Centrale Apennijnen. Ik hoop dat mijn proefschrift ook van nut blijkt te zijn bij het ontrafelen van de structuren in dit gebied.

Dr. Ton Romein bedank ik voor de vele discussies rond het kampvuur, op die wat winderige stek in Cagli, en voor het doornemen van het hoofdstuk Stratigrafie.

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Ik heb gebruik mogen maken van veldwerkgegevens uit doctoraal scripties van aangrenzende- en overlappende gebieden: beste Hans, Peter, Laurens, Martin, Eduard, e.a.: bedankt.

Magda Martens ben ik zeer erkentelijk voor het met veel geduld en grote voortvarendheid typen van het manuscript.

De teken- en fotokamer van het Instituut voor Aardwetenschappen dank ik voor de hulp bij het totstandkomen van een aantal figuren, en het afdrukken van de foto's.

Non mi e possibile menzionare, come vorrei, i tantissimi Italiani che meritano gratitudine da parte mia. Tante grazie per la vostra amicizia e ospitalità durante i miei soggiorni nell'Appennino. Di aver potuto conoscere la vita italiana, e la sua cucina casareccia, dimenticarò mai.

SAMENVATTING

Het sediment-pakket van het onderzochte gebied bestaat uit een dikke serie (Trias - Mioceen) van kalken en mergels, bekroond door de turbidiet-zandstenen van de "Laga Formatie" (Messinien - Vroeg Plioceen). Er is geen pre-Trias ondergrond ontsloten.

De meest opvallende struktuur is de Umbrische Overschuivingszone, deel uitmakende van de zogenaamde Ancona-Anzio lijn. Dit scheef verlopende lineament wordt gemeenlijk beschouwd als de grens tussen de Noordelijke en Zuidelijke Apennijnen, al is zijn duiding hevig omstreden.

Overschuiving en bijbehorende plooiing zijn echter niet beperkt tot de Umbrische Overschuivingszone: ze beslaan de gehele centrale Apennijnen. De overschuivingen zijn grotendeels geen scherpe vlakken maar doorbewogen zones, sterk onderhevig aan druk-oplossing. De schuifrichting, zichtbaar aan glijspiegels, was overal noordoostwaarts ongeacht de strekking van de afzonderlijke strukturen.

De tektoniek is "thin-skinned". Twee belangrijke décollements - een onderste in de ondergrond, aan de basis van het hele pakket, en een bovenste vlak onder de Laga Formatie - staan in verbinding via een reeks opstappen ("ramps") waar overschuivingen de tussengelegen serie opwaarts doorsnijden. Verdubbeling van lagen over deze opstappen heeft in het bovenblok grote anticlines veroorzaakt met ingewikkelde, disharmonische buitenflank. De opstappen zijn na elkaar gevormd, de binnenste (zuidwestelijke) het eerst. Het kromme en scheve verloop van vele bovenblok-anticlines, of veeleer van de ondergelegen opstappen, was voorgetekend door onregelmatigheden binnen het sediment-pakket, te wijten aan Jurassische bloktektoniek.

Door herhaalde verdubbelingen is het onderste deel van het pakket aanzienlijk ingekort. Doch deze verkorting heeft nauwelijks doorgewerkt op de Laga Formatie, die vrijwel uitsluitend tot het bovenblok behoort en als een samenhangend geheel is verplaatst. Aldus behoort het bestudeerde gebied, alsmede de aangrenzende Umbria-Marche Apennijnen en Abruzzi met inbegrip van de "Ancona-Anzio lijn", tot eenzelfde allochthoon overschuivingscomplex.

SUMMARY

The sedimentary cover of the investigated area consists of a thick sequence (Triassic-Miocene) of limestones and marls, overlain by turbiditic sandstones of the "Laga Formation" (Messinian- Early Pliocene). No pre-Triassic basement is exposed.

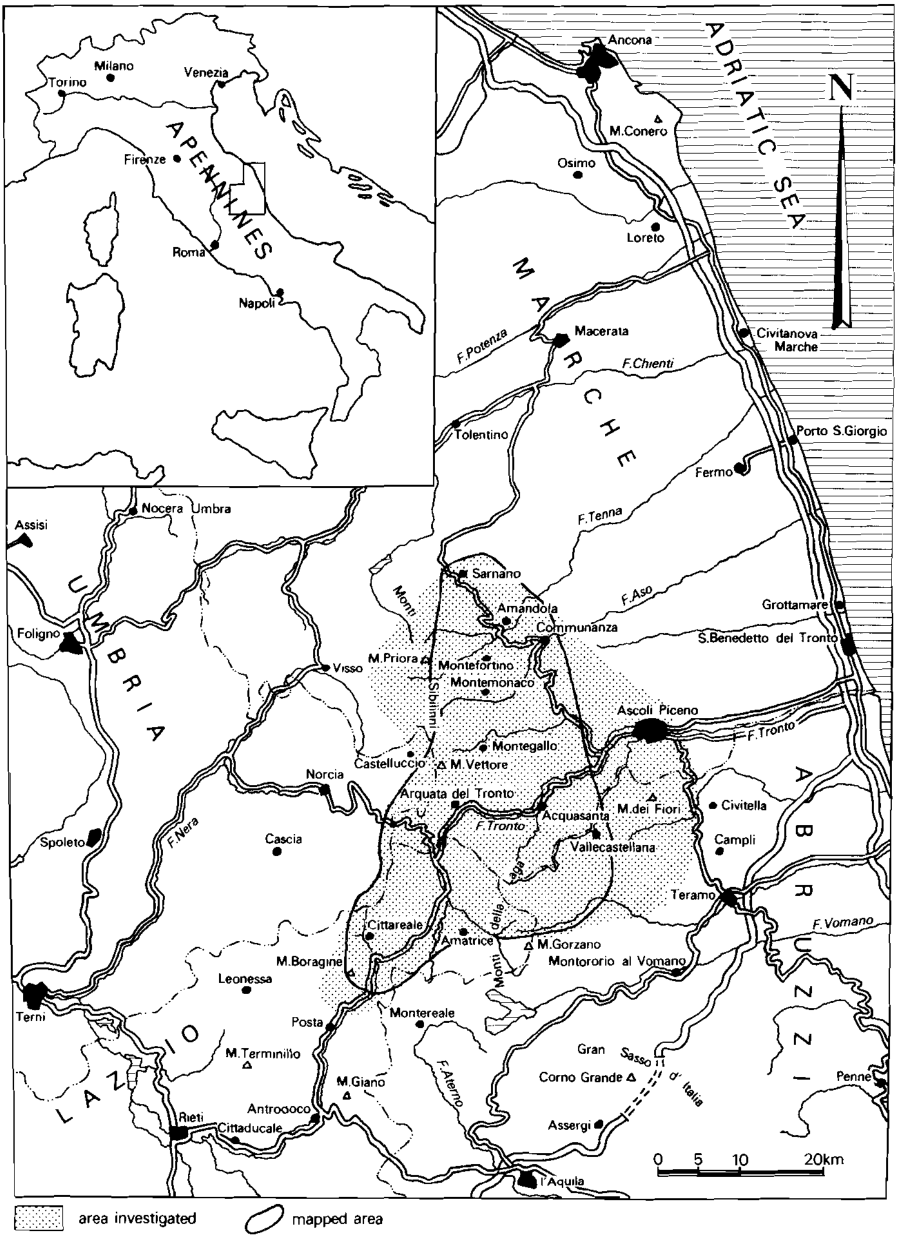
The most consipicuous structural feature is the Umbria Thrust Zone, a segment of the so-called Ancona-Anzio Line. This oblique lineament is generally taken as the boundary between the Northern and Southern Apennines, although its significance is highly controversial.

But thrusting and associated folding is not confined to the Umbria Thrust Zone: it prevails all over the Central Apennines. The thrusts are mostly not single planes, but pervasive deformation zones, strongly affected by pressure solution. Slip, as indicated by slickensides, was everywhere towards the NE, regardless of the strike of the various structures.

The style of deformation is "thin-skinned". Two major detachment levels - a lower, subsurface one at the base of the cover sequence, and a higher one just below the Laga Formation - are connected by a series of ramps where thrusts cut up-section. Doubling of strata above and beyond these ramps has resulted in large rootless anticlines with complicated, disharmonic forward limbs. The thrust steps developed successively, from the internal (SW) side outward. The arcuate and oblique trends of many rootless anticlines, or rather of the ramps below, have been controlled by pre-existing irregularities inside the sedimentary cover due to Jurassic block-faulting.

By repeated doublings, the lower part of the cover has been shortened considerably. But very little of this shortening has affected the Laga Formation, which belongs almost entirely to the hanging wall and has been displaced as a whole. Thus the investigated area, as well as the adjacent Umbria Marche Apennines and Abruzzi including the "Ancona-Anzio Line", belong to a single allochthonous thrust complex.

Fig. 1: Maps showing the location of the area investigated in the Central Apennines.



CHAPTER 1

INTRODUCTION

1.1. GENERAL

This thesis deals with the structural geology of an area in the central part of the Apennines (Italy). Fieldwork has been done during the summers of 1979, 1980 and 1981. The area, situated between Rieti and Ascoli Piceno (fig. 1) forms part of the regions Umbria (province of Perugia), Marche (province of Ascoli Piceno), Latium (province of Rieti) and Abruzzi (province of Teramo).

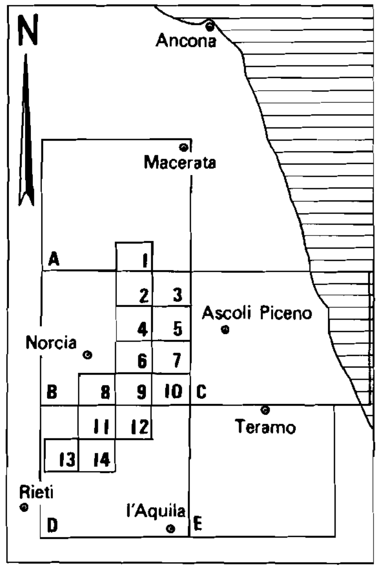
Most of the investigated area lies NE of the Apennine divide (at the Adriatic side of the peninsula), in the drainage areas of the Fiume Tronto, the Fiume Tenna and the Fiume Aso. Only the Southern part lies to the SW of the main divide, mainly in the upper reaches of the Fiume Velino.

The area covers part of two geomorphologically quite different mountain groups: the Monti Sibillini (mainly calcareous, with the M. Vettore (2476 m) rising about 1850 m above the level of the nearby Fiume Tronto), and the Monti della Laga (mainly terrigenous-clastic with the M. Gorzano (2458) as highest peak). In Pleistocene times especially the Monti Sibillini were modelled by glaciers; the U-shaped Valle del Lago di Pilato is surrounded by numerous cirques. Another prominent topographic feature is the Piano Grande di Castellucio, to the SW of the M. Vettore Massif: an intramontane former lake, without discharge, which lies about 600 m above the adjacent river valleys. (Fiume Tronto to the E and the upper reaches of the Fiume Nera to the W).

The main road in the area is the superstrada nr. 4 "Via Salaria", from Rome via Rieti and Ascoli Piceno to Porto d'Ascoli. It follows for the greater part the Roman Via Salaria. Other important roads are the nr. 396 across the Canapine mountain-pass to Norcia, and the nr. 78 from Ascoli Piceno to Amandola and Sarnano.

Fig. 2

1 : 25.000 topographic maps (1951 - 1955).



1 :	124 II SO	Sarnano
2 :	132 I NO	Bolognola
3 :	132 I NE	Amandola
4 :	132 I SO	Montemonaco
5 :	132 I SE	Montegallo
6 :	132 II NO	Arquata del Tronto
7 :	132 II NE	Acquasanta
8 :	132III SE	Ocrîcchio
9 :	132 II SO	Accũmoli
10 :	132 II SE	Pietralta
11 :	139 IV NE	Cittareale
12 :	139 I NO	Amatrice
13 :	139 IV SO	Leonessa
14 :	139 IV SE	Borbona

1 : 100.000 topographic maps (1955) and geological maps (resp. 1967, 1941, 1969, 1955 and 1963).

A :	124	Macerata
B :	132	Norcia
C :	133/134	Ascoli Piceno/Giulianova
D :	139	l'Aquila
E :	140	Teramo

The field study has included a structural analysis of the regional folds and thrusts, as well as the mesoscopic to small scale structures (mesoscopic folds, minor faults, cleavage, etc.). Conclusions are drawn on the significance of the various structures and their succession, including the relationship between processes of folding and thrusting. The regional structural development and deformation mechanisms are determined, and it will be discussed to what extent the tectono-stratigraphic units present in the area and the adjacent regions must be considered allochthonous.

A map and structural sections of the central part of the investigated area are presented in 2 separate enclosures.

Mapping was done on 1 - 25.000 topographic maps, issued by the "Istituto Geographico Militare" in Florence. Use was also made of 1 - 10.000 topographic maps obtained from the same institute. The sheets are listed on p. 16, together with the sheets of the "Servizio Geologico d'Italia" (Scale 1 - 100.000) that cover the area.

1.2. GEOLOGICAL SETTING

The Apennines mountain belt belongs to the Alpine System. During the paroxysm of the Alpine Orogeny deformation by folding and thrusting has developed progressively from the interior of the belt (in the SW, along the Tyrrhenian side of the Italian peninsula), outwards, to the external side, which faces the Adriatic Sea.

The tectonic movements started during the Late Cretaceous, and lasted till the present. By the internal compressional tectonics and consequent upwharping large scale thrusting was induced towards the NE, facilitated by gravity. Pre- to syn-orogenic sedimentation, in a series of NW - SE striking turbidite basins, became progressively younger towards the NE. These elongated zones of strong subsidence developed mainly in front of the advancing tectonic units, thus providing the slope for gravitational gliding of the sedimentary cover (Sestini, 1970; Dallan Nardi & Nardi, 1974; Reutter & Groscurth, 1978;

etc.). Corresponding with the SW - NE migration of folding and thrusting there is a decrease in intensity of deformation in the same direction.

Also the post-paroxysmal tensional faulting (related to the uplift of the orogene), and the associated magmatism along the Tyrrhenian coast have the same polarity in space and time, as the preceding orogenic events (Bortolotti & Passerini, 1970; Elter et al., 1975). Contemporaneously, at the external side, a strong subsidence of the basement beneath the Po plain and the Adriatic Sea (the Pedeapennine Zone) has led to last tangential movements until very recent.

Because of the general SW - NE polarity of the orogene a widely accepted and logical structural subdivision is longitudinal.

Another twofold division is commonly made into the Northern and the Southern Apennines. These are considered as orogenic subprovinces, each of which is characterized by distinctive topographic, stratigraphic and structural features. A NNE - SSW trending lineament, known in literature as the "Ancona - Anzio Line" cuts across the central part of the belt, and is regarded as the boundary between the Northern and Southern Apennines (Migliorini, 1950).

The area investigated is a folded and thrust-faulted terrain situated in a relatively external position, in what will be here referred to as the Central Apennines (Scarsella, 1964; Devoto & Praturlon, 1972; Pieri, 1966, 1975). It comprises the SE part of the Northern Apennines (mainly in Umbria and Marche), and the NW part of the Southern Apennines (the Laga Mountains Area, mainly in Latium and Abruzzi). Thus it contains a section of the "Ancona - Anzio Line": the Umbria Thrust Zone of the present paper (see chapter 3).

CHAPTER 2

STRATIGRAPHY

2.1. INTRODUCTION

The Central Apennines consist of deformed Mesozoic - Tertiary rocks of the Alpine sedimentary cycle, on top of a pre-Alpine basement.

The character of the basement in this part of the Apennines is not known. Only Martinis & Pieri (1964) describe a 100 m thick sequence of chloritic shales at the bottom of a well near Perugia (Umbria), which may be correlated with the basement exposed in the internal part of the belt (W. Tuscany). There, it consists of Hercynian metamorphic rocks, unconformably overlain by clastic sediments of Permian age (Verrucano s.l.; Abbate & Sagri, 1970; Azarro et al., 1976).

Generally speaking the sedimentary cover on top of this basement can be divided into mainly calcareous lower sequences of Mesozoic to Paleogene age, and on top of these mainly terrigenous-clastic sequences of Neogene Age (fig. 3).

2.1.a. MESOZOIC - PALEOGENE

All over the Central Apennines the basal part of the Alpine sedimentary cycle consists of the Late Triassic Burano Formation, characterized by anhydrites, marls, dolomites and dolomitic limestones. The unit cropps out extensively in W. Tuscany; in the Central Apennines and adjacent areas it is only known from several deep wells (Burano I, Fossombrone I and II, Perugia II; Antrodoco I, Trevi I, Foresta Umbria; see Martinis & Pieri, 1964; Pieri, 1966; Fancelli et al., 1966; Dondi et al., 1966). Dessau (1962) and Ghelardoni (1962) describe the top of the Burano Formation, exposed at M. Malbe, near Perugia; it consists

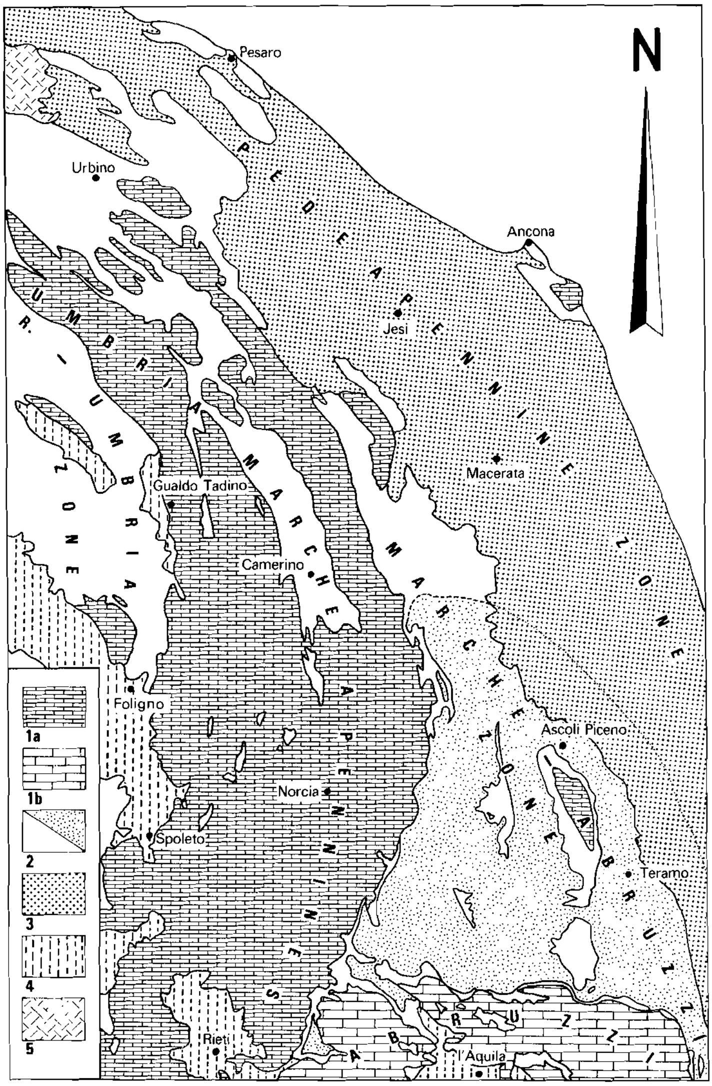


Fig 3: Simplified geological map of the Central Apennines.

Legend: 1. Mesozoic - Paleogene terrains: a. Umbria-Marche basinal Sequence; b. Latium-Abruzzi platform Sequence (including platform edge and transitional sequence); 2. Miocene terrains: only the Laga Formation is differentiated (dotted); 3. Pliocene - Quaternary sediments of the Pedeapennine Zone; 4. Pliocene - Quaternary post-orogenic sediments; 5. Liguride Complex.

of cavernous limestones and gypsum. The evaporitic facies is dominant in the Northern Apennines sequence, while in the Southern Apennines the Formation consists mainly of dolomites and limestones (Assereto, 1968; Crescenti et al., 1969; Castellarin et al., 1978). Martinis & Pieri (1964) give an average thickness of 1400 m, but due to tectonic deformation the thickness of the unit may be quite variable (see chapter 3).

The Burano Formation is followed by shallow water carbonates of Late Triassic to Early Liassic Age: the Castelmanfrino Formation of the Southern Apennines (Crescenti, 1969), and the Calcare Massiccio of the Northern Apennines (see p. 28). These units indicate a period of uniform subsidence balanced by massive carbonate sedimentation. Subsequently such shallow water conditions only persisted in limited areas, whereas in surrounding areas there was a change to pelagic facies. Therefore from the Jurassic onward, two sequences can be distinguished: a carbonate platform sequence in the Latium-Abruzzi Apennines (Jurassic - Paleogene), contrasting with a dominantly pelagic sequence in Umbria and Marche (Umbria-Marche sequence: Jurassic - Miocene).

The Latium-Abruzzi Sequence is exposed extensively to the S of the area investigated (fig. 3). The sequence consists mainly of shallow water dolomites and limestones, indicating a fore-reef to tidal flat environment of deposition. A bauxite horizon (Senonian) indicates a period of emersion of the platform. Environmental conditions show strong similarities with the present day Florida-Bahama carbonate platform (d'Argenio, 1970; Bernoulli, 1972; Bernoulli & Jenkyns, 1974).

The total thickness of this platform sequence may reach 3.5 km (Selli, 1957; Colacicchi, 1966; d'Argenio, 1966). Along most of the outer margin of the platform a Transitional Sequence is present towards the surrounding pelagic facies realm (Pieri, 1975). The position and width of this transitional zone show some variation through time; its characteristics are mainly described from the NE margin of the Abruzzi (Alberti et al., 1963; Zamparelli, 1964, 1966; Colacicchi, 1964, 1967; Colacicchi & Praturlon, 1965; Bernoulli, 1967; Crescenti et al., 1969; Praturlon & Sirna, 1976; Colacicchi et al., 1978; Castellarin et al., 1978). During the whole Mesozoic and Paleogene debris from the platform edge was discharged onto the platform slope and the adjacent basin. Some platform material was transported over large distances, by way of turbidity currents. At present a large part of this Transitional Sequence is covered by younger stratigraphic units (for example in the Laga Mountains Area), or by Neogene overthrusts.

The Umbria-Marche Sequence is mainly developed in a pelagic basinal facies, on top of its Triassic to Early Jurassic lower part of evaporites and shallow water carbonates (Burano Formation and Calcare Massiccio). Its most extensive area of outcrop is in a complex arcuate mountain chain, roughly between Urbino in the NW and Rieti in the S, which is generally considered as the outer part of the Northern Apennines (Fig. 3). This moutain chain will be called the Umbria Marche Apennines in the present paper (Scarsella, 1964; Parotto & Praturlon, 1975; it equals the "dorsale mesozoica umbromarchigiana" of Signorini, 1941; Merla, 1951 and Selli, 1954). The stratigraphy of the basinal sequence is remarkably constant over a wide area. Deposits with the same characteristics are present to the NE of the Abruzzi (in the Laga Mountains Area of the present paper; in the Molise Basin: Parotto & Praturlon, 1975), in Tuscany (see for example Dallan Nardi & Nardi, 1972) and also in the Southern Alps (Bernoulli & Jenkyns, 1974; Praturlon & Sirna, 1975).

In the Umbria Marche Apennines local differences in facies and thickness in the rocks of Jurassic Age are present. They were already known in the 19th centry (Canavari, 1891). In the last 15 years a large amount of studies has been published on this subject (Bernoulli, 1967;

Farinacci, 1967, 1970; Centamore et al., 1969, 1971, 1972; Colacicchi et al., 1970; Bernoulli & Jenkyns, 1974; Chiocchini et al., 1976). Three time-equivalent sub-sequences can be distinguished: the Complete (i.e. basinal) sub-sequence, the Condensed sub-sequence (highly reduced in thickness), and the Composite sub-sequence (partly condensed, and composed of units belonging to both the Complete- and Condensed sub-sequences). The areas of the Condensed and Composite sub-sequences are of relatively small extent; paleogeographically they represented fault-bounded isolated submarine highs, with a special type of sedimentation with respect to the much deeper surrounding basin. A more uniform development in the Umbria Marche basin began with Upper Jurassic Maiolica (see p. 34).

Mainly in the E and SE part of the Umbria Marche Apennines, i.e. towards the Latium-Abruzzi carbonate platform to the E of the Umbria Thrustzone, frequent intercalations of limestone turbidites and debris sheets were noted by several authors (Manfredini, 1966; Colacicchi et al., 1970; Parotto & Praturlon, 1975; Pieri, 1975; Chiocchini et al., 1976; Cantelli et al., 1978; Castellarin et al., 1978). They are most proximal towards the E and ESE (in the hanging wall units of the Umbria Thrustzone), and contain platform debris of Mesozoic Age. This evidences a paleogeographical relationship between the Latium-Abruzzi platform Sequence (situated in the present Southern Apennines) and the Umbria-Marche basinal Sequence (mainly in the Northern Apennines), despite the fact that a large part of the facies transition is superimposed by Alpine tectonics. Moreover, an original stratigraphic connection is proved by Carbone et al. (1971); they describe a Mesozoic platform succession and its transition towards the basin at Rocca di Cave in the Monti Prenestini (about 50 km to the N of Rome); this area is considered part of the Northern Apennines, to the W of the main structural lineament.

Towards the Adriatic Sea the lower calcareous sequence is only exposed in the basinal facies, in the isolated culmination of the

M. Conero (Ancona) (see fig. 3). Below the Adriatic Sea the character of the sequence is unknown, because it lies deeply burried under the thick Pliocene and Quaternary sediments of the Pedeapennine Zone. It may be present in platform facies, as the NW continuation of the Apulian Platform (Pieri, 1966; Celet, 1977; Wezel, 1979).

Paleogeographically, in Mesozoic times the Latium-Abruzzi Platform, the Apulian Platform and the Umbria-Marche basin belonged (together with the depositional areas of the Southern Alps, Dinarides and Hellenides) to the S continental margin of the Tethys (Argand, 1924; Aubouin, 1965; Bernoulli, 1967, 1972; Laubscher, 1971; Bosellini, 1973; Bernoulli & Jenkyns, 1974; Celet, 1977; Catalano et al., 1976; D'Argenio et al., 1973; etc.). Their diversification is the result of a phase of synsedimentary distensive faulting, initiated during the Early Liassic, with differential subsidence of the formerly uniform shelf. Mainly during the Late Jurassic the sea bottom morphology of isolated horsts was leveled by the basinal sediments, while the Apulian and Latium-Abruzzi Platforms persisted during the whole Mesozoic. These inhomogeneities in the sedimentary cover exterted a decisive influence on the subsequent tectonics during the Neogene, as shall be shown.

2.1.b. NEOGENE

After the Paleogene, the lithostratigraphy becomes much more complex and varied. During the Neogene the physiography of the sea bottom was modified by incipient orogeny, which had migrated from the internal towards the external zones. In Early Neogene time the investigated area still belonged to the stable foreland of more internal zones already affected by important tectonic movements. The development of rapidly subsiding syn-tectonic turbidite basins began in the interior, and generally their depot-centers migrated in front of the outward moving orogenic wave.

Finally the sedimentary infill of the basins was also affected by thrusting and folding. In both the Northern and the Southern Apennines the basins are generally elongated with NW - SE trends, i.e. parallel to the orogenic axis.

After the Paleogene period of general emersion and non-deposition on the Latium-Abruzzi carbonate platform, differential subsidence began in the Neogene. The transgression varied in age from Late Oligocene to Tortonian (Ogniben, 1969; Parotto & Praturlon, 1975; Pieri, 1975; Alberti et al., 1975), and led to a very non-uniform distribution of lithologies: mainly marly deposits and detrital limestones, with a provenance from the still emerged parts of the former platform. A lot of material was transported over considerable distances by turbidity currents, forming limestone turbidite sequences, distally interfingering with the basinal sediments of the adjacent areas (to the S of the area investigated, the Sabina Flysch of Late Oligocene to Serravallian Age: Parotto & Praturlon, 1975; the Cerrogna limestones in the Acquasanta Group: see p. 37). Subsequently terrigenous-clastic sediments were deposited, mainly in NW - SE trending narrow syntectonic basins (Frosinone Sandstones: Pieri, 1975; Valle Sacco unit: Bergomi et al., 1975; Val Roveto unit: Devoto, 1967); the oldest ones in the SW (Tortonian: F. Sacco Basin, F. Liri Basin: Accordi et al., 1969-b; Bergomi et al., 1975; Centamore et al., 1978; Castellarin et al., 1978; Catalano et al., 1976; D'Argenio et al., 1973), and than in the younger Laga Basin to the NE (Messinian - Early Pliocene: see p. 39).

This Laga Basin (S. Marche - Abruzzi Basin: Selli, 1973) is considered as the common Messinian - Early Pliocene foredeep of both the Abruzzi (to the SE) and the Umbria Marche Apennines (to the W); see fig. 3. Its area of outcrop will be called the Laga Mountains Area in the present paper (outer or external Marchean Basin of Centamore et al., 1972, 1980; Marche and N. Abruzzi Region of Crescenti, 1975).

Heteropic with the Laga Formation is the Gessoso-Solfifera Formation, a generally gypsum- and sulfur-bearing marly unit with more or less thick terrigenous intercalations (Selli, 1954, 1973). It overlies the Umbria-Marche sequence in the NE part of the Umbria Marche Apennines and Marche Abruzzi Zone (Ricci Lucchi, 1973; Borsetti et al., 1975; Carloni et al., 1974), and it is known from subsurface data in a strip along the Adriatic coast, external of the Laga turbidite series (Crescenti, 1975).

Also in the Northern Apennines widespread terrigenous-clastic sedimentation occurred, and turbidite sequences cover large part of the Umbria-Marche sequence. The Marnoso Arenacea (Lower to Middle Miocene) is present NW of Urbino and at the internal side, i.e. SW side of the Umbria Marche Apennines (W of the line S. Angelo in Vado - Gualdo Tadino - Spoleto). Its area of outcrop lies in the Romagna - Umbria Zone (fig. 3; Umbrian Basin of Centamore et al., 1972, 1978; Inner Basin of Ricci Lucchi, 1975). In the N part of the Umbria Marche Apennines the Miocene depositional area is progressively subdivided into several separate elongated minor basins (Centamore et al., 1978). The most SE one of these is the Camerino Basin, some 30 km NW of the area investigated.

In the SW-most part of the orogene (along the Tyrrhenian coast) the base of post-orogenic sediments is of Messinian Age. They are mainly deposited in elongated grabens. To the NE the marine late- to post-orogenic sediments (Lower/Middle Pliocene to Quaternary Age) are mainly gently dipping towards the Adriatic Sea (see fig. 5), and overlie the earlier sedimentary-structural units, locally with an angular unconformity. Offshore, below the Adriatic Sea, these post-orogenic series of the Pedeapennine Zone (Parotto & Praturlon, 1975; Apennine foredeep of Crescenti, 1975) can reach thicknesses of 5 to 6 km.

2.2. STRATIGRAPHY OF THE INVESTIGATED AREA

All Mesozoic - Paleogene rocks in the area belong to the Umbria-Marche basinal Sequence. They are predominantly of the Complete sub-sequence (p. 23), with frequent intercalations of detrital limestones, at various levels. Only very locally small isolated areas of Condensed sub-sequences are exposed (in the Monti Sibillini).

The Umbria-Marche Sequence is overlain by the Acquasanta Group (as defined in the present paper: p. 36) and the Laga Formation, both of Miocene Age. A columnar section of the lithostratigraphy is presented on the enclosure of the Geological Sections.

As the primary aim of the present study to analyse the structural development, no emphasis is put on the stratigraphy of the area. A subdivision of the stratigraphic sequence is made on lithostratigraphic characteristics. In naming of the units current nomenclature is followed, and most stratigraphic boundaries are taken over from the 1 : 100.000 geological maps of the Servizio Geologico d'Italia, and recent literature. The current stratigraphic divisions are often rather informal by modern standards, but they provide convenient mapping units; boundary criteria, easily manageable in the field, are added in order to obtain correct mapping results.

Only the Forca Canapine Group (p. 30) and the Acquasanta Group (p. 36), some formational units known in the literature under varying names, are taken together.

The textural classification of the limestones is mainly after Dunham (1962).

The given age of the units is mainly after Cati et al., 1968 (for the Neogene), Crescenti et al., 1969, and Micarelli et al., 1977.

2.2.a. DESCRIPTION OF THE FORMATIONS

Calcare Massiccio

The Calcare Massiccio is the lowermost unit in outcrop, and it is common to both the Complete and Condensed sub-sequence. The most extensive exposures are in the M. Vettore Massif, in the upstream parts of the Fiume Aso and Fiume Tenna, in the M. Bove Massif, to the SW of the M. Utero, to the W of the M. Boragine, and in the Montagne dei Fiori.

Its thickness exceeds 750 m (Crescenti, 1969). The formation is characterized by fine-to coarse-grained grey-to white-coloured (bio)clastic limestones. Macroscopically bedding is badly developed; if visible at all it is irregular, with thicknesses of the beds ranging up to 10 m. The limestone shows mainly a grainstone texture, with coarse sparry calcite. Packstones, wackestones and mudstones may also be present at several levels. Clasts are of varying size and character: pellets, pelletoids, oolites, bioclasts of all kind, algal accretionary grains (oncolites), etc. Locally stromatolitic laminations are present. The lower part of the formation and its transition to the underlying Burano Formation (p. 19) are not exposed. The lowermost visible part crops out at the base of the E side of the M. Vettore Massif (Aia della Regina), and it is characterized by coarse grained dolomitic limestone, with a saccharoidal texture and partly cavernous; cement and/or matrix are replaced by euhedral dolomite. In the Montagna dei Fiori this epigenetic dolomitisation has progressed to much higher stratigraphic levels: here the complete unit and also the lower part of the overlying Corniola consists of dolomitic limestone and saccharoid dolomites. Therefore Crescenti et al. (1969) defined this predominantly dolomitic unit separately from the Calcare Massiccio as the Castelmanfrino Formation (see also Giannini et al., 1970; Deiana et al., 1971).

The upper boundaries with the overlying Corniola (Complete sub-sequence) and the Nodular Limestones (Condensed sub-sequence) are defined at the first appearance of well bedded biomicritic limestone. The unit may also be directly overlain by the Forca Canapine Group (for example to the S of the M. Boragine and to the N of the M. Sibilla.

The lithological characteristics indicate deposition of the Calcare Massiccio in a carbonate platform environment, within the shallow subtidal and intertidal realm (Colacicchi et al., 1970; Pialli, 1971; Centamore et al., 1969, 1971, 1972; Chiocchini et al., 1976; etc.).

The age of the Calcare Massiccio is Hettangian - Sinemurian (Early Liassic).

Corniola (Calcare Selcifero)

The Corniola lies on top of the Calcare Massiccio in the Complete sub-sequence. It is exposed extensively all along the E edge of the Umbria-Marche Apennines, and in the Montagna dei Fiori.

The thickness of the unit is quite variable, and may exceed 400 m (locally in the M. Vettore Massif, and in the area of the Forca Canapine). The formation is characterized by grey and brownish, well-bedded biomicritic limestones, locally interlayered by thin greenish marly levels. Bedding is regular and the thickness of the individual beds is 10 to 45 cm. Grey and black chert is present in lenses and nodules. In the Montagna dei Fiori the lower part of the unit endured partial dolomitisation (in continuity with the underlying Calcare Massiccio). Depositional texture varies from mudstone to wackestone; in the latter most grains consist of radiolaria and sponge spicules.

Medium- to coarse-grained bio/lithoclastic limestones (so-called Marmarone) interbed the mudstones in varying amounts. Bedding thicknesses may range from some tens of cm up to 4 m, and it is laterally not constant. Some of the beds show a gradual wedging-out, over long distances, whereas others show a channel-shape on cross-section. Some of the thinner beds show an overall positive grading; thicker, coarse beds are mainly ungraded, with locally a rapid positive grading in their upper parts. They have a packstone - grainstone texture. The lithological characteristics point to deposition by turbidity currents. In the M. Vettore Massif, near the contact with the underlying Calcare Massiccio large discontinuous bodies of limestone breccia are present. (Megabreccias of Castellarin et al., 1978; see also Cantelli et al., 1978). The bodies are irregularly shaped and their thickness may exceed 20 m. The upper boundaries are irregular; the basal contacts with the Corniola mudstones are planar to undulous, locally with a channel shape on cross section. The bedding of the rocks below may be distorted, scoured and truncated, indicating deformation in unconsolidated sediments. All lithoclasts consist of Calcare Massiccio material. Also large solitary blocks of Calcare Massiccio material occur imbedded in the mudstones; their size may be 10 m or more.

The limestone breccias are debris sheets; the solitary blocks olistoliths. Together with the limestone turbidites they indicate large scale sediment gravity flows (Middleton & Hampton, 1973), mainly derived from the Calcare Massiccio, into the depositional area of the Corniola mudstones. They occur mainly along the E edge of the Umbria Marche Apennines, to the S of the Fiume Aso Valley. The channelized coarse-grained limestones and debris sheets pinch out rapidly, and only the thinner distal turbidites have a large lateral extent to the W. Obviously the largest influx of debris originated from the E, i.e. from the Abruzzi carbonate platform. The configuration attests to a pelagic depositional environment at the foot of a high to the E and SE. This relief was caused by the phase of distensive tectonic activity, initiated during the Early Liassic (p. 24). The former carbonate platform of the Calcare Massiccio was broken up, and on the downthrown blocks the shallow water carbonate sedimentation ceased quite abruptly, and deposition of the Corniola started. Other segments of the platform, presently exposed in the Abruzzi, remained at shallow depths. Due to tectonic activity and erosional processes along the edge of the platform, large masses of debris could slide down slope. Turbidity currents transported finer debris further away from the platform edges into the pelagic realm. Castellarin et al. (1978) describe a large scale truncation surface in the Calcare Massiccio of the M. Vettore Massif (E side of the Scoglio del Lago and Pizzo del Diavolo: see fig. 33). Here, large masses of Calcare Massiccio material were probably detached and disappeared to the W by submarine sliding. The concave upward truncation surface is disconformably overlain by the Corniola; olistoliths, debris sheets and limestone turbidites are present near the interface Calcare Massiccio/Corniola. The surface is burried completely by the Corniola, which consequently shows considerable variation in thickness.

The upper boundary of the Corniola in the gradual transition to the overlying Forca Canapine Group, is defined at the first appearance of marly intervals, exceeding thicknesses of 10 cm.

The age of the Corniola is M. Liassic.

Forca Canapine Group

The stratigraphic succession between the Corniola and the Maiolica (Complete sub-sequence) is quite variable in thickness and composition. In the current literature on the Umbria Marche Apennines several stratrigraphic units are distinguished, many of them only of local importance, and defined in the NW part of the Umbria Marche Apennines, outside the investigated area. The units are partly heteropic and transitions occur in vertical and lateral sense. In the present study they have been taken together in the Forca Canapine Group.

The pelagic basinal sediments can roughly be divided into a predominantly marly lower part and a more calcareous upper part. Directly on top of the Corniola, interbedding of marl and fine-grained limestone is quite regular, with upward increasing thicknesses of the marly levels. The thicknesses of the limestone beds varies between 20 and 50 cm. Detrital limestone intercalations occur at various levels. The characteristics of these lithotypes correspond quite well with those of the Calcare e Marne del Sentino (Centamore et al., 1971; Chiocchini et al., 1976) and the Marne del Serrone (Pialli, 1969), defined in more NW parts of the Umbria

Marche Apennines (see also Castellarin et al., 1978).

To the N of the M. Vettore and in the Montagna dei Fiori these sediments are overlain by an alternation of red coloured marls and marly limestones: the Rosso Ammonitico of the current literature (see for example Pialli, 1969; Dallan Nardi & Nardi, 1972). The marls contain horizons of calcareous nodules, and remnants of ammonites. Only locally some fine-grained detrital limestone beds are intercalated. In the Forca Canapine area and in the Valle Cupa, to the S of the M. Ciambella, lithoclasts of Rosso Ammonitico material are present in the detrital limestones at the base of the Calcari e Marne del Sentino-equivalent. Here the Rosso Ammonitico itself is completely absent, and the presence of these lithoclasts contradicts the position of the Rosso Ammonitico on top of this unit, to the N of the M. Vettore. It indicates complex mutual relationships between the various lithotypes, probably related to a complex relief of the sea bottom, due to distensive tectonic activity.

The overlying calcareous upper part of the Forca Canapine Group (the so-called Scisti ad Aptici) has a thickness of 150 to 250 m, mainly depending on the amount of detrital limestone intercalations. The basal part consists of well-bedded fine- to medium-grained limestones with a wackestone/packstone texture. The grains consist of abundant small pelagic bivalves (Bernoulli & Jenkyns, 1974; resti filamentosi Auct.), radiolaria, fragments of echinoderms, aptychi, etc. This interval corresponds, at least partly, with the Calcari e Marne a Posidonia (Centamore et al., 1969, 1971; Chiocchini et al., 1976).

Upward a gradual transition occurs to fine- to medium-grained cherty limestones, interlayered by thin marly levels, and locally abundant detrital limestones. The cherty limestones are well-bedded; bedding thicknesses vary between 5 and 30 cm. The prevalent colour is greenish grey, with locally brown and reddish intervals. The depositional texture varies from wackestone to packstone. Radiolaria are very abundant, giving a granular appearance to the rock on fresh surfaces. Cherts, probably originated from desintegrated radiolaria, are present in layers, lenses and nodules. Their colour is dark green, blueish, black and locally pink or red. (Diaspri(ni) of the Italian literature; Calcari granulari con diaspri: Centamore et al., 1971; Calcari diasprini umbro-marchigiani: Centamore et al., 1972, Chiocchini et al., 1976; Calcari Selciferi e Selce: Castellarin et al., 1978).

Characteristic for the whole Group are the fine- to very coarse-grained detrital limestone intervals (fig. 4). Their thicknesses range from some tens of cm up to 9 m. (Very thick beds are present at the S sides of the M. Macchialta and M. Ciambella). Individual beds are highly discontinuous, wedging out locally over very short lateral distances; they may also show a channel-shape in cross-section, which truncates the underlying beds. Generally their upper and lower boundaries are well defined. Locally scour marks are detected (Valle Cupa, to the S of the M. Ciambella: provenance of material from 140^{0} - 150^{0} SE). Some of the beds show

Fig. 4: Detrital limestone within the limestones of the Forca Canapine Group (Diasprini lithotype). Bioclasts and lithoclasts (consisting of subangular mudstone, wackestone and packstone fragments) are floating in a packstone matrix. Location: along the road from the Forca Canapine to the Piano Grande (hammer is 30 cm).

a positive grading. The depositional texture varies from wackestone, packstone to grainstone. Clasts are of various size, and may be quite unsorted, angular to subangular; they can be tightly packed to mud-supported. Generally clasts of both pelagic mudstones and shallow-water carbonates are present. The bioclasts consist mainly of debris of spicules, echinoderms, corals, and molluscs (Ellipsactinidae).

All detrital limestones are turbidites, with transitions to debris sheets. Again, as has been said for the Corniola, there is a general increase towards the E in the amount of detrital limestones and average grain-size. Obviously, the provenance of most material was from the Abruzzi carbonate platform. However, increase of detrital limestones, increment of grain-size, and local occurrence of slump structures towards the areas of a Condensed sub-sequence indicate also local provenance from the isolated fault-bounded highs (the Calcari detritici del M. Valvasetto: Chiocchini et al., 1976; Calcari detritici nocciola; Centamore et al., 1971; Formazione del Torrente Salinello: Giannini et al., 1970; Microbrecce calcaree: Giannini, 1960).

The transition of the Forca Canapine Group to the overlying Maiolica is gradual, and the boundary between the formations is defined at a bedding thickness exceeding 30 cm.

The age of the Forca Canapine Group ranges from Toarcian (Late Liassic) to Portlandian (Late Malm).

"Nodular limestones"

This mapping-unit comprises several lithotypes between the Calcare Massiccio and the Maiolica, in the Condensed sub-sequence. In the investigated area it is exposed only in the Monti Sibillini (in the upstream part of the Fiume Tenna valley: see section B; in the area of the M. Bove and in the Torrente Ambro valley: see section A; in the upstream part of the Fiume Tennacola valley: Valle Tre Santi), and in the Montagna dei Fiori (Fiume Salinello gorge).

Its thickness is only some tens of meters. The unit is heteropic with the Corniola and/or the Forca Canapine Group of the Complete sub-sequence. In the Monti Sibillini it is named Calcari Nodulari del Bugarone by Chiocchini et al. (1976), after the location of its type section at the M. Nerone (NW Umbria Marche Apennines). In the Umbria Marche Apennines the unit is known by several other names: Grigio Ammonitico of Pialli (1971); Formazione del Bugarone of Centamore et al. (1972) and Jacobacci et al. (1974).

A detailed study of the various lithotypes is beyond the scope of this paper. Its main characteristics can be summarized as follows: generally well-bedded grey- to brown-coloured fine-grained limestone with a wackestone/packstone texture, interlayered by thin greenish argillaceous levels. Locally bedding is absent and the limestone forms irregular encrustations on the underlying Calcare Massiccio. Part of the limestone is nodular. Nodules are of cm scale, and generally cemented by coarse calcite. Locally ferruginous crusts and nodules are present. Bioclasts are mainly unsorted and of various sizes: sponge spicules, gastropods, small pelagic bivalves (resti filamentosi Auct.), ammonites, aptychi, crinoid fragments.

The boundary with the overlying Maiolica is defined at the appearance of mudstone texture. Along the edges of the fault-bounded structural highs the Nodular limestones cover the mainly horizontal Calcare Massiccio with an irregular disconformable contact. Here the unit is evidently part of the talus of the structural high. Its lithotypes interfinger with the basinal sediments. The appearance of the latter define the lateral lithostratigraphic boundary.

Maiolica (Calcare Rupestre)

The Maiolica follows on top of either the Forca Canapine Group or the Nodular limestones. The thickness is up to 450 m in the Complete sub-sequence, and much less (minimal some 100 m) in the Condensed sub-sequence.

The unit is characterized by white-coloured, well-bedded and very fine-grained mudstones, with radiolaria. The average bed-thickness is about 30 cm (maximal 1 m). Grey- to pink-coloured cherts in nodules and lenses are present throughout the unit. The basal part, near the contact with the Nodular limestones endured dolomitisation by growth of euhedral dolomite. Bioclastic limestone intercalations are scarce; they are present mainly near the base and in the upper part of the unit. At the top of the Maiolica in the Montagna dei Fiori an about 25 m thick interval of limestone breccia is present; its angular components are mudsupported.

The scarcity of detrital limestones in the Maiolica may point to a period of relatively low tectonic activity along the Abruzzi carbonate platform-edge (Castellarin et al., 1978) and/or withdrawal of the platform-edge by increased subsidence. Moreover, the Maiolica indicates the initiation of uniform environmental conditions in the Umbria-Marche basin, because it constitutes the top of both the Complete sub-sequence and the Condensed sub-sequence. The lateral stratigraphic continuity of the upper part of the unit indicates that the boundary-faults of the structural highs became definitely inactive; continuous subsidence of the isolated submarine highs together with the surrounding basinal area resulted in burial of the relief.

The transition to the overlying Marne a Fucoidi is gradual; the upper boundary is defined at a 1/1 limestone/marl ratio.

The age of the Maiolica is late Portlandian ("Titonico" in most Italian literature) to Early Aptian.

Marne a Fucoidi

This unit lies between the Maiolica and the Scaglia. The thickness is generally less than 70 m; thickness variations are mainly due to tectonic deformation.

The unit is characterized by pelitic sediments: mainly a regular interlayering of greenish-gray and variegated marly limestones and marls, locally with thin, dark-coloured fissile marly shales. Individual limestone beds have thicknesses varying from 10 to 40 cm. Bedding planes may be distinct, but the marl - marly limestone transitions are mainly gradual. All sediments contain radiolaria and planctonic foraminifera, the latter becoming more abundant towards the top of the unit. Generally, the original sedimentary texture has been modified by burrows (fucoidi Auct.). In some localities directly W of the Umbria Thrust Zone variegated cherts in lenses and layers may be abundant (for example in the area around the M. Ciambella, to the W of Terracino, and in the M. Pizzuto area).

Thin white or greenish-coloured bioclastic limestones are present, mainly to the S of the M. Vettore Massif. In some localities in the hanging wall of the Umbria Thrust Zone very thick bioclastic limestones are present (up to 10 m. at I Pavoni, to the E of the M. Ciambella), consisting of unsorted coarse limestone breccias, with mainly coarse sparry calcite cement.

In the upper half of the unit the marly limestones constitute the major component, and upwards a gradual transition to the Scaglia is present: the lithostratigraphic boundary is defined at 1/1 marl/limestone ratio.

The age of the Marne a Fucoidi is Aptian-Albian.

Scaglia

This unit forms a very characteristic lithology in the Umbria-Marche Sequence. In current literature parts of the unit are commonly named after their most characteristic colour: Scaglia bianca, Scaglia rosata, Scaglia rossa and Scaglia variegata. The overlying Scaglia Cinerea will be treated separately. The unit crops out extensively in the Umbria-Marche Apennines and the Montagna dei Fiori. The top of the unit is also exposed in the Acquasanta Structure.

The thickness of the Scaglia is quite variable, due to tectonic deformation; the estimated stratigraphic thickness is about 400 m. The unit is characterized by white to pink, well-bedded limestones, mainly towards the top interlayered by calcareous marls. The average bedding thickness is about 20 cm.

The lower part of the unit consists mainly of white-coloured mudstones (the Scaglia bianca), with red and black chert lenses and nodules. A very characteristic level (about 1 m) consisting of bituminuous shales, laminated silts and locally diatomites, is present some 40 m above the base of the unit; it is known as the Livello Bonarelli. In the middle and upper part of the unit the characteristic salmonpink and reddish colours dominate (Scaglia rosata, Scaglia rossa), although large part of the rocks may have become white by bleaching. The middle interval is characterized by regularly bedded mudstones and wackestones, without marly levels and cherts.

Towards the top of the Scaglia the argillaceous content increases; characteristic here are levels of red coloured fissile calcareous marls, and also red chert nodules may be present. The top part contains still more marls and calcareous marls of variegated colour (the Scaglia variegata: Carloni, 1962). Throughout the complete unit the limestones contain abundant planctonic foraminifera and radiolaria.

Locally, intercalations of bioclastic limestones are abundant. They are mainly white coloured, and show well defined regular bedding planes (see fig. 22). The coarse- to medium-grained ones are relatively abundant in the upper part of the unit. They may be very thick (up to 15 m, for example on the M. Prato and M. Laghetto), and wedge out laterally to the W and NW. Depositional texture: packstone and grainstone. Some of these beds consist of coarse breccias, containing unsorted fragments of corals, rudists, echinoderms, and lithoclasts of various kind of platform debris. Fine-grained thinner bioclastic limestones have much larger lateral extent, and generally reach far to the W and NW in the Umbria Marche Apennines. Also in the Scaglia, the debris originated from the still existing carbonate platform of the Abruzzi (Castellarin et al., 1978).

The transition of the Scaglia to the overlying Scaglia Cinerea is gradual, and the upper boundary is defined at the disappearance of the mudstones with well-defined bedding.

The age of the Scaglia is Cenomanian - Late Eocene.

Scaglia Cinerea

This unit lies on top of the Scaglia; its average stratigraphic thickness is about 200 m (Montefortino Structure). However, in most places in the investigated area the original stratigraphic characteristics are largely obliterated, and the thickness is reduced by tectonic deformation (see chapter 3).

The unit is characterised by an irregular alternation of marly limestones and marls, mainly without discrete bedding planes, but with a gradual transition of more calcareous layers to more argillaceous layers. The colour is grey and greenish-grey. Towards the top of the unit the argillaceous content increases.

Mainly in the lower and middle part of the unit fine- to coarse-grained pink to brownish bioclastic limestones are intercalated. Their thicknesses range from some 30 cm to 3 m. They have mainly a grainstone texture, and show no gradation or lamination. Macrosopic bioclasts, if present are mainly fragments of echinoderms and benthonic foraminifera. Abundant nummulites have been found in the M. Prato Structure to the E of the Valle S. Rufo, and in the Montagna dei Fiori.

The age of the unit is Late Eocene - Oligocene.

Acquasanta Group

Within the investigated area the stratigraphic sequence continues with a succession in which several units are distinguished in the literature: Bisciaro, Marne con Bisciaro (Colacicchi, 1958), Schlier, Marne con Cerrogna (Scarsella, 1934), Marne a Pteropodi (Centamore et al., 1978) or Marne a Orbulina (Castellarin et al., 1978). They are exposed in the footwall of the Umbria Thrust Zone, in the

Acquasanta Structure and in the Montagna dei Fiori Structure. Bisciaro and Schlier have been defined in more northwesterly parts of the Umbria Marche Apennines, and the Marche Abruzzi Zone. In the investigated area they are ill-defined: the Marne con Cerrogna is at least partly heteropic with both, and relations in lateral and vertical sense are complex. Moreover, mutual relations are obscured by tectonic deformation. Therefore, all lithotypes are here taken together in the Acquasanta Group, named after the small town of Acquasanta, in the centre of the area, where the unit is exposed extensively in the crest zone of the Acquasanta Structure.

The group is characterized by an irregular alternation of marly limestones calcareous marls, argillaceous marls and a variable number of bioclastic limestone intercalations. The thickness of the group is quite variable, mainly due to tectonic imbrication and disharmonic folding (see chapter 3). The average original stratigraphic thickness in the Montefortino Structure is about 300 m. Generally , stratigraphic thickness increases with the amount of bioclastic limestone intercalations. The grey coloured marly limestone-beds ("Bisciaro": Selli, 1952) have thicknesses of 20 cm to 60 cm. They are fine- to medium-grained mudstones/wackstones, and they are locally laminated. In the S. Giovanni/Terracino area lenses and nodules of black cherts are present in the basal part of the Group.

This Bisciaro lithotype characterises mainly the lower part of the Acquasanta Group; towards the top bedding thickness diminishes, and the argillaceous content increases. The marls ("Gegna": Selli, 1952) are blueish-grey; the wheathered colour is yellow to white. In the upper part of the Group a very regular and rhytmic alternation of thin marly limestones and marls occur, without discrete bedding-planes.

Throughout the whole Group grey to brown bioclastic limestones are present, the so-called Cerrogna limestones (Scarsella, 1934). Their thicknesses range from some tens of cm up to 10 m. They show irregularly but sharply defined bedding planes. Positive gradation, parallel and convolute laminations, and scour marks at their bases may be present. In the Acquasanta Structure and Montagna dei Fiori Structure some of the thickest bioclastic limestones, interbedded by thin marly levels are present in the top part of the Group; large balls consisting of marl, may be incorporated in the basal part of the beds. They have a packstone depositional texture, with partial or complete replacement of the mud-matrix by coarse sparry calcite. The bioclasts consist mainly of fragments of Bryozoa, corals, and smaller and larger benthonic foraminifera. Commonly the thicknesses and the number of Cerrogna limestone beds increase towards the S and SE, i.e. towards their source area in the Abruzzi Apennines (Colacicchi, 1958).

The upper 15 - 25 m, on top of the uppermost Cerrogna, consist of dark grey argillaceous Pteropoda marls (Marne a Pteropodi: Centamore et al., 1978; Marne a Orbulina: Castellarin et al., 1978).

All deformational structures in the Acquasanta Group have been interpreted as being the result of slumping and submarine sliding (Ricci Lucchi & Parea, 1973; Mutti et al., 1978; Centamore et al., 1978). However, the majority of the folds has a tectonic origin (see 3.3.c). Slump structures and synsedimentary flap folds are present only in the Selva Grande Area, in addition to the folds of tectonic origin. They occur also in the Cima Alta Area, in the southern continuation of the Montagna dei Fiori Structure (S of the investigated area). Both localities are near the Abruzzi carbonate platform in the S. The provenance of the Cerrogna limestones from the S indicates that during the deposition of the Acquasanta Group this platform still had an elevated position with respect to the surrounding basinal area. The synsedimentary structures in the Selva Grande Area and in the Cima Alta Area indicate the vicinity of the instable platform slope.

The age of the Acquasanta Group ranges from Aquitanian - Tortonian.

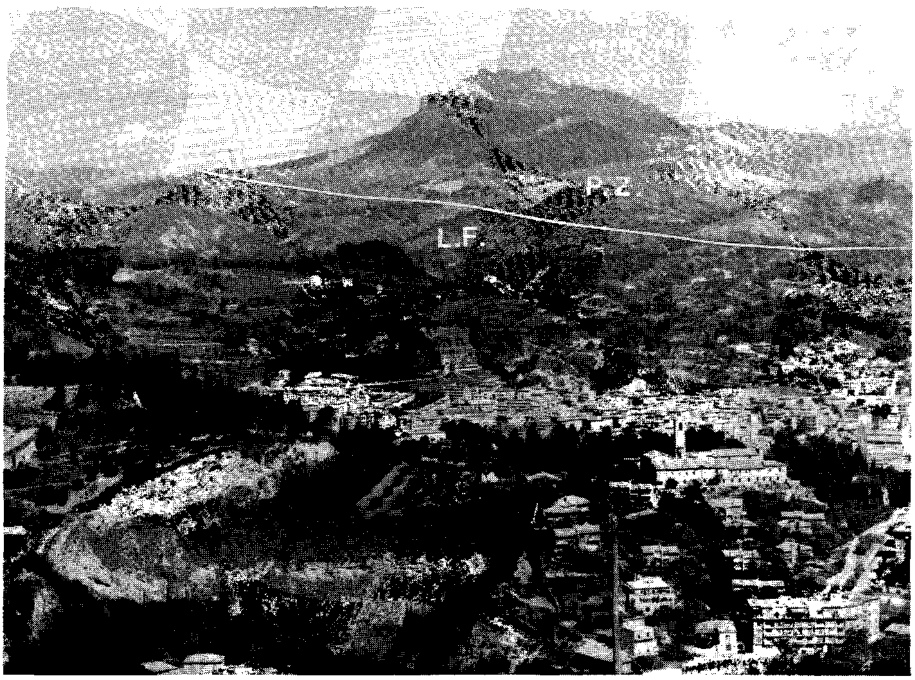


Fig. 5: N-ward view on Ascoli Piceno and the M. dell'Ascensione (1110M). Where the Laga Formation (L.F.) is overlain by argillaceous marls, sands and conglomerates of the Pedeapennine Zone (P.Z.) (M. Pliocene). In the foreground a recumbent syncline in the Laga Formation is present in the NW ward plunging Montagna dei Fiori Structure.

Laga Formation

The Laga Formation (Flysch della Laga: Scarsella, 1953; Crescenti et al., 1969; Bernardini, 1969; Flysch Piceno and Flysch Teramano: Ten Haaf, 1959; Sestini, 1970) is exposed in a large area situated N and NE of the Gran Sasso d'Italia chain (Abruzzi). To the W its outcrop is delimited by the Umbria Marche Apennines, and towards the Adriatic Sea the unit is overlain by deposits of the Pedeapennine Zone (fig. 5).

The unit is characterized by well-bedded, thick, impure sandstones (locally greywackes), interlayered by argillaceous and more or less marly layers. Already in 1958 (Colacicchi) and 1959 (Ten Haaf) studies of the sedimentology of the unit established its turbiditic character. In the investigated area the maximum thickness of the Formation in a single outcrop is 1500 m (in the Monti della Laga). By construction and extrapolation of surface measurements a thickness of about 2500 m can be calculated. This is less than the total thicknesses indicated in the current literature: more than 3000 m (Centamore et al., 1978); about 4000 m (Parotto & Praturlon, 1975; Crescenti, 1975; Centamore et al., 1980; Ricci Lucchi, 1975); 3600 - 4000 m (Selli, 1975). Because the depot-centre of the Laga Basin migrated from SW to NE (Ricci Lucchi, 1975; Castellarin et al., 1978) these relatively high thicknesses are probably cumulative calculations of partly lateral series.

Stratigraphic and sedimentological studies in the last decade have revealed several facies associations within the turbidite sequence (Ricci Lucchi & Parea, 1973; Ricci Lucchi, 1973, 1975; Mutti et al., 1978; Centamore et al., 1978). An analysis of these turbiditic facies (Mutti & Ricci Lucchi, 1972) is beyond the scope of the present study. Three main associations are distinguished, with complex lateral and vertical relations: channelized mid-fan turbidites, non-channelized outer-fan turbidites, and basin-plain turbidites. The non-channelized outer-fan turbidites form the most outstanding association (fig. 6). Individual sandstone beds may be as thick as 20 m. They are medium- to coarse-grained, and internally mainly rather homogeneous, although locally also beds with a positive gradation are present. These beds are interlayered by generally thin argillaceous levels. The bases of the sandstones are mostly erosional: mud-pebbles and -balls may be incorporated in the sandstones. The fan-turbidites show an abrupt onset on the top of the unit below (the Marne a Pteropodi of the Acquasanta Group). In the upper part of the Laga Formation (i.e. towards the NE) the argillaceous content increases.

The basin-plain association is characterized by an alternation of thin-bedded sandstones and argillaceous levels, with a generally low sandstone/shale ratio The thicknesses of the sandstones range from a few cm to 50 cm, with locally some

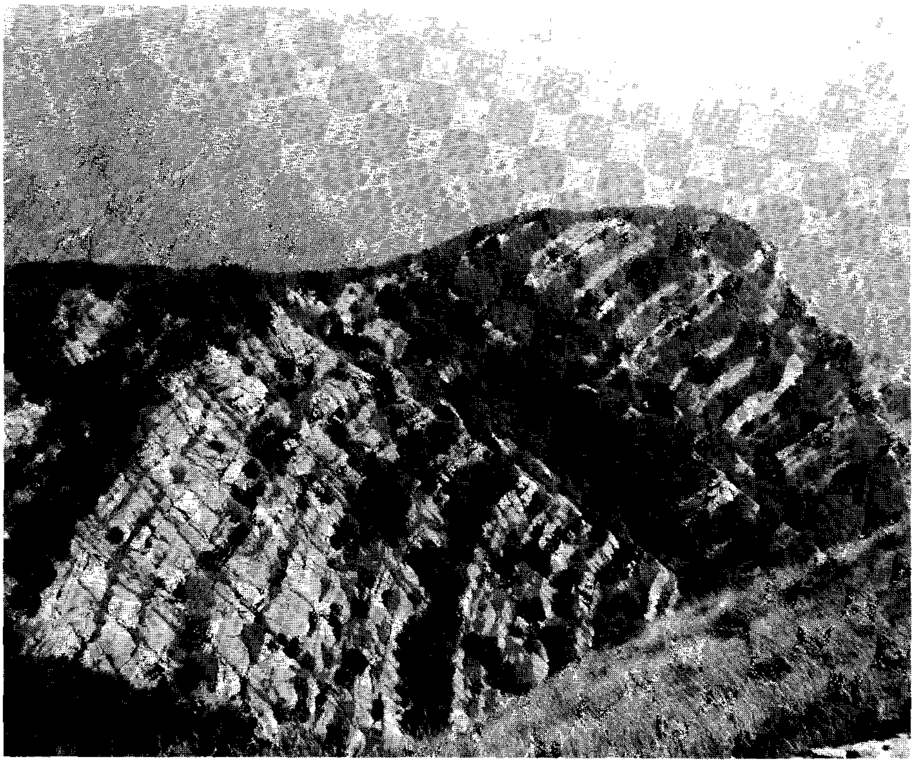


Fig. 6: Fan turbidites of the Laga Formation, Monti della Laga, N of the Pizzo di Sevo.

thicker beds. Grain-size varies mainly from very fine to medium but locally also very coarse-grained beds are present (with grain sizes exceeding ½ cm). The sandstones are mainly fining upwards, and show more or less complete Bouma-sequences.

The provenance of the terrigenous material is from the N and NW (Ten Haaf, 1959; Mutti & Ricci Lucchi, 1972; Bernardini, 1969). The source area could have been the Alps (Brambati, 1969; Castellarin et al., 1978) or the material was derived by cannibalism of earlier turbidite units of the Northern Apennines, to the NW and W (Ten Haaf, 1964, Borsetti et al., 1975; Centamore et al., 1978; Ricci Lucchi, 1975).

A 30 to 20 m thick zone of gypsarenites and bituminous marls is intercalated in the terrigenous clastic turbidites in the NE part of the investigated area. The gypsarenites have been interpreted as turbidites, derived from the crystalline gypsum of the Gessoso Solfifera Formation (see p. 26). (Bernardini, 1969;

Ricci Lucchi, 1973; Parea & Ricci Lucchi, 1972). Girotti & Parotto (1969) describe some volcanic ash layers in the upper part of the Formation (at Collegallo to the N of Ascoli Piceno), recently dated by K./Ar.-method at 7.7. M.A. (Carloni et al., 1975).

The original size of the Laga Basin is not known exactly. In the W along the Umbria Marche Apennines the Laga Formation is generally dipping steeply to vertical in a more or less wide zone (see 3.4). Here the sedimentary facies is not indicative for the presence of a former basin-periphery. Since the Laga Formation appears to belong to the hanging wall of the Umbria Marche thrust-complex (see chapter 3) this W periphery should be sought on top of the Umbria Marche Apennines; it is not preserved anymore due to erosion. Only to the E of Spoleto a restricted outcrop of conglomerates and sandstones may represent a proximal facies near the basin periphery (the Belvedere Formation of Late Tortonian - Early Pliocene age: Decandia & Giannini, 1977). The time-equivalent units of the nearby Camerino Basin (p. 26) belong to the Gessoso Solfifera Formation, like those in the N Marche and Romagna.

Beyond the S -edge of the investigated area, along the NE side of the Gran Sasso d'Italia chain, the proximity of the local basin periphery appears from discontinuous sheets of limestone breccias and conglomerates, which interlayer the terrigenous turbidites. Towards the S these detrital limestones also cover disconformably the Mesozoic rock units of the Abruzzi. (Alberti et al., 1963; Desio, 1968; Castellarin et al., 1978; Parotto & Praturlon, 1975). This influx of limestone debris in the Laga basin was of local SW-ward origin, from the already emerged parts of the more internal units of the Abruzzi (like the Cerrogna limestones of the underlying Acquasanta Group).

The Laga Basin must be considered as the Late Miocene - Early Pliocene foredeep of the developing orogene; sedimentary infill took place in a rapidly subsiding basin, during major tectonic activity in the adjacent areas to the W and SW (Abbate & Sagri, 1970).

The age of the Lage Formation is Messinian to Early Pliocene (Crescenti, 1966, 1971).

2.2.b. COMMENT

It will be clear from the description of the stratigraphic units that the sedimentary cover consists of sequences of contrasting ductilities. This vertical anisotropy determines the structural style at the various levels, as will be shown in the next chapters. Mechanically, 5 main tectonostratigraphic levels can be distinguished:

level 1: The Burano Formation, consisting of incompetent rocks, mainly anhydrites, interlayered with dolomites.

level 2: The Calcare Massiccio, the thickest coherent and essentially rigid unit; in the overlying Corniola a gradual transition occurs to:

level 3: The mechanically anisotropic sequence between the Corniola and the base of the Scaglia Cinerea, consisting of well-bedded limestone units, interbedded by minor competent levels.

level 4: The Scaglia Cinerea/Acquasanta Group, which is also highly anisotropic, but where incompetent layers are dominant.

level 5: The Laga Formation: a very thick terrigenous-clastic unit, with its own specific properties.

CHAPTER 3

TECTONICS

3.1. HISTORIC REVIEW AND STRUCTURAL SETTING

Geological work in the Central Apennines has been done since the beginning of this century. In several studies (Sacco, 1907, 1937; Lotti, 1926; Lotti & Crema, 1927; De Wijkerslooth, 1934; Behrmann, 1936) a more or less N - S trending line across the mountain belt was emphasized. Most of these studies dealt mainly with the contrasting stratigraphy of Northern and Southern Apennines, but some authors already ascribed important tectonic significance to the line. For example De Wijkerslooth (1934) mentioned a Rimini - Tivoli transcurrent zone. During the period 1940 - 1960 the sheets 132 "Norcia" (Scarsella, 1941) and 139 "l'Aquila" (Alberti et al., 1955) of the 1 : 100.000 Geological Map of Italy, and several studies concerning the tectonic line and adjacent areas, were realised.

It was argued by Scarsella (1951, 1953), Segre (1948) and Behrmann (1958) that the contact between the pelagic series of the Umbria Marche Apennines and the carbonate platform series of Latium and Abruzzi is tectonic everywhere, with overthrusting of the former on the latter. Others, like Merla (1952) considered the line as basically a transcurrent fault. From this period on a distinction was made between the structural character of the line and the stratigraphic significance as a facies boundary. Several names have been given to the line by successive authors; it is presently best known as the "Ancona - Anzio Line", firstly proposed by Migliorini (1950).

Most investigators emphasized the significance as facies boundary. A fair agreement exists on the relationship between the Mesozoic pelagic basinal facies (Umbria-Marche Sequence) and the carbonate platform facies (Latium-Abruzzi Sequence), as has been outlined in chapter 2.

However, much controversy exists on the structural significance of the present lineament. Ogniben (1969) has interpreted the "Ancona - Anzio Line" as a dextral transcurrent fault, displacing the Northern Apennines 40 - 80 km NE wards with respect to the Southern Apennines. In his schematic map the transcurrent fault cuts across the Italian peninsula indeed from Anzio at the Tyrrhenian Sea to Ancona at the Adriatic Sea. This configuration is also expressed in many geotectonic models of this part of the Mediterranean (see for example figs. 12 and 14 of Caire, 1975; Bodechtel & Smolka, 1978). Many investigators considered the "Ancona - Anzio Line" as a reaction of the sedimentary cover on a major basement feature (Centamore et al., 1972). However, its outcrop is essentially a continuous line of overthrust in the sedimentary cover (Abbate et al., 1970; Bortolotti et al., 1970; Funiciello et al., 1981). Dallan Nardi et al. (1971) considered the lineament as the outcrop of an overthrust of the entire Umbria Marche Apennines onto the domains to the E and NE.

Several authors (f.e. Devoto & Praturlon, 1972; Pieri, 1975) emphasized complex relative movements of the structural units on both sides of the lineament, in separate deformation phases, always perpendicular to the various trends. Also Caire (1975, 1978) suggested, that movements along the line could have taken place in different directions at different times. He proposed that the sedimentary cover on both sides of the line is tectonically displaced towards the exterior, but that the mixture of overthrusts and transcurrent faults has not fundamentally altered the relative position of the Umbria Marche Apennines and the Abruzzi. According to him the line has subsequently acted as a flexure during the Pliocene.

Castellarin et al. (1978) synthesized a model in which the Mesozoic facies boundary was reactivated as a dextral strike slip fault in the basement during the Alpine orogeny; in a separate second stage (early Pliocene) E-ward thrusting of the Umbria Marche Apennines onto the E domain occurred. However, a structural analysis along the Velino Gorgo to the S of the area investigated (Coli, 1981) revealed

NE ward thrusting along this part of the "Ancona - Anzio Line", with a dextral strike slip component of movement.

From the surface data of the Central Apennines, it is difficult to extend the structural lineament to Anzio and Ancona (Manfredini, 1966; Parotto & Praturlon, 1975; Castellarin et al., 1978). Therefore the denomination "Ancona - Anzio Line" is avoided in the next chapters. Since in the area investigated the lineament manifests itself as a line of overthrust it is called the Umbria Thrust Zone (Dallan Nardi et al., 1971).

The Umbria Marche Apennines to the W of the Umbria Thrust Zone comprises the mountain chain between Urbino in the NW and Rieti in the S (see fig. 3). It is arcuate in trend, convex towards the ENE (the so-called "Umbrian Arc"). The NW part of the chain is composed of large fold structures, trending NW - SE and mainly facing to the NE. Generally the crest zones of the anticlines ("ruge": Scarsella, 1951) are wide, and no single hinge can be defined. To the S (roughly at the latitude of Perugia) the anticlines crowd together in a more or less N - S running mountain chain. Here the axes of many folds turn from NW - SE to N - S, and even NNE - SSW, oblique to the general NW - SE axis of the mountain belt. Concomitantly the large anticlines become very complex: the limbs are increasingly cut by reverse faults and thrusts (Scarsella, 1941, 1951; Alberti et al., 1955; see also Deiana, 1965; Accordi & Moretti, 1967; Dufour, 1970; Giannini & Lazzorotto, 1975; Decandia & Giannini, 1977). Moreover, other folds in the S part of the Umbria Marche Apennines still have NW - SE trends, up to very near the Umbria Thrust Zone. The curvature of the fold structures and the associated interference pattern is called "virgazione scalare" (Scarsella, 1951; Parotto & Praturlon, 1975).

The structures developed from Late Oligocene through Miocene times, at least far into the Pliocene (Dallan Nardi, 1972; Sestini, 1974; Reutter & Groscurth, 1978). The continuity of folds and thrusts is broken by subsequent normal faults, mainly striking NW - SE, which may show considerable offsets. Some of these faults continue in a SE direction, cutting the Umbria Thrust Zone, and extending into the Abruzzi Apennines. Generally this tensional faulting is largely independent from the previous folds (Elter et al., 1975). It is associated to the post-paroxysmal period of uplift in the orogene. Considering the amplitude and wave length of the folds, in more recent studies a deformation restricted to the sedimentary cover is postulated (Baldacci et al., 1967; Giannini & Lazzarotto, 1975; Caire, 1975; Decandia & Giannini, 1977; Coli, 1980; Lavecchia, 1981; Coli, 1981). Despite the detachment along the Triassic evaporites of the Burano Formation (p. 19) and the obvious presence of thrust faults, the Umbria Marche Apennines are generally regarded as autochthonous (Reutter & Groscurth, 1978).

The controversy on the allochthony or autochthony of the sedimentary cover of the Umbria Marche Apennines affects the applicability of paleomagnetic data, obtained from the Scaglia, to the whole Italian peninsula (c.g. Adriatic subplate). Lowrie & Alvarez (1974, 1975, 1976) and V.d. Berg et al. (1976, 1978) considered the Umbria Marche Apennines as autochthonous, and interpreted the westerly paleomagnetic declinations as an evidence for a counterclockwise rotation of the whole Italian peninsula.

Against this opinion, the allochthony of the Umbria Marche Apennines is argued from paleomagnetic studies by Channell (1976) and Channell et al. (1978). The paleo-declinations in the NW part of the Umbria Marche Apennines are more westerly than in the S and SE, which seems to reflect a progressive increase in counterclockwise rotation of the NW part. They suggested that the curvature of the "Umbrian Arc" and the declination-change may both be the result of the bending of an originally straight fold-system (orocline bending c.f. Carey, 1955, 1958) probably resulting from dextral strike-slip movements along the Umbria Thrust Zone, with the effects dying out towards the NW.

In the Abruzzi Apennines normal faults are the dominant elements, obscuring the earlier structures. The present morphology is mainly due to this block faulting (post Middle Pliocene and still partly active (Devoto & Praturlon, 1972)). For a long time the Abruzzi Apennines have been considered autochthonous (Behrmann, 1958). However, already early in this century thrust faults and nappes had been reported (Grzybowski, 1921; Franchi, 1924). Thrust-tectonics have been confirmed by new studies, and by several wells drilled by the Agip Mineraria (see Martinis & Pieri, 1964; Pieri, 1966; Accordi, 1966; Devoto, 1970; Parotto & Praturlon, 1975, Pieri, 1975). In the literature much debate still exists on the degree of allochthony of the tectonic units. Fancelli et al. (1966) postulated complete allochthony of the Mesozoic sedimentary cover. According to most authors (for example Catalano et al., 1977) the amount of displacement has been largest for the structurally higher thrust sheets: the tectonic units in the SW (M. Simbruini Structure and M. Lepini Structure) are considered as true nappes, while allochthony of the more external units is less certain (M. Giano Structure and Gran Sasso Structure). However, duplication of the Mesozoic cover below the M. Giano Structure, revealed by the results of the Antrodoco I well (Martinis & Pieri, 1964), and the presence of thrust faults at the NE side of the Gran Sasso (Alberti et al., 1963; Calembert et al., 1972), indicate considerable thrusting also here.

The general trend of the structures is NW - SE; the synclines are mostly narrow, and overthrust from the SW by complex wide-crested anticlines, with steep to overturned NE limbs and many internal thrust faults. Also here the tangential tectonics are considered to be restricted to the sedimentary cover (Accordi, 1966; Pieri, 1966), and to have progressed from SW to NE during Late Miocene - Middle Pliocene (Devoto & Praturlon, 1972). According to Accordi (1966) the mechanism of transport of the allochthonous units was gravitational gliding.

In the Laga Mountains Area, to the N and NE of the Abruzzi Apennines some N - S trending broad folds are present (the Acquasanta Structure and the Montagna dei Fiori Structure of the present paper), but generally more severe deformation is considered to be restricted to the margins: along the Umbria Thrust Zone and the N side of the M. Giano and Gran Sasso Structures (Castellarin et al., 1978). Only at the E side of the Montagna dei Fiori Structure a thrust fault has been reported (Giannini, 1960; Girotti, 1968; Accordi et al., 1969-a).

Most investigators agree that beneath the external zones of the Apennines the pre-Triassic basement behaved rigidly during the Alpine orogeny. It is essentially unshortened (see for example Sestini, 1970; Dallan Nardi & Nardi, 1972; Reutter & Groscurth, 1978; Reutter et al., 1978); although some authors postulate large scale tangential shortening also in the basement (Kligfield, 1979). The basement of the Central Apennines is dipping slightly to the NE: the difference in level between the exposures of the basement in W Tuscany, and the basement below the Adriatic Sea is about 10 km (Elter et al., 1975).

The disposition of the gravity anomalies in the Central Apennines shows a regular decrease from positive along the Tyrrhenian Sea, to negative towards the NE, with a steepening gradient and a strong minimum in a narrow belt along the SW border of the Adriatic Sea (Morelli, 1973). No geological correlation can be made between this gravity field and the structural configuration in the investigated area (Morelli 1955; Scarsella 1955). This supports the idea that the deformation has been superficial, which means largely restricted to the sedimentary cover.

3.2. THE UMBRIA THRUST ZONE

3.2.a. INTRODUCTION

The Umbria Thrust Zone is a long continuous regional thrust, only locally offset by steep normal faults. In the northern part of the area investigated the thrust front forms the edge of the N part of the Monti Sibillini (fig. 7) and strikes about NW - SE; it continues so beyond the NW edge of the area, at least up to the latitude of Tolentino

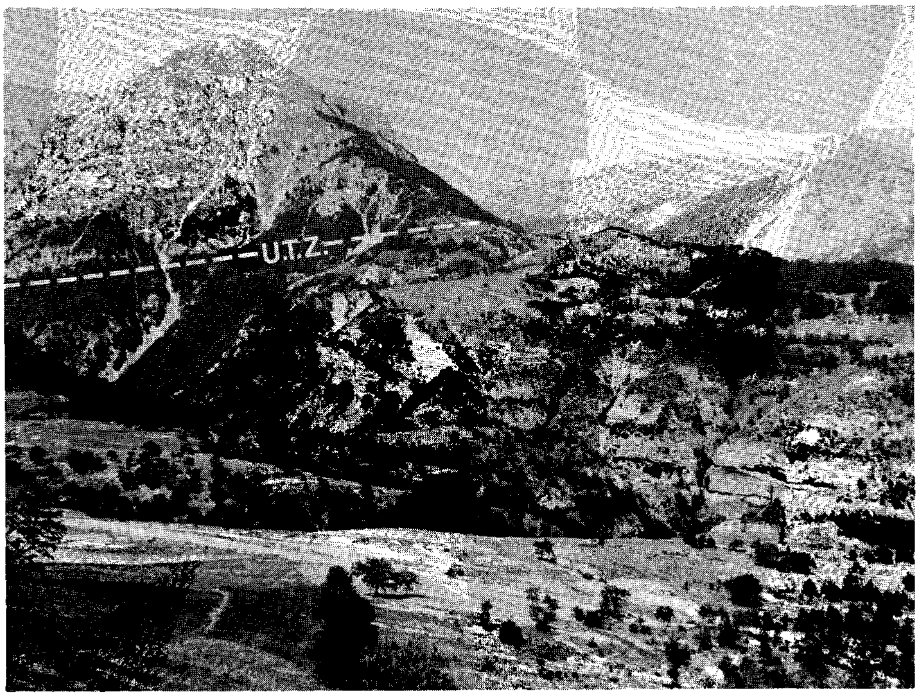
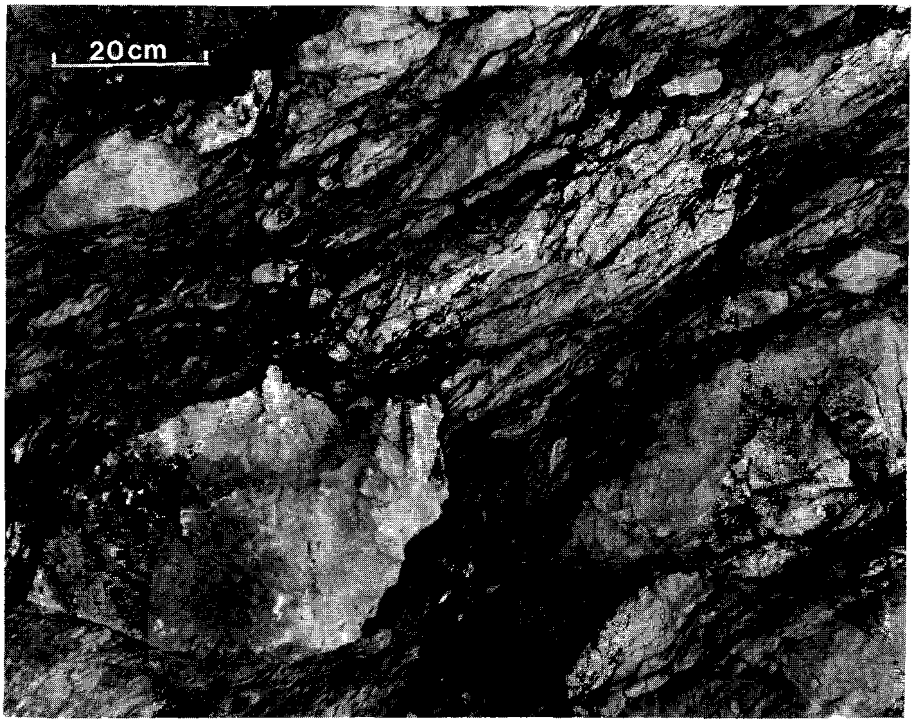


Fig. 7: View to the NW on the Monti Sibillini (with Il Pizzo to the left and M. Castel Manardo right in the background), showing the Umbria Thrust Zone (U.T.Z.) below the M. Sibilla Structure. The foot-wall is composed by the wide crest zone of the Montefortino Structure, deeply incised by the Fiume Tenna. Within the hanging wall the mainly vertical to overturned Maiolica is thrusted onto a wedge-shaped slice of inverted Scaglia along a subsidiary splay thrust.



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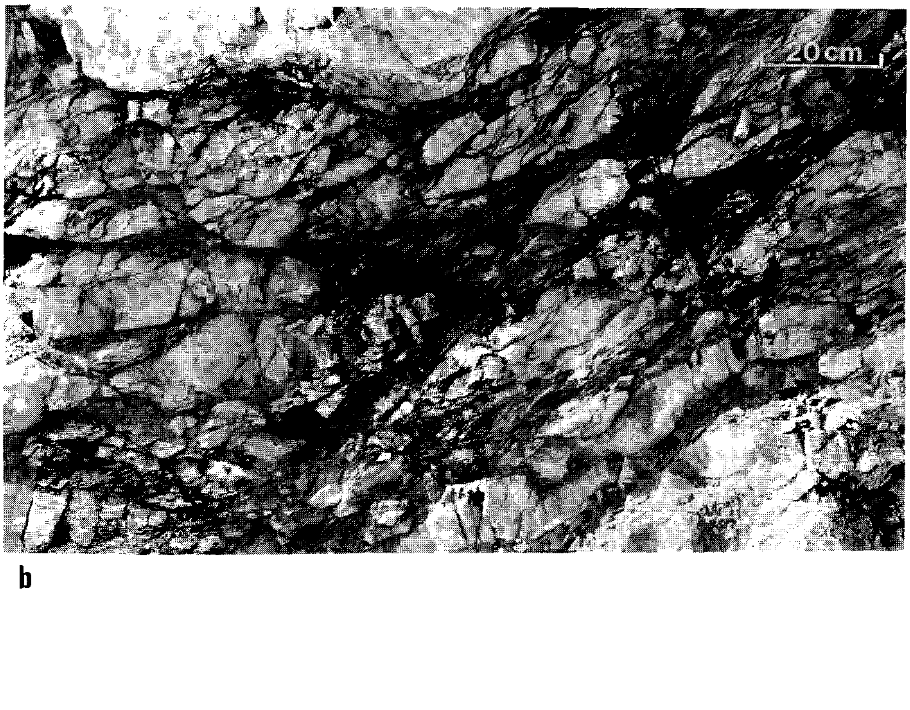


b

(Bortolotti et al., 1970; Lavecchia, 1979); on the tectonic map of Funiciello et al. (1981) the outcrop line continues even much further to the NW. Towards the S the outcrop line turns to a N - S direction along the M. Vettore. From here onward the trend is about NNE - SSW; it continues so, beyond the S edge of the area, along the E side of the M. Terminillo Massif (Scarsella, 1951; Castellarin et al., 1978; Coli, 1981).

For convenience the hanging wall has been divided arbitrary into four segments; each segment is named after one or two of its summits. From N to S the M. Sibilla Structure, the M. Vettore Massif, the M. Utero - M. Macchialta Structure and the M. Boragine - M. Pizzuto Structure (see Geol. Map); in S ward direction the latter continues in the M. Terminillo Massif. In the N a separate M. Bove Structure is distinguished, to the SW of the M. Sibilla Structure. Moreover, later on, in a separate section (3.4), footwall structures will be dealt with, like the Montefortino Structure and the M. Prato Structure.

3.2.b. CHARACTER OF THE THRUST ZONE

The outcrop line of the thrust is largely determined by the topography. So on a regional scale the general attitude of the main thrust is horizontal to slightly dipping. Steeper inclinations are related to subsidiary splay thrusts (see 3.2.f) and subsequent large-scale folding over footwall structures (see 3.4). Along most of its length the thrust overrides the Scaglia Cinerea and the Acquasanta Group of the footwall (level 4 of the multilayered sequence: see p. 42). Generally the overlying Laga Formation is missing in the footwall. It is slightly overridden only along the thrust segment between the Fiume Aso valley in the N and Capodacqua in the S (see Geol. Map and Sections D, E and G), with a maximum stratigraphic offset

← *Fig. 8-a,b: Examples of deformation in the Umbria Thrust Zone. Tectonic lenses of limestone in pervasively sheared marls. Inverted top of the Scaglia along the road to the Forca Canapine, near Capodacqua.*

Fig. 9: Tectonic lenses of pink coarsely grained bioclastic limestone, embedded in incompetent pervasively sheared marl (Scaglia Cinerea). Orientation of the slickensides on the blocks and on shear veins in the marl is SW - NE (back to front in the picture); they indicate a 60° NE direction of thrusting. Location: Umbria Thrust Zone, to the W of Terracino.

to the E of the M. Vettore Massif, where the Calcare Massiccio (level 2) overrides the Laga Formation (level 5; see Section E).

The thrust zone is accompanied by penetrative whole rock deformation (Elliott, 1976). A more or less wide zone of distributed shear (Kehle, 1970) affects the incompetent rocks of the Scaglia Cinerea and adjacent levels of the Acquasanta Group and the Scaglia. The original bedding has been destroyed completely: the competent limestone intercalations are fragmented as tectonic lenses of all sizes in the pervasively sheared marls (figs. 8 and 9). In the Acquasanta Group the deformation pattern is even more complex and inhomogeneous,

Fig. 10: Pervasively sheared marls of the Acquasanta Group. Location: Umbria Thrust Zone, along the road from Roccasalli to Terracino, to the N of Colleposta.

mainly due to the stronger contrasts between its marl and limestone layers. Along much of the thrust the Acquasanta Group is exposed as a highly tectonized zone of variable thickness *) (see fig. 10).

On top of this deformation zone the thrust contact with the hanging wall is generally sharply defined. Where the overthrust truncates the hanging wall Calcare Massiccio (level 2), and the lower part of level 3, this discrete surface may be accompanied by a thin level of tectonic breccia. Generally in these units penetrative deformation decreases in a short distance away from the overthrust, whereas in the upper part of level 3 deformation reaches much further upward in the hanging wall. A generally thin level of pervasively sheared Scaglia Cinerea, with a thickness reduced to some tens of cm,

*) This zone is very well exposed in a small window to the SE of the M. Utero: the window of S. Giovanni/Terracino; along the road from Accumoli via Terracino to Roccasalli; to the E of Cittareale (M. Prato Structure) and in a zone from the Valle S. Rufo to Aleggia, which continues to the E side of the M. Terminillo Massif.

is present all along and directly below the hanging wall block *). Obviously the highly argillaceous marl of this unit has served as a main lubricant for thrusting.

Because the main thrust zone follows a high level in the footwall stratigraphic sequence, and the Calcare Massiccio is the lowermost unit in the hanging wall, a large scale duplication of the cover must exist, above a level at least below the Calcare Massiccio. It is postulated that along the underlying Burano Formation (level 1; see p. 42) a total detachment has taken place of the complete sedimentary cover from its pre-Triassic basement. As noted in section 3.1. similar conclusions have been drawn in adjacent areas by several authors.

The thrust segment that connects this low level Burano Detachment Zone with the high level Umbria Thrust Zone cuts the mechanically anisotropic sequence steplike, forming tectonic ramps where the thrust climbs up-section through the competent units (Rich, 1934; Douglas, 1950; Harris & Milici, 1977). The schematic diagram of fig. 11 shows a highly simplified configuration: only one major step in a single thrust fault is drawn through the Calcare Massiccio, merging smoothly through the overlying limestone units into the high level overthrust or flat (Douglas, 1950; Butler, 1982). In general the situation will not be as simple as shown, due to the ductility contrasts in the multilayered sequence.

The main flats of the stepped thrust follow the Burano Formation (level 1) and the Scaglia Cinerea/Acquasanta Group (i.e. the overthrust in outcrop; level 4). The major ramp is where the thrust fault cuts across the thick competent Calcare Massiccio (level 2). Smaller high angle segments may be present through the other competent units of level 3. However, the well-defined bedding in these units may also favour lower inclinations of the thrust segments. This is shown for

*) For example to the E of the M. Torrone (M. Vettore Massif), in the tributaries of the Torrente Fluvione (Fosso di Casale and Fosso di Colleluce); along the contact around the window of S. Giovanni/Terracino (very well exposed in the S. part of the Valle Cupa, W of the Fonte Cerasa, and near the Fonte d'Utero); and to the SE of the M. Boragine.

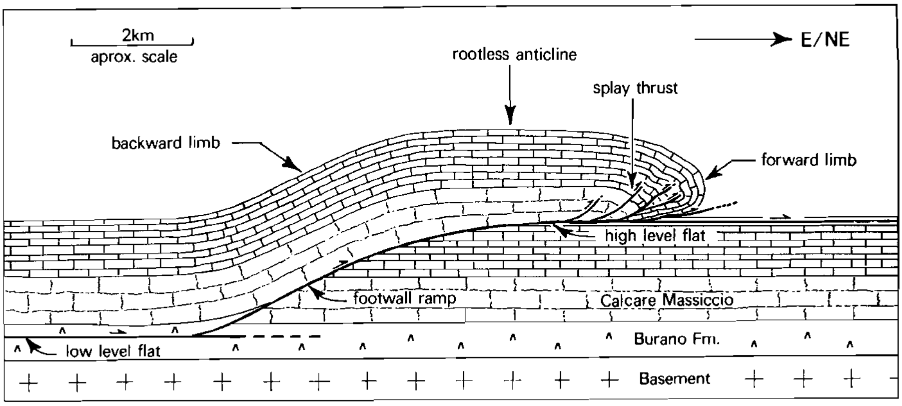


Fig. 11: Schematic diagram showing the concept of the Umbria Thrust Zone as a stepped thrust. The backward limb is generally covered by the next higher overthrust.

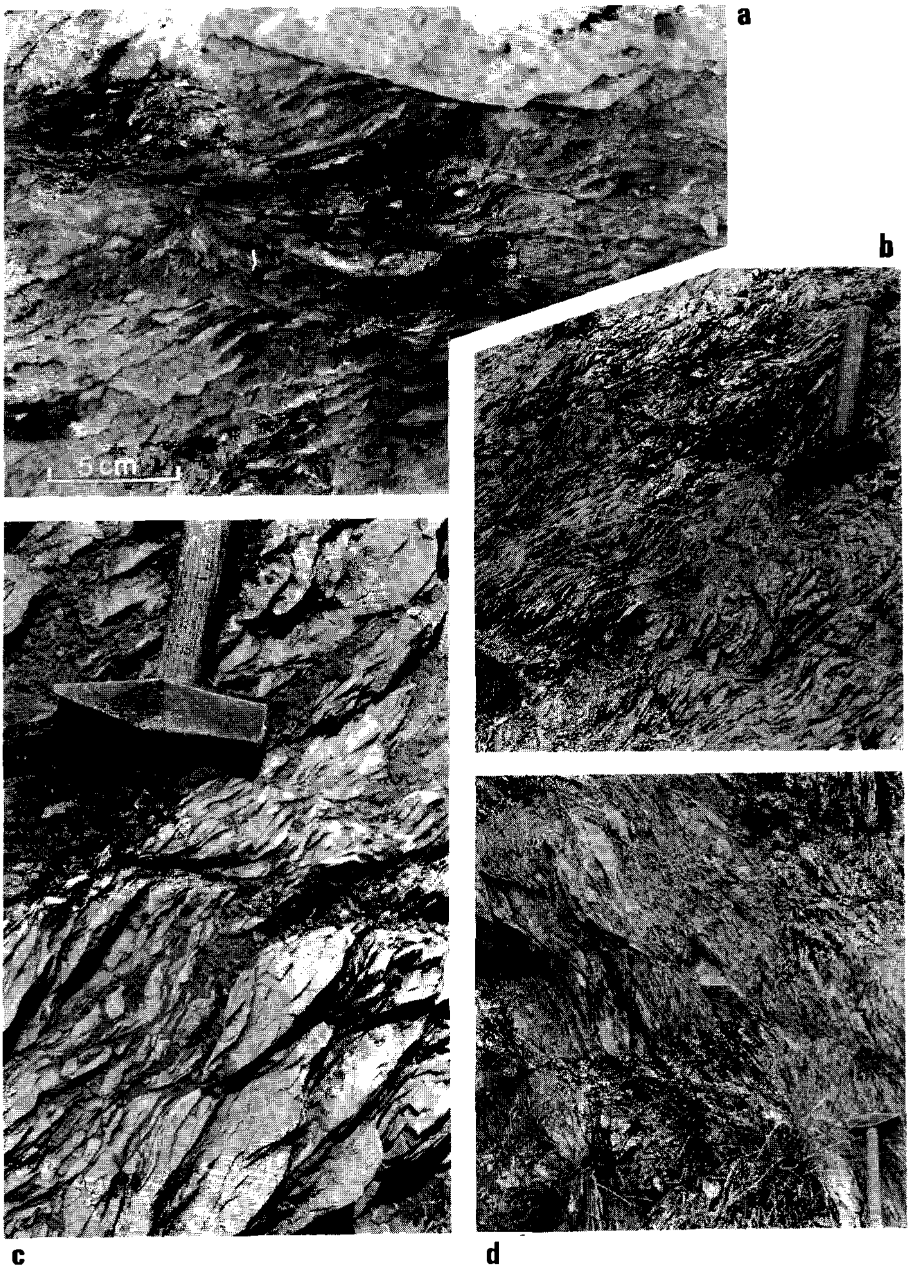
example along the N edge of the window of S. Giovanni/Terracino (Sections F5F10 and H1H4), where the main thrust zone cuts the bedding of the hanging wall Corniola mainly at a very low angle.

Only the high level flat of the Umbria Thrust Zone is exposed. The major footwall ramp and the low level flat remain well below the present erosion surface *). However, their general trends and attitudes can be deduced from the geometric configurations in the hanging wall, as will be shown (see 3.2.d).

3.2.c. SOLUTION CLEAVAGE AND SHEAR VEINS

The geometries in the overthrust zone are similar to those in shear zones, as described by Ramsay & Graham (1970) and Ramsay (1980); actually, shear along the deformation zone has been highly inhomogeneous,

*) In W Tuscany the Tuscan Nappe has also thrusted mainly along the levels of its Triassic evaporites (equivalent with the Burano Formation). Here the underlying basement is exposed in a few tectonic windows (of the Alpi Apuane, M. Pisani and Siena regions), mainly due to Miocene to recent uplift (Giannini & Lazzarotto, 1967; Abbate & Sagri, 1970; Giannini et al., 1972; Dallan Nardi & Nardi, 1972; Elter & Trevisan, 1973; Giannini & Lazzarotto, 1975; etc).


a
5 cm
b
c
d

due to variations in shear strength of the rocks involved, and movement occurred along numerous discrete slip surfaces (Elliott, 1976; Mandl & Shippam, 1981).

The shear zone is characterized by a very penetrative solution cleavage (Geiser, 1974; Geiser & Sansone, 1981; spaced cleavage of Alvarez et al., 1976, 1978; stylolitic cleavage of Powell, 1979; etc.). Generally this cleavage is subsequently pervaded by single or multiple sets of minor faults, which may be characterized as shear veins (Ramsay, 1981). Solution cleavage and shear veins are closely related, and indicate that pressure solution slip (Elliott, 1976) was by far the most important thrust mechanism.

The solution cleavage varies: from coarse, wavy and weakly developed in bioclastic limestones; more closely spaced (40 mm to less than 1 mm), undulose to quite regular in biomicritic limestones; to highly penetrative in more argillaceous rocks, while the content of argillaceous material on the cleavage planes increases in this order. The pressure solution origin of the cleavage is reflected by these films of insoluble residue, and in the more calcareous rocks also by the presence of stylolites, that may be perpendicular to highly oblique to the cleavage planes. Increasing intensity of the cleavage is characterized by thicker films of insoluble residue and closer spacing in all lithologies. Gradual variations occur within individual beds, whereas sharp contrasts in cleavage intensity are present on well-defined competent/incompetent transitions (see for example fig. 8b).

Maximum cleavage intensity occurs in the incompetent levels of the Scaglia Cinerea, Acquasanta Group, and part of the Scaglia in the Umbria Thrust Zone. Here local variations in cleavage orientation increase. Mainly in the incompetent argillaceous rocks (figs 12a, b, d,

←*Fig. 12: Examples of penetrative deformation patterns in the Umbria Thrust Zone. In a, b and c NE is to the right; in d to the left. Locations: a. Acquasanta Group near Aleggia;*
b. Scaglia Cinerea: Fiume Aso Valley W of Rocca;
c. Scaglia to the W of Villanova;
d. Acquasanta Group: Colleposta.

fig. 8; fig. 9), but locally also in the biomicritic limestone (fig. 12c; fig. 8a) the cleavage is curved into numerous narrow bundles with a strong preferred orientation towards the general thrust plane. In these zones pressure solution, partly at new cleavage planes, probably has been continuous with progressive deformation; the new cleavage planes tend to parallelism with the curved and reorientated older ones, resulting in still closer spacings, and generally anastomosing patterns (fig. 13a). Large cleavage intensity is accompanied by strong reduction

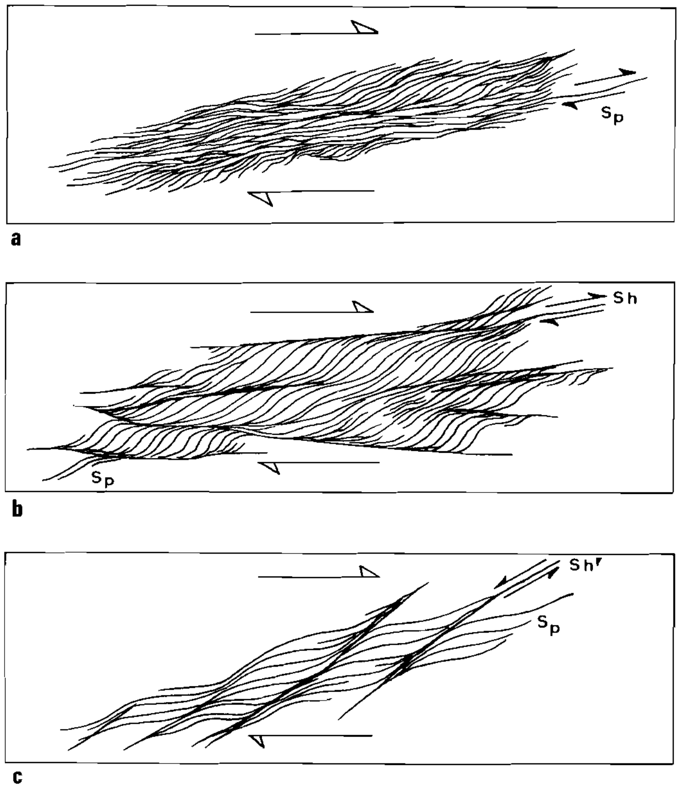


Fig. 13: Tectonic elements of the thrust zone.
Open arrows indicate the direction of thrusting.

s_p = solution cleavage

sh = low angle shear veins

sh' = high angle shear veins.

of the cleavage domains. Originally biomicritic limestone may even have changed into a strongly argillaceous aggregate. Slip is indicated by very fine grooves in the argillaceous residue on the cleavage planes, produced by solution-resistant grains. Due to larger internal shear strength, the cleavage in the competent tectonic lenses has generally remained at a relatively high angle to the general thrust zone. Such lenses behaved mainly completely passive amid the intensively strained incompetent rocks (fig. 8b).

The attitude of the cleavage in the thrust zone indicates that its development is closely related to shear (Ramsay & Graham, 1970; Alvarez et al., 1978; Helmstaedt & Greggs, 1980). Where solution cleavage is the only tectonic fabric element, it has been developed and partly rotated to parallelism with the general thrust plane (XY plane, or plane of flattening; Williams, 1977).

However, in most places with large cleavage intensity the rocks are also pervaded by single or multiple sets of shear veins. As distinct from solution cleavage these are minor faults, generally covered by bundles of elongated fibrous calcite crystals, syntaxially grown on irregularities of the fault walls (Durney & Ramsay, 1973; accretion steps c.f. Elliott, 1976). They indicate a component of extension subparallel to the faults. The calcite fibres may be called slickensides (in a descriptive non-genetic sense, following Elliott, 1976) and the small steps at the ends of the fibre bundles indicate the sense of shear (Durney & Ramsay, 1973; Ramsay, 1981). The length of the individual bundles may vary between some mm to tens of cm; the latter on faults extending up to several meters.

The shear veins are generally curviplanar, and locally splay into anastomosing systems. They cut the solution cleavage and also previous anisotropies (like bedding, where preserved) at a moderate to very low angle (fig. 13a, b). Slickensides of elongated fibrous calcite are generally also present on the tectonic lenses (fig. 9a).

At the shear veins the solution cleavage is curved gradually towards their orientation, which has resulted in a sigmoidal shape of the cleavage in cross section (figs. 12, 13, 14). Curvature of the

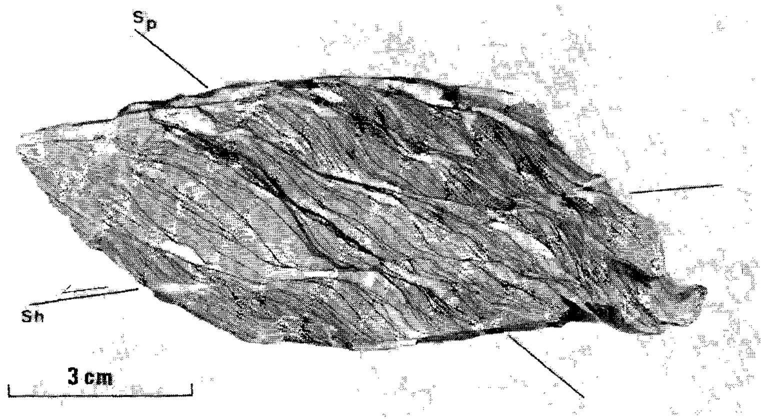


Fig. 14: photograph of a polished surface, showing a penetrative solution cleavage (S_p), sigmoidally curved at irregular discontinuous shear veins (Sh). Scaglia; Umbria Thrust Zone in the Fiume Tenna valley.

cleavage is always in accordance with the sense of shear, as indicated by the slickensides on the adjacent shear vein. Locally only domains of sigmoidally shaped cleavage are present bounded by narrow zones of pervasive solution cleavage, without true discontinuities by failure. The bending of the small domains between the sigmoidally curved cleavage planes is attended with slip along the cleavage, continuing pressure solution, locally at new stylolitic planes, and perpendicular extension veins, mainly in the outside bends of the domains (see fig. 14). Subsequent small offsets of these extension veins may indicate continuing pressure solution and/or slip along the cleavage. Highly discontinuous extension veins and shear veins with short accretion steps may also follow earlier solution planes.

Two sets of shear veins can be distinguished, with opposite sense of slip. Those at a moderate to very small inclination to the thrust zone (low angle set: Sh; fig. 13b), and shear veins at a relative high inclination to the thrust zone (high angle set: Sh'; fig. 13c). Low angle sets have a sense of shear in the direction of thrusting (indicated by the steps of the slickensides and the sigmoidal shape of the

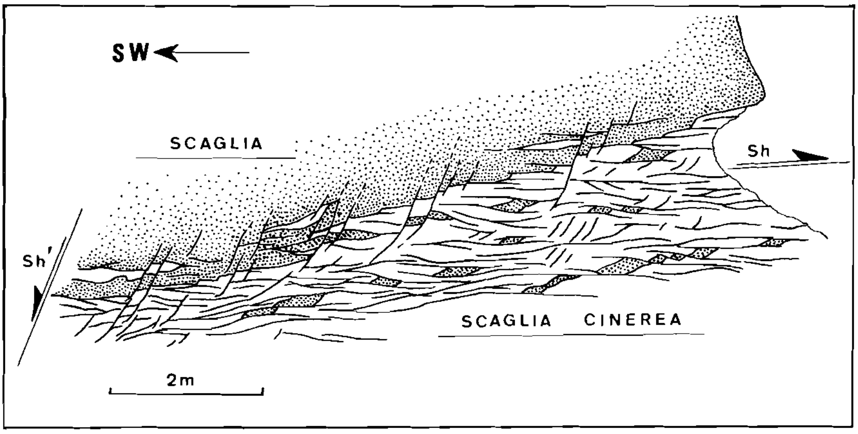


Fig. 15: Sketch of the Umbria Thrust Zone to the W of Scanzano (M. Boragine - M. Pizzuto Structure), showing the complex pattern of low- and high angle shear veins. Competent rocks in the Scaglia Cinerea and the overlying inverted Scaglia are dotted. Solution cleavage in the incompetent rocks and mesoscopic folds in the Scaglia are not shown. The rocks of the Acquasanta Group below are also highly deformed. General view drawn in the field; details are partly traced from photographs.

adjacent cleavage). The high angle sets dip mainly to the W and SW, and the sense of shear is opposite to the direction of thrusting. Commonly Sh and Sh' are unequally developed: Sh is always dominant, and generally more closely spaced. Sh and Sh' may be present in multiple systems of various spacing (between several meters to 1 mm in zones of strongly localized shearing). In some localities the high angle shear veins cut across the low angle sets *), offsetting them. Displacement along the latter must have been blocked. However, movement seems to have been taken over by low angle sets at other levels, because the high angle set may be curved, and merge into anastomosing younger systems (fig. 15). This may suggest that the multiple sets have developed during a protracted phase of deformation.

*) For example at the W side of the Valle S. Rufo; to the E of the M. Boragine (fig. 15); and also well exposed along the valleys of the Torrente Scura and Torrente Rara, both running from the E side of the M. Terminillo Massif to the Fiume Velino (to the S of the mapped area).

Moreover, near and in the thrust zone the shear veins and/or penetrative solution cleavage may be disharmonically folded on a small scale (1 - 50 cm), (fig. 16). These folds are mainly strongly asymmetric to recumbent, generally non-cylindrical, and their limbs may be cut by subsequent shear veins, along which the hinges are transposed. It is proposed that this folding was contemporaneous with thrusting, due to local adhesional drag by inhomogeneous internal strain.

The orientations and the attitudes of the shear veins correspond quite well with the synthetic and antithetic secondary faulting in a thrust zone, as analysed by Mandl & Shippam (1981). Moreover, they also show the morphology of shear-bands or extensional crenulation cleavage, as described from shear zones or mylonitic zones in metamorphic terrains (Cobbold, 1977a, b; Platt & Vissers, 1980). According

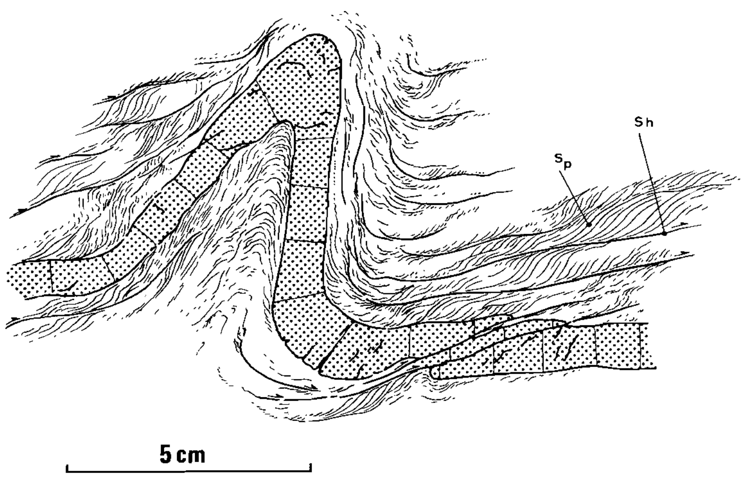


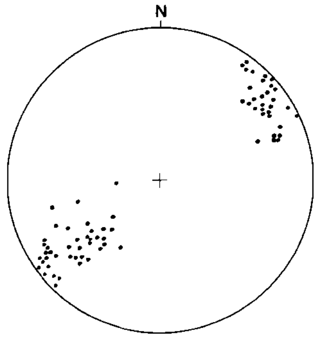
Fig. 16: Small scale fold in the Scaglia Cinerea. Solution cleavage planes (S_p) and shear veins (Sh) are folded together with a bed of competent coarsely grained lithoclastic limestone. Location: Umbria Thrust Zone in the Valle Cupa, to the N of S. Giovanni.

to Platt & Vissers (1980) their development seems to have been controlled by high rates of shear strain at a high angle to pre-existing inhomogeneities (bedding and solution cleavage). The sigmoidal shape of the cleavage in the domains suggests that shear strain gradually increased in zones of limited width. Strong reduction in size of the cleavage domains and increase of the insoluble residue by continuous pressure solution resulted in a softening of the rock in these localized zones, and beyond a certain limit of coherent deformation the true discontinuities by failure developed. Sh and Sh' have developed in orientations parallel to the directions of maximal shear strain of the local finite strain ellipsoid. With progressive deformation they have rotated, while they are followed by new sets in more favourable orientations, as long as displacement has continued.

The dominance of solution cleavage and shear veins in the thrust zone indicates that pressure solution slip (Elliott, 1976) rather than sliding by brittle failure was by far the most important thrust-mechanism. The azimuth of the slickensides (both the calcite fibres on the shear veins and the striations in the films of insoluble residue on the cleavage) in the Umbria Thrust Zone are indicative for the direction of thrusting. This azimuth is remarkably constant: SW - NE, with a maximum around 60^o (fig. 17). Moreover, it also corresponds quite well with the grooves produced by frictional sliding (Byerlee, 1967) on brittle stretches of the thrust fault *).

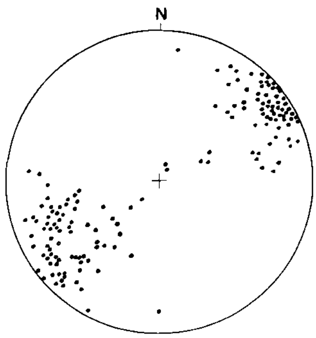
These lineations produced by all kinds of sliding indicate unambiguously a NE direction of thrusting, regardless of the strikes in the hanging wall and the direction of the outcrop line of the overthrust.

*) At the base of the Maiolica,at the NW side of the Fiume Tenna valley (Section B1B2); below the Corniola, to the SE of the M. Utero; and below the hanging wall-Maiolica to the E of the M. Boragine (Section M).



Slickensides: NW - SE trending part of the Umbria Thrust Zone (Fiume Tenna and Torrente Ambro valleys).

n = 72



Slickensides: NNE - SSW trending part of the Umbria Thrust Zone (S of the Fiume Aso valley).

n = 150

Fig. 17: Equal area projections of the slickensides on the shear vein-systems, along the Umbria Thrust Zone.

3.2.d. THE LARGE ANTICLINES

Contemporaneously with movement along the stepped overthrust the thrust sheet must bend over the footwall ramp, generating an anticlinal structure (fig. 11; rootless anticline: Harris & Milici, 1977; Harris, 1979; culmination of Dahlstrom, 1970; Butler, 1982; ramp anticline of Suter, 1981). Such a rootless anticline is shaped like a boxfold, with a more or less wide flat crest zone (Rich, 1934; Berger & Johnson, 1980). However, no anticlinal core is present below the thrust.

The lower stratigraphic units in the hanging wall (level 2: Calcare Massiccio, and generally also the competent units of the lower part of level 3: mainly the Corniola) are everywhere present in normal upright position, only moderately inclined (see Sections A, B1B2, E and H). Obviously in the relatively rigid and coherent Calcare Massiccio the stepping-up to the high level flat was preceeded by very limited buckling. The thrust truncates its unfolded strata, and movement up the ramp has caused bending only in the backward limb of the rootless anticline, above the footwall ramp (Berger & Johnson, 1980).

On the contrary the overlying units of the hanging wall sequence (level 3 from the top of the Corniola to the Scaglia Cinerea) become increasingly vertical to overturned near the thrust zone. They describe a complex asymmetric forward limb of the rootless anticline, (proximal limb of Berger & Johnson, 1980, 1982; frontal culmination wall of Butler, 1982). Weak to penetrative deformation is largely concentrated in this overturned forward limb and extends far away from the overthrust. Here the rocks are generally disharmonically folded on mesoscopic scale (3.2.e), and offset by subsidiary splay thrusts and associated minor faults (3.2.g).

As the rocks in the forward limb get completely overturned, mesoscopic folding, splay faulting, bedding plane slip, and cleavage are intensified, till finally the rocks are sheared out in the thrust zone. Only a thin level of Scaglia Cinerea has remained behind everywhere along the thrust *).

In the wide flat crestzone of a rootless anticline no axial plane can be defined (see for example Sections A, B, G1G4 and L1L2); the width depends on the amount of displacement along the stepped thrust (see fig. 11). Generally deformation in the crest is slight, unless it forms the footwall of a higher thrust, as can be seen in the SW parts of Sections A and B and in the NW part of Section L1L2.

The backward limb of the rootless anticline (ramp flexure of Suter, 1981; dorsal culmination wall of Butler, 1982; distal limb of

*) To the S of the M. Utero (in the NW part of the window of S. Giovanni/Terracino) also a thrust slice of Scaglia has remained behind, below the sharply defined thrust with the Corniola in hanging wall-position (see Section H3H4).

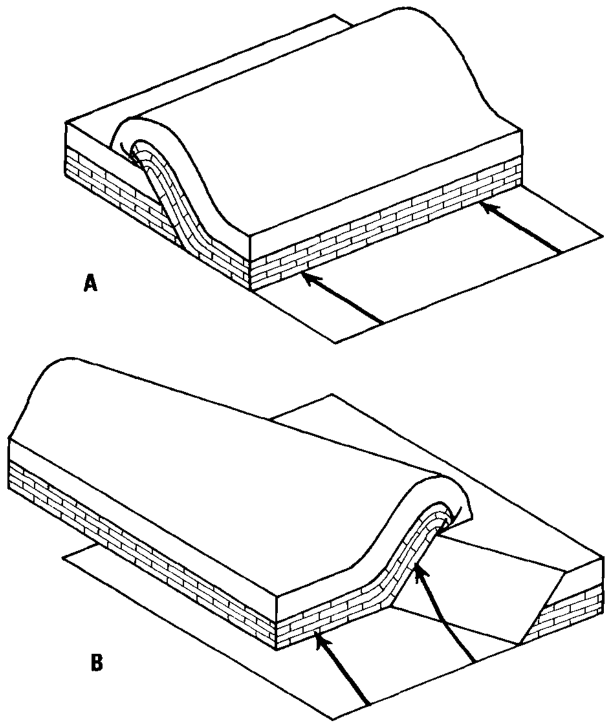


Fig. 18: Block diagrams to illustrate the independence between the strike of a rootless anticline on top of a ramp and the direction of thrusting.
Note the similar cross sections.
A. strike of the ramp perpendicular to the direction of overthrust.
B. strike of the ramp oblique to the direction of overthrust; this results in a strike slip component of movement along the ramp.

Berger & Johnson, 1980, 1982) reflects the position and the attitude of the underlying footwall ramp. It is, however, often impossible to find this limb, for two reasons. Firstly, the W and SW part of the rootless anticline above the Umbria Thrust Zone is covered by similar structures. For example in the Monti Sibillini (Section A and B) the backward limb of the M. Sibilla Structure is hidden below the disharmonically folded forward limb of the overlying M. Bove Structure. In the second place, large parts of the area directly to the W of the Umbria Thrust Zone are cut by steep normal faults, like those bordering the Piano Grande of Castelluccio and the Piano S. Scolastica. This subsequent block-faulting obscures many of the older structures, by offsetting them well below the present erosion surface.

The strike of the forward limb reflects the general strike of the footwall ramp; also when the step-up to the high level flat is completed, and the hanging wall ramp lies far beyond its footwall counterpart (see fig. 18).

In the N part of the area the forward limb of the M. Sibilla Structure strikes NW - SE and the rootless anticline faces to the NE. Therefore, the footwall ramp, along which the structure was generated also strikes NW - SE, i.e. about perpendicular to the direction of thrusting.

On the contrary in the S part of the area (to the S of the M. Vettore Massif) the forward limb in the hanging wall faces mainly to the ESE (M. Utero - M. Macchialta Structure; M. Boragine - M. Pizzuto Structure), reflecting a SSW - NNE striking ramp in the footwall. Here the trace of the Umbria Thrust Zone, the strike of the forward limb and therefore of the footwall ramp make an acute angle with the NE ward direction of thrusting (see fig. 17 and Geol. Map). The continuity of the regional thrust along the E side of the Monti Sibillini indicates that the perpendicular and oblique ramps are joined, and are parts of one integrated thrust-system.

3.2.e. MESOSCOPIC FOLDS

Complexes of mesoscopic (second order) folds (i.e. between 1 m and 50 m) are very abundant in the large scale first order structures. Wavelengths and amplitudes vary widely and the folds are generally strongly disharmonic. The fold-style and intensity varies with lithology and position within the large scale structures.

In the Calcare Massiccio no mesoscopic folds occur at all because of its competence and the lack of bedding planes. In all the overlying well-bedded rocks of level 3 and 4, mesoscopic folds may be present (notably in the Scaglia). They occur mainly in the steep to overturned forward limbs of the rootless anticlines, while the intensity of folding increases towards the thrusts.

Fazzini (1973), who described the mesoscopic folds of the NW part of the Umbria Marche Apennines considered them as parasitic to the large scale folds. Chiocchini et al. (1976) interpreted the disharmonic folds of the Pizzo Tre Vescovi (M. Bove Structure, see Section A1A2 and figs. 22, 19a, c and 20) as slump structures, developed in unconsolidated sediments.

Also Centamore et al. (1980) ascribe the considerable thickness variations in the Scaglia to large scale slumping and gravity sliding, mainly by detachment along the Marne a Fucoidi.

The deformation mechanism in the folds, their geometries, and the fact that such folds are not restricted to the Scaglia but occur in all well-bedded limestone units, indicate a development in already consolidated rocks. Also, the folds have a distinct spatial relation to the large scale anticlines and the thrusts. They are clearly of tectonic origin.

Fold geometry

The folds, whether open or tight, have generally flat limbs and sharp hinges; they can be characterized as kinkfolds (Hobbs et al., 1976; see fig. 19).

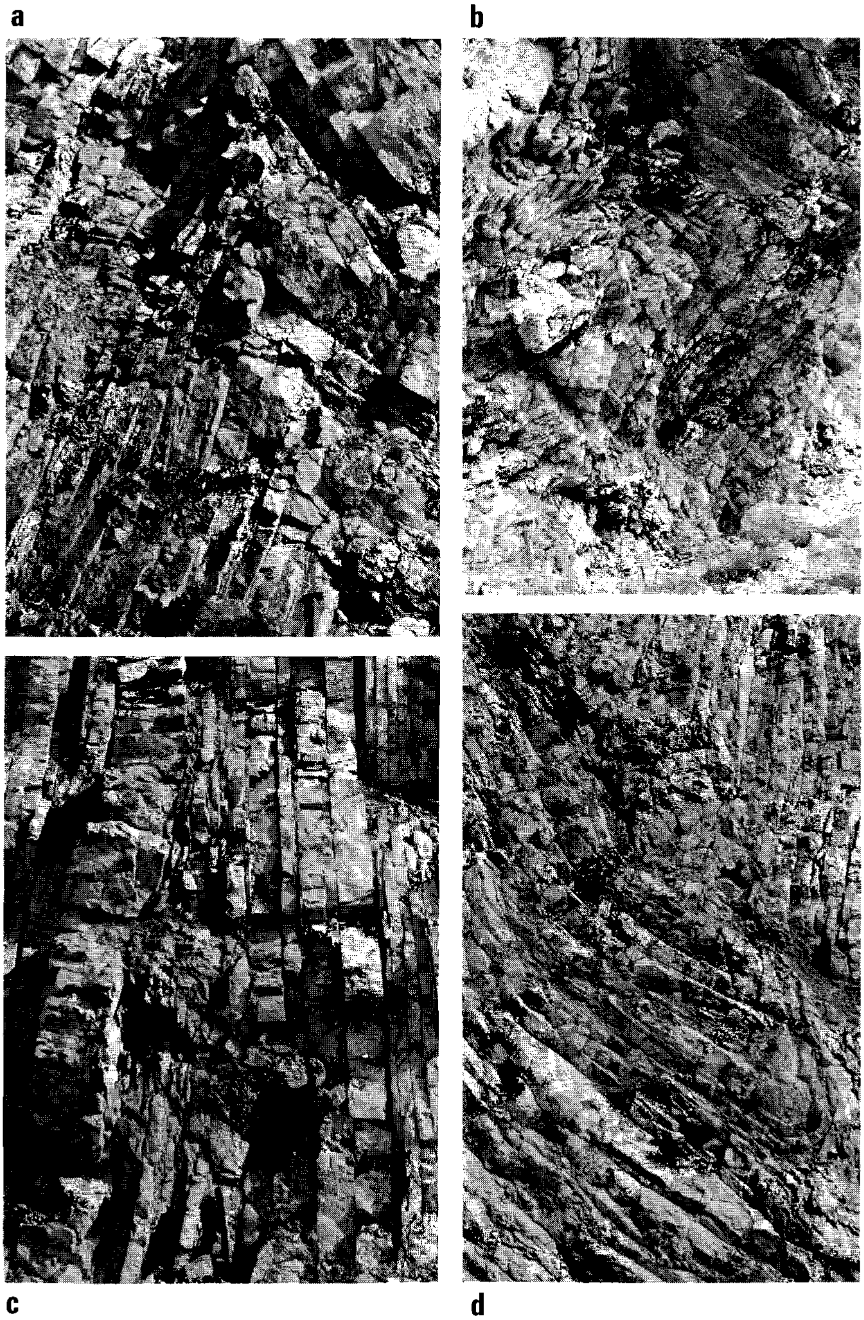
Most open kinkfolds (interlimb angles between 120^0 and 45^0) have steeply dipping axial planes (kink boundaries). The interlimb angle may vary both along strike and upwards within one and the same fold. Internal deformation is concentrated at the hinges and in the incompetent layers of the limbs. These limbs have merely rotated, with flexural slip along the bedding. The folds correspond mainly with class 1B and 1C of the fold classification of Ramsay (1967).

On the contrary, tight to isoclinal folds are generally strongly inclined to recumbent. Their attitude and tightness is associated with increased flexural slip, minor faults mainly cutting the hinges, shear veins, and also internal deformation of the limbs. A thinning of the limbs relatively to the hinges is related to the tightness of the folds, and to the argillaceous content of its constituent layers. They vary between class IC and 3 (Ramsay, 1967).

Despite the general angularity of the folds most hinges are smoothly curved (figs. 19 and 20c, d). This is achieved by cataclastic deformation with all kind of adjustment features (Laubscher, 1976). The curvature is accommodated by rotations and translations of small rigid rock segments, bounded by solution planes, microfractures, extension veins and the bedding planes. Because of the importance of dissolution processes such folds are called dissolution folds by Alvarez et al. (1976).

Phenomena related to pressure solution

Pervasive pressure solution at the contacts of individual grains has been small: the domains between the privileged solution planes (Groshong, 1975) suffered no significant internal dissolution; for example planctonic foraminifera in the Scaglia are not strained at all, even in very small rock segments (Alvarez et al., 1976). Generally the solution planes are stylolitic (stylolitic joints: Arthaud & Mattauer, 1969; Choukroune, 1969; Laubscher, 1979; Droxler & Schaer,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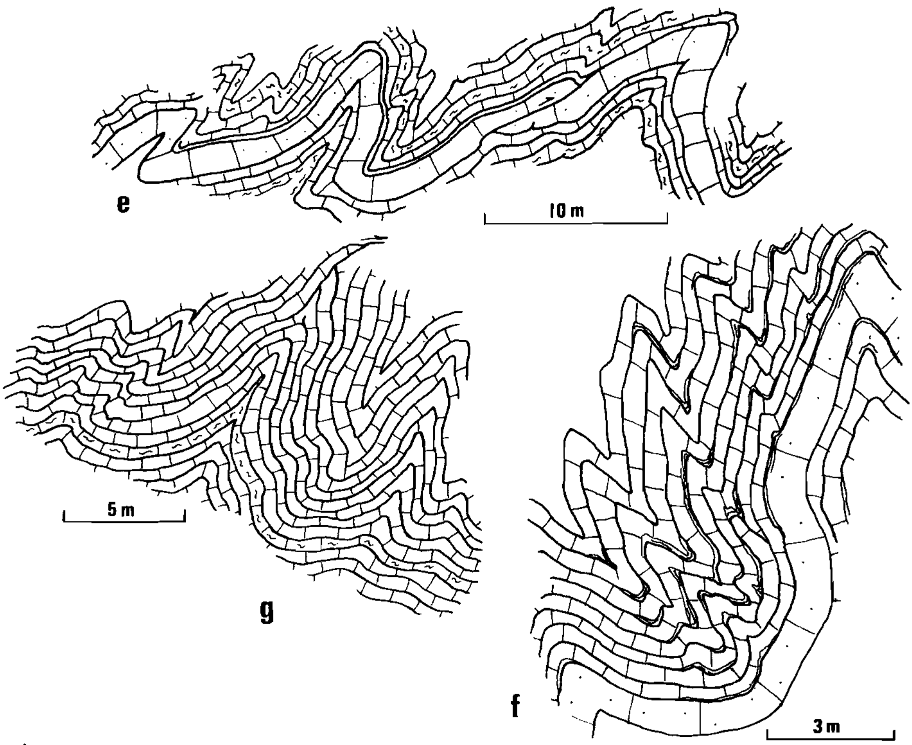


↑
← *Fig. 19: Examples of mesoscopic kinkfolds. Locations:*

a and c. Scaglia; NW side of the Pizzo Tre Vescovi (forward limb M. Bove Structure);
b. Scaglia; Fiume Aso valley, to the N of Tofe (forward limb M. Sibilla Structure);
d. Scaglia; road from La Forca to M. la Specula (forward limb M. Boragine-M. Pizzuto Structure);
e. Forca Canapine Group; S side of the M. Macchialta (crest zone M. Macchialta-M. Utero Structure);
f. Scaglia; E side of the M. Capoduro (forward limb M. Boragine-M. Pizzuto Structure);
g. Maiolica; S side of the M. Priora (crest zone M. Sibilla Structure).

e., f. and g. are drawn in the field.

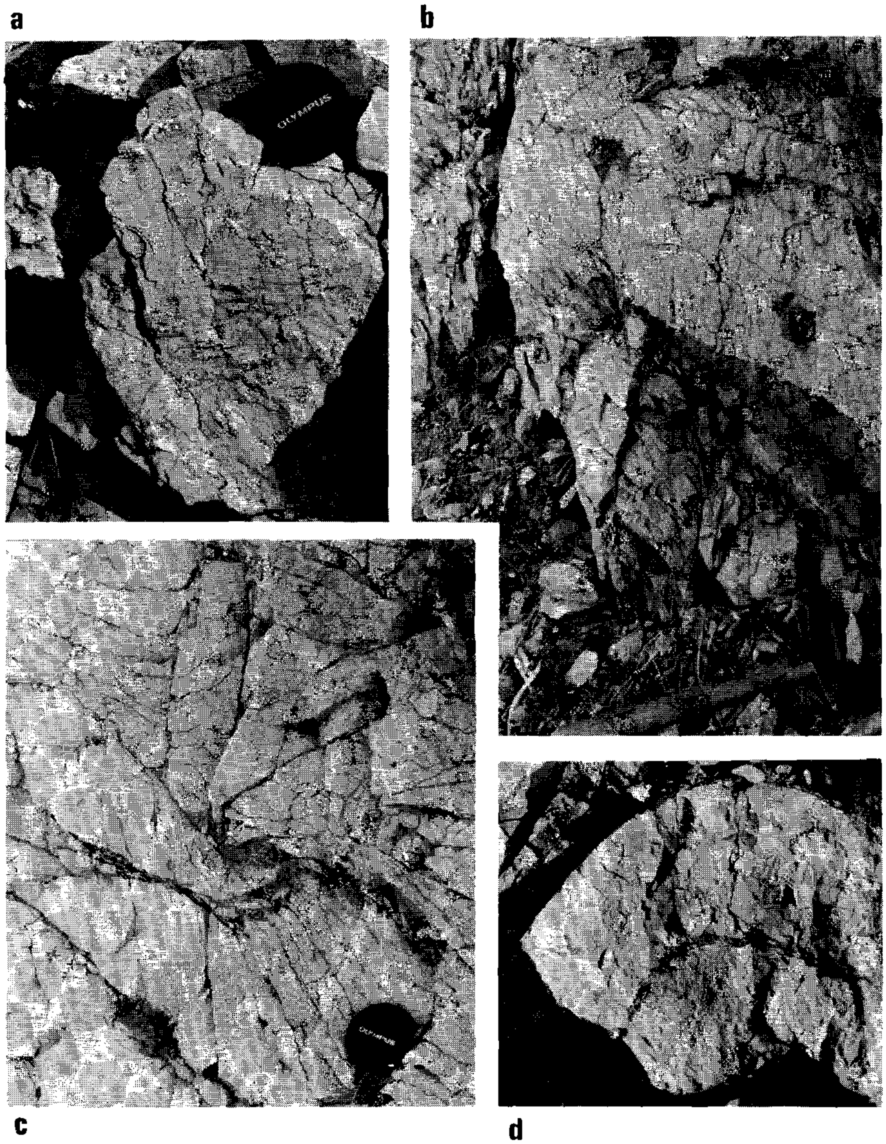


Fig. 20: Examples of deformation patterns in hinges of mesoscopic folds, showing small scale adjustment features. See text for explanations.
Location: NW side of the Pizzo Tre Vescovi (M. Bove Structure).

1979; Geiser & Sansone, 1981). In the fine-grained biomicritic limestones of level 3 (Scaglia, Maiolica and Corniola) the maximum amplitude of the stylolites is about ½ cm (see fig. 29). Larger stylolites (both in amplitude and width of the cones) may be present in the medium to coarse grained bioclastic limestones. The stylolites may be perpendicular or oblique.

Bedding parallel stylolitic planes, with perpendicular stylolites are locally abundant, also in unfolded beds. They may represent a first generation of solution planes, probably due to overburden in a pre-folding stage (Stockdale, 1922; see fig. 4). The competent beds in the limbs of open upright kinkfolds have generally weakly developed stylolitic planes; they are undulose and mainly at high angles to bedding (60^{o} - 90^{o}). These have been active only during initial stages of folding, because they are rotated together with the fold limbs, while near the hinges they are cut by younger ones. Obviously with progressive development of the folds the dissolution phenomena were concentrated in the hinges. Here stylolitic planes are of variable orientation and spacing, generally undulose to anastomosing in complex patterns of several generations, increasing with the tightness of the fold. The latest system may form a more systematic pattern fanning around the axial plane of the fold (see fig. 20a, c), with approximately perpendicular stylolites indicating a Z-axis of the local finite strain ellipsoid ($X>Y>Z$) perpendicular to the axial plane (Choukroune, 1969). In general, associated extension veins are developed approximately perpendicular to the stylolitic planes (fig. 20a). At the hinges extension occurred mainly at a high angle to the fold axis. With progressive development of the folds earlier veins may have lost their extensional character, due to rotation, and are cut again by younger veins and/or stylolitic planes,

Because the loss of volume must have been much larger (Alvarez et al. (1978) give estimates up to 25% volume loss), only part of the dissolved calcite can have recrystallized in the extension veins within the rocks nearby; the system must have been open, with transport of the soluble phase to elsewhere, as has been proposed by Geiser &

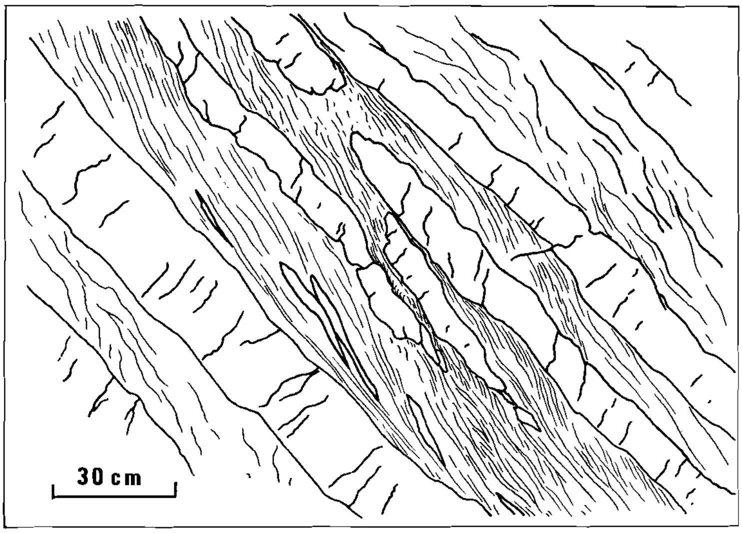


Fig. 21: Small scale imbrications of thin competent limestone beds in a fold limb, by slip at a pervasive cleavage in the more argillaceous beds. Drawing traced from a photograph. Location: N side of the Pizzo Tre Vescovi (M. Bove Structure).

Sansone (1981).

In the incompetent layers of the fold limbs much more systematically arranged patterns of solution cleavage (p. 57) are present. They are generally inclined to bedding (60^0 - 10^0). In very thin levels with high argillaceous content between much thicker competent limestone beds the cleavage may be almost parallel to bedding. Very fine striations in the argillaceous film of insoluble residue indicate slip. Where competent beds are thin and widely spaced this slip has caused their imbrication on fold limbs (fig. 21).

Systematically arranged solution cleavage is not regionally distributed; it is associated with all zones of localized shear: in the major thrust zones, as well as in zones of flexural slip in kinkfolds.

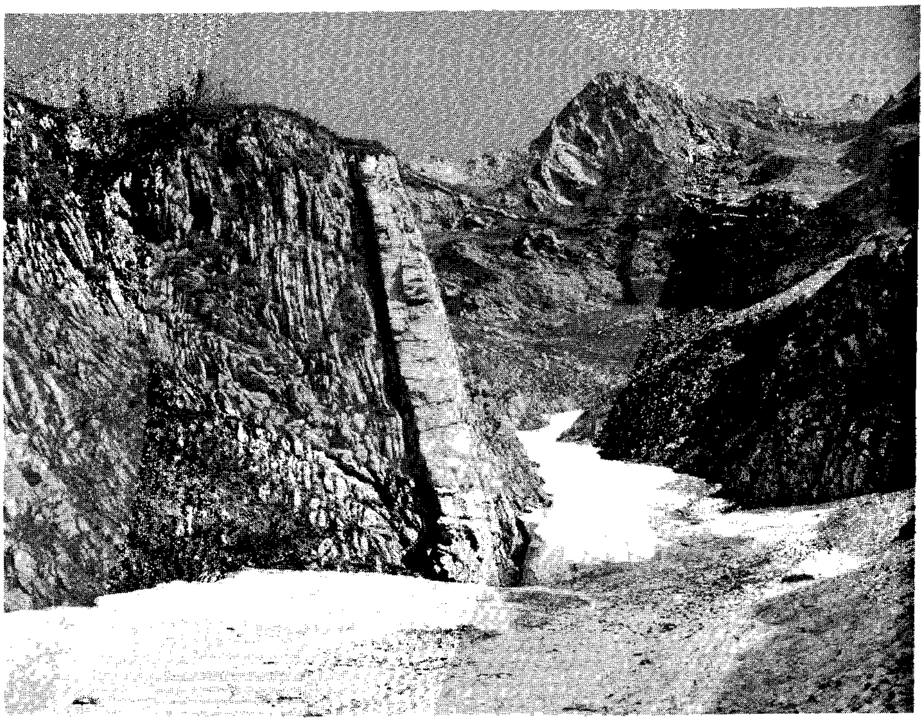


Fig. 22: SE view towards the Pizzo Tre Vescovi, showing disharmonically folded Scaglia in the forward limb of the M. Bove Structure. Amplitude and wavelength of the larger folds are mainly governed by thick bioclastic limestone intercalations (like the bed in the foreground that continues up the mountain side). The folds are relatively open and generally face to the right (i.e. towards the crest of the large scale structure). The axial planes dip 70° - 45° to the SW. Details of the folds are shown in figs. 19a, c, 20 and 21.

3.2.f. Relation to the large scale structures and thrusts

Within the enveloping surfaces of the large scale rootless anticlines each component unit has been folded more or less disharmonically with respect to the adjacent ones. Major disharmonies follow the intermediate incompetent formations; mainly the basal part of the Forca Canapine Group, and the Marne a Fucoidi (see for example Sections

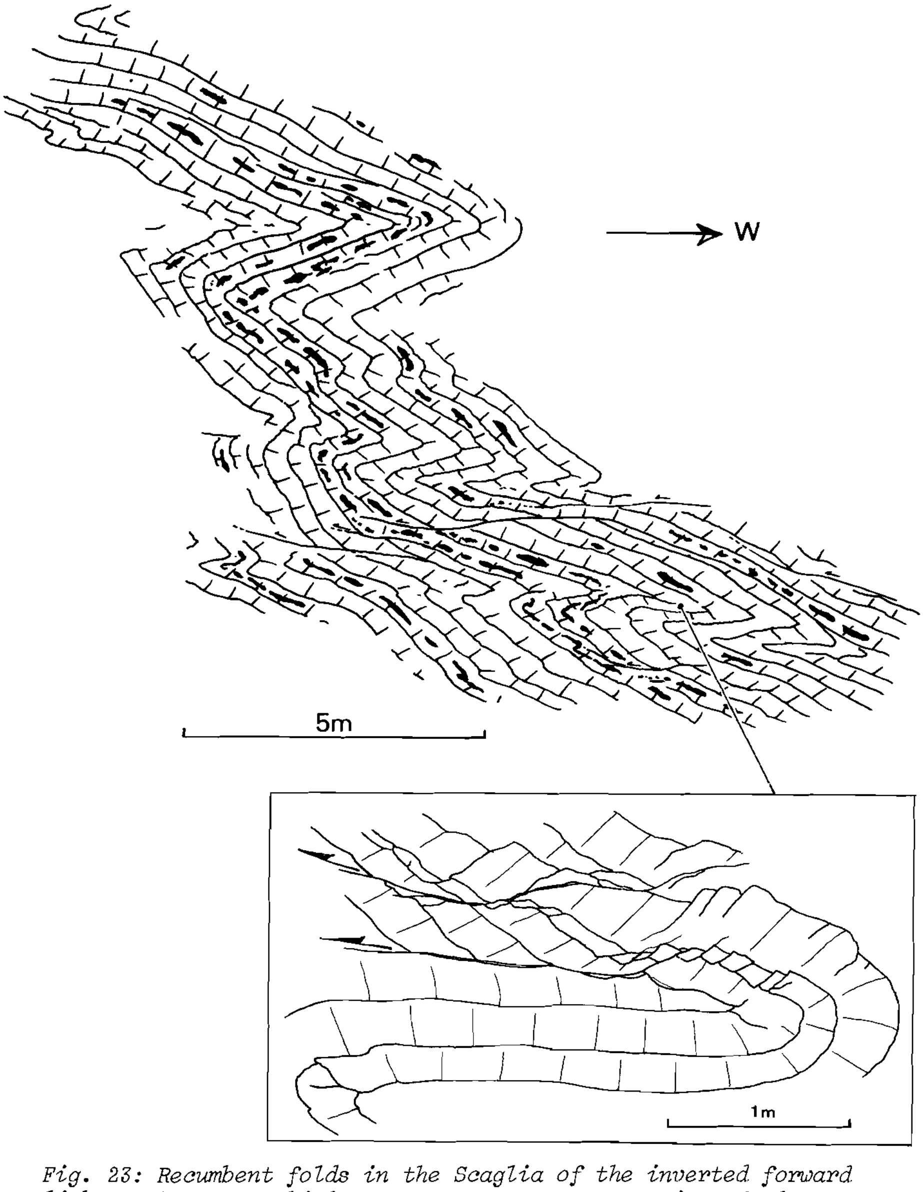


Fig. 23: Recumbent folds in the Scaglia of the inverted forward limb of the M. Macchialta - M. Utero Structure. Minor faults merge into bedding. Chert lenses and nodules are indicated in black. Schematic drawing from outcrop, near Madonna delle Coste (W of Accumoli).

D1D2 and G1G4). Along these levels large scale detachment of the overlying units occurred (hanging wall detachments c.f. Thompson, 1981; Butler, 1982).

In the forward limb the facing of the mesoscopic folds corresponds with hanging wall detachment towards the crest zone of the rootless anticline (fig. 22; see also fig. 19c, f).

On the contrary, the mesoscopic folds beyond the forward limb face in the same direction as the large scale rootless anticline to which they belong. This can be seen in the crest of the M. Sibilla Structure (M. Priora and SW side of the M. Castel Manardo: see Sections A and B), where the facing of the strongly disharmonic mesoscopic folds is clearly associated with northeasterly detachment beyond the forward limb of the M. Bove Structure. Downwards they become symmetrical chevron folds (fig. 19g), their interlimb angles decrease and they die out at a level approximately 80 m below the top of the Maiolica.

Fig. 24: View towards the N side of the Fiume Aso valley (Scoglio della Volpe), showing disharmonically folded Scaglia in the inverted forward limb of the M. Sibilla Structure. Folds are mainly strongly inclined to recumbent, and face towards the crest of the large scale structure. Down the mountain side, (i.e. towards the thrust below) cataclastic deformation in the fold limbs increases.

Fig. 25: Cataclastic deformation pattern in the Scaglia: bedding is only preserved by the brecciated and highly disrupted chert lenses. Hammer is 30 cm. Location: S side of the Fiume Tenna valley.

Intensity of folding is great in the steep to inverted forward limbs of the rootless anticlines (especially in the Scaglia), and increases towards the thrusts. Outside the zones directly influenced by thrusting kinkfolds are uprigth and relatively open.

With approach to a zone of thrusting (i.e. the main low angle thrust zone, but also towards subsidiary splay thrusts (see 3.2.g)) the folds become tight and more inclined to recumbent (figs. 23, 24 and 26). Generally also the internal cataclastic deformation in the fold limbs increases (fig. 25). Here the hinges seem to have migrated, which resulted in more continuously distributed distortion.

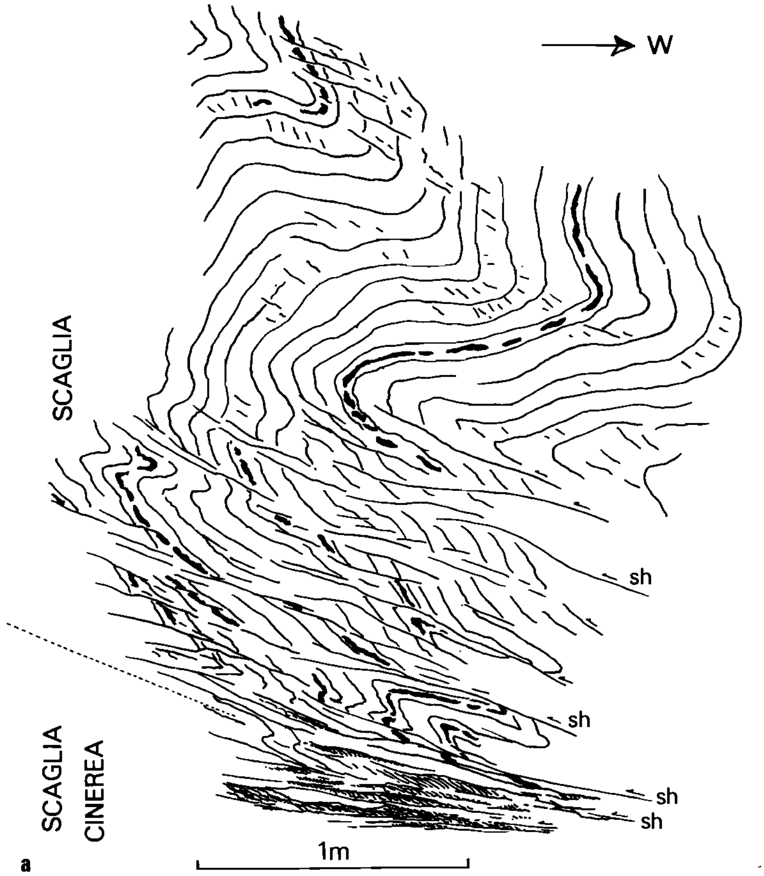
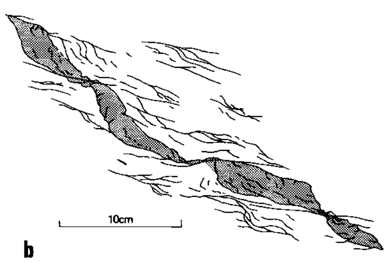
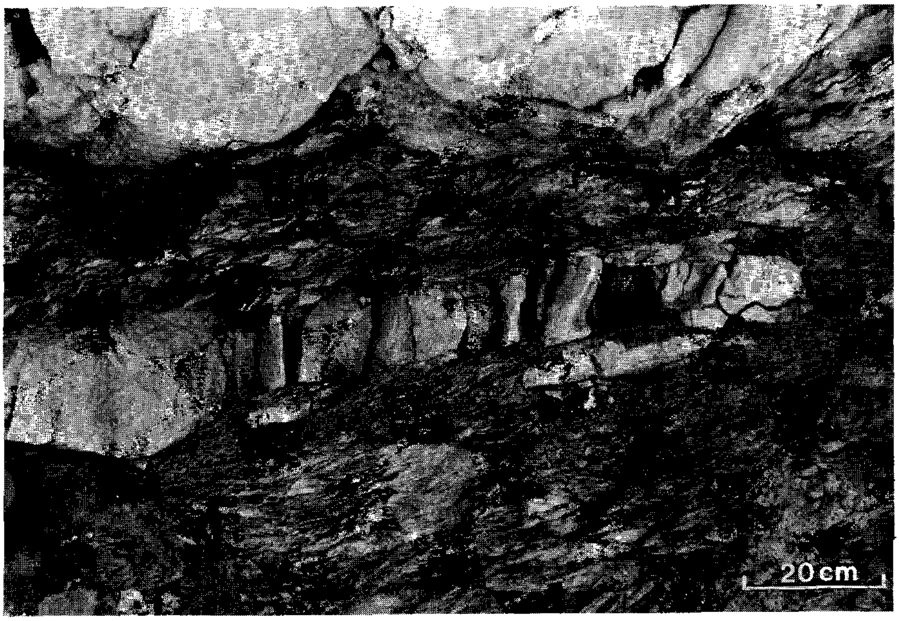
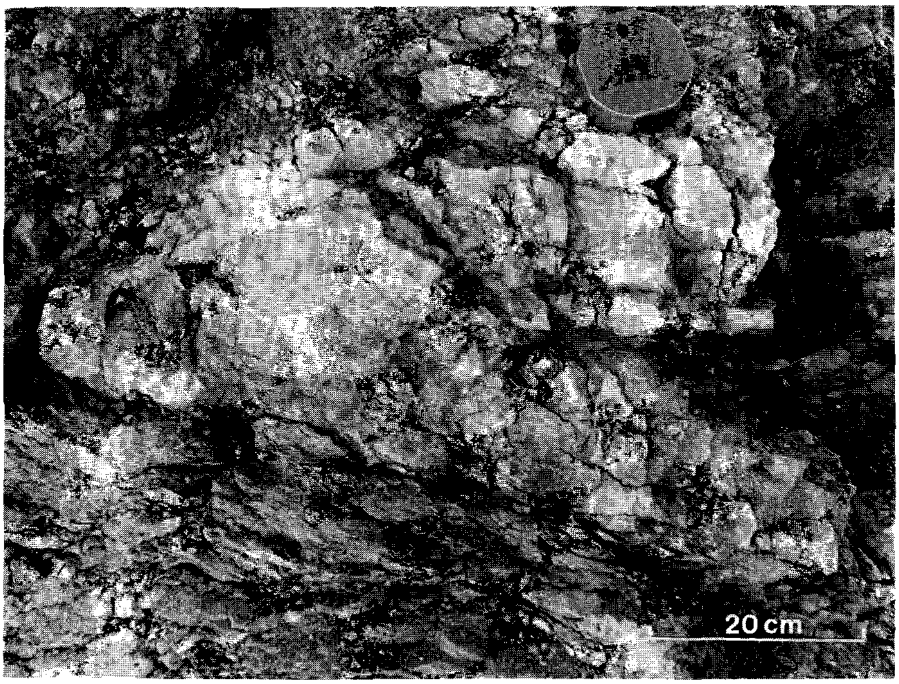


Fig. 26: Mesoscopic folds in over-turned Scaglia. Major chert lenses are indicated in black (b. shows a detail). Towards the contact with the incompetent Scaglia Cinerea (i.e. towards the thrust zone) the folds are increasingly transposed at a pervasive system of shear veins. Sketch from outcrop, and partly traced from a photograph. Location: Umbria Thrust Zone, to the E of Il Pizzo (M. Vettore Massif: see Section E3E4).

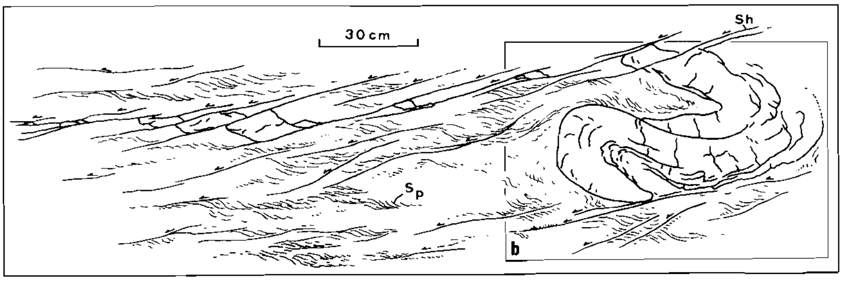




a



b



a

b

Fig. 28a, b: Transposed recumbent fold of coarsely grained bioclastic limestone in pervasively sheared marls (Scaglia Cinerea). Small tectonic lenses from the upper limb indicate the amount of slip along the shear veins (Sh). NE direction of thrusting (average 60°) makes an acute angle with the hinge of the fold (27°/5°). S_p = solution cleavage. Drawing partly from outcrop, and partly traced from a photograph (b). Location: Umbria Thrust Zone at the road from Madonna delle Coste to i Pavoni (W of Accumoli).

←Fig. 27a, b: Completely transposed fold hinges in pervasively sheared marls of the Scaglia Cinerea. Photographs are perpendicular to the hinges. Note in fig. 27a the acute angle between the fold hinge and the slickensides on the tectonic lens in the upper part of the photograph. Location: Umbria Thrust Zone along the road to the Forca Canapine, near Capodacqua.

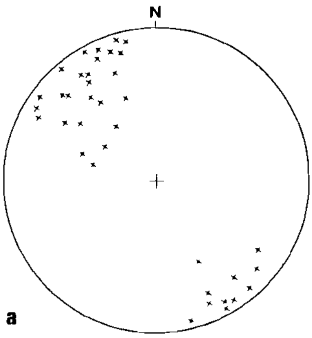
Locally the original bedding is largely obliterated, and may only be preserved by brecciated chert lenses and nodules.

In other places fold limbs may still be preserved undeformed, but bedding continuity is lost by transposition, partly by slip along the bedding in the limbs and partly along minor faults, generally subparallel to bedding, which may form more or less pervasive systems of shear veins (fig. 26). Transposition is facilitated by shear along the incompetent layers. Along the Umbria Thrust Zone it is most intense towards the top of the Scaglia, (in the basal part of the forward limb completely overturned) and in the Scaglia Cinerea/Acquasanta Group. In the Scaglia Cinerea of the thrust zone fold hinges are preserved only very locally; they are tight to isoclinal recumbent folds, completely isolated in the incompetent pervasively sheared marls (figs. 27 and 28).

Axial trends of the folds:

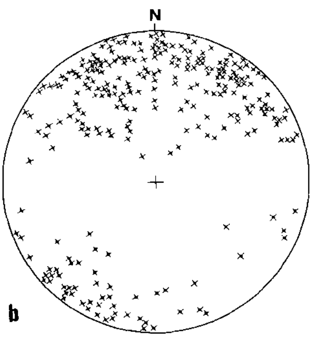
Generally the three dimensional shape of the disharmonic folds is rather complex. The kinkfolds not influenced by thrusting and transposition have relatively straight axes; any plunges are generally slight, and in both directions. Axial plunges and complexity of the fold patterns increase towards the thrusts. A large number of mesoscopic folds have been measured and are plotted in fig. 29. Along the Umbria Thrust Zone north of the F. Aso valley, where the rootless anticline of the M. Sibilla faces NE, the variations in axial trends are small. Here all mesoscopic folds are parallel to the NW - SE strike of the large scale structure; i.e. perpendicular to the NE ward direction of thrusting (fig. 29a). This plot fits quite well with the situation in the NW part of the Umbria Marche Apennines, from which Fazzini (1973) gives a plot of the mesoscopic fold axes (fig. 29c).

The fold axes in the NNE - SSW trending forward limb, to the S of the M. Vettore Massif, have much larger variations in direction and plunge (Fig. 29b). Here also a number of folds is perpendicular to the NE ward direction of thrusting, mainly plunging to the NW;



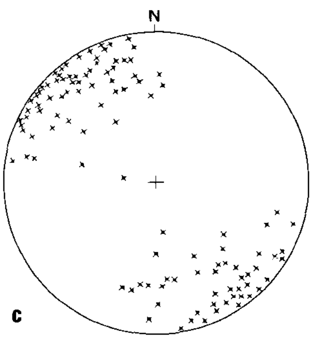
NW - SE striking part of the Umbria Thrust Zone (M. Sibilla Structure, N of the Fiume Aso valley).

n = 37



NNE - SSW striking part of the Umbria Thrust Zone (S of the Fiume Aso valley)

n = 279



NW part of the Umbria Marche Apennines (Fazzini, 1973).

n = 109

Fig. 29: Equal area projections of mesoscopic fold axes.

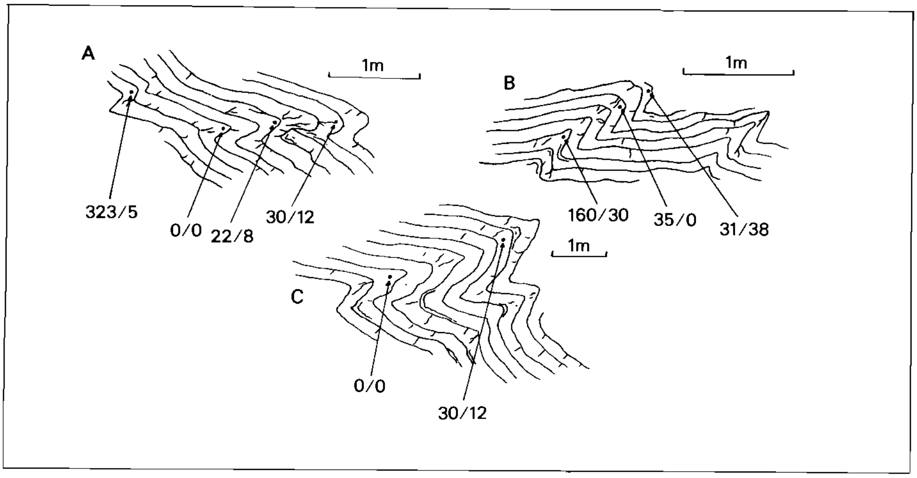


Fig. 30: Fold profiles with varying orientations of the hinge lines in one and the same fold. Drawings from the field.

A: Scaglia: Rotolone, W of Roccasalli (30/12 is exactly normal to the plane of drawing);
B: Scaglia, 2 m above the inverted contact with the Scaglia Cinerea: Umbria Thrust Zone to the W of Scanzano;
C: Maiolica: NE side of the M. Laghetto, W of Roccasalli.

but part of the fold axes is N - S to NE - SW, i.e. parallel to the forward limb of the rootless anticline. These folds plunge in both directions. The distribution of the axial trends is quite non-systematic: the various axes occur within one and the same forward limb, even within a single outcrop. Many folds are strongly non-cylindrical, and the axial planes and/or hinge lines are curved. The hinges may show varying orientations within one and the same fold (fig. 30).

The amount of N - S to NE - SW trends, i.e. not perpendicular to the direction of thrusting is large near and in the major thrust zone (fig. 31). This holds for both the main thrust along the Scaglia Cinerea/Acquasanta Group, and the subsidiary splay thrusts in the hanging wall.

3.2.f. SUBSIDIARY SPLAY THRUSTS

Within the rootless anticlines many upward splay thrusts branch off the main thrust zone along the Scaglia Cinerea/Acquasanta Group. They may terminate upwards after short distances, but locally they reach considerable lengths.

Most important splays follow the incompetent units in the steep to inverted forward limbs. The incompetent rocks may be completely

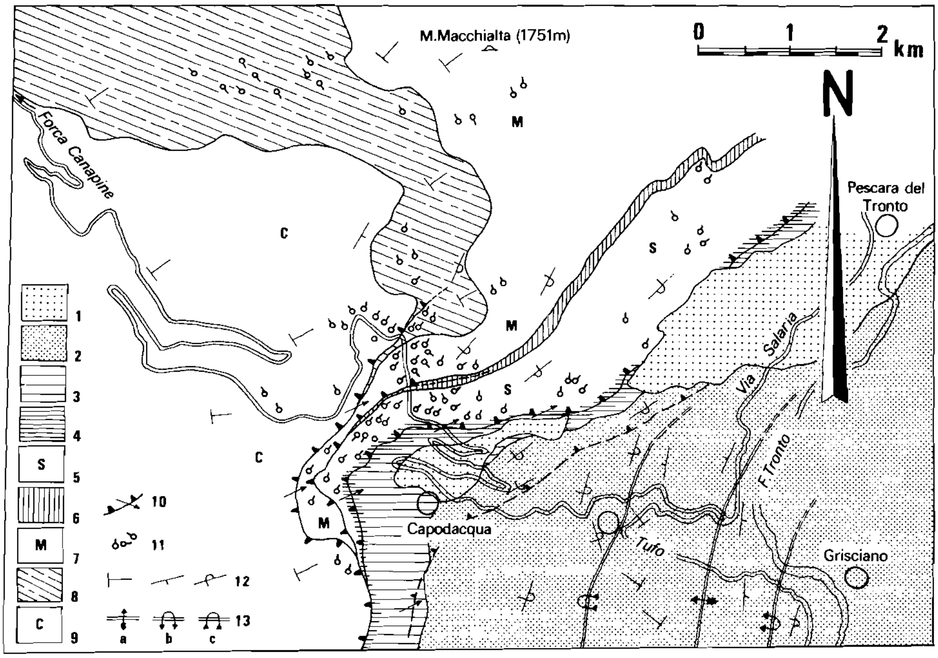


Fig. 31: Tectonic map of the Umbria Thrust Zone near Capodacqua (M. Utero - M. Macchialta Structure). The axes of mesoscopic folds are perpendicular to the 60^{o}-direction of thrusting (as indicated by slickensides) and plunge both ways, except in and near the thrust zone, where acute angular relationships and N to NE ward plunges prevail. Legend: 1. Debris; 2. Laga Formation; 3. Acquasanta Group; 4. Scaglia Cinerea; 5. Scaglia; 6. Marne a Fucoidi; 7. Maiolica; 8. Forca Canapine Group; 9. Corniola; 10. major thrusts, arrows indicate direction of thrusting; 11. mesoscopic fold axes, line indicates the direction of plunge; 12. strike and dip symbols: a. 0^{o} - 40^{o}; b. 40^{o} - 90^{o}; c. overturned; 13. major fold traces in the Laga Formation: a. assymetric anticline; b. overturned anticline; c. overturned syncline.

sheared out. Upwards in the hanging wall the displacement along the splays is generally distributed among numerous faults of lower orders, until they merge into the bedding, where their displacement is transferred into slip on the mesoscopic fold limbs.

The splays have mainly developed subsequent to the disharmonic folding: they cut the hinges and/or the fold limbs. Also the interlimb angles decrease laterally towards the faults. However, in some places splays are folded across the mesoscopic folds. Thus these fault-systems have considerably complicated the deformation patterns in the hanging wall.

Along the Umbria Thrust Zone to the S of the Fiume Aso valley the general NNE - SSW strikes of the splays are oblique with respect to the NE ward direction of thrusting. In the hanging wall many indications are present for a dextral strike slip component of movement. For example between La Valle (Section F5F6) and the road from Capodacqua to the Forca Canapine a WNW dipping splay thrust between the Corniola and the Maiolica follows the Forca Canapine Group. The marls of the intermediate Forca Canapine Group are completely sheared out, and along the fault contact several tectonic lenses of competent bioclastic limestone are present. Long axes of the lenses plunge steeply to the NNW, i.e. perpendicular to the oblique sense of movement along the fault. Oblique slickensides also have been found to the E of the M. Boragine (Section M), to the SW of the M. Ciambella (Section H1H2), and along the splay thrusts in the M. Vettore Massif (see below).

Moreover, the NNE - SSW directions of a large part of the folds to the S of the Fiume Aso valley (fig. 29b) also reflect this dextral strike slip component of movement. Especially near the upward splays the hinge lines turn from NW - SE to NNE - SSW and have generally steeper plunges, mainly to the N or NE; the axial planes tend to be parallel to the adjacent splays (Fig. 32).

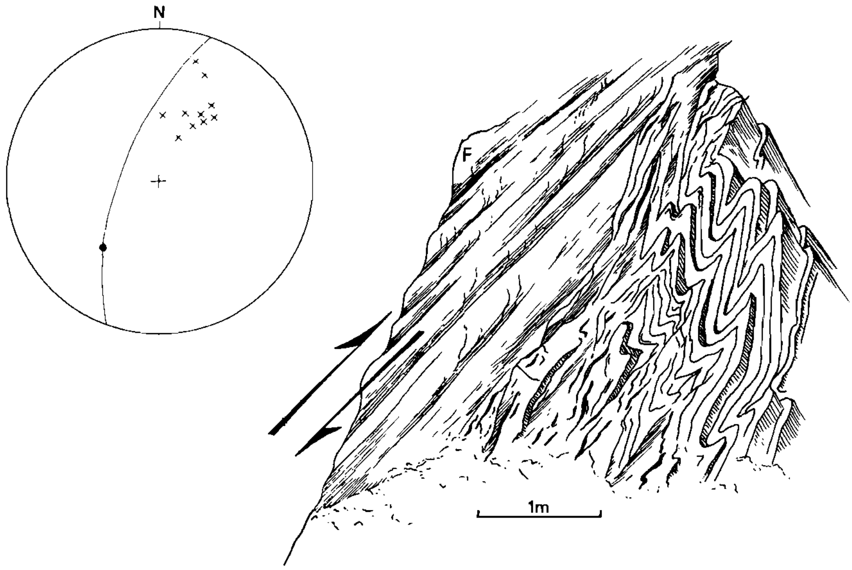


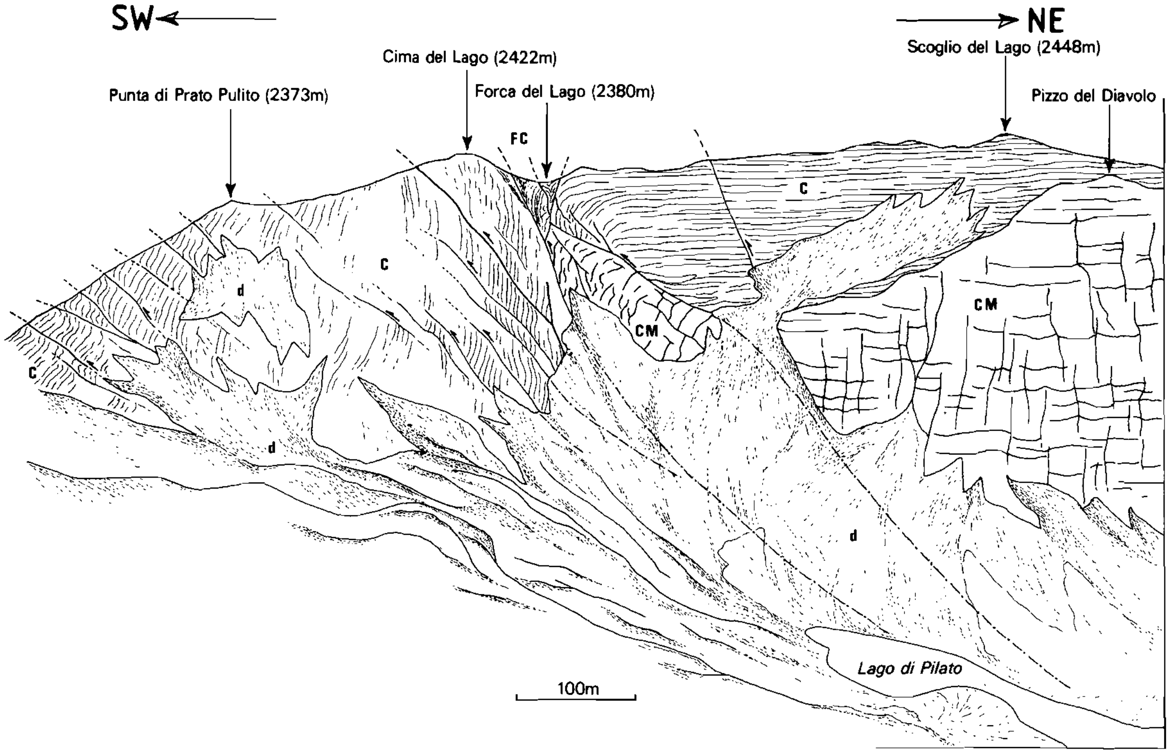
Fig. 32: Sketch of an exposed fault plane (F) between the Calcare Massiccio (left) and a tightly folded slice of the Forca Canapine Group. Grooves on the fault indicate dextral oblique slip. The strongly NE ward plunging fold axes are perpendicular to the direction of movement (see equal area projection). Location: SE of the Aia della Regina, along the W side of the M. Vettore Massif.

trace of the fault plane with slip direction;

× *fold axes.*

The M. Vettore Massif

The M. Vettore Massif forms the S continuation of the M. Sibilla Structure. Here the strikes in the hanging wall of the Umbria Thrust Zone turn gradually from NW - SE to NNE - SSW. Along the E edge of the M. Vettore no forward limb is preserved, and only the Calcare Massiccio and the Corniola are extensively exposed; they are mainly horizontal to E ward dipping (Section E). Especially in this area large parts of the thrust faults and the Laga Formation to the E are covered by debris. However, some isolated outcrops of the Scaglia


SW
NE
Cima del Lago (2422m)
Scoglio del Lago (2448m)
Punta di Prato Pulito (2373m)
Forca del Lago (2380m)
Pizzo del Diavolo
FC
C
d
CM
Lago di Pilato
100m

←*Fig. 33: View from the M. Vettore to the SW, on the mountain ridge W of the Valle del Lago di Pilato (M. Vettore Massif). The horizontal Calcare Massiccio (CM) of the Pizzo del Diavolo, disconformably overlain by the Corniola (C) is cut by a fault-system striking SSW - NNE. The main fault zone, accompanied by a slice of the Forca Canapine Group (FCG), runs along the Forca del Lago. To the left steeply dipping Corniola is cut by series of NW dipping faults, which branch off the main fault zone of the Forca del Lago. Local changes in the strike of bedding, slickensides and tectonic lenses (fig. 34), indicate a dextral strike slip component of movement along the fault system (see also Section E1E2). In the NE direction (back to front in the picture) the fault zone is lost from view below the fan debris (d) around the Lago del Pilato, and dies out in the area of the M. Torrone (see Geol. Map).*

Cinerea and Acquasanta Group evidence the existence of these units along the overthrust (Section E5E6) *). To the E of Il Pizzo some wedges of inverted and disharmonically folded Scaglia and Maiolica are also present below the Calcare Massiccio (Section E3E4 and fig. 26). The hanging wall Calcare Massiccio and overlying Corniola are cut by several mainly SSW - NNE striking high angle faults (see Geol. Map, Section E and fig. 33). The Umbria Thrust Zone, exposed along the M. Banditella - M. Torrone - M. Vettore alignment, and the Laga Formation in the footwall are not offset by these fault-systems. They are splays restricted to the upper block and merge downwards in the low angle thrust. Upwards, through the Corniola a whole array of faults of lower orders branches off these main faults (fig. 33). In general narrow zones of cataclastis accompany the fault planes . The slickensides on these planes, if present, are oblique to the strikes of the faults (fig. 34a). Steps of the fibrous calcite growths, changes in strikes of the bedding from NW - SE via N - S to NNE - SSW, and offsets indicate dextral strike slip components of movement. Upwards the faults terminate in flexures, or merge into the incompetent rocks of the Forca Canapine Group. Tight mesoscopic folds, generally trans-

*) For example in the Fosso di Casale and Fosso di Colleluce; to the E of Il Pizzo; to the SE of the Aia della Regina, in some gullies running down the slope of the M. Vettore. The only place that has been found where the Calcare Massiccio lies directly in contact with the Laga Formation is along the road from Pretare to the Forca di Presta (Section E7E8).

Fig. 33a: Oblique slickensides along a fault zone running SSW - NNE across the mountain ridge between the M. Vettore and Il Pizzo.

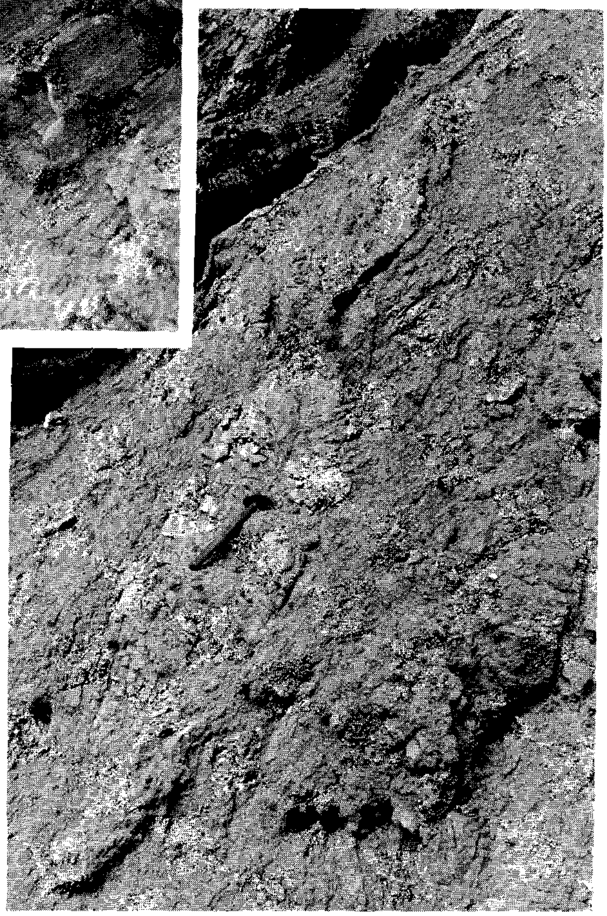


Fig. 33b: Large tectonic lenses of limestone in a wide zone of fault breccia; a strike slip component of movement is indicated by their steep plunges. The fault zone parallels mainly the base of the Forca Canapine Group. Location: E of the M. Vettoretto (M. Vettore Massif).

posed and long axes of tectonic lenses in the incompetent marls of the Forca Canapine Group plunge steeply to the NNW (30^{0} to 55^{0}), i.e. perpendicular to the oblique slip (fig. 34b). *[1])

The continuation of the oblique fault systems to the S is obscured by subsequent NW - SE striking normal faults, which border the NE side of the Piano Grande Depression, and by a large amount of debris that covers the terrain. Therefore the Geological Map gives a highly schematized situation in the area around the Forca di Presta. *[2])

3.3. THE LAGA MOUNTAINS AREA

3.3.a. INTRODUCTION

The Laga Mountains Area occupies the central and eastern part of the investigated area, to the east of the Umbria Thrust Zone. To the S it extends beyond the area, and is bordered by the Gran Sasso d'Italia chain (Abruzzi). In the NE its rocks disappear under the late- to post-orogenic sequence of the Pedeapennine Zone (see fig. 3; Crescenti, 1975).

The landscape in the Laga Mountains Area is strikingly different. However, the geological structures, although cut at a higher level, turn out to be quite comparable with those in the Umbria Marche Apennines. East of the Umbria Thrust Zone the calcareous rocks of the Umbria-Marche Sequence lie much deeper, being mostly covered by the thick turbidite sequence of the Laga Formation (p. 39). The older rocks are only exposed in the cores of a few large anticlines: the Acquasanta

*[1]) For example along a narrow zone running N - S over the mountain ridge between the M. Vettore and Il Pizzo (Section E3E4), to the NE of the M. Vettoretto and at the Forca del Lago.

*[2]) Possibly in the downthrown SW blocks, one or several oblique slip faults cut the Maiolica at Sasso Tagliato, and merge and flatten into the disharmonically folded Scaglia, that crops out in a NW - SE trending zone from the Forca di Presta via Costa Ferrone (Section F3F4) to the W of Pescara del Tronto.

Structure (Colacicchi, 1958; Parotto & Praturlon, 1975) and the Montagna dei Fiori, and in some places in the footwall of the Umbria Thrust Zone. The latter will be described in part 3.4. (p. 113).

3.3.b. LARGE SCALE FOLD STRUCTURES

The Acquasanta Structure is a N - S to NNE - SSW trending regional anticline with a steep to overturned E limb and a general N ward plunge. To the N of Communanza the anticline dies out in the Laga Formation (see Geol. Map). To the S the structure continues beyond the investigated area, and seems to merge with the structure of the Gran Sasso d'Italia (Abruzzi; see p. 129).

In the S of the investigated area its crest zone is very wide and flat, consisting mainly of the Laga Formation (this part contains the highest peaks of the Monti della Laga: Pizzo di Sevo, Cima Lepri and M. Gorzano). The distinction of a "Laga anticline" (Parotto & Praturlon, 1975; Castellarin et al., 1978; see also Funiciello et al., 1981) separated from the Acquasanta Structure by a syncline is invalid (see Section G5G10). Only to the E of Amatrice (Selva Grande Area: see Geol. Map), and in the area around Acquasanta, erosion has been deep enough to expose older units below the Laga Formation.

The Montagna dei Fiori Structure lies to the E of the Acquasanta Structure (E of the mapped area) and forms the second N - S trending regional anticline. To the S the structure continues beyond the area investigated in the Cima Alta Area (to the W of Montorio al Vomano, see fig. 1) and disappears below the NE side of the Abruzzi Apennines (Gran Sasso d'Italia; see p.129). The segment between Ascoli Piceno and the latitude of Teramo forms a high axial culmination, with even the Calcare Massiccio in outcrop (see fig. 35a, b). On the W side a normal fault truncates this culmination. Near Macchia del Sole (fig. 35b, Section AA') this fault has at least 1.5 km offset; it places the Calcare Massiccio (E block) against the Scaglia Cinerea (W block). The northern and southern continuations of this fault however, are lost very quickly down-plunge; in the N the base of the Laga Formation shows no offset anymore (Section BB' of fig. 35b).

The culmination is cut by the Torrente Salinello; in the deep gorge through the rocks of the Umbria-Marche Sequence a low angle thrust is exposed with the series of Calcare Massiccio, Corniola, Forca Canapine Group and Maiolica overriding the Scaglia and Scaglia Cinerea (Giannini, 1960). Towards the E the thrust splits up in several splay thrusts that merge into a zone of disharmonically folded Scaglia (Section AA' of fig. 35b).

Although not eroded as deeply, the configuration is identical with the one along the Umbria Thrust Zone. Evidently, the series in outcrop form the hanging wall of a stepped overthrust, with a steep to inverted and disharmonically folded forward limb in the Maiolica and Scaglia. Therefore, the Montagna dei Fiori anticline is also rootless, at least in its central part between Ascoli Piceno and Teramo. The NNW ward plunge and termination of the structure to the W of Ascoli Piceno point to a gradual extinction of the stepped overthrust in the subsurface.

The core of the Acquasanta Structure is not exposed at all, but by analogy, it should also be rootless. The very long backward limb, dipping to the WNW, would than reflect a NNE - SSW striking ramp. The decreasing width of the crest zone to the N, and the NNW ward plunge and termination of the structure indicate a gradual decrease in riding-up the footwall ramp.

Two regional synclines are present: the Arquata del Tronto Syncline, which stretches between the Acquasanta Structure and the positive structures along the E side of the Umbria Marche Apennines, and the Vallecastellana Syncline between the Acquasanta Structure and the Montagna dei Fiori (see Geol. Map). In both synclines only the Laga Formation is exposed; they are passive features between the rootless anticlines, without a definite axial plane or axial trend.

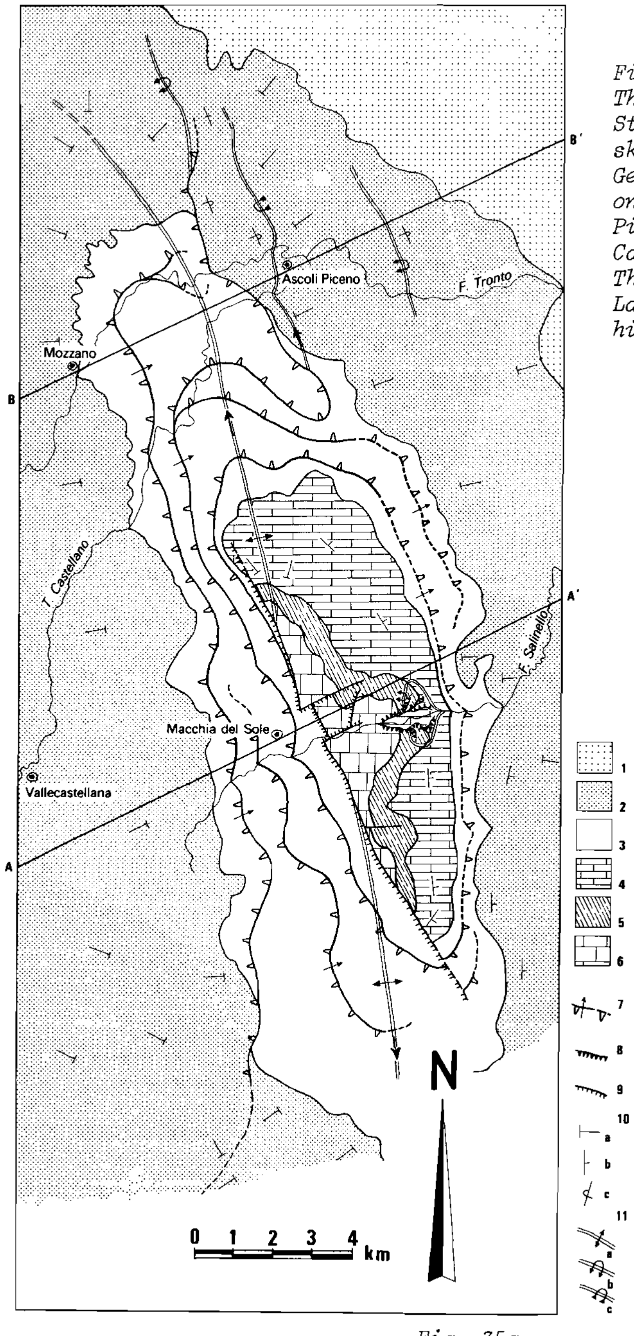


Fig. 35a, b:
The Montagna dei Fiori Structure. Structural sketch-map and sections. Geology is mainly based on sheet 133-134 (Ascoli Piceno-Giulianova) of the Carta Geologica d'Italia. The thrust faults of the Laga Detachment Zone are highly schematized.

Fig. 35a

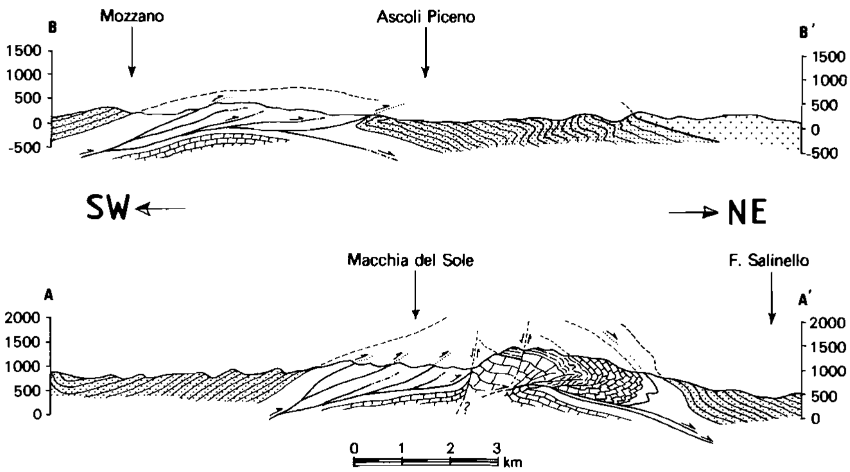


Fig. 35b:

Legend:
1. Pliocene sediments of the Pedeapennine Basin; 2. Laga Formation; 3. Scaglia Cinerea and Acquasanta Group; 4. Scaglia; 5. Maiolica; 6. stratigraphic units below the Maiolica; 7. Laga Detachment Zone; arrows indicate direction of thrusting; 8. thrust zone at the base of the Montagna dei Fiori Structure; 9. normal faults; 10. strike and dip symbols: a. 0 - 40°, b. 40° - 90°, c. overturned; 11. major fold traces: a. normal anticline, b. recumbent anticline, c. recumbent syncline.

3.3.c. THE LAGA DETACHMENT ZONE

Wherever erosion has been deep enough to expose the Umbria-Marche Sequence, the incompetent rocks of the Scaglia Cinerea and part of the Acquasanta Group (level 4 of the sequence) show a penetrative whole rock deformation (Elliott, 1976). This zone of shear, along which the overlying part of the sedimentary cover (the Laga Formation) has been detached from the Umbria-Marche Sequence, will be referred to as the Laga Detachment Zone.

In the crest of the Acquasanta Structure the basal part of this tectonized zone is well exposed in the deep valley of the Fosso Garaffo (a tributary of the Fiume Tronto, about 2½ km to the S of Acquasanta; see Section G7G8 and fig. 36). The flat lying Scaglia is

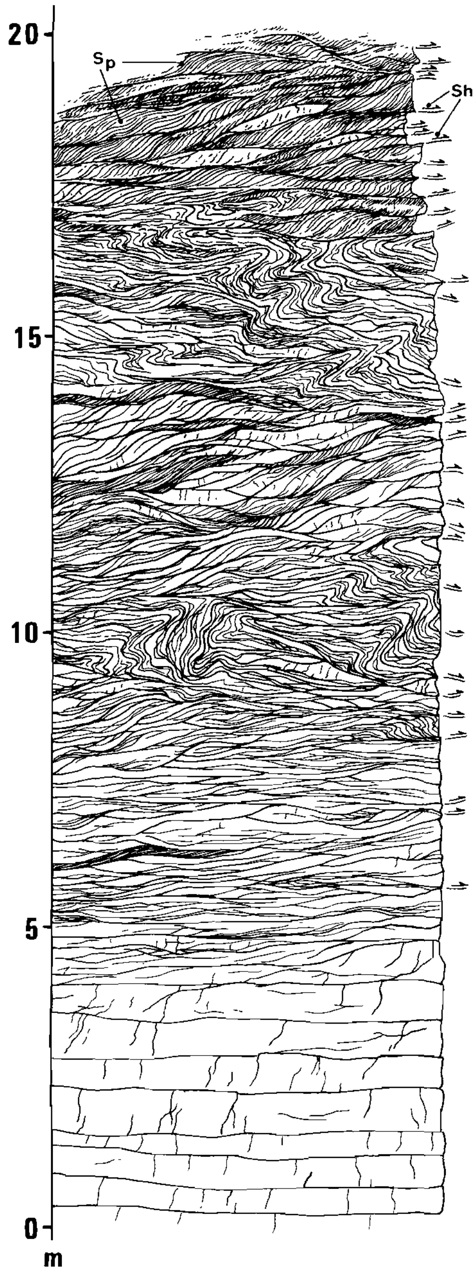


Fig. 36a: Lower part of the Laga Detachment Zone in the Rio Garaffo valley (Acquasanta Structure). The top of the Scaglia and the complete Scaglia Cinerea are thoroughly deformed by pervasive shearing. Largest displacement has taken place along the more argillaceous levels.

± 16 - 20 m:

Scaglia Cinerea: anastomosing systems of closely spaced shear veins, cutting a pervasive sigmoidally shaped solution cleavage (see 36b);

± 8 - 16 m:

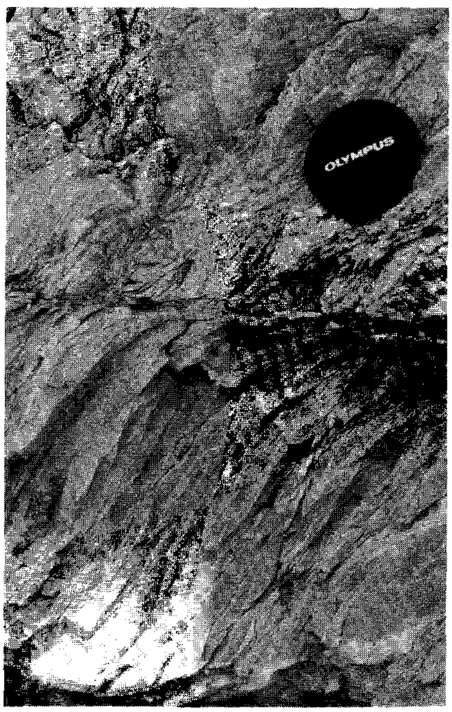
sigmoidally shaped solution cleavage, also present in competent limestone (see 36c) cut by multiple systems of shear veins. Disharmonic small scale folding (1 cm - 1 m; see 36d); flexural slip has been facilitated by insoluble residue on the solution planes. New stylolite planes, cutting the earlier ones mainly at the hinges indicate a continuously active pressure solution. Folds are non-cylindrical and their hinges are highly erratic, and generally curved; they may be transposed along subsequent shear veins;

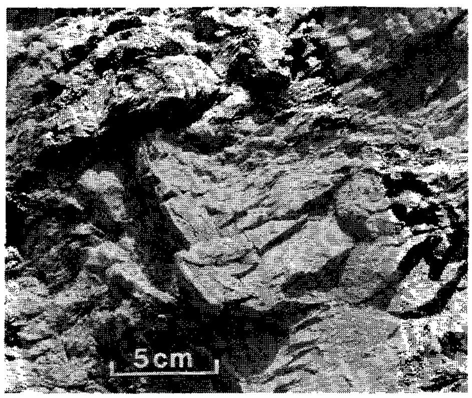
± 4 - 8 m:

anastomosing system of solution planes, about parallel to bedding (see 36e), getting more and more pervasive upwards. Pressure solution slip is indicated by NE striations in the films of insoluble residue and small offsets of extension veins in the rock segments. Locally additional shear veins are present;

± 0 - 4 m:

relatively undeformed Scaglia with sporadic stylolite planes, mainly at a high angle to bedding.





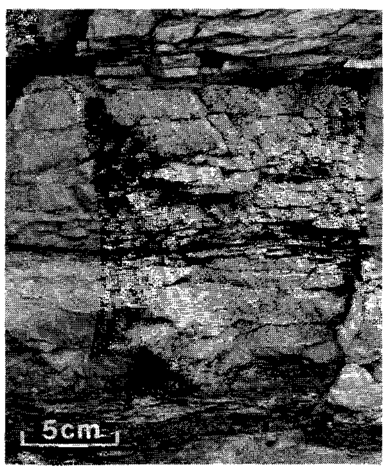


Fig. 36b, c, d, e.

the lowest unit of the Umbria-Marche Sequence exposed. It is remarkably undeformed, while the overlying uppermost part of its micritic limestone succession and the complete Scaglia Cinerea are thoroughly tectonized. The various structural elements (indicated in fig. 36) are very similar to those at the same stratigraphic level in the Umbria Thrust Zone: a highly penetrative solution cleavage, multiple sets of shear veins and small scale folds are associated to pervasive shearing, dominated by the mechanism of pressure solution slip (Elliott, 1973, 1976). See for the description of the elements 3.2.c. on p. 55.

Bedding is largely destroyed in the Scaglia Cinerea; its more competent layers are separated into tectonic lenses of various sizes bounded by shear veins and solution cleavage. Accretion steps of long fibrous calcite bundles on the shear veins, fine striations in the films of insoluble residue on the cleavage planes and sigmoidal shape of the cleavage in the domains reveal unambiguously a NE ward sense of shear (fig. 37).

The deformation may be confined to the Scaglia Cinerea only (fig. 38), but generally also the overlying Acquasanta Group is involved. Splay thrusts initiating from the common detachment along the Scaglia Cinerea have locally resulted in imbrication of the Acquasanta Group. These splays and associated minor faults are also accompanied by zones of increased cleavage intensity and more or less closely spaced spaced patterns of shear veins. Moreover, they may be associated with mesoscopic folding.

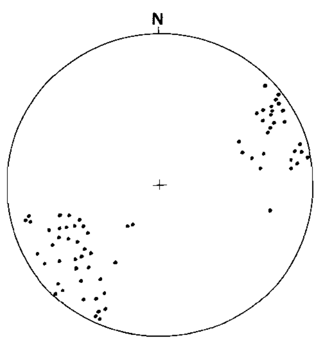


Fig. 37: Equal area projection of the slickensides on shear veins in the Laga Detachment Zone.

$n = 68$

Fig. 38: Top of the imbricated Scaglia Cinerea (Laga Detachment Zone), overlain by the relatively undeformed basal part of the Acquasanta Group (Laga Formation in the distance). N side of the Fiume Tronto valley, near S. Emidio. (Location is SW of the situation depicted in fig. 48).

Mesoscopic folds

Mesoscopic folds occur mainly in the Acquasanta Group. Generally they die out towards the top of this unit.

The folds are highly disharmonic, and their geometries may be very complex, mainly due to the competence contrasts of the rocks involved and the complex relations with adjacent folds and faults. Generally the amplitudes of the folds do not exceed 30 m. They may be symmetric to strongly asymmetric, open to tight and recumbent. In the latter case they are generally cut up by faults (fig. 39). Folding is largely accomplished by flexural slip, as locally indicated by shear veins on bedding surfaces around the hinges, and the arrangement of solution cleavage in the incompetent beds (fig. 40).

Facing of the asymmetric folds is to the E or NE, all over the crest zones and also in the forward limbs of the regional anticlines. Their hinge lines may be curved and vary between NW - SE and NNE - SSW,

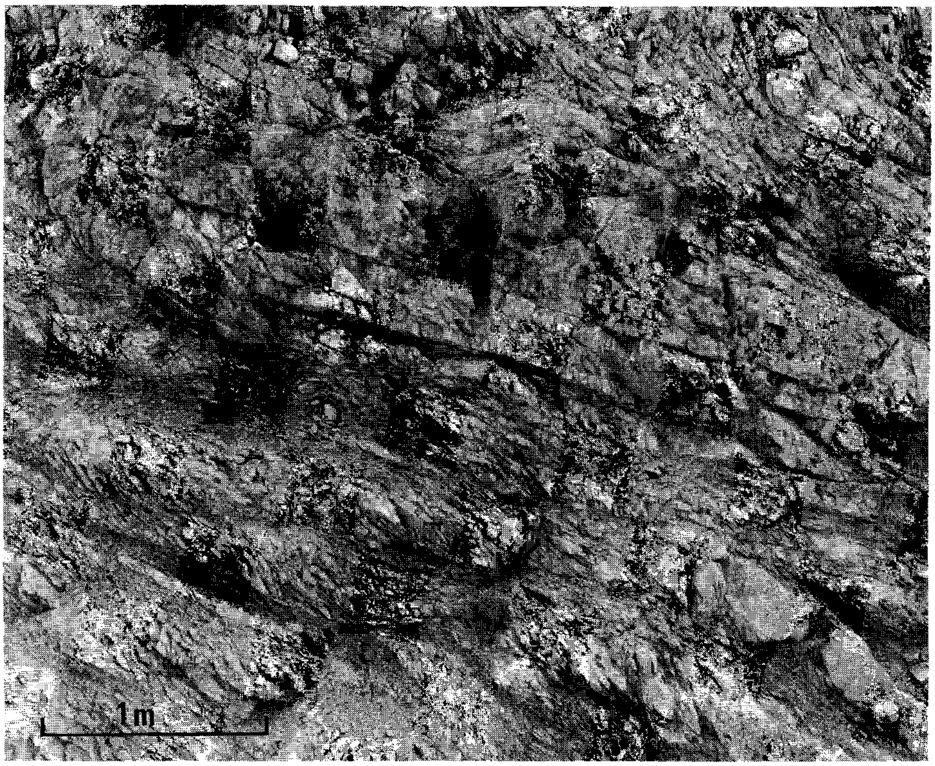


Fig. 39: Recumbent fold, of which the inverted limb is truncated by a minor fault zone, following pervasively sheared marls. Note the penetrative solution cleavage. Acquasanta Group near Quintodecimo (Acquasanta Structure).

with generally slight plunges in both directions. Part of the folds is associated with minor stepped bedding plane thrusts (fig. 41). The small scale ramps may be perpendicular or oblique, and partly account for the scatter in axial trends. Other disharmonic fold trains have developed by shortening above detachment zones, following incompetent levels (fig. 42).

Previous authors (Ricci Lucchi, 1975; Mutti et al., 1978; Ricci Lucchi & Parea, 1973) interpreted all the mesoscopic folds in the Acquasanta Group of the Laga Mountains Area as slump structures, due to collapse of the unconsolidated slopes of the rapidly subsiding Laga basin (Centamore et al., 1980). Prior to the deposition of the Laga Formation some slump folds, flap folds etc. have developed indeed; mainly in the Selva Grande Area, and in the southern continuation of the Montagna dei Fiori Structure (Cima Alta Area). The majority of mesoscopic folds, however, is clearly of tectonic origin. They are associated with solution cleavage, shear vein-systems, etc., of the Laga Detachment Zone.

Solution cleavage

Across the Acquasanta Structure and the Montagna dei Fiori Structure the morphology and development of solution cleavage is quite variable. Cleavage intensity is always strong in the Scaglia

Fig. 40: Upright mesoscopic fold in the Acquasanta Group. The cleavage in less competent beds show low angles to bedding. Cleavage in the competent limestone (Cerrogna) is stylolitic and maintains the same angular relation to bedding across the folds. Location: N of Macchia del Sole, in the WSW dipping backward limb of the Montagna dei Fiori Structure.

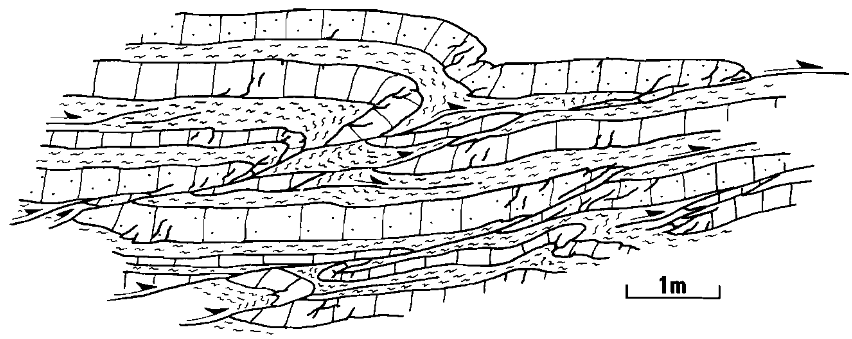


Fig. 41: Minor thrust faults and associated folds in the Acquasanta Group, showing relation to competency of the strata. The pervasive solution cleavage is not drawn. Sketch from outcrop. Location: W of S. Paolo, Acquasanta Structure.

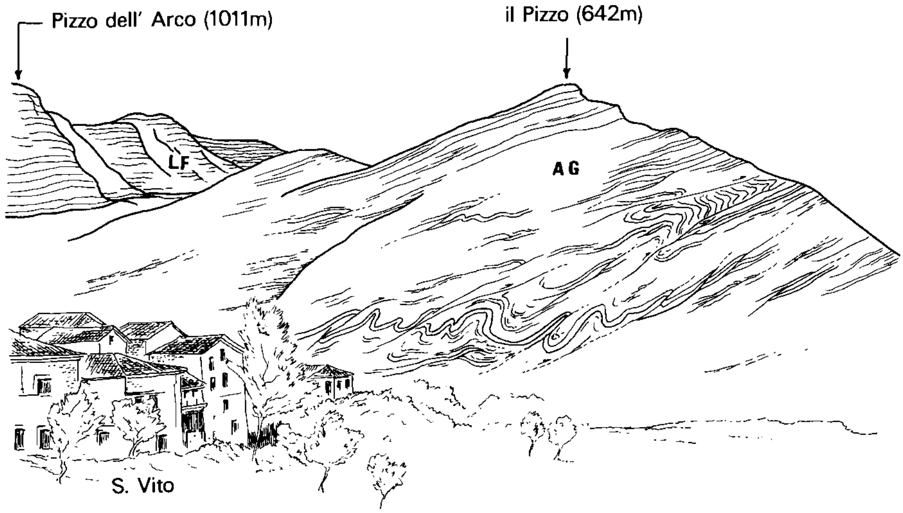


Fig. 42: Upward splays, minor fault zones and associated detachment folds in the Acquasanta Group. View from S. Vito to the N; Acquasanta Structure. Sketch partly from outcrop, and partly traced from a photograph. (LF = Laga Formation; AG = Acquasanta Group).

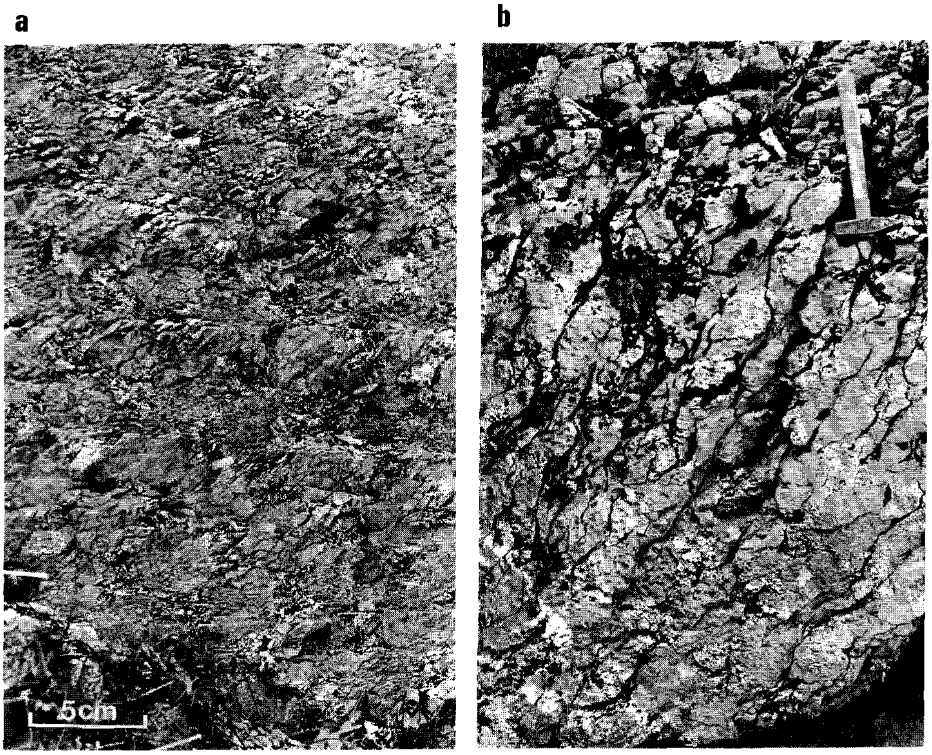


Fig. 43: a. Regular cleavage in a rhythmic alternation of marl and marly limestone (Acquasanta Group); Location: W of S. Vito, Acquasanta Structure. b. Irregular undulose solution cleavage in coarse grained Cerrogna limestone (Acquasanta Group). Location: Selva Grande valley to the E of Amatrice.

Cinerea (fig. 36), and diminishes gradually towards the top of the Acquasanta Group. In the Pteropoda marls (p. 37) at the base of the Laga Formation cleavage is mainly very weak to absent.

In the fine-grained calcareous marls and marly limestones of the Acquasanta Group the solution cleavage may be quite regular and planar (fig. 43a), whereas in the medium- to coarse-grained bioclastic Cerrogna limestones cleavage is generally stylolitic and less well defined, with very irregularly shaped undulose surfaces (fig. 43b and top part of fig. 40).

Where present in flat lying relatively undeformed rocks (like in the upper part of fig. 38) the cleavage is generally at a high angle

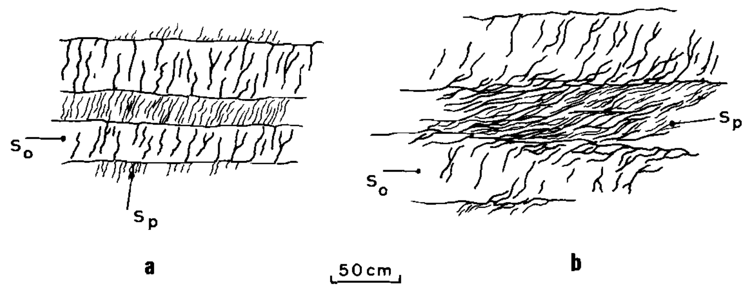


Fig. 44a, b: Examples of cleavage-bedding relation in an alternation of limestone and marl (Acquasanta Group); the configuration in b is caused by bedding parallel shear along the incompetent marl. A gradual increase of shear strain is reflected by the curvature of the cleavage from high angles inside the limestone beds to low angles near the contact with the adjacent incompetent level, while the cleavage intensity increases. Both a. and b. are drawn in the field. Location W of S. Paolo (Acquasanta Structure); a. lies 5 m above b. (S_o = bedding; S_p = solution cleavage).

or even perpendicular to the bedding (60^o - 90^o; figs. 43 and 44a).

In thrust zones, minor fault zones and in levels of more limited bedding parallel shear, like in the mesoscopic folds, the cleavage intensity increases, and here the orientations of the cleavage planes show larger variations. Especially in the more incompetent levels the cleavage shows lower angles to the zone of shearing (figs. 39, 40 and 44b).

High rates of shear strain in the fault zones are reflected by very strong cleavage, generally accompanied by shear veins (fig. 45). Original position of the cleavage may only be preserved in the larger tectonic lenses of competent limestone.

In some mesoscopic folds the cleavage fans asymmetrically across the hinges, with an angular relation to the bedding in the same direction in both limbs (fig. 40). It is possibly an indication that this cleavage has developed before the folding, by bedding parallel shear. However, cleavage may also be subsequent to the mesoscopic folds, but without a consistent pattern.

All these field relations suggest a simultaneous and protracted generation of cleavage, folds and fault zones.

a

b

Fig. 45a, b: Examples of deformation in splay thrust zones in the Acquasanta Group. Pervasive shearing occurred mainly along the incompetent layers, and is associated with strongly penetrative solution cleavage and additional shear veins. Locations: a. W of Macchia del Sole, in the backward limb of the Montagna dei Fiori Structure. b. Fosso S. Martino, Selva Grande Area.

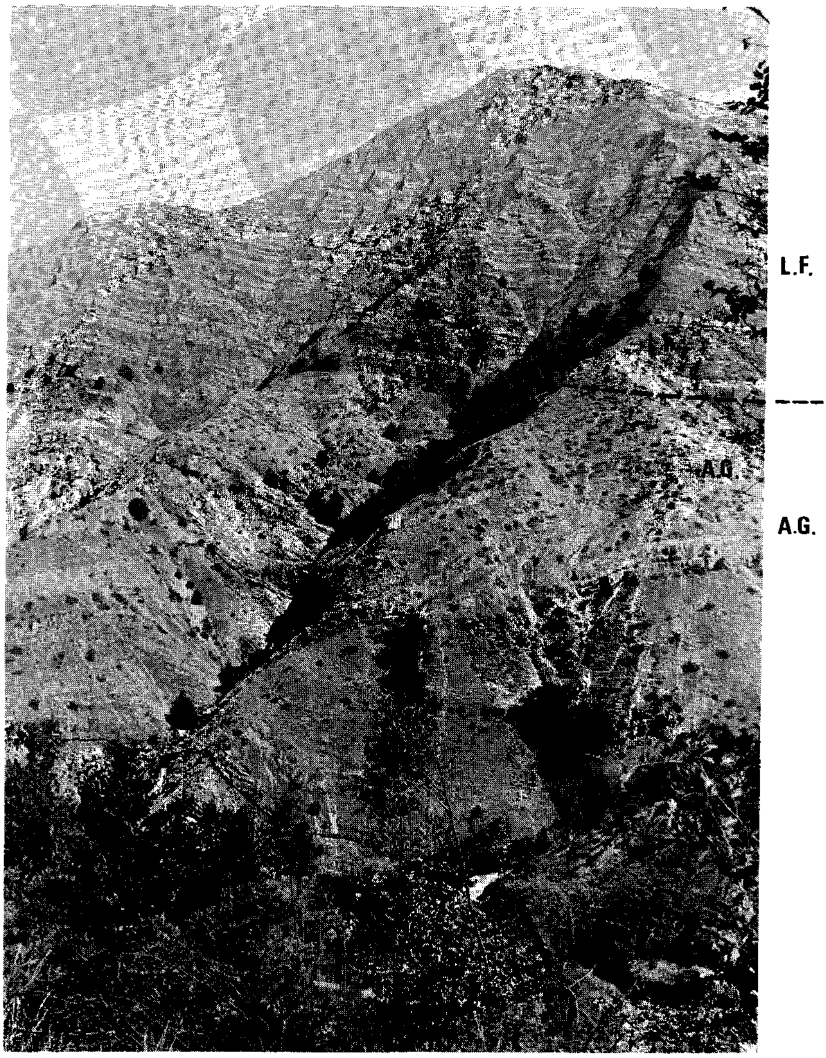


Fig. 46: N ward view on the Cima Lepri (2445 m; Monti della Laga). Lower part of the photograph shows the Fosso di Selva Grande and its tributaries; here the upper part of the Laga Detachment Zone is exposed. Disharmonic mesoscopic folds and imbrications have caused considerable tectonic thickening of the Acquasanta Group (A.G.). Towards the top of the unit deformation decreases; the top part (Pteropoda marls) and the overlying Laga Formation (L.F.) are essentially undeformed.

Fig. 47: Slice of Scaglia Cinerea, with on top of it the Acquasanta Group, thrusted onto the Acquasanta Group. Note the tight recumbent folds below the thrust slice. Deformation is very penetrative and chaotic, mainly due to the competence contrasts of the rocks involved. Location: Fosso di S. Martino, Selva Grande Area.

Splay thrusts and fault zones of lower orders

The strike lengths of the splay thrusts initiating from the common detachment zone along the Scaglia Cinerea do not exceed some km. Generally they are not straight; their strikes vary between NW - SE to N - S with W to SW dips of the steeper segments. Where dominating the structural pattern they may form very complex integrated systems with considerable tectonic thickening by repetetive imbrications (for example in the Macchia del Sole area, in the WSW dipping backward limb of the Montagna dei Fiori Structure: see fig. 35). Locally slices of highly tectonized Scaglia Cinerea are thrusted onto rocks of the Acquasanta Group (for example along the road from Acquasanta to S. Paolo, and in the valleys of the Fosso di S. Martino and Fosso di Selva Grande in the Selva Grande Area: figs. 46, 47), but imbrication has mainly involved the Acquasanta Group.

Upwards, and also laterally the splays split up into fault zones of lower orders which may climb up stratigraphic section step-

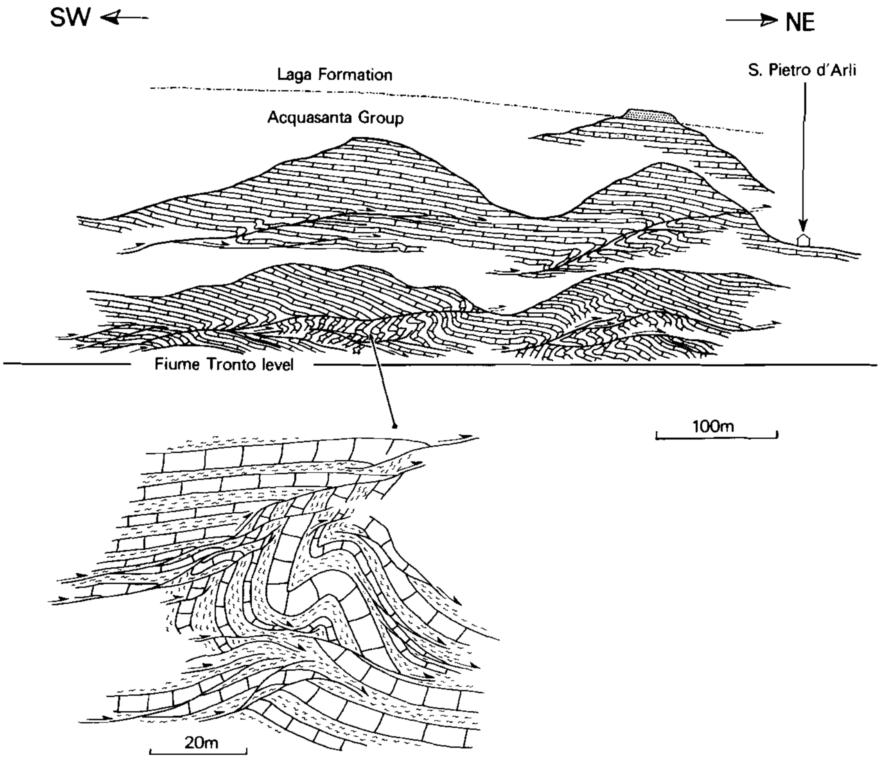


Fig. 48: View on the NW side of the Fiume Tronto valley, near S. Emidio (between Acquasanta and Arli), showing the Acquasanta Group and overlying Laga Formation in the crest zone of the Acquasanta Structure. Splay thrusts branching off the common detachment zone along the underlying Scaglia Cinerea, cut up stratigraphic succession, and are locally associated with complex folding (see detail). The thrust faults do not reach the base of the Laga Formation; their displacement is gradually transferred to fault zones of lower orders, which flatten out and merge into various incompetent layers with limited pressure solution cleavage.

wise (fig. 41). Part of the displacement is than transferred to successive incompetent marly levels (figs. 41 and 48), where solution cleavage indicates a moderate amount of shear (fig. 44b). Thus, most faults fade out in the incompetent levels below the thick Cerrogna Limestones, and at the level of the Pteropoda marls deformation is slight to absent. However, a few splay thrusts cut the competent Cerrogna Limestones and the base of the Laga Formation (figs. 49, 50; see also Section G11G12). Here these faults become generally concave upward, fading out laterally and distally. Some die out in the cores of detachment folds in the Laga Formation, like for example the splay thrust in the NNW ward plunging crest of the Montagna dei Fiori Structure, to the W of Ascoli Piceno (fig. 35).

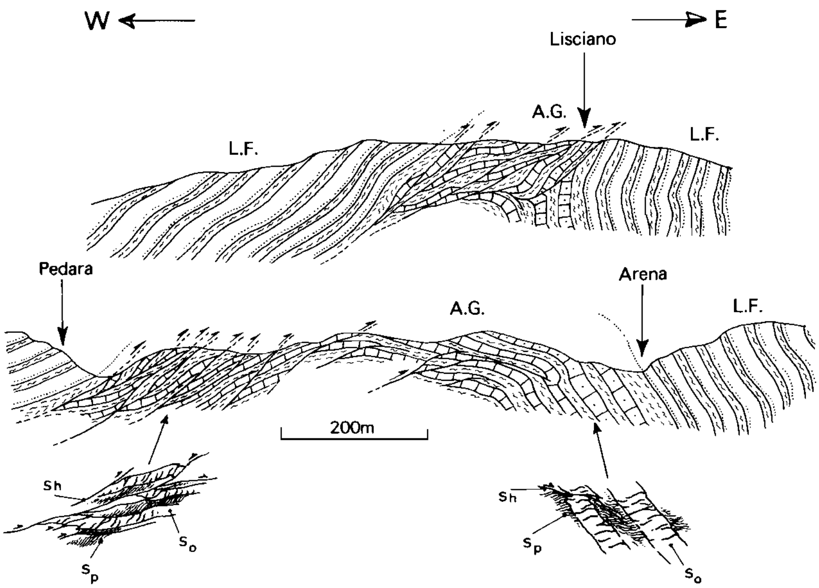


Fig. 49: Two schematic sections across the N part of the Acquasanta Structure (the Lisciano section is situated about 5 km N of the Pedaro - Arena section). The structure plunges, and N of the Lisciano the splay thrusts from the Laga Detachment Zone terminate in the core of the NNW ward plunging asymmetric anticline in the Laga Formation. (L.F. = Laga Formation; A.G. = Acquasanta Group). S_o = bedding; S_p = solution cleavage; Sh = shear veins). Note the attitude of S_p and Sh on both fold limbs.

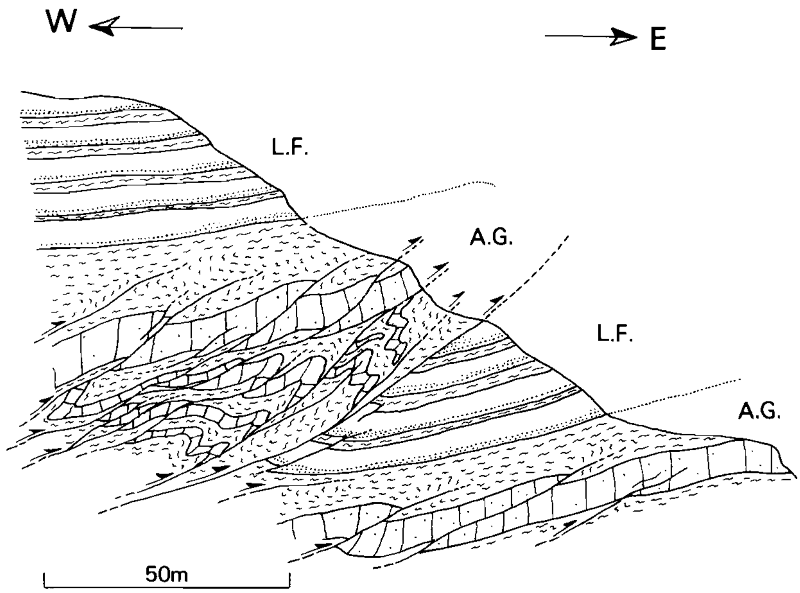


Fig. 50: Base of the Laga Formation in the crest zone of the Acquasanta Structure, offset by a splay thrust from the Laga Detachment Zone. Associated solution cleavage in the Acquasanta Group is not drawn. Compilation of field measurements along the road of S. Martino to Fleno (to the N of Section G11G12). (L.F. = Laga Formation; A.G. = Acquasanta Group).

Already in 1958 Colacicchi pointed out the possibility of detachment between the Laga Formation and the underlying Umbria-Marche Sequence along the incompetent rocks of level 4 (fig. 1 on p. 61 of his paper is from the same locality as fig. 38 of the present paper). He ascribed this detachment to large scale flexural slip in the Acquasanta Structure; according to him also along the incompetent Pteropoda marls. This level is however, essentially undeformed in most places.

Detachment due to flexural slip must be rejected for the following considerations: 1. the NE to E ward facing of all mesoscopic folds in the Acquasanta Group; they are not parasitic to the regional anticlines; 2. the overall NE ward sense of shear, indicated by the slickensides, and orientation of cleavage and upward splays; including on the wide crest zones and in the forward limbs; 3. the acute angle between the regional anticlines and this NE ward sense of shear; 4. in the forward limb the angular relationship between the cleavage and bedding in the Laga Detachment Zone is opposite to the sense that would be expected by flexural slip.

In the Montagna dei Fiori Structure the tectonized Scaglia Cinerea and Acquasanta Group continue across the crest zone into the ENE limb *), and disappear from view below the Laga Formation and the overlying weakly tilted Pliocene/Quaternary deposits of the Pedeapennine Zone. Moreover, the high level flat of the stepped overthrust below the Montagna dei Fiori Structure, exposed in the Torrente Salinello gorge, evidently does not cut upwards through the ENE dipping Laga Formation on the forward limb. Therefore it has to merge also into the Laga Detachment Zone below, as indicated in fig. 35.

Thus in the Laga Mountains Area the Umbria-Marche Sequence has been shortened considerably by two stepped overthrusts, whereas the overlying part of the sedimentary cover (the Laga Fm.) has been hardly shortened at all. The stepped thrusts of the Acquasanta Structure and the Montagna dei Fiori Structure flatten out and merge into the Laga Detachment Zone, which persists to the NE, to end blind towards, or even below the Adriatic Sea (see p. 132).

*) In the NNW ward plunging crest of the Montagna dei Fiori: in the F. Tronto valley, 3 km to the W of Ascoli Piceno; in the Torrente Castellano valley near Castel Trosino, and to the W of S. Giacomo. In the SSE ward plunging part to the W of Roiano.
In the WSW dipping backward limb between Macchia del Sole and Castelmanfrino (Torrente Salinello valley) the pervasively sheared Scaglia Cinerea is also exposed in a narrow zone to the W of the normal fault contact with the Calcare Massiccio (see p. 92); slickensides, facing of the folds and sigmoidal shape of the cleavage indicate a NE ward direction of shearing, opposite to the sense of displacement along the normal fault.

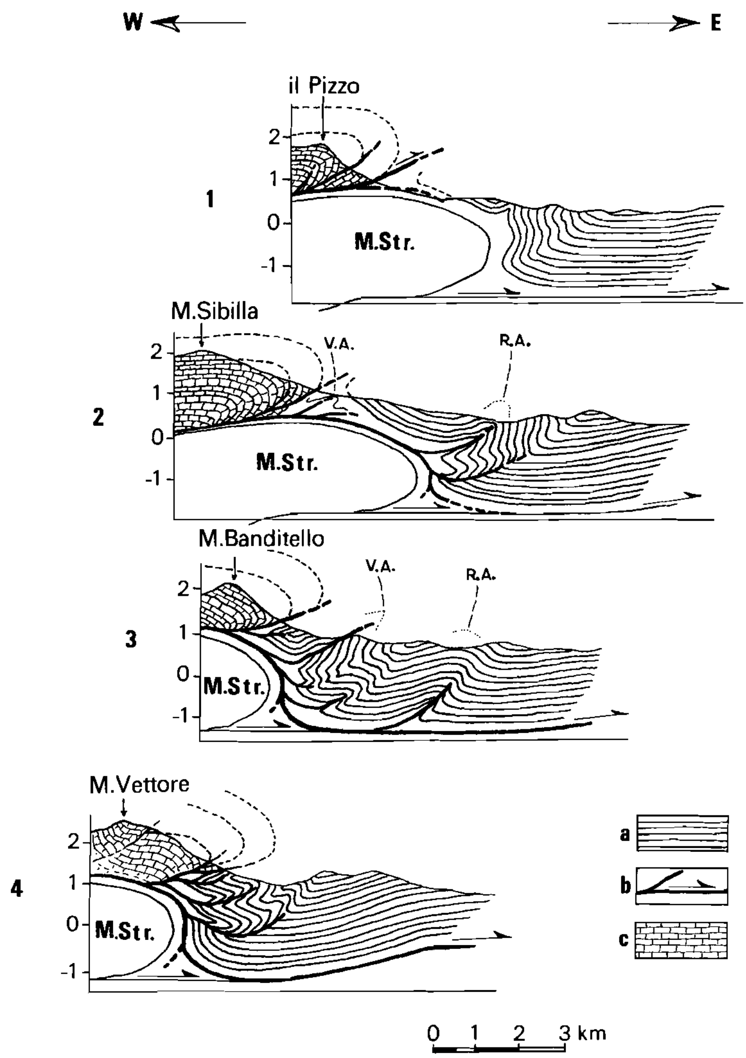


Fig. 51: Interpretative sections across the Umbria Thrust Zone in the N part of the area. See text for explanation. Legend: a. Laga Formation; b. Umbria Thrust Zone and its continuation in the Laga Detachment Zone; c. Umbria-Marche Sequence of the M. Sibilla Structure and M. Vettore Massif; M.Str. = Montefortino Structure; V.A. = Vallegrascia Anticline; R.A. = Ropaga Anticline.

3.4. ON THE RELATION BETWEEN THE UMBRIA THRUST ZONE AND THE LAGA DETACHMENT ZONE

The relation between the Umbria Thrust Zone and the Laga Detachment Zone can be studied in three places where the footwall of the Umbria Thrust Zone is exposed: in the Montefortino Structure, in the Window of S. Giovanni/Terracino, and in the M. Prato Structure.

The Montefortino Structure (see the Geol. Map and the Sections A, B and C) is a broad anticline in the N part of the investigated area. It lies in front of the M. Sibilla Structure of the Umbria Thrust Zone, which covers its SW limb and part of the crest.

In the NE limb the Laga Formation can be seen, overlying the exposed part of the Umbria-Marche Sequence (from the Scaglia onward) with an undisturbed stratigraphic contact (see Sections A5A6, B1B2, and fig. 51, section 1). It is the only place in the area without detachment along the Scaglia Cinerea/Acquasanta Group.

It is likely that the Montefortino Structure is a structurally lower and more distal rootless anticline above a NW - SE striking ramp. The stepped thrust remains below the erosion surface (fig. 51), since it has not cut up through the Laga Formation to the NE. It probably continues at the level of the Scaglia Cinerea/Acquasanta Group, as the Laga Detachment Zone.

Towards the S, the axial trend of the Montefortino Structure turns gradually from NW - SE through N - S to NNE - SSW, probably reflecting a change in the strike of the footwall ramp. Because the M. Sibilla Structure maintains its NW - SE direction, the Laga Formation in the forward limb of the Montefortino Structure approaches the Umbria Thrust Zone, until it is overridden to the S of the latitude of Vallegrascia (compare Sections B, C and D). But here, in the Fiume Aso valley, the Scaglia Cinerea/Acquasanta Group below the Laga Formation is highly imbricated and pervasively sheared (see Section C). Therefore, in SE direction an increasing amount of displacement on the Umbria Thrust Zone is transferred into the Laga

Detachment Zone, and the Laga Formation becomes progressively part of the hanging wall (fig. 51). Some shortening is transferred to the level of the Laga Formation, as indicated by two small S plunging anticlines: the Vallegrascia and Ropaga Anticlines (fig. 51, sections 2 and 3). Both are asymmetric to the E, indicating that they are not parasitic to the Montefortino Structure. Splay thrusts from the underlying detachment terminate in their cores; they fade out as one goes down-plunge to the S.

To the S other folds in the Laga Formation directly E of the Umbria Thrust Zone have much the same morphology: the hinges are cut by minor thrust faults, fading out upward and/or along strike. To the S they become gradually more recumbent (Section E). In analogy with the Vallegrascia and Ropaga anticlines, where the associated detachment can be seen, these folds must also be considered as detachment folds, generated in front of the Umbria Thrust Zone (fig. 51, section 4).

It is likely that the development of the Umbria Thrust Zone, and the related detachment folds in the Laga Formation came first, followed by the development of the structurally lower Montefortino Structure.

In the N the forward limb of the Montefortino Structure lies beyond the forward limb of the M. Sibilla Structure, whereas towards the S, where its trend turns to NNE - SSW, the Montefortino Structure is covered progressively by the S end of the M. Sibilla Structure, the M. Vettore Massif, and the M. Utero - M. Macchialta Structure. Consequently all these earlier structures, related to the Umbria Thrust Zone, were subsequently warped across the forward limb of the rootless anticline below. To the E of the M. Vettore Massif the originally steep detachment folds have become recumbent (fig. 51). Further S, also the N part of the M. Macchialta - M. Utero Structure and the Umbria Thrust Zone itself have been tilted to an easterly dip.

The Window of S. Giovanni/Terracino (see the Geol. Map and the Sections F and H) is determined by a slight culmination in the Umbria Thrust Zone, deeply cut by the topography. No Laga Formation is present in the footwall of the thrust zone. Instead, to the E the highly deformed Acquasanta Group continues below the steep to inverted Laga Formation, as the Laga Detachment Zone.

The Scaglia Cinerea in the centre of the window (see Section H3H4) composes the top part of at least one other Umbria-Marche Sequence below. This footwall-sequence apparently represents the crest zone of a structurally lower rootless anticline. The very wide steep to inverted zone in the Laga Formation (Section H5H6) forms the forward limb. The stepped thrust at its base remains blind, and probably continues also in the Laga Detachment Zone.

In analogy with the configuration in the N, also here the structurally lower stepped thrust has been active after the emplacement of the hanging wall of the Umbria Thrust Zone (including the Laga Formation), since the latter is folded across the underlying rootless anticline.

The M. Prato Structure (see the Geol. Map and the Sections K, L and M) is a NW - SE trending brachy-anticline to the E of Cittareale, in the SW part of the investigated area. Its development was posterior to the thrusting, because all the regional thrusts culminate over the anticline. Only a N - S normal fault-system, offsetting the anticline, is still later.

The brachy-anticline comprises three structural units. The uppermost one (1 of fig. 52) is the hanging wall of the Umbria Thrust Zone: the M. Boragine - M. Pizzuto rootless anticline, and the contiguous Laga Formation above the Laga Detachment Zone.

In the footwall of this thrust the forward part of a second rootless anticline is exposed: the M. Laghetto Structure (see Section L; 2 of fig. 52). Its inverted limb consists mainly of the Scaglia and the sheared-out Scaglia Cinerea (exposed to the E of the normal fault-system running along the Valle S. Rufo), whereas the Maiolica and the Forca Canapine Group are preserved in the upper normal limb. The steep plunge, due to its position in the NE limb of the brachy-anticline, reveals that the thrust at the base of the M. Laghetto Structure also merges with the Laga Detachment Zone (in the area between the M. Rota

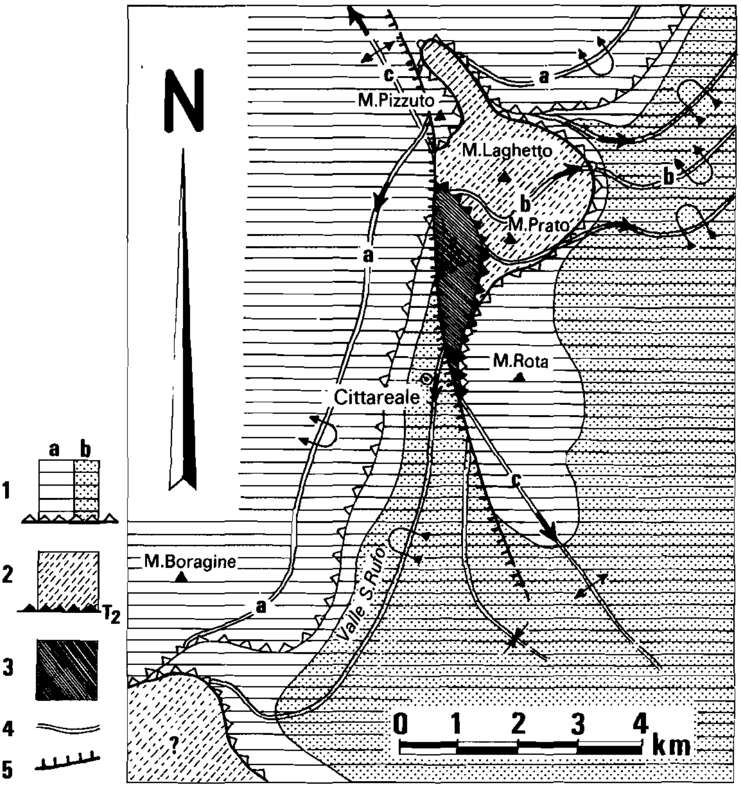


Fig. 52: Schematic map, showing the main structural units in the M. Prato Structure. The splay thrusts are omitted. Legend: 1. hanging wall of the Umbria Thrust Zone (a) and the continuation above the Laga Detachment Zone (b); 2. hanging wall of the structurally lower thrust zone: T2 (M. Laghetto Structure and the Laga Formation; to the S of the investigated area the M. Laghetto Structure continues in the recumbent anticline of the M. Cerasa); 3. Scaglia in the footwall of T2; 4. major axial traces: a. M. Borganine - M. Pizzuto Structure; b. M. Laghetto Structure; c. M. Prato Structure; 5. normal fault-system.

and M. Prato, to the E of Cittareale). Therefore, the Laga Formation belongs to the hanging wall of both the Umbria Thrust Zone and the second underlying stepped thrust of the M. Laghetto Structure, and has been doubly displaced. Because the highly tectonized Scaglia Cinerea/Acquasanta Group of the Laga Detachment Zone passes over, as well as under the M. Laghetto Structure dominant thrusting along the second stepped thrust has been posterior to the displacement along the Umbria Thrust Zone (fig. 53).

The lowermost tectonic unit (3 of fig. 52) is only exposed to the E side of the Valle S. Rufo, and reveals the undeformed Scaglia in the footwall of the M. Laghetto thrust, only folded in the M. Prato brachy-anticline. Thus, not only another rootless anticline below the Umbria Thrust Zone is exposed, but also the high level thrust and the footwall below it. The crest zone and NE limb of the M. Prato brachy-anticline comprises a small double window.

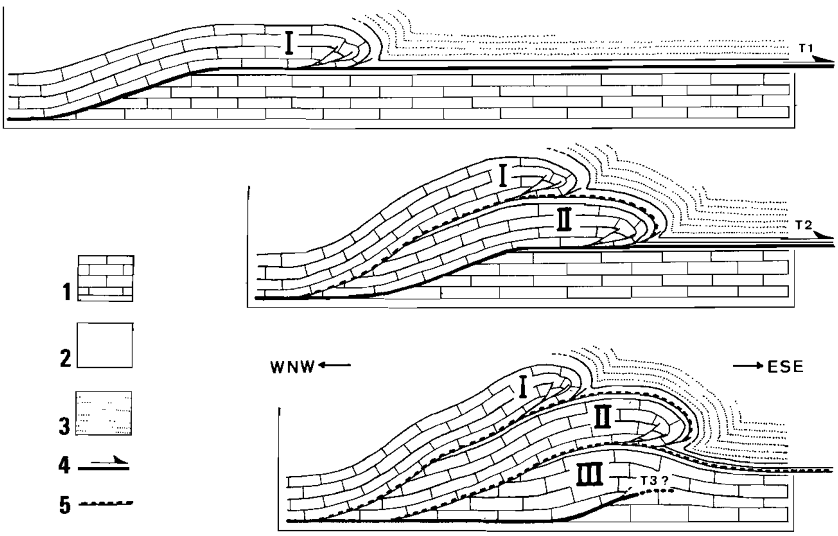


Fig. 53: Schematic three-stage model illustrating the development of the M. Prato Structure. Displacement along the Umbria Thrust Zone and its high level continuation in the Laga Detachment Zone (T1) is followed by the initiation of a more distal thrust (T2) at the base of the M. Laghetto Structure (II), which also merges in the Laga Detachment Zone. The Umbria Thrust Zone is folded in the forward limb of the M. Laghetto Structure. Subsequent development of the brachy-anticline results in the present configuration. Note that the sections are oblique to the direction of thrusting. Legend: 1. Umbria-Marche Sequence; 2. Scaglia Cinerea/Acquasanta Group; 3. Laga Formation; 4. Dominant active thrust; 5. deformed older thrust.

The Sections K, L and M, and the Geological Map indicate that the configuration just described is highly complicated by disharmonic folding and subsidiary splay thrusts, which cut both the crest (Section L1L2) and the overturned forward limb (Section L5L6) of the M. Laghetto Structure.

From these observations a consistent picture emerges: the Umbria Thrust Zone was formed first as a stepped thrust, that only in the N partly overrode the Laga Formation (Montefortino Structure). In the S the thrust flattened beyond the forward limb at the level of the Scaglia Cinerea/Acquasanta Group to continue as the Laga Detachment Zone (M. Prato Structure). The situation between the Fiume Aso valley and Capodacqua is transitional: here the Laga Formation is pushed up into detachment folds (exemplified by the Vallegrascia and Ropaga Anticlines), and is also slightly overridden. Subsequent stepped thrusts below and in front carried along the whole Umbria Thrust Zone "piggy-back", uplifting and deforming it. These thrusts, however, remain below the present erosion surface (except in the M. Prato Structure); they flatten and merge also in the Laga Detachment Zone, which persists and is exposed further E in the crests of still later rootless anticlines: the Acquasanta Structure and the Montagna dei Fiori Structure.

CHAPTER 4

CONCLUSIONS AND DISCUSSION

Stepped thrusts and rootless anticlines are the key tectonic features in the studied part of the Central Apennines. The structures are the result of a thin-skinned style of deformation (Rodgers, 1949), under little overburden.

During the Alpine Orogeny the Mesozoic - Neogene sedimentary cover was detached from its pre-Triassic basement along the incompetent Burano Formation, and shortening took place by NE ward movement on a series of stepped thrusts, branching off this common low level detachment zone. Regional folding in the cover was largely passive, and due to the doubling of the Umbria-Marche Sequence above footwall ramps.

4.1. ON THE RELATION BETWEEN MESOSCOPIC FOLDING AND THRUSTING

In the lower part of the cover shortening by buckling has been relatively small, mainly due to the rigidity of the Calcare Massiccio. In the backward limb of the rootless anticlines the complete cover has simply been bent over the footwall ramp. On the contrary the uppermost cover units form a disharmonic steep to inverted forward limb. With significant exception of the Laga Formation, the higher strata in this forward limb are severely shortened by mesoscopic folding and pressure solution. Field relations and areal distribution suggest a close relation between this folding in the high level cover and the upward propagation of the thrust in the low level cover. The following deformation sequence is proposed (fig. 54).

Initially, a large part of the horizontal shortening by progressive doubling of the strata in the low level cover is transferred into mesoscopic folding, in a more or less wide zone of the overlying cover. This folding occurs in the front of the leading edge of the thrust, in the forward limb of the developing rootless anticline. Part of the displacement is also distributed among subsidiary splays

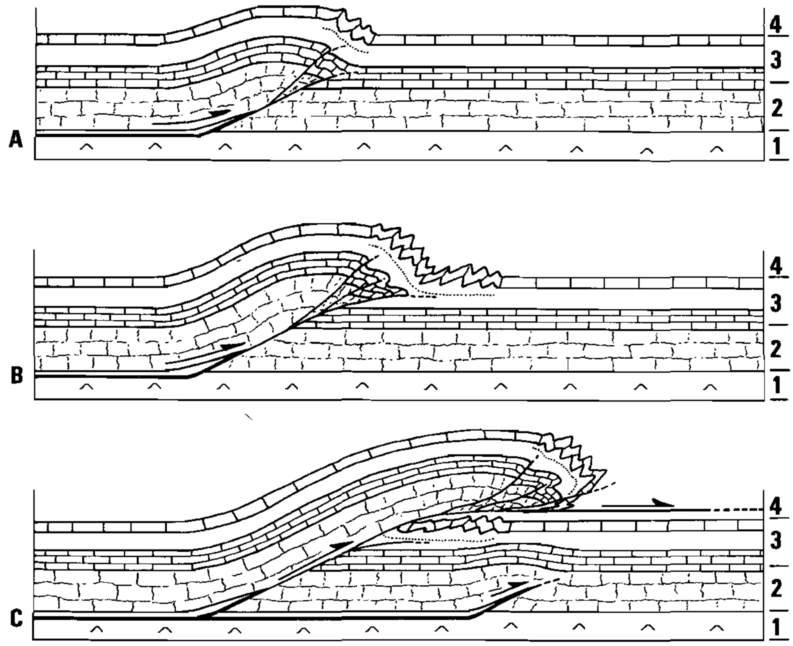


Fig. 54: Sequential diagram of the development of a surficial rootless anticline, showing the relation of the thrust zone to the high level mesoscopic folds. The numbers 1-4 correspond with the tectonostratigraphic levels as defined in 2.2.b (p. 42). Level 5 (the Laga Formation) is not shown.

and faults of lower orders, branching off the main thrust. The first mesoscopic folds may have initiated to resolve local space problems, as "escape structures" (Laubscher, 1976). However, as long as the thrust is blind and the overlying part of the stratigraphic succession is not yet intersected, its displacement is compensated by further disharmonic folding (displacement transfer mechanism c.f. Dahlstrom, 1970).

Intensity of deformation is largest near the leading edge of the propagating thrust, where the stress is maximal (as demonstrated in photoelastic models by Rodgers & Rizer, 1981). However, ductility contrasts and well-defined bedding have favoured secondary hanging wall detachments (Thompson, 1981), that have resulted in spreading of the disharmonic folding, mainly towards the crest zone of the developing anticline. The incompetent rocks, mainly of the Forca Canapine Group and Marne a Fucoidi, have permitted each overlying unit to fold disharmonically. The increase of disharmonic folds from the Corniola to the Scaglia reflects the importance of such hanging wall detachments. Thus, accommodation of the shortening has been largest in the Scaglia, which generally composes thick disharmonically folded zones. This is about the stage of development present at the NE side of the M. Bove Structure (compare fig. 54B with Sections A and B).

Finally, as compensation of the shortening by disharmonic folding cannot be maintained, the thrust cuts up across the folded zone. The forward limb of the anticline is displaced beyond the footwall ramp, and the thrust flattens at the level of the Scaglia Cinerea/Acquasanta Group (compare fig. 54C with the structures along the Umbria Thrust Zone). Propagation of the thrust through the high level cover units is associated with a simple shear deformation, superimposed on the previous deformation patterns (fig. 55). This overturns the lower part of the forward limb near the thrust. Shear near the fault zone changes the folds to tight, strongly inclined to recumbent, and in the main high level thrust zone they are transposed completely. Also, penetrative deformation phenomena are concentrated near and in the thrust.

The distribution of simple shear deformation in the forward limb is non-uniform. Large parts of these variations are caused by the subsidiary splays. They have generally rapid lateral and upward terminations, and the loss of slip towards the termini is compensated by faults of lower orders, and increase in fold intensity. Only away from the thrust and its splays, mesoscopic folds keep their original positions and geometries.

The sequential development given in the diagram of fig. 54 is valid not only where the direction of thrusting is perpendicular to the strike of the rootless anticline, like in the N part of the Umbria Thrust Zone. Further S, where the axes of the folds are NNE - SSW, such schematic cross-sections will look very much alike,

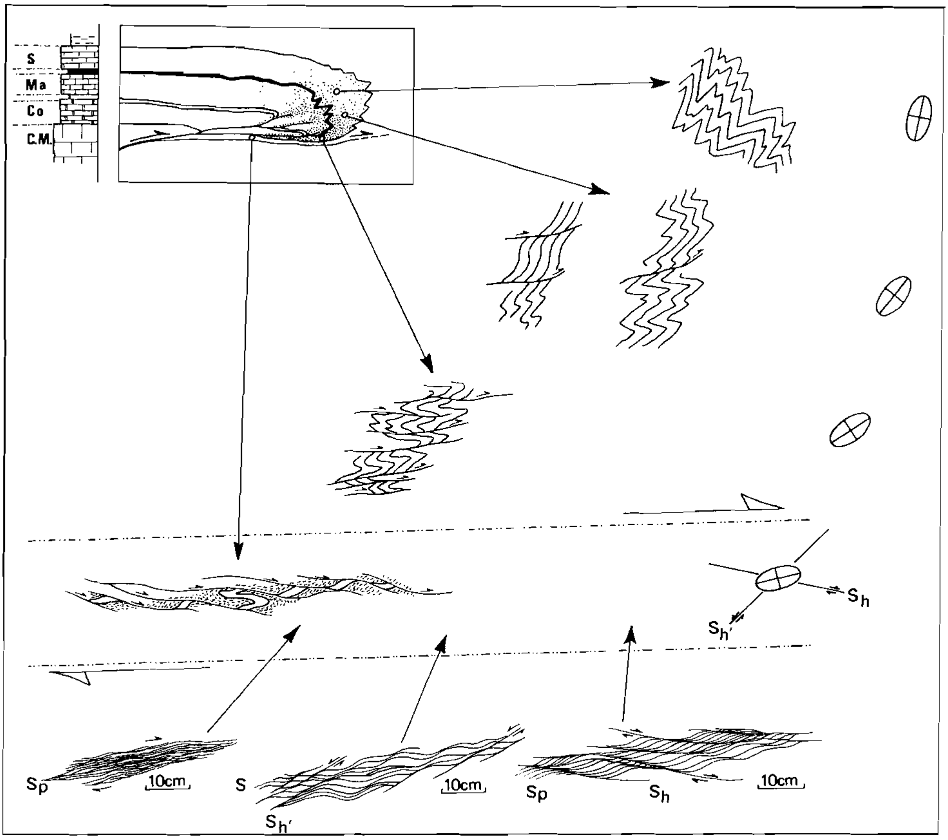


Fig. 55: Diagram showing the geometrical relation between thrusting and mesoscopic folding in the hanging wall of the Umbria Thrust Zone. In the schematic cross-section (upper left) of a rootless anticline the intensity of mesoscopic folding in the forward limb is indicated schematically by dots. The attitudes of the mean finite strain ellipsoids are shown; note that the magnitude of strain is not represented. In the lower part the attitudes of solution cleavage (Sp) and shear veins (Sh and Sh') in the main thrust zone are indicated.

even though the direction of thrusting is not parallel to the plane of section. However, the three dimensional picture is more complex there. The early disharmonic folding is not coaxial with the later shear pattern in which a large dextral strike slip component prevails. In the forward limb, developing at an acute angle to the direction of thrusting, this has resulted in refolded fold axes and oblique transposition near and in the thrust zone.

4.2. ORIGIN OF THE OBLIQUE RAMPS

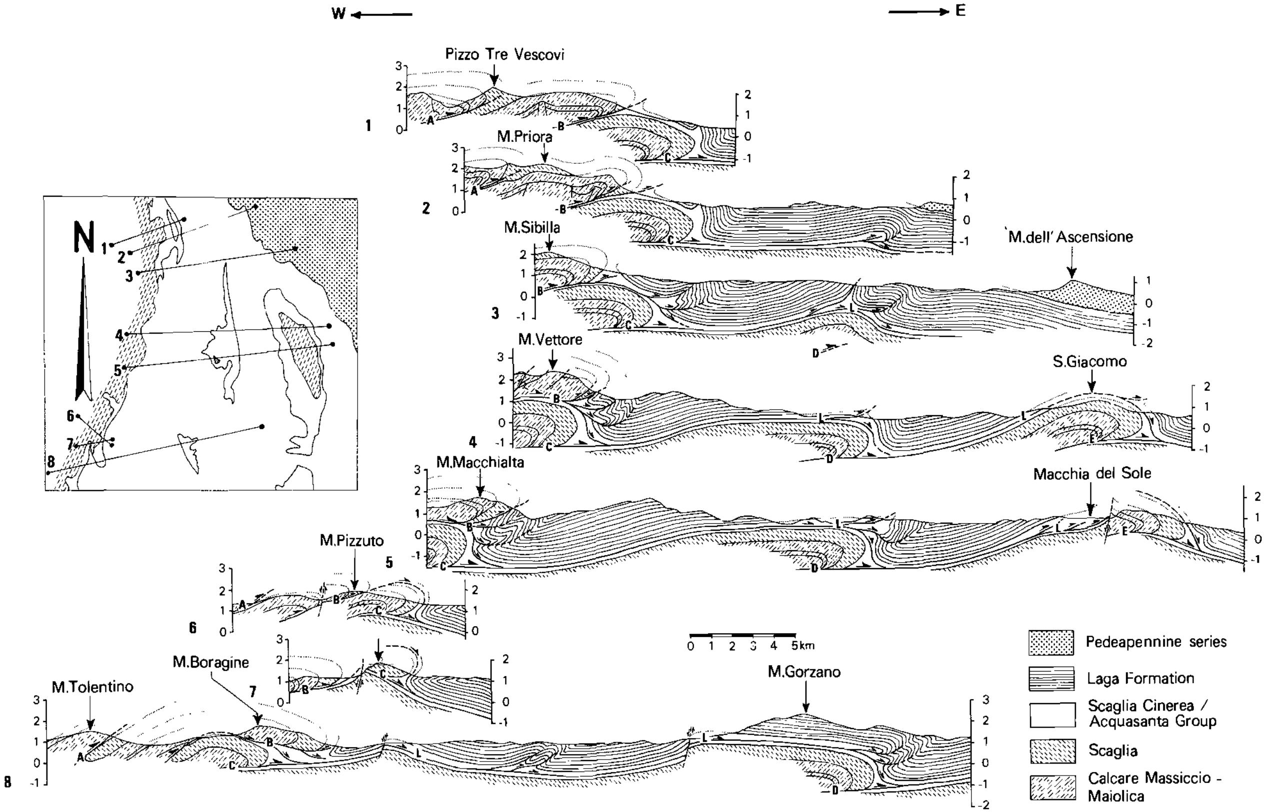
The most conspicuous lateral discontinuity in the sedimentary cover of the Central Apennines is the boundary between the Latium-Abruzzi carbonate platform sequence, and the basinal sequences to the W and NE (see 2.1.a). The N platform boundary runs about E - W, along the Gran Sasso d'Italia chain, whereas the W boundary strikes N - S to NNE - SSW (see chapter 2, and Castellarin et al., 1978; Cantelli et al., 1978).

Although in the Umbria Marche Apennines, Laga Mountains Area and Abruzzi the overall translation turns out to be the same, across this platform boundary the change in structural morphology and scale is obvious (see also Pieri, 1975). Also the buried Jurassic fault-blocks and associated variations in the stratigraphic sequence (see chapter 2), which are present all over the Umbria Marche Apennines, constitute irregularities in the sedimentary cover. Directly to the W of the Umbria Thrust Zone one of the Jurassic normal fault-systems has also a prevalent NNE - SSW strike; for example in the buried horst exposed in the Fiume Tenna valley (see also Chiocchini et al., 1976).

These NNE - SSW striking ancient lineaments make an acute angle with the NE direction of thrusting that has been found all over the investigated area (see figs. 17 and 36). During orogeny they have acted as preferential locations for thrust steps.

4.3. LARGE SCALE PATTERN OF RAMPS AND THRUSTS

The pre-determined inhomogeneities have resulted in various structural trends, all over the Central Apennines. The footwall ramps and overlying rootless anticlines are unevenly spaced, and largely non-parallel. NW - SE striking ramps with reverse dip slip displace-


W
E
Pizzo Tre Vescovi
M.Priora
M.Sibilla
M.dell'Ascensione
M.Vettore
S.Giacomo
M.Macchialta
Macchia del Sole
M.Pizzuto
M.Boragine
M.Tolentino
M.Gorzano
N
0 1 2 3 4 5km
Pedeapennine series
Laga Formation
Scaglia Cinerea / Acquasanta Group
Scaglia
Calcare Massiccio - Maiolica

ments generate structures approximately parallel to the general strike of the mountain belt. These alternate and interfere with N - S to NNE - SSW striking oblique ramps with important dextral strike slip components of displacement.

In the investigated area to the N of the Fiume Aso valley the rootless anticlines strike NW - SE and the thrusts have stepped up perpendicular ramps, whereas to the S they merge into NNE - SSW trending rootless anticlines on oblique ramps.

The regional anticlines of the Laga Mountains Area have also developed on oblique ramps. Their N ward plunges and terminations indicate a rapid loss of displacement along the stepped thrusts below, and termination of the subsurface ramps.

At least four stepped thrust zones flatten out at the level of the Scaglia Cinerea/Acquasanta Group (fig. 56): the Umbria Thrust Zone (coded B in fig. 56), except in the N part of the area investigated (compilation sections 1 and 2 of fig. 56); the stepped thrust in its footwall (coded C in fig. 56), and the thrusts below the Acquasanta Structure (D) and the Montagna dei Fiori (E). In front of the forward limbs of the rootless anticlines, very little shortening is transferred up to the level of the Laga Formation. The main thrusts merge below it and continue to the NE as the Laga Detachment Zone (coded L in fig. 56). Therefore the Laga Formation belongs everywhere to the hanging wall of these thrusts, and must have undergone considerable displacement. In modern terminology the configuration may be described as a duplex (Dahlstrom, 1970): a series of rootless structures ("horses", c.f. Elliott & Johnson, 1980; Butler, 1982), bounded by stepped thrusts, which branch off the common Burano Detachment Zone (low level flat or floor thrust), and rejoin in the high level Laga Detachment Zone (high level flat or roof thrust). The deformation

←*Fig. 56: Compilation-sections across the Umbria Thrust Zone (Eastern Umbria Marche Apennines) and Laga Mountains area. The subsurface geometries of the rootless anticlines, and thrust-displacements are drawn so, as to minimize internal inconsistencies. Splay thrusts are highly simplified. The configurations to the W of the M. Boragine and to the E of the M. Gorzano (section 8) are inferred from the Carta Geologica d'Italia (1:100.000).*

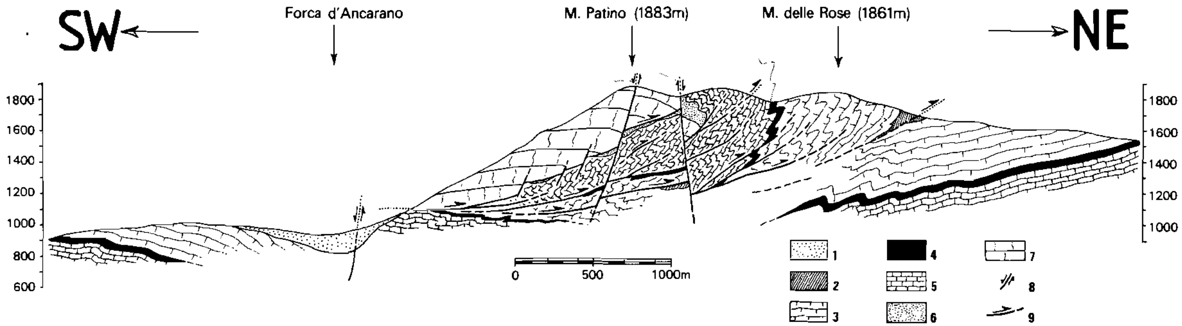


Fig. 57: The rootless structure of the M. Patino, to the NE of Norcia (Umbria Marche Apennines). Legend: 1: debris; 2: Scaglia Cinerea; 3: Scaglia; 4: Marne a Fucoidi; 5: Maiolica; 6: Forca Canapine Group/Corniola; 7: Calcare Massiccio; 8: normal fault; 9: Thrust fault.

pattern indicates a successive NE ward development of the regional structures and stepped thrusts, in the order A to E (fig. 56). This is in accordance with the general progression of the Apennine orogeny from the interior towards the external Adriatic foreland. At any one time only one or possibly a few stepped thrusts were active. After the emplacement of a rootless anticline, a more external stepped thrust was activated, possibly due to tectonic loading by the former one(s) (Gretener, 1981; Burchfiel & Davies, 1975). Each rootless anticline including the detached Laga Formation in front, is carried "piggy back" on a subsequent lower structure, by which it is uplifted and deformed. In the Laga Mountains Area the Laga Detachment Zone is folded and carried along by the Acquasanta Structure and Montagna dei Fiori Structure. The outcrops of the Umbria-Marche Sequence in their crest zones are tectonic windows in the Laga Detachment Sheet.

4.4. TECTONIC IMPLICATIONS FOR ADJACENT AREAS

The pattern of the Umbria Marche Apennines to the W of the investigated area, looks very much like the structures along the Umbria Thrust Zone. The M. Bove Structure on the backward limb of the M. Sibilla Structure (SW part of Sections A and B), and the thrust-units to the NW of the M. Boragine - M. Pizzuto Structure (Section L1L2) represent the forward parts of more internal rootless anticlines. To the W these are followed by still higher ones, like for examples the M. Patino Structure, to the NE of Norcia (fig. 57). The 1:100.000 Carta Geologico d'Italia shows several overthrusts (see also Deiana, 1965; Dufour, 1970; Decandia & Giannini, 1977, etc.) that follow incompetent levels; mainly the Scaglia Cinerea, but also the Forca Canapine Group and the Marne a Fucoidi (fig. 57).

Regardless of the directions of the folds (both regional and mesoscopic) the movements along the thrusts have been towards the NE. (For example in the M. Patino Structure; the thrusts of the M. Sassatelli and M. Pozzoni, to the S of Norcia; the M. Tolentino overthrust, to the NE of Leonessa; the thrusts along the ESE side of the M. Serano, to the E of Trevi nell'Umbria; and the Spoleto overthrust).

The general arcuate shape of the Umbria Marche Apennines (see p. 45 and fig. 58a), convex to the E, is the result of interference between perpendicular and oblique ramps. In the S and SE the distance across strike between successive anticlines gradually diminishes; the synclines get narrower and are increasingly overridden at their W and SW sides. Generally highly tectonized Scaglia Cinerea fills the narrow synclinal hinges. In the zones where oblique ramps prevail, a bundling up of anticlines occurs, associated with complex interference patterns of NW - SW (perpendicular) and NNE - SSW (oblique) trends (the "virgazione scalare", already mentioned on p. 45). Possibly also in this part of the Umbria Marche Apennines, higher thrusts and arcuate rootless anticlines have been uplifted and deformed on top of the more distal and lower ones.

To the NW in the Umbria Marche Apennines the strike of the regional structures changes to NW - SE, and the fold pattern becomes more regular. Here the outcrop lines of overthrusts gradually disappear from the Italian geological maps. This suggests their northwesterly termination in a zone where large scale buckling dominates, associated with a flow of incompetent material of the Burano Formation into the cores of the anticlines (Lavecchia, 1981).

However, also here the box-shape of the regional anticlines, their constant elevation and sharply plunging terminations are suggestive of rootlessness on the common low-level Burano Detachment Zone. Moreover, the lack of overthrusting is more apparent than real. Wide zones of disharmonic folding, overturned forward limbs, secondary detachments, splay thrusts, etc. are still present in the high level cover (levels 3 and 4: see p. 42), indicating a shortening that largely exceeds the requirements of simple buckling.

All these features suggest the NE continuation of stepped overthrusts below the regional anticlines, much the same as described in this paper, but in less advanced stages. Therefore, the NW part of the Umbria Marche Apennines may be much less autochthonous than supposed by most authors. However, allochthony of the Umbria Marche Apennines does not imply oroclinal bending (as proposed by Channell, 1976; Channell et al., 1978; see p. 46). Everywhere across the belt, detachment and thrusting was towards the NE, perpendicular to the general Apennine trend.

In the Abruzzi less uncertainty exists about the allochthony of the structural units (see 3.1). The NE boundary - a vertical to overturned series, cut S to SW ward dipping thrust faults (Alberti et al., 1963; Parotto & Praturlon, 1975; Calembert et al., 1972), along the NE side of the Gran Sasso d'Italia massif - may be considered as the forward limb of the rootless Gran Sasso Structure (4b in fig. 58a). Along it, the Laga Formation is only slightly overridden along upward splay thrusts, while the main thrust flattens to the NE in the Laga Detachment Zone (the tectonized Acquasanta Group of the Cima Alta Area (5b in fig. 58a). This hanging wall position of the Laga Formation appears also from the indications for the local periphery of the Laga Basin (see p. 41).

A W ward continuation of the overthrust front of the Gran Sasso Structure is suggested on many schematized maps of the area (see for example: Pieri, 1975: figs. 15 and 17; Castellarin et al., 1978: fig. 1; Funiciello et al., 1981). In fact however, to the W the Gran Sasso Structure plunges away, and the Latium-Abruzzi Sequence disappears under the Laga Formation. The situation is depicted correctly on the sheets 139 (Alberti et al., 1955) and 140 (Alberti et al., 1963) of the Carta geologica d'Italia. On our maps (fig. 58) a connection of the forward limb of the E part of the Gran Sasso Structure (4b) with the forward limb of the Acquasanta Structure (4a) is postulated, but further investigations are needed.

The Montagna dei Fiori Structure (5 in fig. 58b) was apparently posterior to the emplacement of the Gran Sasso Structure, which is arched up over the Cima Alta crest zone.

The allochthony of the M. Giano Structure to the SW of the

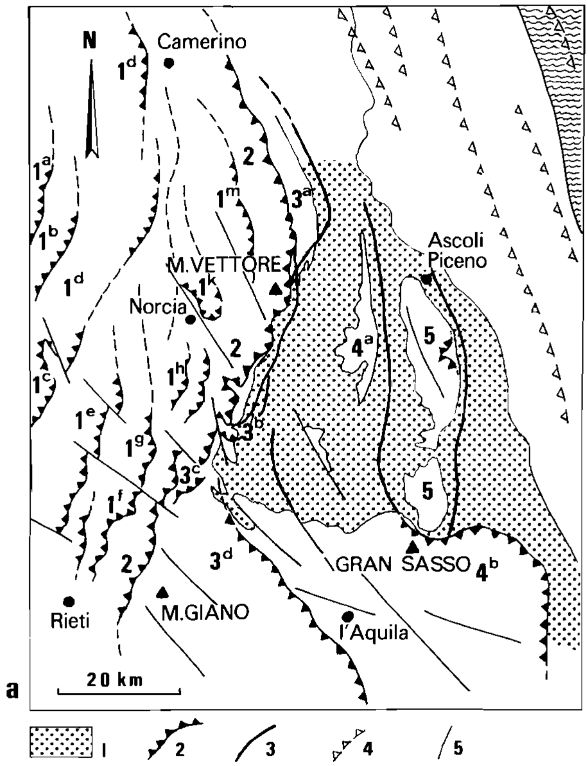


Fig. 58: Structural sketch map (a) and interpretation (b) of the Central Apennines.

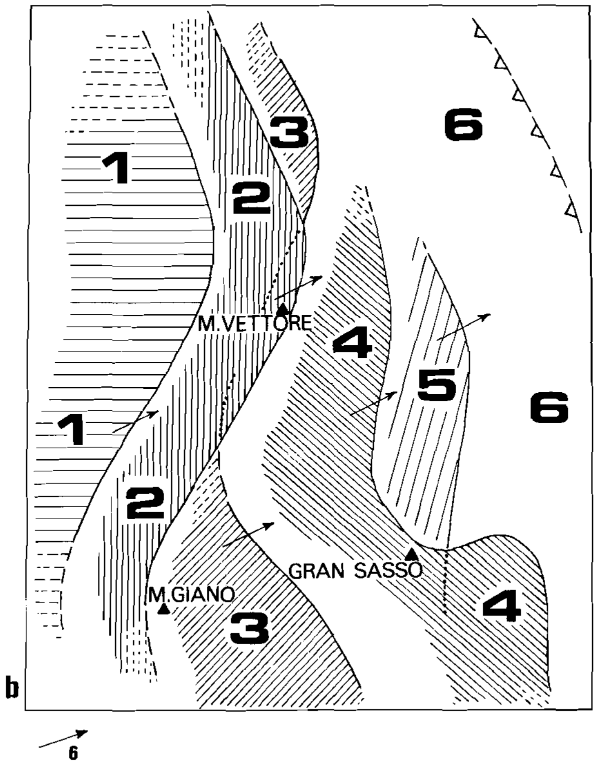
1. *Inner rootless anticlines:*

a. M. Aguzzo	*f. M. Tilia*
b. M. Serano	*g. M. Tolentino*
c. Str. of Spoleto	*h. M. Sassatelli-M. Pozzoni*
d. M. Primo-M. Maggiore	*k. M. Patino*
e. M. Aspro	*m. M. Bove*

2. *Rootless anticlines of the Umbria Thrust Zone.*

3. *Rootless anticlines in the footwall of the Umbria Thrust Zone:*

a. Montefortino	*c. M. Cerasa*
b. M. Laghetto	*d. M. Giano*



4. *a. Acquasanta*
   b. Gran Sasso

5. *a. Montagna dei Fiori*
   b. Cima Alta Area

6. *External part of the Laga Thrust Sheet; its frontal structures and buried by the Late- to Post-orogenic series of the Pedeapennine Zone.*

Legend:

1. *Laga Formation*
2. *thrust in outcrop*
3. *traces of the forward limbs in the Laga Mountains Area*
4. *buried splayed thrust front*
5. *normal faults*
6. *thrust direction*

Gran Sasso Structure (3d in fig. 58a) has been proved by a well drilled at Antrodoco: at a depth of 2730 m inverted Cretaceous rocks were found below the late Triassic Burano Formation (Martinis & Pieri, 1964; Pieri, 1966). The high level flat of the overthrust (M. Gabbia thrust of Parotto & Praturlon, 1975) continues to the NE as the Laga Detachment Zone. All along the W part of the Gran Sasso d'Italia Chain the Scaglia Cinerea and Acquasanta Group are highly tectonized. Also the M. Giano Structure plunges to the NW, and its hanging wall is overridden by the rootless structures along the Umbria Thrust Zone.

In the Pedeapennine Zone, which extends below the Adriatic Sea, geophysical and drilling data suggest the presence of a splayed thrust front, buried by continuing sedimentation (Ogniben et al., 1975; Funiciello et al., 1981). Similar buried structures are well documented more to the NW beneath the River Po Plain (AGIP, 1959; Lucchetti et al., 1962; Elter et al., 1975; Marchetti et al., 1978). Deformation lasted into the Quaternary. It is much more likely to associate these subsurface thrust faults with the front of the high level Laga Detachment Zone, than to connect them straight away with a level below the Mesozoic - Paleogene cover by steep reverse faults.

This interpretation is supported by the general picture shown on sheet 118 (Ancona) of the 1 : 100.000 Carta geologica d'Italia (Pieri et al., 1962). In the W limb of the M. Conero a low angle thrust doubles the Schlier and overlying Gesoso Solfifera Formation (equivalents of the Acquasanta Group and Laga Formation). The thrust seems to cut up from the level of the Scaglia Cinerea. Subsurface data from the surroundings of Recanati (about 25 km S of Ancona) reveal the existence of several shallow concave upward reverse faults, which may be splays from a detachment at the level of the Scaglia Cinerea/Acquasanta Group.

It implies that thin-skinned tectonics have been active till very recently, and reached far into the foreland of the present-day Apennine mountain range.

A major factor in the horizontal offset between the Abruzzi and Umbria Marche Apennines may have been the lithology of the Burano Formation. It is very likely that because of its predominantly anhydritic facies, the Burano Formation at the base of the Umbria Marche Apennines is mechanically much weaker than its dominantly dolomitic counterpart under the Abruzzi. In the former the initial low level detachment could propagate far outward. In the Abruzzi the greater shear stress soon exceeded the strength of the cover, and serial imbrication by stepped thrusts started in a more internal zone.

Both the Abruzzi and the Umbria Marche Apennines are domains - the former more internal, the latter much farther out - of imbricated thrusts stepping up from the Burano Formation to the Laga Detachment Zone. They are connected by the oblique ramps and rootless anticlines (fig. 58b), that follow pre-existing inhomogeneities in the sedimentary cover. Although this imbrication has considerably shortened the Mesozoic - Paleogene part of the cover in a SW - NE direction (in the order of 40 km) the Laga Formation has been hardly shortened at all, and the Laga Detachment Zone persists beyond the outermost forward limbs.

Thus the Laga Mountains Area, Abruzzi and Umbria Marche Apennines (including the "Umbrian Arc" and "Ancona - Anzio Line") appear as integrated parts of one great allochthonous thrust complex.

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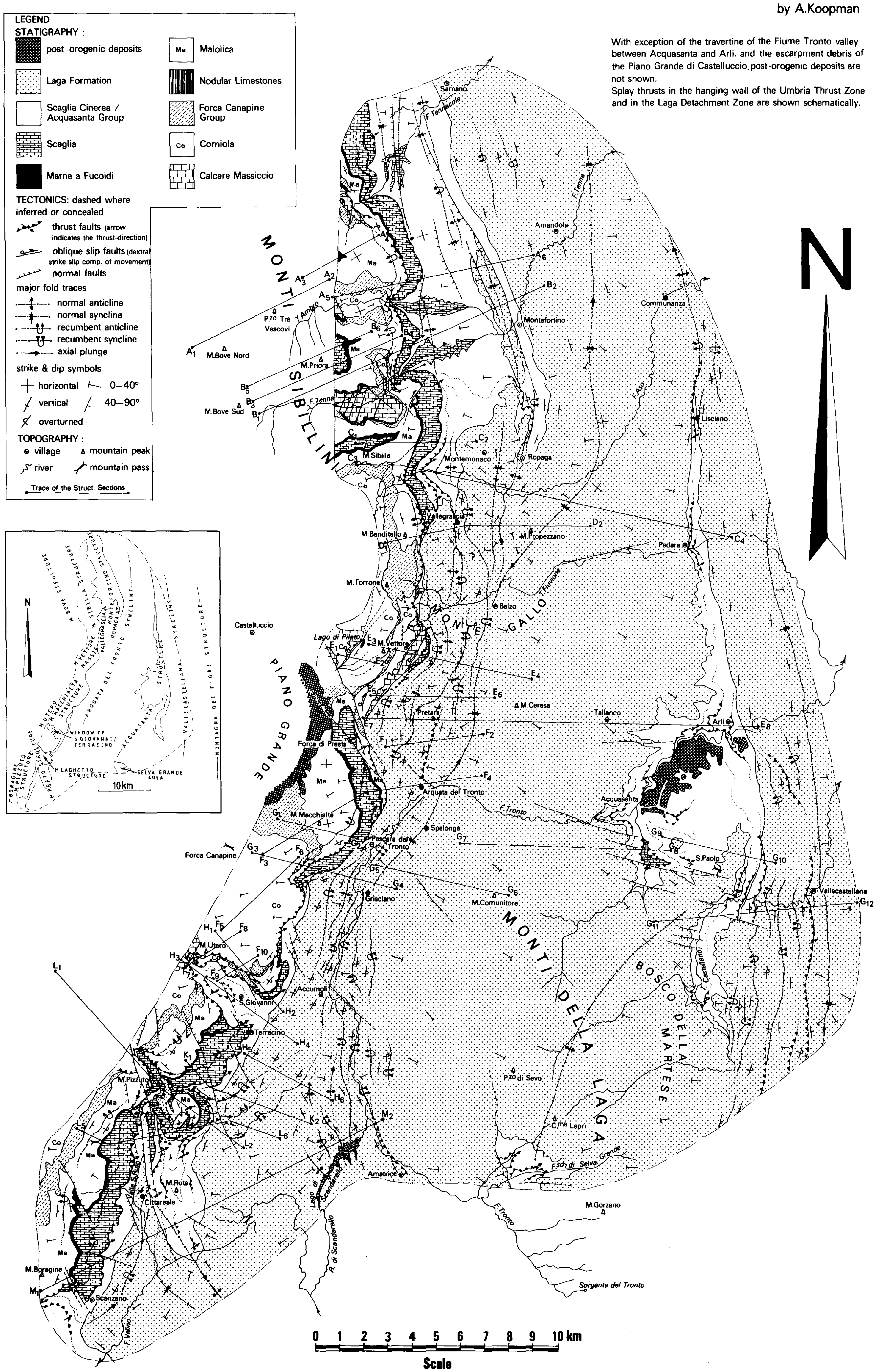
CURRICULUM VITAE

De schrijver van dit proefschrift behaalde in 1971 het diploma H.B.S.-B aan het Christelijk Lyceum te Almelo. In hetzelfde jaar werd begonnen met de studie in de geologie aan de Rijksuniversiteit Utrecht. Het kandidaatsexamen G1 werd op 10 maart 1975 behaald, en op 26 juni 1978 volgde cum laude het doctoraal examen, met hoofdrichting Structurele Geologie en bijvakken Sedimentologie en Micropaleontologie/Stratigrafie. Na de studie was de schrijver tot januari 1983 als wetenschappelijk medewerker verbonden aan de vakgroep Structurele en Toegepaste Geologie van het Instituut voor Aardwetenschappen der Rijksuniversiteit te Utrecht.

GEOLOGICAL MAP OF THE EASTERN EDGE OF THE UMBRIA MARCHE APENNINES (UMBRIA THRUST ZONE) AND LAGA MOUNTAINS AREA

by A.Koopman

With exception of the travertine of the Fiume Tronto valley between Acquasanta and Arli, and the escarpment debris of the Piano Grande di Castelluccio, post-orogenic deposits are not shown.
Splay thrusts in the hanging wall of the Umbria Thrust Zone and in the Laga Detachment Zone are shown schematically.



STRUCTURAL SECTIONS ACROSS THE UMBRIA THRUST ZONE (EASTERN UMBRIA MARCHE APENNINES) AND LAGA MOUNTAINS AREA

By A. Koopman

The mesoscopic folds and thrust zones are represented schematically; their scale and the bedding thicknesses are exagerated.