Riv. It. Paleont. Strat.	v. 96	n. 2-3	pp. 241-270	Novembre 1990

THE ANALYSIS OF SHEAR ZONES IN CALABRIA; IMPLICATIONS FOR THE GEODYNAMICS OF THE CENTRAL MEDITERRANEAN

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Key-words: Shear Zones, Neogene Basins, Calabria, Italy.

Riassunto. L'analisi sistematica delle strutture del basamento e degli elementi morfotettonici neogenici, confrontata con i risultati delle ricerche su "shear zones", ha portato alla creazione di un nuovo modello strutturale sintetico dell'Arco Calabro.

Possono essere identificati sei sistemi di faglie, che hanno prodotto vari tipi di bacini ("piggy-back basins", "pull-apart basins" e "complex oblique strike-slip basins"). Questi sistemi sono determinati da tre meccanismi morfotettonici: A) Segmenti orientati N130, separati da zone trasversali oblique di sovrascorrimento. B) Zone di sovrascorrimento orientate SO-NE, che rappresentano la parte più interna dell'"accretionary wedge system" calabro. C) Segmenti radiali cuneiformi che determinano il collasso del Bacino Sud-Tirrenico, accompagnato verso l'interno da un sistema concentrico di faglie tensionali e verso l'esterno da centri di sollevamento, che costituiscono l'arco attuale. I meccanismi A e B possono essere legati all'evoluzione Serravalliano-Pliocene inferiore ("shear zone tectonics"), mentre il meccanismo C può essere riferito all'evoluzione pleistocenica ("extreme vertical tectonics"). Il tardo Pliocene è caratterizzato da un regime tensionale.

Il quadro geodinamico del Mediterraneo Centrale nel Neogene si è sviluppato attraverso tre meccanismi principali: 1) compressione orientata NE-SO (creata da "dextral shear" lungo il margine nord- africano); 2) sollevamento diapirico nell'area tirrenica; 3) "roll-back" e distacco dei residui della litosfera ionica subdotta ("passive subduction"). L'interazione di questi tre processi ha determinato lo spostamento gravitativo dell'Elemento Calabro verso SE, sovrapponendosi nell'Appennino meridionale al sovrascorrimento obliquo.

Un "Proto-Mediterranean shear zone pattern", connesso con la torsione sinistrorsa dell'emisfero nord, ha controllato lo sviluppo del Mediterraneo Centrale.

Abstract. Systematic analysis of basement structures and Neogene morphotectonic elements -calibrated with research data on shear zones -has led to the construction of a new synthetic structural model for the Calabrian Arc.

Six fault systems can be distinguished which have generated various types of basins, such as piggy-back, pull-apart and complex oblique strike-slip basins. These systems are determined by three morphotectonic pat-

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terns: A) N130 trending segments separated by oblique transversal thrust zones. B) SW-NE trending thrust zones representing the most internal part of the Calabrian accretionary wedge system. C) Radial wedge-shaped segments confining the collapsed Southern Tyrrhenian Basin with accompanying concentric patterns of tensional faults internally and dome-shaped uplift centres situated externally, determining the actual arc. The patterns A and B can be linked to the Serravallian-Early Pliocene development of crustal shear zones ("Strike-Slip Cycle") while pattern C can be linked to the Pleistocene development (extreme vertical tectonics). The Late Pliocene was characterised by a tensional regime.

A scenario for the Neogene Central Mediterranean geodynamics has been developed by means of three mechanisms: 1) NE-SW compression (dextral shear along the N. African margin); 2) diapiric rise within the Tyrrhenian area and 3) roll-back and detachment of remnants of the subducted Ionian lithosphere ("passive subduction"). The interplay of these three mechanisms led to basal detachment and the gravitational displacement of the Calabrian Element to the SE, superimposed upon oblique overthrusting in the Apennines.

A proto-Mediterranean shear zone pattern -evolved as a result of sinistral megatorsion of the northern hemisphere -controlled the development of the Central Mediterranean.

Introduction.

One of the main problems concerning palinspastic reconstructions of the Western Mediterranean is the structural development of the Central Mediterranean arc-shaped orogenic belt (Fig. 1). Of particular interest is the Calabrian structural block, which constitutes the link between the North African-Sicilian Maghrebide Chain and the Italian Apennine Chain.

Various models have been presented to describe the kinematic evolution of the Calabrian Arc. These models can be grouped as follows:

1) Translation Models (NW-SE drift of parallel blocks): Moussat (1983), Auroux et al. (1985, 1987), Meulenkamp & Hilgen (1986), Meulenkamp et al. (1986).

2) Rotation Models (E-W (rotative) opening of the Tyrrhenian Sphenochasm): Locardi et al. (1976), Scandone (1979, 1982), Bouillin (1984), Boccaletti & Dainelli (1984), Selli (1985), Mantovani et al. (1985), Boccaletti et al. (1984, 1986).

3) Oroclinal Bending Models (Bending of an originally straight zone): Ghisetti & Vezzani (1982 a, b), Ghisetti et al. (1982), Van der Linden (1985), Carey (1986), Luongo (1988).

4) Radial Drift Models (Radial drift of wedge-shaped segments): Dubois (1976), Wezel (1981, 1985), Finetti & Del Ben (1986).

The geometric reconstruction of the Calabrian Arc plays a key-role in these kinematic evolution models and their related dynamic mechanisms such as passive subduction, lateral expulsion of crustal blocks, oroclinal bending and mantle diapirism. Analysis of the shear zones intersecting the Calabrian Arc appears to be a major tool approaching the problem since directions of shearing play a widely different role in all models.

In the Translation Models the NW-SE trending fault zones are considered a set of parallel shear zones, sinistral in the NE and dextral in the SW of the arc. Main point of discussion concerns the orientation of the major shear zones which varies from N120 (Moussat, 1983) to N140 (Meulenkamp et al., 1986). The Rotation Models put more emphasis on the E-W and SW-NE trending fault zones which are regarded as dextral shear

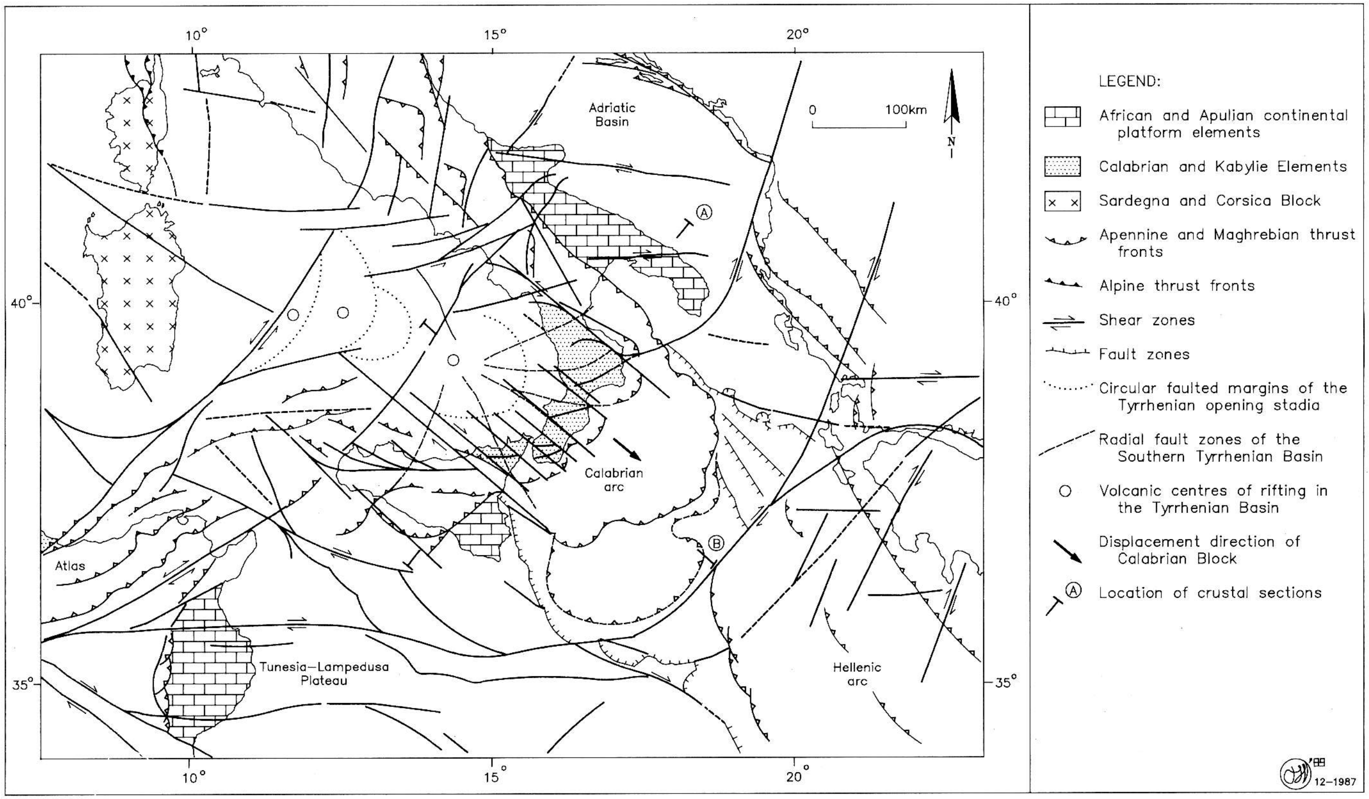

Fig. 1 - Schematic map of the Central Mediterranean. Compiled and modified after: Cohen (1980), Gasparini et al. (1982), Moussat (1983), Ciaranfi et al. (1983), Wezel (1981, 1985), Boccaletti et al. (1984), Fabbri et al. (1984), Jongsma et al. (1985), Finetti & Del Ben (1986), Auroux et al. (1985, 1987), Cello (1987), Ben-Avraham et al. (1987), Locardi (1988), Lavecchia (1988).

zones displacing the northern parts of the arc relatively to the east. According to the Bending Models and Radial Drift Models no large-scale lateral movements have occurred along the before-mentioned fault zones. They focus on the importance of normal faulting along radial and concentric fault patterns within the Southern Tyrrhenian area.

To solve these apparent contradictions, the Neogene terranes of the Calabrian Arc have been studied (see also Meulenkamp & Hilgen, 1986). One of the main fault zones, the Petilia-Rizzuto Fault Zone in Northern Calabria, was analysed in more detail to reconstruct its kinematic history. The datasets on Neogene stratigraphy, fault zone geometry, basin development schemes and structure of the crystalline basement -as can be deduced from various sources in literature -are combined in a new synthetic structural and related kinematic model for the Calabrian Arc. Finally, some implications for the geodynamics and palinspastic reconstructions of the Central and Western Mediterranean will be discussed to a limited extent.

Neogene stratigraphy and basin development.

Extensive reviews and discussions on stratigraphy and basin development in Calabria can be found in Ogniben (1973), Amodio Morelli et al. (1976), Moussat (1983), Meulenkamp & Hilgen (1986) and Meulenkamp et al. (1986). The results of some earlier studies of the Calabrian neotectonics are presented by Philip & Tortorici (1980), Tortorici (1981, 1983), Moussat et al. (1983), Moussat (1983) and Auroux et al. (1985).

Summarizing literature and our own dataset, the following systems of faults and fault zones can be recognized in the Calabrian Arc (see also Fig. 4a).

1) Large N110-N150 orientated wrench faults within the segments of the arc.
These faults determine strike-slip and pull-apart basins.

2) Chaotic thrust zones/wrench faults along the boundaries of the N130 trending segments of the arc (Riedel shear set; flower structures).
These fault zones have been interpreted as oblique thrust zones and determine piggy-back basins (Ori & Friend, 1984) and strike-slip basins.

3) SW-NE trending fault zones along the SE side of the arc.
These fault zones have been interpreted as oblique thrust zones and determine piggy-back basins.

4) Radial and concentric faults within and confining the Sila and Aspromonte dome-shaped massifs.

5) Radial tensional fault zones intersecting the entire arc constituting a fan-shaped Southern Tyrrhenian pattern.

6) Concentric tensional fault zones along the Tyrrhenian side of the arc.

The following basin development scheme has been constructed in which the activity of the fault systems has been incorporated.

The Oligocene-Lower Miocene terranes have been reconstructed in the Southern Calabrian Segment (see for preliminary results Meulenkamp & Hilgen, 1986). New data

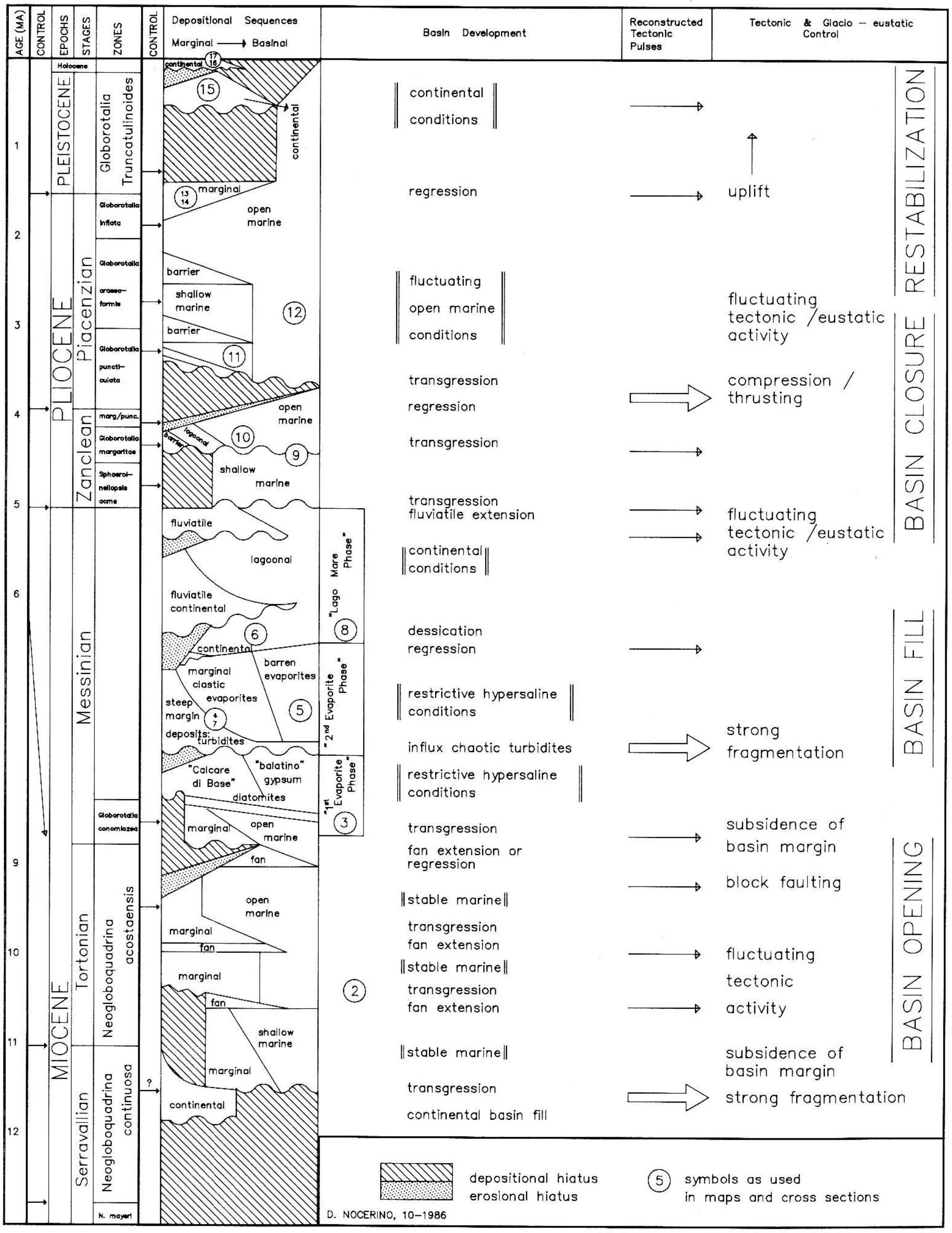

Fig. 2 - Synthetic diagram for the Neogene basin development of Central Calabria.

from this area and from the Sila Piccola are interpreted analogous to the model discussed below for the Neogene Central Calabria.

The development during this period was probably essentially controlled by progressive thrusting to the SW along thrusts of the system 3) with associated deposition of mainly coarse clastic sequences in piggy-back basins, confined by the NW-SE trending fault zones of the systems 1) and 2). In late Burdigalian times, these sequences were incorporated in gravitational gliding and thrusting to the SE and related back-thrusting to the NW, which is probably related to a major phase of shortening in the Apennines and Sicily. Traces of Burdigalian overthrusting tectonics have also been detected in N. Calabria by Dietrich (1976), reflecting a NE-SW directed component of shortening.

After a phase of onlap in the late Burdigalian-Langhian (restabilization), the subsequent Serravallian-Early Pliocene basin development along the major fault zones of systems 1) and 2) can be divided into three stages, on the basis of a detailed analysis of the Petilia-Rizzuto Fault Zone and surrounding Central Calabrian Area (Fig. 2).

a) Basin Opening Stage (Serravallian-early Messinian).
During this stage, tectonic pulses have occurred at the Serravallian-Tortonian boundary, in middle Tortonian times and at the Tortonian-Messinian boundary.

b) Basin Fill Stage (middle Messinian-late Early Pliocene).
Tectonic pulses have occurred in the middle Messinian, late-middle Messinian, latest Messinian and earliest Pliocene.

c) Basin Closure Stage (late Early Pliocene).
In this stage, the sedimentary cover thrusted towards the basin margin, resulting in a chaotic thrust zone along the basinward side of the fault zone (system 2).

Altogether, six sedimentary and eight tectonic phases can be reconstructed, resulting in an extremely accurate tectono-stratigraphic frame (Fig. 2). This frame mirrors the Strike-slip Cycle of Reading (1980) and Mitchell & Reading (1978). Probably, basin development along the fault zone can be regarded as the manifestation of the tectonic evolution of the shear zone, from deep crustal shear migrating upwards, to thrusting of the overlaying sedimentary cover. The accompanied fault and thrust pattern (and mesoscopic features such as striae and cleavage within shear bands) indicate that the zone acted as an oblique convergent sinistral shear zone (Fig. 3).

Research has been extended to fault zones orientated parallel to the Petilia-Rizzuto Fault Zone such as the margins of the Catanzaro Depression and the Rossano-San Nicola Fault Zone and also to the Crotone Basin. The geodynamic history of these fault zones strongly resembles that of the Petilia-Rizzuto Fault Zone. The constructed frame can therefore be considered representative for the Central and Northern Calabrian area and can probably also be applied to the rest of the Calabrian realm.

During Serravallian-Early Pliocene times, these NW-SE running shear zones controlled the development of complex pull-apart basins -mainly half grabens with sediment supply along the steep margins confined by the shear zones -such as the Crotone Basin within the various segments (see also brief remarks in this matter by Moussat,

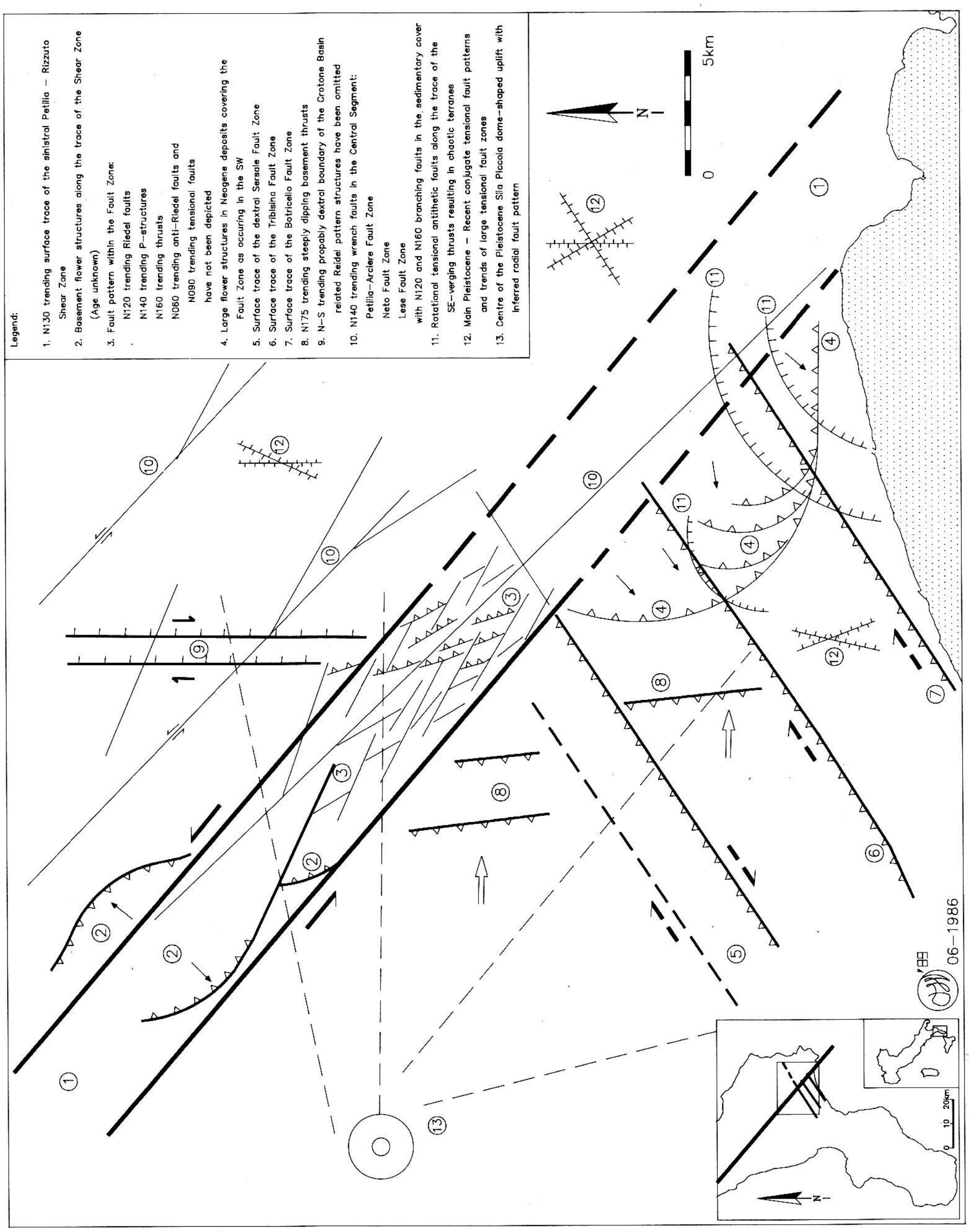

Fig. 3 - Model for the structural configurations in the Petilia-Rizzuto Shear Zone of Central Calabria.

1983; Boccaletti & Dainelli, 1984; Meulenkamp & Hilgen 1986; Meulenkamp et al., 1986 and Tortorici, 1981, 1983). Within each of the segments a unique set of wrench faults with characteristic orientation developed (system 1). These orientations show divergences up to 150 from the main N130 trend. During the Early Pliocene, the basins were subsequently deformed and inverted by convergent shearing along these wrench faults. The expression of this Early Pliocene phase of shortening can mainly be found as chaotic zones of oblique back-thrusts along the traces of all shear zones. Most striking example is the zone of deformation along the Rossano-San Nicola Fault Zone comprising an allochthonous thrust mass ("Crotonidi" or "Cariatidi"). These Cariatidi can be regarded as a large-scale back-thrust that was caused by oblique convergent sinistral movements along the SW-dipping shear zone. The structural and stratigraphic complications of the thrusts along the Petilia-Rizzuto Shear Zone have been depicted in Fig. 3.

Along the NE-SW trending external side of the arc, the faults of system 3) determined the development of piggy-back basins. Along the SW-NE trending thrust zones, oblique back-thrusts have also been observed, which can probably be placed in the Early Pliocene-Pleistocene. Best example is the so-called "Benestare Block", which thrusted inwards (NE-wards) along the Bianco Zone and Torbido Zone (see Fig. 4a).

The NW-SE and SW-NE trending fault systems are interconnected by faults which jointly display a curved surface trace. At the hanging wall near the intersection points, tectonic stacking occurs. These features can be considered to be indicative of the listric geometry of the fault zones. Fine examples can be seen in the Sila Piccola near Sellia and Catanzaro, and in the Aspromonte near Bova. The basin development along the two intersecting thrust zone systems shows affinity with the piggy-back basin models of Ricci Lucchi (1986) for the Northern Apennines and models for inversion of half grabens reviewed by Graciansky et al. (1988) for the Western Alps and by Watson et al. (1987) for China.

In some areas, it can be proved that basement was involved in the late Early Pliocene thrusting (see further).

The middle Pliocene-Pleistocene finally seems to reflect a phase of restabilization with major vertical movements, especially in the Pleistocene. Dome-shaped uplift centres such as the Sila Piccola and Aspromonte massifs dominate the geomorphology of the Calabrian area. Basin development during this final phase was mainly controlled by normal faulting along faults of the systems 4), 5) and 6).

Basement Structure.

Numerous studies have been presented concerning the Calabrian crystalline basement among which Dubois (1970, 1976), Ogniben (1973), Amodio Morelli et al. (1976), Caire (1970, 1978), Grandjacquet & Mascle (1978), Zanettin Lorenzoni (1982), Lorenzoni et al. (1983) and Bonardi et al. (1980, 1984) give extensive reviews.

The various descriptive models and explanatory hypotheses will not be discussed here in detail but the following groups can be distinguished which are shortly summarized below:

1) Calabro-Apennino Suture Model (Caire, Glangeaud & Grandjacquet, 1960; Dubois, 1970, 1976):

   From M. Cretaceous to Eocene N-S directed shortening occurred followed by superficial "écaillages post-nappes" and Post-Oligocene radial external shortening, resulting in "African vergence".

2) Concentric Orogene Model (Caire, 1970, 1978; Ogniben, 1973, 1975);

   From M. Cretaceous-Recent, progressive migration of thrust nappes from internal to external took place, along the S. margin of the European Plate. External directed gravitational sliding resulted in internal verging units.

3) Double Chain Model (Haccard et al., 1972; Wezel, 1975; Amodio Morelli et al., 1976):

   From Cretaceous-Eocene, a "Europe-verging" chain was constructed, which in the Oligo - Miocene overthrusted an "Apennine-verging" chain. During the Neogene, progressive external directed thrusting occurred.

4) Two Blocks Models:

   These models divide the Calabrian Basement in two separate blocks, S. and N. Calabria, on bases of Alpine and Burdigalian tectonics.

   4a) Bonardi et al. (1980, 1982, 1984):

   These authors favour a separated evolution up to the M. Miocene. The N. Calabrian Block has been affected by l. Burdigalian tectonics, the S. Block shows no traces of this tectonic phase. Remarkable are the indications for M. Miocene and L. Miocene basement thrusting (Zanettin Lorenzoni, 1982).

   4b) Boccaletti et al. (1984, 1986):

   These authors subdivide the arc in two parts: N. Block (part of Apennine Chain) and S. Block (part of Maghrebide Chain), separated by the SW-NE trending dextral Capo Vaticano-Soverato Fault Zone (see Fig. 4a, n. 10). Only the N. Block has been affected by Alpine metamorphism.

5) Transtensional Mesozoic Continental Margin Models (Bouillin, 1984; Santantonio & Teale, 1987):

   According to the models, the N. Calabrian Mesozoic-Paleogene terranes represent a NW-SE trending transcurrent continental margin of a Mesozoic-Paleogene oceanic basin (part of the Tethys).

6) Neogene Basement thrusting Model (this paper):

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

Combining the new data (group 6 from this paper) with a systematic analysis of the available data in literature the following picture emerges.

The south-western and north-eastern sides of the arc each constitute a pile of nappes with an external vergence, in the literature often referred to as "African" and "Apennine vergence" respectively. The lowermost unit in both parts of the arc consists of granitic/metamorphic ("Hercynian") basement nappes, covered with Mesozoic-Paleo-

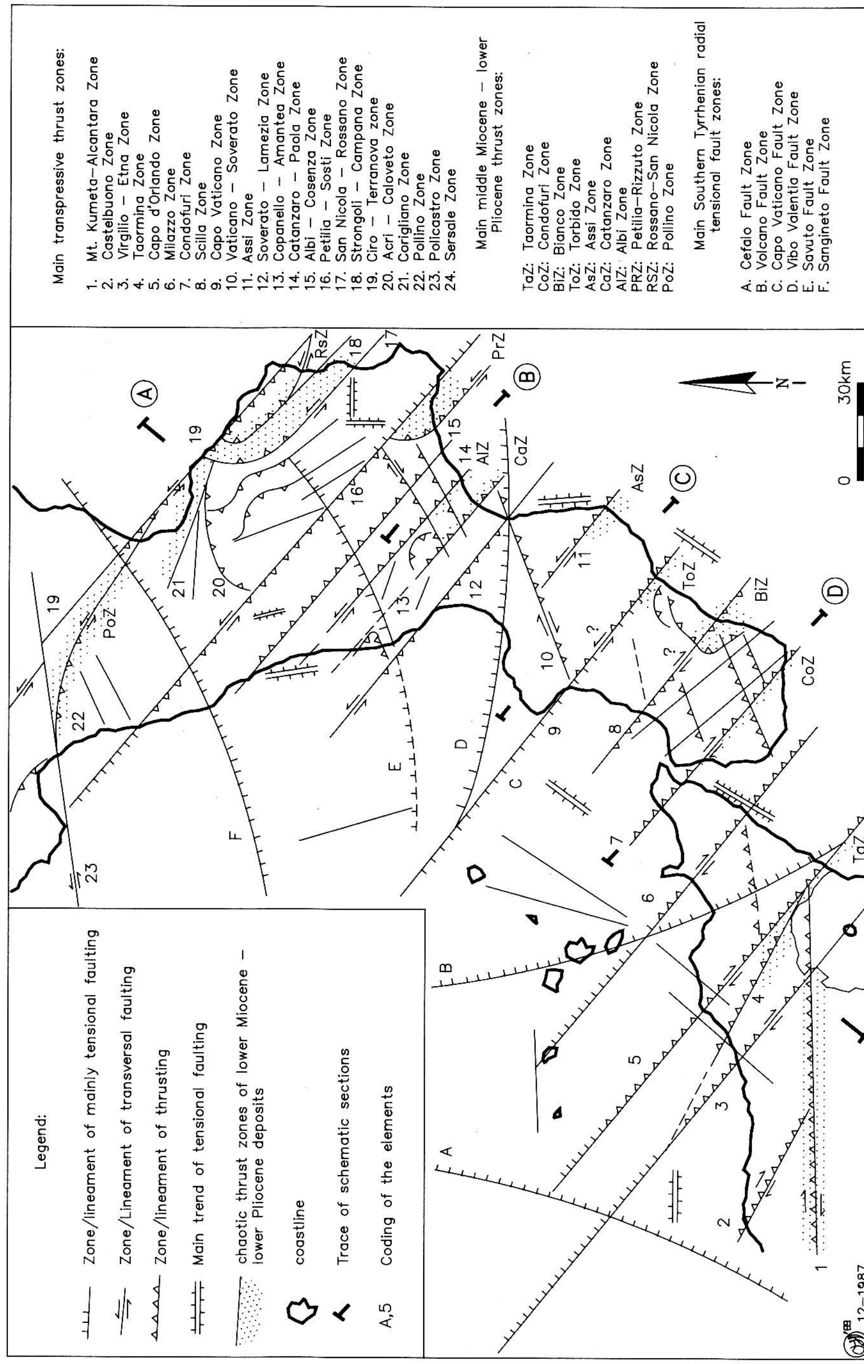

Fig. 4 - a) Schematic structural map of the main Neogene tectonic elements of the Calabrian Arc.

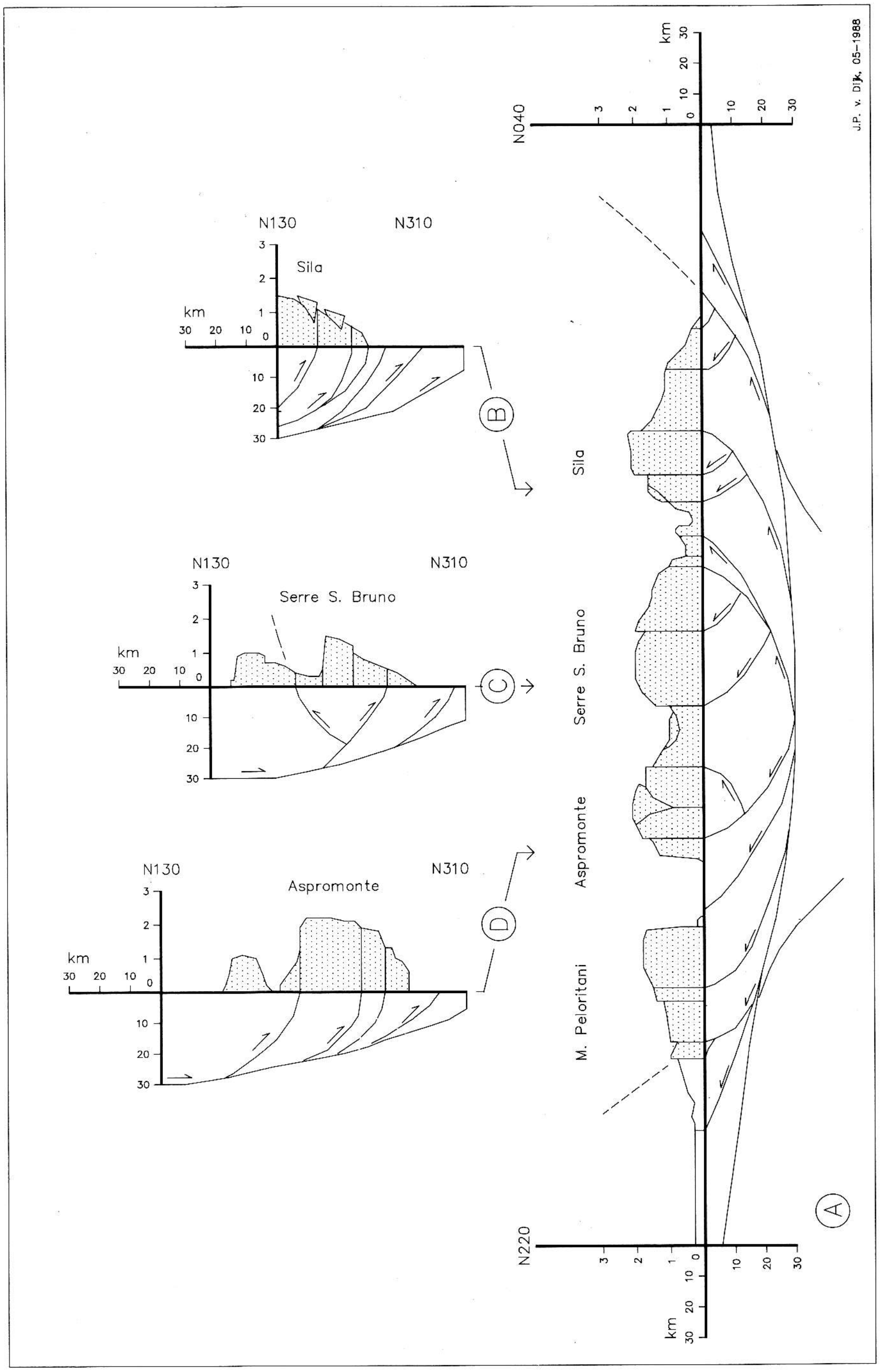

Fig. 4 - b) Schematic cross-sections of the Calabrian Arc.

gene-(?) lower Miocene sediments. Both sides are overthrusted by the central part of the arc along two major boundaries: the Petilia-Sosti Line in the north-east (Fig. 4a, n. 16) and the Condofuri Line in the south-west (Fig. 4a, n. 7). The central part of the arc can be regarded as a large klippe consisting of a pile of "Alpine Nappes" (Hercynian basement, Cretaceous-Paleogene cover; Alpine metamorphism) with a "European vergence". The frontal part of this central block is formed by the "Stilo Unit/Tiriolo Unit" consisting of Hercynian basement with a Mesozoic-Paleogene cover. This unit obliquely overthrusted the lower units to the north-west along the Capo Vaticano-Soverato Fault Zone (Fig. 4a, n. 10). It can be regarded as a huge "back-thrust" in relation to the externally verging African-Apennine Nappes in the NE and SW of the arc (Fig. 4b). Oligocene-lower Miocene parautochthonous terranes are present along the central external SE side of the arc. Along the NW-SE trending fault zones basement wedges are present, back-thrusted in late Early Pliocene times.

Of course, this symmetrical picture highly simplifies the real basement structure but represents a good working model for further reasoning.

The following general flow-chart for the basement development can be deduced.

Trias-Middle Cretaceous. Development of a NW-SE trending continental margin which was probably dextral transtensional.

Middle Cretaceous-Eocene. Destruction of the continental margin with associated Alpine metamorphism accompanied by "European vergent" thrusting.

Oligocene-late Burdigalian. Phase of basin development and progressive translation of the thrustbelt towards the SE culminating in the late Burdigalian phase of compression which is coupled with the formation of nappes with various vergences. Thrusting of the Calabrian domain on the Apennine domain (translation to the NE).

Neogene phases. Postulated are Early Pliocene phases of basement thrusting along the major shear zones.

The entire Calabrian Basement Complex can be regarded as an collage of terranes sensu Helwig (1974), accreted in Eocene, Oligocene, Early Miocene and Early Pliocene times. This complex has travelled to the SE during the Neogene as one large allochthonous element. The reconstruction of the accretion process of this element gives an insight in the development mechanisms of terranes as have been described from various parts of the world.

Synthesis: A new structural model.

Comparing the data concerning basement structure and neotectonics, it became clear that many of the Neogene shear zones coincide with breaks in composition of the nappe pile. These breaks in the crystalline basement are in fact large overthrust zones. This indicates that neotectonic shearing of the arc principally occurred along pre-existing basement thrusts and fracture zones. Taking all available information into account, the following hypothetical synthetic structural model has been developed (Fig. 4a, 4b).

The Calabrian Arc can be divided into N130 trending segments, separated by shear zones. These zones (widths of 5-10 km) are defined by either NE or SW verging basement thrusts. Within these shear/thrust zones, a complex surface pattern of braided fault sets and basement thrusts is present (sometimes well development Riedel shear sets but often more complex).

Each segment between the shear zones has its own characteristic nappe pile geometry and is intersected by large N110-120 and/or N140-150 trending basement wrench faults (fault system 1). Blocks between opposite verging thrusts form heights (Sila Piccola, Aspromonte, Serre) whereas blocks between facing thrusts form depressions (Catanzaro Depression and Central Southern Calabrian Segment). Blocks between equal verging thrusts form intermediate areas (Sila Grande, Sila Greca, Peloritani) (Fig. 4b A).

The Neogene basins where delimited by the wrench faults of system 1 and by the block boundaries, defined by wrench faults and chaotic allochthonous back-thrusted terranes of fault system 2. This geometry is the result of the Miocene-Pliocene development of piggy-back basins/half grabens and subsequent inversion along the sheared zones.

Remarkably is that the principal wrench fault orientation in the Peloritani and Aspromonte Blocks is N140 while the Catanzaro Zone, Sila Piccola Block and Sila Grande Block are mainly intersected by N120 trending wrench faults. This is caused by a change in differential movement of the segments, from dextral in the southern part to sinistral in the northern part of the arc. The Serre Block forms the Central Segment of which the shearing direction is unclear. On a 1:25,000 map-scale, N120 and N140 faults dominate the structural pattern, whereas on the scale of satellite photography (1:1,000,000) N130 trending lineaments tend to be conspicuous (e.g. the Bianco Fault Zone in S. Calabria; Fig. 4a, n. 8 equals Bottari et al., 1986; their fig. 7).

Intersected and displaced by this thrust system, a SE-verging second thrust system has developed, in continuity with the accretionary wedge in the outer arc region which is visible on seismic profiles such as MS-60 (Finetti, 1981, 1982; Finetti & Del Ben, 1986). This second system defines a vector of basin opening to the SE in the course of the Neogene (Fig. 4b, B-D). Back-thrusting of Neogene deposits along this system has occurred, also visible on the seismic section MS-60. A comparable feature - but on a larger scale - is the Serre Block (Fig. 4b). The internal ENE-WSW trending internal margin of this block has been described as a dextral wrench zone (Boccaletti et al., 1984) and as a SE verging thrust (Amodio Morelli et al., 1976). Probably, the Serre Block was back-thrusted to the NNW along this dextral zone with related tilting to the SSE.

Using this structural model, the six Neogene fault systems have been interpreted as the result of three large-scale patterns of morphotectonics.

A) N130 trending segments separated by obliquely transcurrent fault zones (fault systems 1 & 2).

B) SW-NE trending thrust zones representing the most internal part of the Calabrian accretionary wedge system (fault system 3).

C) Radial wedge-shaped segments determined by the collapse of the Southern Tyrrhenian Basin. These are accompanied by concentric patterns of tensional faults and dome-shaped uplift centres within the arc situated at the external side of the segments (fault systems 4 to 6).

Patterns A and B seem to be linked to a Serravallian-Early Pliocene development of shear zones with accompanied opening of the Northern-Central Tyrrhenian Basin. Pattern C is the result of the Southern Tyrrhenian collapse. A middle-late Pliocene opening of the Southern Tyrrhenian is postulated with mainly tensional faulting within the arc and compressional thrusting in the outer arc region ("Calabrian Ridge").

The models presented by Görler & Giese (1978), Scandone (1979), Cello et al. (1981) and Finetti & Del Ben (1986) fit well into the new geometric model for the two intersecting thrust systems. The "mushroom-structure" of the S. Tyrrhenian isobaths described by Wezel (1985) neatly corresponds with the morphotectonic pattern C.

Consequences for geodynamic models.

The structural model presented has important implications for models on structure and evolution of the Central Mediterranean.

The Neogene development of the Calabrian Arc has been controlled by two intersecting thrust systems with NW-SE and SW-NE directed shortening (morphotectonic patterns A & B). The Calabrian Block can be seen as a "boat-shaped" element, overriding Apulian, Ionian and Pelagian Blocks (Fig. 5). This configuration is essentially asymmetric, which probably results from an increase in shortening to the NE resulting in oblique movement of the Calabrian Block and a transpressive regime along the S. Apennines. Main present-day morphological features in the S. Tyrrhenian display an intersection of radial and concentric structures (morphotectonic pattern C), overprinting patterns A and B. The continuation of these structures into the Calabrian Arc partly coincides with the NW-SE trending boundaries of the segments (Fig. 1).

From the kinematic models for the development of the Central Mediterranean, as mentioned in the introduction, the Translation Models fit in the activity of patterns A and B (Serravallian-Early Pliocene), although the authors have erroneously used wrench faults of the Riedel shear pattern (N120 and N140) as indicative for the main shearing directions. The patterns C obviously has been over-emphasized in the Bending- and Radial Drift Models. Pattern B has been used in the Rotation Models for the opening of the Tyrrhenian Sphenochasm. This will be discussed further on.

The following geodynamic mechanisms for the evolution of the Calabrian Arc have been proposed in literature:

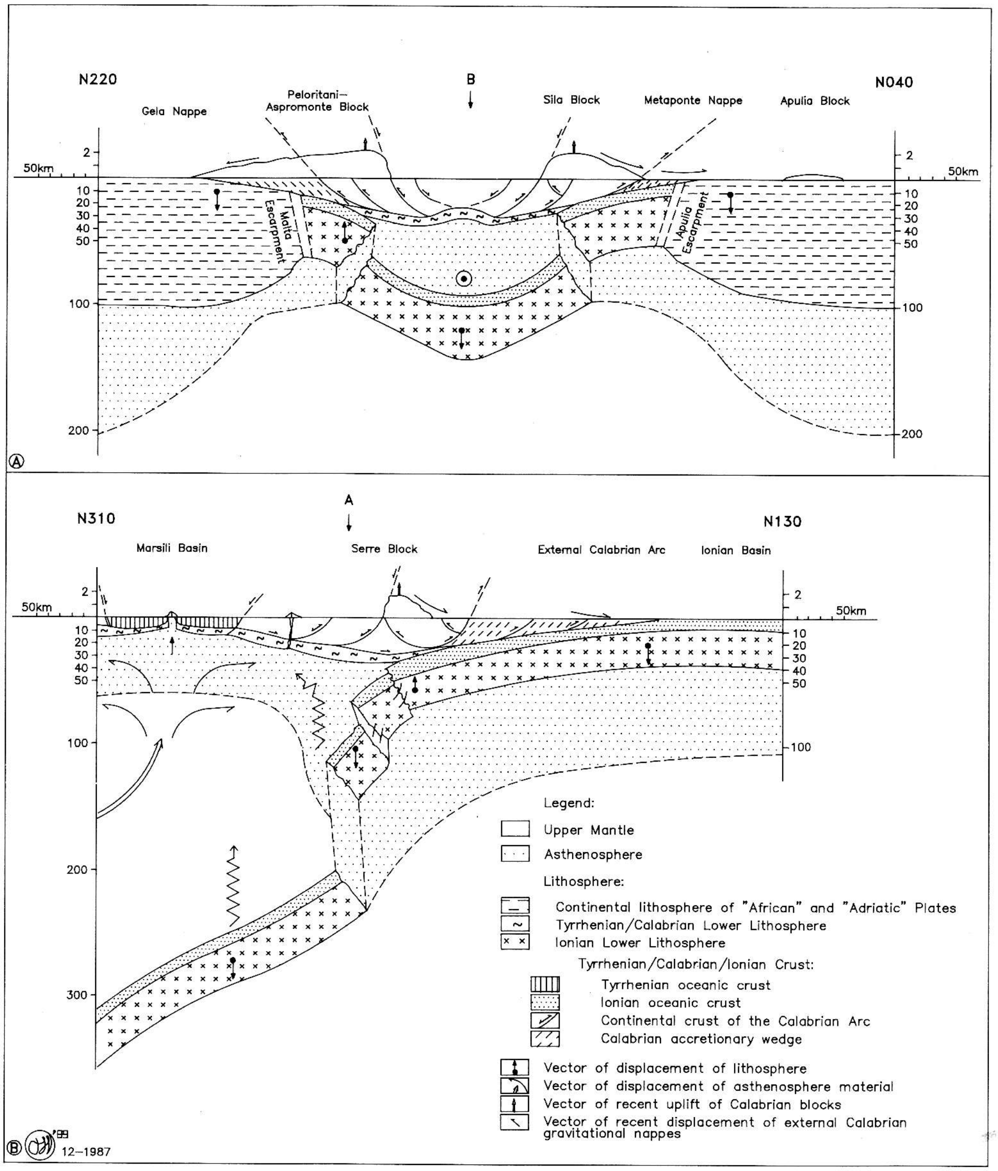

Fig. 5 - Synthetic crustal sections in the Central Mediterranean region. Compiled and modified after: Peterschmitt (1956), Cassinis et al. (1969), Ritsema (1972, 1979), Caputo & Postpischl (1973), Giese & Morelli (1975), Van Bemmelen (1978), Schütte (1978), Görler & Giese (1978), Giese & Reutter (1978), Roeder (1978), Cassinis et al. (1979), Cello et al. (1981), Giese et al. (1982), Horvath & Berckhemer (1982), Ghisetti & Vezzani (1982a), Mantovani (1982), Mantovani et al. (1985), Finetti & Del Ben (1986), Spakman (1985, 1986), Rapolla (1986), Anderson & Jackson (1987), Moretti & Royden (1988).

1) Slab pull/roll back-migration of the Calabrian Block to SE as a "pull arc".
Model after Elsasser (1971); suggested by Ritsema (1979), see also Malinverno & Ryan (1986).

2) Mantle metasomatism - diapiric uplift - radial nappe shedding.
Model suggested by van Bemmelen (1969); see also Wezel (1981, 1985), Selli (1985), Locardi (1986).

3) Frontal crushing - lateral expulsion of blocks - formation of (micro-) push arcs.
Model after Gzovsky (1959) / Pavoni (1961); suggested by Caire (1973), see also Brunn (1976), Tapponnier (1977), Boccaletti & Dainelli (1984), Boccaletti et al. (1984).

4) Lateral compression of the area - rotation of the Tyrrhenian Block - formation of Tyrrhenian Sphenochasm.
Model suggested by Vogt et al. (1971); see also Locardi et al. (1976), Mantovani et al. (1985), Weijermans (1987).

In this paper, a synthetic model for the geodynamic evolution of the Central Mediterranean is proposed in which all the above-mentioned mechanisms are incorporated.

Due to NE-SW directed compression of the Central Mediterranean with accompanied deformation of the Ionian lithosphere slab below the Calabrian Arc (see also Mantovani et al., 1985), the following sequences of processes were initiated.

A) Flow of mantle material filling the "flattened cone"-shape between the Ionian lithosphere slab and Tyrrhenian lithosphere accompanied by mantle metasomatism (see discussion in Locardi, 1986) resulted in diapiric uplift of the back-arc area. This uplift was followed by active spreading as discussed by Keen (1985) which again may have resulted in subsequent diapiric spreading and gravitational radial "superficial" nappe shedding. A suggestion about a possible initiation of this process was done by Laubscher (1988) in his description of the Aegean "Pull Arc". The processes of diapiric rise, wedge flow and "hot region" as distinguished by Uyeda (1986) are not mutually exclusive and may be genetically linked and together responsible for the active back-arc spreading (see also Oxburg & Turcotte, 1970; Karig, 1971; Khutorskoy et al., 1986 and Luongo, 1988).

B) Subsidence of the Calabrian Arc due to slab-pull and roll-back combined with process A), may have created enough inclination to initiate a process of rotational dissymmetrical graben formation. This resulted in the gravitational migration of the Calabrian Block to the SE, above a detachment zone between lower and upper crust. This was accompanied by Tyrrhenian extension with a steep margin at the Sardinian side and a compressional margin along the Calabrian Arc.

Within the accretionary wedge, the displacement process was associated with frontal collision resulting in lateral rotational expulsion of "nappe flakes" to the E (S. Apennines; anti-clockwise) and to the S (Sicily; clockwise), like the opening of saloon doors. Furthermore, the central segments of the arc logically move faster than the lateral segments, because of higher cumulative velocities.

Based on the accurate reconstructions of the Central Calabrian structure and basin development - calibrated with literature data - the process of NE-SW directed compression and accompanied shearing must have occurred between Serravallian and Early Pliocene, while the south-eastward movement of the Calabrian Block probably occurred during the middle-Late Pliocene.

Two processes can be held responsible for the extreme vertical movements in the Calabrian Arc and the Southern Tyrrhenian area during the Pleistocene.

1) Collapse of the mantle diapire, with uplift of its margins (Wezel, 1985; see also Weijermans, 1985 for a review of the Alboran Arc), especially at the external part of the rapidly subsiding wedge-shaped segments (morphotectonic pattern C).

2) Detachment of the lithosphere slab, resulting in large isostatic adjustments in the whole region (Görler & Giese, 1978; Spakman, 1985, 1986).

Due to detachment of the slab the upper, non-detached parts of the lithosphere rapidly "bounce upwards" which results in an extremely rapid uplift of the overlaying blocks, while former relatively uplifted external platform areas subside. These movements result in a gravitational transport of large slabs/olistostromes to the external side of which the Metaponte "Nappe" (Ogniben, 1969; Finetti & Morelli, 1972, 1973) and the Gela "Nappe" (Beneo, 1957; Ogniben, 1960) are the best examples (see Fig. 5). The model mirrors the process of "vertical uplift and lateral spreading" as discussed by Ogniben (1969, p. 680).

The two described processes probably also played a role after the middle Pliocene shortening phase, of which the detached lithosphere slab below the Tyrrhenian Basin (Fig. 5) bears witness. Comparable features in Pacific and Indonesian arcs can be found in Oxburgh (1972) and Price & Audley-Charles (1987).

The opening of the Calabrian Arc can be deduced from the pattern of rifting centres. These centres are seemingly aligned along a N110- N120 directed axis (Moussat, 1983), but are in fact distributed between N130 and N045 trending fault zones (Fig. 1). The rifting centres may be linked to positions of core complexes, like the associated shear zones could be surface traces of large-scale crustal detachments. Lateral compression as described may lead to the subsequent uplift of the back-arc core complexes.

A stepwise development of the described geodynamic scenario would result in an undulatory evolution which shows affinity with older concepts of global undation and oscillation tectonics (Haarmann, 1930; van Bemmelen, 1933, 1978) recently adapted and elaborated on by Wezel (1988).

The shear zone pattern dissecting the Central Mediterranean consists of dextral NW-SE and SW-NE trending shear zones with E-W to NE-SW trending dextral splays connected with the Eastern Mediterranean shear zones (Fig. 1). Exactly this pattern explains the NE-SW directed stress component which gave rise to the displacement of the Calabrian Block to the NE upon which its translation to the SE is superimposed. This stress component provides an explanation for the E-W and NNE-SSW trending large wrench faults within the Apennines which may be conjugate sets, a response to the NE-SW compression. The tectonic patterns A and B in the Calabrian Arc show comparable trends but different sense of translations.

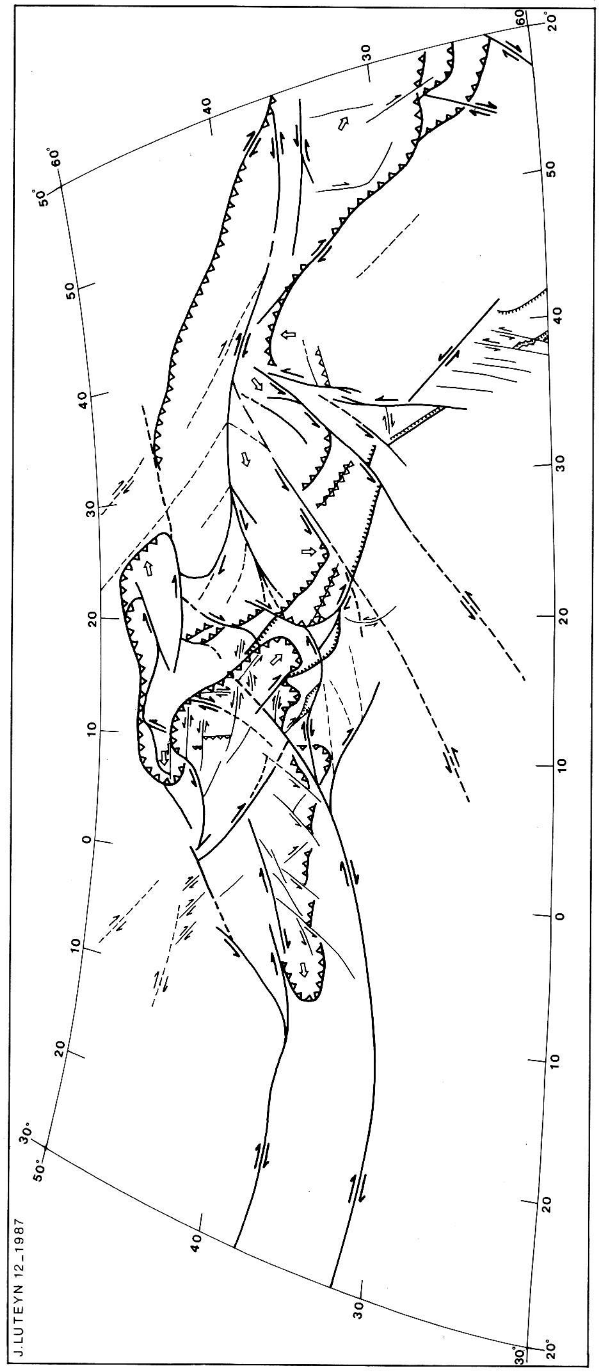

Fig. 6 - The Mediterranean Neogene shear pattern. Compiled and modified after various sources.

The process, of NE-SW shortening, is compatible with suggestions of Mantovani et al. (1985) and Weijermans (1987).

The shear zone pattern within the Central Mediterranean can be related to a larger shear pattern (Fig. 6, 8) in which the North African orogene can be regarded as a large-scale dextral transcurrent zone (Neev & Hall, 1982; Weijermans, 1987). This Mediterranean zone system has been incorporated in a new geodynamic torsion model (Fig. 7). This new geodynamic unifying concept implies an E-W orientated megatorsion of the northern hemisphere. This torsion generated a set of NW-SE and NE-SW trending megashears. The interaction of these megashears can be held responsible for the rotation and expulsion of microplates (showing a consequent 90 degrees overall rotation which fits in the shear pattern; see Fig. 7), small-scale folding of lithosphere and large-scale pull-apart processes. Locally, mechanisms as passive subduction and rupture of oceanic crust, and diapiric rise of the asthenosphere play an important role.

The concept shows affinity with models presented by Vening-Meinesz (1947) and Moody and Hill (1956); "Global wrench fault pattern", Carey (e.g. 1986); "Tethyan Torsion", Gidon (1974) and Caire (1979); "Géotectonique giratoire", and Cronin (1987); "Cycloid tectonics". These original concepts were recently elaborated on by O'Driscoll (1980); "Double Helix Tectonics", Neeve & Hall (1982); "Slice Tectonics" and Wezel (1988); "Helicyclic Tectonics". The Megatorsion model combines the various mechanisms describing directions and global synchronism of horizontal and vertical movements in a more satisfying way.

The described geodynamic model for the Central Mediterranean implies that the palinspastic reconstruction of the Calabrian Element can be achieved by displacement to the NW and SW-NE "stretching". This results in a middle Miocene crustal strip along the trace of the present Central Tyrrhenian Fault Zone (cf. Fabbri & Curzi, 1979). Further reconstruction of the Eocene/Oligocene situation probably results in a more western position of this strip which could well be along the southern margin of the Iberian Plate as suggested by Görler & Giese (1978), followed by Knott (1987). This margin was situated along a large NW-SE trending trans-Mediterranean shear zone, which can be followed from the Pyrenees up to Egypt (see also Durand-Delga, 1980 and Ben-Avraham et al., 1987).

The displacement of the Calabrian Element to the SE not only overprints the Neogene Mediterranean shear zone pattern but was also governed by this system. Synchronism of tectonic phases in the Alpine system can only be explained by accepting the dominating role of one process: in this case the activity of the "proto-Mediterranean shear system". Its activity triggered stages in the sequences of geodynamic processes like described above for the Calabrian Arc. Main phases of high activity of the system can be placed in the Middle and Late Cretaceous, Late Eocene, late Burdigalian, Middle Pliocene and Pleistocene (stages in development of the Megatorsion Cycle, analogous to the

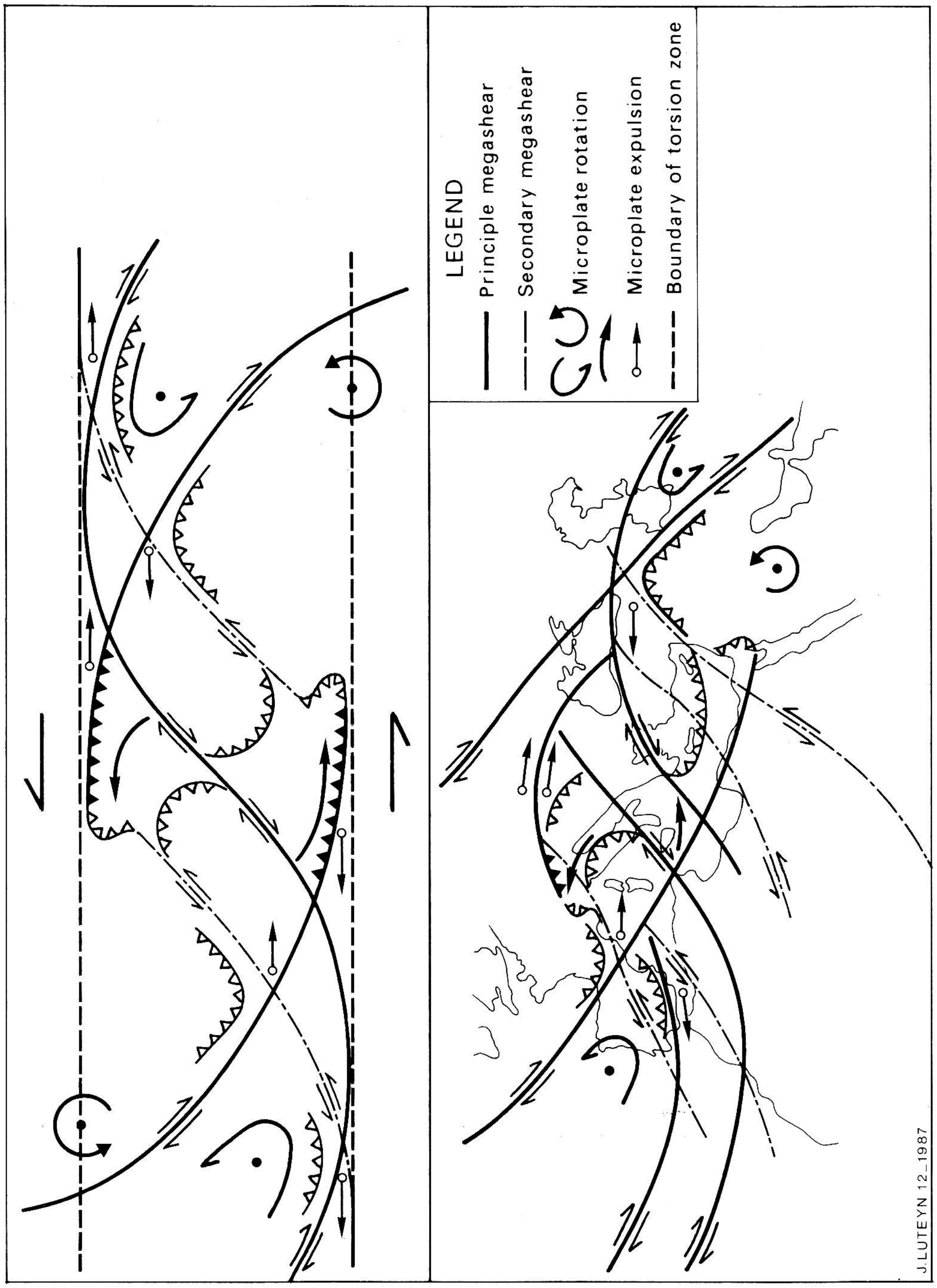

Fig. 7 - Model of Megatorsion for the evolution of the Mediterranean area.

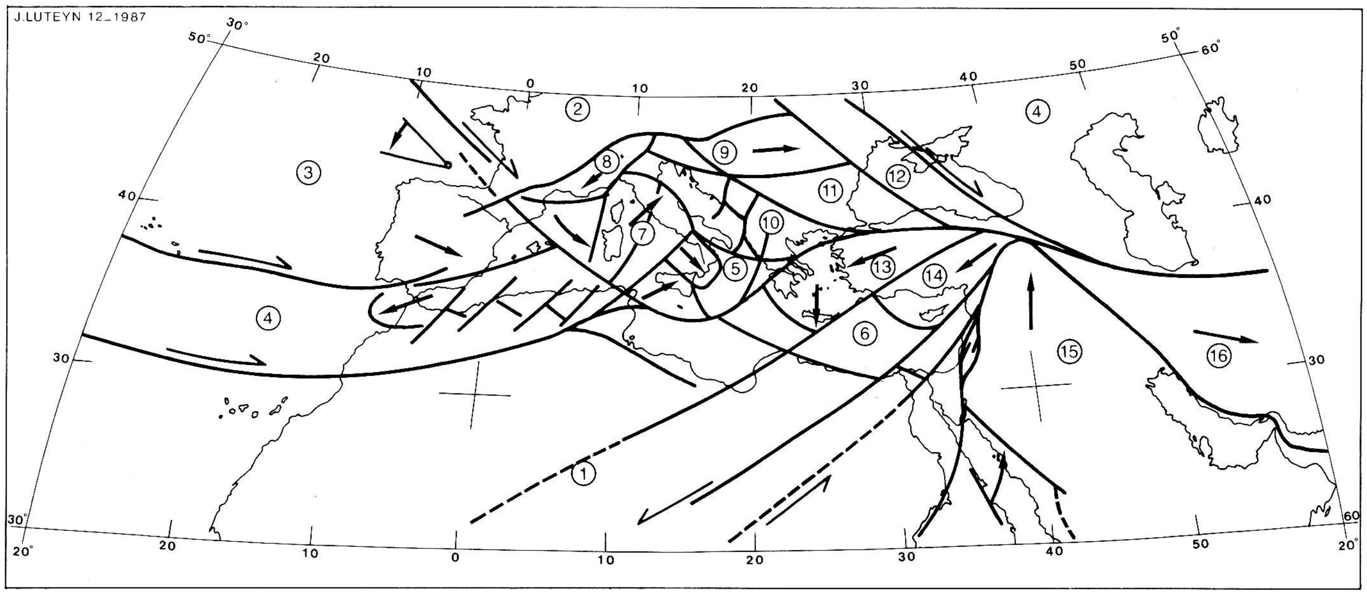

Fig. 8 - The Mediterranean microplate subdivision. Compiled and modified after various sources. 1) South Atlantic-African Plate. 2) European Plate. 3) North Atlantic-Iberian Plate. 4) Central Atlantic-North African Shear Zone. 5) Adriatic Plate: a. Sicilia Microplate; b. Ionian Microplate; c. Adria Microplate. 6) Eastern Mediterranean Plate: various NE-SW trending fragments. 7) Western Mediterranean Plate: a. Provencal Microplate; b. Sardegna-Corsica-North Tyrrhenian Microplate; c. Central Tyrrhenian Microplate; d. Calabrian-South Tyrrhenian Microplate. 8) Alpine Microplate. 9) Pannonic Microplate (s). 10) Dinaride Microplate. 11) Balkanide Microplate. 12) Black Sea Shear Zone. 13) Aegean Microplate. 14) Cyprian Microplate. 15) Arabian Plate. 16) Iranian Plate.

Strike Slip Cycle). The Late Pliocene-Pleistocene activity ("Closing Phase" of the Megatorsion) can be deduced from the extreme vertical movements (see e.g. Mantovani et al., 1987), related to an increase in NE-SW compression in the Central Mediterranean which triggered lithosphere rupture. This is also reflected by the accelerating subsidence in the S. Tyrrhenian Basin (Okkes, 1988), which is possibly due to downbending of the Tyrrhenian oceanic lithosphere.

Conclusions.

A synthetic structural model is proposed, based on the interaction of two thrust zone systems overprinted by a radial/concentric tensional fault pattern. The geodynamic evolution of the Central Mediterranean is believed to be the result of the interplay of NE-SW compression, diapiric rise, and roll-back and detachment of lithosphere remnants, resulting in gravitational displacement of the Calabrian Element to the SE above a basal detachment zone.

By means of the Central Calabrian basin development scheme, the geodynamic scenario can be placed in a chronostratigraphic frame: 1) Serravallian-Early Pliocene shear zone development; 2) late Early Pliocene NE-SW compression; 3) Middle Pliocene-Pleistocene active overthrusting of the Calabrian Element; 4) Pleistocene NE-SW compression, lithosphere rupture and Southern Tyrrhenian collapse.

It is the combination of all mentioned mechanisms and processes that caused the complex, multidirectional Central Mediterranean shear/thrust system. Due to the large vertical Plio-Pleistocene tectonic movements, this system can nowadays be observed at various crustal levels. In reconstructing one should take notice of all the above mentioned considerations and not relate all structures to one single mechanism. They have various origins and should be judged that way.

Acknowledgements.

Thanks are due to R.P.A. Kievits, F. Hilgen and G.J. Weltje for valuable suggestions and corrections of the manuscript. We are grateful to D. Nocerino, T. van Hinte, J. Luteyn and W.A. den Hartog for the skilful preparation of the illustrations. The research in the central Calabrian area was partly financed by the Moolengraaff Foundation. All students of the Department of Stratigraphy are gratefully acknowledged for the usage of their data.

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