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POST-TORTONIAN MOUNTAIN BUILDING IN THE APENNINES. THE ROLE OF THE PASSIVE SINKING OF A RELIC LITHOSPHERIC SLAB

Riassunto. - L'evoluzione tettonica dell'Appennino può essere ragionevolmente descritta in termini di convergenza continente-continente fino al Miocene medio, vale a dire fin quando non sono ancora iniziati i processi distensivi responsabili dell'apertura del bacino tirrenico. A partire quantomeno dal Tortoniano superiore (se non, addirittura, dal Serravalliano-Tortoniano) i modelli correnti appaiono inadeguati a giustificare i fenomeni geodinamici riconosciuti nell'area. La catena appenninica, infatti, continua a svilupparsi a spese dell'avampaese padano-adriatico-ionico secondo assi di compressione totalmente discordi (fino a 180°) con i vettori di spostamento dell'avampaese; ai processi compressivi lungo il margine esterno della catena, inoltre, fanno riscontro nell'area tirrenica processi estensionali che sembrano seguire con una certa regolarità la migrazione spazio-temporale del sistema catena-avanfossa-avampaese.

In questa nota vengono descritte, nelle linee essenziali, le fasi tettoniche responsabili della compressione post-tortoniana nell'Appennino e viene individuato nella subduzione passiva della litosfera padano-adriatico-ionica il possibile motore dell'apertura del bacino tirrenico e della migrazione spazio-temporale del sistema catena-avanfossa-avampaese.

Abstract. - The post-Tortonian structural evolution of the Apennines cannot be satisfactorily justified by plate-convergence models, in spite of the severe compressional tectonics recognized along the outer margin of the mountain chain. The vectors of the orogenic transport, in fact, fully disagree with the expected slip vectors of the Po-Adriatic-Ionian rigid foreland; widespread extensional features in the Tyrrhenian area, moreover, have developed contemporaneously with thrust propagation, the extensional fronts closely pursuing the compressional ones.

At least five compressional phases have been recognized, which are responsible for post-Tortonian mountain building in the Apennines; the single phases of orogenic transport (usually consisting of several deformation events evidenced by the structural analysis) occurred within short time intervals separated by longer periods in which the subsidence played an important role for the sedimentation of clastic deposits in the foredeep basinal areas. The deformation did not act cilindrically, that is to say the amount of transport and the tectonic style considerably changes across different segments of the mountain chain. The trend of surface and subsurface structures allows the recognition in the Apennines of two major arcs which have developed in post-Tortonian times. The amount of shortening is only some tens of kilometres in the north-western Apennines, while it reaches about three hundred kilometres in the Calabrian Arc; the average velocity of shortening, therefore, varies from less than 1 cm/y in the north to around 5 cm/y in the south, in agreement with the extension

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pattern of the Tyrrhenian Sea. The deep-focus earthquakes beneath the Southern Tyrrhenian Sea are related to the presence of a lithospheric slab which may represent, in its deepest part, the remnant of the Po-Adriatic-Ionian lithosphere which was subducting the Corsica-Sardinia block before the opening of the Tyrrhenian basin.

Passive subduction of the Po-Adriatic-Ionian lithosphere by gravitational sinking with progressive retreat of the flexure zone appears as a reasonable mechanism to explain first-order contemporaneous phenomena such as mountain building in the Apennines and extension in the Tyrrhenian area, as well as the time-space migration of the thrust belt-foredeep-foreland system in post-Tortonian times.

The Pleistocene and, probably, the present-day compression along the outer margin of the Apennines is confined at the apex of the northern Apenninic arc and in the External Calabrian Arc, suggesting the existence of two major zones of differential lithospheric sinking.

KEY WORDS - Tectonic phases, compressional tectonics, Messinian, early, middle and late Pliocene, Pleistocene, palinspastic maps.

The deformational history of the Apennines may be roughly divided into two parts, separated by the onset of rift-processes which affected the Tyrrhenian area in late Tortonian times. Plate tectonics supplies an available model for interpreting the first part of this history, which is entirely dominated by plate convergence from middle Cretaceous to late Oligocene times, with continent-continent collision in the Eocene and consequent subduction of the African lithosphere beneath Europe (Scandone, 1980). The succession of these events is recorded in the pile of the Ligurian, Sicilide and Calabrian nappes (Haccard *et al.*, 1972; Elter, 1975; Amodio Morelli *et al.*, 1976), as well as in the Oligocene calc-alkaline volcanics of Western Sardinia (Barberi and Cherchi, 1980). At the Oligocene-Miocene boundary, Corsica-Sardinia began counterclockwise rotation and the Provence basin opened in the wake (Cherchi and Montadert, 1982). Subduction of the western margin of the Adriatic Promontory continued during (Scandone, 1980) and after this rotation, producing severe compression in the Apennines and widespread calc-alkaline volcanic activity in Western Sardinia. Regional metamorphism, piling up of nappes with considerable crustal shortening and orogenic transport of the tectonic edifice towards the Adriatic foreland mainly occurred during Burdigalian times (Ippolito *et al.*, 1975; Scandone 1980). Another important phase of orogenic transport dates from Tortonian, and new deep-sea drilling data from Leg 107 (Sartori, this volume), suggest that this phase is the last compressional event before the Tyrrhenian opening.

A drastic change in the tectonic evolution of the Apennines took place in late Tortonian times, when rift-processes occurred along the western margin of the Apennines and in the northern and western Tyrrhenian area (Sartori, this volume). The Corsica-Sardinia margin and the root-zone of the adjacent mountain chain were dissected by listric faults; subsiding basins strictly controlled by synsedimentary tectonics developed; the calc-alkaline activity ceased completely in Western Sardinia, while granitic and granodioritic bodies intruded into the highest nappes of the stretched tectonic edifice. The Tyrrhenian Sea started opening. Continent-continent convergence continued along the outer margin of the Adriatic Promontory in the Southern Alps and Dinarides. Post-Tortonian convergence in these areas, deduced by the Atlantic spreading pattern, is roughly described by N-S trending slip vectors (Dewey *et al.*, 1973). Additional vectors related to a differential counterclockwise rotation of the Adriatic Promontory (Lowrie, 1985) should be taken into account. The resultant directions agree with the active subduction of the African lithosphere beneath the Hellenic Arc (Mc Kenzie, 1970) and also agree with the compressional phenomena observed in Friuli at the northern edge of the Adriatic Promontory (Amato *et al.*, 1976; Castellarin *et al.*, 1980; Cavallin *et al.*, 1984; Slejko *et al.*, 1986), as well as with the transpressive features recognized in the Adriatic Dinarides (Aljinovic *et al.*, 1984). Within this framework, what is really surprising is that the most severe compression actually occurred in the Apeninnes, along the inner margin of the Adriatic Promontory where extensional phenomena should be expected. This compression has usually been justified by postulating an underthrust of the Po-Adriatic-Ionian lithosphere beneath the Apenninic chain and considering, therefore, the Tyrrhenian Sea as a sort of back-arc basin (see, e.g. Boccaletti and Guazzone, 1972; Boccaletti *et al.*, 1981; Rehault *et al.*, 1984). Evidence of subduction processes of the Ionian lithosphere is supplied by the occurrence of deep-focus earthquakes in the southern Tyrrhenian area (Caputo *et al.*, 1972), as well as by the presence of a calc-alkaline volcanism in the Aeolian Islands (Barberi *et al.*, 1973). Nevertheless, when we consider the whole kinematic system on the scale of the Mediterranean region, we see that active subduction processes of the Po-Adriatic-Ionian lithosphere beneath the Apennines in post-Tortonian times are incompatible with the admissible slip vectors of the Adriatic Promontory (Scandone and Patacca, 1984). Therefore, all compressional features which have developed at the outer margin of the Apennines after Tortonian times must derive from an active thrust of the mountain chain over its foreland (Castellarin and Vai, 1986). The source area for this shortening should be sought in the Tyrrhenian basin and in the adjacent extensional regions.

A reliable model which entirely describes the evolution of the Tyrrhenian basin and of the Apennines, taking into account, at the same time, the deep seismicity of the Southern Tyrrhenian Sea and the young orogenic volcanism from the Tuscan region to the Aeolian Islands, has still to be produced.

Our research was addressed to the definition of the present-day structural arrangement of the Apennines, to the chronological scanning of the deformation and to the palinspastic restoration of the deformed system by filtering the different compressive events. Finally, we tried some speculations on the deep sources for the recognized deformational processes and a preliminary model has been elaborated. According to this model, folding and thrusting along the outer margin of the Apennines, time-space migration of the thrust belt-foredeep-foreland system and rifting in the Tyrrhenian area are different products of a unique, major geodynamic process controlled by gravitational sinking of a relic and fragmented lithospheric slab of the Adriatic Promontory.

Geological outlines of the Apennines

Fig. 1 is a simplified structural sketch of the Italian Peninsula and surrounding areas.

Deep-focus earthquakes in the Southern Tyrrhenian region reveal the existence of a peculiar Benioff zone dipping towards NW (Gasparini *et al.*, 1982). The length of the slab measures about 650 kilometers, exceeding the maximal (NW-SE) extent of the Tyrrhenian Sea. If we assume a subduction rate of 4-5 cm/y, corresponding to the rate of post-Tortonian shortening calculated for the Southern Apennines and Calabrian Arc, it results that the deep portion of the slab underwent subduction before the beginning of the rift-processes in the Tyrrhenian area. We may therefore reasonably assume that the deepest part of the slab represents a lithospheric remnant from which the Tortonian and Burdigalian nappes were detached, while the upper part of the slab represents the original lithospheric basement of the post-Tortonian thrust-sheests. The whole slab is constituted, in our opinion, by continental lithosphere, ancient oceanic crust having already been destroyed in Eocene times when the continent-continent collision occurred.

No deep-focus earthquakes have been recorded in the Northern Apennines, but studies on seismic-wave propagation suggest the existence of deep-seated lithospheric roots beneath the Tyrrhenian margin of the mountain chain (Panza *et al.*, 1980; Suhadolc and Panza, this volume). Subduction processes in the Northern Apennines, on the other hand, are also suggested by the close similarities in the tectonic evolution between this area and the Southern Apennines.

The Bouguer anomalies show a gravimetric trough along the outer margin of the Apennines which is almost continuous from the Po Plain to Sicily and corresponds to the flexure of the rigid foreland lithosphere beneath the thrust belt (Royden and Karner, 1984; Royden *et al.*, 1987). Bouguer anomalies and base-of-Pliocene isobaths draw two major Apenninic arcs, convex towards the foreland, underlined also by the trend of the surface and subsurface tectonic features; the two arcs touch in correspondence with a first-order transversal accident, the so-called "Maiella-Roccamonfina" or "Ortona-Roccamonfina" line (Locardi, 1982). Crossing this accident, the strikes of the tectonic structures abruptly change from a N-S direction to a W-E one. The northern Apenninic arc consists of several minor arcs (Pieri and Groppi, 1981; Castellarin and Vai, 1986), the most prominent being constituted by the Monferrato, Emilia, Ferrara and Adriatic folds. The southern arc too consists of several minor segments (Molise-Sannio, Irpinia-Basilicata, Calabria and Sicily) linked by complex kinematic relationships. The kinematic relationships between the northern and the southern Apenninic arcs, as well as between the different segments within the same arc will be discussed later on in the paper.

The Tyrrhenian margin of the Apennines is mainly characterized by extensional features, most of which have been active during the same time-span in which the outer border of the mountain chain has been affected by compression. The coexistence of a compressive stress-field at the outer margin of the Apennines and of an

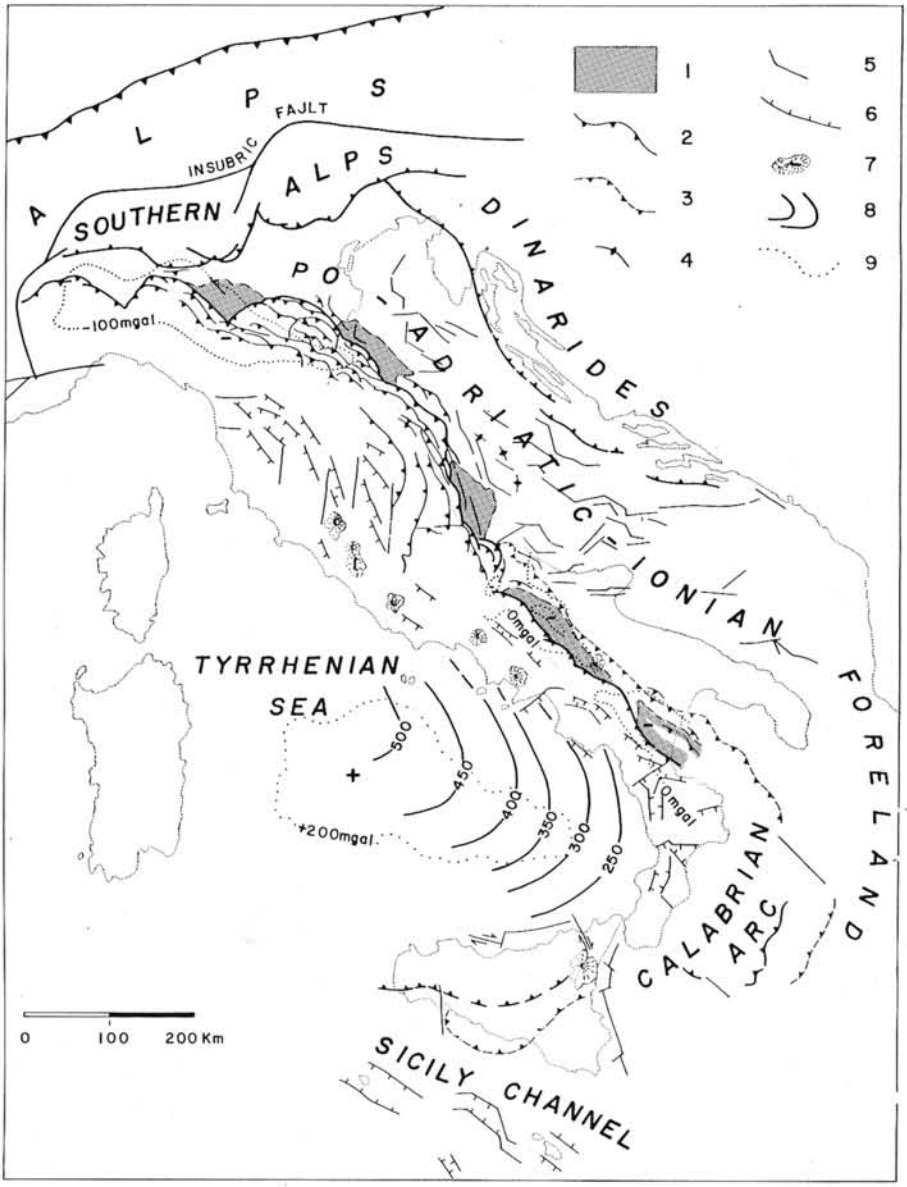

Fig. 1. - Major structural elements of the Italian Peninsula and surrounding areas.
1) Foredeep basinal areas where the Pliocene-Quaternary deposits overlying the Po-Adriatic crust exceed 4.000 metres in thickness. 2) Major overthrusts in the Apennines; compression fronts in the Alps, Southern Alps and Dinarides. 3) Front of the "plastic" allochthonous sheets in the southern Apenninic arc. 4) Upper Pliocene-Quaternary folds in the Adriatic foreland. 5) Faults (mostly strike-slip faults). 6) Normal faults. 7) Quaternary subaerial volcanoes. 8) Isobaths of the subducted lithosphere in the Southern Tyrrhenian region. 9) Maximal absolute values (positive and negative) of the Bouguer gravity anomalies.

extensional one, at the inner margin, is evidenced also by the present-day seismic activity (see, e.g., Eva *et al.*, 1978).

A basic contribution for understanding Apennine geology comes from oil exploration (Pieri and Groppi, 1981; Dondi, 1985; Bally *et al.*, 1986; Mostardini and Merlini, 1986). Some published sections based on seismic lines, in particular, clearly demonstrate that a large part of the mountain chain (and not only the outer margin) consists of post-Tortonian rootless thrust-sheets underlain by the underformed Po-Adriatic crust which dips towards the Tyrrhenian Sea.

Fig. 2 shows two simplified and idealized sections across the Central and the Southern Apennines. Tectonic styles, volumes and geometries of the thrust-sheets, distribution of the compression fronts and total amount of shortening appear quite different in the two regions. Across the northern transect, referred to the Marche region, the thrust propagation mostly proceeded by imbricate fans in piggy-back sequences. The majority of the structural elements originally located outside the Tortonian compression-fronts are therefore outcropping or are easily recognizable in the subsurface at shallow depths. Across the southern transect, referred to the Irpinia-Basilicata Apennines, piles of foreland-detached horses developed, completely overridden by "plastic nappes" of more internal provenance mainly derived from the Burdigalian-Tortonian edifice. The identification of all these elements only by means of seismic profiles and boreholes may be problematic. Moreover, the complexity of the structure, reached through several deformational events, together with the existence of large-scale lateral displacements, makes the construction of reliable balanced sections very difficult.

Plate 1 is a geological-structural map of the Apennines and related foredeep system from the Po Plain to the Taranto Gulf. The major tectonic units built up in post-Tortonian times have been distinguished and singled out from the older parts of the tectonic edifice. Fig. 3 shows simplified palinspastic restorations of the Apennines at different times. The analytical data on which the geological-structural map and the palinspastic sketches are based are a matter of discussion in a forthcoming paper (Patacca and Scandone, 1987). Here we only wish to underline that the basic information used to interpret controversial or ambiguous data have systematically been:

— geometrical relationships between the distinguished tectonic units;

— sedimentary evolution of the sequence representative of every unit;

— age of the earliest siliciclastic flysch-deposits conformable on shallow-water and basinal sequences;

— age of the first compressional event and of the first phase of orogenic transport for every tectonic unit;

— age and facies of the deposits belonging to sedimentary cycles limited by two consecutive compressive phases (1).

(1) We are using the term "tectonic phase" - although it is an inappropriate word - to describe a deformative event (or a sum of deformative events) which is separated from the previous one and from the following one by a period of relative tectonic quiescence long enough to allow the deposition of a sedimentary cycle, which is well defined by unambiguous biostratigraphic and/or lithostratigraphic constraints. A compressional phase may consist of several deformational events, evidenced by the structural analysis, which follow one another so closely that it is impossible to obtain a reliable resolution in a time scale.

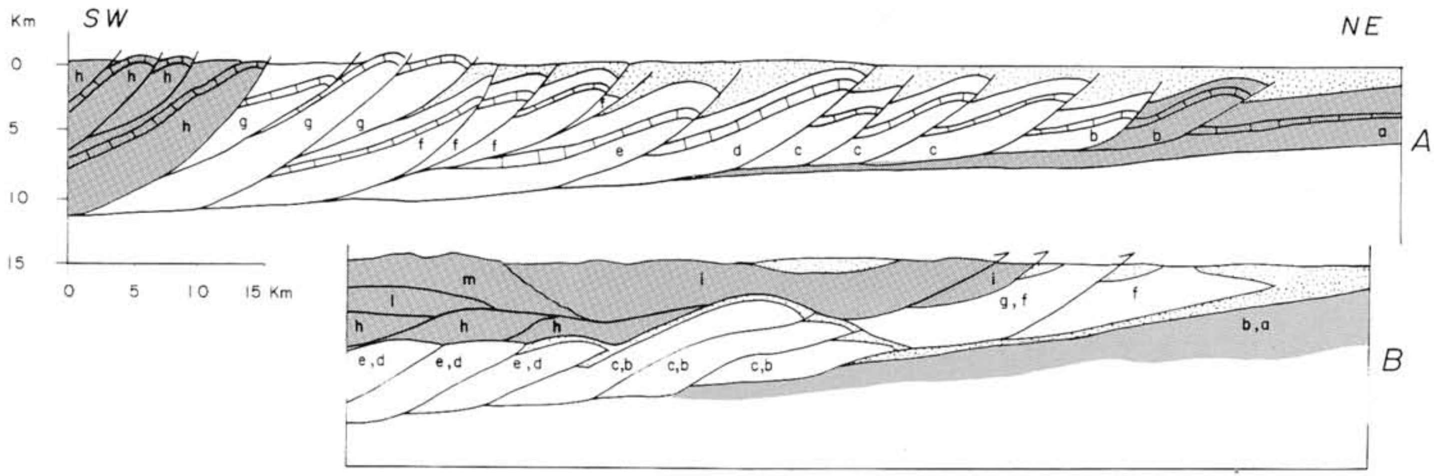

Fig. 2. - Simplified geological sections across the Central(A) and the Southern Apennines(B). The section A has been re-drawn, with slight modifications, from Bally *et al.*, 1986.
The two sections show the different tectonic styles W and E of Maiella. The italics allow the reader to correlate the structural units distinguished in the northern transect with the units recognized in the southern one. The original paleogeographic domains followed one another according to the alphabetic order, starting from the underformed foreland areas (a). The h-m sequence refers to units already deformed by the Tortonian and Burdigalian tectonics. Stipples indicate Pliocene and Quaternary deposits.

Many problems are still unsolved. Some of them will be briefly discussed in this paper.

Palinspastic restoration of the Apennines in late Tortonian times

The boundary conditions we assumed to constrain the pictures of Fig. 3 are the fixed positions of the eastern and southern margins of Corsica-Sardinia, the motion of the Adriatic Promontory according to slip vectors coherent with the Europe-Africa convergence and with the independent counterclockwise rotation of the rigid Adriatic Promontory, the present-day location of the most external compressional fronts of the Apennines. The palaeogeographic realms of the late Tortonian Apennine foreland (Fig. 3a) have been restored smoothing out step by step the Messinian-Quaternary deformation and removing from the external domains the tectonic units already affected by the Tortonian and older compressional events. The Calabrian Arc has been accommodated following the assumption that a continuous Alpine thrust-belt bordered the eastern margin of the Corsica-Sardinia block. Trying such restorations, a lot of problems arose which have no univocal answer. We shall briefly discuss some of them which may strongly influence the possible reconstructions.

The Tertiary deposits of the Piedmont-Liguria basin have been usually considered (see, e.g. Boccaletti and Coli Eds., 1982) an autochthonous and complete sequence ranging in age from Eocene?/Oligocene to Messinian times, although evidence of a severe synsedimentary tectonics has been recognized by some authors (Gelati and Gnaccolini, 1982; Ghibaudo *et al.*, 1985).The understanding of the space relationships between the Piedmont-Liguria basin and the sedimentary domain of the so-called Ranzano-Bismantova group, as well as the reconstruction of the synsedimentary tectonics recorded in the respective sequences is an essential datum-element to fix the compression front of the upper Tortonian Apennines. However, regional studies addressed to answer these problems are still lacking.

The Umbria-Marche area has been classically considered, and systematically represented in geological maps, as a single structural belt, in spite of the different sedimentary evolution of the sequences in Miocene and Pliocene times and in spite of the different ages of the tectonic structures proceeding from the Umbrian region towards the Adriatic Sea. This current view, moslty deriving from the widespread occurrence in the whole area of comparable Mesozoic facies, leads to several paradoxes. An evident nonsense, for instance, is to consider the Conero folds, which occupy an external position as regards the lower-middle Pliocene foredeep basin, as part of the Marche structural domain which, on the contrary, occupies an internal position. Further problems arise from the southern part of the Umbria-Marche fold-belt where it meets the Latium-Abruzzi platform units. Assuming a structural continuity from the Sabina region to the Sibillini mountains through Monte Terminillo, and accepting an original contiguity of Sabina and Abruzzi domains (Parotto and Praturlon, 1975) we reach the inconsistence that rather internal elements (Abruzzi) were overthrust with Adriatic vergence by external units (Sibillini Mountains, deriv-

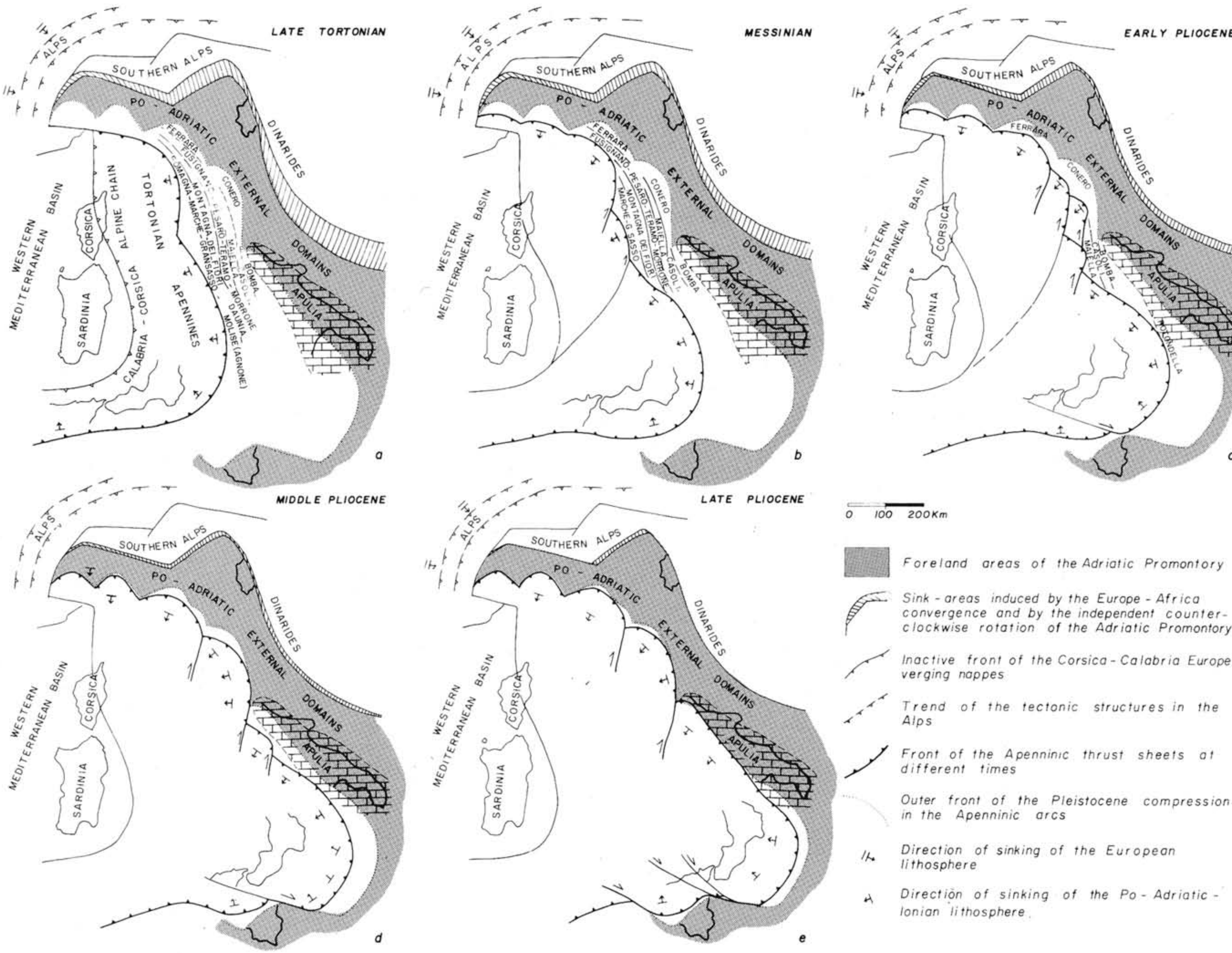

Fig. 3. - Palinspastic sketches showing the tectonic evolution of the outer margin of the Apennines from late Tortonian to late Pliocene times.

ing from the Marche domain). The list of open problems could be continued, extending to the relationships between Abruzzi and Gran Sasso as well as to the relationships between the Gran Sasso and Molise domains.

Conscious of the many persisting uncertainties, we reached the picture of Fig. 3a favouring the criterium of the time-space migration of the earliest siliciclastic flysch deposits and the criterium of the time-space migration of the first compressive deformation. In this sketch, the Tortonian compression front includes the Langhian-Tortonian part of the "marnoso-arenacea-romagnola" formation and the Umbrian units where the "marnoso-arenacea" formation constitutes the highest element of the stratigraphic sequence; it also includes at least a portion of the Latium-Abruzzi and Sabina units, as well as the Matese unit. Dubitatively, we attributed the Monte Alpi unit to the Tortonian Apennines, but we do not exclude the possibility that its original position was outside the Tortonian compression front.

Sediments belonging to the original foredeep basin of the Tortonian thrust-belt are unknown in the Po-Plain subsurface. In Romagna, they may be represented by the Messinian part of the "marnoso-arenacea-romagnola" formation and by the turbidite deposits of the "ghioli di letto" formation. In the Marche region, the lower Messinian foredeep is represented by the terrigenous deposits of the well-known Laga formation. In Abruzzi and in the Matese mountains, rock units equivalent to the Laga formation unconformably cover the carbonate units (Devoto, 1967; Sgrosso, 1978). In Molise the late Tortonian-lower Messinian foredeep is recognizable in the "Agnone flysch". These terrigenous deposits conformably overlie a middle Miocene carbonate sequence ("Tufillo" formation, Selli, 1957) which displays close analogies with the "Schlier" formation of the Marche region and with the Daunia formation ("Faeto flysch" in Crostella and Vezzani, 1964).

The Daunia formation has generally been attributed to the Irpinian units (Pescatore, 1978; Dazzaro and Rapisardi, 1984) and has therefore been considered as part of the Tortonian Apennines. According to Mostardini and Merlini (1986), on the contrary, the Daunia formation derived from an external basinal realm (the "Inner Apulia Basin") originally located between the Apulia platform and the Maiella-Casoli-Bomba domains ("Inner Apulia Platform"). We disagree with both interpretations, since gradual transitions from the Tufillo to the Daunia formations are very clear, as already seen by Selli (1957). The Daunia formation, on the other hand, underwent compressional deformation before Maiella, so that its original position outside of this domain appears improbable.

The Messinian tectonic phase

Messinian tectonics has been described by several authors in various Italian regions (see, e.g. Decima and Wezel, 1971; Castellarin *et al.*, 1978; Di Nocera *et al.*, 1976). The meaning of the described deformations, however, is rather ambiguous (except perhaps in Sicily) because of the widespread occurrence, in the Messinian sequences, of huge gravity slides (e.g. the "Cariati nappe" in Calabria) which cannot be easily distinguished from real thrust-sheets, because of uncertainties in the chronological attribution of some major tectonic features (e.g Ancona-Anzio Line) and, sometimes, because of the low reliability of the analytical data. The first proof of a severe Messinian compression was provided, in our opinion, by Marabini and Vai (1985) who described in Romagna a sharp angular unconformity between the lower Messinian evaporites and the upper Messinian "Argille a colombacci" formation grading upwards to lowermost Pliocene deposits. The existence of this compressional phase along the Padan border of the Apennines suggests that the siliciclastic turbidites of the Fusignano formation (Dondi, 1985) may be considered good evidence of a late Messinian foredeep basin in the Po Plain subsurface. The S. Donato sandstones (Savelli and Wezel, 1978), cropping out in Southern Romagna – Northern Marche, may be considered the southward continuation of the Fusignano formation. It is probable, but not proved, that the Messinian tectonics was responsible for the activation of the Valnerina line (Calamita and Deiana, 1986) and for early folding in the Marche-Gran Sasso and Montagna dei Fiori domains. An indirect evidence of this tectonics in the area is supplied by the eastwards shifting of the bulk of the terrigenous input and of the subsidence in the foredeep-basin system from late Tortonian-Messinian (Laga region, Montagna dei Fiori) to late Messinian-early Pliocene times (Morrone-Porrara). The heterochronous development of the flysch deposits (Laga formation *sensu stricto*, Civitella del Tronto sandstones, Teramo flysch p.p. and upper Messinian-lower Pliocene terrigenous sediments belonging to the Morrone-Porrara carbonate units) in such a short time-interval has been recognized by using as correlation datum-horizon a regional key-bed constituted by late Messinian acidic tuffites (Girotti and Parotto, 1969; Moruzzi and Follador, 1973) widespread along the outer margin of the Apennines.

The Messinian compressional tectonics has been recognized in Abruzzi, where thrust surfaces cut across lower Messinian turbidite deposits (Accordi, 1966; Devoto, 1967) while the thrust sheets are in turn unconformably covered by upper Messinian lacustrine sediments (Accordi *et al.*, 1969).

The major evidence of the Messinian compressional phase in the Southern Apennines has been observed E and NE of Matese, where the "plastic" nappes tectonically overlie (Sgrosso, 1987) the upper Tortonian-Messinian siliciclastic deposits of the Frosolone and Molise units and are unconformably covered by upper Messinian-lower Pliocene terrigenous deposits.

The Messinian compression was probably responsible for the early outline of the Apenninic arcs. Along the outer border of the northern arc an almost continuous foredeep basin developed from the Po Plain to the Marche-Abruzzi region through the present-day buried Romagna folds and the Pesaro folds. In the southern arc no typical foredeep basin developed, due to the different style of the orogenic transport (see Fig. 2) characterized by long flats and short ramps which determined the thrust of the allochthous sheets over more external parts of the foreland. The subsequent subsidence, affected a foreland segment already covered by thrust sheets, and the siliciclastic deposits of the new sedimentary cycle unconformably covered the previously deformed tectonic units.

The depositional cycle following the Messinian tectonic phase ranges in age from late Messinian to early Pliocene (near the boundary between the *G. margaritae* and the *G. puncticulata* zones), and includes the well-known Pliocene transgression related to the re-establishment of normal marine conditions in the Mediterranean region after the Messinian event. The lower Pliocene deposits systematically overlie the upper Messinian ones by conformable contacts (De Castro Coppa *et al.*, 1969; Carloni *et al.*, 1974; Iaccarino and Papani, 1980; Crescenti *et al.*, 1980; Colalongo *et al.*, 1982), showing that no variation in the tectonic history happened within this time internal.

The lower Pliocene tectonic phase

A new sedimentary cycle, starting from the *G. puncticulata* zone and reaching in its upper part the *G.* gr. *crassaformis* zone (*G. aemiliana* subzone) has been recognized in the whole Apennines. Along the northern Apenninic arc, *G. puncticulata* deposits lie transgressively, in angular unconformity, over different terms of the previously described upper Messinian-lower Pliocene cycle and, sometimes, over older rock-units belonging to the Messinian thrust-sheets. In the southern Apenninic arc, the lower-middle Pliocene deposits unconformably cover most of the outcropping tectonic units of the mountain chain. This transgression, outlined by an angular unconformity or a regional disconformity, is the surface expression of a severe compressional tectonics which affected the whole Apennines and was responsible for an important migration of the compression fronts towards the Po-Adriatic-Ionian foreland.

In the Northern Apennines, the lower Pliocene compression has been recognized in the subsurface, mainly along the outer margin of the Romagna Apennines (see cross-sections in Pieri and Groppi, 1981 discussed in Patacca and Scandone, 1986 and in Castellarin *et al.*, 1986).

The most impressive evidence of the lower Pliocene tectonic phase is exhibited in the Marche-Abruzzi region. Here, the severity and the complexity of the deformation is entirely delivered by the following events:

— early folding (Messinian?) in the Marche external domains and, perhaps, in the Gran Sasso domain

— counterclockwise rotation of Gran Sasso which overthrusts (E-W trending front, N-S trending lateral ramp) the southern termination of the N-S trending Montagna dei Fiori-Montagnone anticline

— thrust of both Montagna dei Fiori and Gran Sasso units over the Morrone domain

— transport of this pile of units over the inner margin of Maiella

— thrust of the Sibillini unit over the deformed Gran Sasso-Acquasanta-Montagna dei Fiori-Montagnone-Morrone system. The eastern margin of the thrust belt is overlain, in angular unconformity, by *G. puncticulata* deposits.

In the Abruzzi-Molise region, the lower Pliocene tectonic phase was responsible for the thrust of the Molise units over Maiella. The Molise units, together with most of the Apenninic nappes, were afterwards stratigraphically covered, in angular unconformity, by *G. puncticulata* deposits.

The lower-middle Pliocene foredeep basin subsequent to the described tectonic phase extended continuously from the Po Plain (Porto Corsini formation, Dondi, 1985) to Abruzzi (Crescenti *et al.*, 1980) through Romagna-Marche (Borello sandstones, Cremonini and Farabegoli, 1982). In the southern Apenninic arc, no typical foredeep basin developed since the allochthonous sheets, which already occupied the flexural depression along the inner border of the Messinian foreland, moved forewards also during the lower Pliocene tectonic phase and reached the subsiding margin of the new foreland areas. Lower-middle Pliocene deposits, therefore, unconformably covered the pile of the Apenninic thrust sheets, and filled structural depressions which may simulate extensional intramontane basins (e.g. Benevento, Ofanto, Potenza basins; see geological map of Plate 1(*)). Later on, in middle and late Pliocene times, these sediments were piggy-back transported towards the Apulia foreland by the prograding Apenninic nappes.

The middle Pliocene tectonic phase

The well-known and widespread "middle Pliocene" transgression was the consequence of a new tectonic phase which occurred in a time interval confined within the *G.* gr. *crassaformis* zone near the boundary between the *G. aemiliana* and the *G. crassaformis* subzones.

The middle Pliocene compression was responsible for the shaping of the present-day northern Apenninic arc and for the generation of the minor arcs along the Padan margin of the mountain chain (Pieri and Groppi, 1981; Castellarin *et al.*, 1986; Castellarin and Vai, 1986; Patacca and Scandone, 1986). The latter were usually bounded at the eastern edge by N-S or NNE-SSW trending strike-slip faults playing the role of dextral tear faults or lateral ramps which allowed differential forward movements of the compressional fronts and counterclockwise rotations of the tectonic structures. In the Marche-Abruzzi area, the compression front reached the present Adriatic coast, from Gabicce-Conero to Maiella following the Tortoreto Lido structure (Paltrinieri *et al.*, 1982). In this time, finally, the Maiella unit overthrust the Casoli structure which, in turn, tectonically overrode the inner part of the Bomba domain transporting the Molise allochthonous sheets. The timing of the deformation in this area has been established by means of stratigraphical constraints mainly derived from well-log analysis (Crescenti *et al.*, 1980; Casnedi *et al.*, 1981).

In the southern Apennines, the middle Pliocene tectonic phase is documented by the occurrence of angular unconformities or marked disconformities between lower-middle Pliocene and middle-upper Pliocene deposits, but the exact location of the compressional fronts and the real amount of the orogenic transport are poorly known.

(*) The Map of Plate 1 is inserted inside the back cover.

The foredeep basin subsequent to the described tectonic phase extended continuously from the Po Plain (Porto Garibaldi formation, Dondi, 1985) to the Pescara basin, following the regional trend of the present-day outer margin of the Apennines. In the Southern Apennines, the greatest part of the middle-upper Pliocene foredeep is buried by a thick cover of allochthonous sheets, but the corresponding basinal deposits, reached by numerous boreholes, have been exhaustively described by Casnedi *et al.*, (1981), Balduzzi *et al.*, (1982a), Balduzzi *et al.*, (1982b), Casnedi *et al.*, (1982). The location of the foredeep basin along the inner margin of Apulia suggests that the middle Pliocene compression also involved the Bomba domains ("Inner Apulia Platform" *p.p.* and "Inner Apulia Basin" *p.p.* of Mostardini and Merlini, 1986).

The upper Pliocene tectonic phase

During late Pliocene times, within the *G. inflata* zone, the Apennines underwent a new compressional tectonics which determined a structural configuration similar to the present one.

In the northern Apenninic arc, the main compressional features have been recognized along the northern margin of the Ferrara arc (Pieri and Groppi, 1981) and in the Adriatic Sea, Conero off-shore. In this area, the deformation is mainly expressed by a system of thrusts and folds - the latter usually displaying a dextral en échelon arrangement - which are limited eastwards by N-S and NNE-SSW trending strike-slip faults. These faults controlled the fold propagation in the Conero off-shore and inhibited the generation of compressive features east of the Pescara basin.

In the Southern Apennines, the carbonates of the Bomba unit underwent more severe folding and thrusting towards the foreland, and the overlying allochthonous sheets were transported over *G. inflata* basinal deposits (Casnedi *et al.*, 1981; Balduzzi *et al.*, 1982a; Balduzzi *et al.*, 1982b) stratigraphically covering the inner margin of Apulia.

A new sedimentary cycle followed the upper Pliocene tectonic phase, but actual foredeep basins developed only in the Ionian Sea, in the central-northern Adriatic region (Ravenna off-shore) and - with a moderate subsidence - in the Parma-Bologna area, revealing the occurrence, in late Pliocene-Pleistocene times, of a notable change of the stress pattern controlling the time-space migration of the thrust belt-foredeep-foreland system.

The Pleistocene compressional tectonics

A new compressional tectonics affected the Apennines during Pleistocene times, with major evidence along those segments of the edifice which were bordered by strongly subsiding basins subsequent to the upper Pliocene tectonic phase. The deformation either propagated by gentle folding of the foreland sedimentary covers rather far from the most external upper Pliocene structures (e.g. central-northern Adriatic region), or concentrated along few compressional fronts running somewhat inside the thrust belt (e.g. Emilia Apenninic margin, Calabrian Arc; see Castellarin *et al.*, 1986; Patacca and Scandone, 1986; Barone *et al.*, 1982).

An accurate analysis of the Pleistocene deformation in the Apennines has still to be carried out, but the available information allows us to recognize the most convex parts of the two major Apenninic arcs as the areas of maximal shortening. In such a view, we should expect in Pleistocene times prevailing N-S or NNE-SSW dextral lateral motions in the Central-Northern Apennines and NW-SE or WNW-ESE sinistral displacements in the Southern Apennines.

THE POSSIBLE MECHANISM FOR THE POST-TORTONIAN DEFORMATION OF THE APENNINES

Underthrust processes of the foreland lithosphere beneath the thrust belt can be excluded as the possible source for the Late Tertiary mountain building in the Apennines (Scandone and Patacca, 1984; Castellarin and Vai, 1986). An active subduction of the Po-Adriatic-Ionian lithosphere beneath the Tyrrhenian Sea is in fact inconsistent with the slip vectors which describe the motion of the Adriatic Promontory at that time. A model which interprets the evolution of the Calabrian Arc and the generation of the Tyrrhenian basin in a scheme of regmatic system has recently been proposed by Boccaletti *et al.* (1984). In our opinion this model is plausible but does not fully satisfy the available analytical data and, in particular, does not justify the geometry of the deep-seated lithospheric slab beneath the southern Tyrrhenian Sea.

Starting from the present-day structure of the Apennines and analyzing the time-space evolution of the thrust belt-foredeep-foreland system, we reached the conclusion that the deformation has been strictly controlled by the dipping of the foreland lithosphere sinking beneath the mountain chain. The elastic flexure of the Po-Adriatic-Ionian lithosphere has been scarcely influenced by the topographic load and by the infilling-material load (Royden *et al.*, 1987). A prominent role, therefore, has been played by the hidden load. The hidden load - any active subduction being absent, and the Tyrrhenian region toghether with the western margin of the Apennines being underlain by a soft mantle - must mostly result from the high density of the subducted slab. The time-space migration of the thrust belt-foredeep-foreland system, that is to say the time-space migration of the flexural loading of the foreland lithosphere, may have been entirely controlled by gravity processes responsible for the passive subduction of the original slab which underlays the Tortonian Apennines. This mechanism also justifies the pattern of the Bouguer gravity anomalies and, in particular, the distribution of the positive values observed in the foreland and interpreted (Royden *et al.*, 1987) as the effect of a peripheral bulge. If the lithosphere sunk with no uniform dip, as the offset of the positive highs in the foreland is suggesting, then we should expect, at the surface, differential motion in the thrust sheets guided by strike-slip faults with maximal transport in correspondence with the maximal retreat of the down-going lithosphere. The junction of the two Apenninic arcs could easily be explained admitting the existence of a major free-boundary in the lithosphere in correspondence with the "Ortona-Roccamonfina" line, with a dextral lateral motion of the northern Apenninic arc due to a more pronounced sinking of the lithosphere in this area. The Quaternary kinematic behaviour of the Apennines is schematized in Fig. 4, where three major free boundaries have been hypothesized.

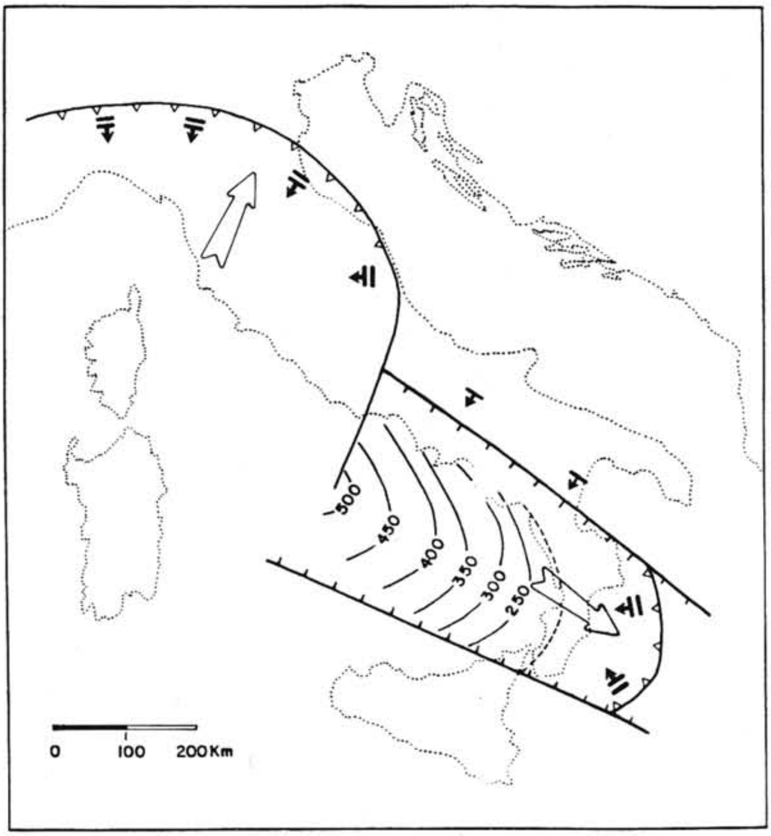

Fig. 4. - Differential sinking of the Po-Adriatic-Ionian lithosphere during Quaternary times. White arrows indicate the present-day directions of the orogenic transport. Small arrows describe the gravitational sinking of the litosphere in the northern and southern Apenninic arcs. In the Southern Tyrrhenian Sea, the Ionian litosphere dips nearly vertical to a depth of about 250 kilometers.

Conclusions

The analysis of the deformation of the outer margin of the Apennines in post-Tortonian times lead us to the following conclusions:

— the trend of surface and subsurface structures allows the recognition in the Apennines of two major arcs which have developed in post-Tortonian times;

— at least five compressional phases are responsible for the post-Tortonian evolution of the Apennines;

— a systematic migration of the thrust belt-foredeep-foreland system has been observed in correspondence with every tectonic phase;

— the single phases of orogenic transport occurred within short time intervals separated by longer periods in which the subsidence played an important role for the sedimentation of clastic deposits in the foredeep basinal areas;

— the deformation did not act cilindrically, that is to say the amount of transport and the tectonic style considerably change across different segments of the mountain chain;

— the transport of the "plastic" allochthonous sheets towards the foreland in the Southern Apennines was not controlled by gravity processes, as often has been assumed, since the thrust geometry clearly indicates real compression at shallow depths;

— the total amount of shortening is several tens of kilometers in the Northern Apennines, around hundred kilometers in the Central Apennines and at least threee hundred kilometers in the Calabrian Arc. Therefore, the average velocity of shortening varies from less than 1 cm/y in the north to around 5 cm/y in the south;

— the results of the kinematic analysis and the consequent palinspastic restorations suggest that remarkable dextral lateral motion must have occurred in Sicily during the whole period of time considered;

— the deep-focus earthquakes beneath the Southern Tyrrhenian Sea must be related to the presence of a lithospheric slab which may represent, in its deepest parts, the remnant of the Adriatic lithosphere subducting Corsica-Sardinia before the opening of the Tyrrhenian basin;

— passive subduction of the Po-Adriatic-Ionian lithosphere by gravitational sinking appears as a reasonable mechanism to explain contemporaneous geodynamic events such as mountain building in the Apennines and extension in the Tyrrhenian area, as well as the time-space migration of the thrust belt-foredeep-foreland system in post-Tortonian times;

— the partition of the Apennines into two major arcs may be related to the differential sinking of the foreland lithosphere in the Northern Apennines and in the Calabrian Arc. The main free-boundary, along which the two arcs touch, is expressed at the surface by an important fault-zone ideally joining Gaeta and Ortona, known in the geological literature as "Ortona-Roccamonfina line". The areas of maximal convexity of the arcs should correspond to the areas of maximal retreat of the sinking lithosphere;

— the Pleistocene and, probably, the present-day compression along the outer margin of the Apennines is confined at the apex of the northern Apenninic arc and in the External Calabrian Arc, suggesting that two major zones of differential lithospheric sinking exist in the Quaternary Apenninic foreland.

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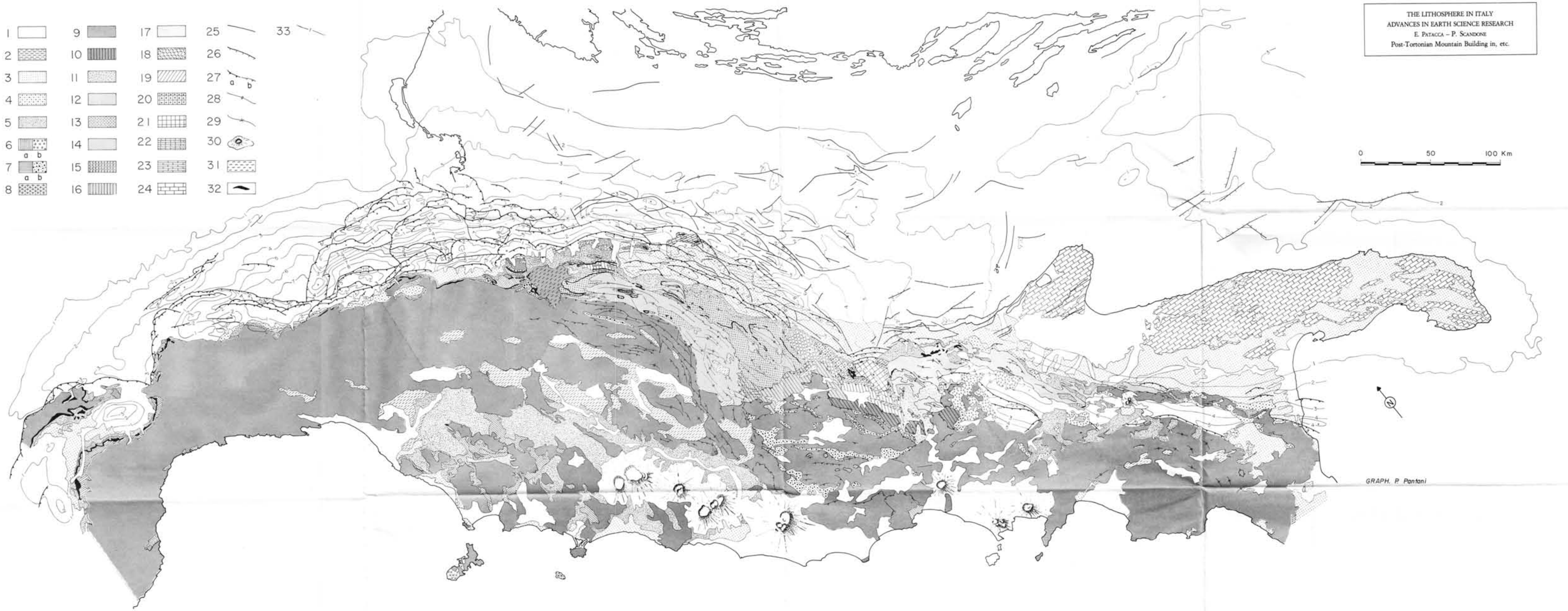

Autochthonous and parautochthonous rock-units post-dating the upper Pliocene tectonic phase

1 Continental and subordinate shallow-marine deposits; volcanites and volcanoclastites. Holocene-Middle Pleistocene
2 Lacustrine and fluviolacustrine deposits. Villafranchian
3 Continental to shallow-marine clastic deposits, marine clays; calcarenites in the Apulia region. Lower Pleistocene-Upper Pliocene

Miocene-Pliocene deposits unconformably covering the Apenninic thrust sheets, belonging to sedimentary cycles intervening between consecutive phases of orogenic transport after the Tortonian tectonic phase

4 Marine clastic deposits, pre-dating the upper Pliocene (*G. inflata* zone) tectonic phase and post-dating the middle Pliocene (*G.* gr. *crassaformis* zone, uppermost part of the *G. aemiliana* subzone) tectonic phase. Upper-Middle Pliocene
5 Marine and subordinately paralic clastic deposits, pre-dating the middle Pliocene tectonic phase and post-dating the lower Pliocene (lowermost part the *G. pucticulata* zone) tectonic phase. Middle-Lower Pliocene
6 Marine terrigenous deposits (Lower Pliocene) and hypohaline sediments (Upper Messinian), pre-dating the lower Pliocene tectonic phase and post-dating the Messinian (after the salinity crisis) tectonic phase
6a: prevailing pelites (Lower Pliocene), overlying terrigenous deposits, reworked evaporites and chemically-precipitated carbonates (Upper Messinian)
6b: terrigenous basinal resediments, mainly deposited by grain-flow mechanism
7 evaporites, evaporitic limestones and "tripoli" (black); overlying terrigenous deposits, pre-dating the Messinian tectonic phase and post-dating the Tortonian (*G. menardi* zone) tectonic phase. Lower Messinian-Tortonian
7a: lacustrine and marine terrigenous deposits
7b: terrigenous basinal resediments unconformably overlying the Tortonian Apenninic units and conformably covering the adjacent external units not yet affected by orogenic transport

Miocene-Pliocene Tuscan plutonites intruded across the Apenninic units after the Tortonian tectonic phase

8 granites and granodiorites (4.3 ± 0.13 - 10.2 Ma)

Allochthonous units affected by Tortonian and pre-Tortonian orogenic transport

9 Undifferentiated internal and external units building up the Tortonian Apenninic chain

Apenninic units reached by the compression front during the Tortonian tectonic phase and affected by orogenic transport during the Messinian tectonic phase

M. Genzana-Frosolone units. These units derive from a basinal domain originally located east of the Abruzzi-Matese carbonate platform
10 Marly clays and marls with rare intercalations of fine-grained sandstones in the upper part (Lower Tortonian); globigerinid marly limestones, shelf-derived calcarenites and calcirudites (Serravallian-Langhian); basinal carbonate deposits analogous to the Umbrian sequences (Lower Miocene-Lower Liassic)
A part of the Umbria fold-belt may be ascribed to this group of units, but the available analytical data do not allow a certain attribution.

Apenninic units reached by the compression front and affected by orogenic transport during the Messinian tectonic phase

Molise units. These units, whose Mesozoic part is unknown, derive from basinal realms originally located between the M. Genzana-Frosolone and the Morrone-Porrara domains
11 Siliciclastic basinal resediments. Lower Messinian-Upper Tortonian
12 Globigerinid marls and marly limestones (Lower Tortonian-Serravallian); polymict lime breccias and calcarenites, pelagic cherty limestones, and red-greenish radiolarites (Lower Miocene); red and greenish siliceous clays with rare intercalations of graded calcarenites (Lower-Miocene-?Oligocene)

Apenninic units reached by the compression front during the Messinian tectonic phase and affected by orogenic transport during the lower Pliocene tectonic phase

Marche-Montagna dei Fiori units. These units derive from deep-marine palaeogeographic realms located east of the Umbria belt
13 Siliciclastic basinal resediments (Lower Pliocene-Lower Messinian), including a gypsarenite key horizon (black)
14 Globigerinid marls and marly limestones mixed with (Montagna dei Fiori, Acquasanta) shelf-derived detritus (Tortonian-Langhian); deep-marine carbonate deposits analogous to the originally contiguous Umbrian sequence (Lower Miocene-Middle Liassic); shallow-water carbonates (Lower Liassic-Upper Triassic)
Gran Sasso units. This group of units derives from the same palaeogeographic realm as the Marche-Montagna dei Fiori units. Its differentiation is justified by the different structural setting related to an independent counterclockwise rotation accompanied by northward large displacements
15 Siliciclastic basinal resediments (Messinian)
16 Deep-marine carbonate sequences deposited in various environments ranging from foreslope to basin to submarine hill (Tortonian-Middle Liassic); shallow-water carbonates (Lower Liassic-Upper Triassic)
Daunia unit. This unit, usually attributed to the Tortonian Apenninic chain (Irpinian units), is here considered, on the contrary, as the most external one among the Molise units
17 Evaporites and evaporitic limestones (black), marls (Messinian); globigerinid marls and marly limestones, graded biocalcarenites, occasional intercalations of sandstones (Tortonian-Lower Miocene); red and greenish clays with intercalations of graded calcarenites (Lower Miocene-?Oligocene)

Apenninic units reached by the compression front and affected by orogenic transport during the Lower Pliocene tectonic phase

Pesaro-Morrone-Porrara units. These units derive from a belt originally located between Marche and Conero (north) and between Molise and Maiella (south). Along this belt the sedimentary environment gradually changed from carbonate-platform (Porrara) to basin (Pesaro)
18 Siliciclastic basinal resediments. Lower Pliocene-Upper Messinian
19 Evaporites, evaporitic limestones and "tripoli" (Messinian, black). Sedimentary sequence analogous to the Marche-Montagna dei Fiori ones. (Tortonian-Upper Triassic)
At Monte Porrara, open-shelf to basinal, coarse grained, carbonate deposits (Tortonian-Upper Cretaceous); shallow-water carbonates (Upper Cretaceous-Jurassic)

Apenninic units reached by the compression front during the lower Pliocene tectonic phase and affected by orogenic transport during the middle Pliocene tectonic phase

Maiella unit. This unit derives from a palaeogeographic belt adjacent the Porrara domain and belonging to the same carbonate-platform system grading northwards to basinal environments
20 Siliciclastic basinal resediments (Lower Pliocene-Uppermost Messinian)
21 Lime resediments and evaporites (Messinian, black); sedimentary sequence analogous to the described Porrara and Morrone units (Tortonian-Jurassic)

Apenninic units reached by the compression front and affected by orogenic transport during the middle Pliocene tectonic phase

Conero unit. This unit belongs to the same deep-marine domain as the Marche and the Pesaro belts. The correlation between the Conero and the Casoli units is highly speculative and mostly derives from the age of the earliest siliciclastic deposits (Lower Pliocene, *G. puncticulata* zone) and from the age of the first orogenic transport (Middle Pliocene, *G. aemiliana* subzone)
22 Pelites with intercalations of fine-grained sandstones (Middle-Lower Pliocene)
23 Bioclastic calcarenites; hypohaline deposits consisting of clays and chemically-precipitated limestones ("Argille a colombacci" Upper Messinian); evaporites and clays (Messinian); sedimentary sequence analogous to the Marche one (Tortonian-Cretaceous) with shelf-derived lime resediments in the Upper Cretaceous

Casoli unit. This unit, mostly known by subsurface exploration, belongs to the same carbonate-platform system as the Maiella and Morrone units
22 Clays and silty clays. Middle-Lower Pliocene

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24 Shallow-water calcarenites (Miocene and, locally, Paleogene); shallow-water limestones in western and central Gargano and in the Murge-Salento area (Upper Cretaceous-Upper Jurassic); slope and basinal limestones in eastern Gargano (Upper Cretaceous-Upper Jurassic)
25 Faults, mainly strike-slip faults
26 Normal faults
27 Overthrust: a) subsurface, b) surface
28 Anticlines
29 Synclines
30 Volcanic edifices
31 Huge post-Tortonian submarine slides (Val Marecchia, Lower Pliocene)
32 Main outcrops of Messinian evaporites
33 Base of Pliocene isobaths; intervals in Km.