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FOREDEEPS AND THRUST SYSTEMS IN THE NORTHERN APENNINES

Abstract. There is condiderable evidence that in the evolution of the Northern Apennines, rather than one migrating foredeep basin, at least three distinct foreland basins formed, which are progressively younger toward the east: the Macigno, the Marnoso Arenacea and the Marche foredeeps. Applying Beaumont's foredeep model, the possible deep-rooted thrust system and the possible peripheral bulge regions to connect to them are described. We suggest that they are bounded by three thrust stacks complexes: the Liguride accretionary wedge, the Tuscan metamorphic chain and the Umbria Marche thrust fold belt respectively. A prograding suture model can account for the evolution of such foreland basins. The present day Northern Apennines correspond to the thrust of a crustal element responsible for the flexure of Adria lithosphere required to explain the presence of the Messinian to Present Marchean foredeep basin.

INTRODUCTION

During the last 15 years, knowledge and understanding of the Alpine orogenic belt has greatly increased as a consequence of structural geologic studies, combined with deep exploration geophysical investigations. Two international projects, namely the EGT and the CROP-ECORS, and the National Swiss NFP have, on the one hand, produced geophysical data to constrain interpretations of the major Alpine structures and, on the other, added new question marks to the evolution of the entire orogen. Their impact in fact affects not only the geology of the Alpine chain "sensu stricto" but also that of the Southern Alps and Apennines as well. In this framework, a reapprisal of the tectonic setting and of the geological evolution of the Northern Apennines is necessary.

The aim of this paper is, starting from an analysis of the well established migration towards the foreland of the Northern Apennines foredeeps (Merla, 1952), to evaluate the implications this fact involves for the thrust systems which form the orogenic building and its evolution. After a brief description of the main tectonic units of the Northern Apennines along a SW -NE transect from Elba Island (Tyrrhenian Sea) through Perugia to Ancona (Adriatic Sea) three main thrust stacks, their related foredeep basins and their tectonic evolution will be outlined. Then, the extensional phase that affected the Northern Apennines from the Late Tortonian to the Late Pliocene will be described. In conclusion a possible model for the tectonic evolution of the entire belt will be suggested. For all the geographic names refer to Fig.1.

GEODYNAMIC AND GEOLOGIC FRAMEWORK OF THE NORTHERN APENNINES

In the tectonic evolution of the Northern Apennines-Alps system we recognize a passive-

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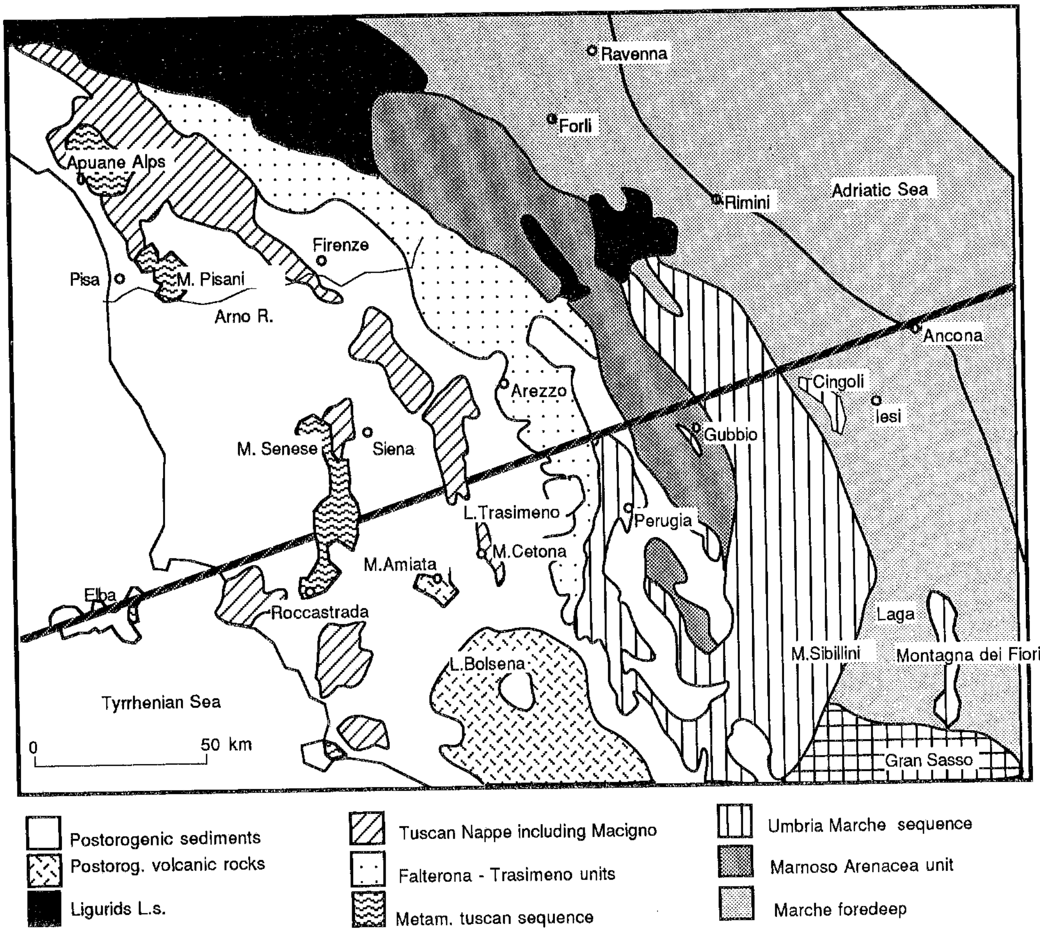

Fig. 1 — Simplified geological map of the Northern Apennines. 1a) Post-orogenic sediments; 1b) post-orogenic magmatic rocks; 2) L.s. Ligurids; 3a) Non-metamorphic Tuscan carbonate sequence (Tuscan nappe); 3b) Non-metamorphic Tuscan siliciclastic sequence (Macigno); 4) Metamorphic Tuscan carbonate and siliciclastic sequence; 5a) Umbria Marche carbonate sequence; 5b) Umbria Marche siliciclastic sequence (Marnoso Arenacea); 5c) Marche foredeep sediments, 6) Line of cross section Elba- Ancona.

margin phase, from the Jurassic to the Lower Cretaceous, with African continental crust to the east and the Liguride Ocean to the West (present position). This was followed by an active-margin phase, in which the Alpine chain formed during the Late Cretaceous-Middle Eocene times, involving the Ligurian domain of Apennines as well. At the end of this period, a collision began between the already formed Alpine chain and the Italian thinned continental crust, which caused the latter in part to override, in part to act as a wedge (Bernoulli et al., 1990; Polino et al., 1990) against the Alps, causing backthrusting and backfolding of Alpine units onto the most internal Apenninic ones. This wedge went on advancing toward WNW during Oligocene-Miocene times, causing in Europe foreland basins to be formed and, in the Southern Alps, severe backthrusting that affected basement and cover rocks, with the birth of foreland basins as well.

This history seems to apply to the Northern Apennines as well (Roeder, 1990; Minelli et al., 1991); complications are here related to the rapid rotation of the Corsica - Sardinia microcontinent during the Upper Oligocene - Early Miocene and later on, to the development of the Tyrrhenian extensional basin. In fact, starting in the Upper Miocene in Tuscany, and Middle Miocene in the Corsica basin according to Bartole et al. (1991), the new Apenninic ridges underwent severe extension, allowing a post-orogenic basin to form during Late Tortonian, Messinian, and Lower Pliocene. Extension was followed during the Upper Pliocene by a rapid uplift that formed the present landscape. Extension and uplifting migrated from west to east in the same way as compression did, so that while western sectors of the Apennines were subjected to extension, thrusts were acting in the Marche-Romagna area.

In geodynamic terms, thrusts and foreland basins develop in front of the Adriatic subducting slab, whereas extension occurs at its rear when it began to roll back; uplifting is supposed to have occurred at the rear as well, in connection with asthenosphere intruding and swelling, according to many Authors.

A schematic geologic map of the Northern Apennines (Fig. 1) shows this orogene to consist of the following terrains:

1) Mio-Plio-Quaternary postorogenic deposits and igneous rocks.

They include the sediments that fill the extensional basins from the eastern border of the Corsica-Sardinia block to the western border of the Umbria Marche thrust and fold belt.

Tertiary and Quaternary volcanic and magmatic products are included in these units.

2) L.s. Ligurid units.

They include the Liguride sequences (Decandia e Elter, 1974; Abbate e Sagri, 1982), the Schistes Lustré thrusted over them, and the epi-Ligurids which have sealed the Alpine building since the M. Eocene. These units were displaced eastwards, onto the Adria crust, beginning in the Late Oligocene.

3) Tuscan Nappe.

This consists of the Mesozoic through Tertiary sedimentary cover of western Tuscany, detached either on top of Triassic evaporites or on top of Paleozoic phyllites and thrust over a homologous but metamorphosed sequence.

4) Tuscan metamorphic unit.

This includes the 'autochthonous' and 'parautochthonous' Paleozoic basement, with polyphase tectonics relatable to the Hercynian phases, and the Mesozoic through Tertiary cover quite similar to that of the Tuscan Nappe and affected by a greenschist facies metamorphism of Early Miocene age (Deino et al., 1994).

5) Umbria-Marche unit.

The Umbria-Marche sedimentary sequence, principally evaporites plus platform and pelagic carbonates, was deposited on subsiding Adria continental crust from the Triassic to the early Tertiary. The basement of this domain does not outcrop, but it has been reached by the Perugia 2 (Martinis e Pieri, 1964) and S. Donato wells (Anelli et al., 1992)

FORELAND BASINS OF NORTHERN APENNINES

Since Merla's classic work (1951) many Authors have pointed out an eastward migration of foredeep basins in the Northern Apennines which started in the Upper Oligocene in western Tuscany and propagated toward the Adriatic sea where the present trough is located.

Such an evolution is commonly related to the classic concept of the foredeep basin. According to Allen and Allen (1990), Beaumont (1981) and Quinland and Beaumont (1984) a foredeep basin originates as a flexure of the continental lithosphere adjacent to a pile of thrust stacks in response to tectonic loading. Recently, however, Royden and Karner (1984) and Royden et al. (1987) have shown that, in the case of the Apennines, the load of only the advancing tectonic pile is insufficient to bend the lithosphere, and that for it to form, an additional cause should be sought in the roll back of the lithosphere itself. In Beaumont's model, the thrust sheet stack creates an asymmetric trough that has a gentle outer flank, rising to a peripheral bulge before reaching the foreland. The thrust sheet-foredeep system migrates progressively toward the foreland, so that the depocentre is continuously shifted. During such a migration it is possible that the thrust stacks overthrust the proximal part of the foredeep basin. On the basis of this model, every foredeep basin should be limited in its hinterland by a thrust stack,

Ma		THRUST STACK	FOREDEEP BASIN	PERIPH. BULGE
1.6 6.5	E. Pleist. Messinian	Umbria Marche thrust fold belt	Marche Foredeep	Offshore Marche
8.8 16.0	E.Tortonian U. Burdig.	Present position of M. Cetona	Marnoso Arenacea	Umbria Marche thrust fold belt
16 26.0	U. Burdig. M. Chattian	Accretionary wedge	Macigno	Present position of M. Cetona

Fig. 2 — Main foredeep basins in the Northern Apennines.

and this should be sufficiently deep-rooted to generate a flexure of the lithosphere in response to tectonic loading. This model has been invoked in several scientific papers on the geology of the Northern Apennines (Boccaletti et al.,1987; Ricci Lucchi,1975; Centamore et al. 1978; Bortolotti et al., 1970; Dallan e Nardi, 1972). All of them agree on the existence of a unique foredeep progressively migrating from west to east related to the development of the Northern Apennines orogen.

This means that the orogenic piles, responsible for the tectonic loading that generated the single foredeeps, formed in sequence from west to east starting in the Oligocene and continuing today. As a matter of fact, however, we find in the tectonic piles from Tuscany to Umbria-Marche many examples of out-of-sequence thrusts which today cannot be correctly collocated in the model.

In our opinion there is much evidence that in the Northern Apennines evolution, rather than one foredeep basin, at least three foreland basins developed progressively younger toward the east, excluding the L.s. Ligurid complex .

As shown in Fig. 2, along a section from Elba Island (Tyrrhenian Sea) through Perugia to Ancona (Adriatic Sea), the three main foredeeps are the following:

i) the Macigno basin,
ii) the Marnoso Arenacea basin,
iii) the Marche - Adriatic basin.

Respectively, they are bounded by three thrust stack regions:

a) the Liguride accretionary wedge,
aa) the Tuscan metamorphic chain,
aaa) the Umbria Marche thrust fold belt;

and three peripheral bulge regions could be suggested:

b) the region between M. Cetona and the Perugia Massifs,
bb) the Umbria Marche thrust fold belt,
bbb) the drowned Adriatic platform.

THE MACIGNO BASIN

The Macigno rocks belong to two broad tectonic units:

1) the Tuscan nappe of which the Macigno represents the stratigraphic top;

2) the Trasimeno -Falterona thrust sheet overthrusted onto the Umbria Marche domain entirely formed by Macigno and the Scisti Policromi fm. (Middle Cretaceous - Upper Oligocene). A modern and integrated stratigraphic study of the Macigno is still to be made, so that any conclusion on its kinematics and palinspastic restoration made at the present time risks being

naive and overtaken by new findings. Montanari e Rossi's research (1983) on the dating of the macigno base shows that north and south of the Arno river, the base of the siliciclastic turbidites is younger from inner to outer tectonic units.

However, old and recent stratigraphic data do not confirm such a migration: the onset of Macigno sedimentation seems to be about the same (Upper Oligocene) in western Tuscany at the front of the Tuscan nappe and in most part of the Falterona -Trasimeno nappe. In this latter unit, (southwestern Umbria and Monti di Cortona) the age is Middle Chattian (Damiani et al., 1989; Costa et al., 1991; Damiani et al., 1991) whereas in proximity to the contact with the Marnoso Arenacea its base reaches the Lower Miocene (Nocchi, 1961; Damiani et al., 1991; Costa et al., 1991). As far as thickness and facies distribution of the Macigno is concerned, in Southern Tuscany we observe proximal facies and low to zero thickness on Elba, and on the Tyrrhenian coast, and metamorphic Monticiano-Roccastrada units; while Monti del Chianti (Tuscan nappe) and Monti di Cortona - Castiglion Fiorentino - Pratomagno (Trasimeno-Falterona unit) display both proximal and distal turbidites and high to very high thicknesses. The outer portion of the Macigno of this unit tends to reduce again in thickness. On this basis it seems questionable to separate in different basins of the Macigno the Tuscan nappe from that of Trasimeno-Falterona. Rather, all stratigraphic and sedimentologic data seem to indicate the presence of a single large foredeep basin whose outer most flank displays a younger filling due to the effect of onlap sedimentation. The major problem in correlating northern and southern Tuscany lies in the fact that, assuming a western provenance for the Tuscan nappe, we have to locate the Macigno foredeep to the west of the metamorphic complex in northern Tuscany, whereas in southern Tuscany the evidence for a true foredeep basin is present to the east of metamorphic complexes only. In fact on Elba, on the tyrrhenian coast and on Monticiano-Roccastrada ridge the thicknesses of the Macigno are trivial compared with those of Monti del Chianti and of Trasimeno. Such a mismatch is overcome if we assume that elongation of the Macigno-Falterona basin was not coaxial with the attitude of the future metamorphic chain, and that the latter, formed later than 27 Ma, possibly during at the Aquitanian-Bourdigalian boundary, as suggested by Deino et al. (1994). Should the Chattian age of the onset of the Macigno and Trasimeno (Costa et al., 1991; Damiani et al., 1991) sedimentation be confirmed throughout the basin, then the time of its deposition is almost coincident with the beginning of the Corsica -Sardinia block rotation. This could explain why, in southern Tuscany, the Macigno -Trasimeno trough was positioned in a more external location than in northern Tuscany.

Under these conditions, it seems reasonable that north of the Arno river the Macigno developed in a trough whose outer flank was the deposition site of the outermost imbricates of the Cervarola nappe. Somewhere eastwards, adjacent to this latter, in the Umbro-Romagnan domain, the coeval upper part of the Scaglia Cinerea-Bisciaro was being sedimented. The metamorphic core developed later in a position formerly and approximately occupied by the most external thrusts of the Cervarola nappe.

In southern Tuscany, the troughs of Macigno and of Trasimeno, in the same manner developed adjacent to the Umbrian domain with the Macigno "costiero" in the inner part of the trough itself. Here too, the metamorphic cores formed later in a much more central position with respect to the sedimentary trough than in northern Tuscany.

Thrust stack

The Macigno basin developed outwards of an accretionary prism (Principi e Treves, 1984) emplaced on the Adria continental crust during early stages of collision (Late Oligocene). It consisted of Ligurid nappes of oceanic provenance overridden by thrust sheets of Schists Lustrés with HP metaophiolites of clear Alpine nature, as recent seismic data from the Tyrrhenian sea (Bartole et al., 1991) show. The accretionary prism has been sealed since the Middle Eocene by the M. Piano marls followed by other epi-Ligurian deposits (Ranzano basin) subcoeval with the Macigno. The Schistes Lustrés nappe is well documented also by magnetic anomalies that form a long strip running south of Elba Island for more than 100 km in an almost N-S direction.

Peripheral bulge

Evidence of the peripheral bulge of the Macigno basin must be searched for in areas where a) the thickness of the Macigno is strongly reduced or even absent, and it grades to pelagic marls or prototurbidites (Vicchio); b) the age of the Macigno and of the formation directly underlying is Lower Miocene.

The first condition applies in the Northern Apennines in the metamorphic cores of the Alpi Apuane where the Pseudo Macigno has a strongly reduced thickness. In southern Tuscany this condition applies in the front of the outermost imbricates of the Trasimeno nappe i.e., restoring this nappe between the Monte Cetona structure and Perugia Massifs area.

THE MARNOSO-ARENACEA FOREDEEP

The Marnoso Arenacea basin developed from the Burdigalian (Perugia Massifs area) till Late Serravalian - Middle Tortonian (Gubbio-M. Vicino area). From the Middle Tortonian through to the Lower Messinian, it evolved to the Inner Marchean Basin, where evidence of turbiditic sedimentation involves only small, scattered basins rather than a true foredeep (Cantalamessa et al., 1986). The width of the foredeep was progressively reduced during its existence, due to the advance of the Trasimeno-Falterona nappe and to the nucleation of thrust systems inside the Marnoso-Arenacea, so that a large Langhian-Serravallian basin, more than 100 km wide, was narrowed Middle Tortonian corridor of a few km (the M. Vicino syncline). The depocentre of the trough was located in the Umbro-Romagna units which from the so-called parautochthon (Ten Haaf and Van Wamel, 1979). Thickness in that area reaches values higher than 3000 m, while to the south, in southern Umbria (Narni-Amelia ridge), it is strongly reduced and the basin seems to come to an end in a longitudinal rise. Only a few scattered data exist in the region to the north-west of the Sillaro line where the Marnoso-Arenacea disappears under the Ligurids l.s.

The Marnoso-Arenacea consists of two broad tectonic units (Ten Haaf and Van Wamel, 1979):

i) the autochthonous unit which rests stratigraphically on top of the Umbro-Marchean sequence of the main Apenninic ridge and

ii) the parautochthonous unit which forms a sequence of imbricates, detached on to the pre-flysch Schlier formation, between the front of the Trasimeno-Falterona nappe and the autochthonous itself over which they are thrusted. The beginning of the emplacement of the Trasimeno-Falterona nappe onto the Marnoso Arenacea foredeep is testified to by the presence in the Marnoso Arenacea stratigraphic sequence of large bodies of Ligurids l.s. discharged as olistostromes east of the Tiber Valley and in western Romagna (Pialli, 1966; Capozzi et al., 1991; Damiani et al., 1991) from the top of the advancing Trasimeno nappe. It started early, at the beginning of the Serravallian, and went on dumping olistostromes till the end of that period. The parautochthonous imbricates formed probably very soon after the final emplacement of the Trasimeno nappe, which should have occurred during the Middle Tortonian when the Marnoso Arenacea trough was reduced to a narrow corridor corresponding to the M. Vicino syncline.

Thrust stack

Considering the Burdigalian to Serravallian age of the Marnoso Arenacea turbidites, the tectonic pile that caused the formation of that foredeep is certainly in sequence with that which determined the birth of the Macigno foreland basin. It should be sought in western areas where, at the same time, compression was reaching its paroxism i.e., in the metamorphic cores of Elba and Dorsale Monticiano - Roccastrada. The thrust system responsible for the metamorphism of these areas and for their emplacement must have been deep enough rooted to double the crust in order to generate the necessary structural relief and tectonic load to bend the lithosphere. A Moho doubling in western Tuscany has been hypothesized by Cassinis et al. (1991) on a gravimetric basis. In its outward propagation, the thrust system detached along shallower levels so generating the thrust pile adjacent to the Marnoso Arenacea trough.

In Elba, Ligurides appear to be thrusted onto the Tuscan nappe (III complex) and sandwiched in between the latter and low grade metamorphic terrains of Tuscan affinity (II complex). As Keller and Pialli (1991) have shown, this is indicative of a two stage thrusting, the first being due to the superposition of the Ligurids onto the Tuscan nappe, the second to a rethrusting of this pile which brought the Tuscan nappe with its basement to the top of the Ligurids. The presence of Macigno sandstones in the footwall of both thrust contacts indicates that compression started in this area not before the Upper Oligocene. A more precise age determination comes from the greenschist facies metamorphism of rocks of the II complex, which gives 19.6 Ma (Deino et al., 1994) corresponding to the Early Burdigalian.

The two deformation events probably reflect a continuous compression that caused significant shortening of both the basement-cover and its linked ophiolitic units to form an orogenic prism advancing eastwards and accreting new tectonic units.

Peripheral bulge

The peripheral bulge of the Marnoso Arenacea basin is envisaged in the main Apennine region, where turbiditic sedimentation was very poorly developed during Middle Late Tortonian.

THE MARCHE FOREDEEP

The easternmost and last foredeep basin in the Northern Apennines is the Marche foredeep which formed adjacent to the main Apenninic ridge of Umbria-Marche and Gran Sasso. It is part of the composite, elongated basins, which developed out of the forming Apenninic ridge from the Po valley to the Abruzzi region, from the Messinian. The most important of them, as far as the Elba - Ancona section is concerned, is the Laga basin, which formed from the Messinian and consists of about 3.5 km of siliciclastic turbidites in its southernmost sector. Its thickness decreases toward Ancona and increases again toward the north. During the Early Pliocene, its depocentre shifted to the east, and the once wide trough became a narrow depression elongated in the NNW - SSE direction from Iesi to the eastern front of Gran Sasso. To the north the depocentre shifted eastward as well, but a wide basin was maintained. In the Middle and late Pliocene, compression reached the Marche offshore and the foredeep assumed its present configuration. Summing up the thickness of Messinian and Pliocene deposits, two major troughs appear to characterize the Marchean foredeep: that of Gabicce - Rimini to the north, and Laga - Cellino to the south. They are separated by a saddle in between at the latitude of Ancona. The tectonic pile responsible for its formation is in sequence with the one that formed the foredeep of the Marnoso Arenacea during Burdigalian - Serravallian times. It refers to the Umbria-Marche fold and thrust belt with which it forms a complex tectonic domain. According to Patacca and Scandone (1988), in the Marche foredeep, at least four main compressive events, well marked by seismic and stratigraphic data, can be recognized. The Tortonian - Messinian event is responsible for activation of the early folding of the Umbria-Marche thrust fold belt and for the Gran Sasso and Montagna dei Fiori structures.

During the Lower Pliocene event, the folding of the external Marche domain began to develop and the counter clockwise rotation of the Gran Sasso started, which overthrusted the southern termination of the NS trending Montagna dei Fiori anticline.

Contemporaneously, thrusting of the M.ti Sibillini over the already deformed Gran Sasso developed. It is in Middle Pliocene that the compressive front reached the Adriatic coast from Gabicce - Conero to Maiella, and in the Upper Pliocene the Conero offshore. The duration of the compressional phase was about 5 Ma, between the Late Tortonian in the inner areas (Gubbio - M. Vicino) and the end of the Early Pleistocene in the Marche offshore.

According to Bally's et al. (1986) data, the structured Umbria Marche belt overthrusted the Messinian foredeep; on this basis the main thrust fold belt building developed from Tortonian to the Upper Messinian. Subsequently, in the Lower Pliocene, it overthrust its own foredeep out of sequence and developed more external structures.

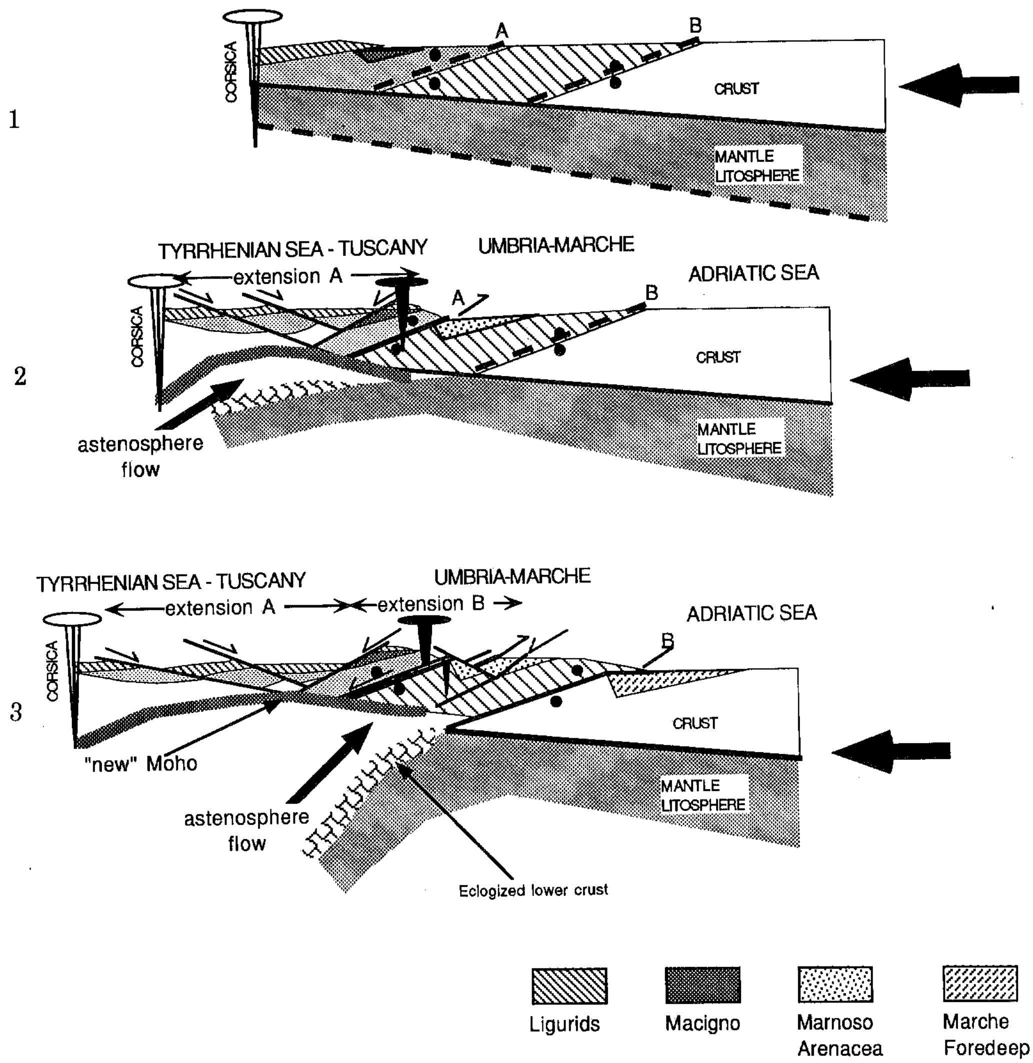

Fig. 3 — Diagram showing the evolution of foreland basins in the Northern Apennines. In 1 (end of Oligocene) the Macigno basin, including the Trasimeno unit, formed beside the l.s. ligurid prism, begins to be overthrust by the prism itself, and accreted in the orogenic wedge. 'A' refers to the future crustal thrust responsible for the formation of the Marnoso-Arenacea basin, and 'B' to the one that will form the Marchean foredeep. In 2 (Serravallian - Late Tortonian) the M-A basin is subject to overthrusting by the Tuscan units which transport the L.s. Ligurids piggy back. Extension, since the Middle Miocene in the Corsica basin, reaches western Tuscany and dismembers the Elba-Monticiano-Roccastrada metamorphic complex. Adriatic lithosphere goes on rolling back so allowing asthenosphere to intrude. In 3 (end of Lower Pliocene) crustal thrust B, which began during Messinian times and formed the Marchean foredeep, propagates up-section, so permitting the Umbria-Marche cover to overthrust this latter basin. In the rear, extension propagated to central Tuscany forming the Pliocene marine basins. At the same time Adriatic litosphere went on rolling back enlarging the area of extension and permitting a further intrusion of the asthenosphere that lead to the formation of a 'new Moho'.

Thrust stack

The crustal stack responsible for the formation of the Messinian -Pliocene Marchean foredeep is envisaged in the area of the present Tiber valley, where doubling of the Moho is documented by seismic refraction (Alfano et al., 1982; Wigger, 1984; Minelli et al., 1991) and gravimetric data (Cassinis et al., 1991). Such a doubling is therefore in sequence with respect to that in western Tuscany assumed responsible for the formation of the Marnoso Arenacea foredeep. In its eastward propagation, the relative thrust system cuts and refolds the previously formed Umbria Marche Apenninic structures.

Peripheral bulge

The present day peripheral bulge of the Marche foredeep could be located approximately 60 km east of the Adriatic coast line, and corresponds roughly to a drowned carbonate platform.

EXTENSIONAL TECTONICS

Since the Late Tortonian, western Tuscany has undergone an extensional tectonic phase which has given rise to several grabens where lacustrine and marine sediments deposited unconformably on top of pre-existing rocks. On Elba the extension was approximately coeval, since normal faults cut porphyric dykes whose emplacement predates (Trevisan, 1950) the granitic stock of M. Capanne (6.2 Ma, Serri et al., 1991). The granite itself displays several extensional shear zones of ductile regime suggesting they occurred in the final phase of crystallization (Boccaletti et al., 1987). According to Serri et al. (1991) and Bartole et al. (1991) in Corsica the extension started earlier than in Elba, since the Sisco lamproite (13.5-15.5 Ma) is relatable to deep seated magmas rising in a stretching regime.

In the Northern Tyrrhenian sea, seismic data (Bartole et al., 1991) evidence a pre-Messinian rifting sequence, suggesting a Middle Miocene age for the beginning of the rifting phase. Carmignani and Kligfield (1990) have shown that in the Apuane Alps the extensional phase started at about 12 Ma and went on until the Pliocene. On mainland Tuscany, a system of NNW-SSE elongated lacustrine marine basins began to develop during the Early Pliocene and reached their maximum width in the Middle Pliocene. Later on, during the Late Pliocene, the region underwent a general uplift that caused regression and subaerial erosion (Bartolini et al., 1982). In eastern Tuscany and Umbria, extension started later, during the Middle - Late Pliocene and was responsible for the origin of the lacustrine grabens of the Arno-Chiana Valleys, of the Mugello-Casentino-Tiber Valley and of Gubbio. During the Pleistocene, a subsequent uplift led the sedimentary infillings to high elevations. As is documented by focal solutions of earthquakes, which are transtensive in character (Gasparini et al., 1985) with T-axes oriented WSW-ENE, the present extensional front is now in the Umbria-Marche Apennines.

On the basis of these observations, it is evident that, like the compressional phases, the extension migrated from west to east. In particular, a very close time relationship between the compressive phenomena, that piloted the development of the Umbria Marche fold belt and the Marche foredeep in Messinian-Pliocene times, and the extensional phase in Tuscany is evident.

From the geophysical point of view, according to Alfano et al. (1982) seismic refraction experiments evidence from Elba to Perugia an almost constant crustal thickness of 20-25 km and, from Perugia to the Adriatic sea, a thickness of 30-35 km.

This data have been used to evaluate the extension of the crust after the compression, but there are several discrepancies to note:

1 - the heat flow measurements evidence very high values in western Tuscany (M. Amiata, Larderello) rapidly decreasing toward the east (Mongelli e Zito, 1991).

2 - in Elba and the western Tuscany region, very low angle extensional faults that are not so evident in the more eastern areas were mapped.

3 - according to Bertini et al. (1991) the extensional phase affected western Tuscany with a first event in the Tortonian that was followed by another post-Tortonian extensional phase.

The extension related to the first event is about 60% and to the second about 7% (Bertini et al., 1991). The implication of these evolutions is that, taking into account the actual depth of the Moho, the original crustal thickness should be about 50 km.

Such a crustal root is not so easy to explain for a region submerged from the Tortonian to Middle Pliocene.

4 - from the Tyrrhenian Sea to central Umbria, the postorogenic basins are progressively less developed, but the depth of the Moho all along the section is constantly around 25 km.

On the basis of these considerations, in our opinion, the Moho evidenced in the DSS experiments (Alfano et al., 1982; Wigger, 1984) could be a 'new' Moho due to asthenosphere uplift with metasomatization of part of the continental crust (Lavecchia e Stoppa, 1989; Serri et al., 1991); in fact, as proposed by Rosendhal et al. (1992), the Moho may have relatively little paleo-structual memory (no more then 10 Ma in this particular case) and may be able to restore itself to some new equilibrium position after the extension.

CONCLUSIONS

What tectonic model can fit as many as possible of the geological and geophysical observations in the Northern Apennines, and explain the extensional tectonics associated with a convergent boundary scenarios?.

It is generally agreed that the foredeep reflects a thrust zone that dips gently toward the hinterland sector of an orogen. In this particular case, such a thrust zone could be interpreted in two main ways:

1 - B-subduction zone with a back-arc basin (Tyrrhenian Sea) (Malinverno and Ryan, 1986)

2 - prograding suture in a colliding continental margin (Roeder, 1990; Carmignani et al., 1980).

The first model is attractive because it explains the contemporaneous shortening and extension on the eastern and western sides of the Northern Apennines since the Late Miocene.

The second model is basically an outward growth of the collisional orogen by development of new compressive faults or reactivation of previous extensional shear zones in the continental margin. Progradation is accompanied by topographic uplift and folding of the original suture zone, and by outward migration of the peripheral bulge. Typical of this model is also an elastically flexed foreland lithosphere and metamorphism in the lower plate. In both cases, splay thrusts episodically ramp up off the sole thrust as it propagates. At intervals, this intracontinental sole thrust would ramp up to the surface, thus transferring a large body of Italian continental crust and cover sediments from the lower to the upper thrust plate. The evolution of the prograding suture could be strongly influenced by the extensional tectonic features related to the evolution of the Thetian passive margin.

The principal features of the Northern Apennines tectonic scenario, and the scale at which they occur, support the validity of the prograding suture model as the result of a major thrust faulting, which affected levels deep in a previously thinned continental margin.

In this model, on the basis of the available data, two main thrust and fold belts, the Elba-Monticiano - Roccastrada and the Umbria - Marches Apennines, are definable, each of them relatable to major crustal thrusts.

The prograding suture model, together with other considerations, could explain well the thrusting on the Adriatic side of the Peninsula, and the extension on the Tyrrhenian side, proceeding from west to east simultaneously from the Middle-Late Miocene to the present. In fact, the progressive shortening of the Adria paleo-margin generated tectonic building which reached an unstable configuration because it consisted of an 'overthickened' and therefore less resistent crust (Galzner and Bartley, 1985). This led to instability of the system and caused extension and thus formation of normal fault systems from the Middle-Late Miocene to the Late Pliocene. Such normal fault systems stretched and thinned the previously shortened crust and allowed an uplift of asthenosphere to commence. During this process the Moho restored itself to a more stable position with respect to the new boundary conditions (Roshendal et al., 1992). The extension developed only after the Middle -Late Miocene both because the total thickness of the stacked crust was not enough to generate the instability, and because the elapsed time was not enough to add the appropriate strength reduction in the stacked crust. The first was because the westernmost sector of the Adria continental margin was thinner than the Umbria Marche sector.

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