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TERTIARY COMPRESSION AND EXTENSION IN THE SARDINIAN BASEMENT

Abstract. This study describes the Tertiary tectonics of Sardinia and its possible relationships to coeval tectonics in Corsica and to continental collision in the Northern Apennines. The most important Tertiary compressive features of Sardinia are the positive flower structures associated with sinistral transpressive faults that control the location of thrusting of the Paleozoic basement on the Mesozoic and Tertiary cover. The distribution of the deformation and the direction of shortening indicate that this transpression was associated with the collision between the Iberian plate continental margin and the Apulian continental margin. Emplacement of Corsican "Alpine" continental units and the transcurrent tectonics of NE Sardinia occurred after post-Middle Eocene clastic sedimentation and before the deposition of Burdigalian-Langhian neritic formations. Transpressive tectonics of NE Sardinia and of SW Corsica probably developed during the Oligocene-Aquitanian in the hinterland of the Northern Apennines during the ensialic evolution of this chain. During the Early-Middle Miocene, tectonic inversion from compression to extension lead to a) the formation of the Sardinian rift; b) the exhumation of middle-crustal levels of the metamorphic core complexes of "Alpine" Corsica and Alpi Apuane and the development of the "serie ridotta" of Southern Tuscany; c) the transgression of Lower-Middle Miocene marine deposits over the Northern Apennines chain, over Sardinia and Corsica, in the Northern Tyrrhenian and in the Balearic basins. Extension continued during the Late Miocene and Pliocene-Pleistocene with the development, in SW Sardinia, of the Campidano graben and, on the eastern side of the island, with the opening of the Southern Tyrrhenian basin. This last extensional phase is contemporaneous with the NE-migration of the Northern Apennines thrust belt-foredeep-foreland system. If the age of the initiation of post-collisional extension in "Alpine" Corsica and in Tuscany is indeed Early Miocene, it is likely that drifting of the Corsica-Sardinia block was contemporaneous with post-collisional extension of the Northern Apennines and not with the collisional tectonics of this chain as has been often accepted.

INTRODUCTION

The Corsica-Sardinia Hercynian basement is bounded by three margins (Fig. 1):

1) a collisional margin with accretion of oceanic crust beginning in the Late Cretaceous (Boccaletti et al., 1971; Dercourt et al., 1986); and extension beginning, according to some, in the Oligocene (Jolivet et al., 1990; 1991) and according to others in the Early Miocene (Egal, 1992);

2) a passive margin with rifting in the Late Oligocene and drifting in the Burdigalian, associated with the opening of the Balearic Basin and rotation of the Corsica-Sardinia block, according to Cherchi and Montadert (1982, 1984), Bellon et al. (1977), Rehault (1981), Fanucci e Nicolich (1984), Burrus (1984), Gennesseaux et al. (1989);

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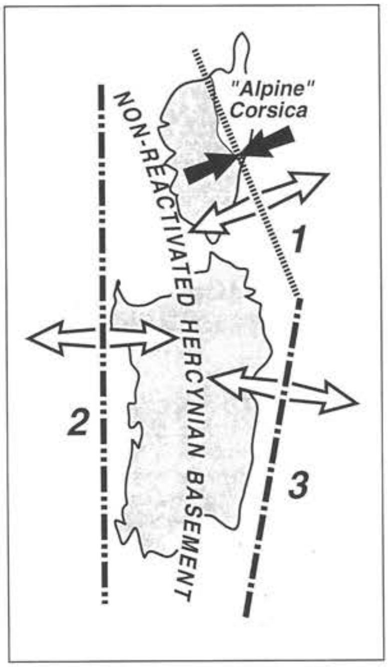

Fig. 1 — Margins of the Corsica-Sardinia block. 1: convergent margin from Late Cretaceous to Aquitanian, and extensional from Burdigalian; it corresponds to the boundary between the non-reactivated Hercynian basement of the Corsica-Sardinia block and reactivated basement of "Alpine" Corsica and Northern Apennines; 2: passive Balearic margin (Burdigalian drifting); 3: passive Late Miocene-Pliocene margin of the Southern Tyrrhenian Sea. Black arrows: convergent margin; open arrows: extensional margin.

3) a passive Late Miocene-Pliocene margin associated with the opening of the Southern Tyrrhenian Sea (Sartori, 1989).

There are various hypotheses on the relationships between the Corsica-Sardinia block, and the Alpine and Apennine chains. Simplifying, we can distinguish two fundamental models:

- the first, arising from initial interpretations of Alpine nappes, considers "Alpine" Corsica as the continuation of the western Alps. Only later would the Corsica-Sardinia block have acted as the hinterland of the Apenninic chain. Hercynian Corsica would have been, therefore, the Alpine foreland and Apennine hinterland (see Boccaletti et al., 1971; Mattauer et Proust, 1976; Mattauer et al., 1981; Durand-Delga, 1984; Gibbons et al., 1986; for a summary of classical interpretations);

- the second (Treves, 1984; Principi e Treves, 1984), interprets the "Alpine" Corsica-Northern Apennines system as an accretionary wedge (Cowan and Silling, 1978; Cloos, 1982; Pavlis and Bruhn, 1983) produced by subduction under the Corsica-Sardinia block in which the units developed vergence toward both Corsica and Tuscany (Fig. 2).

The Corsica-Sardinia block has been situated, at different times, in proximity to different orogenic belts (Pyrenees, Apennines and (?) Alps) and at the opening margins of two oceanic areas (Balearic Basin and Southern Tyrrhenian Sea) (Fig. 3). The Tertiary story of this block, positioned at the intersection of major geodynamic events of the Western Mediterranean, is important for understanding the drastic changes in this area over the past 30 million years.

In this brief note, we limit ourselves to defining the essential characteristics of the post-Hercynian evolution of Sardinia, in particular of the Tertiary tectonics of NE Sardinia, and of its probable relationship to the "Alpine" Corsica and Northern Apennines collision. This possibility, rather neglected by both Apennines geologists and those of the Corsica-Sardinia-Provençal regions, seems interesting for those involved with the CROP-MARE project who work

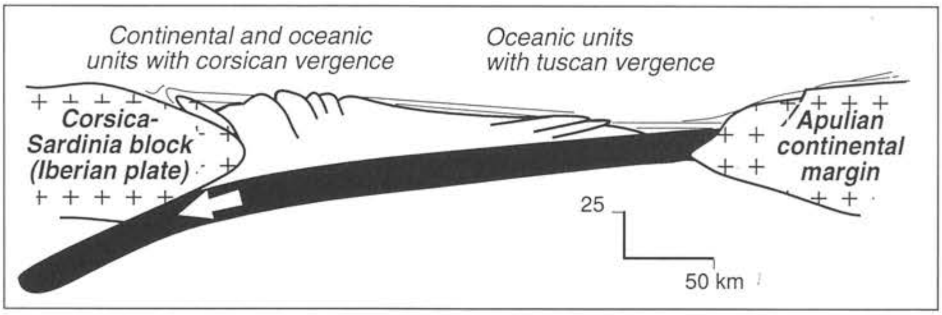

Fig. 2 — Sketch of the Northern Apennines accretionary wedge before collision between the Corsica-Sardinia block (Iberian plate) and Apulia block (after Principi e Treves, 1984, modified).

on the history of the Tyrrhenian Sea.

OUTLINE OF THE POST-HERCYNIAN SUCCESSION

The post-Hercynian succession in Sardinia, at least 6000 m thick, is composed of various sedimentary cycles separated by unconformities correlating with Alpine and Pyrenean-Provençal tectonic phases, with extensional phases of the Miocene Balearic Basin and Pliocene Southern Tyrrhenian Sea evolution (Cherchi and Montadert, 1982; 1984; Cherchi et Trémolières, 1984) and, lastly, according to the hypotheses presented here, with the orogenesis of the Northern Apennines.

Regarding the principal geodynamic events affecting Sardinia between the Triassic and Quaternary, the post-Hercynian succession of Sardinia can be divided into four principal successions.

Succession connected with the evolution of the southern European continental margin

This succession crops out prevalently in Sardinia in the E, NW (Nurra) and, locally, SW (Figs. 4-5). It includes Permo-Triassic sediments that are transgressive on the peneplaned Hercynian chain and the southern European passive continental margin succession associated with the opening of the Ligurian-Piedmont oceanic *hiatus* during the Middle Jurassic (Cherchi, 1985; Carmignani et al., 1989 with bibliography). The transgression initiated in the Middle Triassic and involved the most western part of the island. Only in the Middle Jurassic was Sardinia extensively transgressed by a carbonate platform. This was probably the only period of complete transgression over Sardinia since the Paleozoic.

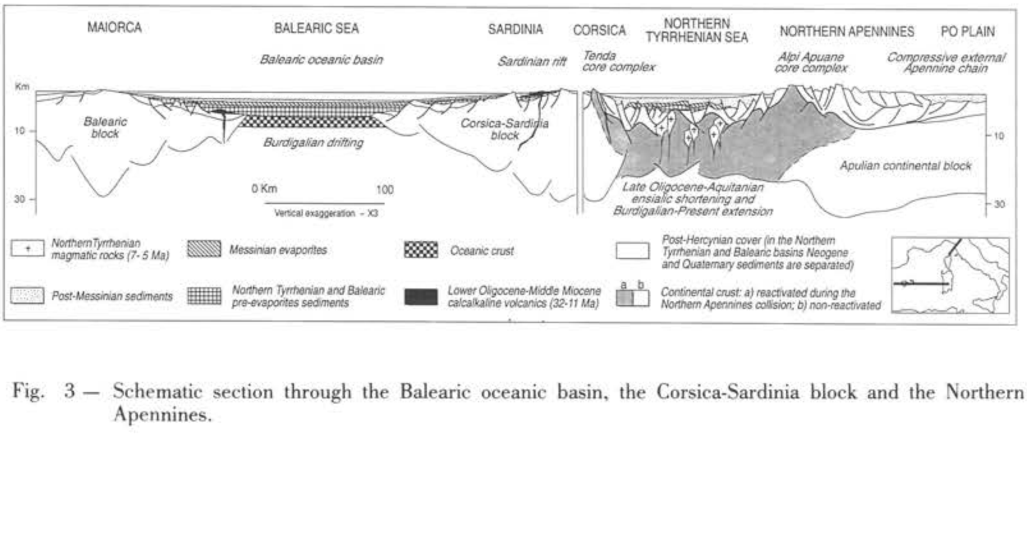

Fig. 3 — Schematic section through the Balearic oceanic basin, the Corsica-Sardinia block and the Northern Apennines.

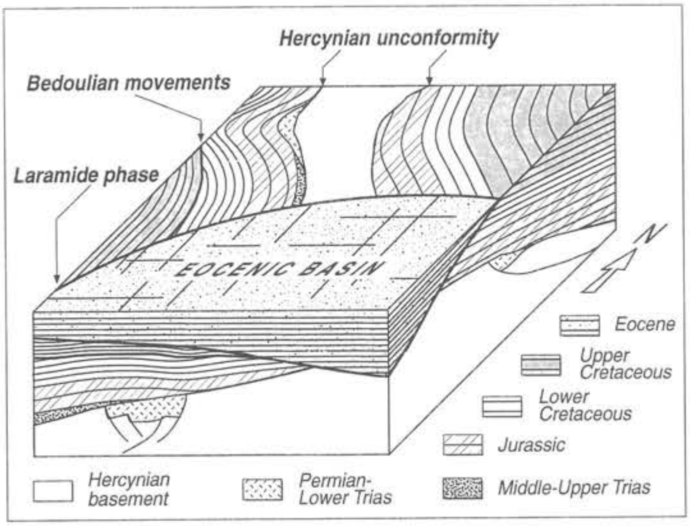

Fig. 4 — Sketch of the post-Hercynian Sardinian succession before the separation of Sardinia from the Iberian plate.

Throughout the long period from the Mesozoic to the Middle Eocene, Sardinia was characterized by coastal and shallow marine deposits. Unconformities between the Lower and Upper Cretaceous (Austrian phase, Cherchi et Trémolières, 1984; Bedoulian movements, Oggiano et al., 1987) and between the Upper Cretaceous and Eocene (Laramide phase, Cherchi et Trémolières, 1984) are not related to important tectonic structures even though the Eocene deposits transgress all underlying successions to the Paleozoic basement (Fig. 4).

Successions connected with the (?) Middle Eocene-Aquitanian compression phase

This complex is composed of sedimentary and volcanic units of between Middle Eocene-Upper Oligocene age (Fig. 6). Locally the Aquitanian is also documented. For Sardinia, the Middle Eocene marked the initiation of a period of great tectonic instability including important phases of shortening (transpression in NE Sardinia, Carmignani et al., 1992). These caused a strong uplift, evidenced by the deposition of the prevalently continental clastic deposits known as the Cixerri Formation, the Cuccuru 'e Flores Conglomerate and the Ussana Formation, with the following characteristics:

- The Cixerri Formation is composed of approximately 300 meters of prevalently fluvial sediments. It crops out exclusively in SW Sardinia (Fig. 5) and rests discordantly on underlying Paleozoic, locally Mesozoic through basal Lutetian formations (Pecorini e Pomesano Cherchi, 1969). The base contains lacustrine carbonates, which include Middle Eocene pollens (Pittau Demelia, 1979); moreover this formation is cut by Oligocene (29.9 ± 1.5 Ma; Bellon et al., 1977; Savelli et al., 1979) andesites. Such data indicate deposition before the opening of the Balearic Basin. Also, paleocurrent directions (Barca e Palmerini, 1973) and microfauna within clasts indicate a Pyrenean source area (Cherchi et Schroeder, 1976; Cherchi, 1979).

- The Cuccuru 'e Flores Conglomerate crops out discontinuosly along transpressive faults in NE Sardinia. It consists of polygenic breccias and conglomerates with clasts from Paleozoic basement and Jurassic-Middle Eocene sedimentary cover (Dieni and Massari, 1966; 1985). These deposits lie unconformably on the Paleozoic basement and on the Jurassic-Cretaceous cover, but their age is uncertain. Chabrier (1970) attributed this formation to the Upper Cretaceous. However, the deposits contain reworked Cuisan-Early Lutetian faunas (Dieni and Massari, 1985; Busulini et al., 1987) and Paleocene clasts (Dieni et al., 1987). According to these authors, the age of the conglomerates is post-Lutetian. We relate these deposits to a Late Eocene or, more probably, to an Oligocene tectonic event.

- The Ussana Formation reaches a maximum thickness of 500 meters, crops out along the

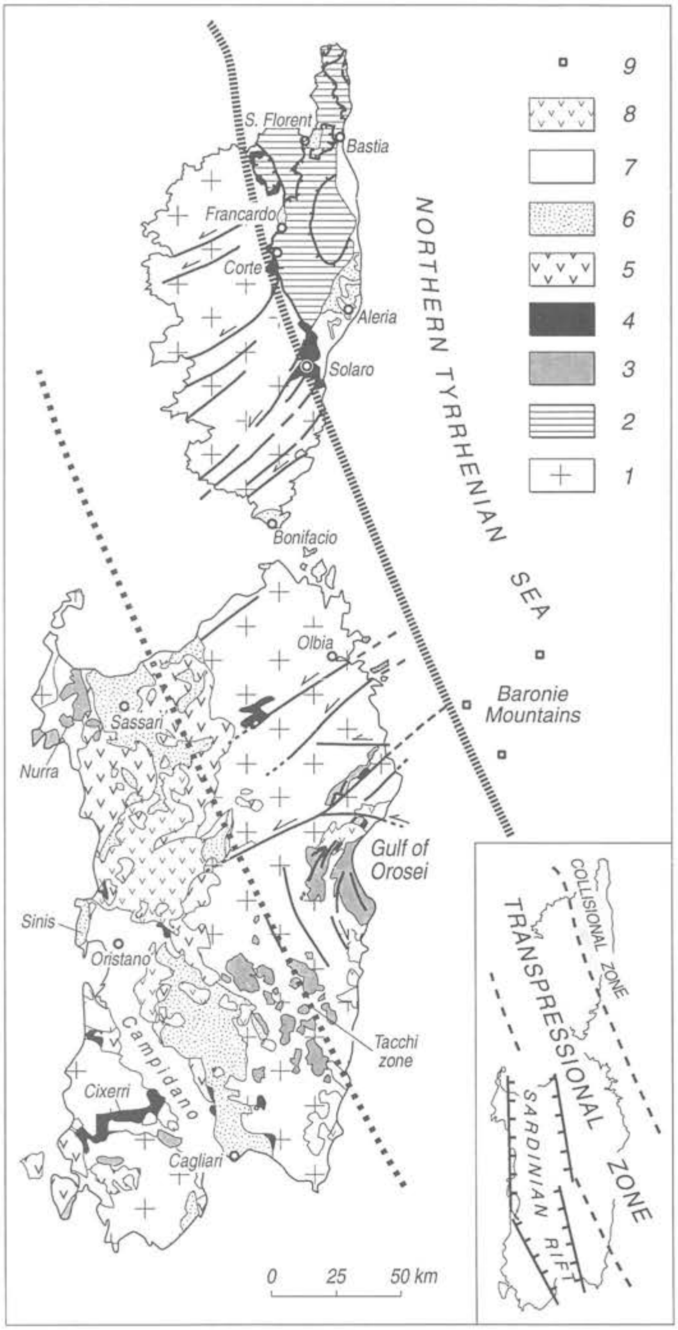

Fig. 5 — Geological sketch-map of the Corsica-Sardinia block. 1. Paleozoic basement. 2. "Alpine" Corsica units (Paleozoic-Eocene). 3. Permian-Eocene cover of Corsica and Sardinia basement. 4. Middle Eocene-Aquitanian conglomerates. 5. Calcalkaline volcanics (32-11 Ma). 6. Miocene deposits of Sardinia and Corsica. 7. Pliocene-Quaternary deposits. 8. Alkaline basalts (5,3-0,14 Ma). 9. Marine coring and dredging points from Wezel et al. (1977).

NE margin of the Campidano (Fig. 5) and consists of alluvial or slope deposits. According to Cherchi and Montadert (1982; 1984) the age of this formation is Chattian-Aquitanian. These continental deposits are interbedded with Upper Oligocene calcalkaline volcanics (Coulon et Dupuy, 1975). Locally they pass to transitional and marine Aquitanian sediments.

Succession connected with the Early-Middle Miocene extension phase

During the Burdigalian developed in W Sardinia a rifting stage (Thomas and Gennesseaux, 1986) (Fig. 5). The Sardinian rift succession has a thickness of a thousand meters and is represented by marine deposits of Lower-Middle Miocene age with interbedded calcalkaline volcanics (Fig. 6). According to Beccaluva et al. (1985) calcalkaline volcanism develops between 32 Ma and 11 Ma (Early Oligocene-Serravallian) but most of the volcanics are emplaced between 25 Ma and 17 Ma (Late Oligocene-Late Burdigalian).

The youngest formation of this rift succession is the Logudoro Marls cropping out in N Sardinia. This formation is composed principally of marls and marly limestones and is referred to the Langhian (Mazzei e Oggiano, 1990).

Succession connected with the Late Miocene-Pleistocene extension phase

The Logudoro Marls is unconformably overlain by a siliciclastic carbonate Upper Tortonian-Lower Messinian succession (Mazzei e Oggiano, 1990; Martini et al., 1992).

According to Cherchi (1973) in the Orosei and Sinis areas (respectively E and W Sardinia, Fig. 5), the transgression on the Miocene sequences could be dated back to Early Pliocene.

The extensional tectonics of this stage are evidenced also by the alkaline volcanic activity (basalts cropping out in the Orosei and W Sardinia regions, Fig. 5) correlatable with the opening of the Southern Tyrrhenian Sea. The volcanic activity began at 5.3 Ma and continued until 0.14 Ma (Beccaluva et al., 1985).

The Pliocene extension resulted in the development of the NW-trending Campidano graben (Fig. 5) which cuts the preexisting Sardinian rift and is filled with approximately 600 m of Pliocene-Quaternary continental deposits (Samassi Formation, Pecorini & Pomesano-Cherchi, 1969).

TERTIARY TECTONIC SETTING

The Tertiary tectonics of the Corsica-Sardinia block are correlated with the evolution of the three margins shown in Fig. 1.

Transpressive tectonics

The basement near the collisional margin of "Alpine" Corsica (NE Sardinia and Corsica Hercynian basement) is characterized by transcurrent faults (Chabrier et Chorowicz, 1982) that are almost always associated with a compressional component (Carmignani et al., 1992) (Fig. 5).

Specifically, in Sardinia north of the Gulf of Orosei, there are two transpressive fault systems (Fig. 7): the most important trends NE (Nuoro, Tavolara and Olbia faults) and is also well developed in the Corsica Hercynian basement (Fig. 5). The second system trends E-W (Cedrino and Posada faults) and seems to follow preexisting late Hercynian basement discontinuities (for example the "Posada Line"; Elter, 1985; 1987).

The sinistral motion of these fault systems is evidenced by numerous kinematic indicators. Fig. 8 shows an example of the situation corresponding to a synthetic fault related to the Nuoro Fault, along the SE flank of Mount Albo (Carmignani et al., 1992): here, on the western side, the Cuccuru 'e Flores Conglomerate uncomformably overlies a Jurassic limestone (Mount Bardia Limestone), while in the east, it is tectonically covered by a slice of the same Jurassic limestone. Kinematic indicators, such as the relationship between the main tectonic contact (steeply dipping to the SE) and the asymmetric shape of deformed clasts in the cataclastic Cuccuru 'e Flores

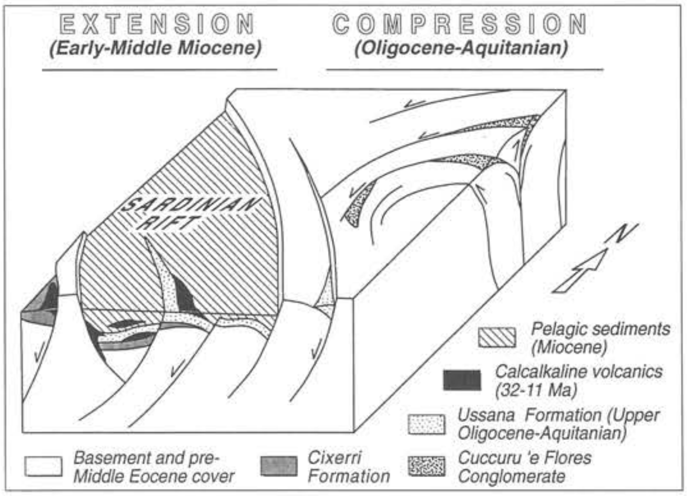

Fig. 6 — Sketch of the volcanic-sedimentary complex related to the Northern Apennines collision and to the opening of the Balearic Basin and the Sardinian rift.

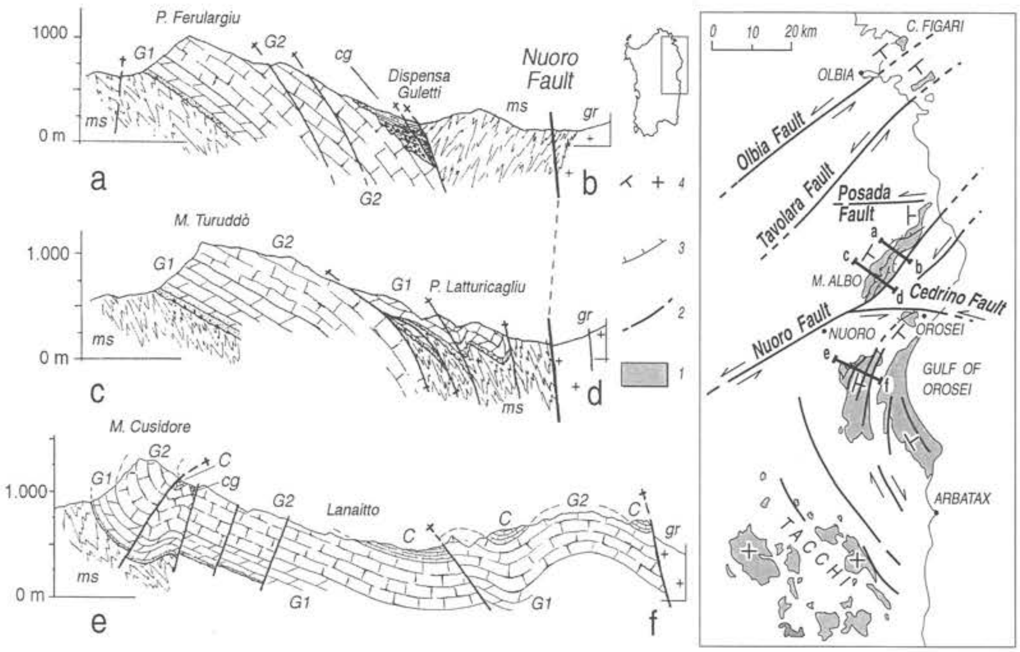

Fig. 7 — Sketch of the transpressional tectonics of NE Sardinia. 1. Mesozoic deposits. 2. Transpressive faults. 3. Overthrusts. 4. Bedding strike and dip; horizontal beds. Geological sections: ms: phyllite, micaschist and paragneiss (Paleozoic); gr: granite (Paleozoic); G1: Dorgali Dolostone (Bathonian-Late Kimmeridgian); G2: Mount Bardia Limestone (Portlandian-Berriasian); C: limestone to cherty-limestone and marl (Cretaceous); cg: Cuccuru'e Flores Conglomerate (post-Middle Eocene).

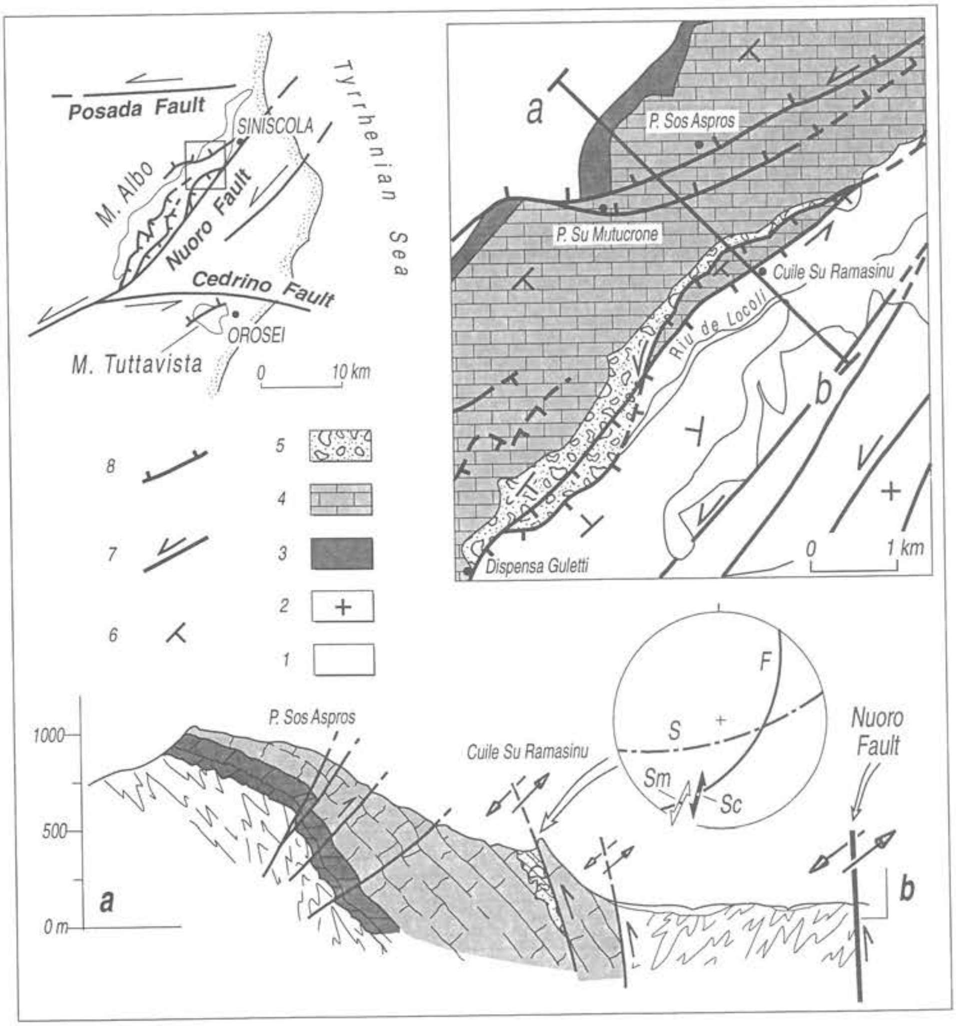

Fig. 8 — Tectonic sketch-map of central Mount Albo area (NE Sardinia). 1. phyllite, micaschist and paragneis (Paleozoic). 2. granite (Paleozoic). 3. Dorgali Dolostone (Bathonian-Late Kimmeridgian). 4. Mount Bardia Limestone (Portlandian-Berriasian). 5. Cuccuru 'e Flores Conglomerate (post-Middle Eocene). 6. Bedding strike and dip. 7. Transcurrent faults. 8. Transpressive faults. Geological sections: F: fault plane; S: flattening plane; Sm: measured striae; Sc: calculated striae; the data indicate left-lateral strike-slip movement with a minor reverse component; Wulff projection, lower hemisphere.

Conglomerate, suggest a dominant left-lateral strike-slip movement with a minor reverse component. Moreover the aereomagnetic map of N Sardinia and S Corsica (Galdeano et Rossignol, 1977; Cassano et al., 1979) shows that important positive anomalies are affected by a left-lateral offset (Fig. 9).

These transpressive tectonics are characterized by typical "flower structures" *sensu* Lowell (1972) (Carmignani et al., 1992) with doubling of the Mesozoic sequences and local thrusting of the Paleozoic basement over the Mesozoic and Tertiary cover (Chabrier, 1970; Dieni e Massari, 1970; Alvarez and Cocozza, 1974). The two fault systems (NE and E-W systems) therefore produce two west-tapered wedges as represented in Fig. 10.

To the south of Nuoro (Fig. 7), the transcurrent faults gradually change direction, first toward the S and then toward the SE ("Gulf of Orosei Fault System"), these latter showing dextral offset. Structures associated with these include *en echelon* folds and thrusts that involve the

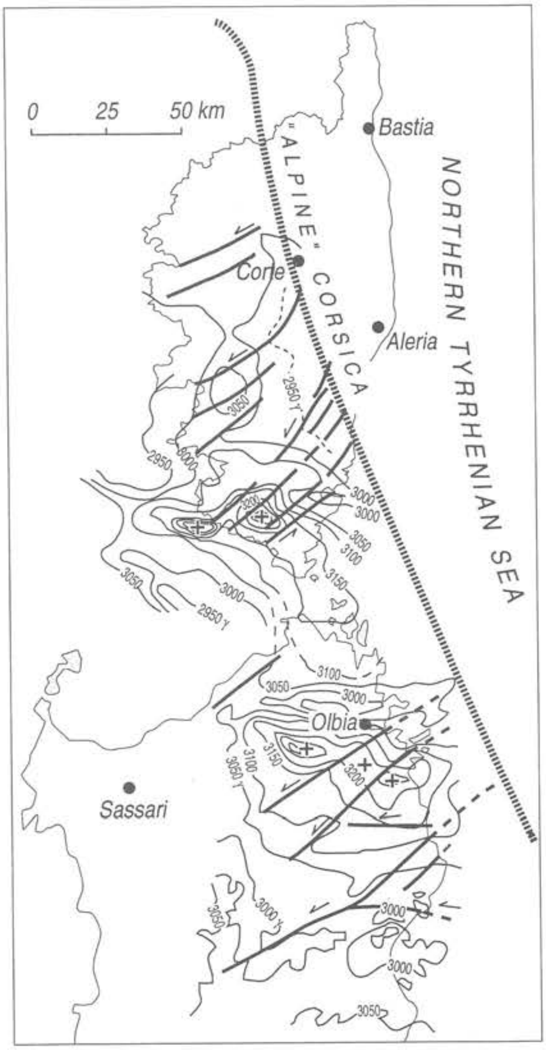

Fig. 9 — Main faults and aeromagnetic map of NE Sardinia and SW Corsica (after Galdeano et Rossignol, 1977; Cassano et al., 1979; modified).

Cuccuru 'e Flores Conglomerate. Farther south, deformation dies out in the tabular Mesozoic of the Tacchi zone (Figs. 5-7).

These transpressive tectonics are related to the most important compressive phase that involved Sardinia after the Hercynian orogeny. Several authors have correlated these deformations with Eocene Pyrenean tectonics (Chabrier and Mascle, 1975, 1977; Cherchi e Montadert, 1984; Letouzey et al., 1982).

Chabrier (1970) assigned the Cuccuru 'e Flores Conglomerate, involved along some of the transpressive faults of NE Sardinia, to the Upper Cretaceous, but Dieni and Massari (1985) and Busulini et al. (1987) report Lower Lutetian nummulite limestone clasts in the same conglomerate. In the Orosei zone (Fig. 7), transcurrent faults cut limestones with Middle Cuisan macroforaminifera (Dieni et al., 1966; Matteucci and Schiavinotto, 1985), but they do not involve Lower Miocene (Burdigalian) deposits of the Sardinian rift (Fig. 5).

In summary, these data indicate that transpressive tectonics in NE Sardinia occurred between

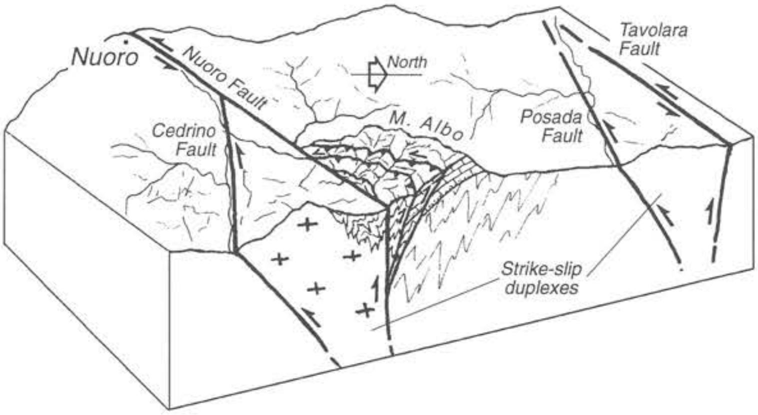

Fig. 10 — Schematic block-diagram of Mount Albo and surrounding areas; the two west-tapered wedges between the Nuoro and Cedrino faults, and the Tavolara and Posada faults can be ascribed to strike-slip duplexes (after Carmignani et al., 1992).

the Lutetian and Aquitanian. Research in progress shows that the deformation connected with the Nuoro and Olbia faults involve Oligocene volcanic rocks (Figs. 5-7). On this basis, the transpressive tectonics in NE Sardinia must be active between Oligocene and Aquitanian.

This age corresponds to continental collision in "Alpine" Corsica (Egal, 1992) and in the Northern Apennines (Carmignani and Kligfield, 1990) (Fig. 11) rather than to the acme of the Middle Eocene Pyrenean tectonic phase. In the Corsica-Sardinia block, the suture resulting from this collision crops out only in "Alpine" Corsica. On the basis of serpentinized ultramafic rocks dredged from the Tyrrhenian Sea along NE Sardinia (Baronie Mountains; Wezel et al., 1977) and of detrital glaucophane recognized in Maastrichtian arenaceous deposits of NE Sardinia (Dieni et Massari, 1982), its continuation has been postulated to stretch along the eastern coast of Sardinia (Wezel et al., 1977) (Fig. 5).

The correlation between transpressive tectonics of NE Sardinia and collisional tectonics of "Alpine" Corsica is suggested also by the kinematic framework delineated by the transpressive Corsica-Sardinia fault system and by the distribution of deformation in the Sardinia Hercynian basement, as shown by the following points:

1) The transpressive system shortening direction is consistent with the NE-directed shortening of the Corsican collisional margin (Fig. 11).

2) The decrease in deformational intensity from NE toward SW in Sardinia until its disappearance in the Tacchi zone (Figs. 5-7), where the Mesozoic formations are tabular, is consistent with the proposed position and development of the collisional front. Additionally, the curved trajectory of dextral transcurrent faults, trending SE in the S of the Gulf of Orosei (Fig. 7) suggests the escape of crustal material from the collisional area toward the SE where an oceanic domain may remain (Fig. 11). This is a transpressional tectonics framework of the hinterland of collisional belts: the most famous example is Tibet, cut by a transcurrent fault system synchronous with the Himalayan collision (Tapponnier and Molnar, 1977; Peltzer et al., 1982; Tapponnier et al., 1982).

In Corsica, according to Egal (1992), three principal deformational phases can be distinguished.

1) During the Late Cretaceous there was a stacking of ophiolitic nappes on the Corsican continental margin (obduction). This stacking is sutured by the Ypresian deposits (Amaudric du Chaffaut, 1973).

2) Between Late Eocene and Oligocene there was a phase of continental collision that thrust parts of the Corsican continental margin with relics of obducted oceanic crust onto Eocene deposits.

3) In the Early Miocene a phase of post-collisional tectonic extension began, although Jolivet

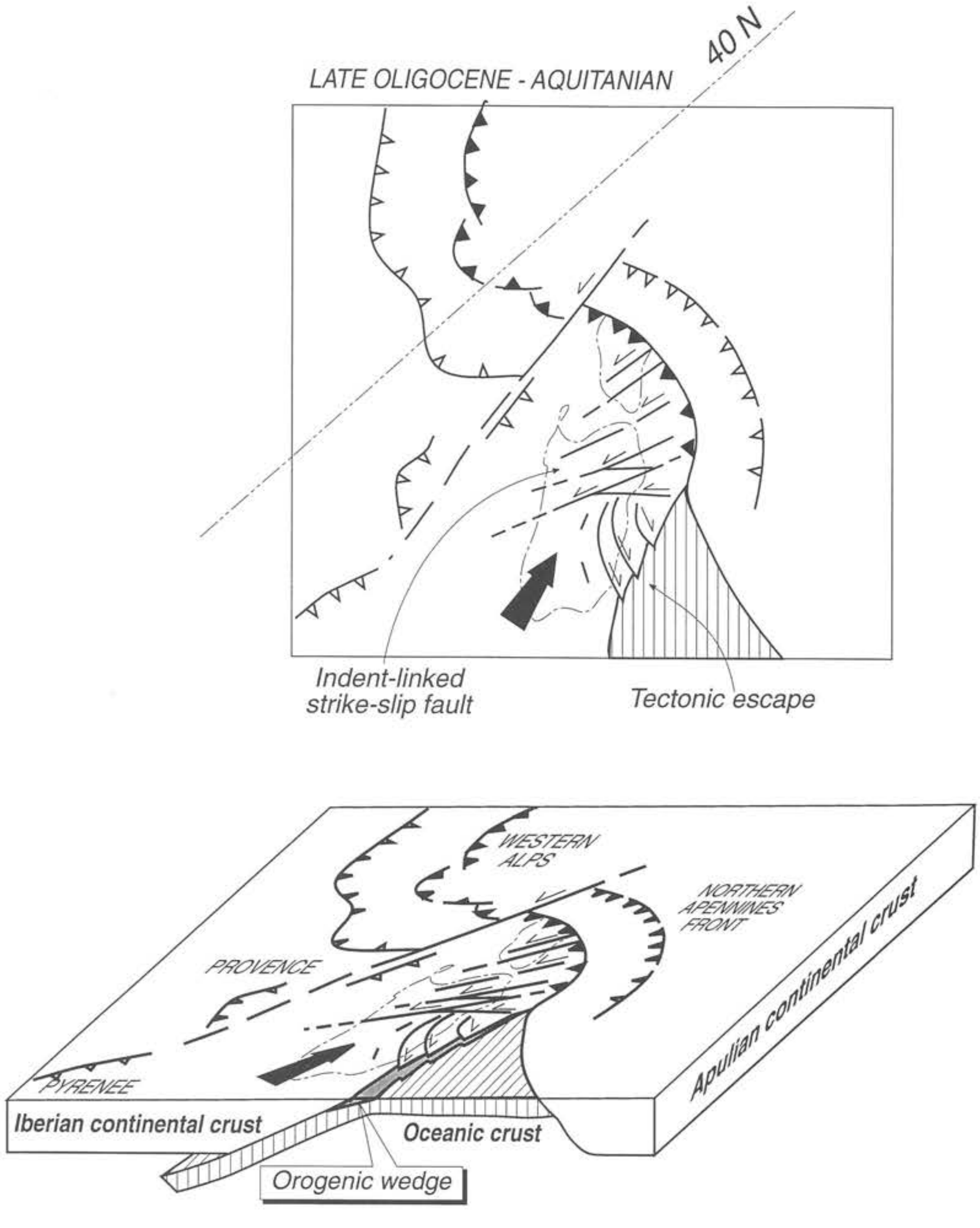

Fig. 11 — Sketch of the Late Oligocene-Aquitanian continental collision of the Northern Apennines.

et al. (1990, 1991) propose that this phase had already started by the Late Oligocene. In this phase all previous compressive structures were sutured with Burdigalian-Langhian transgressive sediments (S. Florent Limestone; Orszag-Sperber et Pilot, 1976).

The Eocene succession of Corsica, including the Ypresian "Calcari a nummuliti" of the "série de Solaro" (Amaudric du Chaffaut, 1973), correlates with those identified in the Orosei zone (Dieni et al., 1966). In Corsica, these limestones are overlain by a thick clastic deposit that contains pebbles of the same nummulite limestone, and Lutetian fauna that were probably reworked (Amaudric du Chaffaut, 1973) (Fig. 5). This coarse clastic deposit could correspond

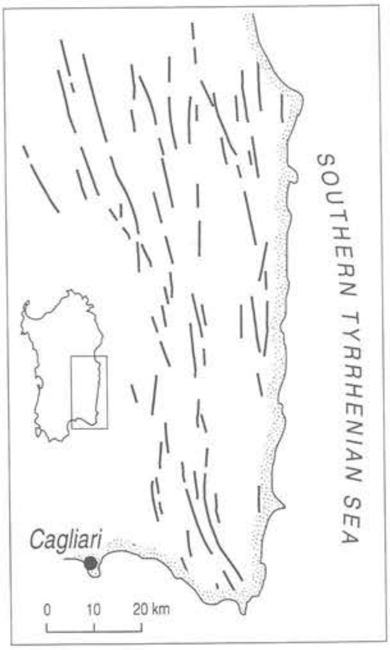

Fig. 12 — Pliocene-Quaternary extensional lineaments along the eastern margin of Sardinia, from Skylab images (after Sgavetti, 1982).

to the Cuccuru 'e Flores Conglomerate, which also contains clasts of Cuisan and Lutetian limestones. Moreover the Burdigalian deposits of NE Corsica, which suture Late Eocene-Oligocene compressive structures, correlate with those already described in Sardinia (Fig. 5). In particular, Burdigalian-Langhian shallow marine limestones and marls are discordant in NE Corsica on the collisional chain (S. Florent Basin and Francardo Basin; Orszag-Sperber et Pilot, 1976) and suture the transpressional structures of NE Sardinia.

In summary, transpressive tectonics in NE Sardinia and continental collision in Corsica occurred in the same time interval, with lower limits defined by the coarse post-Lutetian clastic deposits and upper limits by the Burdigalian transgressive deposits.

Extensional tectonics

In the Late Aquitanian-Early Burdigalian, in the western part of Sardinia, began an extensional phase that produced important tectonic trough (Sardinian rift, Cherchi and Montadert, 1982; 1984) (Fig. 5). The importance of this structure is shown by the more than 1000 m of Miocene sediments and by the associated calcalkaline volcanism. This extensional phase is coeval with the drifting of the Corsica-Sardinia block and the opening of the Balearic and Northern Tyrrhenian basins. Infact, the Burdigalian opening of the Balearic Basin is supported by:

- the age of the marine deposits known around the margins of the basin (W Corsica margin and Balearic area: Rehault et al., 1984; Provençal area: Mauffret et al., 1982; Gorini et al., 1993);

- the Burdigalian age of the tholeiites in the basin (Rehault et al., 1984);

- the paleomagnetic declination of the Sardinian post-Burdigalian calcalkaline volcanics (Montigny et al., 1981).

Moreover, the Burdigalian opening of the Northern Tyrrhenian Basin is supported by:

- the Burdigalian marine deposits cropping out in the Pianosa island (Dallan, 1964; 1967; Colantoni e Borsetti, 1973);

- a succession of more than 3-4,000 m of pre-evaporitic deposits revealed by seismic survey

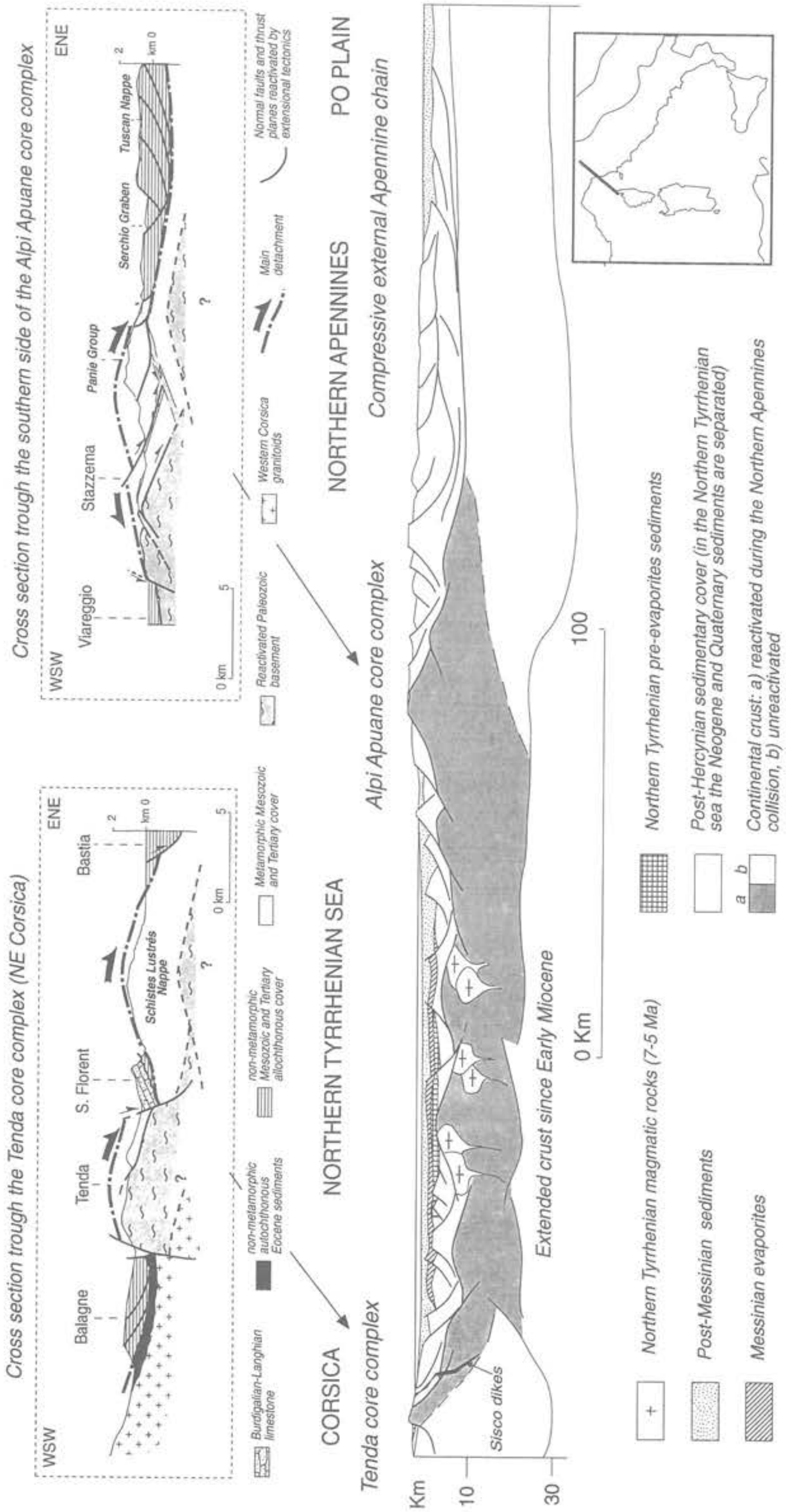

Fig. 13 — Schematic geological section from NE Corsica to the Northern Apennines foreland; note the Tenda core complex (after Jolivet et al., 1991, modified) and the Alpi Apuane core complex.

in the Corsica channel (Gabin, 1972); the presence of the Burdigalian in the Pianosa island and of marine Langhian-Messinian deposits (Orszag-Sperber et Pilot, 1976) in Aleria (Fig. 5), respectively eastern and western margin of the basin, suggests that deposits of this age may be present also in the same basin (Gabin, 1972).

A new Late Miocene-Pleistocene extensional phase associated with alkaline basaltic volcanism followed that previous Miocene extensional event and is generally associated with the opening of the Southern Tyrrhenian Sea. The main extensional structures of this last phase are the following:

- the Campidano graben that trends NW for more than 100 km between the Gulf of Cagliari and Gulf of Oristano (Fig. 5). According to Cherchi and Montadert (1982, 1984), the direction of this graben is probably inherited from the Sardinian rift structures. The formation of this graben occurred in the Middle Pliocene, but the subsidence was particularly fast in the Late Pliocene;

- the N-S oriented fault system that from central-eastern Sardinia (Fig. 12) connects the SE continental platform of the island with the abyssal plane of the Southern Tyrrhenian Sea.

CONCLUSIONS

In Sardinia several pre-Eocene deformational phases have been documented on the basis of angular unconformities and microstructural analyses (Cherchi et Trémolières, 1984), but post-Eocene tectonic evolution seems to be the most important, as evidenced by (a) major tectonic lineaments, (b) volcanism, and (c) large quantities of continental clastic deposits. In Sardinia this tectonic evolution involved post-Lutetian and pre-Burdigalian transpression, and a long period of extension separated into two distinct phases. The first extensional tectonic phase occurred during the Early-Middle Miocene, and is connected with the opening of the Balearic and the Northern Tyrrhenian basins; the second occurred between Late Miocene and the Pleistocene and is related to the opening of the Southern Tyrrhenian Sea. These events correlate with that of "Alpine" Corsica and of the Northern Apennines.

In Corsica, after (a) a compressional evolution related to subduction of the Ligurian oceanic lithosphere (Late Cretaceous-Middle Eocene) and to continental collision until Late Oligocene, there followed (b) an extensional evolution beginning in the Early Miocene (Egal, 1992) which caused the exhumation of crust thickened during the previous continental collision. In NE Corsica, the "Alpine" units exhumed by extension are unconformably covered by Burdigalian-Langhian shallow marine deposits in S. Florent and Francardo (Orszag-Sperber et Pilot, 1976).

In Northern Tuscany definitive dates on the beginning of post-collisional extension do not yet exist. The radiometric ages of closure of muscovites from the Tuscan metamorphic complex are between 27 Ma and 12 Ma (Giglia and Radicati di Brozolo, 1970; Kligfield et al., 1986; Keller and Pialli, 1990). If we interpret these ages as stages of exhumation or, for the oldest date, as the end of the collisional phase (Kligfield et al., 1986), they do not conflict with the idea of initiation of post-collisional extension at the Early Miocene. This possibility is in agreement with biostratigraphic data: there are Late Oligocene microfauna (Dallan Nardi, 1977) within the youngest unit ("Pseudomacigno" of the Alpi Apuane) involved in the Northern Apennines ensialic shear zone.

In Southern Tuscany the initiation of post-collisional extension has usually been placed in the Late Tortonian considering the age of the oldest deposits filling grabens in this area. Recent works show that the beginning of extension occurred much earlier (Bertini et al., 1991; Carmignani et al., 1993). In fact, the so-called "serie ridotta" auctt. of Southern Tuscany, in which the highest units in the nappe building (Ligurids) frequently overly deeper units (even the metamorphic substrate), is likely an effect of early extension characterized by low-angle normal faults that often reactivate preexisting thrusts (Lavecchia, 1988; Bertini et al., 1991). The high angle faults bounding late Miocene-Pliocene grabens systematically cut these low-angle faults, and Upper Tortonian deposits lie discordantly and transgressively on the "serie ridotta". The amount of extension needed to produce the "serie ridotta" is approximately 60%, while that produced by movement on high angle faults is around 10% (Bertini et al., 1991).

According to these data, the first extensional phase (pre-Late Tortonian extension) must have been the most important extensional event. So in Tuscany, in the Late Tortonian, the post-collisional extension was nearly completed. Moreover, assuming realistic strain rate values, the extension probably had initiated before the Tortonian, in the Middle or Early Miocene. In this hypothesis, the scattered outcrops of Middle-Late Miocene marine deposits lying over the allochthonous Ligurids of Southern Tuscany (Langhian "Arenarie di Manciano"; Giannini, 1957; Fontana, 1980; Serravallian-Lower Tortonian "Arenaria di Ponsano"; Mazzei et al., 1981), could represent the first transgressive deposits on the exhumed Northern Apennines chain.

Data on the initiation post-collisional extension in Tuscany are still uncertain; if it were confirmed that the initiation occurred contemporaneously with extension in Corsica, W Sardinia, Northern Tyrrhenian and Balearic basins, in the Early Miocene, it would follow that:

1) The effects of post-collisional tectonics are different depending on the characteristics of the crust inherited from earlier convergent and collisional phases (Fig. 3): in the zone of crustal thickening from continental collision (ensialic shear zones of "Alpine" Corsica and Tuscany), the inversion of tectonic regime from compressional to extensional caused the gravitational collapse of the Northern Apennines orogenic wedge, which provoked intrusive and effusive magmatism of the Northern Tyrrhenian Sea and of Tuscany. The metamorphic core complexes that developed are characterized by synmetamorphic, ductile extensional deformation and by normal fault zones (Fig. 13). Whereas, in the zone of unthickened crust, extension caused rifting (Sardinian rift and Balearic Basin).

The shortening that continued to involve the external zone of the Northern Apennines during the Miocene and Pliocene was synchronous with exhumation of the internal zone and involved only the Northern Apennines foreland cover.

2) The important transpressional tectonics of NE Sardinia and of Hercynian Corsica were synchronous with the ensialic shortening of the Northern Apennines and represent the main tectonic framework of the hinterland of this chain (Fig. 11).

3) The continental units of the Northern Apennines and "Alpine" Corsica were stacked before drifting of the Corsica-Sardinia block.

4) "Alpine" Corsica and the Northern Apennines were part of the same collisional zone (Fig. 11) as proposed by Treves (1984) and Principi and Treves (1984).

5) The opening of the Balearic Basin cannot be invoked as the cause of the Northern Apennines collision (Letouzey et al., 1982; Cherchi and Montadert, 1982; 1984) because it is synchronous with extension of the chain.

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