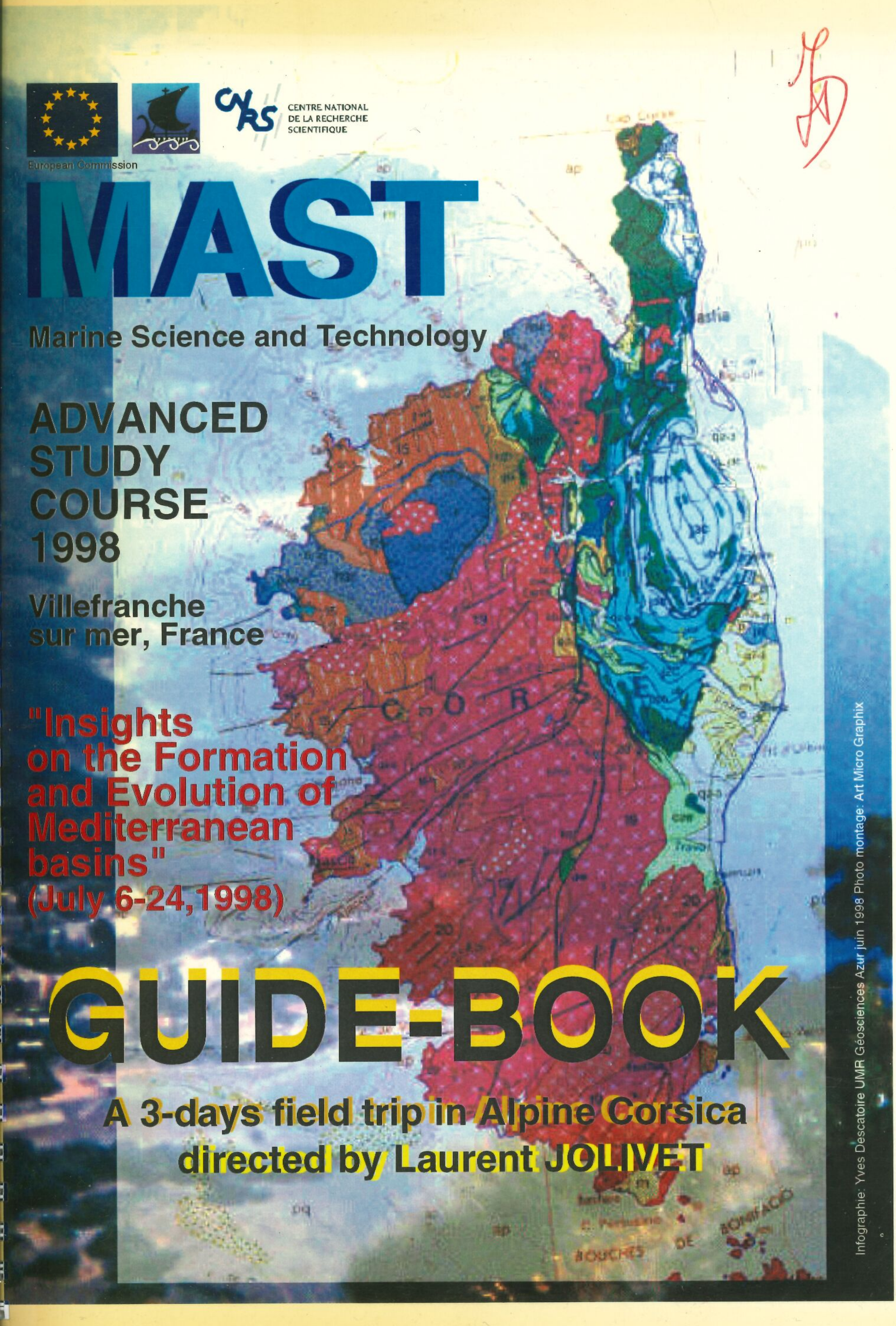

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GUIDE-BOOK

A 3-days field trip in Alpine Corsica

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A 3-days field trip in Alpine Corsica

Introduction, guide-book and selected bibliography

1. Introduction and geodynamic setting

During a 3-days trip in the northern part of Alpine Corsica we shall visit key-outcrops of a complicated structure which involves a first episode of crustal thickening from the Late Cretaceous to the Early Oligocene, and a second episode of crustal scale extension and basin formation from the Late Oligocene to recent times.

During many years Alpine Corsica was considered a piece of the Franco-Italian Alps rifted away from the European margin during the Oligocene without much internal deformation after the end of compression. The mountainous landscapes of Corsica are indeed often very similar to those of the Alps but one had forgotten one important aspect of the area: Corsica is an island. It turned out that most structures seen today in the field resulted from the extensional part of the tectonic history of Corsica. Nowadays extension is more precisely understood and the kinematics and dynamics of the early compressional stage is more enigmatic. There is still work to be done to unravel the crustal stacking episode and the associated HP-LT metamorphism.

The outcrops examined during this field-trip are distributed along an E-W transect from the autochtonous Eocene foreland basin in the west to the exhumed high-pressure and low-temperature metamorphics rocks in the east.

Before the description of the outcrops we present a general introduction which aims at placing the geology of Alpine Corsica in its geodynamic context. This introduction corresponds to the text and figures of a paper now in press:

Jolivet, L., Faccenna, C., Goffé, B., Mattei, M., Rossetti, F., Brunet, C., Storti, F., Funiciello, R., Cadet, J.P., d'Agostino, N. & Parra, T., Mid-crustal shear zones in postorogenic extension: the northern Tyrrhenian Sea case, J. Geophys. Res., in presse, JB96-0650, 1998.

1.1. Introduction

The geometry and kinematics of postorogenic extension have been the subject of many studies during the last two decades. Postorogenic extension has been documented in several regions, such as the Basin and Range of the western United States, the Aegean Sea [*Wernicke*, 1981; *Coney and Harms*, 1984; *Lister et al.*, 1984; *Lister and Davis*, 1989; *Wernicke*, 1992; *Malavieille*, 1993; *Gautier and Brun*, 1994b], the Massif Central [*Malavieille*, 1993; *Brun and Van Den Driessche*, 1994] and the Norwegian Caledonides [*Séranne and Séguret*, 1987; *Andersen and Jamtveit*, 1990; *Andersen et al.*, 1994]. A common characteristic of postorogenic extension is the presence of distributed midcrustal shear zones, decoupling the ductile lower crust from the brittle upper crust [*Gans*, 1987; *Lister and Davis*, 1989; *Jolivet et al.*, 1991; *Jolivet et al.*, 1994b] and juxtaposing terrains characterized by different thermal and burial history. Though several models concerning the mechanics of these shear zones do exist (see the review by *Wernicke* [1995]), little attention has been directed to the mechanism that controls the sense of shear along them.

This paper is an attempt to better understand the origin and role played by midcrustal shear zones in the extensional process. We first present the results of the ductile and brittle deformations analyzed along a transect throughout the northern Tyrrhenian Sea and then compare them with other examples of postorogenic extension. We use the tools of structural geology and metamorphic petrology to constrain the tectonic evolution of the area. We choose the Tyrrhenian Sea (Figure. 1) because it represents an example of continental extension contemporaneous with accretion (Apennines thrust belt). In particular, the northern Tyrrhenian Sea represents a favourable test area because it has the advantage of a shallow sea and numerous

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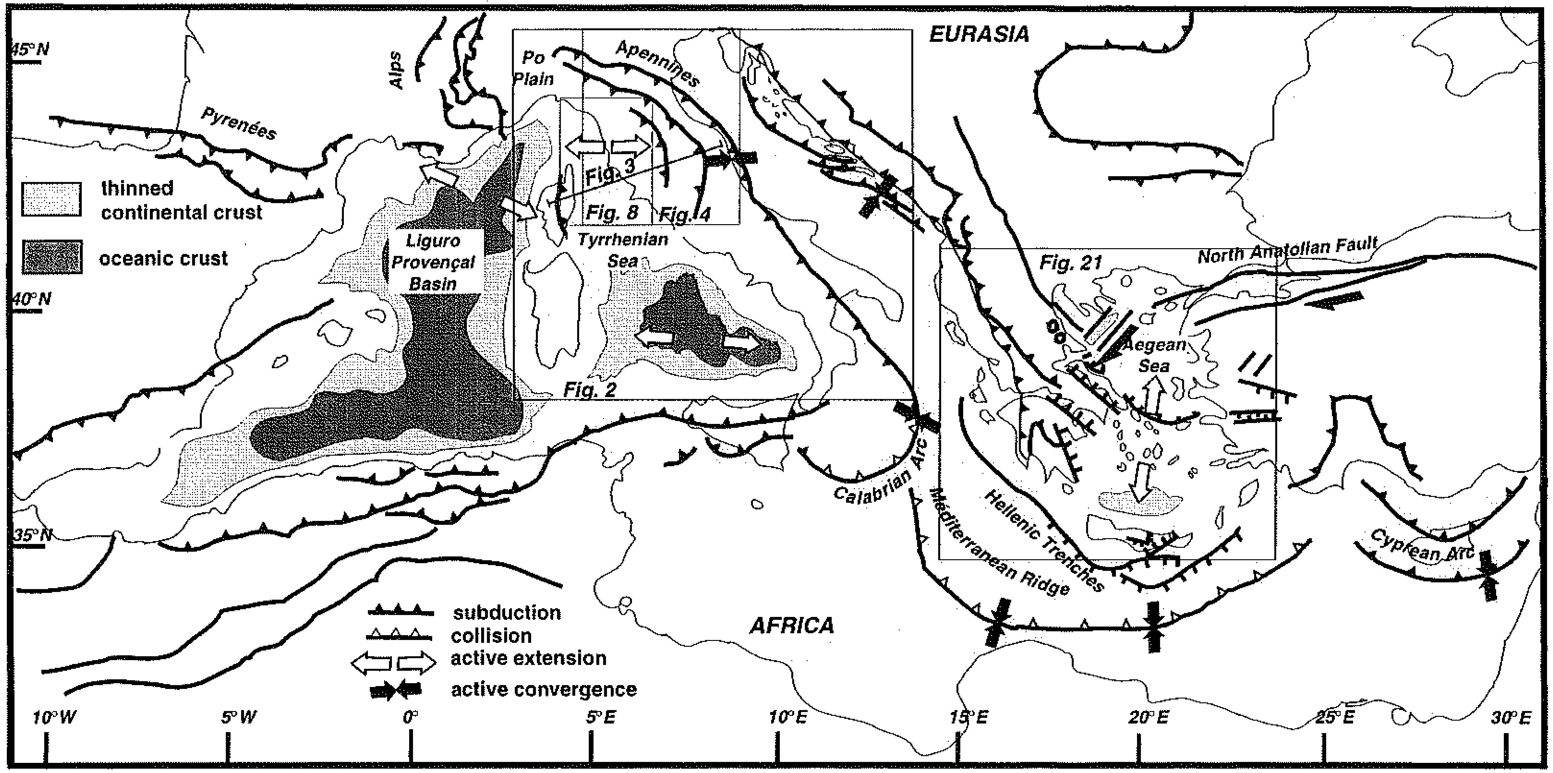


Figure 1. Index map of the Mediterranean area and locations of Figures 2-4, 8, and 21. The Tyrrhenian and Aegean Seas are both located within the upper plate of the Calabrian and Hellenic subduction zones, respectively. Both basins are superimposed on alpine mountain belts, and convergence is still occurring south of the Calabrian accretionary prism and Mediterranean Ridge. Although not discussed herein the Liguro-Provençal Basin opened during the same event that led to the opening of the Tyrrhenian Sea.

islands where field observations can be made nearly continuously from Corsica to the Tuscan archipelago and then to Tuscany.

In this paper we describe a sequence of events that led to the formation of the northern Tyrrhenian Sea during the eastward migration of the Apennines thrust front. We show that (1) extensional processes first started during nappe stacking at the top of the wedge and subsequently continued in backarc environment as in the southwest Tyrrhenian region [*Kastens and Mascle*, 1990; *Sartori*, 1990] ; (2) extension migrated from west to east, together with magmatic activity (for a review see *Serri et al.* [1993], from the late Oligocene-early Miocene to the present, and (3) deformation was characterized by east dipping detachments that accommodated crustal thinning and enabled granitic plutons to intrude the upper crust. We conclude that ancient examples of the deformation now active at depth below the northern Apennines inner zones, in the vicinity of the geothermal fields of Larderello and Monte Amiata are exposed on land in Corsica and the Tuscan archipelago (for example, at Elba and Giglio). Using a comparison with a similar tectonic environment in the Aegean Sea, we suggest that the sense of shear observed in the brittle-ductile transition zone could be controlled by the position and migration of the magmatic arc.

In this paper we describe structures and the metamorphic evolution of various parts of the Tyrrhenian Sea in terms of "synorogenic" or "postorogenic" extension. By synorogenic extension we mean extensional structures that form within or above a growing thrust wedge [*Platt*, 1986]. No crustal-scale thinning is involved; instead, continuous thickening is recorded. In the examples described herein syn-orogenic extension is associated with the preservation of high-pressure (P) and low-temperature (T) mineral assemblages because of a high-P/low-T gradient within the thrust wedge. Postorogenic extension occurs during crustal thinning after crustal thickening has ceased in the back arc domain (Tyrrhenian Sea or Aegean Sea) after outward migration of the thrust front. Those structures are often associated with high-temperature and low-pressure overprints. In our case, however, though crustal thickening is no longer active in the back arc domain, convergence is still occurring. Extensional structures that formed in the back arc region in the center of the Cyclades (Naxos island, for instance [*Lister et al.*, 1984; *Gautier et al.*, 1993]) are postorogenic because they relate to crustal thinning following crustal thickening. Therefore, during the Miocene in the Aegean Sea, syn-orogenic extension was occurring in Crete and postorogenic extension in the Cyclades [*Jolivet et al.*, 1994b; 1996].

1.2. Geological Context

1.2.1. Crustal and Lithospheric Structure in the Tyrrhenian Sea Region

Reduced crustal thickness and high heat flow are typical of the Tyrrhenian region (Figure. 2). Below the Apennine chain a doubling of the crust is suggested by the overlap between the Adriatic-Ionian Moho below the Tyrrhenian Moho [*Nicolich*, 1989], in fairly good agreement with the distribution of deep and intermediate earthquakes (for a review see *Amato et al.* [1993]. Furthermore, the presence of an east dipping crustal reflector has been suggested [*Letz et al.*, 1977; *Wigger*, 1984] to a depth of 60 km below Elba island. For a decade this crustal image has been used to draw crustal-scale sections from Corsica to the northern Apennines, enhancing the presence of a double vergent wedge [*Giese et al.*, 1982] linked with the crustal root forming during the west vergent eoalpine Corsica orogenic event. Nevertheless, recent investigation [*Ponziani et al.*, 1995], through reprocessing of the same data set, has ruled out the presence of this deep reflector that appears as a multiple of the *P* wave. This second interpretation fits better with geophysical and geological data, such as the position of the lithosphere/asthenosphere boundary (50 km deep [*Suhadolc and Panza*, 1989]), the high heat flow [*Della Vedova et al.*, 1991] and extensional tectonics that should have reshaped, by crustal thinning, a possible crustal root of a Cretaceous-Eocene orogeny.

Lithospheric thickness is considerably reduced in the entire Tyrrhenian region, ranging from 50 to 20 km in the Vavilov basin [*Suhadolc and Panza*, 1989]. Below the Calabrian arc a continuous, steep (70°-80°), NW deeping Benioff plane and a high-velocity zone down to 400-500 km show the subduction of the Ionian lithosphere [*Giardini and Velonà*, 1988; *Suhadolc and Panza*, 1989; *Cimini and Amato*, 1993; *Spakman et al.*, 1993; *Selvaggi and Chiarabba*,

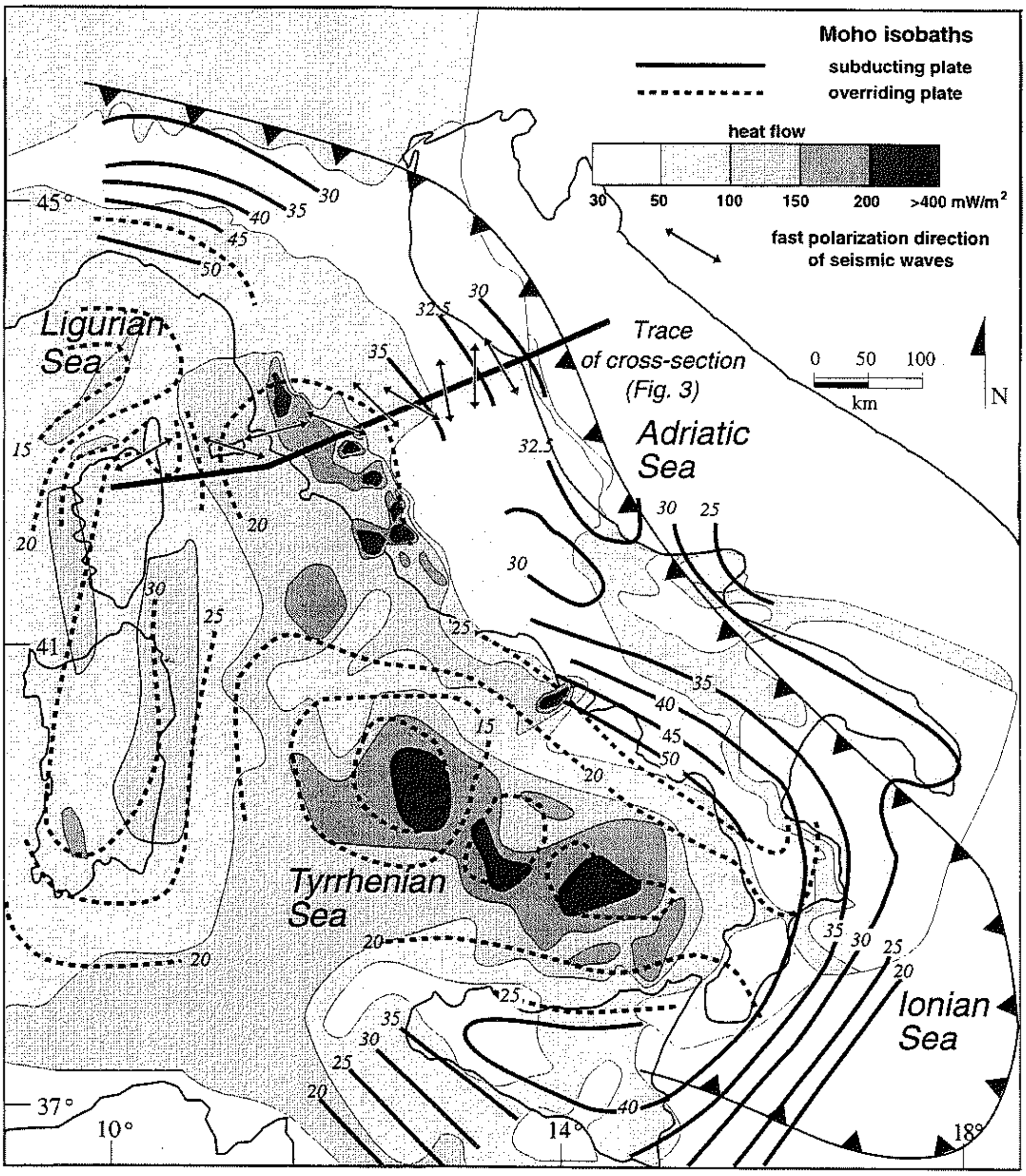


Figure 2. Moho isobaths (simplified from *Nicolich* [1989]) and heat flow (simplified from *Della Vedova et al.*, [1991b]) in the Tyrrhenian Sea. Moho isobaths of the subducting plate are shown as thick lines. The Moho is up to 50 km deep in the Alps and southern Apennines and only up to 35 km in the northern Apennines. Thin continental crust is observed in the northern Tyrrhenian Sea (less than 20 km), and oceanic crust is seen in the southeastern Tyrrhenian Sea. Below Corsica and Sardinia the continental crust is approximately 30 km thick. High heat flow measured in Tuscany along the western coast of Italy, midway between Corsica and the Apennines, corresponds to the recent magmatic arc, though Quaternary volcanic products are known east of this zone (see Figure 3). Arrows show the fast polarization direction of seismic waves along the Corsica-Apennines transect [*Margheriti et al.*, 1996].

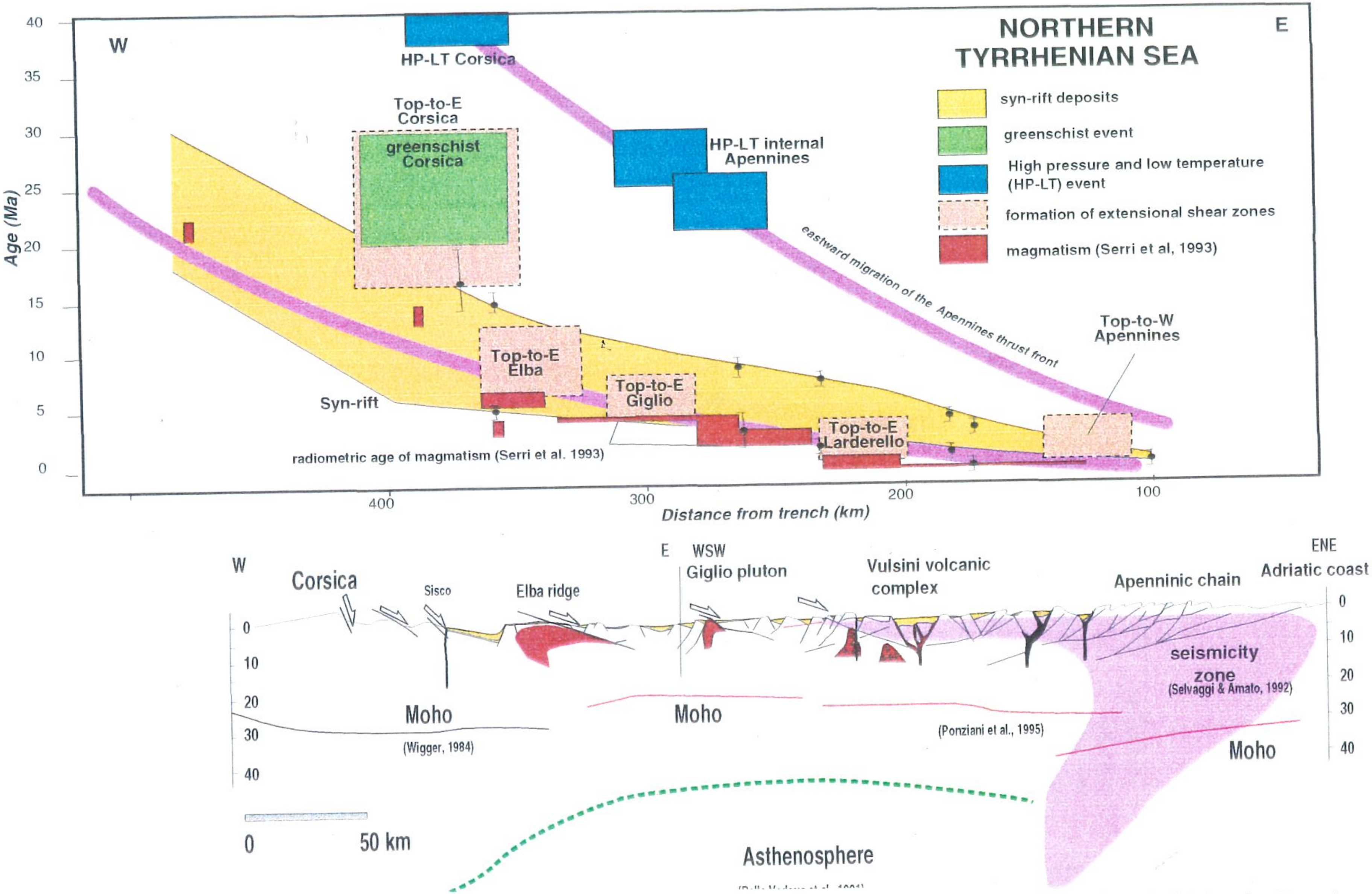


Figure 3. Crustal-scale cross section from Corsica to the northern Apennines (location in Figure 2) and age-distance diagram of volcanism and synrift basin-fill deposits. Tectonic and magmatic events become younger to the east. Compressional events (including frontal thrusts and high-pressure and low-temperature metamorphic stages related to subduction) migrate eastward more slowly than extensional events which tend to catch up with time, in agreement with the relatively thin crust observed today in the Apennines compared with the Alps. Synrift deposits and magmatic events are intimately correlated; volcanism occurs at the end of the rifting episode, at least during the late Miocene to Recent. Everywhere along the transect west of the present-day volcanic arc, extension is achieved along east dipping, shallow shear zones, while west dipping, normal faults are recognized in the Apennines. Crustal structure is from *Wigger* [1984], *Della Vedova et al.* [1991a], and *Ponziani et al.* [1995], seismicity from *Selvaggi and Amato* [1992], geological structure is from *Zitellini et al.* [1986], and *Lavecchia et al.* [1987], age of syn-rift deposits are from *Bossio et al.* [1993], *Martini and Sagri* [1993], and *Bartole* [1995], radiometric ages of magmatism are from *Serri et al.* [1993], radiometric ages of metamorphic rocks are from *Brunet et al.* [1997].

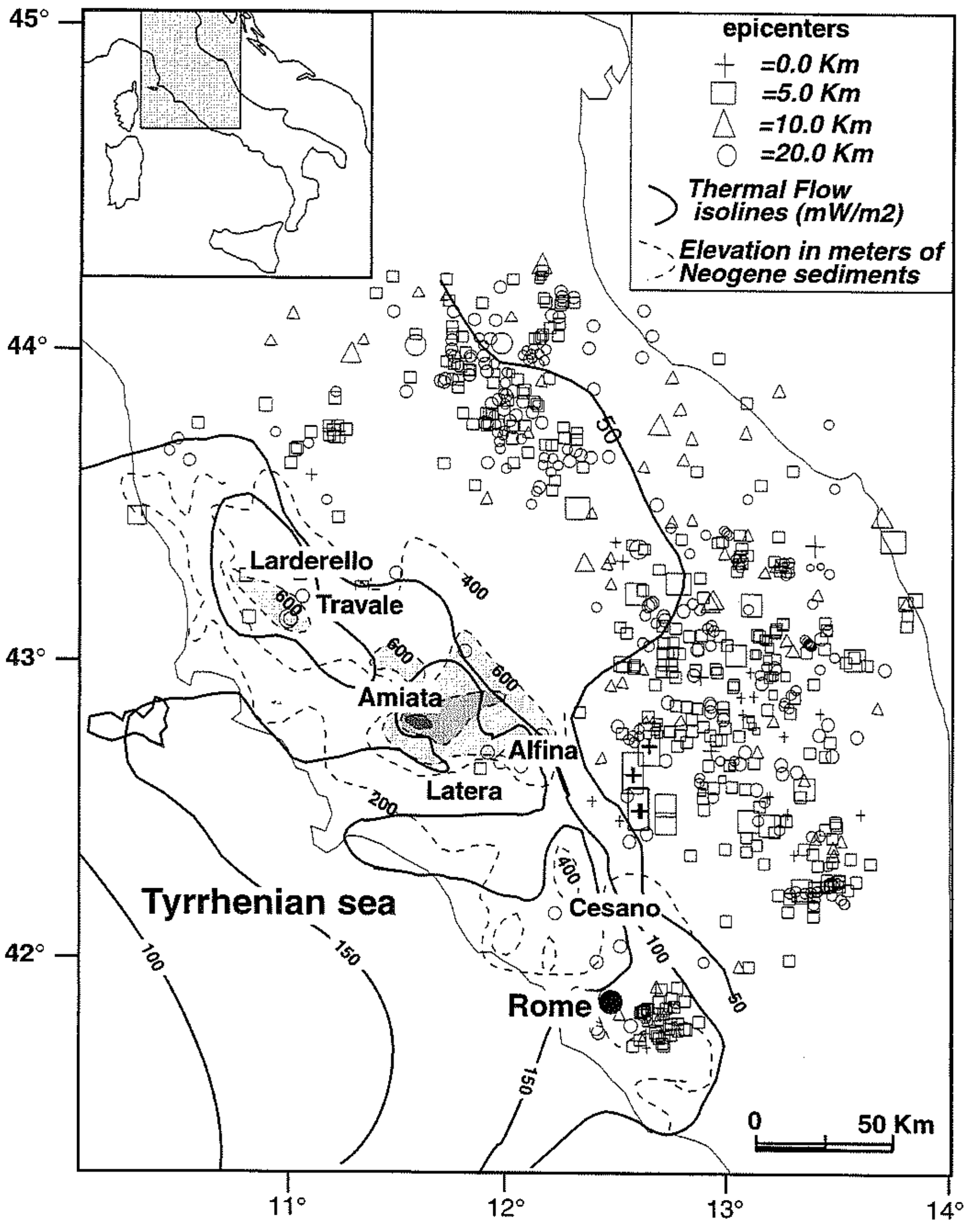


Figure 4. Seismicity [*Selvaggi and Amato*, 1992], heat flow [*Mongelli and Zito*, 1991], and elevation (in meters) of Neogene sediments [*Barberi et al.*, 1994] in the northern Tyrrhenian-Apennines area. Density of shading depicts the elevation of Neogene sediments along the western coast of Italy. Highest elevations correspond to active geothermal fields (Monte Amiata and Larderello), and a large part of this uplift is probably related to pluton emplacement in the crust. Recent plutons have been reached by drilling below Monte Amiata and Larderello at a depth of approximately 4 km [*Villa et al.*, 1989]. Seismicity is concentrated below the Apennine belt where the heat flow is lower. Inset map shows location of northern Tyrrhenian Sea.

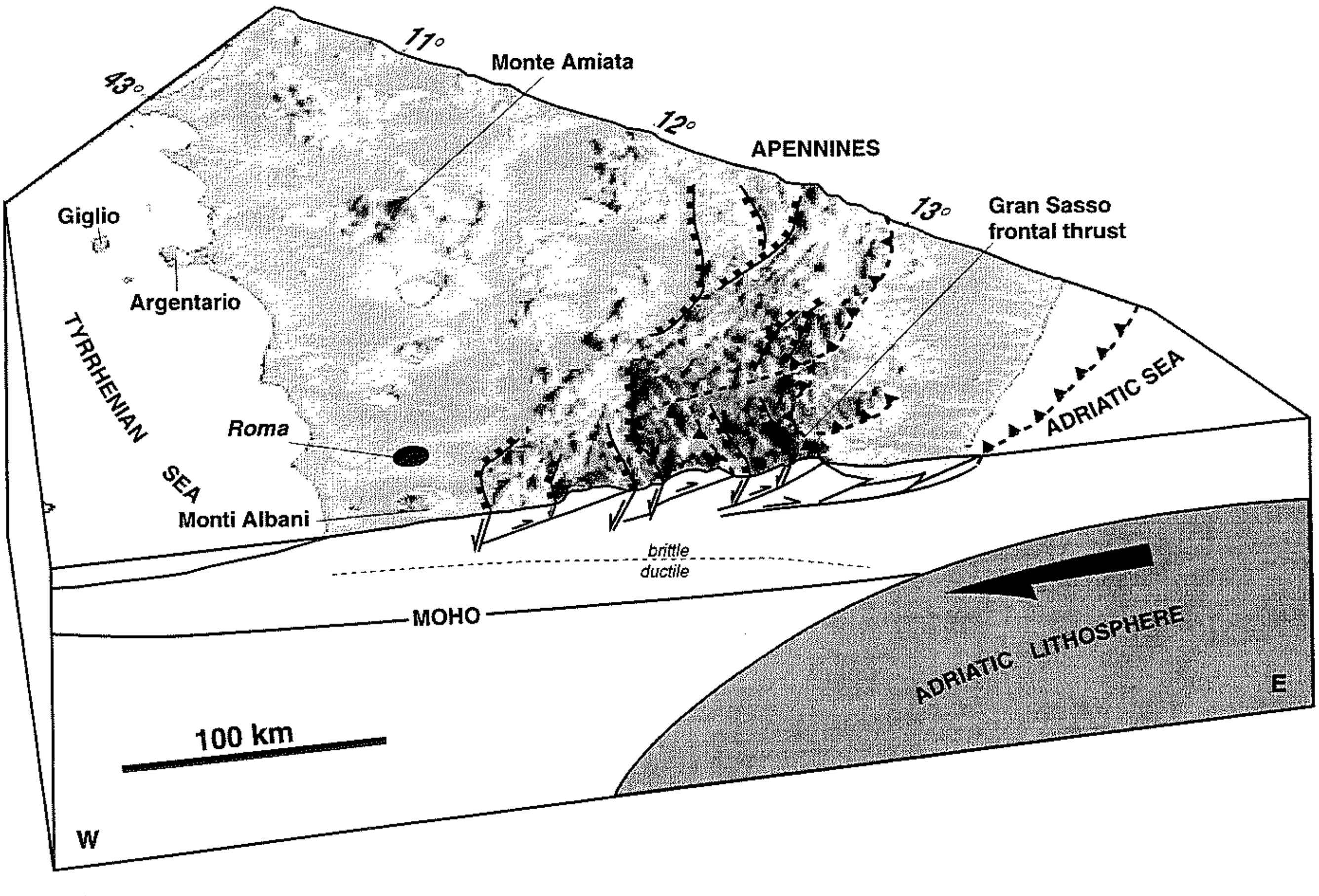


Figure 5. Oblique view of the Apennines and western Italy from the Adriatic to the Tyrrhenian coastlines. Highest topography is located in the Apennines where recent thrusts are reactivated by west dipping normal faults. The most recent thrusts are offshore below the Adriatic Sea, and most of them are covered by late Quaternary sediments. The eastern limit of extension is the crestline of the Apennines near the Gran Sasso. Also shown is the elevated topography of the high heat flow region around Monte Amiata. The recent volcanic edifices of Monti Albani are shown south of Rome.

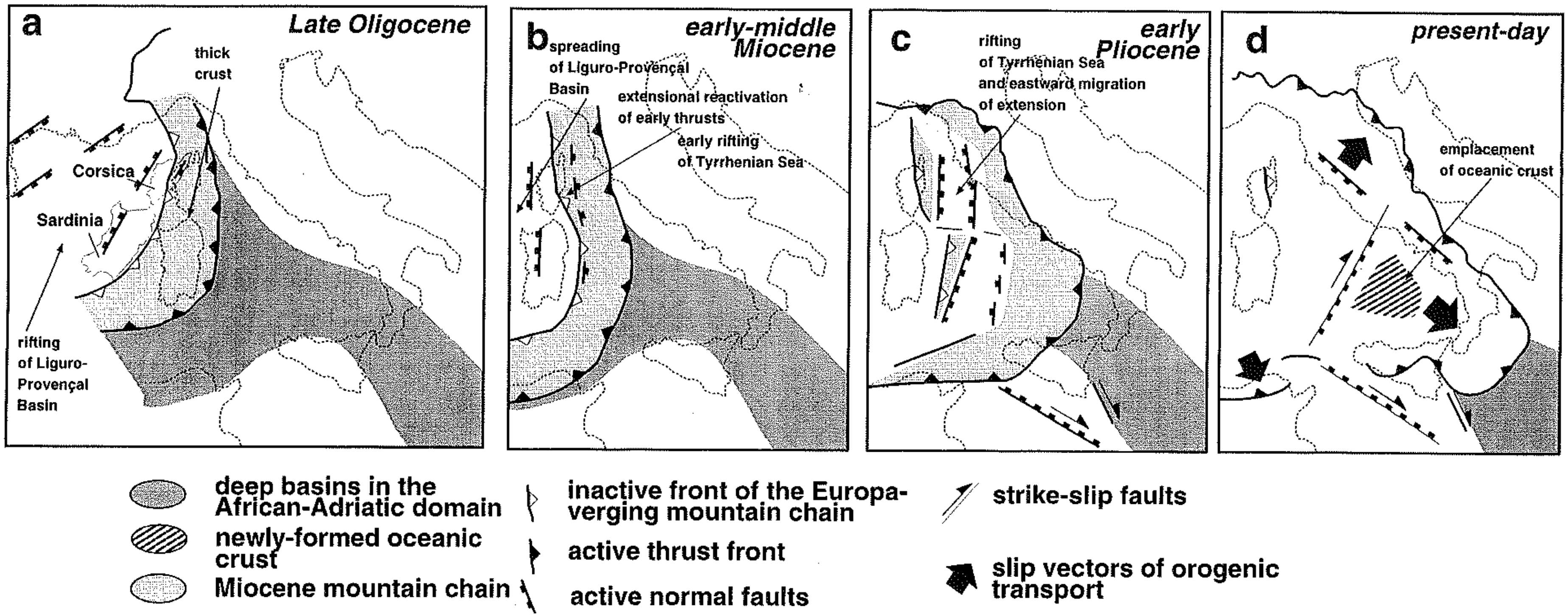


Figure 6. Tectonic evolution of the central Mediterranean area. The eastward migration (slab retreat) of the Apennine compressional front is followed by the eastward migration of extension. (a) In the late Oligocene, rifting is active in the Liguro-Provençal basin. This extensional episode belongs to the west European rift system. The last effects of compression are felt in Alpine Corsica. (b) During the early and middle Miocene oceanic crust is emplaced in the Liguro-Provençal basin while thrust faults are reactivated as extensional shear zones in Alpine Corsica. The Corso-Sardinian block rotates counterclockwise. (c) In the late Miocene and early Pliocene, rifting is active in the Tyrrhenian Sea and extension progressively shifts eastward following the Apennines thrust front. (d) Oceanic crust starts to form in the southern Tyrrhenian Sea and is still forming today.

1995]. The continuation of this surface in the southern and central Apennines is not clear. In the northern Apennines, however, ongoing subduction has been recently postulated based on the distribution of subcrustal seismicity (Figure 3) down to 90 km and a high-velocity, WSW-dipping zone down to 250 km [*Selvaggi and Amato*, 1992; *Cimini and Amato*, 1993] (shaded zone in Figure 3). The seismicity shown in Figure 4 is distributed in compressional earthquakes in the foreland region of the Northern Apennines and extensional earthquakes west of the crest line of the Apennines [*Anderson and Jackson*, 1987; *Frepoli and Amato*, 1997]. P axes of earthquakes in the foreland area and T axes in the internal zones are roughly perpendicular to the strike of the thrust front [*Frepoli and Amato*, 1997]. Active modern extension in the Apennine belt itself west of the topographic divide is characterized by west dipping normal faults [*Lavecchia and stoppa*, 1989; *D'Agostino et al.*, 1998] (Figure 5). Recent seismological studies reveal a low-velocity anomaly beneath the Apennines, probably located in the lower crust [*Chiarraba and Amato*, 1996, *Mele, et al.*, 1996] beneath the region of active extension.

Seismic anisotropy of the upper mantle beneath the transect from Corsica to the Apennines shows a strong change in orientation of the high-velocity direction within the lithosphere [*Margheriti et al.*, 1996] (Figure 2). Its orientation is parallel to the Apennines in the east, but it changes to become perpendicular to the belt farther west. From Corsica to Tuscany the direction is approximately E-W and may be due to stretching of the upper mantle below the Tyrrhenian Sea. This observation implies that the E-W direction of extension observed in exhumed metamorphic complexes along the transect is significant at the scale of the lithosphere.

1.2.2. Paleogeographic Evolution

The present-day lithospheric structure reflects 30 Myr of tectonic evolution, summarized below. The opening of the central Mediterranean basins (Liguro-Provençal basin and the Tyrrhenian Sea), at least from the late Eocene to present, is classically considered the consequence of the NW-W dipping retreating subduction of the Ionian-Adria lithosphere [*Dercourt et al.*, 1986; *Malinverno and Ryan*, 1986; *Lonergan and White*, 1997] (Figure 6). Early extension occurred within the Hercynian crust with the development of the Liguro-Provençal basin rift zone (late Eocene-middle Aquitanian) (Figure 6a). It was followed by formation of oceanic crust in the Liguro-Provençal basin and fast rotation of the Sardinian-Corsica block, probably during the Burdigalian [*Burrus*, 1984]. From early Miocene to Pleistocene, deformation migrated eastward in the future Tyrrhenian Sea and the Apennines, toward the Adria-Ionian foreland domain (Figures 6b-6d). Extension reactivated earlier thrusts as in Corsica [*Jolivet et al.*, 1991; *Daniel et al.*, 1996]. Nearly N-S oriented extensional basins developed on the previously thickened Alpine crust in the hinterland, contemporary with flexural basins in the foreland [*Elter et al.*, 1975; *Rehault et al.*, 1987; *Kastens et al.*, 1988; *Sartori and ODP Leg 107 Scientific Staff*, 1989; *Patacca et al.*, 1990]; foreland basins and extensional basins migrated eastward following the flexural retreat of the subducting Adria-Ionian lithosphere (Figures. 3 and 6). Extension in the Tyrrhenian Sea led to the formation of an attenuated continental crust and ultimately to modern oceanic crust north of Sicily (Figure 6d). Thrusting was accompanied by complex rotations of the compressional front [*Oldow et al.*, 1990; *Sagnotti*, 1992; *Scheepers et al.*, 1993; *Mattei et al.*, 1995] forming major arcuate thrust fans convex toward the Adriatic foreland [*Patacca et al.*, 1990], while, in the innermost part of the chain, the N-S/NW-SE Messinian-Pleistocene extensional basins of the northern Tyrrhenian margin developed without any rotation [*Sagnotti et al.*, 1994; *Mattei et al.*, 1996]. Therefore extensional axes turned passively during arching from E-W to NE-SW in the northern Tyrrhenian area and to NW-SE in the Southern Tyrrhenian Sea, always oriented perpendicular to the subduction front [*Sartori and 107 Scientific Staff*, 1989]. In the Northern Tyrrhenian area the rotation of the maximum extensional axis, deduced from the strike of basins and paleomagnetic data, excludes the possibility of rigid rotation of the northern Italian peninsula during its opening about a nearby pole. Lithospheric thinning caused high heat flow, magmatism, and, in the southern Tyrrhenian and Liguro-Provençal basin, emplacement of oceanic crust [*Sartori and ODP Leg 107 Scientific Staff*, 1989].

The preextension geometry (Eocene and early Oligocene) has long been a matter a debate. The westvergent nappe structures and top-to-the-west sense of shear recorded during the high pressure and low temperature episode of Alpine Corsica (see section 2.3) were related to an east dipping subduction [*Mattauer et al.*, 1981; *Malavieille*, 1982], by comparison with the nearby

Franco-Italian Alps. Thus a switch in the polarity of subduction must have occurred during the Oligocene to produce the present-day geometry. Recent studies showed, however, that most of the E-W trending stretching lineations in Alpine Corsica were produced during the Oligo-Miocene extensional episode and that major earlier compressionnal shear zones were reactivated as ductile normal faults [*Jolivet et al.*, 1994a; *Daniel et al.*, 1996]. Once those structures are subtracted, little information is left about the kinematics of the Eocene compressional stage or the geometrical links with the Alps. In an alternative model it is assumed that the polarity of subduction has always been as it is today and that the west vergent thrusts of Alpine Corsica are back thrusts in a large accretionary complex [*Principi and Treves*, 1984]. The choice of models is only marginally related to the topic of this paper which deals with the late Oligocene to present evolution of the Tyrrhenian Sea. However, until the Eocene tectonic history of Corsica is more precisely known, the second model is simpler because it does not involve a switch in the polarity of subduction.

1.2.3. Main Geological Units in the Northern Tyrrhenian Sea

Before we describe the structural and petrological data, we summarize the stratigraphy along the transect (Figures 3, 7, and 8). Alpine Corsica and the northern Apennine represent a double-vergent, orogenic wedge [*Principi and Treves*, 1984] built up by stacking of units belonging to different paleogeographic domains. Along our transect, from east to west, the main units are summarized as follows [*Carmignani et al.*, 1994] and in Figure 7.

1. The continental basement of western Corsica, overlain by the Schistes Lustrés and Balagne nappes, represents the European continental basement before the opening of the Liguro-Provençal basin. It is composed of granitoids of late Carboniferous to Permian age, intruding an early Paleozoic metamorphic basement [*Durand Delga*, 1984]. The eastern part of it was involved in the alpine orogeny and is found today as large-scale lenses in the Schistes Lustrés nappe thrust sheets [*Mattauer et al.*, 1981].

2. The Ligurian domain is represented by oceanic (Ligurides) and transitional (sub-Ligurides) domain units, characterized by the occurrence of Jurassic ophiolites and their Jurassic-Early Cretaceous sedimentary cover, overlain by Cretaceous-Oligocene flysch sequences. Along the studied transect the ophiolitic complexes mainly crop out in Alpine Corsica, within the stacked units of the Balagne Nappe and Schistes Lustrés [*Durand Delga*, 1984], in the Tuscan archipelago (Gorgona, Elba, Monte Cristo and Giglio), and in Tuscany (Monte Argentario) [*Abbate et al.*, 1980]; they consist of metabasites and serpentinites metamorphosed to various degrees, often in a high-pressure and low-temperature environment. The Ligurides units were thrust eastward over the Tuscan domain units beginning in the late Oligocene [*Principi and Treves*, 1984]. It is noticeable that ophiolite units always constitute the uppermost nappe on either side of the Ligurian ocean. Continental units (orthogneiss) are always included as small tectonics slices and metamorphosed together with the oceanic nappe stack. No equivalent of the overthrust Austro-Alpine nappe of the Alps occurs above the oceanic domain in this locality.

3. Upper Triassic to Miocene marine carbonates and sandstones constitute the Tuscan unmetamorphosed sequence, deformed in an array of thrust sheets (Tuscan nappe). Coeval metasedimentary sequences, also of Tuscan affinity, crop out in the Monticiano-Roccastrada ridge, Apuan Alps, and Monte Pisani. Both metamorphic and unmetamorphic successions constitute the Tuscan domain (Tuscanides). These sequences overlie a Paleozoic to Triassic metamorphic sequence that forms the core of the Apuan Alps and the lower part of the Massa and Punta Bianca units [*Carmignani et al.*, 1978]. In the Massa and Punta Bianca units, metabasalts interbedded within Permian-Triassic marine metasedimentary rocks are the evidence of aborted rifting preceding the beginning of the Alpine sedimentary cycle [*Cassinis et al.*, 1979; *Martini et al.*, 1986]. The transition from clastic sediments of the uppermost "Verrucano Serie" to bedded limestones and calcareous breccias of the "Calcare Cavernoso" is also evidence of this early rifting episode.

4. The Umbro-Marchean domain consists of sedimentary sequences deposited on a continental margin with basal Late Triassic evaporites, platform carbonates (Lias), and pelagic sequences (Jurassic-Eocene) enriched upward in terrigenous deposits (Paleogene) and flysch-like sequences (Miocene).

In southern Tuscany, some massive clastic deposits, Langhian to lower Tortonian in age, made of massive shallow water sandstones [*Consiglio Nazionale delle Richerche*, 1992], rest

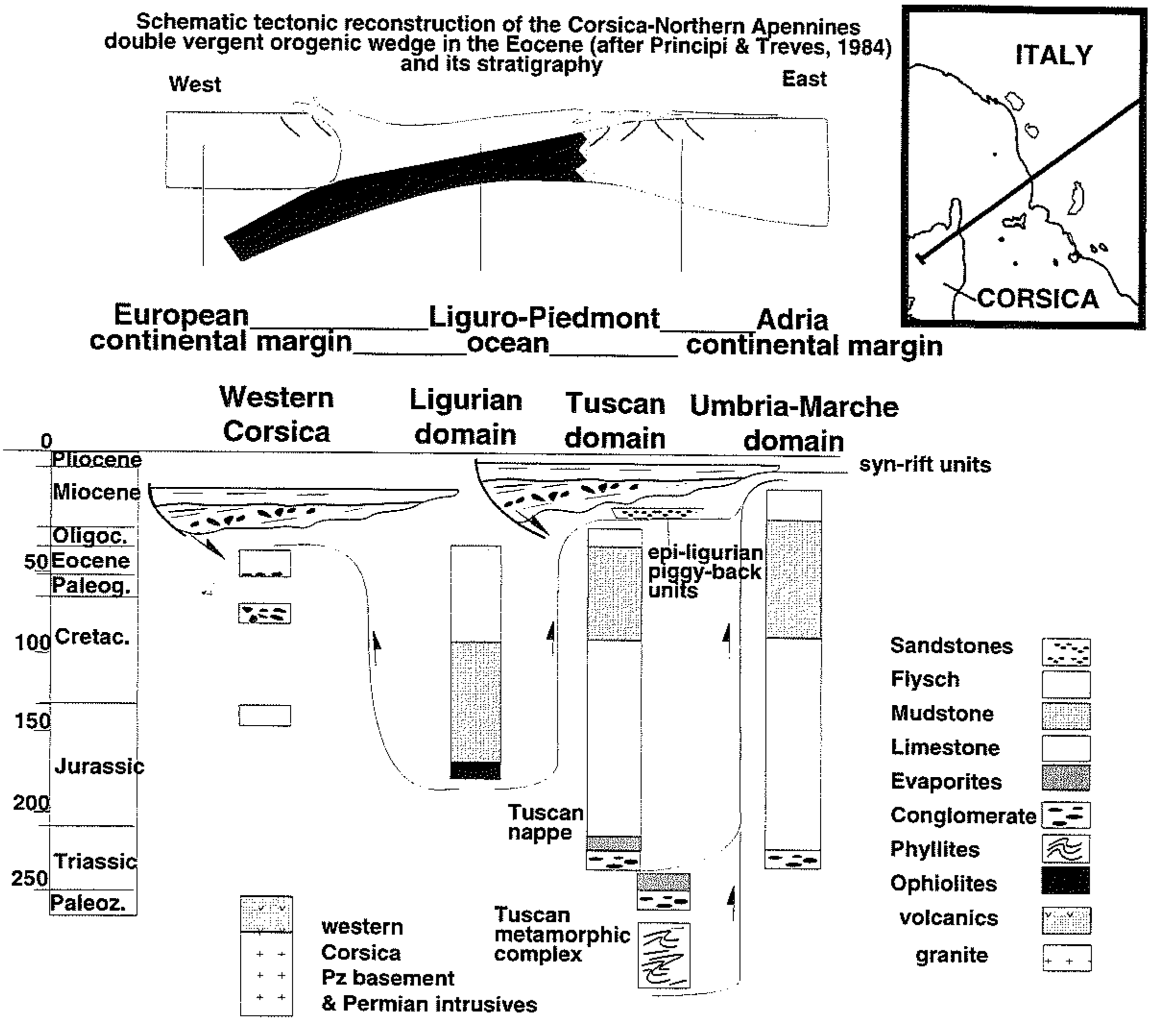


Figure 7. Diagramatic stratigraphic columns of the Corsican-Apennine area (modified after *Durand Delga* [1984] and *Carmignani et al.* [1994]), and a possible reconstruction of the preextension scenario along the studied transect (see insert for location) [*Principi and Treves*, 1984]. The Ligurian (oceanic) domain is sandwiched between the continental units of western Corsica and the Tuscan domain. The proposed reconstruction is only one possible solution. Other scenarios requiring westward subduction have been proposed [*Mattauer et al.*, 1981; *Warburton*, 1986]. The kinematics of the high-pressure compressional episode of Alpine Corsica needs further study to unravel this problem.

unconformably only upon the allochthonous Ligurian units. Known as "epiligurian" units, they have been classically interpreted as lying on Ligurian thrust sheets. This interpretation is mainly based on the fact that they always rest upon Ligurian units and they show similarity with the epiligurian units of the northern Apennines.

1.2.4. Neogene Sedimentary Basins

The most obvious consequence of lithospheric extension is the formation of Neogene sedimentary basins. Extensional basins (Figures 3 and 8) become younger toward the eas, following the eastward accretion of the Apennines and migration of the Adriatic foreland system [*Elter et al.*, 1975; *Patacca et al.*, 1990]. This progressive eastward migration is well documented by the age of the infilling sedimentary sequences. In the westernmost Tyrrhenian Sea (Pianosa island and Corsica) these sedimentary sequences are lower Miocene in age [*Bartole*, 1995], while they are Pleistocene in age in the Umbrian region where extensional tectonics is presently active. The oldest early Miocene basins (Saint Florent and Francardo basins (Figure 8), filled with shallow marine limestone and continental deposits, are found in Corsica and are characterized by N-S trending, east dipping normal faults. Similar early-middle Miocene sediments occur on the island of Pianosa (Figure 9) as poorly indurated and undeformed green silts and marls, Langhian in age (C. Müller personal communication, 1995). The main sedimentary basins, NNW-SSE or NW-SE oriented along the Tuscan-Latium coast, are locally dissected by NE-SW transfer faults that bound minor transverse sedimentary basins [*Liotta*, 1991; *Faccenna et al.*, 1994; *Bartole*, 1995]. In the Apennines most of the normal faults dip towards the west [*Lavecchia et al.*, 1987]. Although the different sedimentary basins evolved in different ways, they have many common features. In the west the synrift sequence contains continental deposits overlain by gypsum-bearing upper Miocene marine sequences and siliciclastic, marine Pliocene deposits [*Bossio et al.*, 1993, and references therein]. In eastern Tuscany and within the Apennines, basin sediments contain upper Pliocene-Pleistocene lacustrine and fluvial clastic deposits [*Martini and Sagri*, 1993, and references therein].

1.2.5. Magmatic Evolution and Geothermal Anomalies

Magmatism was coeval with basin formation. Several magmatic pulses are recognized [*Serri et al.*, 1993] from 15-13.5 Ma to the late Pleistocene in the northern Tyrrhenian-Apennines region (Figures 3 and 8). Magmatic activity, as well as sedimentary basins, becomes younger to the east. The oldest magmatic activity is represented by the Sisco lamproitic sill (15-13.5 Ma) in eastern Corsica, followed by the Montecristo, Monte Capanne (west Elba), and Vercelli plutons (7.3-6.2 Ma) and Capraia composite volcanism (6.9-6.0 Ma) in the northern Tyrrhenian Sea. Between 5.1 and 2.2 Ma, magmatic activity migrated toward the Tuscan-Latium continental shelf with the acidic intrusive bodies (Porto Azzurro east Elba, Giglio, Campiglia, Gavorrano, Castel di Pietra, and Monteverdi), and with rhyolites (San Vincenzo, Roccastrada and Tolfa-Ceriti and the second period of activity of Capraia). Figure 3 shows the progressive migration of magmatic activity toward the east. Although the age of the first magmatic event at one given point along the transect shows a clear eastward migration, the activity can last for several million yaers at the same site. The last magmatic phase started 1.3 Ma with Radicofani, Monti Cimini and Torre Alfina lava domes and evolved to the high-potassium series of the Roman Comagmatic Province [*Washington*, 1906]. Five main volcanic districts (Bolsena, Vico, Sabatini, Colli Albani, and Ernici) formed between 0.6 Ma and late Pleistocene age, mainly in the Latium region.

The Tyrrhenian Sea and the western margin of the Tuscan and Latium regions are characterized by a large positive heat flow anomaly of about 100 mW/m^2 (Figures 2 and 4). Wide zones of high heat flow, up to 200 mW/m^2, occur in the Larderello, Amiata, Vulsini, Vico, and Sabatini mountains, where the major Italian geothermal fields are located [*Mongelli and Zito*, 1991]. In the Amiata, Larderello-Travale, and Tolfa-Cimini regions, these heat flow anomalies correspond to low-gravity anomalies caused by plutons in the shallow crust [*Marinelli et al.*, 1993; *Barberi et al.*, 1994]. Plutonic bodies were intersected at a depth between 3000 and 4200 m in the Larderello-Travale geothermal field. Microgranites dikes in those wells have a radiometric age of 3.8 Ma [*Villa et al.*, 1989]. These geothermal areas underwent considerable uplift (Figure 4), revealed by the present-day elevation of the Neogene sedimentary sequences ([*Barberi et al.*, 1994, and references therein]. Alluvial Messinian and marine lower

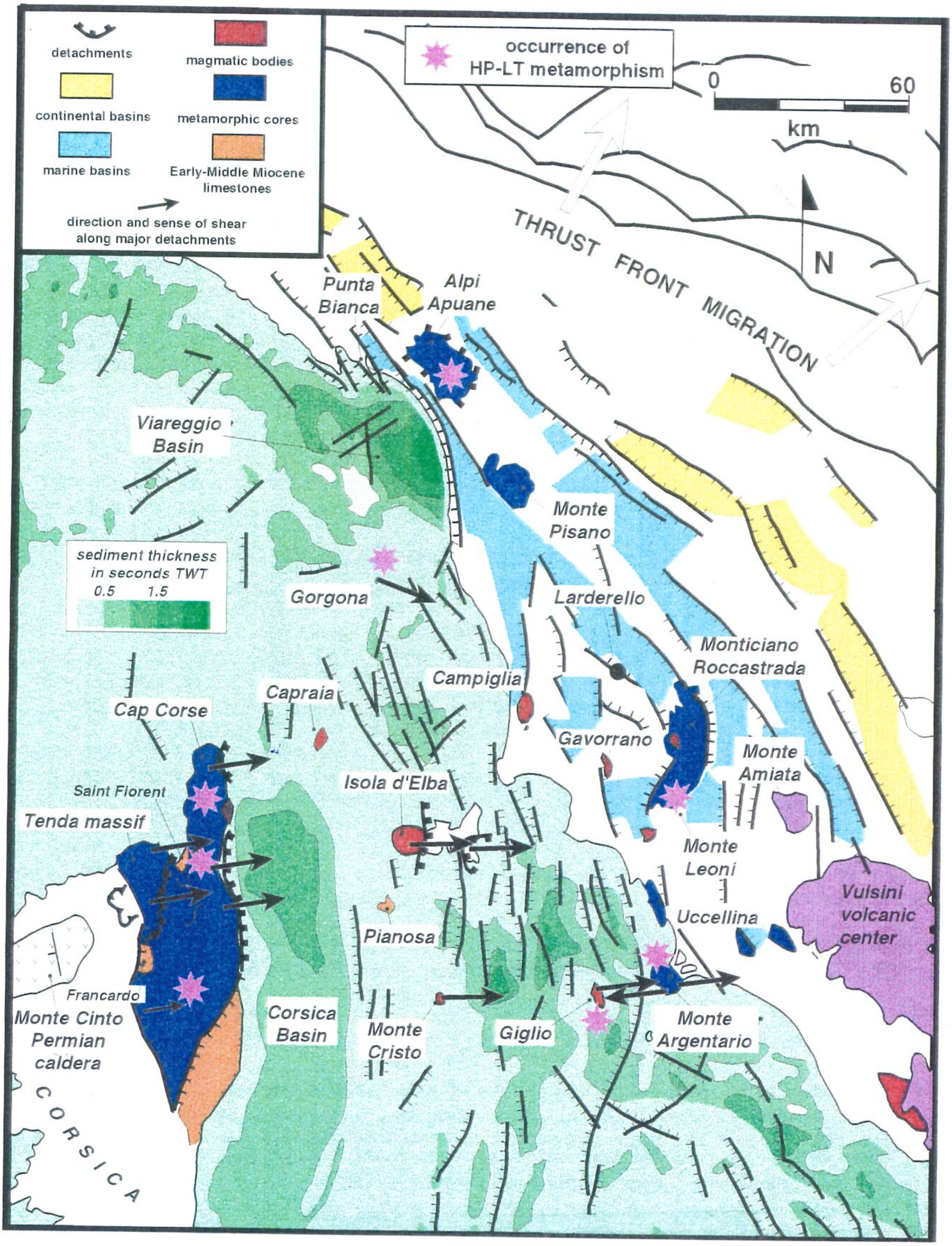


Figure 8. Tectonic map of the northern Tyrrhenian area showing sediment thickness and faults [*Consiglio Nazionale delle Ricerche*, 1992], sedimentary basins on land [*Martini and Sagri*, 1993], occurrence of high pressure and low temperature metamorphism [*Lotti*, 1910; *Di Sabatino et al.*, 1977; *Caron et al.*, 1981; *Giorgetti*, 1995; *Theye et al.*, 1997; Rossetti et al., submitted manuscript, 1996] and new original data from this paper. Isopachs of sedimentary cover (in seconds, two-way time) offshore show the basin and range structure of the northern Tyrrhenian Sea. The largest basins are controlled by normal faults. Along the studied transect the Corsica basin is bounded to the west by a large, east dipping normal fault that reworks east dipping, shallow, extensional ductile shear zones. The Viarreggio basin in the north is controlled by a large, west dipping, normal fault. On land basins are filled with marine deposits in Corsica and Tuscany and with continental sediments farther east. Solid stars show high-pressure and low-temperature metamorphic complexes from Alpine Corsica to the Apuan Alps and Monte Leoni or Gorgona island. Arrows show the direction of stretching and sense of shear within the major ductile extensional shear zones studied along the transect from Alpine Corsica to Monte Argentario.

Pliocene deposits crop out at an altitude of 400, 600, and 800 m in the Tolfa, Larderello-Travale, and Amiata areas, respectively. The strong correspondence between high thermal heat flow and elevation of sedimentary deposits suggests that the uplift is linked to the intrusion of the plutons rather than to a regional isostatic process [*Marinelli et al.*, 1993]. The age of this uplift is constrained by the lack of marine sedimentary deposits of Globigerina Inflata biozone over the whole Tuscan region and by the presence of intraformational slumping and debris flows, suggesting a submersion of this area during the middle-late Pliocene [*Bossio et al.*, 1993]. A similar age has been recently suggested for the exhumation of the Monte Capanne plutonic body in Elba (apatite fission tracks) [*Bouillin et al.*, 1994]; nevertheless, the discovery of pebbles derived from the Monte Capanne intrusion contained within the Messinian-lower Pliocene sedimentary sequences of coastal Tuscan basins suggests an older exhumation episode, at least for the Elba pluton [*Tongiorgi and Tongiorgi*, 1964; *Bossio et al.*, 1993; *Marinelli et al.*, 1993]. In western Tuscany this major phase of uplift ended in the Pliocene, as the lower Pleistocene transgressive deposits are only slightly uplifted or deformed. This uplift episode is responsible for the present-day morphology of the Tuscan area. From a regional point of view some of the previously exhumed metamorphic cores, morphologically corresponding with ranges, underwent a magmatic-driven uplift of the order of 1 km since late Tortonian times. In section 3, we describe the petrological and structural data gathered along the transect.

1.3. Metamorphic and Structural Evolution

The structural and metamorphic study presented herein is the synthesis of several previous studies [*Jolivet et al.*, 1990; *Fournier et al.*, 1991; *Jolivet et al.*, 1991; *Jolivet et al.*, 1994b; *Daniel and Jolivet*, 1995; *Daniel et al.*, 1996], as well as new observations for the islands of Corsica, Gorgona, Giglio, and Monte Argentario or Apuan Alps (Figure 8). Our study concentrated on the major shear zones that may have been active during the exhumation of metamorphic rocks described in section 2. The results are presented in maps of stretching lineations and associated sense of shear and cross sections. Finite strain gradients were systematically analyzed [*Daniel et al.*, 1996], as were the relationships between metamorphic recrystallizations and deformation. Various types of kinematic indicators were applied; however, a preference was given to shear bands at all scales [*Berthé et al.*, 1979; *Platt and Vissers*, 1980] and up to crustal-scale shear bands in the case of Alpine Corsica [*Daniel et al.*, 1996].

The relationships between the deformation history and the pressure-temperature evolution was systematically studied using the petrology of metapelites. In mountain belts, high-pressure and low-temperature conditions are usually well characterized by the blueschist or eclogitic parageneses of metabasites [*Evans*, 1990]. Along the transect between Corsica and the Apennines those lithologies crop out, mostly in Corsica and are less important, farther east where metasediments of pelitic compositions are predominant.

Since the beginning of the 1980s, studies of low-grade metapelites in high-pressure belts have revealed their characteristic mineralogy. The most typical mineral of these rocks is ferro- and magnesiocarpholite [*Chopin and Schreyer*, 1983; *Goffé and Chopin*, 1986], which is abundant under high-pressure and low-temperature conditions. Ferro- and magnesiocarpholites are encountered in various rock types, such as aluminum-rich metapelites (meta-argilites and metabauxites), metaconglomerates, quartzites, marbles, and albite-free pelitic schists. Petrologic observations of these rocks reveal that the main equilibrium reactions of ferro- and magnesiocarpholite involve quartz, kaolinite, pyrophyllite, kyanite, sudoite, chlorite, chloritoid, and phengites, and that Fe-Mg mineral compositions vary as a function of P and T [*Goffé*, 1982; *Chopin and Schreyer*, 1983; *Goffé and Chopin*, 1986; *Theye et al.*, 1992; *Oberhänsli et al.*, 1995; *Jolivet et al.*, 1996; *Goffé and Bousquet*, 1997]. Aragonite, calcite, lawsonite, and epidote can also occur in these metasediments.

Recent thermodynamic data for metapelite mineralogy allow the calculation of a synthetic PT grid including these minerals (Figure 9). This grid is constructed using PTAX, a development of the GEOCALC software [*Berman and Perkins*, 1987], with the internally consistent data set of *Berman* [1988] for chlorite (chl), pyrophyllite (py), kaolinite (kaol), quartz (q), kyanite (ky), lawsonite (lw), epidote (clzo), and margarite (marg), complemented by consistent thermodynamic properties for magnesiocarpholite (car) [*Vidal et al.*, 1992] and phengites (ph) [*Massonne*, 1995]. The thermodynamic data used for magnesiochloritoid (ctd) are provisional

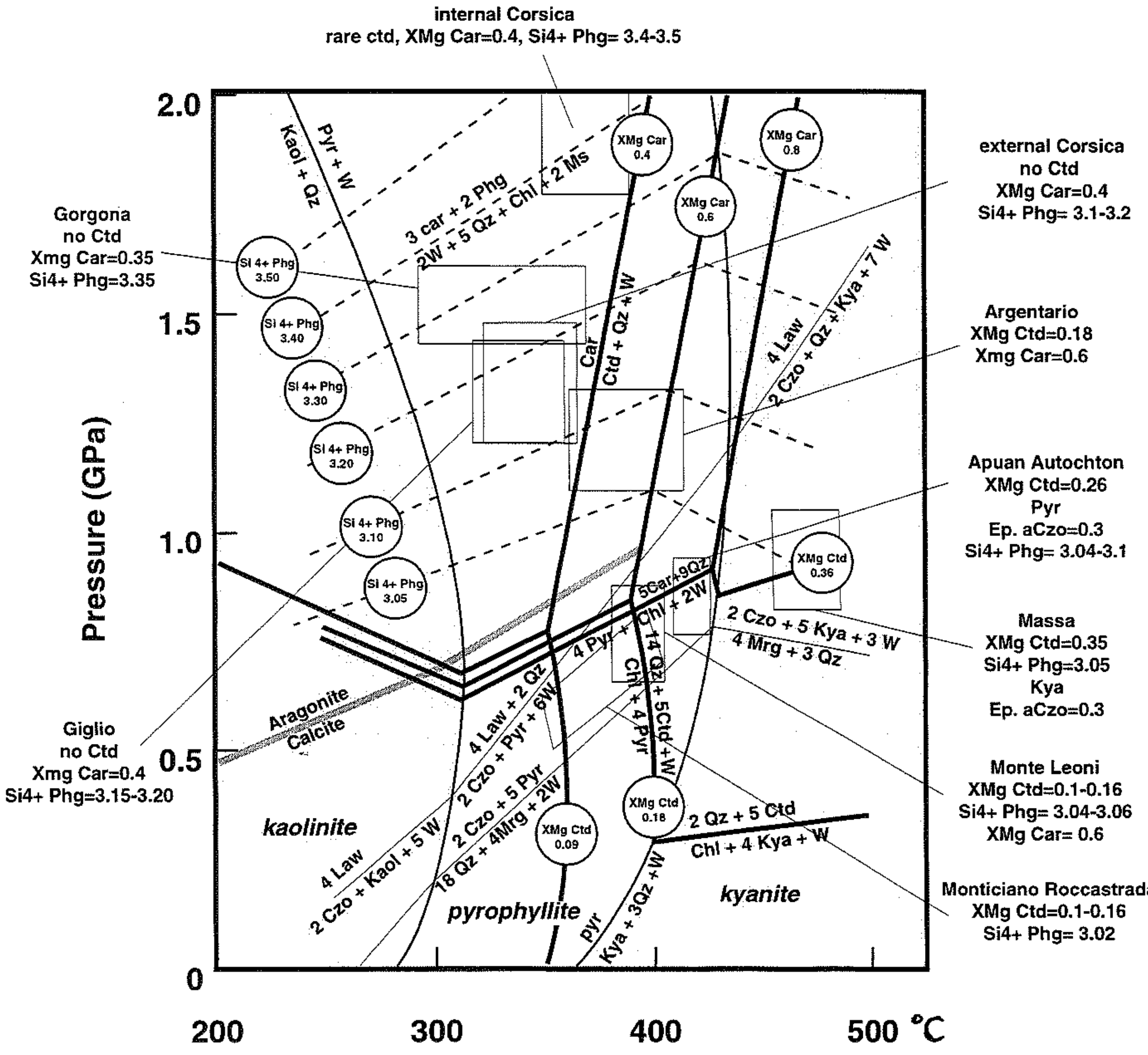


Figure 9. Pressure and temperature evolution along the transect and metamorphic reactions considered to calculate PT conditions [*Goffé and Oberhänsli*, 1992; *Vidal et al.*, 1992; *Liu and Yund*, 1993; *Oberhänsli et al.*, 1995]. Data are from this work and *Giorgetti* [1995],*Theye et al.* [1997], and Rossetti et al. (submitted manuscript, 1996). Two important reactions in the Al_2O_3, SiO_2, H_2O system limit the stability field of pyrophyllite (open domain between the two reactions) compared with those of kaolinite at low temperature and of kyanite at higher temperature. Thick lines represent the major reactions in the Fe0, MgO, Al_2O_3, SiO_2, H_2O system involving chlorite, carpholite, chloritoid, and quartz. The positions of those reactions depends upon the Fe/Mg ratio (X_{Mg}) in carpholite and chloritoid, and several examples are shown. Dotted lines represent the equilibrium reaction where carpholite appears at the expense of muscovite and chlorite in the K_2O, FeO, MgO, Al_2O_3, SiO_2, H_2O system. The position of this equilibrium is controlled by the Tshermack substitution of phengites that vary in the studied region from 3.05 to 3.5. Reactions involving margarite, lawsonite, and epidote, as well as the phase transition aragonite-calcite are also used to constrain PT conditions. Boxes show the maximum PT conditions deduced from this PT grid for each region. The PT conditions were calculated using the computer program PTAX and its database [*Berman and Perkins*, 1987; *Berman*, 1988] and new thermodynamic data for carpholite [*Vidal et al.*, 1992] and celadonite [*Massonne*, 1995]. Abbreviations are car: Fe-Mg carpholite; chl, chlorite; ctd, chloritoid; czo, clinozoisite; kaol, kaolinite; kya, kyanite; law, lawsonite; mrg, margarite; ms, muscovite; phg, phengite; pyr, pyrophyllite; qz, quartz; w, water; Si^{4+}, Tschermack substitution in phengites.

and obtained from B. Patrick and R. G. Berman (unpublished data, 1989) [*Goffé and Bousquet*, 1997]. Mineral activities were calculated following *Evans* [1990] for epidote, *Vidal et al.* [1992] for chlorite, magnesiocarpholite, magnesiochloritoid and using *Massonne*'s [1995] approach for phengites. To estimate PT conditions in the Corsica-Apennines transect, three subsystems were analyzed: one for carpholite, one for the associated phengites, and one for lawsonite and epidote. For the carpholite subsystem, calculations were performed on the basis of measured ferro- and magnesiocarpholite, chlorite and chloritoid in schists and calcschists from the Liguro-Piemontais "schistes lustrées" nappe in Corsica, from Argentario [*Theye et al.*, 1997], Giglio and Roccastrada- Monte Leoni Ridge [*Giorgetti*, 1995]. The resulting mean coefficients K_D are the following: $K_D{}^{Fe/Mg}{}_{car/ctd} = 7.0$, $K_D{}^{Fe/Mg}{}_{car/chl} = 1.2$, $K_D{}^{Fe/Mg}{}_{chl/ctd} = 5.8$. These K_D values are comparable with those observed in Crete [*Theye et al.*, 1997] and central Alpujarrides [*Azañon and Goffé*, 1997].

Isopleths for phengites were calculated using theoretical Tschermak compositions of phengites ranging from Si 3.05 to 3.5. The Fe/Mg partitioning is based on analyzed compositions of phengites associated with the ferrocarpholite in the Liguro-Piemontais domain. In these assemblages the ferrocarpholite composition is fairly constant at 55-65 mol % of pure end-member, while the phengite Tschermak substitution varies from Si 3.1 to 3.5. This observation suggests that the two substitutions vary independently, thus allowing the independent treatment of the two subsystems. For the lawsonite subsystem the activity of clinozoisite, fixed at 0.3, is derived from epidote-pyrophyllite or epidote-kyanite assemblages from Apuan and Massa units [*Goffé*, 1982, and *unpublished data,* 1982].

In the PT grid (Figure 9), carpholite-phengite and chloritoid-phengite pairs act as geobarometers, while the carpholite-chloritoid pair acts as a geothermometer. Magnesiocarpholite is stable at higher temperatures than ferrocarpholite. Pressures recorded by phengite substitution (Si = 3.1-3.5), associated with carpholite, range from 1.0 to 2.4 GPa for temperatures between 250°C and 450°C.

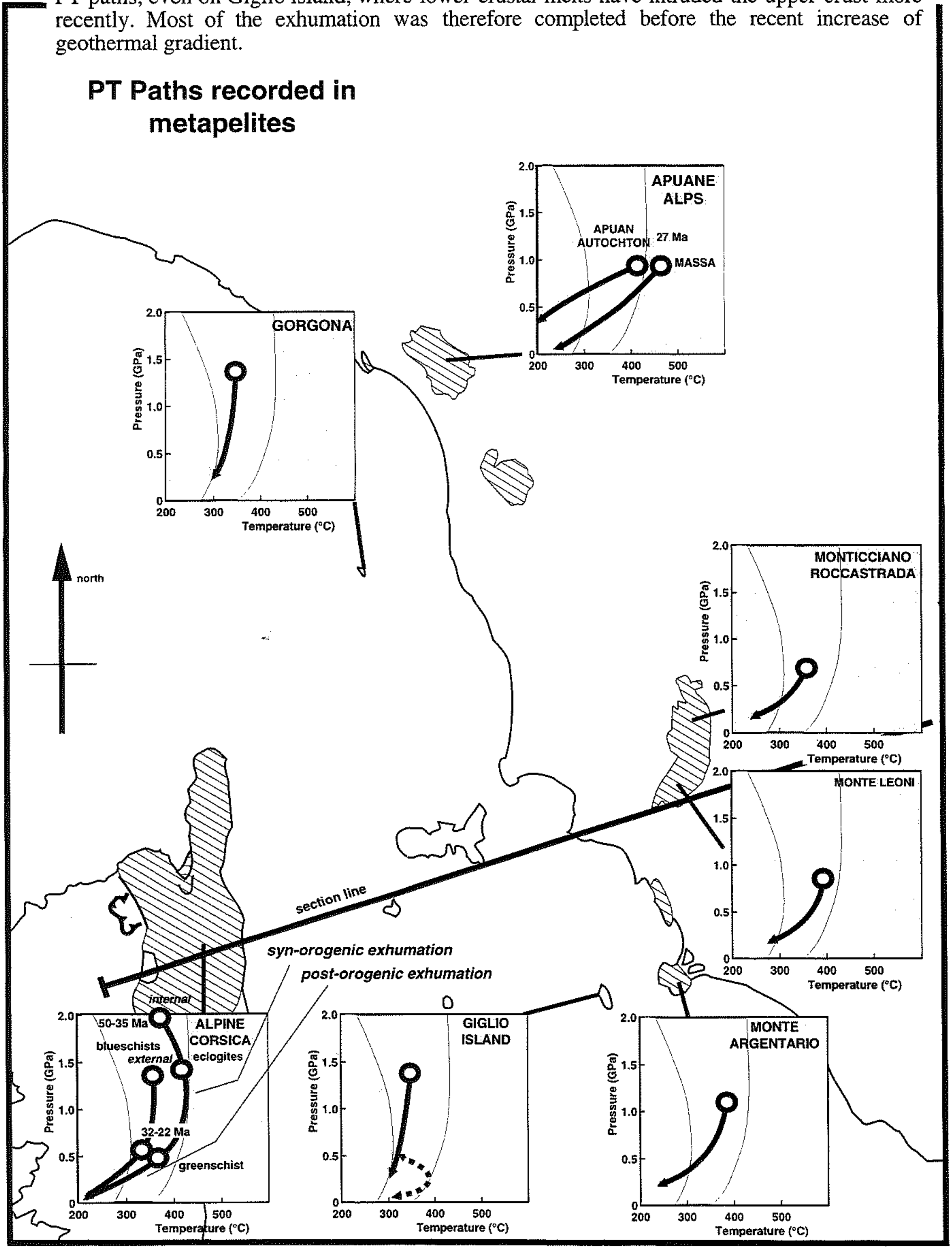
The PT grid shows that ferro- and magnesiocarpholite constitute a high-pressure and low-temperature mineral of the blueschist facies ranging from very low temperature (kaolinite stability [*Goffé et al.*, 1988; *El Shazly*, 1995], to medium temperature conditions (kyanite stability [*Azañon and Goffé*, 1997]), to temperatures of eclogites or garnet in iron rich metapelites [*Bouybaouene et al.*, 1995; *Oberhänsli et al.*, 1995; *Daniel et al.*, 1996; *Goffé and Bousquet*, 1997]. At low pressures, lawsonite- epidote and epidote-margarite phase relations in pyrophyllite-bearing or kyanite-bearing assemblages can be used to constrain PT conditions.

Note that the pressure conditions determined using the phengite compositions coexisting with carpholite or chloritoid contain large uncertainties. Indeed, the muscovite-celadonite solid solution model used here was derived from experiments conducted at temperature above 800°C [*Massonne*, 1995], and its extrapolation to lower temperatures (as inferred in this study) has not been verified. Since the pressure conditions derived from the analyses of phengites often yield values above those defined by independent estimates [*Massonne and Schreyer*, 1989; *Massonne*, 1995] (but not always [*Oberhänsli et al.*, 1995]), we believe that the pressure conditions may be overestimated by about 3-5 kbar; however, we believe that the evolution of pressure paths within the different units is correct as well as the relative positions of various PT paths within the PT grid. Using this PT grid, it is now possible to trace the metamorphic conditions in space and time along the Corsica-Apennines transect (Figure 10).

1.3.1. Alpine Corsica

Two metamorphic stages have been recognized in Corsica (Figures 9-11). The first one corresponds to high-pressure and low-temperature assemblages : eclogites and blueschists in metabasites and ferrocarpholite in metapelites [*Warburton*, 1986; *Lahondère*, 1988; *Waters*, 1990; *Caron*, 1994; *Daniel et al.*, 1996]. Fe-carpholite is widely distributed in the internal (Castagniccia) and external (Inzecca) Schistes Lustrés units. The Si^{4+} substitution of phengites associated with ferrocarpholite or chloritoid varies from Si 3.1 in the external domain to Si 3.5 in eclogites of the internal domain (Figure 9). The absence of chloritoid constrains the peak of pressure and temperature to about 1.0 GPa and 300°-350°C for the external domain. In the internal domain, chloritoid is also absent in the earlier assemblages, therefore peak PT conditions can reach 1.8-2.0 GPa and 350°-380°C. The presence of late chloritoid associated

Figure 10. Pressure and temperature evolution in the northern Tyrrhenian Sea. Maximum PT conditions are deduced from the PT grid shown in Figure 9, and the shape of PT paths is further contrained by the retrograde products after the peak of pressure (see text). A decrease of maximum pressure is observed from west to east. Exhumation is generally achieved along cold PT paths, even on Giglio island, where lower crustal melts have intruded the upper crust more recently. Most of the exhumation was therefore completed before the recent increase of geothermal gradient.



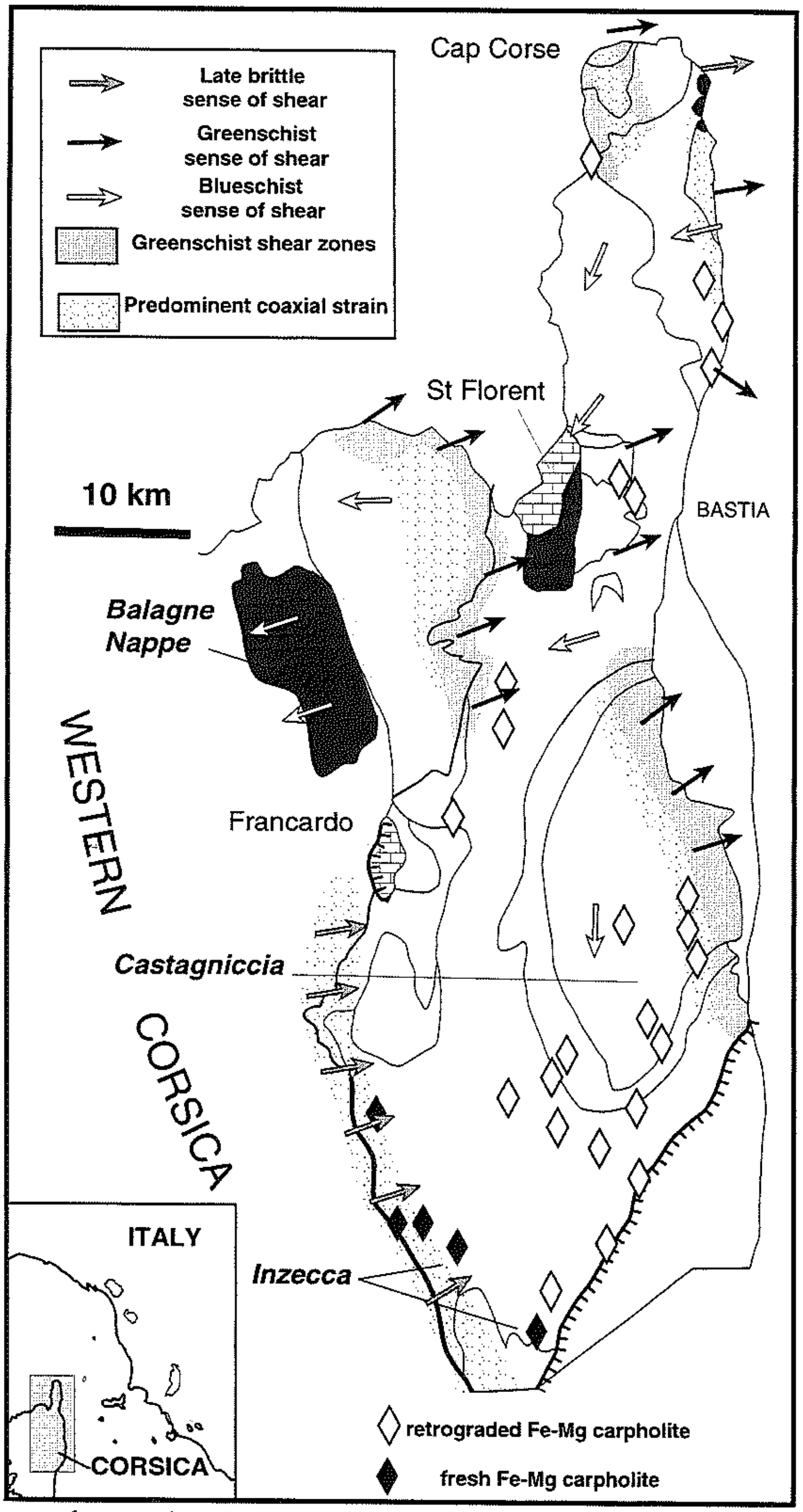
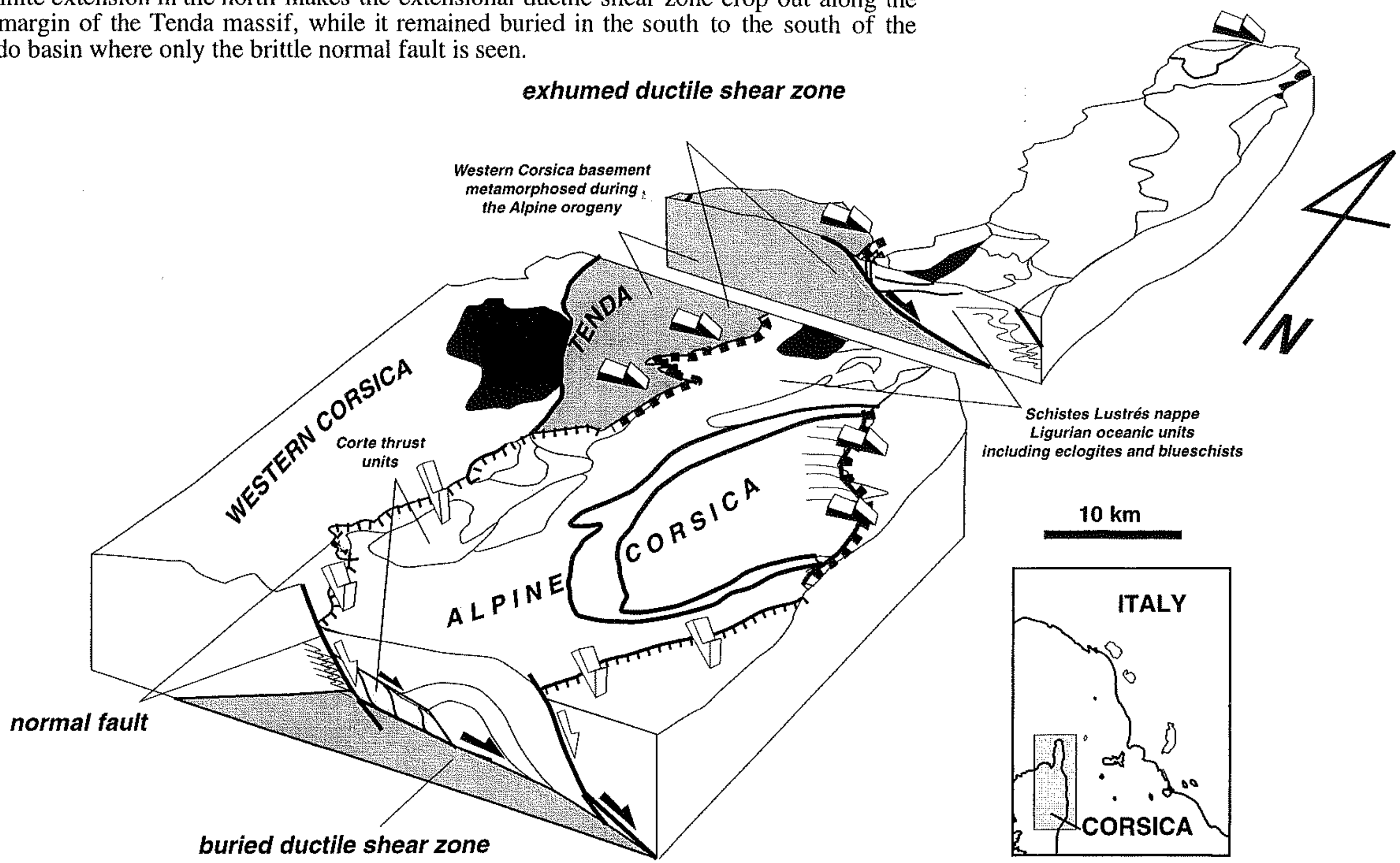


Figure 11. Structural map showing stretching lineations and occurrence of Fe-Mg carpholite in Alpine Corsica (simplified from *Fournier et al.* [1991] and *Daniel et al.* [1996]). The degree of preservation of Fe-Mg carpholite is symptomatic of the retrograde PT path. Colder exhumation is observed in the south, and warmer is seen to the north. This spatial evolution toward warmer conditions in the north is coeval with a larger finite extension in the north. Early Miocene extension is achieved by shallow, east dipping shear zones shown as lightly shaded areas. The sense of shear is consistently toward the east within the shear zones. Earlier Eo-Oligocene compressional high-pressure deformation is less well constrained because most regions show a large rejenuvation of early fabric by extension. The basal contact of the nonmetamorphosed Balagne nappe is a preserved thrust in the west and a brittle detachment in the east where it rests above highly metamorphosed Schistes Lustrés.

Figure 12. Schematic block diagram of Alpine Corsica. The oceanic Schistes Lustrés nappe was thrust over the western Corsica continental basement during the Eocene. The metamorphosed continental basement is observed in the Tenda massif and the Corte thrust units farther south. The contact between the oceanic and continental units was recently reactivated as a ductile, extensional shear zone. Other shear zones developed farther east, along the eastern margin of Alpine Corsica. All the shear zones then evolved as brittle, east dipping normal faults. Larger finite extension in the north makes the extensional ductile shear zone crop out along the eastern margin of the Tenda massif, while it remained buried in the south to the south of the Francardo basin where only the brittle normal fault is seen.



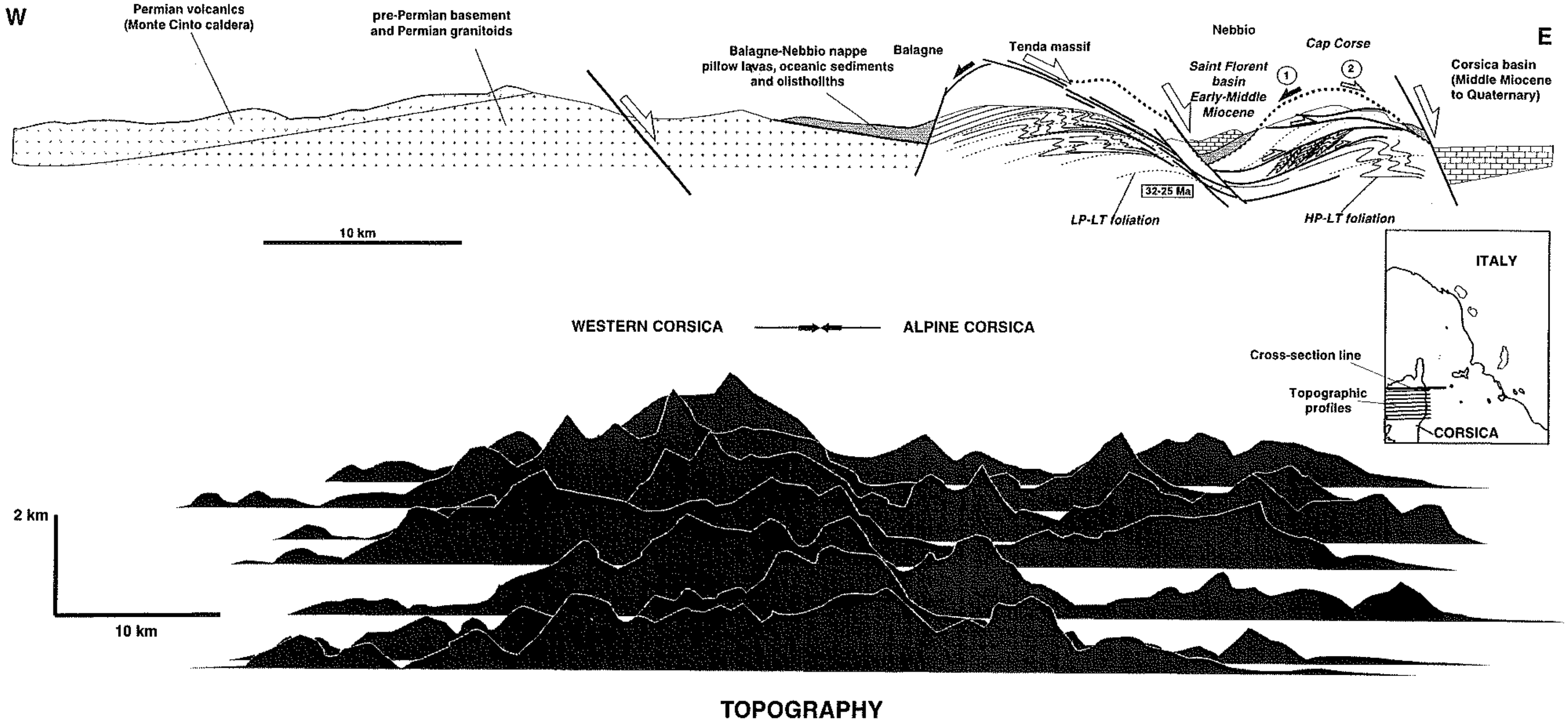


Figure 13. Cross section of Corsica and topographic profiles across the main east dipping, normal faults (modified from *Daniel et al.* [1996]). Ductile shear zones in Alpine Corsica evolve toward brittle normal faults that control the deposition of shallow marine deposits in asymmetric basins. Large-scale, brittle-normal faults control the present day morphology of western Corsica as shown by the topographic sections. The westward tilt of western Corsica is demonstrated by the attitude of Permian volcanic and volcaniclastic deposits.

with less substituted phengites (Si 3.2-3.3) in the most Fe-rich metapelites of the internal domain implies a temperature increase and a drop of pressure from the peak conditions described previously for those of lawsonite-bearing eclogites observed in the metabasites [*Caron et al.*, 1981; *Caron and Pequignot*, 1986].

The second event (greenschist facies) is recorded throughout but is more pervasive in the northern part of the island [*Daniel et al.*, 1996]. The second event is related to the extensional process [*Jolivet et al.*, 1991]. A slight temperature increase during exhumation is recognized in the northern part of the island [*Caron*, 1994; *Daniel et al.*, 1996] but not in the south where chloritoid is limited to the more ferrous compositions of the carpholite-bearing metapelites.

A large part of the exhumation from eclogite or blueschist depth occurred along a cold geotherm, probably during continuing accretion [*Jolivet et al.*, 1990; *Jolivet et al.*, 1994b]. Only the last part of the retrograde PT paths can be attributed to postorogenic extension (Figure 10) [*Fournier et al.*, 1991].

The older high-pressure metamorphic stage in the Bastia-St. Florent region is associated with top-to-the-west sense of shear [*Mattauer et al.*, 1981; *Jourdan*, 1988; *Waters*, 1990], related to the Eocene compressional episode. Farther south, most early stretching lineations trend north-south. The kinematics of the early contractional episode is still unclear in Corsica. Most east-west lineations (Figure 11) are, in fact, related to the late extensional episode [*Jolivet et al.*, 1990; *Jolivet et al.*, 1991; *Daniel et al.*, 1996].

Extension is reflected in Corsica by the presence of crustal-scale shear bands that evolved in time from a ductile to a brittle regime (Figures 12 and 13). Detailed mapping of the strain field reveals at least two extensional shear zones, one rejenuvating the original thrust contact between the continental basement and the Schistes Lustrés nappe and another along the eastern margin of Corsica. Both shear zones show top-to-the-east sense of motion. Between the two shear zones the strain is more coaxial, with a large component of vertical shortening. The period of extension ended with the formation of east dipping, brittle normal faults that are active during and after the deposition of the early and middle Miocene sediments in the Francardo, St. Florent, or East Corsica basins. For example, the boundary between western Corsica and Alpine Corsica is marked by a sharp escarpment, with the western side higher than the eastern one (Figure 13). The escarpment is interpreted [*Daniel et al.*, 1996] as a large, east dipping normal fault scarp that bounds the Francardo basin. Most of western Corsica lies in the footwall of west tilted fault block. The base of the Permian Monte Cinto volcanics is at an altitude of 1700 m in the east and below sea level along the western coast of Corsica. Extension with a top-to-the-east sense of shear occurred during and after the formation of early Miocene basins and continued after the filling of the middle Miocene basin east of Corsica.

1.3.2. Tuscany and the Tuscan Archipelago

In Tuscany and the eastern part of the Tuscan archipelago, metamorphic complexes were produced by two successive metamorphic events. The first event corresponds to high pressure and low temperature assemblages of probable late Oligocene-early Miocene age [*Kligfield et al.*, 1986]. Known since 1910, as with the metabasites of the island of Gorgona [*Lotti*, 1910; *Mazzoncini*, 1965], the presence of the high-pressure and low-temperature stage was recently confirmed by work on the Verrucano metapelitic assemblages of Monte Argentario [*Theye et al.*, 1997] and Monte Leoni [*Giorgetti*, 1995] and on the islands of Giglio (F. Rossetti et al. (Syn- versus post-orogenic extension in the Tyrrhenian Sea, the case study of Giglio island (northern Tyrrhenian Sea, Italy), submitted to *Tectonophysics*, 1997, hereinafter referred to as submitted manuscript) and Gorgona (this work). The second low-pressure event is characterized by the intrusion of Pliocene and Quaternary granitoids within the metamorphic complex of the islands of Elba and Giglio.

3.2.1. Monte Argentario. In Monte Argentario (Figure 14), high-pressure and low-temperature metamorphic assemblages in the metapelites of the Verrucano complex contain Fe-Mg carpholite, chloritoid, pyrophyllite, and late sudoite [*Theye et al.*, 1997]. Figure 14 shows the distribution of high-pressure minerals (carpholite, glaucophane, and lawsonite) within the Verrucano and Ligurian units. Metabasites of the upper unit also contain high-pressure mineral assemblages with glaucophane and lawsonite [*Theye et al.*, 1997]. X_{Mg} varies from 0.35 to 0.60 for Fe-Mg carpholite and from 0.15 to 0.18 for chloritoid. Temperature conditions can be bracketed between 350°C and 420°C. Si^{4+} of phengites averages about 3.10, implying pressure

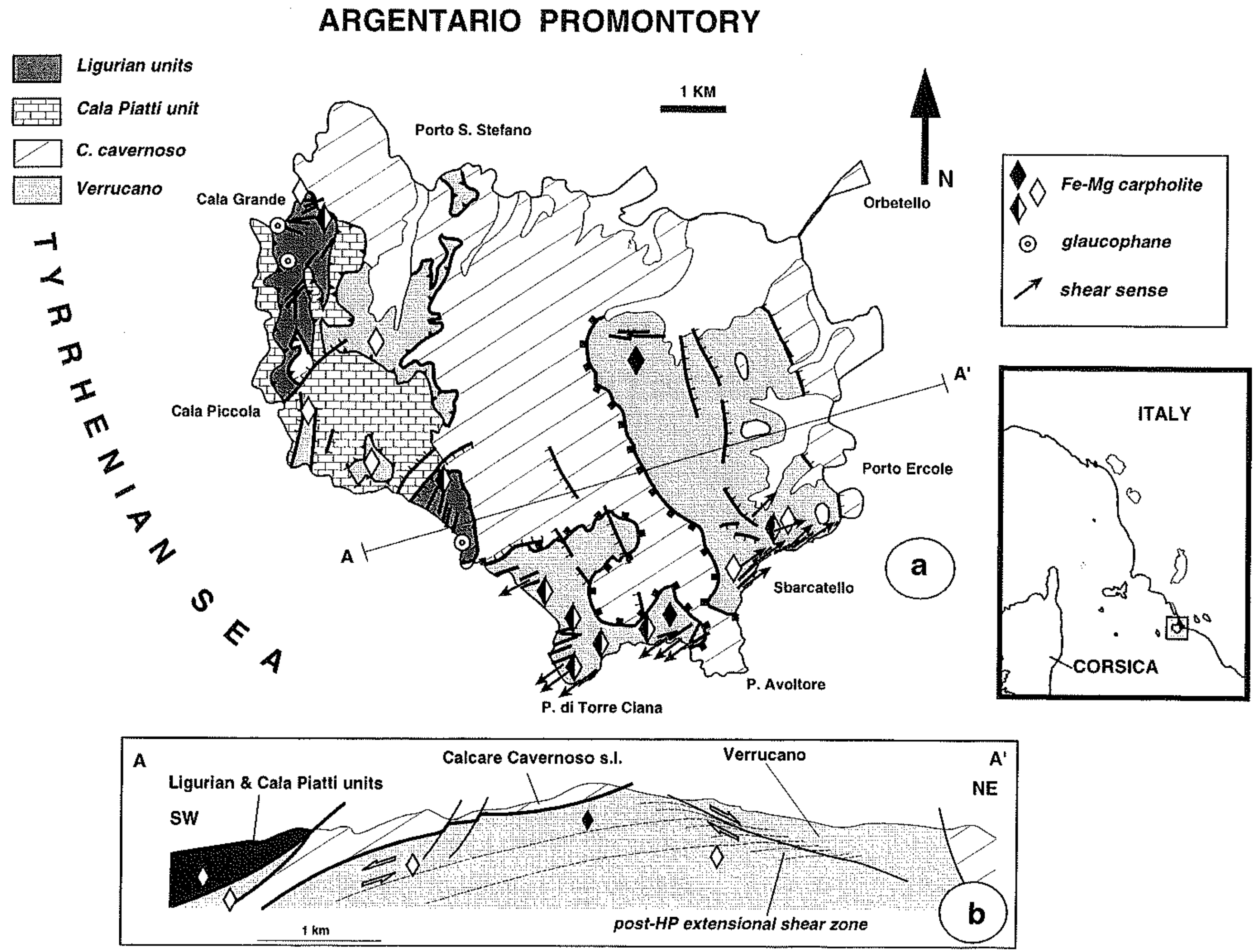


Figure 14. (a) Structural map of the Argentario peninsula and (b) cross-section showing stretching lineations, sense of shear, and occurrence of Fe-Mg carpholite and glaucophane from *Lotti* [1910], *Lazzarotto et al.* [1964] and *Brunet et al.* [1997]. The contact between the unmetamorphosed Calcare Cavernoso and the metamorphosed Verrucano is a detachment fault. The direction of stretching is consistently ENE-WSW within the Verrucano. Both senses of shear are seen. Top-to-the-east extensional shear zones seem more localized than top-to-the-west ones, and they evolve toward east dipping, normal faults. Post high pressure metamorphism thrusting is seen in the west of the peninsula where the Ligurian and Cala Piatti units that contain high-pressure parageneses are thrusted over the nonmetamorphosed Calcare Cavernoso.

conditions between 1.0 and 1.2 GPa. Those peak pressure conditions [*Theye et al.*, 1997] are compatible with the occurrence of glaucophane and lawsonite in metabasites (lawsonite blueschist facies of *Evans*, [1990]). In Monte Argentario the destabilization of carpholite into sudoite at low pressure and temperature must also be considered [*Theye et al.*, 1997]. The presence of late sudoite and kaolinite implies a retrograde PT path, with initial isothermal decompression followed by rapid cooling (Figures 9 and 10).

In Argentario Promontory, Tuscan and Ligurian units are superposed (Figure 14) [*Decandia and Lazzarotto*, 1980]. Most of the promontory is formed by the Calcare Cavernoso, part of the Tuscan nappe. High-pressure metamorphic minerals are both below and above the Cavernoso, in the Ligurian nappe, and the Verrucano facies. There is no evidence for high-pressure metamorphism within the Cavernoso itself, which suggests post high pressure contractional deformation.

Extensional shear zones are found within the lowermost unit in the Verrucano facies. They are characterized by ENE-WSW trending, stretching lineations and divergent kinematic indicators, either toward ENE or WSW (Figure 14). This deformation is associated with brittle-ductile shear bands of various scales that evolved toward brittle, shallow-dipping faults. Top-to-the-west shear is more distributed within the Verrucano than top-to-the-east shear. One east dipping extensional shear zone near Sbarcatello evolved in time into a brittle, east dipping normal fault. This event may suggest that the top-to-the-west shear is an older event in the process of exhumation. The whole stack is then cut by late, steeply dipping, normal faults.

3.2.2. Giglio. Giglio island (Figure 15), composed of 5 Myr old monzogranitic intrusives and, in the Franco Promontory, metamorphic and sedimentary assemblages [*Decandia and Lazzarotto*, 1980] was affected by two main tectonic events (Rossetti et al., submitted manuscript, 1997). The older event is contemporaneous with high-pressure and low-temperature metamorphism, and the second concurs with a post to syn-low-pressure and low-temperature stage. Both events are characterized by ductile and semibrittle strain, later overprinted by a brittle event.

In the metasediments (Figure 9) X_{Mg} varies only slightly from 0.39 to 0.45 for Fe-Mg carpholite. The absence of chloritoid implies temperature conditions below 350°C. Si^{4+} of phengites are quite constant between 3.15 and 3.20, giving pressure conditions between 1.2 and 1.4 GPa. The absence of chloritoid and aragonite implies an isothermal decompression path (Figures 9 and 10).

The only evidence for a thermal overprint of the granite within the mineralogical association of the high-pressure rocks is the presence of late stage green biotite. The overall preservation of high-pressure assemblages and the semibrittle character of the deformation suggest that the granite intruded the sedimentary units at very shallow depth once they had been exhumed. The slight thermal overprint indicated by the presence of green biotite probably occurred at low pressure. The two units were thus brought into close contact in a late tectonic event along the normal fault that bounds the granite to the west.

The second stage is the best developed event and is characterized by a penetrative L-S tectonic fabric associated with the retrograde metamorphism of the high-pressure and low-temperature minerals. Finite strain is partitioned between predominantly vertical coaxial shortening and E-W stretching and localized noncoaxial strain with top-to-the-east shear. Carpholite fibers in Verrucano metapelites are folded, boudinage and sheared during the development of the L-S fabric. Furthermore, retrograde chlorite and micas fill the gaps. The second stage thus clearly postdates the growth of the high-pressure and low-temperature phenoblasts. The evolution toward more brittle conditions is characterized by a constant east-west direction of stretching along east dipping, low-angle extensional shear zones that eliminated parts of the metamorphic zonation and placed unmetamorphosed calcareous-evaporitic rocks (Calcare Cavernoso) on top of a high-pressure assemblage.

In the main intrusive body (Giglio Monzogranite Intrusion [*Westerman et al.*, 1993]), magmatic and solid-state structures (as S and S-L fabric) are localized in the northwestern part of the island [*Burrelli and Papini*, 1992], an area that may represent the original margin of the pluton. In this area, discrete, semibrittle extensional shear zones, developed on low-angle, east dipping aplitic dikes, formed parallel to the early igneous fabric. Stretching directions strike N120°E and the sense of shear, deduced from the offset of preexisting dikes and drag along the plane of intrusion, is always top to the E and ESE. The intrusion is strongly deformed only at

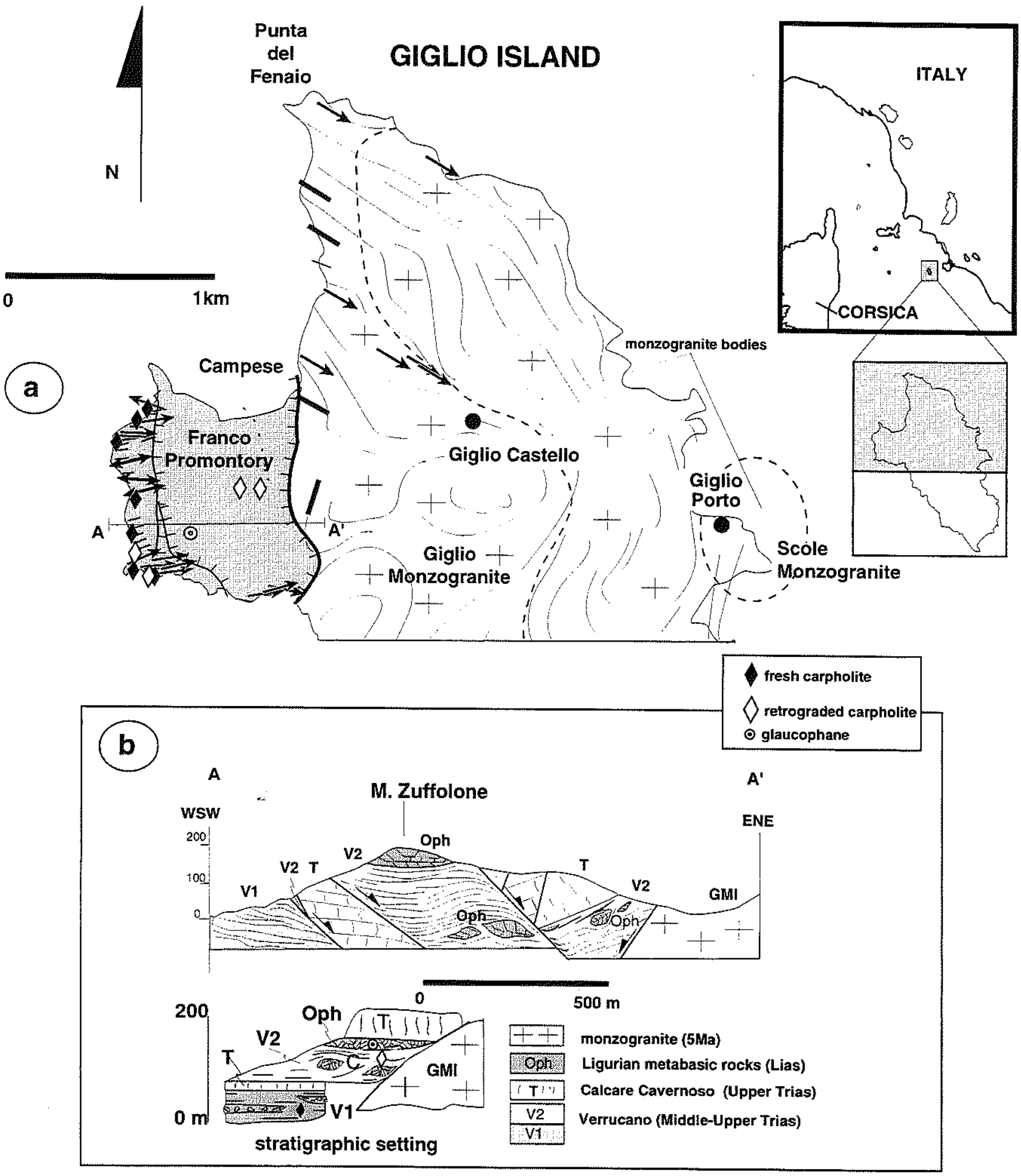


Figure 15. (a) Structural map of the island of Giglio showing stretching lineations and (b) sense of shear and occurrence of Fe-Mg carpholite and glaucophane on a cross section of Franco Promontory from *Lazzarotto et al.* [1964], *Burrelli and Papini* [1992], *Westerman et al.* [1993], Rossetti et al. [submitted manuscript, 1996]. The granitic intrusions are generally little deformed, except along its western margin, near the contact with the metamorphic rocks. The direction of stretching within the intrusion and the metamorphic complex are similar, and the sense of shear is always top to the east. High-pressure low-temperature minerals are well preserved in Franco promontory with fresh Fe-Mg carpholite and glaucophane.

Punta del Fenaio, where high shear strain occurs, and S-C fabric shows the same sense of transport.

In the late stage of cooling the pluton was subjected to an extensional regime with a top-to-the-east sense of shear. Interpretation of seismic lines indicates that a low-angle extensional shear zone is at the top of the intrusion [*Bartole*, 1995]. This suggests that the Giglio Monzogranite Intrusion was emplaced along an east dipping shear zone, which may correlate with similar structures that crop out at Franco Promontory and shear zones on Elba island [*Daniel and Jolivet*, 1995]. Vertical movement induced by the normal faulting that accompanied the late stages of intrusion are responsible for present-day contacts between the Franco Promontory metamorphic complex and the Giglio intrusives.

3.2.3. Gorgona. The island of Gorgona (Figure 16) is an isolated piece of the Schistes Lustrés nappe, and the metamorphic rocks are similar to those of Corsica. An upper ophiolitic unit contains a greenschist assemblage, while a lower unit composed of metapelites and minor metabasites indicates blueschist metamorphism. Relic blueschist boudins are preserved within a greenschist foliation. Sodic amphibole and lawsonite are found in the metabasites [*Mazzoncini*, 1965]. We recently discovered preserved Fe-Mg-carpholite reworked by the major D_2 deformation. Considering $X_{Mg} = 0.35$ for FeMg carpholite, Si^{4+} for phengites around 3.35 and the absence of chloritoid, peak pressure-temperature conditions of 1.3-1.6 GPa and 300°-350°C were associated with an isothermal decompression path (Figures 9 and 10).

A sharp NW-SE trending, NE dipping mylonitic contact separates the two units in Gorgona island (Figure 16) [*Mazzoncini*, 1965; *Capponi et al.*, 1990]. This contact parallels the second-stage mylonitic foliation, which is less steep toward the south of the island. The contact was previously interpreted as a thrust [*Capponi et al.*, 1990]. This second-stage foliation is increasingly penetrative toward the contact. In the south part of the island the second-stage schistosity is axial planar to asymmetric folds (axes from N-S to N45°E) with a top-to-the-ESE asymmetry. Those folds have the same strike across the island, except near the contact where they are rotated parallel to the strike of the schistosity. A stretching lineation is recognized near the contact between the two units and also throughout the island, with decreasing intensity away from the contact. As shown in Figure 16, its trend is constant around N120°E. Consistent kinematic indicators show a top-to-the-ESE sense of shear or a dextral-normal sense along the contact itself where the foliation is steeper.

The high-pressure stage is poorly preserved in Gorgona, but it is noticeable that where the syn-high-pressure lineation is preserved, it is north trending. Owing to the small size of the island, it is difficult to reach a conclusion on the deformation regime at the scale of the crust during stage 2. A comparison with Alpine Corsica, however, shows readily that the same processes operated on the two islands and that the ductile post high pressure deformation observed on Gorgona relates to an extensional stage. In fact, both the present-day attitude and the large difference in metamorphic pressures suggest that the contact between the two units is a detachment fault that moved the upper plate to the ESE.

3.2.4. Elba and Monte Cristo Islands. No high-pressure and low-temperature mineral assemblages were recognized on Elba (Figure 17). High-pressure mineral assemblages, if any, were completely replaced by high-temperature assemblages during the late Miocene and were obliterated by pluton emplacement. Pluton emplacement on Elba island occurred within an extensional regime [*Bouillin*, 1983; *Bouillin et al.*, 1993], well expressed by the shallow-dipping Zuccale detachment fault exposed in the eastern part of the island [*Keller and Pialli*, 1990; *Keller et al.*, 1994]. A top-to-the-east sense of motion along this brittle fault is associated with numerous smaller faults within the lower plate. A more recent study [*Daniel and Jolivet*, 1995] described the ductile deformation associated with the intrusions (Figure 17). The eastern margin of the Monte Capanne intrusion is an extensional shear zone, formed when granite intruded the Ligurian units. The development of a shallow, east dipping foliation and an E-W trending stretching lineation is observed within the pluton and its thermometamorphic aureole. Top-to-the-east kinematic indicators are observed very consistently within the shear zone. The western margin of the island contains a steep foliation that wraps around the pluton. Finite strain corresponds to shortening perpendicular to the foliation. This large-scale asymmetry of the pluton is also interpreted as large-scale top-to-the-east sense of shear. This is confirmed by the magmatic fabric of the pluton [*Bouillin et al.*, 1993]. A clear temporal link between extensional deformation with consistent top-to-the-east kinematic indicators and crystallization of high-

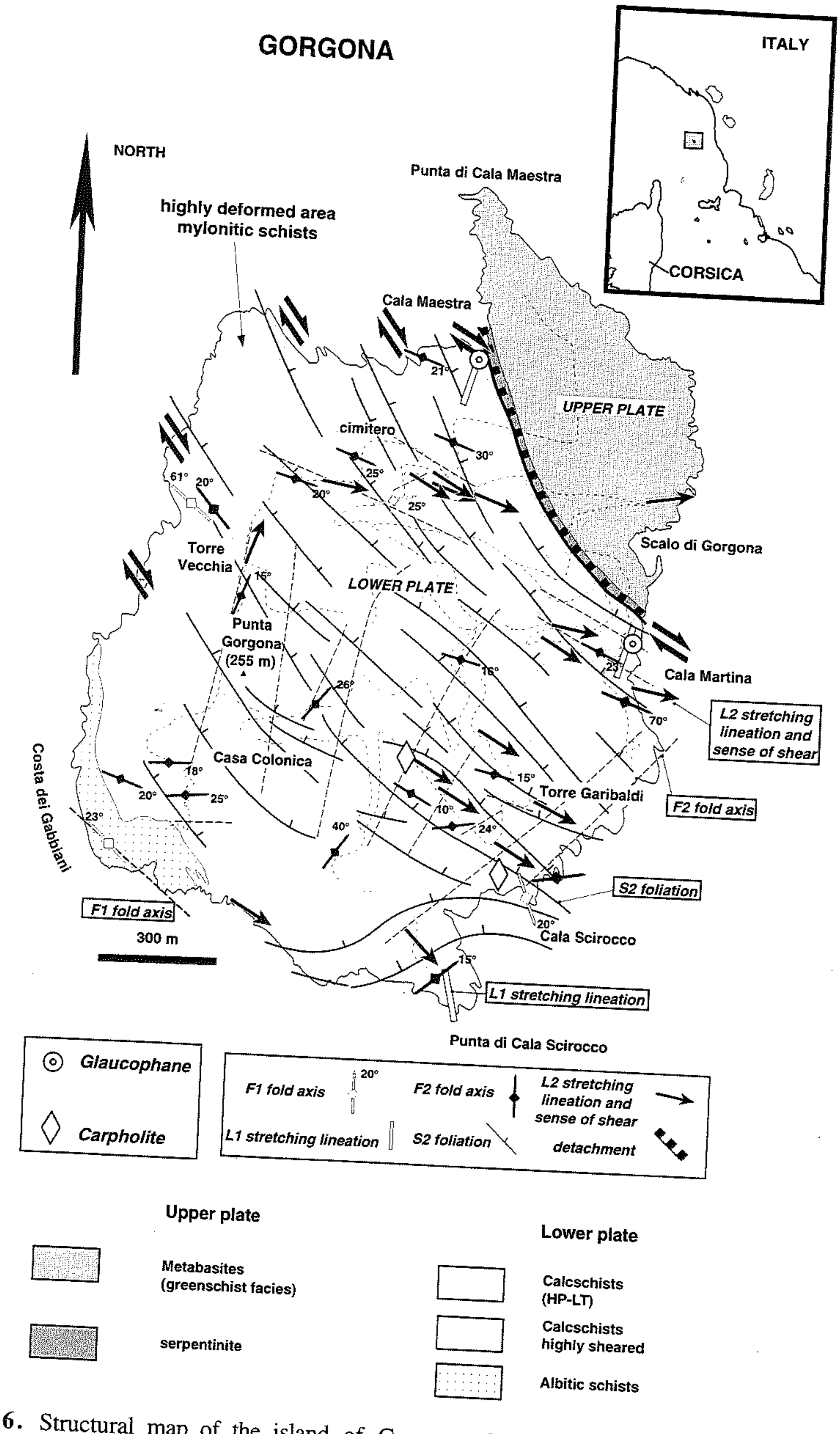


Figure 16. Structural map of the island of Gorgona showing stretching lineations and occurrence of Fe-Mg carpholite and glaucophane (from this work and *Capponi et al.* [1990]).

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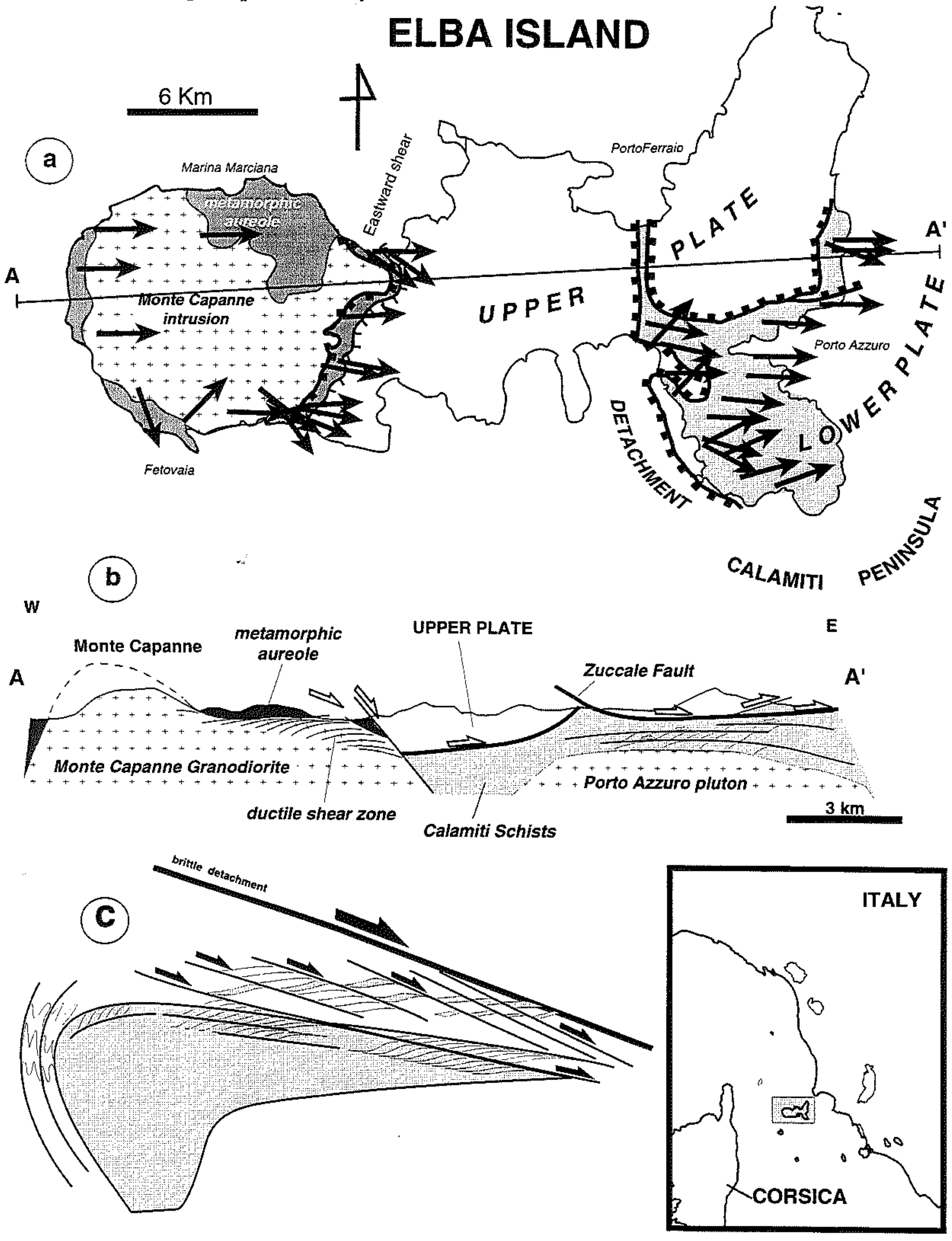
Figure 17. (a) Structural map, (b) cross-section and © schematic model for the island of Elba showing stretching lineations and sense of shear [after *Perrin*, 1974; *Keller and Pialli*, 1990; *Daniel and Jolivet*, 1995]. A brittle horizontal detachment fault separates an unmetamorphosed upper plate from a metamorphosed lower plate. High-temperature metamorphism is contemporaneous with the intrusion of two late Miocene granitic bodies (Monte Capanne and Porto Azzuro intrusions). Ductile deformation is characterized by E-W trending stretching and top-to-the-east sense of shear that evolves from ductile to brittle. The last increments of strain are contemporaneous with the activation of the Zuccale detachement and smaller, shallow-dipping, normal faults. The intrusion of Monte Capanne granodiorite is contemporaneous with the formation of a ductile extensional shear zone along its eastern margin. Figure 17c shows the geometrical relations among the pluton, its dykes, and the extensional shear zone.



temperature minerals during contact metamorphism shows that the formation of the shear zone and the intrusion were contemporaneous.

Ductile deformation is also observed below the Zuccale detachment in the eastern part of the island. In this area it is partly contemporaneous with the Porto Azzuro intrusion which is 2 Myr younger. In addition, a consistent E-W trending stretching lineation is associated with top-to-the-east kinematic indicators. The deformation evolved with time to more brittle style and was finally localized along the Zuccale Fault with the same top-to-the-east sense of shear. In summary, a migration of extension from west to east is observed on the island, and the detachment faults are clearly coeval with the intrusions.

Our preliminary study indicates that the bulk of the Monte Cristo intrusion (Figure 8) is very poorly deformed, except for localized, shallow, west dipping shear zones on the western side. These shear zones were formed during the last stages of magmatic activity where young dikes intruded a shear zone and were then sheared by the same process. E-W trending stretching lineation and top-to-the-east sense of shear are observed within the shear zones. Moreover, a late episode of brittle-normal faults is recorded in the granite

3.2.5. Monte Leoni. Monte Leoni is the southern part of the Monticciano-Roccastrada massif (Figure 8). The most common paragenesis is chloritoid, pyrophyllite, and micas. Rare Fe-Mg carpholite was recently discovered [*Giorgetti*, 1995] in veins, as well as late stage kaolinite and sudoite. X_{Mg} is around 0.6 for carpholite and 0.16 for chloritoid (Figure 9). Micas have Si^{4+} substitution of 3.06. PT conditions are compatible with the lower limit of the carpholite stability field, 0.8-1.0 GPa for 380°C. The retrograde PT path must reach 0.4 GPa and 250°C because of the presence of late kaolinite and sudoite (Figure 10).

3.2.6. Roccastrada. No carpholite has been identified in the northern part of the Monticiano-Roccastrada massif. The common mineral assemblage is otherwise similar to that of Monte Leoni. X_{Mg} for chloritoid is about 0.15, and Si4+ of phengite 3.02 (Figures 9 and 10). Peak PT conditions are 0.6-0.8 GPa and 350°C [*Giorgetti*, 1995].

3.2.7. Apuan Alps. The Apuan Alps (Figure 8) are just to the north of the transect, but the significance of extensional deformation in this area is of great importance for the evolution of the entire area, and their geology may answer the question: does the large-scale detachment that unroofed the metamorphic units relate to the accretionary stage of the internal Apennines or to crustal-scale, postorogenic extension and opening of the Tyrrhenian Sea ?

The Apuan Alps (Figures 18 and 19) have been described [*Carmignani and Kligfield*, 1990] as a metamorphic core complex because of the presence of a thick tectonic breccia (Calcare Cavernoso) between the unmetamorphosed (Tuscan and Ligurian) and metamorphosed units (Massa and Apuan autochthon). A metamorphic gap is observed across the base of the Tuscan units, with unmetamorphosed rocks above and locally high pressure metamorphic rocks below [*Carmignani and Kligfield*, 1990]. Metamorphism is expressed differently in the Massa unit (kyanite, chloritoid, phengites) and the "autochthonous" Apuan basement and cover (aragonite, chloritoid, epidote, pyrophyllite, chlorite, and phengites) [*Di Sabatino et al.*, 1977; *Goffé*, 1982]. Undoubtedly, there is a great contrast in deformation and metamorphic style across the basal contact of the Calcare Cavernoso, with mostly brittle deformation above and ductile deformation below.

Though suitable compositions can be found throughout the Apuan autochthon, no carpholite, nor carpholite relicts has been observed. This fact suggests that metamorphism has never reached the stability field of carpholite. Metaargillite of Triassic age can be used to calculate PT conditions. Their paragenesis is chloritoid, pyrophyllite, epidote, quartz, and phengites [*Goffé*, 1982]. X_{Mg} for chloritoid is about 0.26, the activity of clinozoisite in epidote is about 0.3, and Si^{4+} substitution in phengites varies from 3.04 to 3.1. PT conditions are bracketed in the common stability field of pyrophyllite and epidote, bounded at high pressure by the appearance of lawsonite and quartz and at low pressure by margarite and quartz. For the observed composition of chloritoid, calculated temperature is between 390°C and 410°C, and pressure is about 0.8 GPa. Mg carpholite (X_{Mg} = 0.8) could appear with such PT conditions but only for Mg-rich compositions. These compositions have not yet been found in the Apuan autochthon. The retrograde PT path is further constrained by the preservation of aragonite in marbles [*Di Sabatino et al.*, 1977]. The presence of aragonite implies that the aragonite-calcite transition curve was crossed at temperatures about 200°C at 0.5 GPa [*Gillet and Goffé*, 1988; *Liu and Yund*, 1993]. Such a PT path crosses into the stability field of lawsonite, however lawsonite

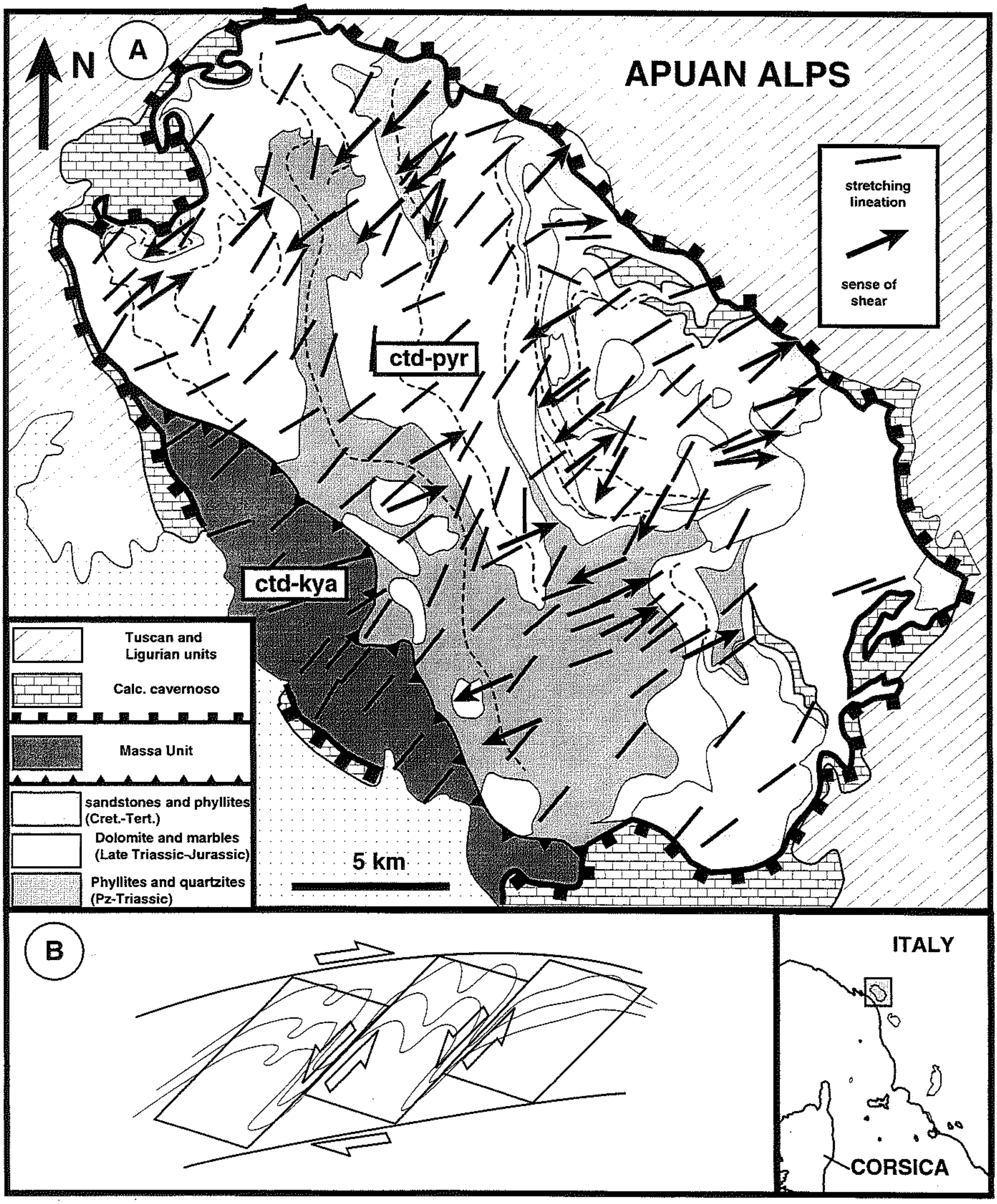


Figure 18. (a) Structural map of the Apuan Alps showing stretching lineations and sense of shear [from *Carmignani and Kligfield*, 1990, and this work]. A detachment fault separates the unmetamorphosed Calcare Cavernoso and the Tuscan and Ligurian units from the underlying metamorphosed Massa and Apuan units. (b) Schematic model explaining opposite sense of shear occurring during progressive eastward thrusting. A general top-to-the-northeast shear is accommodated by the rotation of dominos, and antithetic shear occurs along the contacts. The superimposition of a kyanite-bearing unit on top of a pyrophyllite-bearing unit suggests postmetamorphic shortening and that most of the exhumation occurred before the Tyrrhenian extension.

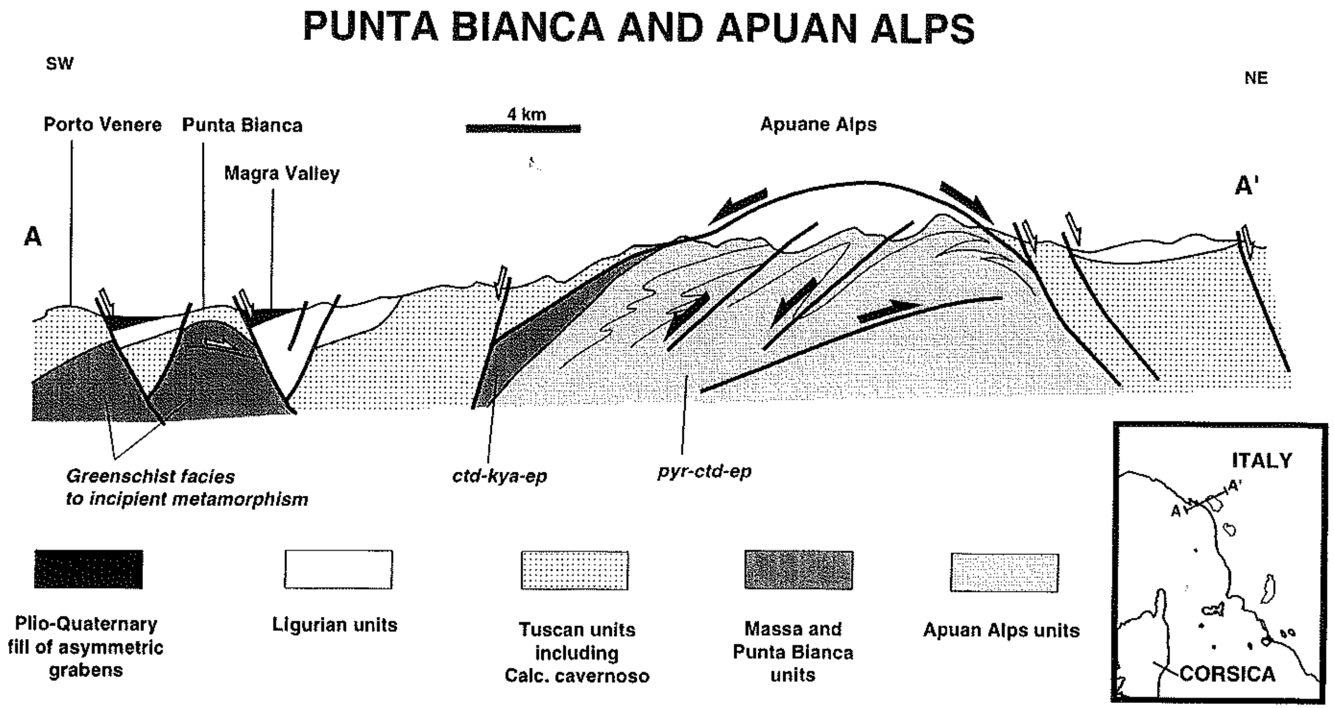


Figure 19. Cross-section from Punta Bianca to the Apuan Alps (adapted from *Carmignani and Kligfield* [1990], and *Storti* [1995]). Location of section line is shown on Figure 8 and in the inset. Steeply dipping, normal faults cut through a detachment that unroofs the Apuan Alps core complex and horizontal foliations in the Apuan Alps and Punta Bianca. The recent normal faults control asymmetric Plio-Quaternary basins with a westward tilt on either side of Punta Bianca. A horizontal brittle detachment also cut by recent normal faults with a top-to-the-west motion of the upper plate is observed in the Punta Bianca complex. Postmetamorphic shortening is shown in the Apuan Alps by the superimposition of the Massa unit onto the Apuan units.

has not yet been found. On the other hand, the formation of lawsonite could have been inhibited by the limited amount of available water. The PT path thus displays a large drop in temperature during decompression (Figures 9 and 10).

Carpholite has not been found in the Massa unit. The major differences between the Massa unit and the Apuan authochton are the presence of kyanite [*Franceschelli et al.*, 1986] and the high Mg content of chloritoid ($X_{Mg} = 0.35$). Si4+ of associated phengites is around 3.05, and the activity of clinozoisite in epidote is 0.3. This contrains the pressure to 0.9 GPa for a temperature of 450°-480°C. The retrograde PT path is constrained by the stability of epidote and the absence of margarite and aragonite. A cooling during decompression is thus recorded as in the Apuan autochthon (Figures 9 and 10).

The mineral assemblages observed in the Massa unit and Apuan autochthon show that post high pressure thrusting was involved in the exhumation of the metamorphic complex. PT estimates show that the Massa unit was heated to higher temperature and perhaps subjected to slightly higher pressures than the Apuan autochthon. These estimates show that the Massa unit, which now rests structurally above the autochthon, underwent higher P and T conditions and was thus buried deeper than the Apuan autochthon. The contact between the two units is thus a thrust that was formed after the high-pressure metamorphic episode in rather low pressure conditions. The retrograde PT paths in both units are also compatible with a very cool gradient during exhumation in an orogenic wedge [*Gillet and Goffé*, 1988; *Jolivet et al.*, 1996].

The lower nappe stack displays large-scale overturned folds separated by major shear zones. Stretching direction within the metamorphic rocks is consistently northeast-southwest, and top-to-the-northeast sense of shear is observed along the major shear zones as well, as below the Calcare Cavernoso along the eastern margin of the complex (Figure 18). Top-to-the-SW kinematic indicators are observed locally between the major shear zones where cascade-type folds with slightly west dipping or horizontal fold axes are observed [*Carmignani and Kligfield*, 1990]. Those domains are interpreted [*Carmignani and Kligfield*, 1990] as second-stage shear zones with top-to-the-SW sense of shear which are responsible for crustal thinning. An alternative interpretation is that the top-to-the-SW sense of shear is related to local shear zones conjugate to the major top-to-the-NE thrusts, accommodating rotation of rigid blocks within the major top-to-the-NE shear during the construction of the nappe stack (Figure 18).

In the Punta Bianca peninsula (Figures 8 and 19) all units are arranged in a broad anticline plunging gently to the NW. Five sets of structures are recognized [*Storti*, 1995]. The first three correspond to ductile and semibrittle deformation. They were followed by high-angle extensional faulting. The second deformation is the most penetrative, and opposing kinematic indicators are observed on either sides of the anticlinal hinge zone. This deformation is interpreted as local extension within the hinge zone of a regional anticline related to the construction of the northern Apennines [*Storti*, 1995]. It may be related to the major deformation seen in the Apuan Alps as discussed above.

Later extensional brittle and semibrittle shear zones indicate tectonic transport to the northeast. Two detachment faults are observed along the western side of the promontory, one juxtaposes upper Oligocene-lower Miocene formation on Triassic quartzites and the other places the upper Cretaceous Scaglia formation on top of lower Jurassic rocks. These low-angle detachment faults were later dissected by steep normal faults that caused the opening of the La Spezia and Lower Magra Valley grabens. Both of these grabens are filled with west dipping, fluvio-lacustrine sediments of early Pliocene age [*Bertoldi*, 1988], which are unconformably overlain by flat-lying, upper Pleistocene fluvial conglomerates [*Raggi*, 1988] The westward tilt of the fluvio-lacustrine sediments is compatible with the top-to-the-east sense of motion seen along the two detachment faults described above.

1.3.3. Discussion of a Model

1.3.4. Conclusions on the Metamorphic Evolution

1. The peak pressure of metamorphism decreases to the east (Figure 10). This trend may relate to either differences in crustal thickening or degree of exhumation. The preferred model is that finite thickening has been increasingly less important in the belt during its eastward migration. A crustal thickness of 60 km may have been attained in Corsica, but only 45 km were reached below the Apennines if maximum metamorphic pressures are considered. The

present-day thickness of the Alps and the Apennines is very similar to those crude estimates. The alternative reason is that exhumation has been less important toward the east and that only upper parts of the thrust wedge were exhumed from below the Apennines.

2. The cool PT paths recorded in all the core complexes suggest that synorogenic exhumation is responsible for most of the retrograde path. Examples of synorogenic exhumation of high pressure and low temperature metamorphics rocks show such cool PT paths [*Jolivet et al.*, 1996] often involve an efficient cooling during decompression. The continuous underthrusting of cold sedimentary or basement units below the nappe prevents a thermal reequilibration of buried rocks [*Davy and Gillet*, 1986]. Postorogenic exhumation is instead often characterized by a loop toward high temperature [*Buick and Holland*, 1989]. Only the slight temperature increase observed in Giglio, the synintrusion detachments of Giglio, Monte Cristo, and Elba, and the pervasive greenschist retrogression and extensional shear zones of the northern part of Alpine Corsica can be attributed to postorogenic extension. The post-metamorphic contraction observed in the Apuan Alps is in agreement with this conclusion. It shows that a large part of the exhumation had already occurred when the thrust contact between the Apuan autochthon and the Massa unit was formed, i. e., before the onset of crustal-scale extension in this area. The very cold retrograde path recorded in those two units also favors synorogenic exhumation.

1.3.5. Regional Significance of Extension in the Apuan Alps

The comparison of the Apuan Alps and Punta Bianca with a cordilleran-type metamorphic core complex [*Carmignani and Kligfield*, 1990; *Carmignani et al.*, 1994] implies that crustal thinning produced the ductile deformation in the core. The metamorphic relations between units imply a significant postmetamorphic shortening. This leads us to the conclusion that a large part of the exhumation occurred before the recent crustal thinning. The pressure gap seen across the tectonic breccia is probably, in large part, the result of synorogenic extension during the formation of the internal Apennines thrust wedge in the late Oligocene-Miocene [*Storti*, 1995].

The significance of the Apuan Alps detachment fault must then be reconsidered. It can be compared with the detachment observed in Crete [*Jolivet et al.*, 1996], below which the high-pressure assemblages are well preserved and which was probably formed at the top of a growing thrust wedge. We do not object to the extensional nature of the basal contact of the Calcare Cavernoso, but we suggest that it is not comparable with other core complexes found in the Basin and Range Province of the western United States or the Aegean. Extensional tectonics observed in the Apuan Alps, except for recent steep-normal faults, would not be a consequence of the Tyrrhenian extension but, rather, of the earlier construction of the nappe stack in the internal zones of the Apennines. This interpretation agrees with the conclusions of others e. g. *Carmignani et al.*, [1978].

Crustal extension, leading to the thinning of the crust and formation of the Tyrrhenian Sea, probably did not begin before the late Miocene in this region. The major difference between our interpretation and the classical one [*Carmignani and Kligfield*, 1990] is the age of inception of extension. In our interpretation the ductile deformation in the Apuan Alps is not related to the formation of the Tyrrhenian Sea but, rather, to the construction of the internal Apennines as a thrust wedge. Outcrops that reveal the ductile expression of the Tyrrhenian extension do not occur in the mainland of Italy. Such outcrops are found only farther west in the Tuscan archipelago, in Elba or Giglio, and are associated with recent granodiorites. The retrograde PT path of high-pressure and low-temperature metamorphic rocks recorded in Giglio island also suggests that much of the exhumation occurred under low-temperature conditions. These conditions are hardly compatible with the high heat flow expected during the intrusion of the granites.

1.3.6. Age of Deformation Along the Transect

In Corsica the first high pressure episode of metamorphism yielded Late Cretaceous radiometric ages [*Maluski*, 1977; *Cohen et al.*, 1981]. However, some lower Eocene sediments have been subjected to one stage of high-pressure metamorphism [*Bézert and Caby*, 1989; *Caron*, 1994]. Recent $^{40}Ar/^{39}Ar$ ages on phengites in the Schistes Lustres nappe [*Lahondère*, 1994] are about 40 Ma, and now most authors consider a late Eocene age for the high-pressure stage [*Bézert and Caby*, 1989; *Caron*, 1994]. This age is consistent with the high pressure episode in the Schistes Lustres nappe of the Alps where both eclogites and blueschist formed

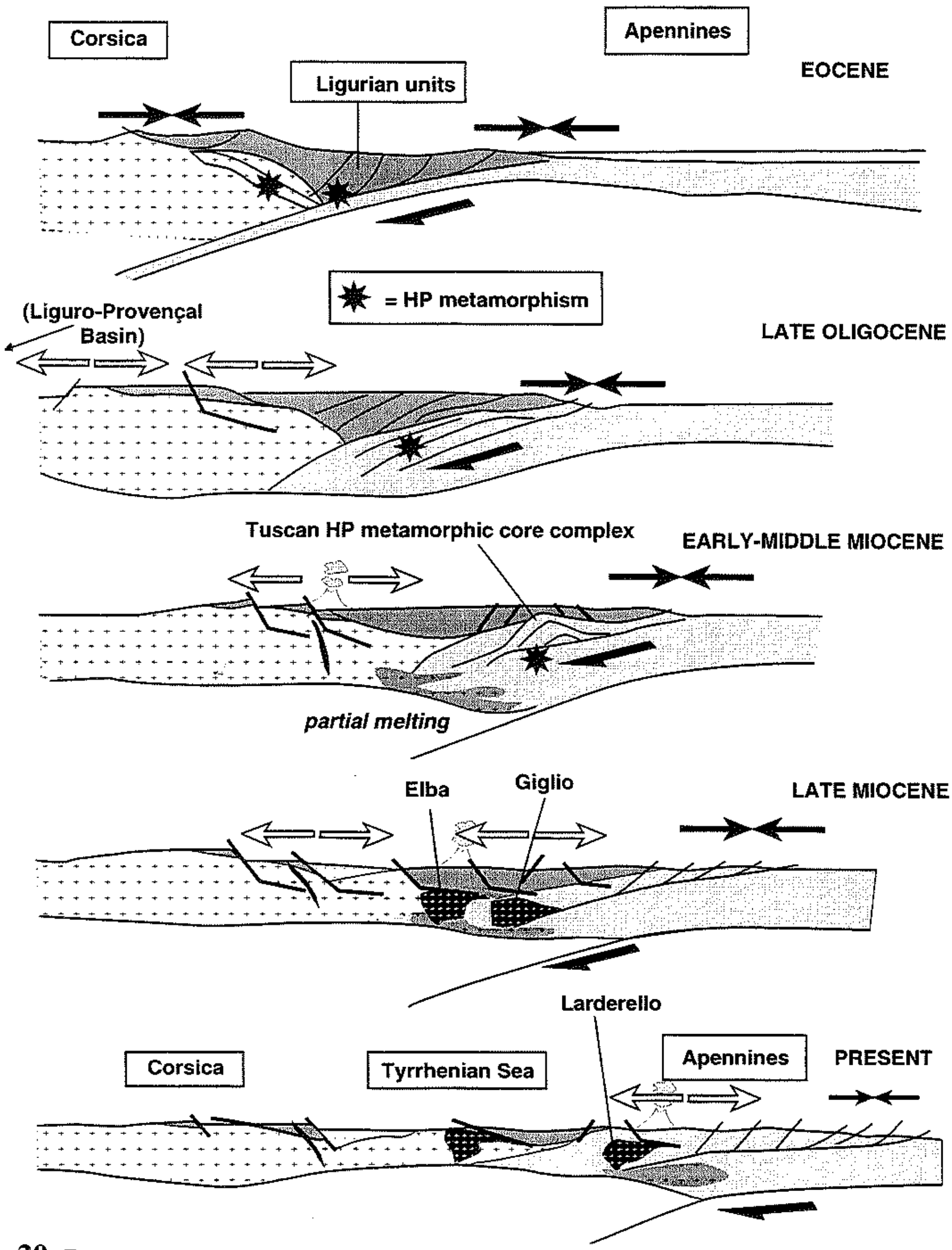


Figure 20. Evolutionary model along the transect from Corsica to the northern see Figure 9 for location). During the Eocene, westward subduction below the continental basement of western Corsica and formation of an accretionnary complex occur. During this stage high-pressure and low-temperature metamorphic rocks are exhumed. The precise kinematics of deformation during this stage is largely unknown. During the late Oligocene to middle Miocene the following occurs, migration of the thrust front eastward during the rollback of the Apennines subduction and first extension in the back arc region; rifting of the Liguro-Provençal basin; first extension in Alpine Corsica along shallow, east dipping, ductile shear zones and east dipping normal faults; formation of high-pressure and low-temperature metamorphic rocks in the deep parts of the accretionary complex (Apuan Alps, Giglio, Gorgona, Argentario, and Roccastarada) and its rapid exhumation; first magmatism west of Corsica, oceanic crust formation in the Liguro-Provençal basin, and fast rotation of Corsica-Sardinia. During the late Miocene to early Pliocene, eastward migration of the Apennines thrust front continues; extension migrates to the region of Elba, Monte Cristo, and Giglio with the same geometry as in Corsica; and intrusion of granodiorites occur-s below the major detachments. During the late Pliocene to present: migration of the thrust front occurs toward its present position, extension migrates into the Apennines, slow convergence occurs in the Adriatic Sea, and intrusions take place in the geothermal field of Larderello and Monte Amiata.

during the Eocene. Recent $^{40}Ar/^{39}Ar$ dates on phengites confirm this Eocene age [*Brunet et al.*, 1997]. In Tuscany, radiometric ages of high pressure metamorphism (K-Ar and $^{40}Ar/^{39}Ar$ method) are available for the Apuan Alps and Elba Island, where ages of 27 Ma [*Kligfield et al.*, 1986] and 20 Ma were determined [*Deino et al.*, 1992], respectively. More recently similar ages were obtained in Gorgona and Monte Argentario [*Brunet et al.*, 1997].

In Corsica radiometric ages on phengites ($^{40}Ar/^{39}Ar$) within the east Tenda ductile shear zone yield Oligocene ages (30-35 Ma) (Maluski [*Jourdan*, 1988]). The late greenschist episode related to top-to-the-east sense of shear (extension) within the Shistes Lustrés nappe was dated at 30-32 Ma [*Jourdan*, 1988]. Samples collected in a transect across the Tenda massif and the Cap Corse for Ar-Ar dating on phengites reveal that ages become younger toward the extensional shear zones, starting at 50-60 Ma in rocks where high-pressure parageneses are well preserved to 25-22 Ma within the highly sheared greenschist gneiss of the East Tenda Shear Zone [*Brunet et al.*, 1997]. There is therefore a progressive transition in time from the ductile extension dated at 35 to 22 Ma to the deposition of the Burdigalian limestone in half grabens some 20 Myr ago. Extension also continued after the deposition of the Miocene limestones as revealed by the tilting of the St. Florent and Francardo basins and the recent morphology of Corsica, the result of crustal-scale block tilting [*Daniel et al.*, 1996]. Extension continued during the Middle Miocene and shifted eastward. The Cap Corse lamprophyres, dated at 15 Ma were emplaced along conjugate normal faults. Moreover, extension in Elba, Monte Cristo, and Giglio was likely active until the upper Miocene-lower Pliocene, as it was contemporaneous with the intrusion of the granitoids 8-5 Myr ago.

Synrift deposits filling extensional basins place a further constraint on the age of extension. Extension ranges from 15 to 20 Ma in the Corsica basin to Pleistocene along the Apennine watershed, where normal faults are presently active (Figures 3 and 5) [*Elter et al.*, 1975; *Bossio et al.*, 1993; *Martini and Sagri*, 1993; *Bartole*, 1995]. Magmatic activity accompanies the end of the synrift growth of basins (Figure 3). Both extensional basins and magmatic centers shift eastward at an average velocity of 1.5-2 cm/yr. Synrift deposits are usually a few million years older than the age of the first magmatic event in one given region, and the ages of sedimentation and magmatism merge along the profile from west to east.

1.3.7. Synorogenic versus Postorogenic Extension Along the Transect

Synorogenic extension is recognized in Gorgona and Giglio islands, Monte Argentario, and the Apuan Alps. It is characterized by localized detachment zones that bring tectonic units with different burial histories together without any significant overprinting of high-pressure and low-temperature mineral assemblages. A cool geotherm during exhumation is required by the proximity to the convergence front.

Postorogenic extension is recognized along the transect. It is characterized by late normal faults in Gorgona and Giglio islands, Monte Argentario, and the Apuan Alps and by ductile shear zones and normal faults in Alpine Corsica, Isola d'Elba, and Monte Cristo. Where ductile deformation is observed, overprinting of earlier high-pressure and low-temperature mineral assemblages is observed. In Alpine Corsica the south-to-north gradient of extension is coeval with a gradient of greenschist retrograde metamorphism.

In Isola d'Elba no relict of the high-pressure episode is observed and early mineral assemblages have been completely overprinted by high-temperature ones. It is thus impossible to observe synorogenic deformation there.

In Alpine Corsica syn-high-pressure deformation, where it is preserved, shows top-to-the-west sense of shear, compatible with the underthrusting of the Variscan basement of western Corsica below the Schistes Lustrés oceanic units [*Mattauer et al.*, 1981]. The question of synorogenic extension in Alpine Corsica is then posed. High-pressure metamorphic rocks that have recorded various maximum pressure conditions can be found, but the finite geometry is mostly due to Miocene extension. Our present knowledge does not us allow to clearly recognize Eocene extensional structures.

1.3.8. Migration of Compression, Exhumation, Extension, Basin Formation and Magmatism

The E-W transect running from Corsica to the northern Apennines is characterized by the coeval migration of compression in the arc front and extension in the backarc region. Eastward migration of deformation in both regions is accompanied by eastward migration of magmatic activity and sedimentation (Figures 3 and 20). An example is the contemporaneity of extension in Corsica (from 25 Ma) and of the formation of a nappe stack in the Apuan Alps (27 Ma), the Plio-Quaternary setting, with an active thrust wedge in the east (Apennines) and postorogenic extension in the west, already existed during the Miocene, offset by some 200 km to the west. At a larger scale this migration also involved the Liguro-Provençal basin to the west of Corsica where extension started in the Oligocene and deformed an Hercynian crust.

Our data allow better constraints to be placed on the evolution of the inner part of the Alpine Corsica-northern Apennines thrust wedge. Two main extensional episodes, synorogenic and postorogenic, are recognized.

4.5.1. Synorogenic extension. Formation of high-pressure low-temperature metamorphic rocks was followed closely by their exhumation along a high-pressure and low-temperature gradients during underthrusting and thrust wedge formation. Structural data indicate that exhumation is accompanied by extensional deformation, such as detachments and smaller scale extensional shear zones. Therefore, before postorogenic extension occurs in a given region, high-pressure and low-temperature metamorphic rocks were already exhumed along a cool gradient during continuous underthrusting of cold units. Rocks of this early stage are exposed in Corsica, Argentario Promontory, Giglio island, Punta Bianca promontory, and Apuan Alps. Tectonic thinning of the Tuscan nappe sequence [*Carmignani et al.*, 1994] may have occurred during this orogenic episode as synorogenic extension. The age of this tectonic episode in the inner part of the thrust wedge occurred between the late Eocene in Corsica and the early-middle Miocene in the Apennines with a overall eastward migration.

4.5.2. Postorogenic extension. Crustal thinning and magmatism are accommodated by east dipping normal faults and flat-lying extensional shear zones in the ductile (or brittle ductile) domain (postorogenic extension). During postorogenic extension, structures responsible for crustal thinning, from Corsica to the Tyrrhenian domain, were very similar through time. Shallow, east dipping extensional shear zones within the brittle-ductile transition zone controlled the uplift of the postorogenic intrusives, and east and west dipping normal faults controlled the deposition of sediments within asymmetric basins. The geometrical and kinematic relations in Elba and Giglio islands between the intrusion and the host rocks and the geometry of the ductile extensional shear zones are probably a good analog to what is now happening below the Larderello geothermal field.

This migration of extension and magmatism from west to east can be compared to a similar pattern observed in the southern Tyrrhenian basin. The results of Ocean Drilling Program Leg 107 [*Kastens and Mascle*, 1990; *Mascle and Réhault*, 1990] showed a migration of subsidence and extensional tectonics from the eastern margin of Sardinia toward the center of the southern Tyrrhenian Sea, from NW to SE, starting in the middle Miocene and continuing to the present. Large extensional strain caused a complete rupture of the continental crust and formation of oceanic crust. In this last stage a migration toward the east is observed as the Vavilov basin opened during the Pliocene and the currently active Marsili basin began to form 2 Myr ago.

1.3.9. Comparison of Migration of Extension and Magmatism in the Tyrrhenian and Aegean Seas

The most striking characteristics of this transect are (1) the eastward migration of extension and (2) the constant top-to-the-east sense of shear along ductile extensional shear zones from the early Miocene in Corsica and Gorgona to the upper Miocene-Pliocene in Elba, Giglio, and Punta Bianca. These characteristics are discussed herein and compared with the example of the Aegean Sea, where constant shear sense has also been documented.

4.6.1. The Aegean Sea. The Aegean domain (Figures 1 and 21) is another notable example of still active postorogenic extension [*Taymaz et al.*, 1991; *Jackson*, 1994; *Le Pichon et al.*, 1995]. Internal deformation of the Aegean domain is shown by a widely distributed seismicity [*Taymaz et al.*, 1991; *Rigo*, 1994]. Seismotectonic data suggest a north-south direction of extension in the Aegean domain itself and E-W extension along the external Hellenic

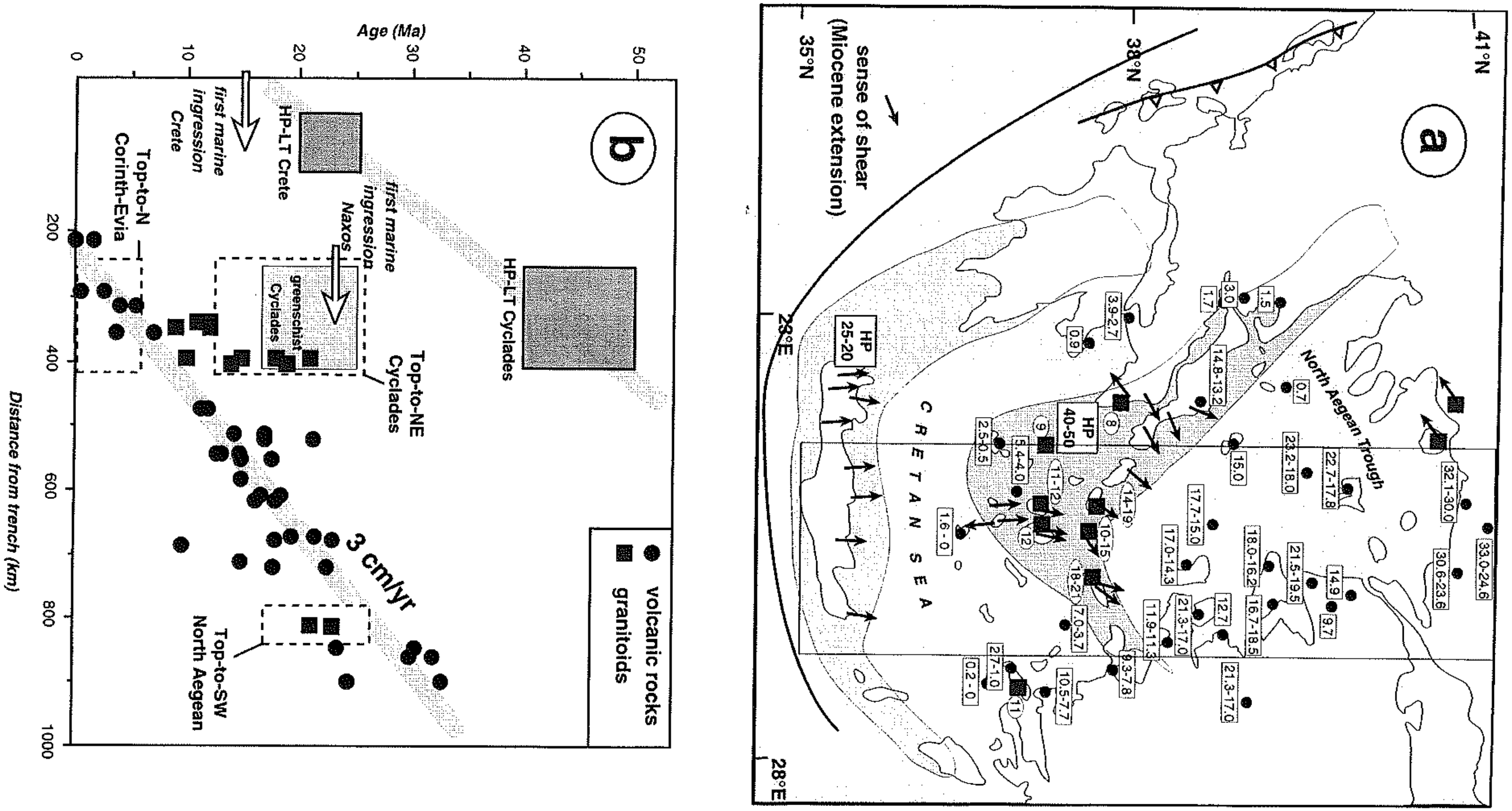


Figure 21. (a) Simplified tectonic map of the Aegean Sea and (b) age-distance diagram established from data contained in the rectangular area of Figure 21a. Stretching lineations and sense of shear are from *Buick* [1991], *Faure et al.* [1991], *Dinter and Royden* [1993], *Sokoutis et al.* [1993], *Gautier and Brun*, [1994a], and *Jolivet et al.* [1996], distribution and ages of high-pressure and low-temperature metamorphism are from *Bonneau and Kienast* [1982], *Seidel et al.* [1982], *Wijbrans et al.* [1993], and *Jolivet et al.* [1996], ages of high-temperature and low-pressure metamorphism and granitoids are from *Altherr et al.* [1982], *Kyriakopoulos et al.* [1988], and*Wawrzenitz and Krohe* [1997], and K-Ar ages of volcanic rocks are from *Fytikas et al.* [1984]. Top-to-the-northeast sense of shear is seen in the whole Cycladic archipelago as well as in Crete during the Early Miocene. High-temperature extension and intrusions of granitic plutons rework the Eocene high-pressure features of the Cyclades during the early Miocene, while low-temperature extension is active during the same period in Crete, where it leads to the rapid exhumation of Miocene high-pressure and low-temperature metamorphic rocks. Top-to-the-southwest sense of shear is observed during the early Miocene north of the North Aegean Trough related to extension and intrusions. Figure 21b shows the migration of the volcanic arc from the late Oligocene to the present, from the northern Aegean Sea to its present position. A velocity of slab rollback of about 3 cm/yr can be measured, assuming that the dip of the slab remained constant. The convergence zone migrated southward at much the same velocity in the frontal region. During the early Miocene the volcanic arc is flanked to the north and south by extensional domains where core complexes formed with opposing shear senses.

arc (Crete) [*Hatzfeld et al.*, 1990; *Armijo et al.*, 1992]. Numerous islands of the Cycladic archipelago are composed of exhumed metamorphic rocks, formed during an Eocene high-pressure and low-temperature event and reworked during a more recent Miocene high temperature low pressure episode [*Altherr et al.*, 1982]. After the first suggestion [*Lister et al.*, 1984] that the island of Naxos is a metamorphic core complex similar to that of the Basin and Range Region, several authors described the ductile extensional deformation in the Cyclades [*Buick*, 1991; *Faure et al.*, 1991; *Gautier and Brun*, 1994b; *Jolivet et al.*, 1994a]. A simple pattern emerges from these studies: the direction of stretching is consistently N-S in the southern Cyclades and Crete and tends to rotate to NE-SW in the north.

As shown in Figure 21, the sense of ductile shear is opposite on both sides of the north Aegean Trough. Top-to-the-northeast sense predominates in the Cyclades, Crete, and Evvia, while top-to-the-southwest sense is predominant along the margin of the Rhodopian massif (sensu lato, Strymon detachment, and Thassos [*Dinter and Royden*, 1993; *Sokoutis et al.*, 1993]) (Figure 21). The sense of tilt of upper crustal blocks is always compatible with the sense of shear observed at depth, and it also changes across this boundary, suggesting opposing sense of shear at depth in the present-day crust. The wavelength of topographic ridges and troughs is of the order of 100-200 km, which is 3 to 4 times the width of one single, tilted block. Note that there is no clear top-to-the-south sense of shear along the northern margin of the Cretan Sea. From Crete to the northern Cyclades a constant top-to-the-north sense of shear is observed.

Figure 21b shows the ages of magmatic rocks in the Aegean region [*Altherr et al.*, 1982; *Fytikas et al.*, 1984], as well as the ages of metamorphic episodes [*Wijbrans et al.*, 1993; *Jolivet et al.*, 1996]. The age/distance diagram shows the migration toward the south of the volcanic arc at a velocity around 3 cm/yr, interpreted as the trench rollback at approximately the same velocity if the dip of the subducting plate and the velocity of convergence is assumed constant. Granitoids plot slightly off the trend, followed by volcanic rocks, but the youngest of them are found at a distance from the trench where little volcanism is recorded during the same period. They are associated with the crust thickening during the Eocene high-pressure episode. High-pressure and low-temperature metamorphism also shows a migration in the same direction with two episodes, one in the Cyclades in the Eocene, and one in Crete and Peloponnese in the early Miocene.

Along a N-S transect from the northern Aegean to Crete one finds successively (1) an extensional domain characterized with top-to-the-SW sense of shear and high pressure and low temperature metamorphism (Strymon and Thassos), (2) a volcanic domain that is migrating southward, (3) an extensional domain with top-to-the-NE or top-to-the-N sense of shear and high pressure and low temperature metamorphism (Cyclades), and (4) a compressional domain with extensional detachments in the upper part of the thrust wedge and high-pressure and low-temperature metamorphism (Crete).

4.6.2. Comparison with the Tyrrhenian Sea. Two observations can be made from the comparison between the Tyrrhenian and Aegean Seas.

The consistent sense of block tilting in the upper crust along both profiles is associated with a consistent sense of shear within the brittle-ductile transition zone and the upper part of the ductile domain. Within the exhumed metamorphic rocks we do not observe any inversion of the sense of shear in the Tyrrhenian Sea as compared with the Aegean. Nevertheless, a change in the polarity of normal faults is observed east of Tuscany, as most normal faults within the Apennine belt itself dip westward (Figures 3 and 5). In conclusion, we can argue that the observed sense of shear is symmetrical and points toward the active magmatic province as in the Aegean Sea. Extension is presently active in the domain of active magmatism and east of it. Farther west, there is no significant active deformation. Active extension in the high heat flow region apparently proceeds to the east, along with top-to-the-east shallow dipping extensional shear zones.

1. The relationships between basin growth and magmatism (Figure 3) and their coupled eastward migration following the retreat of the slab suggest that cooling after magmatic activity and the consequent strengthening of the lower crust could play an important role in the migration. Heat flow decreases after the passage of the magmatic arc, the crust goes back to a higher strength, and extension stops (Figure 22). Extension then tends to localize eastward, always in the vicinity of the magmatic region with a warm and weak crust. Then the domain characterized by active extension and top-to-the-east, shallow-dipping shear zones is always

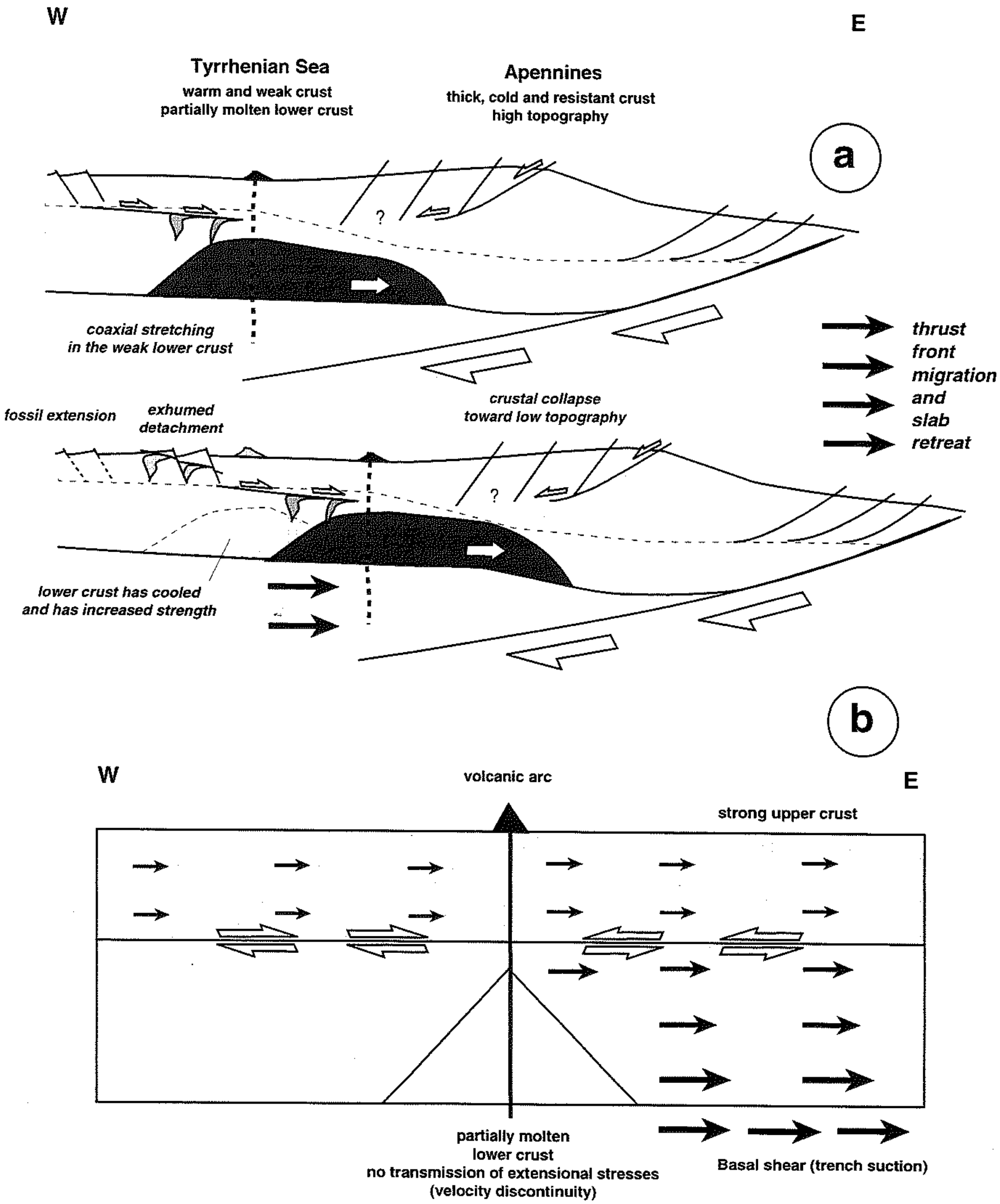


Figure 22. Model for the evolution of the northern Tyrrhenian Sea emphasizing the role of the magmatic arc as a mechanical and kinematic discontinuity controlling the sense of shear along the brittle-ductile transition. (a) Two stages of migration of the subduction zone and displacement of the molten zone in the lower crust. Molten lower crust localizes extensional strain in the deep crust and prevents transmission of extensional stresses west of it. Extensional stresses can only be transmitted through the upper crust. (b) Schematic model illustrating the velocity field expected in the proposed model and the deduced shear sense along the brittle-ductile transition assuming that extension is controlled primarily by basal suction during slab rollback.

rather narrow, making a significant difference with the Basin and Range where very large regions extend at the same time, even though a migration of magmatism is documented [*Wernicke*, 1992].

This scenario also results in fairly good agreement with the one depicted by numerical models of subduction and upper plate extension. Those models predict that the locus of maximum strain rates migrates laterally once the central area (i.e. molten zone) starts cooling and hardens [*Kuznir and Park*, 1987; *Sonder and England*, 1989]. It has been recently demonstrated [*Bassi*, 1995] that the effect of cooling on the necking pattern of the lithosphere depends strongly upon its initial rheology as emphasized by *Buck* [1991]. Specifically, this particular behavior can be obtained only by imposing two boundary conditions: a weak and viscous upper mantle (Moho temperature in between 675° and 770°C) and low stretching velocity (1.2 cm/y) [*Bassi*, 1995]. Only in this case could a lateral shift (at a similar rate) of the maximum strain rate caused by synrift cooling be obtained until strain concentrates at the transition between deformed and undeformed lithosphere after 18 Ma. The shift of the locus of extension, in this case, is mostly due to the fact that strenghtening may be large enough before the yield stress is reached [*Bassi*, 1995]. We can reasonably suggest that both these boundary conditions are present in the northern Tyrrhenian Sea, where extension is imposed on a postorogenic alpine weak crust [*Sonder et al.*, 1987] and extension rate is slow as compared with the surrounding area. Extensional basins shift laterally at a velocity between 1 and 2 cm/yr (whereas in the southern Tyrrhenian Sea the average velocity is around 5-6 cm/yr) during the last 20 Myr.

Similarly, it has been proposed [*Liu and Furlong*, 1994] that strenghtening of the volcanic arc and weakening of the peripheral area occurs after a few million years only if the mantle lithosphere is thermally perturbed and weakened by asthenospheric upwelling. Chemical and isotopic signature of the northern Tyrrhenian region magmatism indicates a close relationship with the subduction process [*Serri et al.*, 1993], validating this hypothesis.

2. The magmatic arc in the northern Tyrrhenian Sea as well as the Miocene Aegean Sea, localizes the extensional process in the weakest area of the crust (Figure 22). The migration and narrowness of the extending area suggest that simple gravity sliding, as that proposed for the Basin and Range, is not sufficient to explain the observed geometry. We suggest that the sense of shear across the northern Tyrrhenian Sea is controlled by the presence of the partially molten lower crust below the active magmatic region.

As observed in two-layered, brittle-ductile analog models [*Faugère*, 1985; *Vendeville et al.*, 1987; *Allemand et al.*, 1989], the velocity field imposed as a boundary condition controls the sense of shear along the decoupling zone between the ductile and brittle layer (Figure 23). In those models a velocity discontinuity is introduced at the base of the silicone layer. This discontinuity can be either symmetrical or asymmetrical. In both cases the sense of shear along the sand-silicone interface is always toward the velocity discontinuity because the sand layer is more resistant to traction than the silicone layer. In nature the velocity discontinuity can be represented by the magmatic arc, where the deformation is likely to be localized. In the northern Tyrrhenian Sea the eastward motion of the upper mantle, as a consequence of the eastward migration of the slab, induces a component of shear toward the molten weak zone below the base of the resisting upper crust. The top-to-the-west asymmetry of normal faults east of the volcanic arc confirms this hypothesis. Furthermore, like the velocity discontinuity in sandbox models, the volcanic arc acts as a barrier for the transmission of the basal mantle trench suction. Therefore the base of the upper crust located to the west of the volcanic arc will resist the general eastward motion, and an opposite sense of shear will develop (Figure 22).

A similar model may also apply for the Aegean Sea as suggested by Figure 24. Forty Myr ago, before the initiation of the present-day oceanic subduction, the convergence front was within a continental domain. The length of the subducted slab as revealed by seismic tomography [*Spakman et al.*, 1988] suggests that the present-day subduction was initiated some 30 to 40 Myr ago. This transition from continental to oceanic subduction must have partly released compressional stresses across the arc because the subducting oceanic lithosphere is relatively old [*Lallemant et al.*, 1994]. Extension proceeded during this period as in the Tyrrhenian Sea with opposing senses of shear along shallow-dipping extensional shear zones on either sides of the volcanic arc. Extension then stopped in the Cyclades and localized at the southern termination of the North Anatolian Fault (Evia, Corinth) as well as along the outer arc (Peloponnese and Crete) [*Armijo et al.*, 1992; *Armijo et al.*, 1996; *Rigo et al.*, 1996]. One

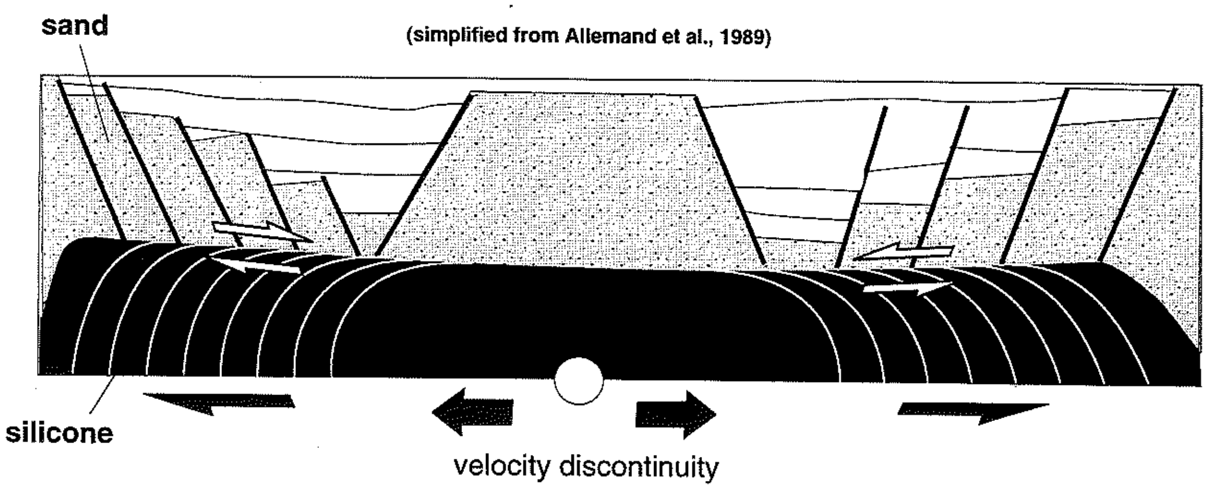


Figure 23. Sandbox model of extension of a two-layer (solid area, silicone putty; stippled area, dry sand; white area, syntectonic sand deposits) crust above a symmetrical velocity discontinuity (simplified after *Allemand et al.* [1989]). Initially vertical markers in the silicone are shown as white lines. The sense of shear along the brittle-ductile transition is always toward the velocity discontinuity.

major difference between the Aegean Sea and the Tyrrhenian Sea must be stressed. Although there is migration of the volcanic arc in both cases, there is no migration of granitoids in the Aegean Sea. Available data suggest contemporaneous intrusion in the northern and southern Aegean; however, no recent granitoids occur in the north. This observation may suggest that postorogenic ductile extension has affected a larger region during a shorter period of time interval in the Aegean Sea than in the Tyrrhenian Sea.

This model requires an inversion of extensional shear sense in each region during eastward migration, from top to the west to top to the east. In most cases, however, the top-to-the-east deformation has totally erased earlier structures, such as in Isola d'Elba or Isola del Giglio. Top-to-the-west sense of shear in Corsica is related to thrusting. Top-to-the-east extensional shear zones in Monte Argentario may be younger than top-to-the-west zones, and they may be remnants of an early stage. Such observations, however, need to be more substantiated by further studies in neighboring regions.

1.3.10. The opening of the Tyrrhenian Sea

Backarc extension migrated in the central Mediterranean from the Gulf of Lion to the Tyrrhenian Sea. The geometry of extension is different in the Liguro-Provençal and the Tyrrhenian basins. Narrow, rifted margins and a wide oceanic domain characterize the Liguro-Provençal basin. A localized single rift probably preceded the formation of oceanic crust. The Gulf of Lion margin is rather wide and shows tilted blocks of crust similar to a classical continental margin; the Provence margin is unusually narrow, suggesting a narrow rift and thus a strong localization of strain during extension [*Burrus*, 1984; *Mauffret et al.*, 1995]. On the contrary, in the Tyrrhenian basin, extension is distributed over a large domain, with a Basin and Range like topography, and oceanic crust was emplaced only in the last stages of rifting after very large magnitude intracontinental stretching. Those differences show different crustal rheologies, with a much weaker crust in the Tyrrhenian. This difference can be explained by the preextension history of these two regions. While the area located east of the alpine thrust front of Corsica had undergone significant crustal thickening during the early Cenozoic and high-pressure low-temperature metamorphism as attested by the blueschists and similar rocks in Corsica and Tuscany, no thickening episode is recorded where the Liguro-Provençal basin is presently located, except perhaps the eastern continuation of the Pyrenées in the Gulf of Lion. One should expect a thick and weak crust east of the Alpine thrust front and a thinner and stronger crust west of it before extension started. As the thrust front of the northern Apennines migrated eastward the high-pressure low-temperature zone close to the subducting slab also migrated eastward and the internal domain was progressively transferred into a domain with a higher thermal gradient. This led to a weakening of the thick crust.

This progressive heating of the crust during extension is recorded in the exhumed metamorphic rocks. In Corsica, only a slight thermal event is recorded north of Cap Corse and the retrograde PT path is mostly isothermal, while in the eastern Tyrrhenian Sea extension is accompanied with lower crustal melting and intrusion of granodiorites and monzogranites in Elba, Monte Cristo, and Giglio. Ductile levels of the crust have not yet been exhumed farther east, but the presence of recent granites and the high heat flow recorded in Larderello and Monte Amiata suggest a similar evolution toward a high-temperature low-pressure gradient. Once the crust has been sufficiently thinned, an evolution toward mantle-derived magmas is observed in the recent volcanic activity of this portion of Italy.

The extensional style in the Tyrrhenian Sea suggests that body forces played a part in the process of extension. On the other hand, the fact that extension started in the late Eocene in the Liguro-Provençal Basin, on a "normal" Hercynian crust, suggests that boundary extensional forces due to slab retreat probably played a major role in the extensional processes.

Deep lithospheric delamination and detachment of the negatively buoyant lithospheric mantle [*Bird and Baumgardner*, 1981; *Fleitout and Froidevaux*, 1982; *Platt and England*, 1994] have been proposed as alternative mechanisms in the Tyrrhenian area [*Reutter et al.*, 1980; *Channel and Marechal*, 1989] to explain the transition from compression to extension observed and the magmatic effects of the removal of a deep lithospheric root. Nevertheless three important points argue against this model. The first point is that the migration described at length in this paper does not agree with a sudden convective removal. The second point is that this mechanism cannot explain that extension started west of the thrust front in a region where there was no significant crustal thickening. The third point is that no surface uplift is recorded in the

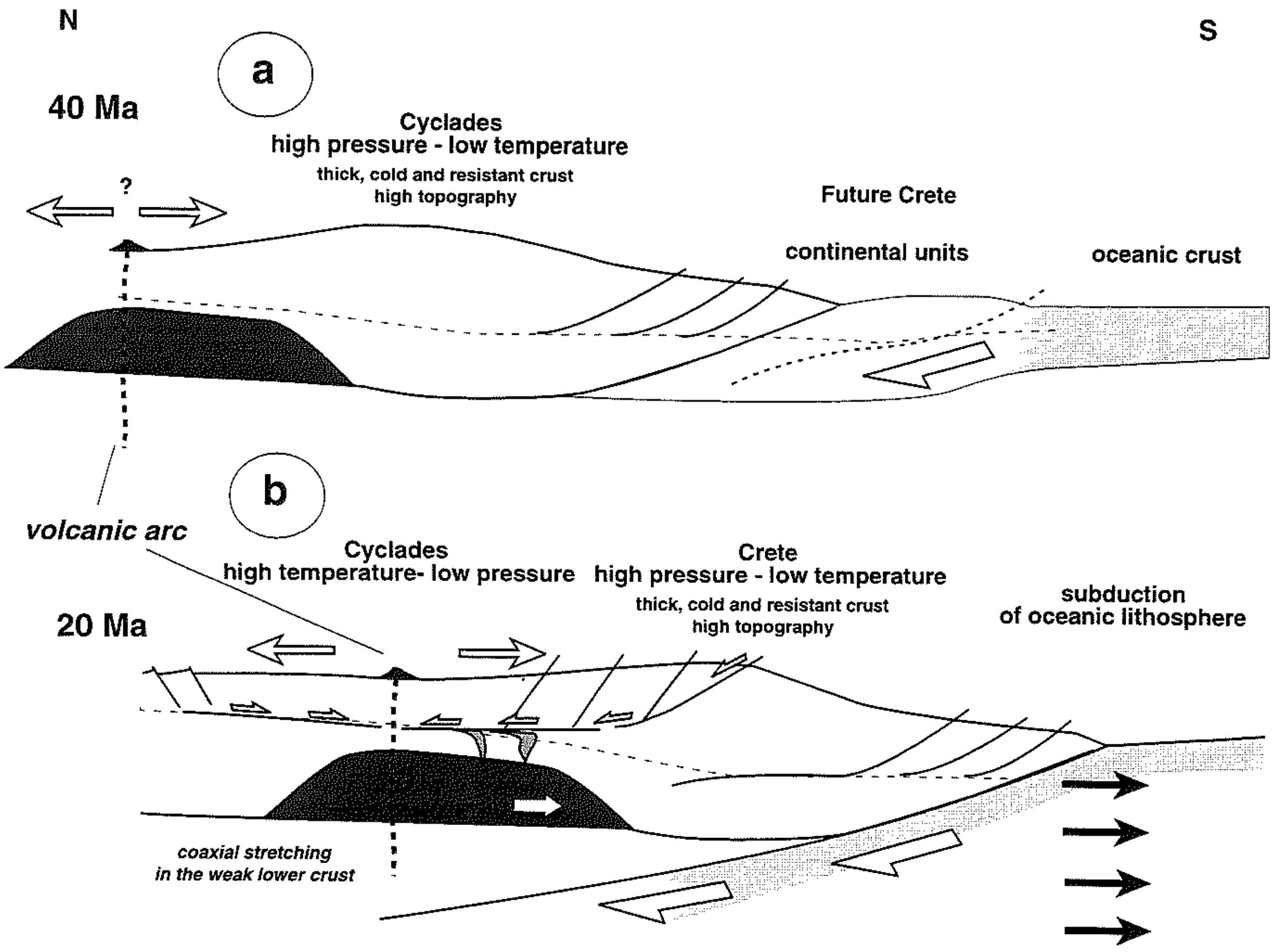


Figure 24. Schematic model for the evolution of the Aegean showing opposite senses of shear on either sides of the volcanic arc. (a) During the Eocene, the accretionary complex is built from continental units. High-temperature deformation is observed to the north, in the Rhodopian massif, while high-pressure and low-temperature deformation is active in the south, within the accretionary complex. (b) In the Miocene, oceanic subduction replaces continental collision. Slab rollback is active. Extension has started in the Aegean Sea, with opposing sense of shear on either side of the weak zone. The previously thickened region collapses, and intrusions rise into the crust below major detachments. The accretionary complex has migrated southward in the vicinity of present-day Crete and Peloponnese. Superficial detachments in the upper parts of the cold accretionary complex root in the warmer domain of the collapsing Cyclades. Those detachments exhume the older high pressure and low temperature metamorphic rocks formed.

stratigraphy before extension. The only uplift recorded in the Tyrrhenian region occurred after the end of extension in Tuscany and is driven by plutonic activity.

An alternative mechanism is the northward indentation of the African plate and consequent eastward lateral extrusion [*Tapponnier*, 1977; *Boccaletti et al.*, 1982; *Mantovani et al.*, 1996]. The main points against this mechanism is that the rate of lateral extrusion is 3 to 5 times higher than the rate of indentation.

The last model [*Malinverno and Ryan*, 1986; *Royden*, 1993; *Faccenna et al.*, 1996; *Giunchi et al.*, 1996] involves a retreat of the subducting slab toward the east. Slab retreat can indeed promote extensional stresses in the back arc region as in a classical back arc basins. It also has consequences similar to the lithospheric delamination by removing a cold and dense slab from below the thick crust and thus leads to extension and to the magmatic effects observed in the Tyrrhenian Sea. It has been suggested [*Faccenna et al.*, 1996] that in the central Mediterranean, in addition to the predominant slab pull forces, the gravitational body forces due to crustal thickening related to the formation of the Alps-Apennines belt, and subordinately, the compressional boundary force due to indentation by the African plate must be taken into account to better reproduce the style of deformation observed in the Tyrrhenian area. The estimation of the contribution of these forces, however, cannot be performed until the rate of opening of the Liguro-Provençal basin is better determined. There, in fact, the contribution of the body force can be reasonably neglected. If we consider a rate of opening of about 3-4 cm/yr for the Liguro-Provençal basin, we suggest that the slab pull component has always had the largest contribution from the late Oligocene to the present, even in the opening of the Tyrrhenian Sea.

1.4. Conclusions

We have described the geological and geodynamic evolution of the northern Tyrrhenian Sea based on new structural and petrological data. We proposed two stages of extension, synorogenic and postorogenic. Both migrated eastward from Alpine Corsica to Tuscany, following the retreat of the subduction front from the Oligocene to the present.

During this migration, high-pressure and low-temperature metamorphic rocks were exhumed during synorogenic extension following cold PT paths. Postorogenic extension proceeded with flat-lying extensional shear zones dipping to the east in the Tyrrhenian Sea, while west dipping, normal faults characterize the internal Apennines.

Postorogenic extension led to the exhumation of metamorphic rocks from the depth of the greenschist facies (between 20 and 10 km) and controlled the emplacement of plutonic bodies. The sense of shear at depth is controlled by the position of the volcanic arc which induces a kinematic and mechanical discontinuity at the base of the crust. A similar evolution is seen in the Aegean during the early Miocene, and a similar model can be proposed.

This evolution confirms the hypothesis that both the slab pull exerted by the subducting lithosphere and the consequent trench retreat and body forces stored in the Alpine-Apennines thickened crust play a major role in the dynamics of extension.