P. Conti

TECTONICS, VOL. 9, NO. 6, PAGES 1275-1303, DECEMBER 1990

CRUSTAL EXTENSION IN THE NORTHERN APENNINES: THE TRANSITION FROM COMPRESSION TO EXTENSION IN THE ALPI APUANE CORE COMPLEX

L. Carmignani
Dipartimento Scienze della Terra, Università di Siena, Italy

Roy Kligfield
Department of Geological Sciences, University of Colorado, Boulder

Abstract. An interpretation of Northern Apennine geology is presented which relates the temporal and spatial occurrence of both compressional and extensional deformation features in terms of the changing dynamic evolution within an accretionary wedge, after a model proposed by Platt [1986], followed by the initiation and development of continental rifting. During Cretaceous to Eocene time an accretionary wedge formed as remnant Tethyan oceanic crust subducted beneath the rotating Corsica-Sardinia microplate. Microplate collision during the Oligocene was characterized by the rapid imbrication of buoyant continental crust of the Italian continental margin, the record of which is preserved within the duplex structure geometry of the Alpi Apuane region. The overthickened wedge geometry returned to a more stable configuration by developing extensional features during the Miocene: both listric normal faults at upper-crustal levels and shear zones indicating evidence of distributed ductile extensional strain at mid-crustal levels are recorded. It is proposed that large-scale regional extension with associated volcanism beginning in the Messinian was represented by the intrusion of asthenospheric material from the subducted plate into the already attenuated accretionary complex. Further rifting, perhaps aided by subduction and back arc processes in the Southern Apennines, led to the formation of the Tyrrhenian Sea as an oceanic basin.

Paper number 90TC01860.
0278-7407/90/90TC-01860$10.00

Both the Apennines and North American core complexes record evidence of crustal thickening followed by crustal thinning, and finally of continental rifting. This suggests that the similar histories of these regions with vastly different plate tectonic settings may both be explained by processes linked to the changing internal dynamics of accretionary wedges.

INTRODUCTION

The Northern Apennines have been regarded as a compressional fold-thrust belt whose innermost (western) portion formed during the collision of the Corsica-Sardinia microplate against the Italian peninsula in the Oligocene [Boccaletti et al., 1971; Alvarez et al., 1974; Kligfield, 1979]. From the Miocene to the present, this thin-skin, accretionary fold-thrust belt propagated from west to east across the Italian peninsula [Merla, 1952; Bally et al., 1988]. Today gravity, structural and magnetic data have been interpreted to suggest that continental crust of the Adriatic plate is underthrusting the central Apennines with a trench located beneath the Po Basin-Adriatic Sea boundary (Figure 1) [Royden et al., 1987].

Beginning in the Miocene, the compressional structures have been affected by large-scale tectonic extension, whose magnitude increases from north to south along the Italian peninsula. In southern Tuscany, horsts and grabens of Late Miocene, Pliocene, and Pleistocene age with associated volcanics have split apart the earlier compressional structures, to form a Basin and Range type rift zone which narrows toward the Alpi Apuane region in the north [Boccaletti and Coli, 1983; Bartolini et al., 1983]. The extensional structures present in this latter region probably preserve features characteristic of an earlier stage of crustal evolution than those found further to the south.

One of the most puzzling features of Apennine tectonics is the migration, beginning in the Miocene and continuing to the present, of both extensional and compressional activity from west to east across the Italian peninsula. At present, extensional features are found along the western part of the Northern Apennines in Tuscany whereas compressional structures occur beneath the Po Basin to the east [Elter et al. 1975] (Figure 1).

The contemporaneous presence of extensional and compressional tectonics in the Apennines has previously been explained by different geodynamic models: (1) In the first model, the extensional features along the western portion of the Italian peninsula are related to the development of the Tyrrhenian Sea as a marginal basin from the Middle-Late Miocene to Present. The compressional features along the eastern part of the peninsula are related to the subduction of lithosphere belonging to the Adriatic microplate beneath the Apennines [Alvarez et al., 1974; Boccaletti and Guazzone, 1974; Scandone, 1979; Malinverno and Ryan, 1986; Royden et al., 1987; Bally et al., 1988; Channell and Mareschal, 1989]. (2) In the second model, the formation of a mantle diapir caused rifting in the Tyrrhenian region. The consequent translation of the crust by gravity tectonics toward the periphery of the resultant asthenospheric dome resulted in extension in the hinterland and compression in the foreland [Van Bemmelen, 1972; Wezel, 1982; Locardi, 1982]. In a variation of this model the thinning of the Tyrrhenian crust was accommodated by progressive eastward motion of extensional allochthonous slices having extensional and compressional displacement senses between the slices in the hinterland and foreland, respectively, of the rotating Adriatic [Lavecchia, 1988].

In this paper we propose a model for the development of extensional structures upon the collided margin of the Apennines along the Italian peninsula. The model is based partially on that of Platt [1986] for the dynamics of orogenic wedges, but modified to take into account the microplate tectonic history of the Apennines as well as its episode of continental rifting. As Bally et al. [1988] present evidence indicating that the amount of post-Messinian extension seen on surface and seismic profiles is significantly less than the amount of shortening derived from balanced cross sections across the central Apennines, another purpose of this paper is to demonstrate that significant, unreported amounts of crustal extension occurred along the

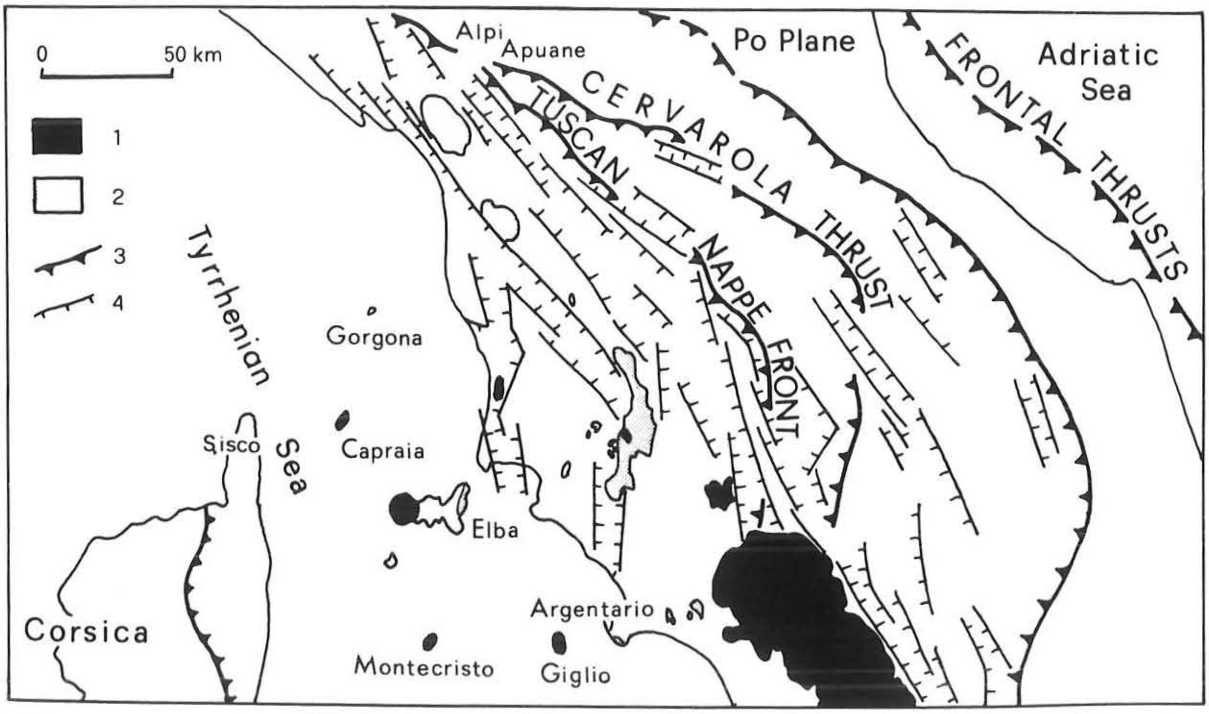


Fig. 1. Compressional and extensional tectonic features of the Northern Apennines. 1: Intrusive and extrusive magmatic rocks. 2: Metamorphic core complexes. 3: Major frontal thrusts. 4: Major normal faults and grabens.

western portions of the Italian peninsula beginning in the Miocene and continuing to the Present.

COMPRESSIONAL DEFORMATION PHASES IN THE APENNINES

Throughout the Northern Apennines, the translation of deformed ophiolites and their sedimentary cover (the Liguride units) onto the adjacent continental margin (Tuscan sequences) occurred by Eocene time [Elter and Trevisan, 1973]. In the western portion of the Italian peninsula, tectonic windows through low-grade and nonmetamorphic cover sequences reveal the presence of a greenschist facies, polyphase deformed sequence of rocks known as theTuscan metamorphic sequences which outcrop in the Alpi Apuane, Monte Pisani, and Monticiano Roccastrada regions (Figure 1).

The structural evolution of the Alpi Apuane region has been the subject of intense study [Carmignani and Giglia, 1975, 1977, 1979, 1983, 1984; Carmignani et al., 1978, 1980; Kligfield et al., 1981, 1986]. During the first major Tertiary deformation phase (D_1), the Tuscan nappe, together with the overlying Liguride Unit, was emplaced over the Alpi Apuane zone which were deformed into tight, recumbent folds with flat-lying axial surfaces (Figures 2 and 3). The presence of the Tuscan nappe above the metamorphic complex at this time is demonstrated by the inclusion of basal Triassic evaporite within the cores of D_1 phase synclines of the metamorphic sequences [Carmignani, 1985; Carmignani et al., 1978, 1980]. Additionally, the tectonic D_1 phase contact between the Tuscan nappe and underlying metamorphic rocks is itself folded during the D_2 deformation phase [Carmignani et al., 1978]. Continued shortening led to the formation of an antiformal stack geometry with the Tuscan nappe forming its roof and with an unexposed floor thrust (Figures 2 and 3). It is likely that the Paleozoic and Mesozoic substrata of the Cervarola unit (Figure 1) lie between the Alpi Apuane metamorphic complex and underlying crystalline basement, a deduction that also follows from reconstructions based on the seismic data presented by Bally et al. [1988]. When restored to its predeformational template, the initial fault trajectories display a ramp-flat geometry in which compressional thrusts are localized along tectonic weaknesses inherited from an earlier Triassic and Liassic rifting stage (Figure 2) [Rau et al., 1985; Kligfield et al., 1986].

THE ALPI APUANE CORE COMPLEX: EVIDENCE FOR MIOCENE CRUSTAL EXTENSION

The large-scale structure of the Alpi Apuane region consists of a complex of greenschist facies, metamorphic rocks (referred to by us as the "lower plate") which is separated from the overlying nonmetamorphic, sedimentary rocks of the Tuscan nappe and Liguride units (the "upper plate") by breccias and cataclasites (the "Calcare Cavernoso" formation) of Triassic depositional age (Figure 4). We will show that the Calcare Cavernoso Formation was utilized repeatedly as a glide horizon, initially during Oligocene age northeastward directed overthrust faulting and subsequently during Miocene and younger extensional detachment faulting. At first glance the cataclasites outline what appears to be a single, antiformal detachment fault zone (Figure 4). However, we demonstrate that the movement directions within the upper plate and along the Calcare Cavernoso formation were of two dominant vergences: the upper plate moved down to the southwest in the southwestern portion of the massif whereas the upper plate moved down to the northeast in its northeastern part (Figure 4). The mechanisms and displacement senses within the metamorphic rocks of the lower plate are described elsewhere in this paper.

The presence of nonmetamorphic rocks above higher grade metamorphic rocks, the presence of rocks having younger stratigraphic ages above those having older ages, the presence of a warped detachment fault characterized by brittle tectonite, and the presence of mylonitic, polyphase deformed metamorphic rocks within the lower plate all indicate that the Alpi Apuane region can be viewed as a classic metamorphic core complex [Coli, 1989] of North American type [Davis, 1980; Lister and Davis, 1989].

Two major Tertiary deformation phases affected all of the metamorphic rocks: a D_1 phase associated with nappe building and a younger phase referred to as D_2 in this paper [Carmignani et al., 1978, 1980; Carmignani and Giglia, 1984; Kligfield et al., 1981] and which we will propose represents tectonic extension. The number of phases within the metamorphic rocks is still the subject of some controversy; additional phases are reported but occur with only limited extent [Carmignani et al., 1978; Boccaletti et al., 1983]. Such zones having more complicated fold interference patterns can be related to progressive shear movements and repeated transpositions during the course of their progressive development within D_1 phase ductile shear zones.

Sense of Shear Criteria

During the D_1 compressional folding phase, the southwest to northeast direction of overthrusting and shear was established by considering the map-scale and mesoscopic-scale geometries of isoclinal, reclined, and overturned folds within the metamorphic rocks of the lower plate as well as through considerations of similar structural features

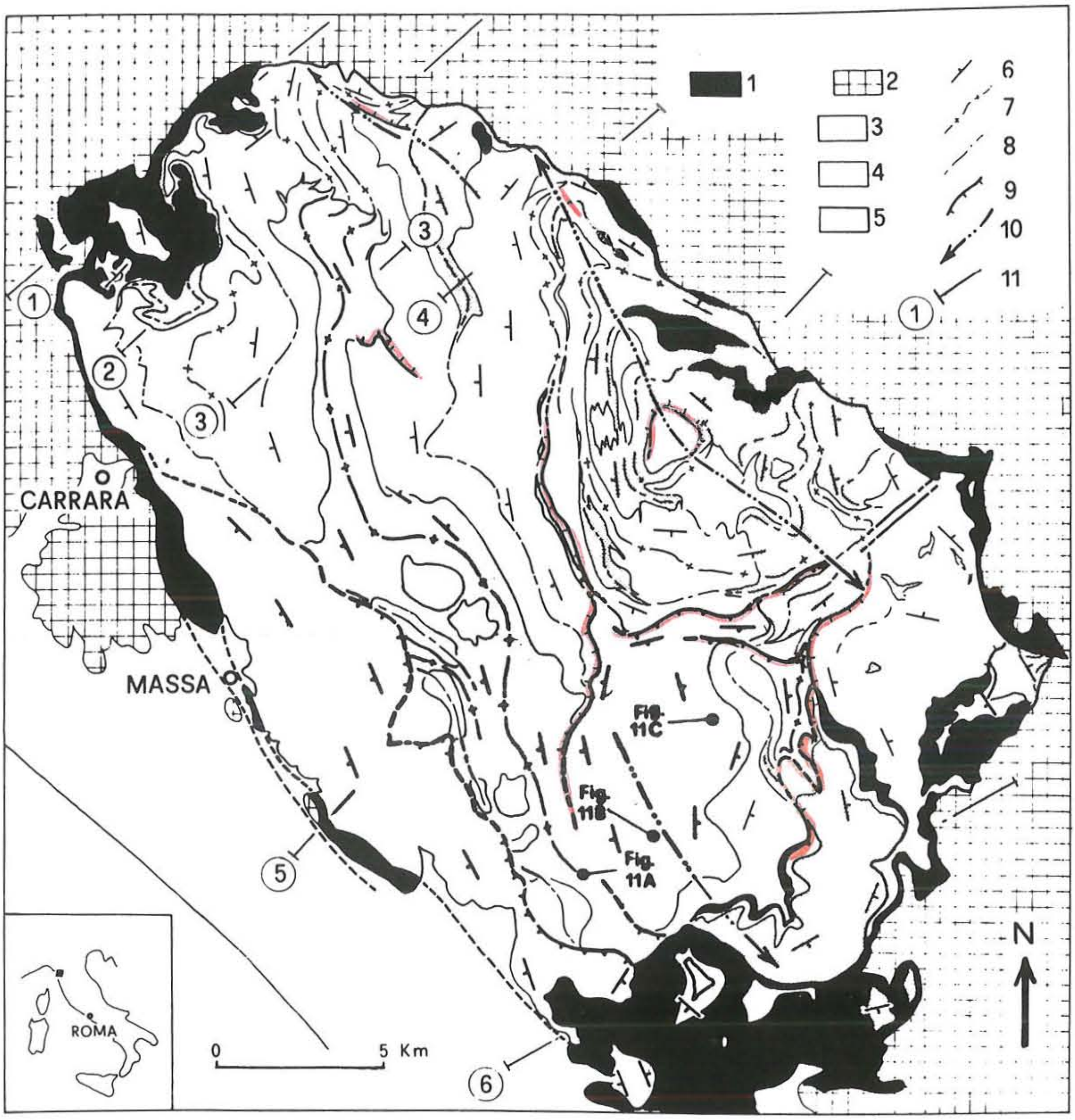


Fig. 2. Structural map of the Alpi Apuane region indicating major compressional tectonic features. 1: Breccias and cataclasites derived largely from Triassic evaporites ("Calcare Cavernoso"). The breccias comprise the detachment horizon which separates low-grade and nonmetamorphic upper-plate rocks from underlying metamorphic lower-plate rocks. These breccias, initially used as a decollement horizon during compressional thrusting, were subsequently used as a detachment fault during extensional phases. 2: Upper-plate, low-grade and nonmetamorphic formations belonging to the Tuscan nappe and Liguride unit. 3+4+5: Lower-plate metamorphic rocks. 3: Cretaceous to Tertiary phyllites and metasandstones. 4: Upper Triassic to Jurassic dolomites and marbles. 5: Paleozoic to Triassic phyllites, metavolcanics, and quartzites. 6: Outcrop strike and dip of D_1 (compressional) phase schistosities. 7: Axial plane traces of major D_1 phase anticlines. 8: Axial plane traces of major D_1 phase synclines. 9: Major extensional shear zones and ductile extensional faults within the metamorphic sequences of the lower plate. 10: Crestal trace of the D_1 compressional phase antiform which separates regions of contrasting transport direction and shear sense during the extensional phase. 11:Traces of the cross sections of Figures 7, 8, and 9.

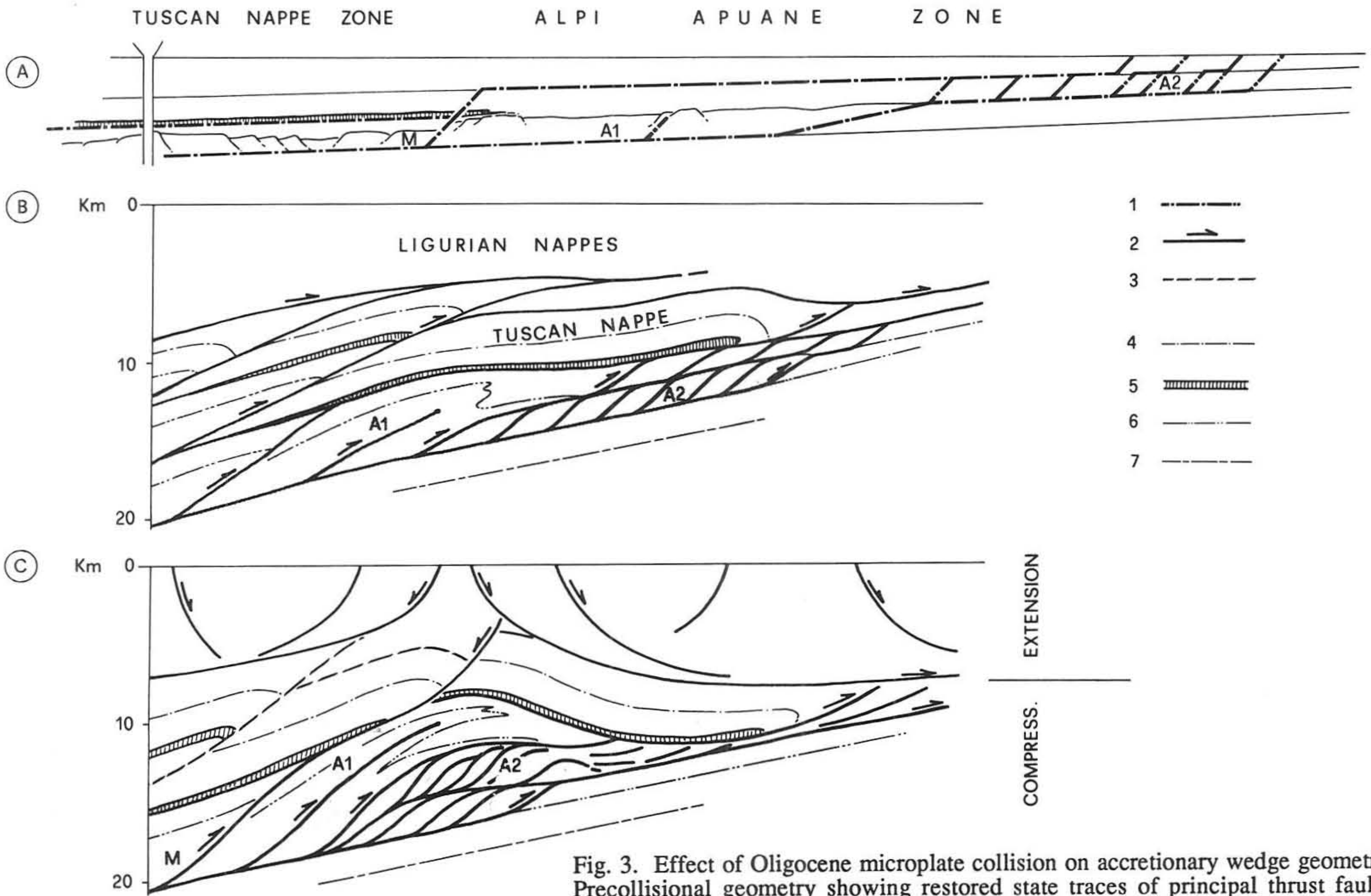
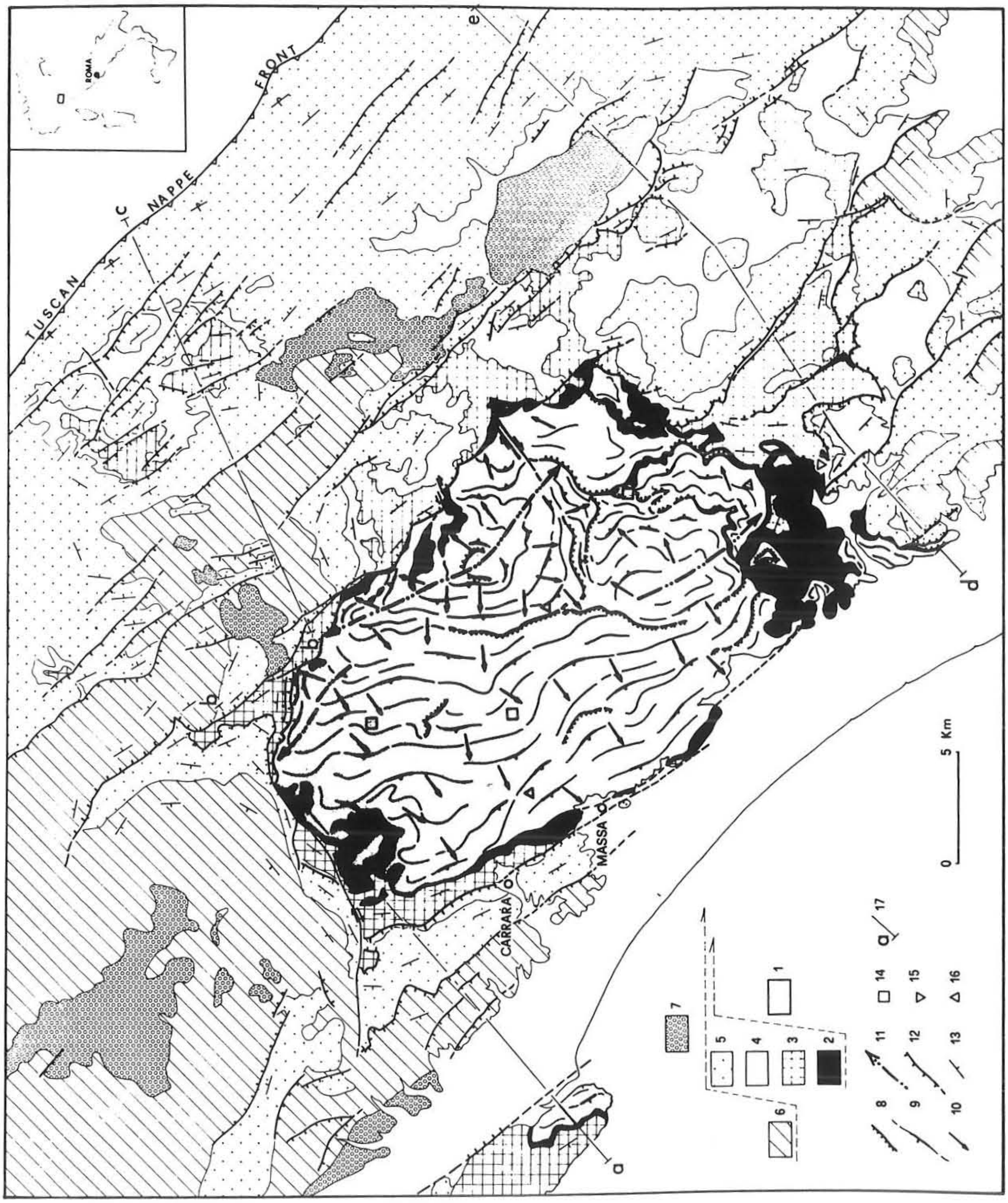


Fig. 3. Effect of Oligocene microplate collision on accretionary wedge geometry. (a) Precollisional geometry showing restored state traces of principal thrust faults and ramp-flat geometry. (b) Development of Alpi Apuane duplex structure. Metamorphic rocks shown in shaded pattern. (c) Development of antiformal stack geometry by rapid underplating and thickening of the accretionary wedge. Note simultaneous development of normal faults and compressional faults at upper- and lower-crustal levels, respectively. Legend: 1: Thrust fault trace. 2: Active thrusts and normal faults. 3: Inactive thrusts. 4: Base of flysch. 5: Triassic evaporite. 6: Top of Paleozoic phyllites. 7: Top of crystalline basement. M: Massa unit. A1 and A2: SW and NE portions of metamorphic complex, respectively. All diagrams at same scale with no vertical exaggeration.


TUSCAN NAPPE FRONT
ROMA
CARRARA
MASSA
0
5 Km
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

within the overlying Tuscan nappe and Liguride units [Carmignani et al., 1978, 1980; Carmignani and Giglia, 1984; Kligfield et al., 1981].

The effects of D_2 phase deformation upon the earlier formed D_1 structures provide characteristic criteria to determine the movement senses associated with D_2 phase deformation within the lower plate metamorphic rocks (Figure 4 and 5). The sense of shear criteria used, summarized in papers by Simpson and Schmid [1983] and by Simpson [1986], include the geometry which results from deforming already folded layers within heterogeneous shear zones (Figures 5a, 5b, and 6) [Ramsay et al., 1983], the geometry of extensional crenulation cleavages (Figure 5c) [Platt and Vissers, 1980], the development of synthetic and antithetic microfaults in fractured rigid grains within mylonites (Figure 5d and 5e), the geometric relationships between porphyroclasts and their recrystallized tails (Figure 5f), and the relationships between shear bands and foliations in mylonites [Berthe et al., 1979]. The displacement senses on planar and listric normal faults in the upper plate were established from examination of the hanging-wall and footwall cutoff relationships of stratigraphic horizons across each fault.

Mid-Crustal Level Extension

The D_1 phase foliations within the metamorphic sequences of the Alpi Apuane region, as well as the overthrust contacts of the Tuscan and Liguride nappes, are refolded during the D_2 deformation phase (Figure 4). The fold interference patterns which develop from the superposition of D_2 phase shear on earlier D_1 phase isoclinal folds and foliations are complex (Figure 6) [Carmignani et al., 1978]. At the regional scale, the entire nappe edifice is folded with what appear to be large-scale reverse drag folds having "S" and "Z" senses of asymmetry on the southwestern and northeastern flanks, respectively [Carmignani and Giglia, 1979] (Figures 4, 7a, 8a and 9a). Within the metamorphic sequences of the lower plate, the "S" and "Z" patterns are produced by the folding of the D_1 phase foliation (Figures 7b, 8b, 9b, and 10). Within the nonmetamorphic rocks of the upper plate, the "S" and "Z" cross section patterns are produced by the folding of stratigraphic layering, D_1 phase thrust contacts, and D_1 phase cleavages, where previously developed. The displacements represented by the fold geometries and the sense-of-shear markers within shear zones record a down-to-the-southwest (Figure 11a) and down-to-the-northeast (Figure 11c) shear sense in the southwestern and northeastern portions of the lower plate, respectively. This pattern is more or less symmetrically distributed on either side of the major antiformal culmination of the entire core complex (Figures 4, 7c, 8c and 9c). However, in certain portions of the lower plate metamorphic sequences, shear zones having both

Fig. 4. Structural map showing major extensional features of the Alpi Apuane region from the Tyrrhenian Sea in the southwest to the crest of the Apennines toward the northeast. 1: Lower-plate metamorphic rocks of the Alpi Apuane core complex. 2: Breccias and cataclasites (Calcare Cavernoso) forming the major detachment fault between upper- and lower-plate rocks. 3-5: Upper-plate low-grade metamorphic rocks of the Tuscan nappe. 3: Upper Triassic to Jurassic limestones, shales, and radiolarites. 4: Cretaceous to Eocene limestones and argillites. 5: Oligocene flysch. 6: Upper-plate low-grade metamorphic rocks of the Liguride units. 7: Pliocene to Quaternary syntectonic continental deposits of the rifting phase. 8: Major extensional shear zones and ductile extensional faults within the metamorphic lower plate. Barbs indicate downthrown side of shear zones and ductile faults. 9: D_1 (compressional) phase schistosity form lines. 10: Movement directions and shear senses of extensional phase structures within the lower-plate metamorphic rocks. 11: Crestal line of the D_1 phase antiform which separates areas of dominantly southwest and northeast vergence during the extensional tectonic phases. 12: Outcrop traces of high-angle normal faults and listric normal faults with barbs on the downthrown sides. 13: Dip of bedding within the nonmetamorphic upper-plate rocks. 14: Locations where 2-5 Ma apatite fission track ages were obtained. 15: Locations where posttectonic 10-12 Ma mica closure ages were obtained. 16: Location of earliest (?Tortonian) syntectonic sedimentary breccias.

a

b

Fig. 5. Sense of shear indicators within lower-plate metamorphic rocks. (a) Intrafolial D_2 folds indicating minor right-lateral displacement by simple shear along the earlier D_1 schistosity (Paleozoic phyllites). (b) Intrafolial D_2 folds indicating high amounts of right-lateral displacement by simple shear along the earlier D_1 schistosity (Paleozoic phyllites). (c) Extensional crenulation cleavage developed across earlier S_1 schistosity indicating left-lateral shear (Eocene calcschists). (d) Bookshelf structure consisting of broken, displaced, and boudinaged cherts within a limestone matrix indicating left-lateral shear (Middle Liassic cherty limestone). (e) Bookshelf structure consisting of broken and displaced phyllite bands adjacent to ductile limestone layers indicating left-lateral shear (Eocene calcschists). (f) s-type porphyroclast/tail system indicating right-lateral shear (Eocene calcschists).

c

d

e

f

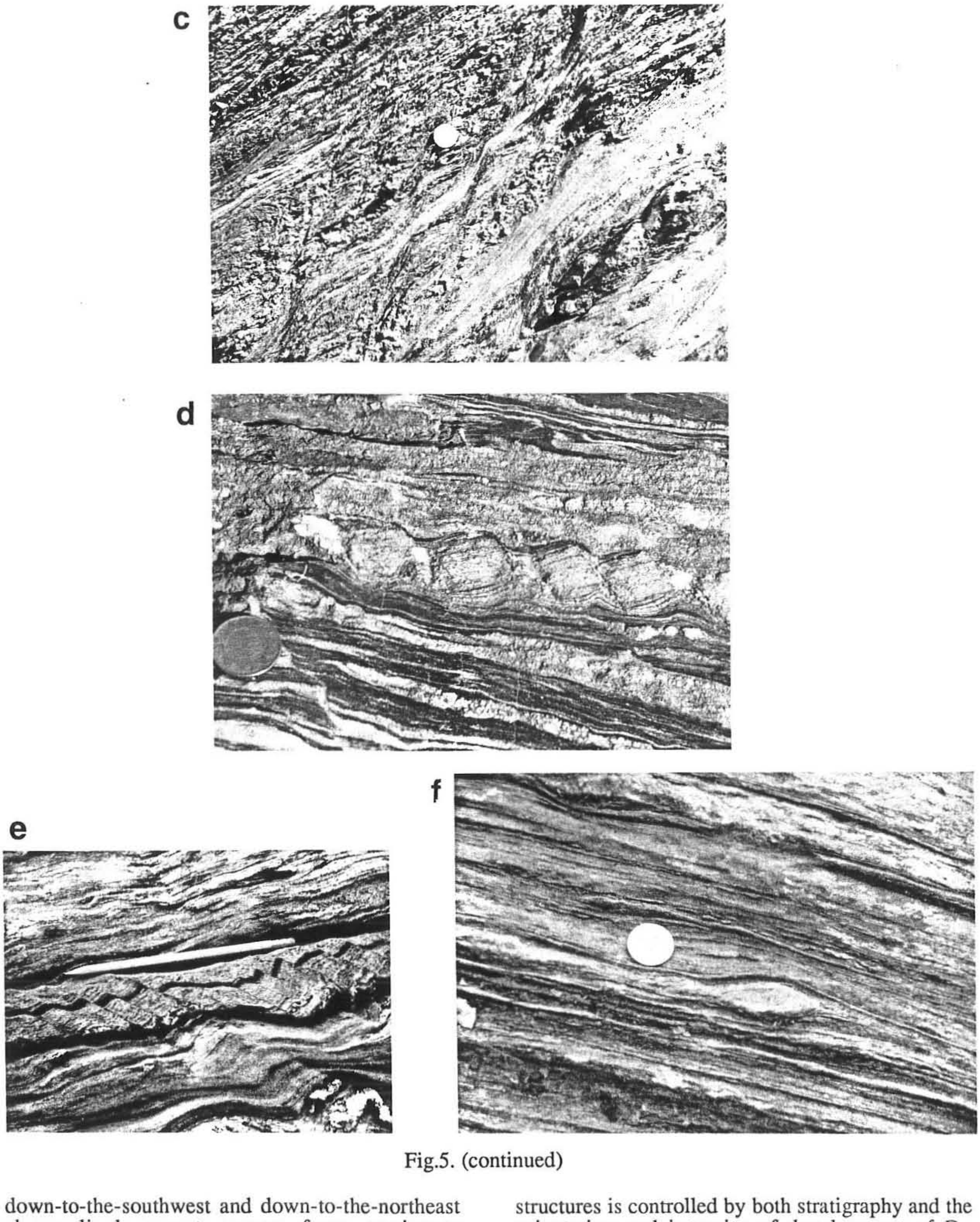


Fig.5. (continued)

down-to-the-southwest and down-to-the-northeast shear displacement senses form conjugate interference patterns at the map scale (Figures 7a and 10) as well as at the mesoscopic scale (Figure 11b).

Within the metamorphic sequences, the distribution and intensity of development of D_2 structures is controlled by both stratigraphy and the orientation and intensity of development of D_1 structures. For example, D_2 structures with a down-to-the-west sense of displacement occur within shear zones which are localized along contacts between relatively competent Triassic

Fig. 6. Fold interference patterns produced by superposition of D_2 phase down-to-the-southwest (right side) extensional shear (right-lateral in photograph) upon isoclinal D_1 phase folds produced during earlier northeast directed (left side) overthrust shear (Cretaceous cherty limestones in lower plate).

dolomite and more ductile marble, within the cores of Paleozoic anticlines, and within phyllitic zones in Middle Liassic-Cretaceous synclines (Figures 7a, 8a and 9a). Such regions are characteristic of the southwestern portion of the Alpi Apuane duplex where the intensity of D_1 deformation was insufficient to obliterate the effects of the original stratigraphic layering. In contrast, the northeastern portion of the region was characterized by the complete transposition of bedding into foliation during the D_1 phase [Carmignani et al., 1978]; as a result the D_2 structures are more evenly distributed.

At the regional scale, we interpret the southwest dipping and northeast dipping D_2 shear zones, axial plane traces of D_2 folds, and the down-to-the-northeast and down-to-the-southwest inferred displacement directions across the Alpi Apuane region to indicate tectonic extension acting on the earlier compressional structures. Of the two possible trajectories which would allow tectonic extension to occur, we observe that the southwest dipping set occurs dominantly where the D_1 phase foliation was also southwest dipping whereas the northeast dipping set occurs where the D_1 phase foliation was dominantly northeast dipping: a situation controlled by the foliation trajectories within the D_1 antiformal stack geometry (Figures 2, 3c, 4 and 7b). We emphasize that tectonic extension was accommodated throughout the metamorphic sequences by distributed ductile strain as demonstrated by the displacement of D_1 foliations (Figures 7b, 8b and 9b) within variable thickness D_2 shear zones (Figures 5a, 5b, 6, 7c, 8c and 9c) whose shear senses have been determined using the criteria outlined previously.

Upper Crustal Level Extension

Upper plate rocks of the Liguride units and Tuscan nappe are present above the Alpi Apuane detachment fault complex as well as within the Magra Valley and Serchio Valley graben systems which flank the southwestern and northeastern sides of the Alpi Apuane region, respectively [Federici, 1973; Raggi, 1985; Bernini, 1988] (Figures 4 and 12). Mapping within the overlying Liguride and Tuscan sequences reveals an abundance of both high-angle and low-angle normal faults which place younger rocks over older rocks and across which stratigraphic section is often missing (Figures 4 and 12). The shapes of normal fault traces on topographic map patterns indicate the listric shape of many of the normal faults. One of the best exposed listric normal faults extends for a length of 40 km where it forms the northeastern boundary of the metamorphic complex (Figure 4). In deep valleys, its listric profile is seen to root downward into the shallowly dipping Calcare Cavernoso horizon, and its hanging-wall strata form a roll-over anticline (Figure 8). Where crosscutting relationships can be observed, it is noted that high-angle normal faults both cut across earlier, lower-angle normal faults and sole into the latter with listric shapes (Figures 7a, 8a and 9a). The principal listric normal faults

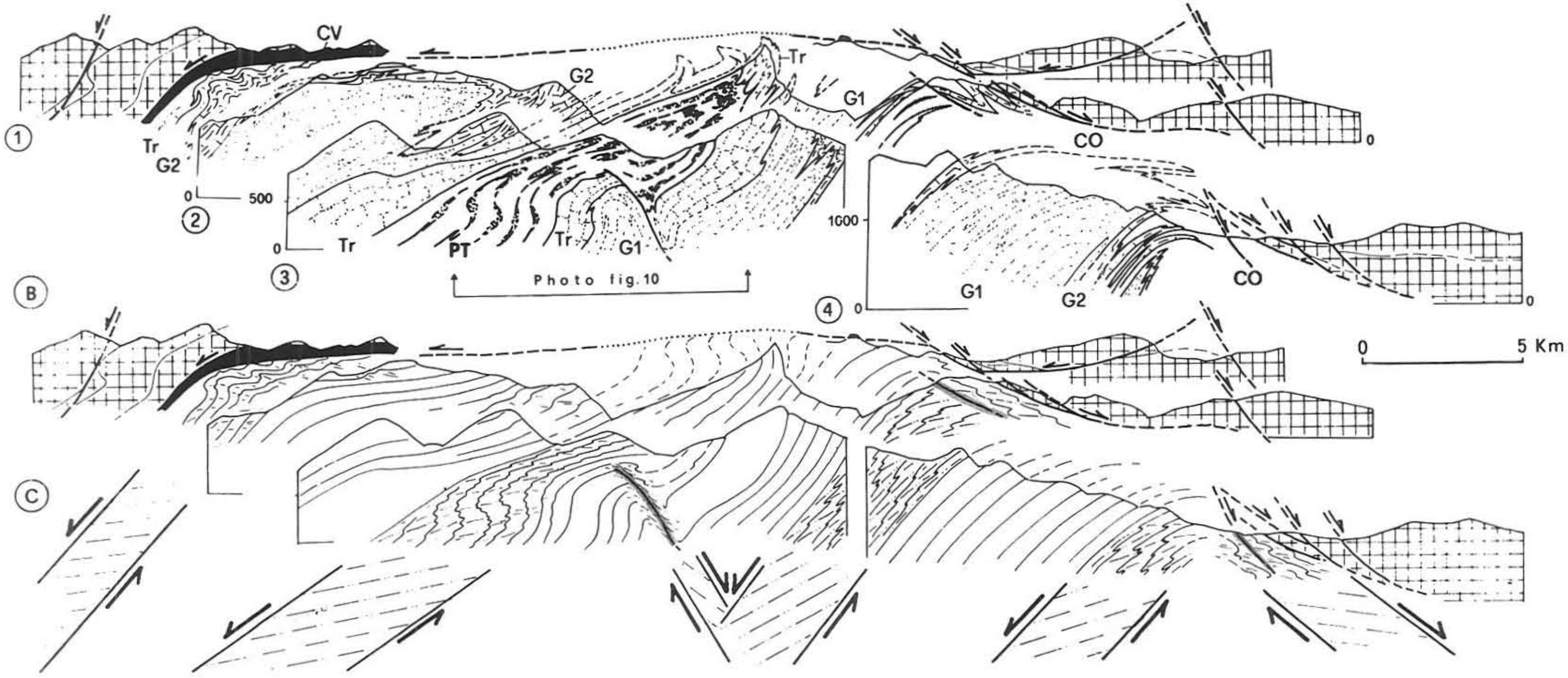


Fig. 7. Composite down-plunge projected cross section across the Alpi Apuane metamorphic core complex illustrating relationships between Miocene and younger extensional structures and earlier Oligocene compressional features. The locations of the numbered cross section lines are indicated on the geological map of Figure 2. (a) Stratigraphy and D_1 structure. The influence of stratigraphy on the development of D_2 phase shear zones and structures is discussed in text. (b) D_1 phase schistosity and distribution of D_2 phase shear zones and foliations. Distributed ductile D_2 shear zones with down to the west and down to the east senses of asymmetry are present in the southwestern and northeastern portions of the core complex, respectively. Note consistency with the "S" and "Z" shaped folds of the earlier D_1 phase foliation. (c) Senses of shear during D_2 phase within lower-plate metamorphic rocks and along upper-plate brittle normal faults. Legend as in Figure 8.

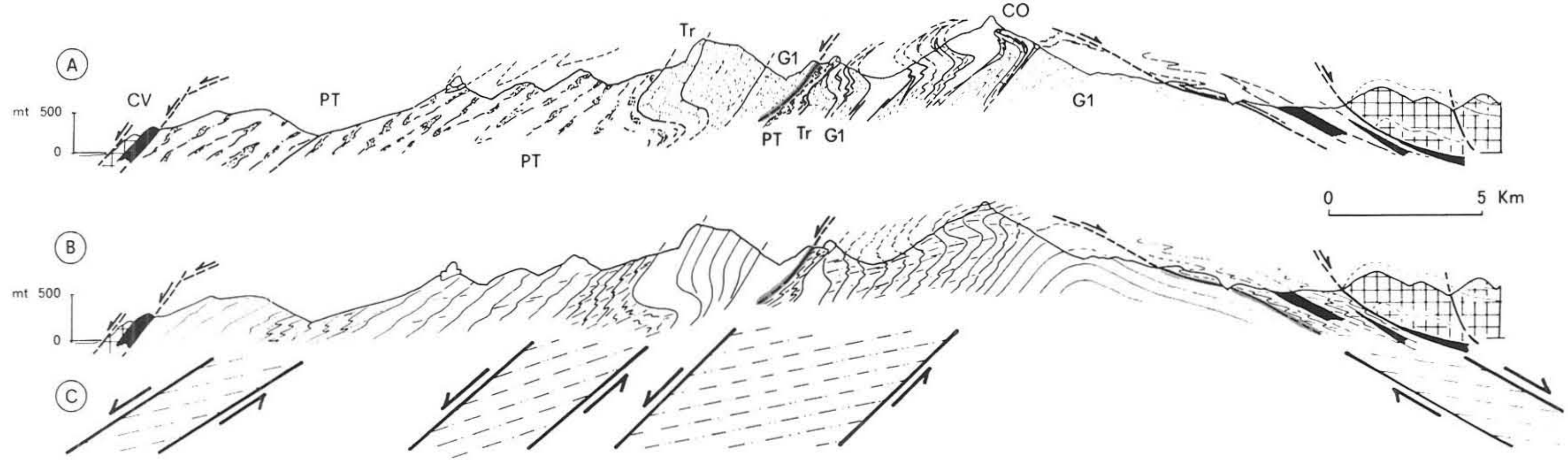


Fig. 8. Composite down-plunge projected cross section across the Alpi Apuane metamorphic core complex illustrating relationships between Miocene and younger extensional structures and earlier Oligocene compressional features. The location of the cross section is given by line 5 on the geological map of Figure 2. Legend: In square hatched pattern: upper-plate nonmetamorphic rocks of the Tuscan nappe and Liguride sequences. Cv: Breccias and cataclasites (Calcare Cavernoso) present along the detachment fault between upper and lower plates. PT: Paleozoic to Triassic phyllites, metavolcanics, and quartzites. Tr: Upper Triassic dolomite. G1: Lower Liassic marbles. G2: Liassic to Malm metamorphosed cherty limestones, radiolarian cherts, and calcschists. CO: Cretaceous to Oligocene metamorphosed cherty limestones, phyllites, and sandstones.

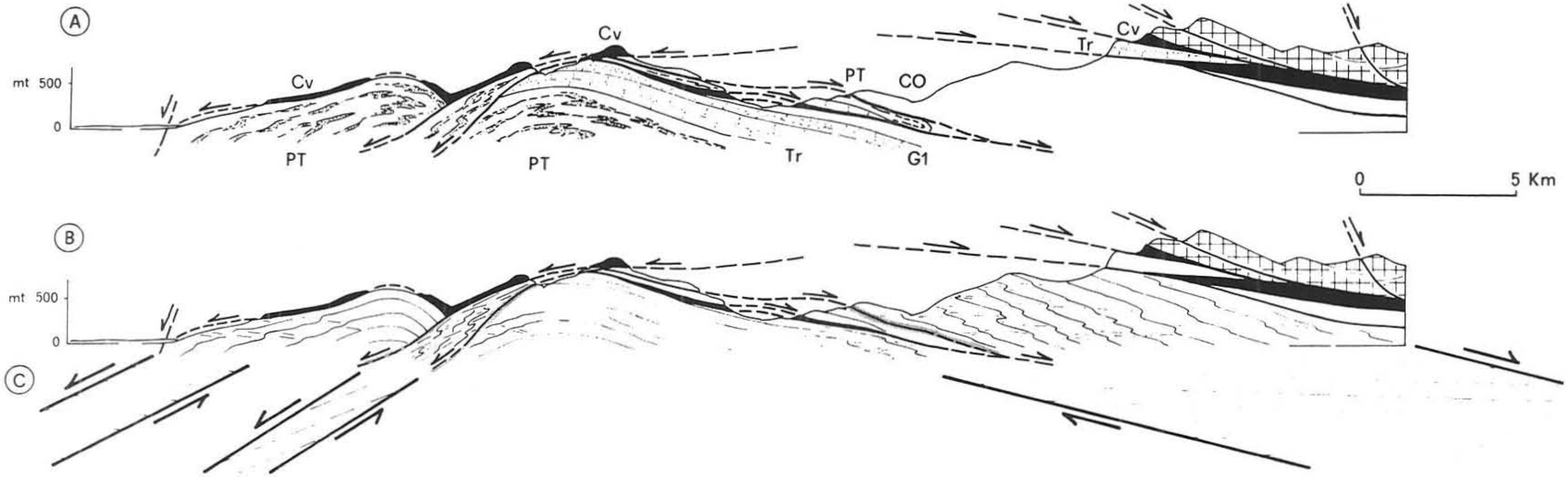


Fig. 9. Composite down-plunge projected cross section across the Alpi Apuane metamorphic core complex illustrating relationships between Miocene and younger extensional structures and earlier Oligocene compressional features. The location of the cross section is given by line 6 on the geological map of Figure 2. Legend as in Figure 8.

Fig. 10. Kilometer-scale development of conjugate extensional shear zones within metamorphic rocks of the lower plate. The center of the photograph records the intersection of a ductile D_2 shear zone having down-to-the-southwest sense of shear (left side) against a zone having down-to-the-northeast sense of shear (right side). The location of the photograph is shown in the cross section of Figure 7a. The interpretation of the photograph in terms of conjugate shear zones is indicated in Figure 7c. Photograph courtesy of G. Gosso.

a

Fig. 11. Mesoscopic-scale development of conjugate extensional shear zones within metamorphic rocks of the lower plate. (a) Cascade folds in Paleozoic phyllites associated with down to the southwest D_2 extensional shear zones within the southwestern portion of the metamorphic core complex. (b) System of conjugate D_2 shear zones in Paleozoic phyllites indicating both down to the southwest and down to the northeast senses of shear within the central portion of the core complex. (c) Cascade folds in Paleozoic phyllites associated with down to the northeast D_2 extensional shear zones within the northeastern portion of the core complex.

b

c

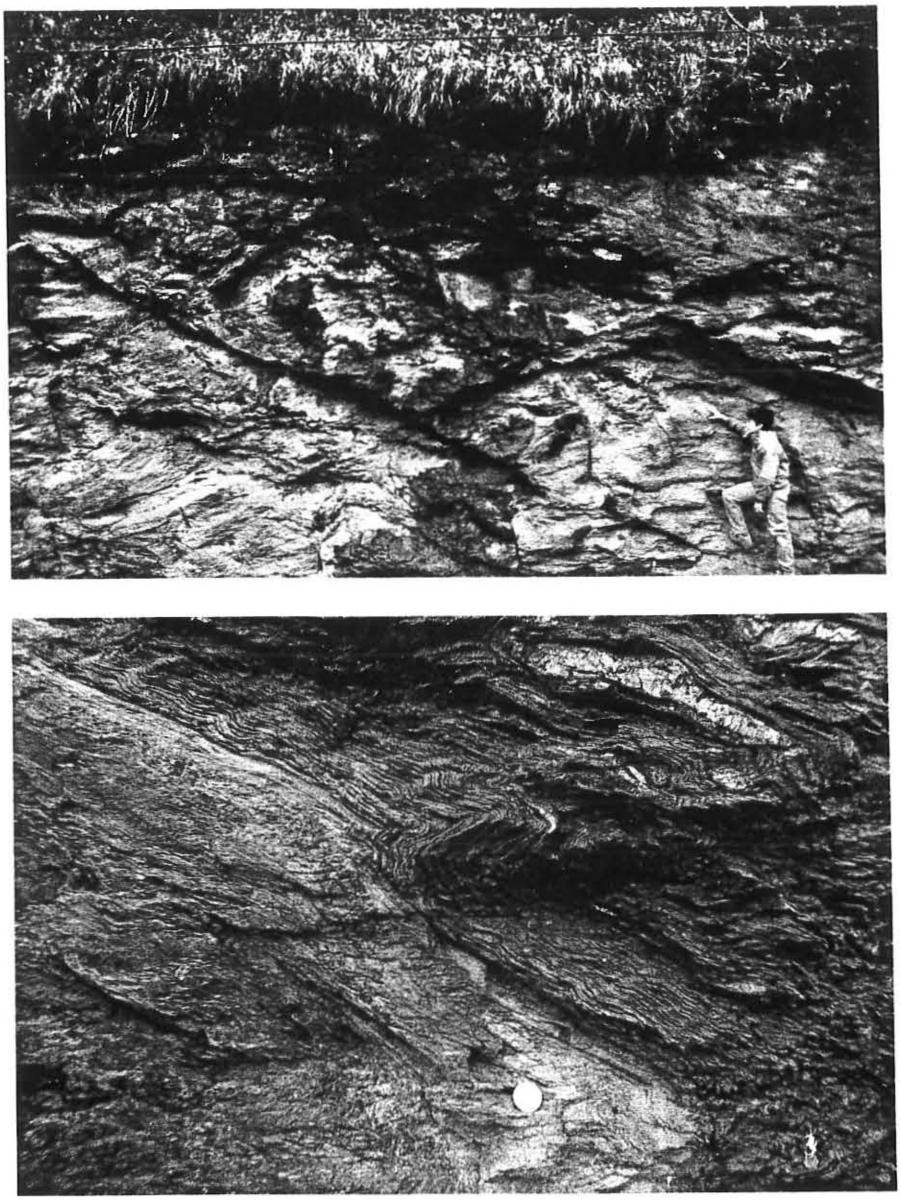


Fig. 11. (continued)

which delineate the Serchio and Magra grabens most likely root into the Calcare Cavernoso formation at depth. The presence of a basal or sole fault beneath the Serchio graben is also supported by the observed rotation senses of faulted blocks between the Serchio graben and the crest of the Apennines (Figure 12).

The Calcare Cavernoso functioned as the principal glide horizon, not only during D_1 phase compressional overthrusting of the Tuscan nappe atop the Alpi Apuane metamorphic sequences, but also as a detachment fault complex during the D_2 extensional phase. However, another important glide level during extensional faulting was the contact between the Liguride units and the Tuscan nappe, which allowed northeastward directed extensional movements to occcur on the northeastern side of the Alpi Apuane region. Within the Tuscan nappe, additional minor displacements were accommodated along the Upper Liassic-Dogger marls (Marne a Posidonia Formation) and Cretaceous to Oligocene age argillites (Scaglia Formation) [Nardi, 1961, Tevisan, 1962].

Unlike the distributed extensional strain patterns in the underlying metamorphic sequences, the

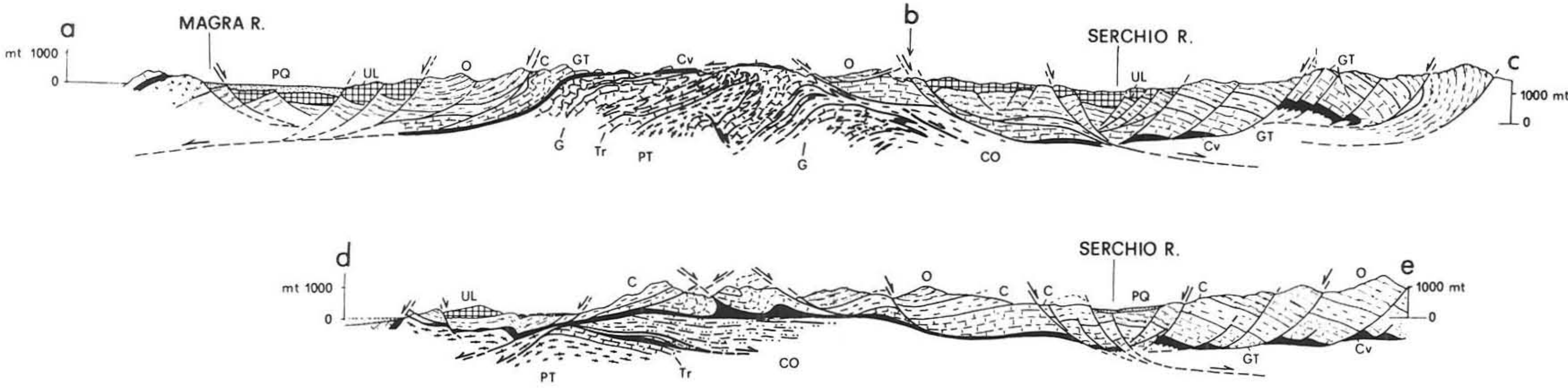


Fig. 12. Large-scale extensional features accommodating upper-plate extension across the Alpi Apuane core complex. Section locations (from the Tyrrhenian Sea in the southwest to the crest of the Apennines in the northeast) are indicated in Figure 4. The Magra and Serchio graben systems flanking the metamorphic rocks of the Alpi Apuane region are interpreted to sole into low-angle, down to the southwest, and down to the northeast detachment systems, respectively. Metamorphic rocks are shown in gray. The breccias and cataclasites along the major detachment faults between upper and lower plates are shown in black. Legend for lower-plate metamorphic rocks: as in Figure 7. Legend for upper-plate nonmetamorphic rocks: Cv: Cataclasites primarily derived from Upper Triassic evaporites (Calcare Cavernoso). GT: Upper Triassic to Jurassic limestones, shales, and radiolarites. C: Cretaceous to Eocene limestone and argillites. O: Oligocene flysch. UL: Liguride units. PQ: Pliocene to Quaternary fluviolacustrine deposits.

occurrence in the upper plate of D_2 phase cascade folds and associated cleavages [Pertusati et al., 1977] are localized near specific stratigraphic levels: along the basal contact of the Calcare Cavernoso evaporite, along the contact between flysch and Cretaceous rocks of the Tuscan nappe, and along the contact between the Liguride units and the Tuscan nappe (Figure 4). As in the lower plate metamorphic complex, the vergence of folds associated with the D_2 extensional phase displays a "Z" and "S" sense of asymmetry indicating that the highest layers were displaced downward with respect to the lowest layers (Figure 7a). The majority of these cascade folds indicate northeast and southwest directed displacement senses in the northeastern and southwestern portions, respectively, of the Alpi Apuane region. However, as in the antiformal culmination region of the lower plate (Figures 4 and 10), cascade folds having conjugate displacement senses can be found within the upper plate rocks, usually associated with earlier D_1 phase structural highs.

Detachment Fault Complex and the Role of Triassic Evaporites

The Alpi Apuane detachment fault system separates the nonmetamorphic upper plate rocks (including listric normal faults which sole downward into the detachment) from the lower plate metamorphic complex. The Calcare Cavernoso is the Triassic evaporite formation which forms the base of the Tuscan nappe [Trevisan, 1962; Baldacci et al., 1967]. It is a tectonic breccia with variable thickness up to a maximum of a few hundred meters. At its base, it consists predominantly of clasts of crenulated metamorphic rocks within a cataclastic matrix. A few meter thick zone of mylonite interposed between the lower plate metamorphic rocks and the cataclastic breccias at the base of the Triassic Calcare Cavernoso formation is sometimes preserved along the detachment fault zone.

Progressive Evolution of Extensional Structures

Our geometric observations suggest that during a single moment in time the type of deformation mechanism which allowed extension to occur depended upon structural position and depth within the core complex: brittle mechanisms were dominant within the upper plate (cataclasites at the base of the Calcare Cavernoso Formation and normal faults), brittle-ductile features were prominent along the detachment fault system (mylonites along the detachment faults), and ductile structures were ubiquitous within the lower plate (metamorphic rocks and ductile shear zones) (Figure 13a). However, brittle features (such as high-angle normal faults) are commonly observed to cut across brittle-ductile features (mylonites) and ductile features (metamorphic rocks). This suggests a process of crustal stretching whereby simultaneous stretching, denudation, and uplift causes higher-level structures to be brought into juxtaposition with lower-level structures (Figure 13b). As the metamorphic lower plate rocks uplifted (see below), the detachment horizon was warped and rose toward more brittle near-surface conditions. In detail, extensional structures of all types and of ages varying from Miocene to Quaternary can be found at the base of the Calcare Cavernoso outcrops.

Metamorphic Discontinuities

It has been noted that a significant jump in metamorphic grade exists across the Alpi apuane detachment fault between greenschist facies metamorphic rocks of the lower plate [Di Pisa et al., 1985] and anchizonal (low-grade) metamorphic rocks of the overlying Tuscan nappe and Liguride units [Venturelli and Frey, 1977; Reutter et al., 1980b; Cerrina Feroni et al., 1983]. The jump in metamorphic grade between this and the overlying anchizonal sequences of the Tuscan nappe seems incompatible with the concept that the latter provided the necessary load for the underlying metamorphism to occur.

The presence of crenulated metamorphic clasts within basal levels of the Calcare Cavernoso has been used to argue that the Alpi Apuane region was already exposed to erosion prior to emplacement of the Tuscan nappe [Federici and Raggi, 1974; Dallan Nardi and Nardi, 1973; Patacca et al., 1973; Dallan Nardi and Nardi, 1978; Sani, 1985; Abbate and Bruni, 1987; Coli, 1989] and therefore the latter could not have been present above the Alpi Apuane region to provide the required load for D_1 phase metamorphism.

These contradictions are resolved if the Calcare Cavernoso acted as a glide horizon during both D_1 phase compressional overthrusting and D_2 phase extensional faulting. The presence of crenulated and metamorphosed clasts within the basal portions of the Calcare Cavernoso is then explained as the natural consequence of reworking of an originally D_1 phase tectonic breccia during D_2 phase extensional faulting (Figures 3 and 13). The metamorphic jump across the detachment fault complex is also compatible with extensional faulting which places lower-grade metamorphic rocks directly upon higher-grade rocks.

Uplift and Cooling History

On the basis of K-Ar and $^{40}Ar/^{39}Ar$ studies of micas associated with D_1 phase fabrics, an age of 27

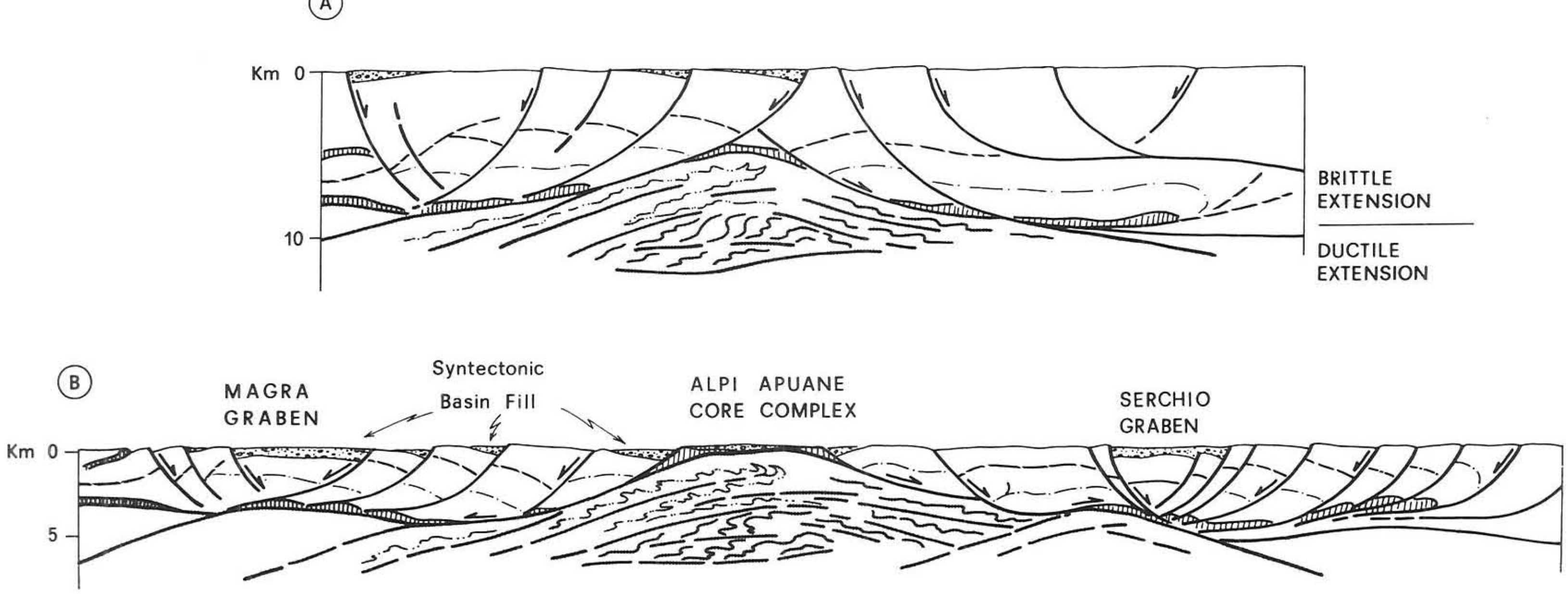


Figure 13. Development of upper-crustal and middle-crustal extension in the Alpi Apuane region during the Miocene and Pliocene. (a) Initiation of tectonic extension results in simultaneous ductile extension at mid-crustal levels (Alpi Apuane metamorphic sequences, shown in shaded pattern) and brittle extension at upper-crustal levels (Tuscan nappe and Liguride units). Metamorphic features associated with tectonic extension at mid-crustal conditions require that significant crustal thinning occurred prior to uplift. Differentiation of the core complex into upper-plate nonmetamorphic rocks and lower-plate metamorphic rocks is aided by the adoption as a detachment horizon of the evaporite-bearing overthrust faults of the earlier compressional phases. (b) Further crustal thinning, now accompanied by denudation and uplift, results in exposure of Alpi Apuane metamorphic core complex. High-angle brittle normal faults of the surrounding Magra and Serchio graben systems are interpreted to root downward against earlier low-angle normal faults.

Ma has been established for the initial crustal shortening in this portion of the Apennines [Kligfield et al., 1986]. This age is consistent with biostratigraphic data from the Pseudomacigno sandstone [Dallan-Nardi, 1977], which indicate a depositional age of approximately 27-34 Ma for the youngest(?) sediment deposited prior to the D_1 phase metamorphism.

Syntectonic minerals which formed during all deformation phases in the metamorphic rocks include muscovite or phengite, biotite, chlorite, quartz, and feldspar during the D_1 phase and muscovite or phengite, and chlorite during the D_2 phase. However, the growth of chloritoid porphyroblasts and kyanite is post tectonic to the D_1 phase and syntectonic to the early D_2 phase [Boccaletti and Gosso, 1980; Di Pisa et al., 1985], suggesting that the thermal peak of metamorphism was attained after the D_1 phase but prior to the onset of the D_2 phase. K-Ar and $^{40}Ar/^{39}Ar$ dates of 12 Ma were obtained from sites dominated by the growth of abundant D_2 phase micas [Giglia and Radicati di Brozola, 1970; Kligfield et al., 1986] (Figure 4 and Table 1). Since these micas formed at greenschist facies conditions [Carmignani et al., 1978], this Miocene phase of extension is interpreted to have formed at mid-crustal depths (8-10 km depth) prior to denudation and uplift of the Alpi Apuane region (Figure 14).

The timing of uplift can be further constrained from recently obtained apatite fission track ages of 2-5 Ma within the metamorphic lower plate rocks and of 10 Ma within the overlying Tuscan nappe (Table 1) [Bigazzi et al., 1988; Abbate et al., 1990]. If interpreted to represent cooling ages as the apatite passes through 120°C, then the data indicate that the lower plate and upper plate were at depths of approximately 4-5 km, depending upon the thermal gradient, at these times (Figure 14). To the north and northeast of the Alpi Apuane, the Lunigiana and Garfagnana grabens (Figure 4) contain Upper-Middle Pliocene age conglomerates with metamorphic clasts [Calistri, 1974; Federici and Rau, 1980]. It would appear from the combined fission track ages and the age of sediments in overlying grabens that the Alpi Apuane metamorphic

TABLE 1. Uplift and Cooling Data

Method (Author)	Location	Age (Ma)	Temperature (C)	Interpretation
Bio-stratigraphic correlation (1)	Lower-plate metamorphic sequences	34-27	0	Deposition of flysch (youngest deposit affected by metamorphism)
K-Ar and 40Ar/39Ar (2)	Lower-plate metamorphic sequences	27-25	350-400	D1 compressive deformation phase
K-Ar and Ar40/Ar39 (2,3)	Lower-plate metamorphic sequences	12-14	350	D2 extensional deformation phase
K-Ar and 40Ar/39Ar (2)	Lower-plate metamorphic sequences	8-10	350	Post tectonic cooling ages of micas
Apatite fission tracks (4,5)	Lower-plate metamorphic sequences	2-5	120	Cooling ages of lower plate
Apatite fission tracks (5)	Upper-plate Tuscan Nappe	4-8	120	Cooling ages of upper plate
Bio-stratigraphic correlation (6, 7)	Breccias on detachment fault	<8	25	Depositional age of breccia subsequently reworked during extensional phases

References: 1, Dallan Nardi [1977]; 2, Kligfield et al. [1986]; 3, Giglia and Radicati di Brozolo [1970]; 4, Bigazzi et al. [1988]; 5, Abbate et al. [1990]; 6, Sani [1985]; 7, Dallan-Nardi [1979].

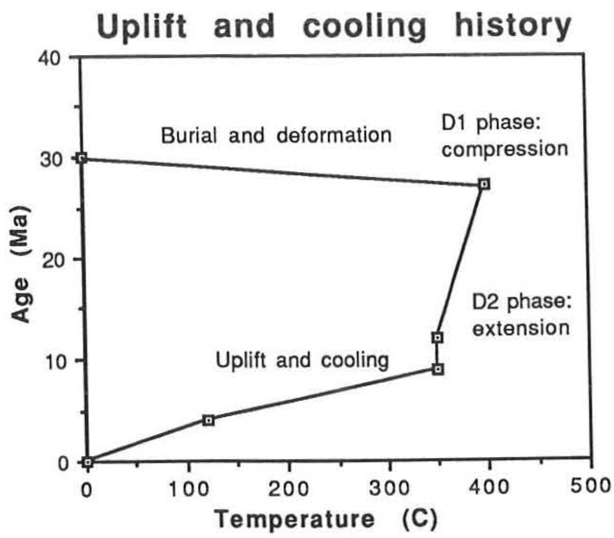


Fig. 14. Uplift and cooling history of lower-plate metamorphic rocks. Age and temperature data given in Table 1.

complex was exposed at the surface about 3 Ma (Figure 14).

The oldest reported sedimentary breccias ("Brecce della Versilia," Sani, 1985] in discordant contact with underlying metamorphic rocks contain Orbulina universa within their matrix [Dallan Nardi, 1979; Sani, 1985; Abate and Bruni, 1989; Coli, 1989]. Although attributed to the Middle Miocene, an age younger than the Tortonian cannot be excluded. However, such an age requires that the Alpi Apuane region was already uplifted and undergoing erosion at this time. This is in conflict with the K-Ar and $^{40}Ar/^{39}Ar$ dates of 12 Ma, with younger cooling ages of 8-10 Ma, and with fission track ages of 5 Ma as reported above. However, the timing of denudation and uplift cannot be constrained uniquely from the depositional ages of overlying sediments because such near-surface extensional activity is itself synchronous with underlying extensional processes. As an alternative explanation, we propose that these breccias were deposited on top of the exposed upper plate at the time that the underlying metamorphic complex was undergoing initial tectonic extension (Figure 13a). As a result of progressive tectonic extension, these breccias would have been emplaced along one of the detachment fault systems and come to lie adjacent to an underlying lens of lower plate metamorphic rock (Figure 13b).

The uplift and cooling history of the Alpi Apuane region is summarized in the age versus temperature curve of Figure 14. Initial burial and compressional deformation at 27 Ma was followed by mid-crustal level attenuation and concomitant high-level denudation at 12 Ma. Very rapid denudation, uplift, and erosion began soon after this time and continued to the Present.

Localization of Core Complex Thinning

The locus of extension in the Alpi Apuane core complex coincided with that of compression in the same region (Figures 2 and 4). The antiformal stack geometry produced at the end of the Oligocene produced a local high which was reactivated as the site of extension during the Miocene (Figures 3c and 4). We further speculate that the location of the duplex structure itself was controlled by structural weaknesses inherited from an earlier Triassic-Liassic rifting stage along the Triassic-Liassic continental margin (Figure 3a) [Rau et al., 1985].

MECHANISMS OF INITIAL CRUSTAL EXTENSION

The structures present in the Alpi Apuane region provide superb examples of the nature of crustal extension at upper (0-8 km) and middle (8-10 km) levels in a mountain belt previously thickened by compressional tectonics. In this context, the extensional history of the Alpi Apuane region is similar to that of North American metamorphic core complexes: both record evidence of the processes of initial stretching and subsequent attenuation of continental crust ("core complex style") prior to being split apart by significant continental rifting ("Basin and Range style extension"). The initiation of tectonic extension at 12 Ma resulted in simultaneous ductile exension in the lower plate and brittle extension at upper-crustal levels (Figure 15). In this section we review the mechanisms which permitted crustal extension to occur and compare them with those observed in metamorphic core complexes of the Basin and Range region [Davis, 1980; Coney and Harms, 1984; Hamilton, 1987; Lister and Davis, 1989].

Attenuation of the Middle Continental Crust

Crustal extension in the lower plate metamorphic rocks is accommodated through a combination of ductile processes. The "Z" and "S" senses of asymmetry of D_2 cascade folds records distributed, nondiscrete displacement throughout the metamorphic rocks. The overall down to the southwest and down to the northeast shear senses throughout the southwestern and northeastern portion of the lower plate, respectively (Figures 4, 7b, 8b, and 9b), can be interpreted to represent a very large-scale mega-boudinage or attenuation of the entire metamorphic lower plate at mid-crustal depths (Figures 13 and 15). This important result demonstrates that oppositely directed movement directions across the Alpi Alpuane region allowed

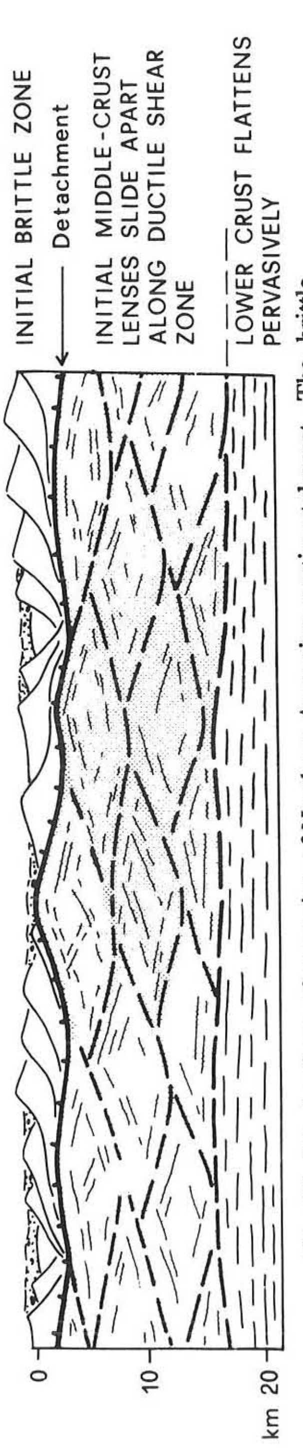


Fig. 15. Mechanisms of extension of Northern Apennine continental crust. The brittle and ductile structures present within the Alpi Apuane region document two contrasting depth-dependent styles of tectonic extension. Deformation at upper crustal conditions results in the formation of brittle structures and graben systems which sole downward into ductile detachment zones. Deformation at middle crustal conditions is characterized by the presence of metamorphosed crustal blocks, which slide past each other in different directions along narrow, anastomosing shear zones. Current erosion levels do not permit direct observation of lower-crustal rocks in this region, but it is speculated that the lower crust attenuates by pervasive pure shear. Similar models for crustal extension in the Basin and Range region of North America have been proposed by Hamilton [1987] and by Kligfield et al. [1984].

stretching of the middle-level continental crust to occur.

Where displacements and strains are greatest, the refold patterns of the D_1 phase foliations outline the boundaries of ductile shear zones, which form a series of southwest dipping and northeast dipping sets (Figures 7c, 8c, and 9c). The majority of these shear zones have displacement senses consistent with the overall down to the southwest and down to the northeast displacement directions of the cascade folds. However, conjugate shear zones displaying oppositely directed movement directions are present in certain portions of the metamorphic lower plate (Figures 7c and 10). This observation indicates that middle-level crustal rocks were also partially stretched by a process in which lenses of crustal blocks moved past each other along relatively narrow shear zones: the so-called "anastomosing shear zone model" [Hamilton, 1982, 1987; Kligfield et al., 1984].

Crustal Attenuation Mechanisms: A Synthesis

Synthesis of the above observations permits us to propose a model for initiation and subsequent development of crustal extension in the Northern Apennines in which upper-crustal extension and middle-crustal extension are compatibly linked by the formation of evolving detachment fault systems (Figure 15). The upper crust extends in a brittle fashion, forming families of high-angle normal faults which root downward as listric normal faults into low-angle linked detachment systems. These detachment systems approximately coincide with the brittle-ductile transition and separate brittle upper plate rocks from underlying ductile metamorphic rocks.

In our model, the middle continental crust is stretched by an anastomosing shear model in which metamorphosed middle-crustal lenses slide past each other along networks of ductile shear zones. In the Alpi Apuane core complex, one of these lenses (the lower plate metamorphic rocks) is exposed and reveals that internally, it is split apart into further cells of anastomosing blocks.

Hill and Hayward [1988] present structural interpretations of seismic sections which cross the Apennines immediately north of the Alpi Apuane tectonic window. In the approximate position where the antiformal stack geometry of the Alpi Apuane lower plate and overlying rocks plunges beneath their seismic line, Hill and Hayward interpret the seismic data to show a similar imbricate structure composed of imbricated nappes with vergence toward the northeast. A major down to the east reflector is interpreted as the boundary between the roof of this imbricate carbonate layer and overlying, less reflective, highly deformed Miocene flysch. We interpret this northeast dipping reflector to represent either the direct extension beneath the

Serchio graben system of the Alpi Apuane detachment fault system, or a separate northeast dipping detachment fault within the Apennines. We suggest that the presence of this northeast dipping reflector provides further evidence of extensional detachments curving downward through the upper crust of the Apennines in the subsurface today.

At an even larger scale, seismic refraction measurements have been carried out between Corsica and southwestern Tuscany in order to investigate the relationships between the crustal structures of the Adriatic microplate and Corsica [Morelli et al., 1977; Reutter et al., 1980a; Buness, 1985]. Whereas the base of the Adriatic plate crust was found to lie at a depth of only 20 km, the base of the Corsican crust appears at a depth of 30 km [Hirn and Sapin, 1977; Egger et al., 1985]. These results have been interpreted to indicate that the Adriatic plate overlies the Corsican crust in a flakelike structure [Morelli et al., 1977; Reutter et al., 1980a; Buness, 1985]. We propose that this east dipping contact of Adriatic plate crust upon Corsican crust might represent a crustal scale, east-dipping, low-angle, detachment fault/shear zone complex due to Miocene or younger age extensional tectonics.

The exposures in the Alpi Apuane region do not permit us to directly observe the mechanisms of extension in the lower crust. We therefore speculate that some sort of compatible transition occurs which enables the anastomosing shear zone model of the middle crust to pass into a pure shear model for the lower crust (Figure 15) [Kligfield et al. 1984].

CONTINENTAL RIFTING AND ITS RELATIONSHIP TO OPENING OF THE TYRRHENIAN SEA

An important tranverse tectonic feature, the Livorno-Sillaro Line [Fazzini and Gelmini, 1982] divides the entire Northern Apennine lithosphere [Royden et al., 1987] into two segments which record different amounts of continental rifting. The northern segment, which includes the Alpi Apuane region, underwent a post collisional extension which was significantly less developed than that further to the south. As a result, the geometric effects of crustal extension on the earlier compressional features can still be examined in the Alpi Apuane region, whereas they are almost completely overprinted by the more strongly developed rift tectonics further south.

Grabens bounding the Alpi Apuane region form the northernmost extent of the Tuscan continental rift province with associated volcanics of Late Miocene, Pliocene, and Pleistocene age (Figure 1) [Bartolini et al., 1983]. The Tyrrhenian coast adjacent to the Alpi Apuane region is composed of high-angle normal faults with down-to-the-west sense of motion (Figure 4). These faults cut across not only the Oligocene age compressional structures, but also the Miocene age, low-angle extensional structures present in the Alpi Apuane region (Figure 4).

The basins along the eastern side of the Tyrrhenian Sea contain thick Tortonian sediments, thin evaporite deposits, and thick Plio-Pleistocene sediments whose geometry indicates Tortonian extension followed by Messinian, Lower Pliocene and Middle Pliocene age extension and subsidence [Fabbri and Curzi, 1979]. This is in general agreement with estimates for the initiation of Tyrrhenian extension in the late Miocene [Hsu, 1977; Scandone, 1979; Malinverno and Ryan, 1986; Finetti and DelBen, 1986; Kastens et al., 1988] and for the onset of major rifting at 9 Ma [Kastens and Mascle, 1990].

MODEL FOR NORTHERN APENNINE COMPRESSION AND EXTENSION

The features present in the Alpi Apuane region of the Northern Apennines record a history of compression followed by progessive tectonic extension of at least two types: 12 Ma extension related to the initial attenuation of continental crust and mid-Miocene and younger age extension related to large-scale continental rifting. The Alpi Apuane region preserves a unique record of the transition from compression to extension within a mountain belt not yet totally overprinted by large-scale continental rifting. Such is the case in the adjacent Tyrrhenian Sea, where the extensional basin developed within thickened continental crust of the former orogenic belt, with large scale rifting beginning at 9 Ma [Kastens and Mascle, 1990].

The transition from compression to extension can be partially explained as a consequence of the changing dynamics within orogenic accretionary wedges as proposed by Platt [1986]. In Platt's model, subduction-accretion complexes are approximated as wedge-shaped media which deform internally until a stable configuration is reached in which gravitation forces and forces generated by the subducting slab balance each other. Accretion of material at the front of the wedge will tend to lengthen the wedge and shorten it internally. Imbrication of crustal material beneath the wedge will thicken the wedge, which then needs to extend internally in order to regain its stable configuration. Such extension is characterized by the formation of listric normal faults that merge downward into more distributed zones of ductile extension producing features similar to those known from North American metamorphic core complexes. A similar model has been applied to certain aspects of Northern Apennine geology by Van den Berg [1990].

Stable Accretionary Wedge Stage (Cretaceous to Eocene)

The Northern Apennine accretionary wedge [Treves, 1984] most likely formed through

Cretaceous to Eocene subduction of remnant Tethyan oceanic crust (the Liguride complexes) beneath the rotating Corsica-Sardinia-Calabria microplate [Alvarez et al., 1974]. As this microplate converged against the Adriatic promontory [Channell et al., 1979; Kligfield, 1980], oceanic material was added at the wedge front, thereby lengthening the wedge to maintain a stable wedge configuration [Platt, 1976] (Figure 16a). Shortening within the wedge created both in-sequence and out-of-sequence thrusts within the Liguride complexes [Elter and Trevisan, 1973; Treves, 1984], which show a distinctive deformation history prior to their emplacement upon the Northern Apennine continental margin [Kligfield, 1979].

Microplate Collision and Rapid Wedge Thickening (Late Oligocene)

The attempted subduction of Northern Apennine continental crust beneath the colliding Corsica-Sardinia-Calabria microplate formed the compressional features of the Alpi Apuane duplex structure, which we have dated at 27 Ma, as well as similar structures within the metamorphic sequences of the Monte Pisani and Monticiano-Roccastrada tectonic windows further to the south (Figure 1). The immediate effect of this underplating was to rapidly thicken the geometry of the wedge (Figure 16b). In effect, the lower boundary of the accretionary wedge shifted, incorporating slices of Apennine continental crust within it. Between the Late Oligocene and Early Miocene, continued imbrication of slices of Appennine continental crust beneath the Alpi Apuane region led to the formation of its antiformal stack geometry (Figure 16c). The resultant thickness is estimated to have been at least twice that required to maintain a stable wedge geometry.

Extensional Collapse of Overthickened Wedge (Early Miocene)

We believe that the onset of the "core complex" type extension in the Alpi Apuane region may be the mid-crustal-level manifestation of the change in internal wedge dynamics from compressional to extensional. As argued by Platt [1986], an unstable overthickened wedge geometry causes the internal stresses within the wedge to become tensional and will lead to extension higher up in the wedge while compression continues lower down (Figure 16c). The cessation of Corsica-Sardinia motion can be dated by the termination of the opening of the Ligurian-Balearic Basin in Burdigalian times [Rehault et al., 1985]. We believe that the termination of convergent movement between Corsica-Sardinia and the Northern Apennines at this time caused all further tectonic underplating to cease, a situation which led to the rapid gravitational collapse of the wedge (Figure 16d).

Northern Apennine Rifting and Opening of the Tyrhhenian Sea

Beginning in the Tortonian and continuing through the Pleistocene, potassic intrusive magmas migrated across the Tuscan-Tyrrhenian region from southwest to northeast (Figures 1, 16d, and 16e) [Civetta et al., 1978]. We suggest that the initiation of these volcanic intrusives was related to the intrusion of asthenospheric material [Conticelli et al., 1986] belonging to the Corsica-Sardinia microplate into the overlying delaminated crust of the Northern Apennine accretionary wedge (Figure 16dD). The crust, already attenuated by the gravitational collapse of the Apennine accretionary wedge, was further weakened by contact with hot asthenosphere. As this process evolved during the Messinian, widespread continental rifting occurred throughout Tuscany (Figure 16e). We speculate that this process, perhaps aided by further back arc processes, was similar to that which led to oceanic rifting further south in the Tyrrhenian Sea [Kastens and Mascle, 1990].

DISCUSSION

Tectonic extension of the order of magnitude indicated in the Tyrrhenian and Apennine regions is best known in continental rifts such as the Basin and Range province. A number of studies indicate the presence of extensional features superimposed within compressional mountain belts [Burg et al., 1984; Royden and Burchfiel, 1987; Ratschbacher et al., 1989]. However, we believe that the tectonic evolution of the Apennines presented above has greatest similarity to that of the early history of the Basin and Range in North America.

Apennine Versus North American Core Complexes

In the Northern Apennines, an overthickened, accretionary wedge-collision complex of Cretaceous-Oligocene age was extended at middle crustal and upper crustal levels during the Miocene, and subsequently evolved into a Basin and Range type extensional province with associated volcanism beginning in the Messinian. The evolution of the Alpi Apuane core complex is similar to that of California, Utah, Idaho, and Canadian core complexes which record early histories of Sevier and Laramide age compression, followed by mid-Tertiary extension, and finally by Pliocene and younger Basin and Range type rifting [Coney and Harms, 1984; Coney, 1987]. In plate tectonic terms, Apennine core complexes formed within an accretionary wedge caused by subduction of oceanic crust beneath a migrating microplate arc complex [Kligfield, 1980]. By contrast, North American core complexes formed largely within the back arc region of the Sevier and Laramide orogenies [Hamilton, 1987; Coney, 1987].

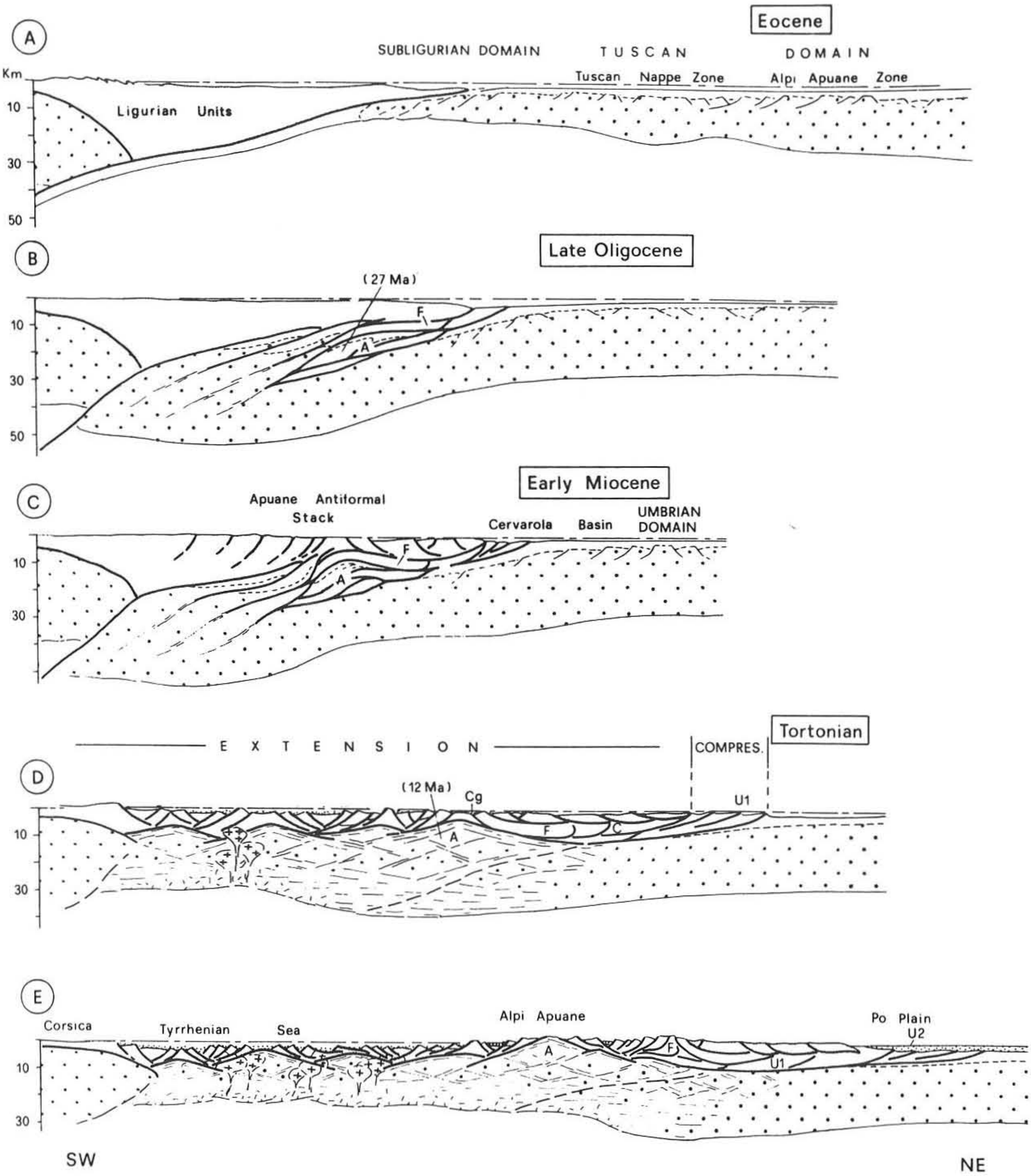


Fig. 16. Evolution of the Northern Apennines within the changing dynamics of an accretionary wedge. (a) Oceanic crust subducts beneath the Corsica-Sardinia microplate. The wedge lengthens to accommodate shortening within the Liguride sequences without a change in wedge thickness. (b) Rapid underplating of continental crust due to microplate collision causes wedge thickening. (c) Gravitational collapse of overthickened wedge geometry leads to extension in upper-crustal portions of wedge. (d) Initiation of extension is followed by denudation, uplift, and erosion of the metamorphic core complexes (Tortonian). (e) Continued large-scale tectonic extension leads to the development of a continental rift province in Tuscany and the opening of the Tyrrhenian Sea. Key: A: Alpi Apuane core complex. F: Tuscan nappe. C: Cervarola flysch. Cg: sedimentary breccias. U1 and U2: Accreted portions of the Umbrian domain involved in thrusting during the Tortonian and Messinian, respectively. Large dots: continental crust.

Surface mapping within North American core complexes commonly reveals a dominantly single-sided sense of shear on both sides of the core complexes. The presence of dipping detachments on either side of an uplifted core complex with the same sense of asymmetry has been explained by folding due to denudation and uplift of the original single-sense shear zone/detachment system [Spencer, 1984]. By contrast, the Alpi Apuane core complex provides evidence of distributed ductile strain at mid-crustal levels having both oppositely directed senses of shear (Figure 4). In this respect it resembles anastomosing shear zone models proposed for middle-crustal levels within the Basin and Range province on the basis of seismic reflection profiles [Hamilton, 1982, 1987] and model studies [Kligfield et al., 1984] rather than single, large-scale, linked detachment fault and mylonite zones which cut downward through the continental crust [Wernicke et al., 1987; Lister and Davis, 1989].

The onset of rifting and associated volcanism in the Basin and Range province represented a second phase of extension which developed within the already attenuated North American crust. In some fashion, the cessation of active subduction along the Pacific margin during the late Cenozoic allowed hot asthenosphere to well up into the already thinned North American lithosphere, forming the Basin and Range province [Coney, 1987]. We argue that the Tyrrhenian Sea may have formed by a similar two-stage process: collision of the Corsica-Sardinia microplate with the Northern Apennines in the Oligocene caused cessation of subduction activity along the Adriatic promontory and the onset of gravitational relaxation of the overthickened wedge. Intrusion of asthenospheric material from the subducted African (?) plate then led to the initiation of large-scale extension in the Northern Apennines, Tuscany, and the Tyrrhenian region. Shortly thereafter a further collision of the Calabria portion of this microplate with the Southern Apennines led to a rearrangement of microplate activity in the region, including subduction of Apulia remnant oceanic crust beneath the Southern Apennines in the Ionian arc [Channell, 1987]. This newer subduction may have allowed the further intrusion of hot asthenosphere into the already attenuated continental crust of the Adriatic promontory's back arc region, leading to large-scale extension in the Southern Apennines [D'Argenio et al., 1987] and the further development of the oceanic part of the Tyrrhenian Sea [Kastens and Mascle, 1990].

Effect of Collision on Wedge Geometry

We have argued that the Oligocene collision of the Corsica-Sardinia microplate with the continental crust of the Adriatic promontory produced two major effects on the accretionary wedge geometry. First, the collision led to rapid underplating beneath the orogenic wedge, causing it to thicken. Second, the collision of buoyant continental crust of Corsica-Sardinia-Calabria with that of the Apennines led to a subsequent cessation of convergence in the early Miocene (Burdigalian). The orogenic wedge then suffered extensional collapse pushing the wedge front forward and producing compressional structures in the Adriatic foreland. Postcollisional extension in the hinterland and compression in the foreland continued throughout the Middle to Late Miocene and Pliocene [Elter et al., 1975] until interrupted by the initiation of Tyrrhenian rifting in the hinterland. The Pliocene and younger compressional structures in the Adriatic foreland (Figure 16e) [Bally et al., 1988] could be interpreted as late-stage adjustments in the front of the wedge to its extensional collapse. This explanation would alleviate the need to explain frontal Apennine compressional features as the product of continued subduction of the Adriatic foreland beneath the Apennines, a mechanism suggested to explain the lack of correspondence of Apennine gravity and topographic data with flexural models [Royden and Karner, 1984]. However, according to Bally et al. [1988], the significant amounts of crustal shortening required from the balanced surface and seismic sections are too great to be explained by gravitational collapse alone.

CONCLUSIONS

The Alpi Apuane region of the Northern Apennines can be regarded as a classical core complex of North American type in which Miocene-Pliocene age extensional structures are superposed on the Cretaceous- Eocene compressional features within the thickened Apennine nappe edifice. The extensional tectonics at high structural levels produced listric normal faults typical of those observed in the Basin and Range. In contrast to observations in the Basin and Range, distributed ductile strain with different shear senses allowed extension to occur within metamorphic rocks at mid-crustal levels.

We propose a four-stage model for the tectonic evolution of the Northern Apennines and Tyrrhenian Sea in which the transition from compression to extension is caused by the changing dynamics within an accretionary wedge according to the theory of Platt [1986]. In our model, (1) an accretionary wedge-subduction complex formed from Cretaceous to Eocene times and was characterized by compressional deformation of ophiolites and deepwater sedimentary rocks; (2) the collision of the Corsica-Sardinia-Calabria microplate in the Oligocene (27 Ma) led to rapid underplating of the accretionary wedge and compressional deformation of the Adriatic continental margin; (3) beginning in the Early Miocene (12 Ma) the overthickened accretionary wedge geometry underwent a gravitational collapse, producing extensional tectonics at upper-crustal and mid-crustal levels in the Apennines; (4) beginning in the Tortonian the cessation of subduction allowed hot asthenosphere of the subducted Adriatic plate to intrude into the already attenuated continental crust of the wedge, producing large-scale regional extension with associated volcanism.

ACKNOWLEDGMENTS

This research is part of a long-term collaborative effort between Italian and U.S. scientists aimed at investigating mountain building processes in the Apennines and surrounding regions. We thank A.W. Bally, M. Boccaletti, J.E.T. Channell, G. Giglia, W. Hamilton, J. Oldow, and L. Royden for critical reviews of the manuscript. R.K. thanks members of the Geological Institutes at the universities of Pisa, Siena, and Cagliari for their long term encouragement and support of such studies, J. C. Hunziker for a stimulating partnership in carrying out geochronological investigations, and W. Alvarez for originally providing the opportunity to study Apennine geology. Partial funding for this research (L.Carmignani) was provided by Fondi MPI 40, University of Siena.

REFERENCES

Abbate, E., and P. Bruni, Torbiditi oligo-mioceniche ed evoluzione del margine Nord-Appenninico, *Mem. Soc. Geol. Ital., 39,* 19-33, 1989.

Abbate, E., M. Balestrieri, G. Bigazzi, P. Norelli, and C. Quercioli, Apatite fission track datings and the uplift of the Apuan Alps and surrounding regions (Northern Apennines, Italy), Abstract in *Proceedings of the Seventh International Conference on Geochronology, Cosmochronology and Isotope Geology,* Canberra, Australia, Sept. 24-29, 1990.

Alvarez, W., T. Cocozza, and F. Wezel, Fragmentation of the Alpine orogenic belt by microplate dispersal, *Nature 248,* 309-314, 1974.

Baldacci, F., P. Elter, E. Giannini, G. Giglia, A. Lazzarotto, R. Nardi, M. Tongiorgi, Nuove osservazioni sul problema della Falda Toscana e sulle interpretazione dei flysch arenarei tipo "Macigno" dell'Appennino Settentrionale, *Mem. Soc. Geol. Ital., 6,* 213-244, 1967.

Bally, A.W., L. Burbi, C. Cooper, and R. Ghelardoni, Balanced sections and seismic reflection profiles across the central Apennines, *Mem. Soc. Geol. Ital.,* 257-310, 1988.

Bartolini, C. et al., Carta neotettonica dell'Appennino settentrionale, Note illustrative. *Boll. Soc. Geol. Ital., 101,* 523-529, 1983.

Bernini, M., Il bacino dell'alta Val Magra: primi dati mesostrutturali sulla tettonica distensiva, *Boll. Soc. Geol. Ital., 107,* 355-371, 1988.

Berthe, D., P. Choukroune, and D. Gapais, Orientations preferentielles du quartz et orthogneissification progressive en regime cisaillement: L'exemple du cisaillement sudarmoricain, *Bull. Mineral. 102,* 265-272, 1979.

Bigazzi, G., A. Di Pisa, M. Gattiglio, M. Meccheri, P. and Norelli, La struttura cataclastico milonitica di Foce di Mosceta Alpi Apuane Sud-orientali (M. Corchia, Gruppo delle Panie), *Atti Soc. Toscana Sci. Nat. Pisa Mem. Ser. A., 95,* 105-116, 1988.

Boccaletti, M. and M. Coli, La tettonica della Toscana: Assetto ed evoluzione, *Mem. Soc. Geol. Ital., 25,* 51-62, 1983.

Boccaletti, M. and G. Gosso, Analisi della deformazione plicativa e rapporti con lo sviluppo della blastesi metamorfica nell'area di Campo Cencina-M. Pisanino delle Alpi Apuane Settentrionali, *Mem. Soc. Geol. Ital., 21,* 101-110, 1980.

Boccaletti, M. and G. Guazzone, Remnant arcs and marginal basins in the Cenozoic development of the Mediterranean, *Nature, 252,* 54-78, 1974.

Boccaletti, M., P. Elter, and G. Guazzone, Plate tectonic models for the development of the Western Alps and Northern Apennines, *Nature, 234,* 108-111, 1971.

Boccaletti, M., S. Capitani, M. Coli, G. Fornace, G. Gosso, G. Grandini, F. Milano, G. Moratti, P. Nafissi, P. and F. Sani, Caratteristiche deformative delle Alpi Apuane settentrionali, *Mem. Soc. Geol. Ital. 26,* 527-534, 1983.

Buness, H., The transition between the Corso-Sardinian block and the Adriatic plate, in *Proceedings of the Second Workshop on the European Geotraverse Project ,The Southern Segment,* edited by D.A. Galson and S. Mueller, European Science Foundation, pp. 215-220, Strasbourg, France, 1985.

Burg, J., M. Brunel, D. Gapais, G. Chen, and G. Liu, Deformation of leucogranites of the crystalline Main Central Sheet in southern Tibet (China), *J. Struct. Geol., 6,* 535-542, 1984.

Calistri, M., Studi di geomorfologia e neotettonica. 2-Il Plicocene fluvio-lacustre della conca di Barga, *Mem. Soc. Geol. Ital., 13,* 1-21, 1974.

Carmignani, L., Carta geologico-strutturale del complesso metamorfico delle Alpi Apuane, scale 1:25,000, Foglio nord, Litografia Artistica Cartografica, Florence, Italy, 1985.

Carmignani, L. and G. Giglia, Le fasi tettoniche terziare dell'autoctono delle Alpi Apuane: Studio delle strutture minori della zona centro-meridionale, *Boll. Soc. Geol. Ital. 94,* 1957-1981, 1975.

Carmignani, L. and G. Giglia, Analasi mesostrutturale della zona occidentale delle Apuane metamorfiche, *Boll. Soc. Geol. Ital., 96,* 429-450, 1977.

Carmignani, L. and G. Giglia, Large scale reverse drag folds in the late Alpine building of the Apuane Alps (N. Apennines), *Atti Soc. Toscana Sci. Nat. Mem. Ser. A, 86,* 109-125, 1979.

Carmignani, L. and G. Giglia, Il problema della doppia vergenza sulle Alpi Apuane e la struttura del M. Corchia, *Mem. Soc. Geol. Ital., 26,* 515-525, 1983.

Carmignani, L. and G. Giglia, "Autoctono Apuano" e Falda Toscana. Sintesi dei dati e delle interpretazioni, in *Ceno anni di Geologia Italiana,* vol. Giub. I Centenario, Societa Geolica Italiana (publisher) pp.199-214, Bologna, 1984.

Carmignani, L., G. Giglia, and R. Kligfield, Structural evolution of the Apuane Alps: An example of continental margin deformation in the Northern Apennines, Italy, *J. Geol. 86,* 487-504, 1978.

Carmignani, L., G. Giglia, and R. Kligfield, Nuovi dati sulla zona di taglio ensialica delle Alpi Apuane, *Mem. Soc. Geol. Ital. 21,* 93-100, 1980.

Cerrina Feroni, A., G. Plesi, L. Leoni, and P. Martinelli, Contributo alla conoscenza dei processi metamorfici di grado molto basso (anchimetamorfismo) a carico della falda toscana nell'area di riccoprimento apuano, *Boll. Soc. Geol. Ital. 102,* 269-280, 1983.

Channell, J.E.T., Paleomagnetism and continental collision in the Alpine belt and the formation of late-tectonic extensional basins, in Collisional Tectonics, edited by M. Coward and A. Ries, *Geol. Soc. Spec. Publ. 19,* 261-286, 1987.

Channell, J.E.T. and J. Mareschal, Delamination and asymmetric lithospheric thickening in the development of the Tyrrhenian Rift, in Alpine Tectonics, edited by M. Coward, D. Dietrich, and R. Park, *Geol. Soc. Spec. Publ. 30,* 285-302, 1989.

Channell, J.E.T., B. D'Argenio, and F. Horvath, Adria, the African promontory, in Mesozoic Mediterranean Palaeogeography, *Earth Sci. Rev., 15,* 213-292, 1979.

Civetta, L., G. Orsi, and P. Scandone, Eastwards migration of Tuscan anatectic magmatism due to anticlockwise rotation of the Apennines, *Nature, 276,* 604-605, 1978.

Coli, M., Time and mode of uplift of the Apuane Alps metamorphic complex, *Atti Ticenese Scienze Terra, 32,* 47-56, 1989.

Coney, P.J., The regional tectonic setting and possible causes of Cenozoic extension in the North American Cordillera, in Continental Extensional Tectonics, edited by M. Coward, J. Dewey and P. Hancock, *Geol. Soc. Spec. Publ. 28,* 177-186, 1987.

Coney, P.J. and T. Harms, Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression, *Geology, 12,* 550-554, 1984.

Conticelli, S., P. Manetti, A. Peccerillo, and A. Santo, Caratteri petrologici delle vulcaniti potassiche italiane: considerazioni genetiche e geodinamiche, *Mem. Soc. Geol. Ital. 35,* 775-783, 1986.

Dallan-Nardi, L., Segnalazione di Lepidocycline nelle parte basale dello "pseudomacigno" delle Alpi apuane. Boll. Soc. Geol. Ital. 95, 459-477, 1977.

Dallan-Nardi, L., Microfossili miocenici nella matrice sedimentaria delle brecce situate alla base della "Falda Toscana" nelle Apuane meridionali, *Boll. Soc. Geol. Ital. 98,* 119-128, 1979.

Dallan-Nardi, L. and R. Nardi, Ipotesi sulla genesi e sul significato delle brecce stratigrafiche associate ai "calcari cavernosi" sulle Alpi Apuane e sul Monte Pisano in rapporto alla messa in posto della falda toscana, *Boll. Soc. Geol. Ital., 92,* 435-452, 1973.

Dallan-Nardi, L. and R. Nardi, Il quadro paleotettonico dell'Appennino Settentrionale: un'ipotese alternativa, *Atti Soc. Tosc. Sci. Nat. Mem. Ser. A., 85,* 289-297, 1978.

D'Argenio, B., A. Ietto, and J. Oldow, Low angle normal faults in the Picentini Mountains, Southern Apennines, *Rend. Soc. Geol. Ital., 9,* 113-122, 1987.

Davis, G.H., Structural characteristics of metamorphic core complexes, southern Arizona, in Cordilleran Metamorphic Core Complexes, edited by M. Crittenden, P. Coney and G.H. Davis, *Mem. Geol. Soc. Am. 153,* 35-78, 1980.

Di Pisa, A., M. Franceschelli, L. Leoni, and M. Meccheri, Regional variation of the metamorphic temperatures across the Tuscanid I Unit and its implications on the alpine metamorphism (Apuan Alps, N. Tuscany), *Neues Jahrb. Mineal. Abh. 151,* 197-211, 1985.

Egger, A., J. Ansorge, and S. Mueller, Crustal structure of Corsica and the lower lithosphere under the Corsica-Sardinia block, in *Proceedings of the Second Workshop on the European Geotraverse Project, The Southern Segment,* edited by D.A. Galson and S. Mueller, European Science Foundation, pp. 207-214, Strasbourg, France, 1985.

Elter, P. and L. Trevisan, Olistotromes in the tectonic evolution of the Northern Apennines, in *Gravity and Tectonics,* edited by K.A. deJong and R. Scholten, John Wiley, New York, pp. 175-187, 1973.

Elter, P., G. Giglia, M. Tongiorgi, and L. Trevisan, Tensional and compressional areas in the recent (Tortonian to present) evolution of the Northern Apennines, *Boll. Geofis. Teor. Appl. 42,* 3-18, 1975.

Fabbri, A. and P. Curzi, The Messinian of the Tyrrhenian Sea: seismic evidence and dynamic implications. *Gi. Geol., 43,* 215-248, 1979.

Fazzini, P. and R. Gelmini, Tettonica trasversale nell'appennino settentrionale, *Mem. Soc. Geol. Ital. 24,* 299-309, 1982.

Federici, P., La tettonica recente dell'Appennino: I, Il bacino villafranchiano di Sarzano e il suo significato nel quadro dei movimenti distensivi a nord-ovest delle Alpi Apuane, *Boll. Soc. Geol.. Ital., 92,* 287-301, 1973.

Federici, P. and G. Raggi, Brecce sedimentarie e rapporti tra le unita' tettoniche toscane nel gruppo delle Alpi Apuane, *Boll. Soc. Geol. Ital., 93,* 709-722, 1974.

Federici, P. and A. Rau, Note illustrative della neotettonica del Foglio 96-Massa, P. 356, pp.1365-1382, *Contr. real. Carta Neot Ital., Publ. 251,* Consiglio Nazionale delle Ricerche, Progetto Finalizzato Geodinamica, Tipografia Senese, Siena, Italy, 1980.

Finetti, I. and A. DelBen, Geophysical study of the Tyrrhenian opening, *Boll. Geof. Teor. Appl., 28,* 75-155, 1986.

Giglia, G., and R. Radicati di Brozolo, K/Ar age of metamorphism in the Apuane Alps (northern Tuscany), *Boll. Soc. Geol. Ital., 89,* 485-497, 1970.

Hamilton, W.B., Structural evolution of the Big Maria Mountains, northeast Riverside County, southeastern California, in Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona and Nevada, edited by E. Frost and D. Martin, pp. 1-28, Cordilleran, San Diego, Calif., 1982.

Hamilton, W.B., Crustal extension in the Basin and Range Province, southwestern United States, in Continental Extensional Tectonics, edited by M. Coward, J. Dewey and P. Hancock, *Geol. Soc. Spec. Publ. 28,* 155-176, 1987.

Hill, K. and A. Hayward, Structural constraints on the Tertiary plate tectonic evolution of Italy, *Mar. Petr. Geol., 5,* 2-8, 1988.

Hirn, A., and M. Sapin, Crustal structure beneath Corscia, *Boll. Geofis. Teor. Appl., 75-76,* 233-235, 1977.

Hsu, K., Tectonic evolution of the Mediterranean basins, in *The Ocean Basins and Margins,* vol. 4A, *The Eastern mediterranean,* edited by A. Nairn, W. Kanes, and F. Stehli, 29-75, Plenum, New York, 1977.

Kastens, K. and J. Mascle, The geological evolution of the Tyrrhenian Sea: An introduction to the scientific results of ODP Leg 107, *Proc. Ocean Drill. Program Sci. Results, 107,* 3-26, 1990.

Kastens, K. et al., ODP Leg 107 in the Tyrrhenian Sea: Insights into passive margin and back-arc basin evolution, *Geol. Soc. Am. Bull. 100,* 1140-1156, 1988.

Kligfield, R., The Northern Apennines as a collisional orogen, *Am. J. Sci. 279,* 676-691, 1979.

Kligfield, R., Structural-geochronological constraints on plate tectonic models for the Corsica-Northern Apennine collision, in Evolution and Tectonics of the Western Mediterranean and Surrounding Areas, edited by A. Udias and J. Channell, *Spec. Publ. 201,* Inst. Geog. Nac., Madrid, Spain, pp. 163-178, 1980.

Kligfield, R., L. Carmignani, and W. Owens, Strain analysis of a Northern Apennines shear zone using deformed marble breccias, *J. Struct. Geol., 3,* 421-436, 1981.

Kligfield, R., J. Crespi, S. Naruk, and G.H. Davis, Displacement and strain patterns of extensional orogens, *Tectonics 3,* 577-609, 1984.

Kligfield, R., J. Hunziker, R.D. Dallmeyer, and S. Schamel, Dating of deformation phases using K-Ar and 40Ar/39Ar techniques: Results from the Northern Apennines, *J. Struct. Geol., 8,* 781-798, 1986.

Lavecchia, G., The Tyrrhenian-Apennines system: structural setting and seismotectogenesis, *Tectonophysics 147,* 263-296, 1988.

Lister, G. and G.A. Davis, The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A., *J. Struct. Geol., 11,* 65-94, 1989.

Locardi, E., Individuazione delle strutture sismogenetiche dall'esame dell'evoluzione vulcano-tettonica dell'Appennino e del Tirreno, *Mem. Soc. Geol. Ital., 24,* 569-596, 1982.

Malinverno, A. and W. Ryan, Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere, *Tectonics 5,* 227-246, 1986.

Merla, G., Geologia dell'Appenninno settentrionale, *Boll. Soc. Geol. Ital., 70,* 95-382, 1952.

Morelli, C., et al., Crustal and upper mantle structure of the Northern Apennines, the Ligurian Sea and Corsica, derived from seismic and gravimetric data, *Boll. Geofis. Teor. Appl., 19,* 199-260, 1977.

Nardi, R., Geologia della zona tra la Pania della Croce, Gallicano e Castelnuouvo Garfagnana (Alpi Apuane), *Boll. Soc. Geol. Ital., 80,* 257-334, 1961.

Patacca, E., A. Rau, and M. Tongiorgi, Il significato geologica della breccia sedimentaria poligenica al tetto della successione metamorfica dei Monti Pisani, *Atti Soc. Tosc. Sic. Nat., Mem. Ser. A., 80,* 126-161, 1973.

Pertusati, P., G. Plesi, and A. Cerrina-Feroni, Alcuni esempi di tettonica polifasata nella falda toscana, *Boll. Soc. Geol. Ital., 96,* 587-603, 1977.

Platt, J., Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks, *Geol. Soc. Am. Bull. 97,* 1037-1053, 1986.

Platt, J. and R. Vissers, Extensional structures in anisotropic rocks, *J. Struct. Geol. 2,* 397-410, 1980.

Raggi, G., Neotettonica ed evoluzione paleogeografica Plio-Pleistocenica del bacino del Fiume Magra, *Mem. Soc. Geol. Ital., 30,* 35-62, 1985.

Ramsay, J.G., M. Casey, and R. Kligfield, Role of shear in the development of the Helvetic fold-thrust belt of Switzerland, *Geology 11,* 439-442, 1983.

Ratschbacher, L., W. Frisch, F. Neubauer, S. Schmid, and J. Neugebauer, Extension in compressional orogenic belts: The eastern Alps, *Geology, 17,* 404-407, 1989.

Rau, A., M. Tongiorgi, and P. Martini, La successione di Punta Bianca: un esempio di rift "abortivo" nel Trias medio del dominio Toscano, *Mem. Soc. Geol. Ital. 30,* 115-125, 1985.

Rehault, J., G. Boillot, and A. Mauffret, The Western Mediterranean Basin, in *Geological Evolution of Mediterranean Basin,* edited by D. Stanley and F. Wezel, pp.101-129, Springer-Verlag, New York, 1985.

Reutter, K., P. Giese, and H. Closs, Lithospheric split in the descending plate: observations from the Northern Apennines, *Tectonophysics, 64,* T1-T9, 1980a.

Reutter, K., M. Teichmuller, R. Teichmuller, and G. Zanzucchi, Le ricerche sulla carbonificazione dei frustoli vegetali nelle rocce clastiche come contributo ai problemi di paleogeotermia e tettonica nell'Appennino settentrionale, *Mem. Soc. Geol. Ital. 21,* 111-116, 1980b.

Royden, L. and B. Burchfiel, Thin-skinned N-S extension within the convergent Himalayan region: Gravitation collapse of a Miocene topographic front, in Continental Extensional Tectonics, edited by M. Coward, J. Dewey and P. Hancock, *Geol. Soc. Spec. Publ. 28,* 611-619, 1987.

Royden, L. and G. Karner, Flexure of lithosphere beneath Apennine and Carpathian foredeep basins: Evidence for an insufficient topographic load, *AAPG, 68,* 704-712, 1984.

Royden, L, E. Patacca, and P. Scandone, Segmentation and configuration of subducted lithosphere in Italy: An important control on thrust belt and foredeep basin evolution, *Geology, 15,* 714-717, 1987.

Sani, M., Le brecce della Versilia tra successione Toscana metamorfica e Falda Toscana nell'area di Casoli-Metato (Apuane meridionali), *Rend. Soc. Geol. Ital. 8,* 25-29, 1985.

Scandone, P., Origin of the Tyrrhenian Sea and Calabrian arc, *Boll. Soc. Geol. Ital., 98,* 27-34, 1979.

Simpson, C., Determination of movement sense in mylonites, *J. Geol. Educ., 34,* 246-261, 1986.

Simpson, C. and S. Schmid, An evaluation of criteria to deduce the sense of movement in sheared rocks, *Geol. Soc. Am. Bull., 94,* 1281-1288, 1983.

Spencer, J., Role of tectonic denudation in warping and uplift of low-angle normal faults, *Geology, 12,* 95-98, 1984.

Treves, B., Orogenic belts as accretionary prisms: the example of the Northern Apennines, *Ofioliti, 9,* 577-618, 1984.

Trevisan, L., Considerations sur deux coupes a travers l'Apennin septentrional, *Bull. Soc. Geol. France Ser. 7, 9,* 675-681, 1962.

Van Bemmelen, R., Driving forces of Mediterranean orogeny. Test case I: Tyrrhenian area, *Geol. Mijnbouw, 51,* 548-573, 1972.

Van den Berg, L., Application of a mechanical model to the Northern Apennines, with special reference to the effect of sea level changes, *Geol. Mijnbouw, 69,* 43-52, 1990.

Venturelli, G., and M. Frey, Anchizone metamorphism in sedimentary sequences of the Northern Apennines, *Rend. Soc. Ital. Mineral. Petrol., 33,* 109-123, 1977.

Wernicke, B., R. Christiansen, P. England, and L. Sonder, Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera, in Continental Extensional Tectonics, edited by M. Coward, J. Dewey and P. Hancock, *Geol. Soc. Spec. Publ. 28,* 203-221, 1987.

Wezel, F., The Tyrrhenian Sea: a rifted krikogenic-swell basin, *Mem. Soc. Geol. Ital., 24,* 531-568, 1982.

L. Carmignani, Dipartimento Scienze della Terra, Univerita di Siena, Via delle Cerchia 34, Siena, Italy.

R. Kligfield, Department of Geological Sciences, University of Colorado, Boulder, CO 80309.

(Received August 2, 1989;
revised June 23, 1990;
accepted July 2, 1990.)