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ALPINE CORSICA METAMORPHIC CORE COMPLEX

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Abstract. Alpine Corsica is an example where superficial nonmetamorphic allochtonous units rest upon a highly strained metamorphic complex. Early ductile deformation under high pressure-low temperature (HP-LT) conditions is due to the westward thrusting of oceanic material onto a continental basement as shown by previous studies. New thermobarometric estimates yield minimal peak HP-LT metamorphism conditions of 11 kbar at 400°C. The early deformation is overprinted by a ductile deformation with an eastward sense of shear postdating or contemporaneous with mineral recrystallizations in the greenschist facies conditions. Early compressive thrust contacts are reworked as east dipping ductile normal faults and the less competent units display only eastward shear criteria. The upper units are affected by an extensional brittle deformation, and east dipping brittle normal faults bound to the west the early to middle Miocene Saint-Florent half-graben. The greenschist metamorphic event lasted until 33 Ma, which is contemporaneous with the beginning of the extension in the Liguro-Provençal basin. We interpret the second deformation stage as the result of a ductile extension following the overthickening of the crust due to the westward thrusting. Extension reduces the thickness of the crust so that upper units free from early P-T conditions are brought into close contact with a HP-LT metamorphic core complex. The geometry of the late extension is controlled by that of the early compressive thrust.

INTRODUCTION

During the extension process which gave birth to the Liguro-Provençal basin and the Tyrrhenian Sea from Oligocene to present, Corsica and Sardinia were left as a stretched continental crust remnant. Crustal thickness in Corsica is about 30 km [Hirn and Sapin, 1976; Morelli et al., 1977], that of a normal continental crust. However Alpine Corsica is part of the western Alps nappe stack, and geological data show that the crust was about 50 km thick in late Eocene time. The crustal thickness had thus been considerably reduced afterwards. Extension and erosion are the two likely processes to reduce this thickness. We describe in this paper the deformation related to the extension process.

Alpine Corsica is an example where superficial nonmetamorphic allochtonous units affected by brittle deformation rest upon a highly strained high pressure-low temperature (HP-LT) metamorphic complex, the Schistes Lustrés nappe. This broadscale structure is that of a metamorphic core complex similar to those described in the Basin and Range or Franciscan provinces [Coney and Harms, 1984; Malavieille, 1987; Platt, 1986; Lister and Davis, 1989] or in the Cycladic area [Lister et al., 1984]. In these classical examples the contact between the upper brittle plate and the lower ductile plate is interpreted as a detachment fault formed during extension. Malavieille [1987] described in the Basin and Range the superimposition of a ductile extensional deformation onto an earlier compressional one.

Observations of the deformation and contemporaneous metamorphic recrystallizations in the Bastia area in Corsica allow us to distinguish two main successive stages of ductile noncoaxial deformation with opposite sense of shear. The Schistes Lustrés nappe, a tectonic stack of metasediments (schistes lustrés sensu stricto), metamorphic oceanic slices, and serpentinized peridotites, was first thrust westward onto the continental basement of western Corsica under HP-LT conditions [Mattauer and Proust, 1975]. This early deformation has been described in detail by Mattauer and Proust [1975, 1976 a] and Mattauer et al. [1977, 1981], Faure and Malavieille [1981], Malavieille [1982], and Warburton [1986]. The age of this deformation is still under discussion. New thermobarometric estimates of the HP-LT metamorphic conditions in the Schistes Lustrés nappe are given in this paper. We use them to restore P-T paths for the nappe.

We show that this early stage was followed by a second deformation with eastward sense of shear which is partly contemporaneous and partly subsequent to greenschist facies parageneses in the Schistes Lustrés nappe. Such eastward kinematic indicators had already been described in Alpine Corsica [Amaudric du Chaffaut, 1982; Jacquet, 1983; Warburton, 1986; Jourdan, 1988] and had been usually considered as evidence for a backthrust stage. However, several lines of evidences show that this deformation is the result of ductile extension coeval with brittle extension in the upper plate. The last thermal event is 35-33 m.y. old [Maluski, 1977; work of H. Maluski, as discussed by Jourdan, 1988], which is contemporaneous with the beginning of the rifting in the Liguro-Provençal basin [Burrus, 1984; Boillot et al., 1984]. The unconformable early Miocene limestone of Saint-Florent was deposited in an asymmetric westdipping graben. Furthermore, the sharp metamorphic contrast between the superficial Balagne-Nebbio-Macinaggio units and the intensively strained HP-LT metamorphic complex (Schistes Lustrés nappe and Tenda massif) suggests that the contact between them is a large detachment fault. We

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interpret this late deformation event as a ductile extension, and we suggest that Alpine Corsica is a metamorphic core complex risen by extensional processes [Wernicke and Burchfield, 1982].

GEOLOGIC SETTING

Corsica island is located between two Cenozoic oceanic basins, the Liguro-Provençal basin to the west and the Tyrrhenian Sea to the east. In the northeast, Alpine Corsica is separated from western crystalline Corsica by a late, vertical N-S fault with a strike-slip component (Figure 1). Two main features characterize the geology of Alpine Corsica. The first one is the crustal-scale thrust of oceanic material (the Schistes Lustrés nappe) onto the European continental margin represented by the Tenda massif on Figure 2 (see location of the cross section on Figure 1). The westward obduction in a simple shear context was responsible for the penetrative ductile deformation and associated HP-LT metamorphism within the thrust stack and at the top of the Tenda massif [Mattauer and Proust, 1975, 1976a, b; Mattauer et al., 1981; Faure and Malavieille, 1981; Malaveille, 1982; Jacquet, 1983]. Similar obduction-related HP-LT metamorphism is described in Oman [Goffé et al., 1988]. The core of the Tenda massif consists of unstrained Paleozoïc granitoïds; metamorphism and deformation increase towards the thrust contact as described by Mattauer and Proust [1975], Jacquet [1983], Gibbons and Horak [1984] and affect the Paleozoic and the Mesozoic (Santo-Pietro di Tenda sequence [Caron, 1977]) cover of the Tenda massif. Low-grade HP-LT assemblages (crossite + epidote [Gibbons and Horak, 1984]) are found in the upper part of the shear zone. A shear zone with blue amphiboles was also observed at the base of the massif with evidence of westward thrusting [Jourdan, 1988].

The Schistes Lustrés nappe is composed of several thrust slices folded in the Cap Corse-Castagniccia late antiform (Figure 1). Five principal units can be recognized. From base to top, they are (Figures 1 and 2): 1, the Castagniccia calcschists unit that crops out both in the Castagniccia and the Cap Corse areas; 2, the lower ophiolitic unit with lenses of eclogites [Autran, 1964; Essene, 1969; Caron et al., 1981; Pequignot, 1984; Harris, 1984; Caron and Pequignot, 1986; Lahondère, 1988; Lahondère and Caby, 1989]; 3, the Inzecca calcschists unit; 4, the Oletta-Serra di Pigno gneisses and their assumed sedimentary cover similar to the Santo-Pietro di Tenda sequence [Caron and Delcey, 1979; Mattauer et al., 1981]; 5, the upper ophiolitic unit composed of serpentinites and metamorphosed basic rocks. The calcschists (Schistes Lustrés sensus stricto) are interpreted as the sedimentary cover of the ophiolites of probable Jurassic to Early Cretaceous age [Caron, 1977; De Wever et al., 1987]. Note that the contact between the "Inzecca schists" and the "Castagniccia schists" of Caron [1977] (also carte géologique de la France a 1/250000: Corse, 1980) is included in our Inzecca schists unit as the metamorphism is similar on both sides. Detailed geological maps resulting from field surveys in the Bastia area and in the Golo valley are presented in Figures 3 and 4. Several E-W cross sections (Figure 5, see location of the sections in Figure 3; see Durand-Delga [1978] for a cross section of the Golo valley; see also Dallan and Puccinelli [1987]) show the structure of the Schistes Lustrés nappe. The Castagniccia schists crop out in the Golo valley and are overlain by the lower ophiolitic unit with a thick glaucophanitic sequence at

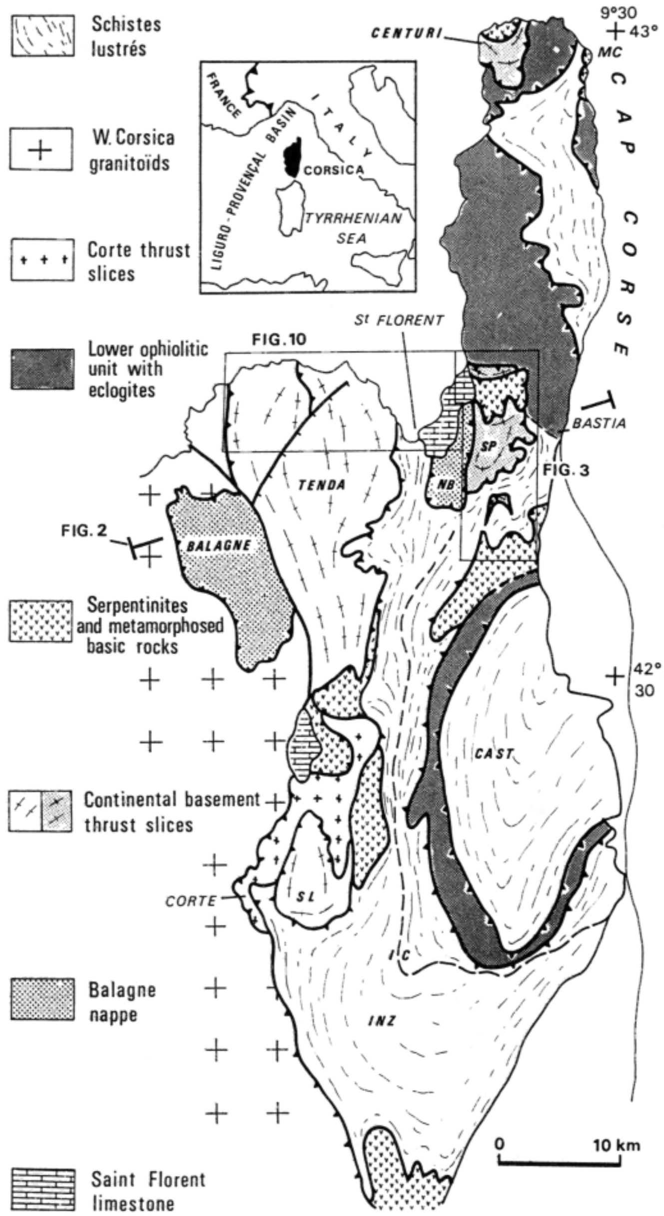


Fig. 1. Simplified tectonic map of Alpine Corsica [after Jolivet et al., 1990]. Abbreviations are CAST, Castagniccia; INZ, Inzecca; MC, Macinaggio; NB, Nebbio; SL, Santa Lucia; and SP, Serra di Pigno. The dotted line within the calcschists represents the contact between the Castagniccia (C) and the Inzecca (I) units of Caron [1977].

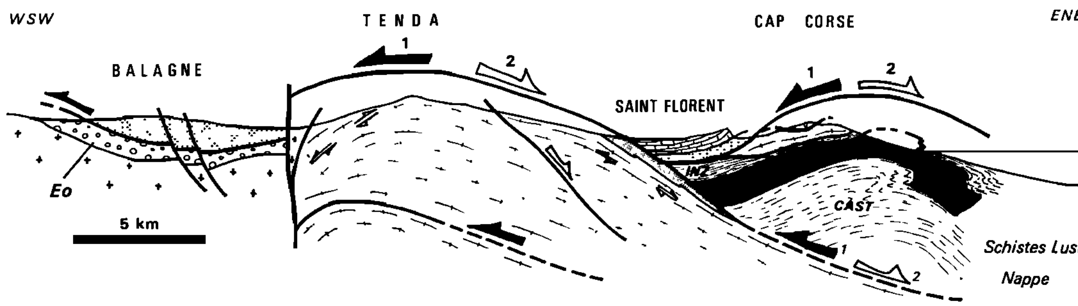


Fig. 2. Synthetic E-W cross section of the Cap Corse in the Bastia area [after Jolivet et al., 1990] (see location of the cross section in Figure 1). Solid arrows indicate the early westward compressional event (HP-LT); open arrows indicate the late eastward extensional event. For abbreviations see Figure 1. EO is Eocene autochtonous sediments.

its base (Figure 5d) covered by ophiolitic material (peridotites and serpentinites, metagabbros, fine-grained glaucophanites and prasinites) associated with schists and gneisses. The Inzecca schists, including ophiolitic slices, cover this ophiolitic unit. The Oletta-Serra di Pigno orthogneisses (Figures 5a and 5b) and their sedimentary cover lay either on the Inzecca schists or on eclogites farther north [Guiraud, 1982; Lahondère, 1988]. The upper ophiolitic unit is superimposed on this stack of tectonic slices. The tectonic contacts are parallel to the main blueschist foliation which is contemporaneous with the thrusting. A similar section is found in the north of Cap Corse near Centuri, where a slice of gneisses is tectonically included between ophiolitic thrust sheets [Malavieille, 1982; Guiraud, 1982].

The second characteristic of the geology of Alpine Corsica the superimposition of a nonmetamorphic and poorly strained superficial nappe upon the HP-LT metamorphic complex of the Schistes Lustrés nappe. The material of the superficial nappe of Ligurian affinity is found in the Balagne, Nebbio, and Macinaggio klippes. It was emplaced onto a terrigenous basin (upper Lutetian) as observed in Balagne [Mattauer and Proust, 1975; Jourdan, 1988]. This last horizontal movement has been correlated to the 33 Ma thermal event in the Tenda upper shear zone by Jourdan [1988].

The early Miocene Saint-Florent limestone lies uncomformably on the Schistes Lustrés nappe and the Nebbio klippe. It is folded in a broad asymmetric syncline whose western limb is covered with horizontal conglomeratic deposits.

In the following, we first present new data on the metamorphism and derive P-T paths for the Schistes Lustrés nappe and then describe the characteristics of the associated deformation with an emphasis on the late stage.

P-T PATHS IN THE SCHISTES LUSTRES NAPPE

Stability Fields of Mineral Assemblages in the Lower Ophiolitic Unit (Lancône Valley)

Thin sections in blueschists of the Lancône valley (Figure 5d) shows clasts of glaucophane, epidote, sphene, +/- garnet (65% almandin, 27% grossular, 4% pyrope, 4% spessartine), and +/- lawsonite included in a late foliation with chlorite, albite, +/- actinolite, +/- quartz. The albite-chlorite assemblage crystallizes in asymmetric pressure shadows around garnet, epidote, and lawsonite, or overprint the earlier HP-LT foliation with blue amphiboles which is preserved in the core of the unit. Sphene is a very early phase included in lawsonite or garnet. Lawsonite can also be included in garnet.

The stability fields of mineral assemblages are given by the phase diagrams computed by Evans [1990] with the program Geo-calc written by Brown et al. [1988], for rocks containing epidote and sodic amphibole and rocks containing assemblages characteristic of neighboring metamorphic facies. According to chemical analysis, we used the phase diagram computed for an intermediate pole between glaucophane and ferroglaucophane. The early lawsonite-glaucophane assemblage characterizes the lawsonite blueschist facies (LBS) delineated in Figure 6a. Refering to Massonne and Schreyer [1987], a curve of minimal pressure (curve 1 in Figure 6a) is obtained with the phengites (atomic Si content from 3.473 to 3.548 per formula unit) from garnet-bearing calcschists tectonically associated with ophiolitic rocks (Figure 5d). Postdating the formation of lawsonite and garnet, epidote crystallized under the epidote blueschist facies (EBS) conditions, following the a or b reactions. The albite-chlorite late assemblage may have appeared following reaction c ; it is symptomatic of the retromorphosis of the HP-LT assemblages in the greenschist facies. The study of titanium phase also allowed us to constrain the retrograde evolution. As remarked before, sphene is an early phase in these rocks, and rutile is never observed. The lawsonite-sphene stability field has been computed with Geo-calc, using the thermodynamic data base of Berman [1988] ($X(CO_2)<0.1\%$ not to destabilize lawsonite). As sphene is not destabilized, the way back to surface conditions is constrained by its stability limit (curve 2 in Figure 6a).

Thus the minimal peak P-T conditions for the glaucophane schists of the Lancône Valley are 11 kbar and 400°C. Previous estimates of blueschist P-T conditions made on the same kind of rocks of the Schistes Lustrés nappe with other thermobarometers are given in figure 6b [Harris, 1984; Gibbons et al., 1986; Lahondère, 1988], and Harris' P-T path for Cap Corse units is indicated. We also added estimates for the eclogites associated with the basal ophiolitic unit [Caron et al., 1981; Guiraud, 1982; Harris, 1984; Lahondère, 1988].

The Schists Units

The Castagniccia and Inzecca calcschists frequently contain the Fe-carpholite-lawsonite-rutile assemblage characteristic of HP-LT conditions (Figure 7). The presence of carpholite is significant for the retrograde

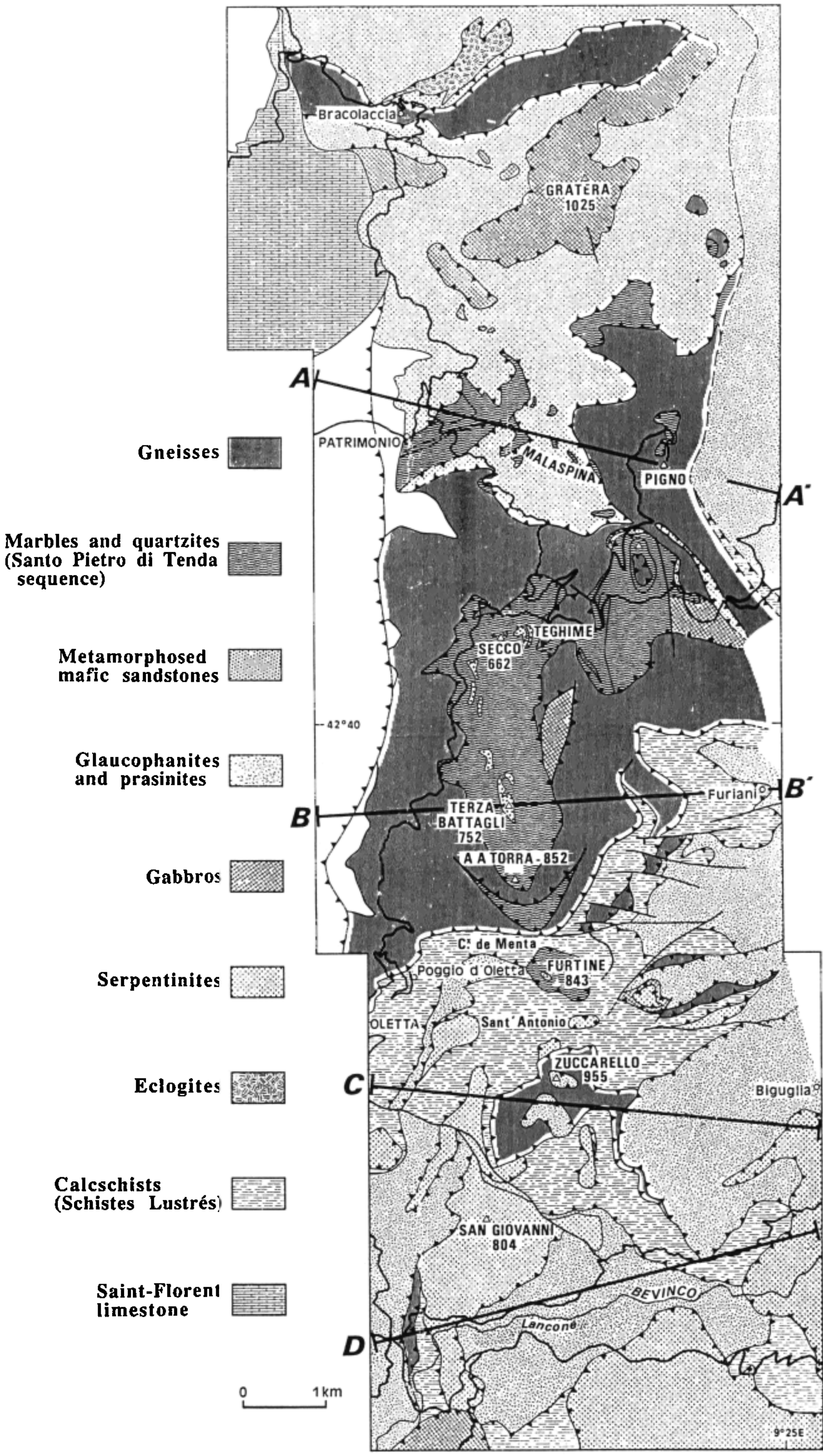


Fig. 3. Geological map of the Bastia-Lancône area.

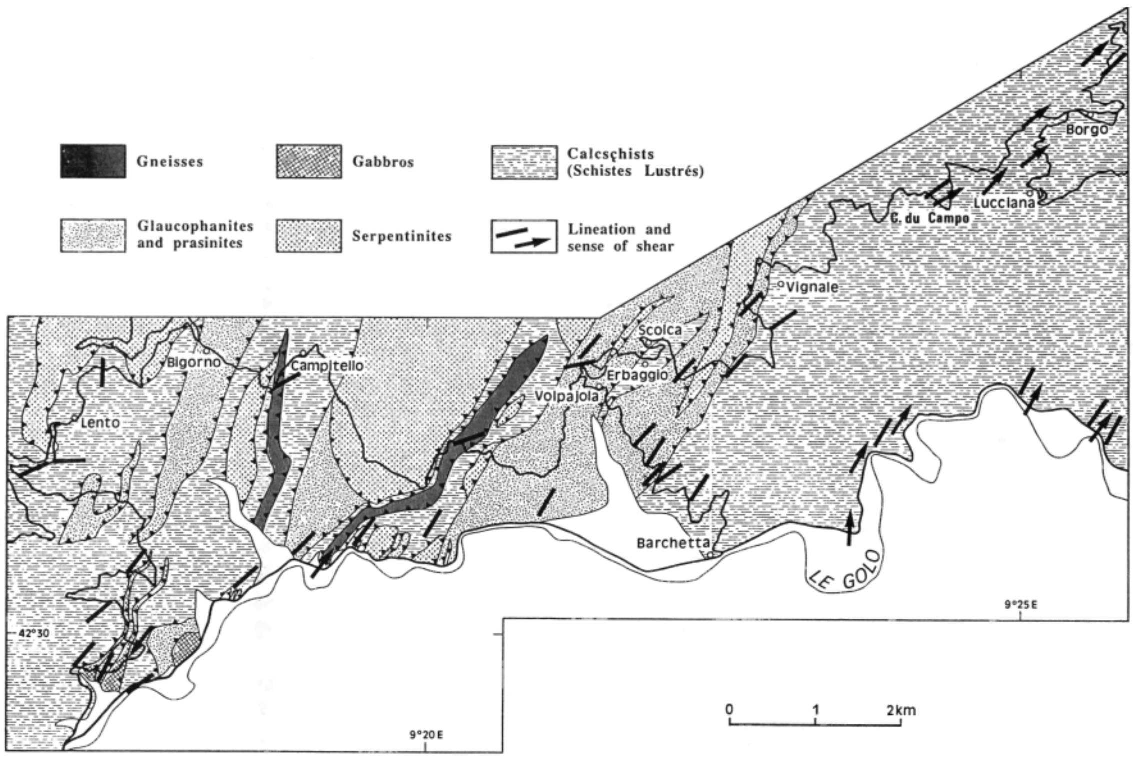


Fig. 4. Geological and structural map of the Golo valley.

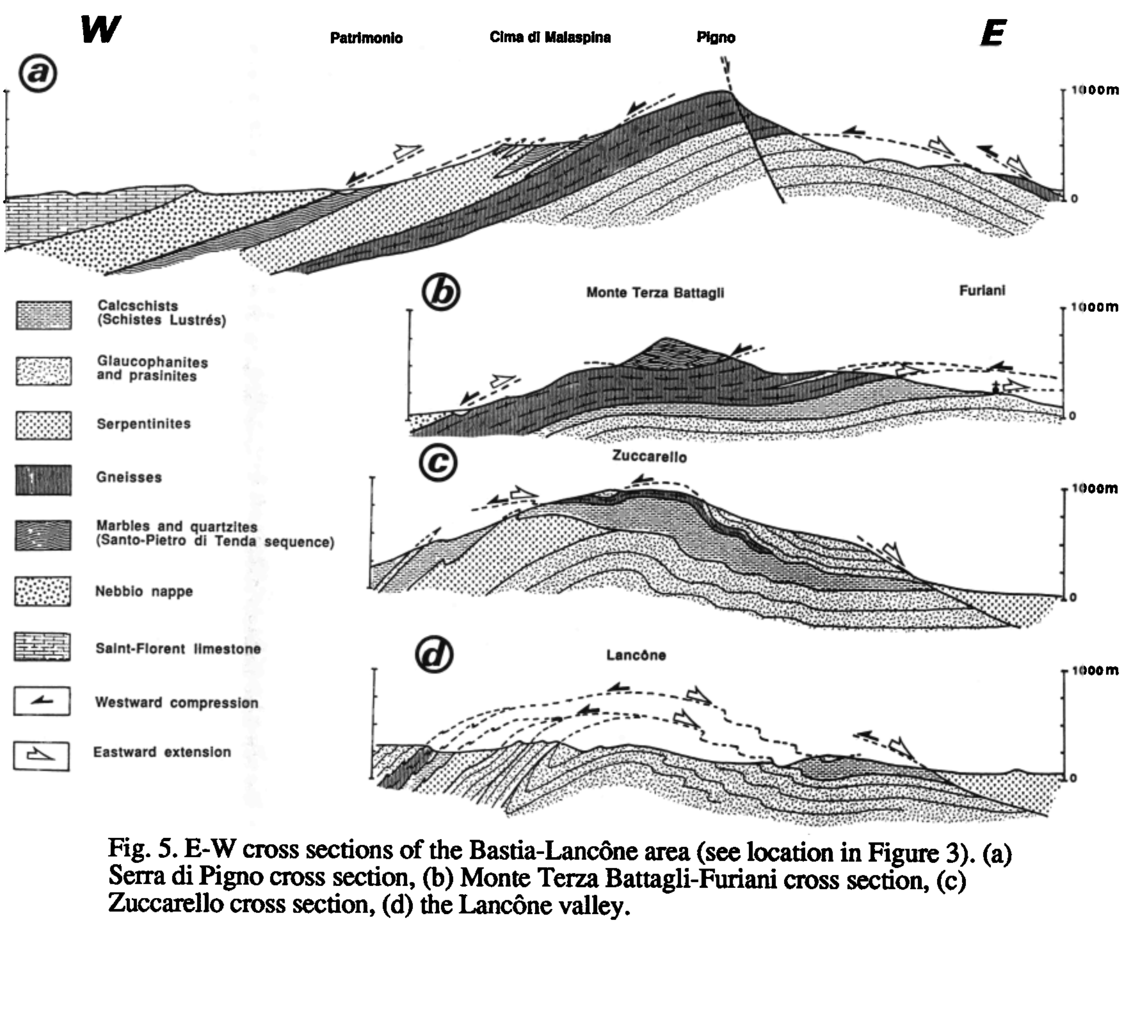


Fig. 5. E-W cross sections of the Bastia-Lancône area (see location in Figure 3). (a) Serra di Pigno cross section, (b) Monte Terza Battagli-Furiani cross section, (c) Zuccarello cross section, (d) the Lancône valley.

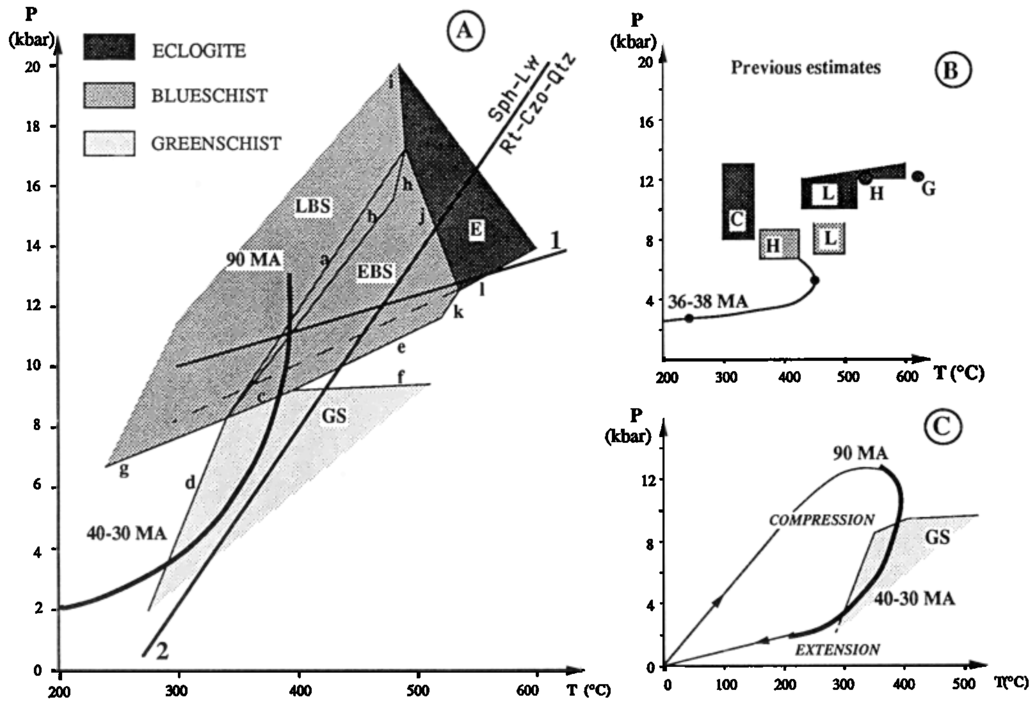


Fig. 6. P-T path in the Schistes Lustrés nappe. (a) P-T path for the Lancône glaucophanites (after calculations of Evans [1990]), E, eclogites; EBS, epidote-blueschist; GS, greenschist; LBS, lawsonite-blueschist. Reaction list (assemblages on the left are stable on the higher-pressure side): a, lawsonite (Lw) + jadeite (Jd) + tremolite (Tr) = clinozoisite (Czo) + glaucophane (Gln) + quartz (Qtz) + H2O (W); b, Lw + Gln = paragonite (Pg) + Czo + chlorite (Chl) + Qtz + W; c, Gln + Czo + Qtz + W = albite (Ab) + Chl + Tr; d, pumpellyite (Pmp) + Chl + Qtz = Czo + Tr + W; e, Gln + Czo + Qtz + W = Ab + Pg + Tr; f, Pg + Tr + W = Ab + Czo + Chl + Qtz; g, Lw + Gln = Pmp + Chl + Ab + Qtz + W; i, Jd + diopside (Di) + pyrope (Prp) + Qtz + W = Gln + Lws; j, Jd + Di + Prp + Qtz + W = Gln + Czo; k, Czo + Qtz = Ab + Prp + Tr + W; l, Jd + Qtz = Ab; 1, Si content of phengites = 3.47 [after Massonne and Schreyer, 1987]; 2, Sphene (Sph) + 3 Lw = Qtz + Rutile (Rt) + 2 Czo + 5 W. (b) Previous estimates for eclogites and blueschists P-T conditions: C, Caron et al. [1981]; G, Guiraud [1982]; H, Harris [1984]; L, Lahondère [1988]. P-T path for Cap Corse blueschists after Harris [1984]. (c) Synthetic P-T path for Lancône glaucophanites included in the basal ophiolitic unit. GS is greenschist.

evolution [Goffé, 1984; Goffé and Velde, 1984; Goffé and Chopin, 1986]: carpholite is rapidly destabilized when temperature increases and albite appears. That is the case further north in the Cap Corse where carpholite is never preserved: retromorphosis increases toward the north. Moreover, chloritoid is never observed associated with carpholite in the studied area and Pequignot [1984] signaled very rare occurrences of chloritoid in schists further to the south. Therefore the retrograde path of the Castagniccia and Inzecca calcschists (curve A in Figure 7) does not cross the Fe-chloritoid stability field and is constrained by the equilibrium Fe-carpholite = Fe-chloritoid + quartz + H2O (curve 4 computed with Geo-calc [Brown et al., 1988] using thermodynamical data from O. Vidal, B. Goffé and T. Theye (manuscript in preparation, 1991) for an Mg-carpholite having an activity of 0.6). The Serra di Pigno calcschists included in the sedimentary cover of the Oletta-Serra di Pigno gneisses also contain relics of carpholite in quartz, and the gneisses provide relics of jadeite. Minimal peak P-T conditions can thus be estimated for these units (Figure 7): because of the presence of Fe-carpholite and absence of Fe-chloritoid the temperature can not have exceeded 350°C. The equilibrium albite = jadeite + quartz constrains the pressure (about 11 kbar at 350°C).

The calcschists included in the basal ophiolitic unit do not provide carpholite and contain garnet, sphene and lawsonite often destabilized in epidote. The lawsonite-sphene stability field with presence of calcite has been computed with Geo-Calc [Brown et al., 1988; Figure 7]. It is limited by the curves 5 (calcite + quartz + rutile = sphene + CO2) and 6 (sphene + 3 lawsonite = rutile + 2 clinozoisite + quartz + 5 H2O) that constrained the way back to surface conditions. The calcschists belonging to the basal ophiolitic unit suffered higher temperature (400°C at least) than the Castagniccia and Inzecca calcschists. Their retrograde evolution (curve B in

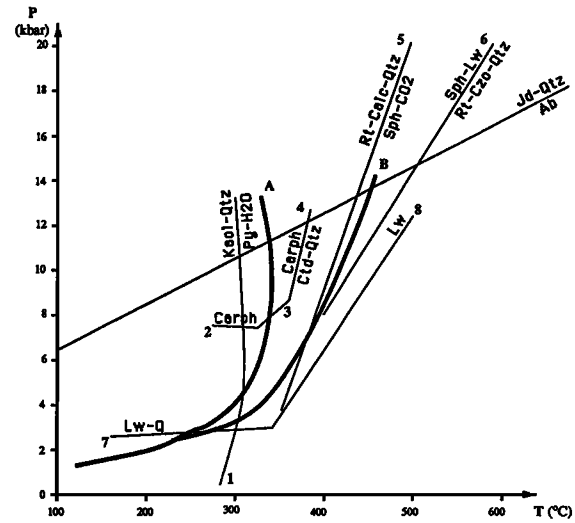


Fig. 7. Stability fields of calcschists assemblages [after Goffé et al., 1988]. A, P-T path for calcschists units; B, P-T path for schists included in the basal ophiolitic unit; 1, kaolinite (Kaol) + Qtz = pyrophyllite (Py) + H2O; 2, carpholite (Carph) = sudoïte + Qtz; 3, Carph + Qtz = Chl + Pyr + H2O; 4, Carph = chloritoid (Ctd) + Qtz + H2O; 5, Rt + calcite (Calc) + Qtz = Sph + CO2; 6, Sph + 3 Lw = Rt + 2 Czo + Qtz +5 H2O; 7, Lw + Qtz = laumontite; 8, Lw = zoisite + margarite + Qtz + H2O.

Figure 7) is similar to that of the associated basic rocks (see Figure 6a).

P-T-t Paths

The Upper Jurassic units display the alpine HP-LT metamorphism and the associated intense deformation, whereas dated Eocene sediments are always less strained [Mattauer and Proust, 1975; Amaudric du Chaffaut, 1982]. Radiochronologic determinations give a mid-Cretaceous age (105 +- 8 Ma , whole rock Rb-Sr [Cohen et al., 1981]; 90 Ma, Ar-Ar on glaucophane]Maluski, 1977]) for the HP-LT metamorphism, and an upper Eocene-early Oligocene age (around 42 Ma, fission tracks on zircon and apatite [Carpena et al., 1979]; 34.4 +- 1 Ma, Ar-Ar on phengites, [Maluski, 1977]; 33 Ma, work of H. Maluski as discussed by Jourdan [1988]) for the late greenschist metamorphism. Actually, recent structural studies of the eastern edge of crystalline Corsica and its autochtonous Eocene cover suggest an Eocene age for the Alpine deformation and the HP-LT associated metamorphism [Bézert and Caby, 1988; Egal and Caron, 1988; Egal, 1989]. Obviously no precise history of the P-T evolution of the Alpine Corsica units can be expected without new radiochronologic determinations on significant metamorphic minerals.

The preceeding informations are synthetized in Figure 6c, where a P-T-t path for the basal ophiolitic unit is presented (based on the study of the Lancône glaucophane schists and calcschists belonging to the basal ophiolitic unit). The P-T prograde evolution is constrained by the HP metamorphic climax, 11 kbar and 400°C at least. Higher values are obtained considering the eclogitic lenses associated with the ophiolitic unit (see Figure 6b). The prograde evolution follows an HP-LT gradient, about 10°C per kilometer, characteristic of the underthrusting of cold units. The retrograde evolution is characterized by a pressure drop at an almost constant temperature in a cold gradient, before a rather warm gradient (about 30°-35°/km). The Castagniccia and Inzecca calcschists followed a similar evolution at lower temperature. These units were lately put into close contact which determined the metamorphic contrast between the "rather hot" basal ophiolitic unit and the "rather cold" Castagniccia and Inzecca units.

DEFORMATION AND STRUCTURAL EVOLUTION

Finite Deformation

The main fabrics in the metamorphic complex are the HP-LT penetrative foliation and the associated stretching lineation [Mattauer et al., 1977; Faure and Malavieille, 1981; Mattauer et al., 1981; Malavieille, 1982] folded in a broad anticline, the Cap Corse-Castagniccia antiform. The stretching lineation is defined by quartz rodding in quartzites and calcschists, stretching and microcrystalline boudinage of amphiboles, epidote and albite in the of pillow lavas, mineral crystallizations in pressure shadows (quartz, albite, amphiboles). Stretching is also expressed by boudins of metamorphosed mafic sandstones levels intercalated with quartzites in the Oletta cover (Figure 8). A crenulation lineation, parallel to the stretching lineation, is sometimes observed in the calcschists, in the gneisses and in the glaucophanites. These lineations are oriented E-W to NE-SW (Figures 4 and 9). As the regional foliation is penetrative and homogeneous, the foliation plane contains the principal X and Y axes of the deformation, and the X axis is parallel to the stretching lineation. Our observation of gneisses

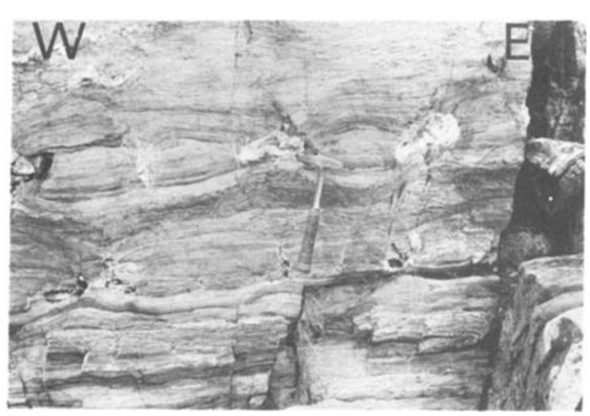


Fig. 8. Boudins of mafic sandstones metamorphosed into quartzites in the Oletta-Serra di Pigno cover (near Monte a a Torra, section b, Figure 3).

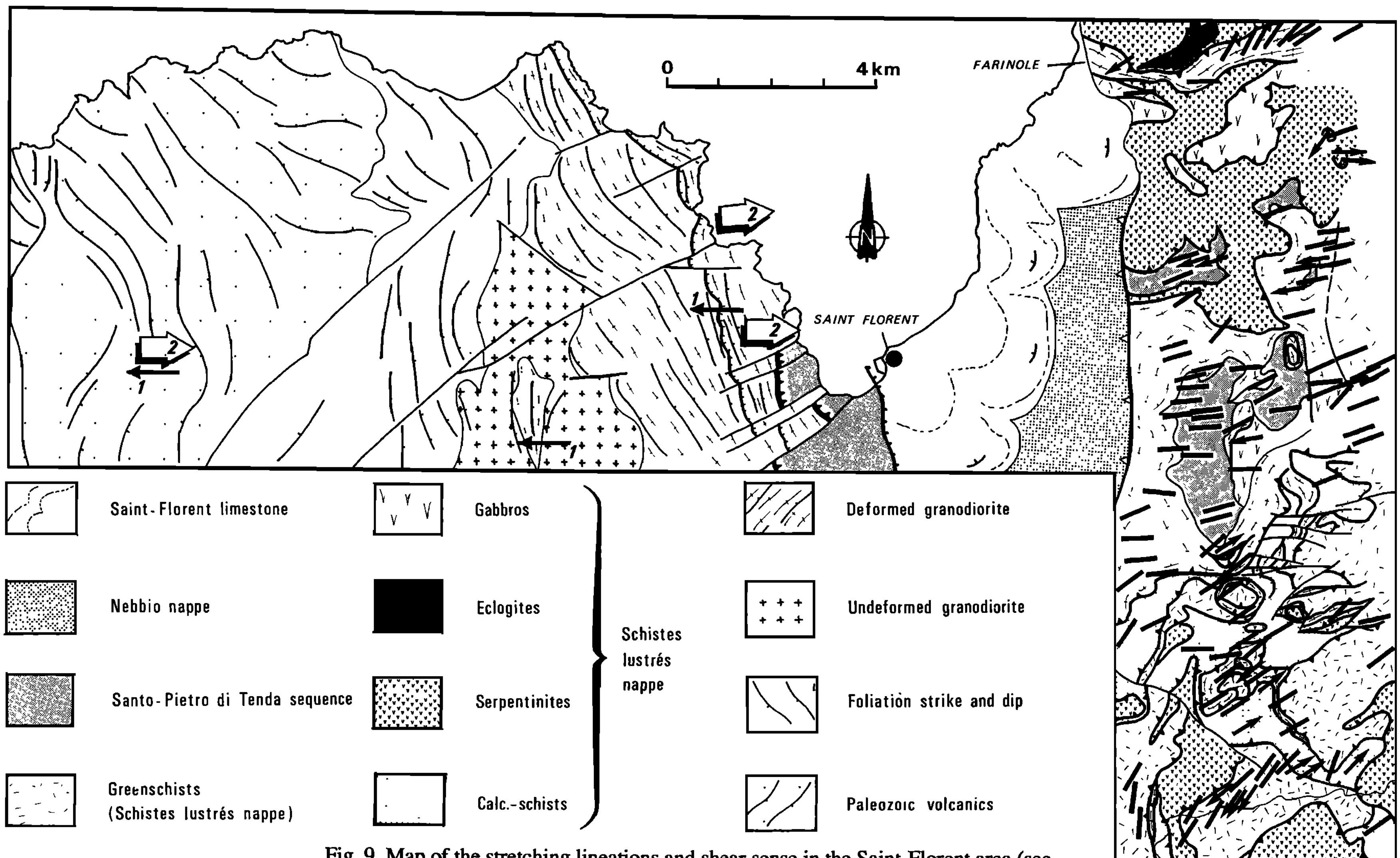


Fig. 9. Map of the stretching lineations and shear sense in the Saint-Florent area (see location in Figure 1), after Jolivet et al. [1990], Malavieille [1982], Jacquet [1983], and Jourdan [1988]. The black bars represent the direction of the stretching lineation in the Schistes Lustrés nappe, with an arrow when the sense of shear is known. Large arrows stand for the average direction of lineation in the Tenda massif after Jacquet [1983] and Jourdan [1988]. The direction of the arrow indicates the sense of shear.

shows that the stretching is intense in the X-Z planes and almost nonexistent in the Y-Z planes, so that the deformation ellipsoid has a cigar shape characteristic of the stretching and/or constriction.

The foliation is axial planar to isoclinal sheath folds (P1) whose axes are parallel to the E-W stretching lineation [Faure and Malavieille, 1980]. The foliation and the early tectonic contacts are folded by eastward vergent folds with N40° axes [Malavielle, 1982]. Lastly, all these structures are refolded by the Cap Corse-Castagniccia antiform.

The Lancône glaucophanites suffered a late brittle extensional deformation expressed by vertical fracture planes trending N100° to N130°, associated with conjugate en échelon cracks.

Noncoaxial Deformation

Observations of deformation in the X-Z section often reveals opposite senses of shear. They can correspond either to a compound component of flattening along the Z axis perpendicular to the foliation or to two successive stages. They are in fact associated with different metamorphic paragenesis: top-to-the-west (westward) shear criteria are associated with HP-LT mineral assemblages while top-to-the-east (eastward) shear criteria are contemporaneous or subsequent to greenschist assemblages. They are therefore due to two separable successive deformation stages.

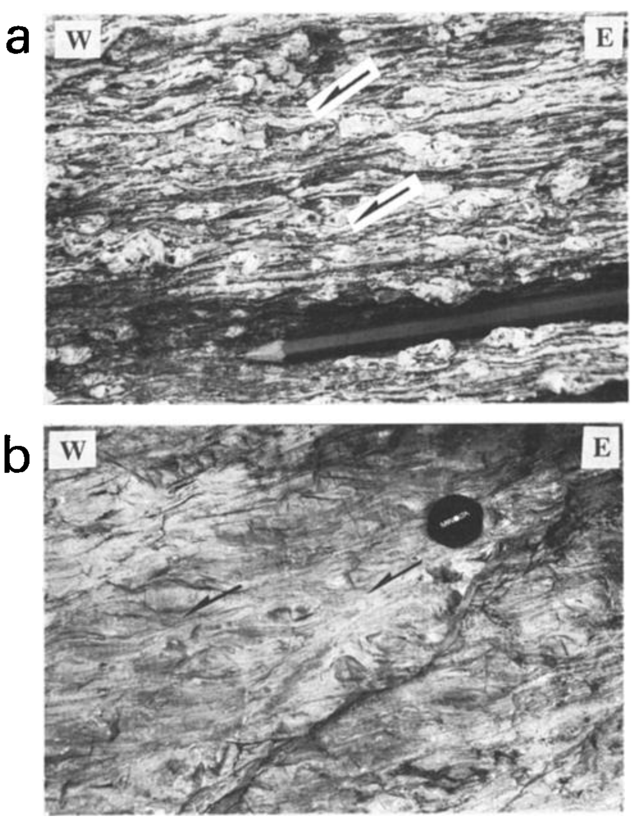


Fig. 10. C' shear planes indicating westward sense of shear in (a) the Zuccarello gneisses (section c, Figure 3) and (b) the Lancône glaucophanite (section d, Figure 3).

Kinematic indicators associated with HP minerals show westward shear sense [Mattauer et al., 1981]. Indicators of shear sense include asymmetric strain shadows around plagioclases in gneisses, pyroxenes in gabbro, and oblique shear planes in gneisses (Figure 10a) and glaucophanites (Figure 10b).

Late kinematic indicators are associated with greenschist paragenesis or postdate them. The whole Castagniccia calcschists unit shows predominant eastward shear planes (Figure 11a), sometimes associated with late en échelon cracks (Figure 11b). The same shear planes are observed in similar calcschists in the Cap Corse near Erbalunga (Figure 11c). Asymmetric quartz lenses confirm this eastward sense of shear (Figure 11d). Plurimetric en echelon cracks associated with an eastward flat shear plane are also observed in the Golo Valley (Figure 11e). The eastward shear planes predate the formation of the Cap Corse-Castagniccia antiform as shown by the evolution of their dip across the Castagniccia dome.

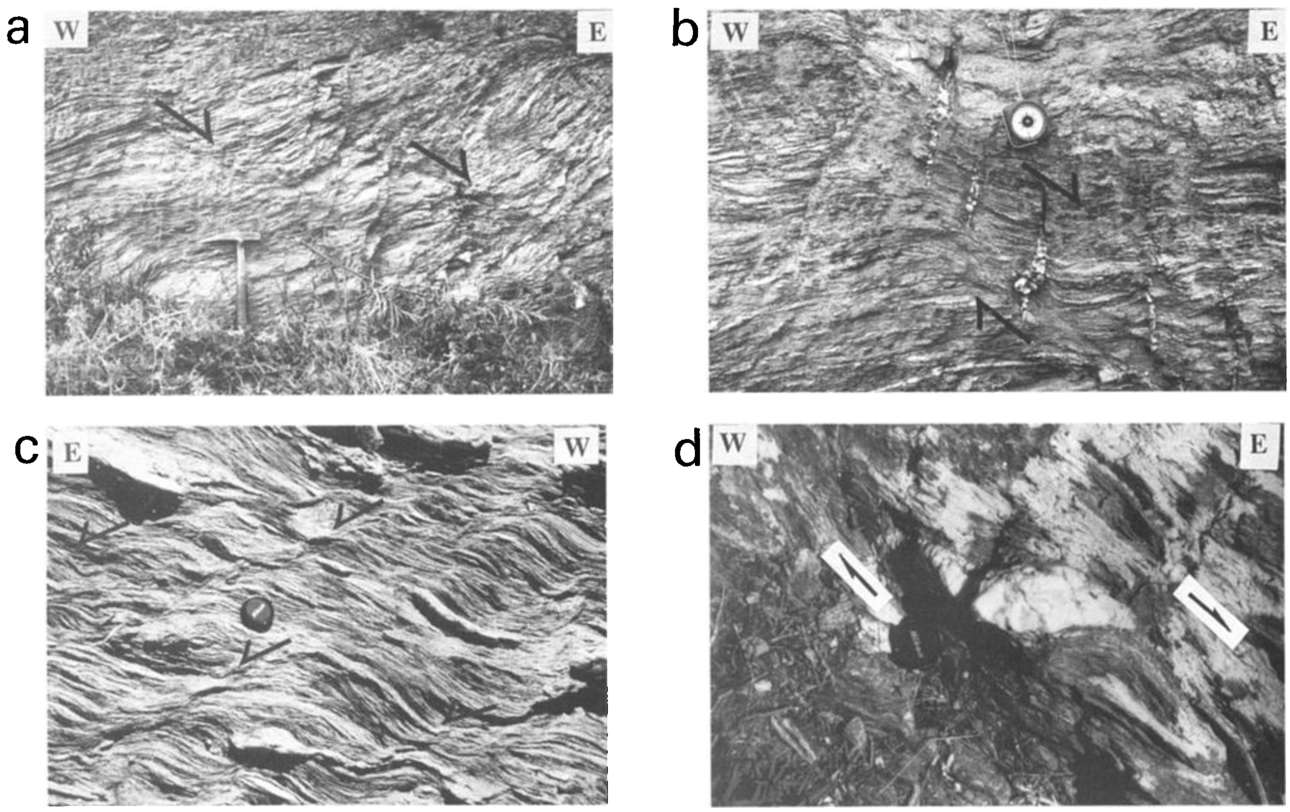
Eastward shear planes are also observed along the major early thrust contacts. At the top of the Tenda massif, the Paleozoic cover displays eastward shear criteria (Figures 12a and 12b) [Jourdan, 1988]. A thermal event contemporaneous with the activation of these planes reset the rejuvenated phengites to 33 Ma (work of H. Maluski, as discussed in Jourdan [1988]). Similarly, the sedimentary cover of the Oletta-Serra di Pigno basement displays eastward shear criteria very near its basal contact (Figure 12c).

In the Lancône gorges, the partly retrogressed glaucophanites show asymmetric strain shadows around garnets with albite crystallized during the retromorphosis of HP assemblages in the greenschist facies, indicating eastward shear senses (Figure 13a). Moreover, eastward shear planes cut through late albite crystals overprinting the earlier foliation (Figure 13b). Thus the eastward shear stage began during the greenschist metamorphic episode (crystallization of albite and rejuvenation of phengites) and continued after albite crystallization. The final stage gave brittle structures such as en échelon tension cracks.

Data showing brittle extensional deformation affecting the upper units are presented by Jolivet et al. [1991]. Extensional deformation is spectacularly well expressed in the Macinaggio klippe at the contact between the upper unit and the lower HP-LT metamorphic unit. Parallel east dipping normal faults separate tilted blocks just above the detachment plane showing E-W striations. Such a structure is compatible with an eastward sense of shear along the detachment.

Conclusion

Two main deformation stages with opposite senses of shear, associated with two successive metamorphic episodes are distinguished in Alpine Corsica. The first one, contemporaneous with HP-LT metamorphism, corresponds to the westward thrusting of the Schistes Lustres nappe onto the



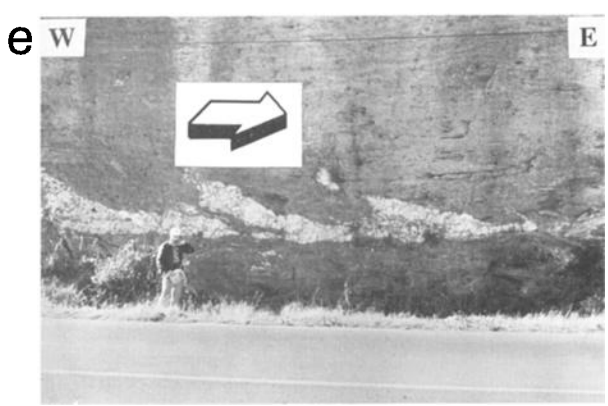


Fig. 11. Eastward shear criterias in the calcschists. (a and b) Shear planes in the Lancône calcschists, associated with late en echelon cracks (Figure 11b); (c) east dipping shear planes in the Cap Corse schists; (d) asymmetric quartz lense in the Golo calcschists; (e) plurimetric en echelon cracks in the Golo valley.

Tenda basement. The regional foliation, stretching lineation and synfolial folds (P1) are associated with this event. The second ductile deformation stage is recorded by 32-33 Ma (early Oligocene) isotopic ages; it started during the greenschist metamorphic episode and continued afterwards. The deformation is mainly concentrated along the major thrust contacts and within the less competent units such as the schists, and shows unequivocal eastward sense of shear. The formation of the Cap Corse-Castagniccia antiform follow this deformation stage.

DISCUSSION

Mattauer and Proust [1976a, b] and Mattauer et al. [1981] first proposed the eastward subduction of the east Corsica margin under the oceanic material of the schistes lustrés nappe, contemporaneous with the HP-LT metamorphism. The progressive imbricate thrusting, in a crustal-scale simple shear context, of the oceanic crust and the subducted continental basement formed the thrust stack of the Schistes Lustrés nappe. A late backthrust stage associated with greenschist metamorphism after the main westward thrusting has been proposed by various authors [Mattauer and Proust, 1975; Warburton, 1986] (see cross section in Figure 14). However, the HP-LT paragenesis of the Oletta-Serra di Pigno gneisses (jadeite) characterizes a higher metamorphic grade than in the Tenda massif. Thus Warburton's cross section must be discussed.

Petrological and structural data show the collision of the east Corsica stable margin and the adjacent oceanic basin during Alpine times. This shortening occurred in an HP-LT gradient related to the underthrusting of cold European units under an Adria plate mostly exposed in the Balagne nappe, an oceanic crust totally free from HP-LT paragenesis and its sedimentary cover resting upon upper Eocene autochtonous sediments. Thermobarometric estimates of the HP-LT metamorphism in the Schistes Lustrés nappe show that the material was underthrust to depths of about 30-40 km. Thus the continental crust became at least 40 km thick and stored gravitational potential energy [Molnar and Lyon-Caen, 1988].

Retrograde metamorphic paths of the Schistes Lustrés nappe first follow a HP-LT gradient constrained by the lawsonite stability equilibrium, showing that convergence continued after the maximum burial. The retromorphosis of the HP mineral associations in the greenschist facies began during the middle Eocene (43.7+-2 Ma [Carpéna et al., 1979]) and went on until the early Oligocene (33 Ma, data of H. Maluski, as discussed by Jourdan [1988]). The eastward shear deformation started at that time. Though active in the entire thickness of the

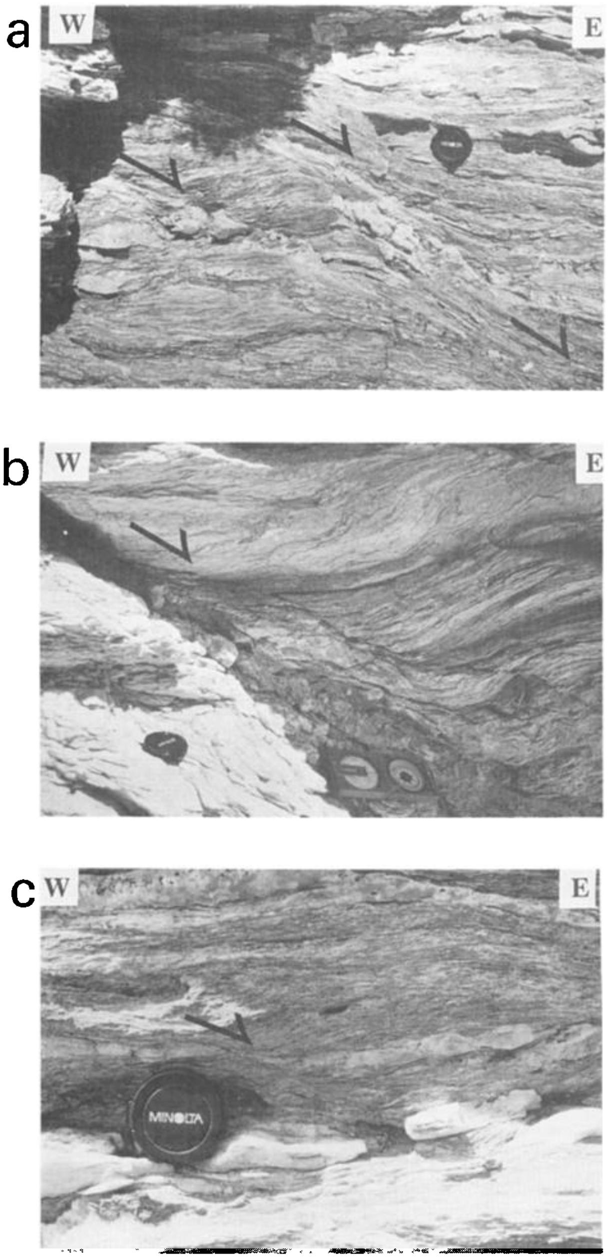


Fig. 12. Eastward shear criteria superposed along the main early thrust contacts. (a and b) Shear planes in the Paleozoic cover of the Tenda massif (west coast of the Saint-Florent gulf); (c) eastward shear plane in the Oletta-Serra di Pigno cover very near the contact with the gneisses.

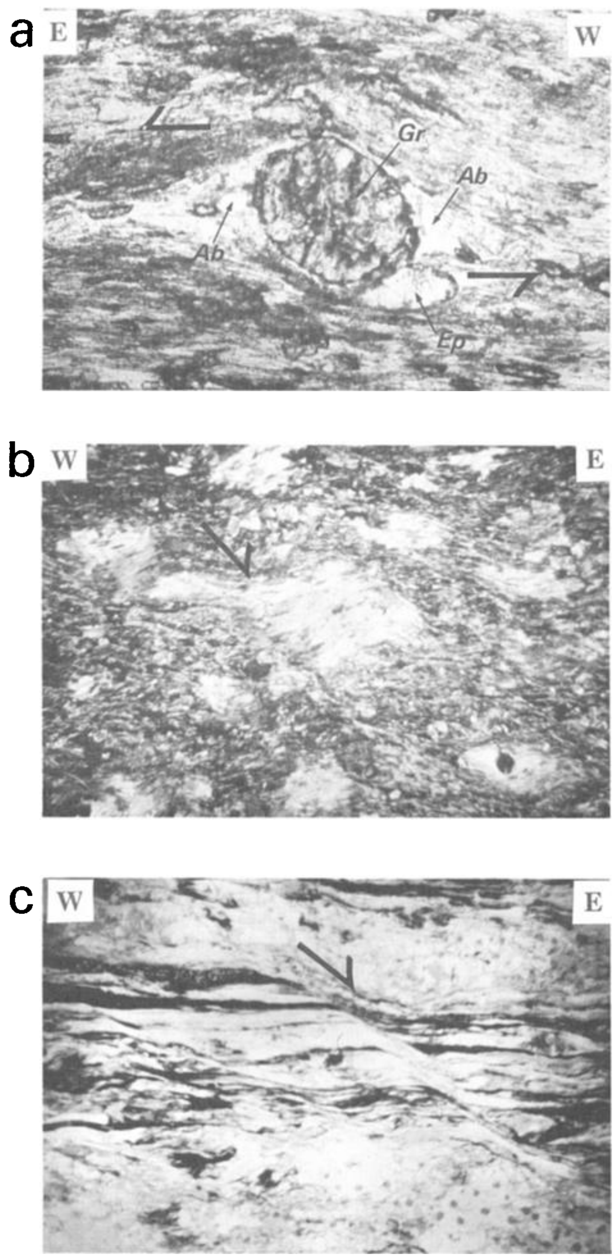


Fig. 13. Microscopic eastward shear criteria. (a) late albite crystallizing in asymetric pressure shadows around garnet in the Lancône glaucophanites; (b) late albite crystal overprinting the earlier HP-BT foliation cut by eastward shear plane; (c) shear planes in the Cap Corse calcschist.

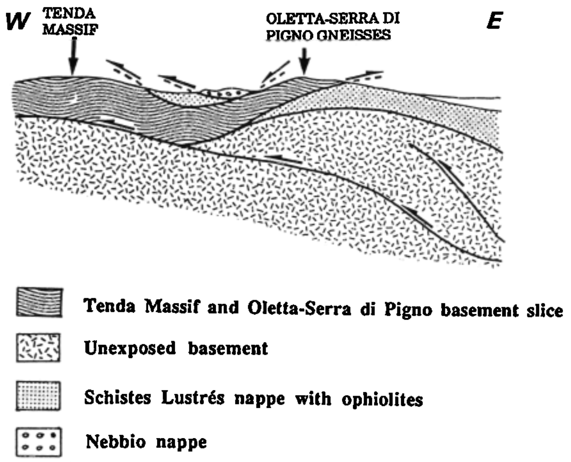


Fig. 14. E-W cross section of the Cap Corse in the Bastia area, after Warburton [1986].

thrust stack, it was essentially localized along the major preceding thrust contacts and within the less competent units. In particular, the eastward dipping thrust contact of the Schistes Lustrés nappe was reactivated toward the east as a ductile normal fault (Figure 2).

At the same time, the Corsica block drifted away from the European continent during the opening of the Liguro-Provençal basin. The rifting started in Oligocene time (35-30 Ma), and ended during the Aquitanian (24-23 Ma) relayed by the drifting until 21-19 Ma [Burrus, 1984; Boillot et al., 1984; Réhault et al., 1984]. On the east side of Corsica, the Tyrrhenian Sea opened during the late Miocene: after an early rifting episode in Oligocene-Miocene time [Boillot et al., 1984], a second stage of rifting started in the late Tortonian (7 Ma) and ceased during the Messinian; the drifting took place during the Pliocene in the south [Kastens and Mascle, 1988].

The Saint-Florent Miocene limestone was deposited from the Burdigalian to the Tortonian [Orszag-Sperber and Pilot, 1976; Dallan and Puccinelli, 1986]. It is gently folded in a strongly asymmetric syncline (the major part of the Miocene basin is west dipping) and is limited toward the west by the east dipping shear zone at the top of the Tenda massif. This syncline is tilted toward the west and may be a half-graben settled above an eastdipping normal fault, parallel to the thrust contact between the Tenda massif and the Schistes Lustrés nappe. The formation of the Cap Corse-Castagniccia antiform may be consecutive to the motion of this normal fault as a rollover antiform.

It is therefore reasonable to relate the post-Eocene deformation in Alpine Corsica to an extentional event that began during the early Oligocene (33 Ma) with the eastward ductile shear partly associated with and partly subsequent to the end of the greenschist overprint, and which continued until the Miocene (tilt of the Saint-Florent limestone and rifting of the Tyrrhenian sea). Extension was driven by the gravitational potential energy accumulated during the obduction and crustal thickening. Superficial brittle normal faulting associated at depth with ductile normal faulting accommodated the crustal thinning: the lower continental crust is dragged out from beneath the superficial units.

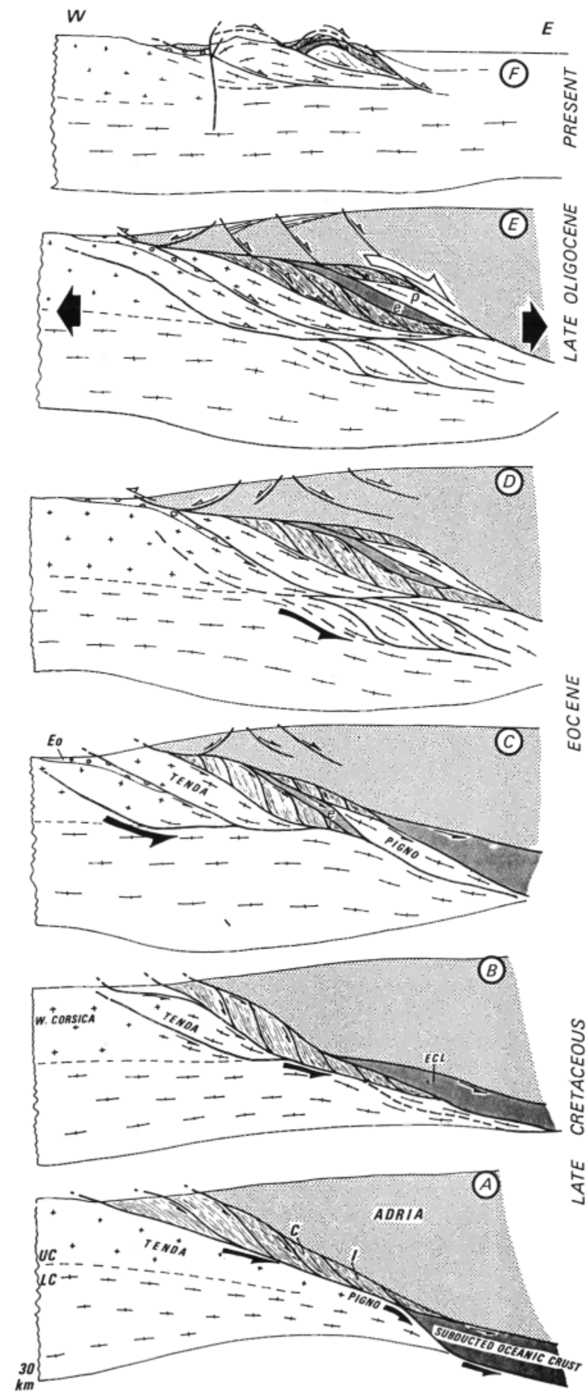


Fig. 15. Evolution scheme along the cross section of Figure 2 from the early compression in HP-LT gradient to the recent extension (explanation in text). Abbreviations are I, Inzecca, C, Castagniccia, ECL, eclogites, UC, upper crust, LC, lower crust, and eoc, eocene. (a and b), Late Cretaceous; (c and d), Eocene; (e and f), late Oligocene to Present.

In Figure 15 a six-stage model of the tectonometamorphic evolution in Alpine Corsica since Late Cretaceous is presented. Four major units are differentiated: (1) the continental margin of the European plate (western Corsica, Tenda Massif, Serra di Pigno gneisses) (2) the Castagniccia and Inzecca units made of the sedimentary cover of the oceanic crust (Schistes Lustrés) integrating tectonic slices of peridotites and oceanic crust, (3) the lower ophiolitic unit made essentially of oceanic rocks (partly eclogites) including small amount of schists and gneisses, and (4) the Adria plate (Balagne-Nebbio nappe). The oceanic crust of the Ligurian Tethys, its sedimentary cover, and the continental margin of the European plate are first underthrust eastward under the Adria plate (Figures 15a-15c). This cold material suffered at depth a HP-LT metamorphism. More deeply buried rocks, oceanic crust and associated schists and gneisses, were metamorphosed under eclogite facies conditions (low-grade). The Castagniccia and Inzecca units, partially blocked during the subduction process, suffered only medium-grade blueschist facies conditions. The Tenda Massif, lately involved in the subduction process, suffered low-grade blueschist facies conditions. Imbricate thrusting propagated toward the west within the slab, progressively adding tectonic slices to the accretionary complex. The major decollement lately isolated the Tenda massif from western Corsica. Once included in the accretionary complex, the tectonic units went up in an HP-LT geotherm preserving the HP-LT assemblages. During this episode the crust thickened to at least 40 km thick.

The extension started first in the thickest part of the stack where the vertical stress overcomes the horizontal stress due to convergence, and the thickening continues more westward (Figure 15d) as suggested by Molnar and Lyon-Caen [1988]. The Balagne nappe glided into the Eocene sedimentation basin. Convergence ceased during Oligocene time, and was replaced by extension. The geotherm relaxed and rose up progressively so that late greenschist assemblages crystallized simultaneously with the eastward shear. Particularly, the main thrust contact between the Schistes Lustrés nappe and the Tenda Massif was reworked eastward as a ductile normal fault. At shallower depth, continuous brittle extension associated with erosion reduced the thickness of the upper crust (Figures 15e and 15f). The Eastward motion above the main contact continued as a brittle normal fault, forming a half-graben in which the Saint-Florent limestone was deposited during Miocene time. The formation of the Cap Corse-Castagniccia as a hanging wall roll-over antiform is related to this motion. A similar mechanism might explain the formation of the Tenda antiform.

Similar evolutions characterize other metamorphic core complexes as in the North American Cordillera [Coney and Harms, 1984; Malavieille, 1987] or the Aegean Sea [Lister et al., 1984]. We propose here a model of crustal thinning in an extensional (brittle and ductile) context, following a compressional thickening by underthrusting. The asymmetry of the ductile extension is controlled by the asymmetry of the structure as strain is essentially localized along the early eastdipping thrust planes. If the basal contact of the Balagne nappe is considered to be the main detachment, considerable extensional deformation affected its footwall. The simple shear is here distributed through the entire thickness of the Late Cretaceous-early Cenozoic nappe stack.

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