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Transverse lineation and large-scale structures related to Alpine obduction in Corsica

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Abstract—In Alpine Corsica, the major tectonic event during the late Cretaceous was the thrusting to the west of an ophiolitic nappe and its sedimentary cover upon the Variscan basement and its Mesozoic cover. A detailed field survey shows that the basal contact of the nappe corresponds to a pluri-kilometric scale shear zone. Thus gneissified basement slices have been tectonically emplaced in the ophiolitiç nappe. The thrusting was responsible for small scale structures: foliation, lineation and folds, initiated in a HP/LT metamorphic context. The deformation analysis shows that the finite strain ellipsoid lies in the constriction field close to that for plane strain. Moreover occurrences of rotational criteria in the XZ planes (sigmoidal micas, asymmetric pressure shadows, quartz C-axes fabrics) are in agreement with shear from east to west. All structural data from microscopic to kilometric scales, of which the most widespread is a transverse stretching lineation, can be interpreted by a simple shear model involving ductile synmetamorphic deformation. At the plate tectonic scale the ophiolitic obduction is due to intraoceanic subduction blocked by underthrusting of continental crust beneath oceanic lithosphere.

INTRODUCTION

IN ALPINE Corsica the presence of many exposures allows detailed studies of deformation associated with ophiolitic subduction (Dewey 1976). As in the whole Alpine belt, the oceanic crust of the Alpine ocean has been thrusted upon the European basement, probably during the Cretaceous. But in contrast to the Franco-Italian Alps, where very strong late deformations have modified the earlier phases, the initial pattern of ophiolitic thrusting in Corsica is well preserved. Moreover, the chain is shorter and palaeogeographically simpler than in the western Alps, so earlier phases can be clearly observed.

The aim of this paper is: (a) to describe at all scales of observation the styles of the deformation structures associated with the obduction; (b) to study the regional transverse stretching lineation and its tectonic significance; (c) to show how the deformation can be explained by a large ductile shear zone at a crustal scale and (d) to provide an example of simple relationships between microstructures and large-scale structures related to nappe emplacement in a plate tectonic framework.

GEOLOGICAL FRAMEWORK

Two series, quite different in their lithology and palaeogeographic position are found in Alpine Corsica (Durand-Delga 1974, Cocozza *et al.* 1974, Mattauer & Proust 1976, Caron *et al.* 1980). The first; an autochthonous series, comprises Permian volcaniclastics lying on Variscan granitoids and Permian intrusive rocks and sediments (conglomerates, quartzites and limestones) of Mesozoic age. The second series is a typical ophiolitic sequence (ultramafics, serpentinites, gabbros, pillow lavas and radiolarian Jurassic cherts), covered by marine sediments presumed to be of Cretaceous age.

During the Late Jurassic to Early Cretaceous, the autochthonous series belonged to the European–Iberian block while the oceanic series was deposited in the Alpine ocean. The present structure of Corsica (Figs. 1 and 2) is the result of two main tectonic phases. The first, which occurred before the Early Eocene (and probably the Late Cretaceous–Palaeocene), was responsible for the thrusting of the oceanic crust onto the continental basement. The associated ductile deformation is synchronous with a HP/LT metamorphism, dated at 80 to 100 Ma by radiometric methods $^{39}Ar/^{40}Ar$, (Maluski 1977), and Rb/Sr (Cohen *et al.* in press).

The second tectonic phase took place after the Middle Eocene and before the Miocene. It is marked by: (i) synschistose folds, commonly of greenschist facies metamorphism (albite, epidote, actinolite, phengite, chlorite) dated between 34–43 Ma by $^{39}Ar/^{40}Ar$ methods (Maluski 1977) and fission track methods (Carpena *et al.* 1979); and (ii) strike-slip faults and gravity gliding tectonics (the Balagne–Nebbio superficial nappes).

This paper deals primarily with the first phase deformations linked to ophiolitic obduction. For this purpose the cross-section near the city of Bastia (Figs. 2 and 3) was chosen for study because the effects of the late phases are of minor importance and the area has already been investigated from a cartographic and microtectonic point of view (Mattauer *et al.* 1977, Faure & Malavieille in press).

GEOMETRY OF THE STRUCTURES

In Corsica three main superimposed units have been established, from the bottom to the top they are: (i) the autochthonous series: (basement gneisses and their sedimentary cover); (ii) the Schistes Lustrés nappe, made up of an ophiolitic sequence and marine sediments, within the nappe, slices of gneisses have been detached from the autochthonous unit and (iii) gravitational nappes emplaced during the Eocene (Figs. 1 and 2).

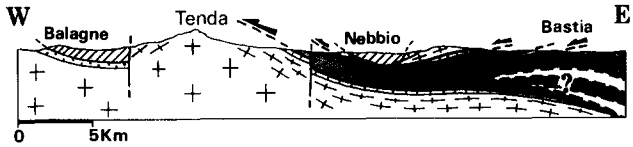

Fig. 2. Schematic cross-section (located on Fig. 1) showing the general structure of Alpine Corsica. The legend is the same as in Fig. 1.

Kilometric-scale structures

The structural map (Fig. 3) shows the general geometrical relationships between the autochthonous basement and the Schistes Lustrés nappe. As mapped in detail the contact is not precisely defined because it is a thick ductile shear zone affecting either sialic basement rocks and their sedimentary cover or ophiolitic rocks and schists.

In the autochthonous basement (Tenda Massif) the Variscan granitoids were gneissified during the major deformation. The gneissic foliation, S_1, is parallel to the thrust contacts (Fig. 2), the thickness of the gneissic zone is between 1 and 2 km, and from the top to the bottom the foliation becomes less and less penetrative. In the core of the Tenda Massif large masses of undeformed granodiorite were observed. The foliation is gently refolded by a late antiform, but was initiated with a subhorizontal attitude in agreement with ideas of tangential tectonics (Mattauer & Proust 1975, Mattauer *et al.* 1977).

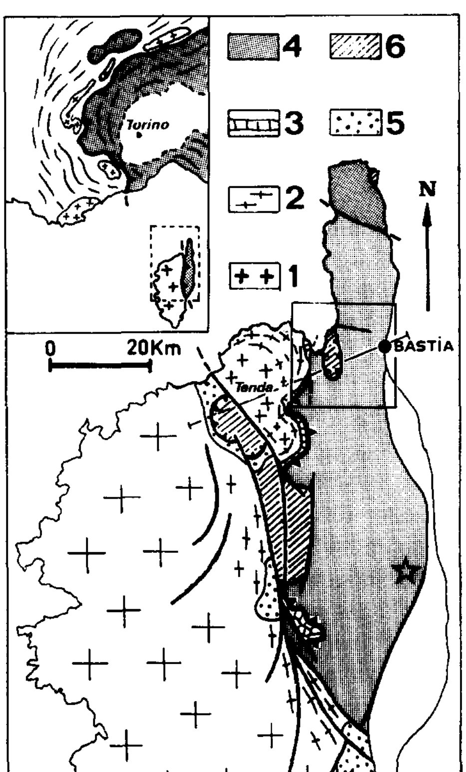

Fig. 1. Simplified map of Northern Corsica. 1, Variscan basement with progressive gneissification. 2, Gneiss. 3, Autochthonous sedimentary cover of the basement. 4, Schistes Lustrés nappe including ophiolites and gneiss slices. 5, Main outcrops of autochthonous Eocene. 6, Superficial post-Eocene nappes.☆ Sant 'Andrea di Cotone area.

The Schistes Lustrés nappe is made of imbricate lens-shaped units separated by flat-lying ductile shear contacts (some mylonitic). Thus one can find slices of serpentinized ultramafics, sheared gabbros and green-blue schists belonging to ancient volcani-clastic pillow basalts, and calcschists belonging to the supra-ophiolitic series, in an irregular succession.

Within the nappe, allochthonous slices of gneisses (similar to those of the autochthonous basement), and limestones and quartzites representing parts of the tectonized autochthonous series are also present (Fig. 3). Similarly, detailed field survey shows that the larger gneissic massif of Oletta-Serra di Pigno, with a N–S extension of 10 km, previously considered to be a window and eastward back-thrusted by late phases (Durand-Delga 1974, 1978, Mattauer & Proust 1975, Caron *et al.* 1980), must be considered as allochthonous. This is suggested by the flat-lying contact, along which gneiss everywhere rests upon the ophiolitic sequence and marine sediments, the HP/LT syntectonic metamorphic mineral assemblages, and the microtectonic evidence along the contact.

The occurrence of sialic slices in the Schistes Lustrés nappe can be explained if one admits that during thrusting the nappe was pulled out and tectonically emplaced on the autochthonous basement and its cover.

Mesoscopic structures

The main structures affecting the whole series are the regional foliation, S_1, and the stretching lineation, L_1, trending N 070° E except in the Farinole area, in the northern part of the map area (Fig. 3). These structures can be analysed in the gneisses and autochthonous series.

In the Permo-Mesozoic sediments of the autochthonous and allochthonous slices, S_1 is axial plane to numerous isoclinal or intrafolial F_{1a} folds of various sizes, mostly decimetric to metric in amplitude (Figs. 4a–c). Their axes are constant in direction and parallel to L_1. The S_1 foliation is refolded by two types of synschistose folds: (i) F_{1b} folds whose axes are also generally parallel to L_1, but some show curved hinges or even sheath structures (Figs. 4d and 6) (Faure & Malavieille 1980); and (ii) F_{1c} folds subperpendicular to L_1 and overturned to the west.

We think that all F_1 folds (F_{1a}, F_{1b} and F_{1c}) belong to the same progressive deformation, and show different stages of the deformation path. Sheath folds observed on centimetric to hectometric scales must also exist on a

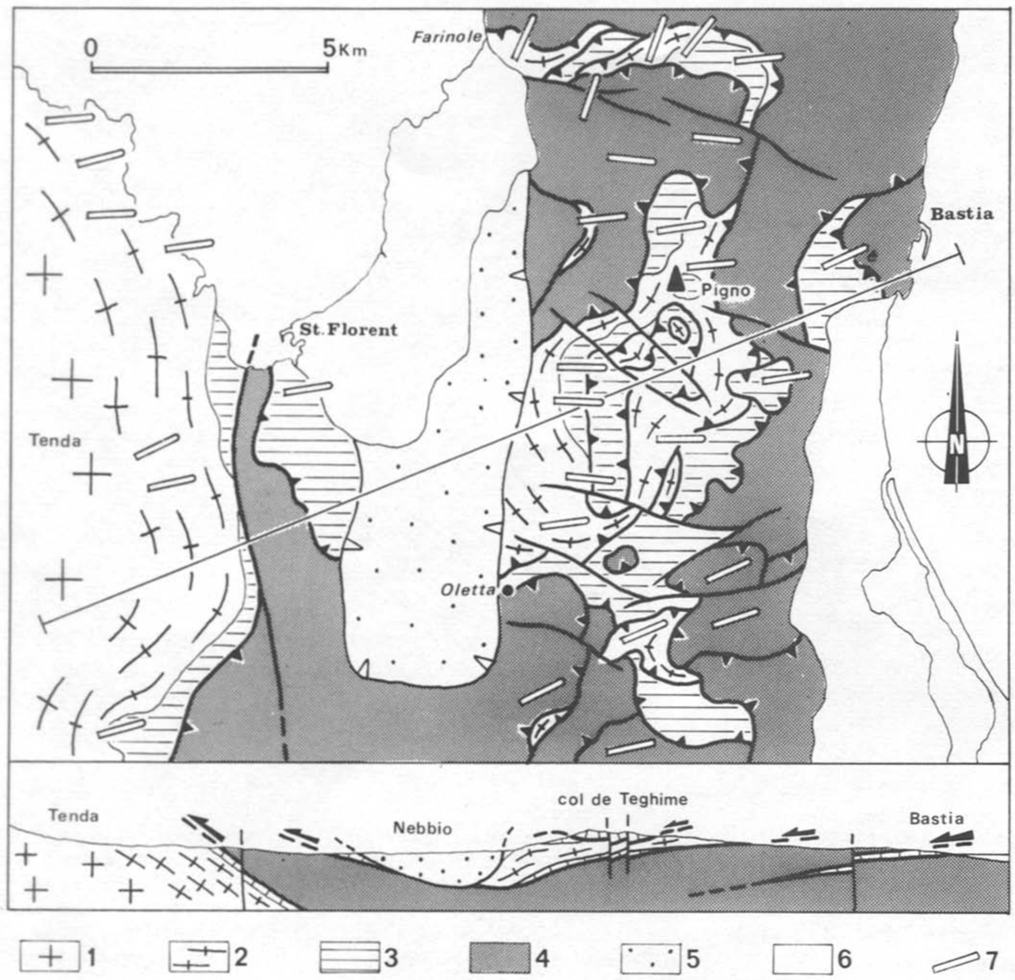

Fig. 3. Geologic map and cross section of Alpine Corsica between the Tenda Massif and the city of Bastia. 1, Variscan granitic basement of the Tenda Massif. 2, Alpine gneisses. 3, Sedimentary Mesozoic series 4, Schistes lustrés nappe including serpentinites, gabbros and greenschists. 5, Superficial nappe of Nebbio. 6, Post nappe sediments (Miocene and Pliocene). 7, direction of stretching lineation.

kilometric scale, but late folding and faulting prevent clear observations. F_2 folds have different styles and orientations, they refold the S_1 foliation and the L_1 lineation; they trend N 040° E, with a strain–slip cleavage dipping 30–40° NW, overturned to the SE.

In the crystalline basement, the foliation, S_1, is generally axial plane to isoclinal F_{1a} folds or sheath folds. On the western margin of the Tenda Massif F_{1c} folds associated with a strain–slip cleavage are well developed.

The ophiolitic material is also affected by ductile deformation. The serpentinites represent deformed ultramafics with typical lozenge-shaped structure; some shear surfaces showing slickenside lineations parallel to the regional L_1 lineation. The gabbros are generally mylonitized. The pillow lavas included in the prasinites are flattened and stretched in the L_1 direction. Very commonly, epidotic layers define isoclinal or sheath-like folds (Fig. 4). The Supra-ophiolitic schists contain the most complicated structures, consisting of polyphase microfolds with a wide scattering of axes, partly due to the planar anisotropy of the material (Caron 1977, Sauvage-Rosenberg 1977). We have not investigated these rocks and their structures in detail.

Microscopic structures

In thin section the foliation is marked by metamorphic minerals and recrystallized primary minerals. In quartzites the quartz grains are strongly recrystallized, some with a subrectangular shape-fabric parallel to the macroscopic foliation. Undulose extinction, deformation bands, serrated grain boundaries and strong lattice preferred orientation suggest a plastic deformation mechanism in quartz (Bouchez & Pécher 1976, Nicolas & Poirier 1976).

Large calcite grains in marbles form bands isolated by thin films of iron oxides and opaque minerals, suggesting that pressure solution might be the dominant deformation mechanism for calcite. In gneisses, the foliation is defined by elongated and comminuted feldspathic augens and stretched quartz grains. An evolution of quartz microstructures with the development of foliation is observed along the Tenda cross-section (Fig. 5). Equant quartz grains, from the core of the massif are progressively elongated in the eastern-margin orthogneissic facies. Moreover, recrystallization processes induced the growth of small grains leading to the development of core-and-mantle texture and sometimes polycrystalline mylonitic

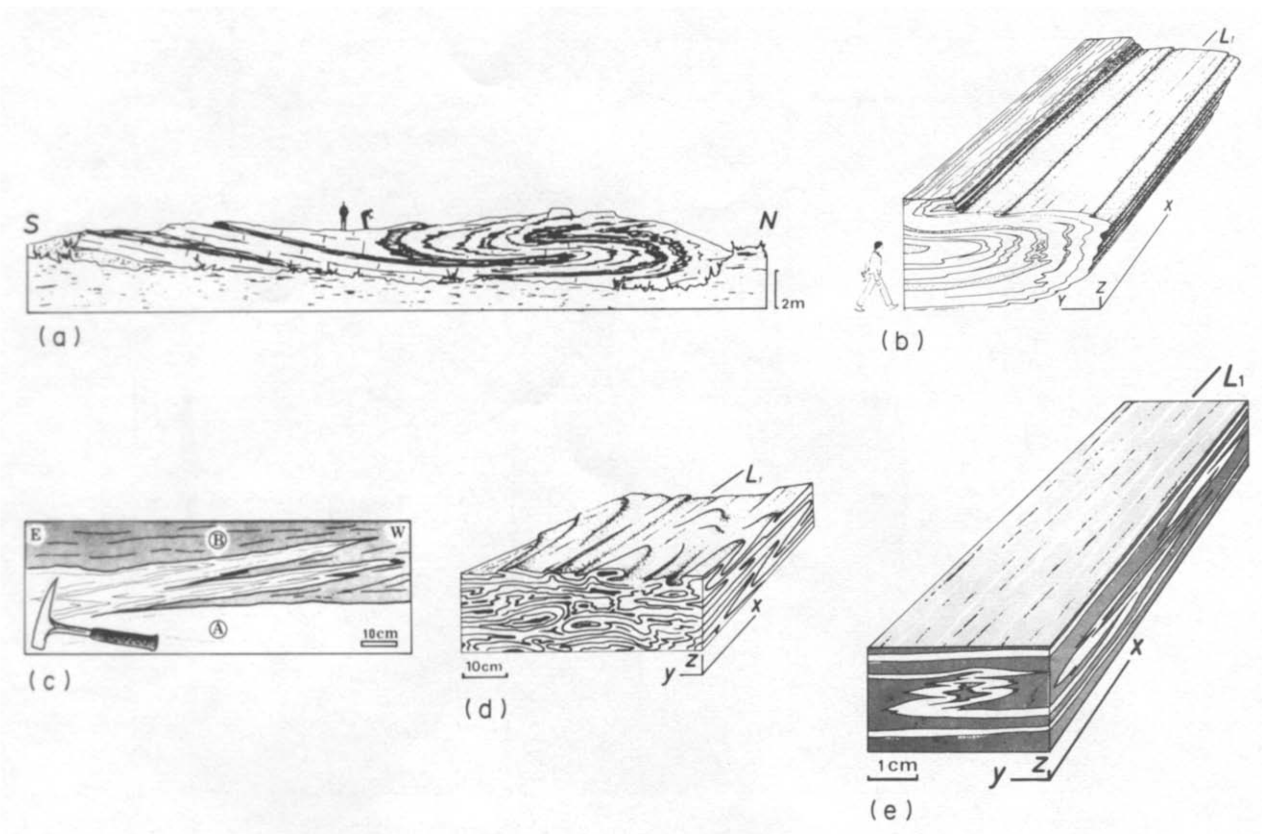

Fig. 4. Some aspects of folding. (a) Decametric-scale recumbent isoclinal fold (F_{1a}) in limestones and quartzites on the crest of the Col de Teghime. The axis is parallel to the L_1 lineation, here trending N 100° E. (b) Diagrammatic sketch of an outcrop showing folds in the *YZ* section and the strong macroscopic linear fabric due to true stretching and intersection structure. (c) 'Flame folds' (F_{1a}) between limestones (white) and greenschists (grey) near Sto Pietro di Tenda. Such a structure is interpreted as having been initiated by a simple shear mechanism (cf. Cobbold & Quinquis 1980). (d) Schematic block diagram of sheath folds (F_{1b}) in quartzites near Patrimonio. Also see Fig. 6. (e) Some aspects of folding of epidotic layers in prasinitic schists (Lancone).

ribbons (White 1976, Boullier & Bouchez 1978). Lattice preferred orientations are well marked in mylonitic ribbons, however, some gneisses from the allochthonous slices around the Col of Teghime present poorly-developed quartz *C*-axes fabrics, probably due to large amounts of phyllosilicates which may have prevented plastic strain in quartz.

THE HP/LT METAMORPHISM

Microscopic structures indicate that the major ductile deformation (S_1–L_1) is associated with a HP/LT metamorphism with the following typomorphic minerals: blue amphiboles, lawsonite, jadeite, garnet, phengites (Brouwer & Egeler 1952, Amaudric du Chaffaut *et al.* 1976, 1979). These metamorphic minerals are generally pre-to syntectonic: for example blue-zoned amphiboles are aligned and boudinaged along the L_1 lineation, garnets enveloped by the S_1 foliation show quartz pressure shadows. Late tectonic minerals such as undeformed and weakly orientated Na-amphiboles are also present. Thus we consider that polyphase crystallization occurred in a continuous way during all stages of the main phase of deformation.

From a study of metamorphic parageneses in the sialic rocks, we infer an increase in metamorphic pressure from west to east. In the eastern part of the Tenda basement, parageneses with Na amphiboles (crossite), lawsonite and stilpnomelane (Brouwer & Egeler 1952, Stam 1952, Amaudric du Chaffaut *et al.* 1976) indicate a pressure about 4 to 5 kbar. In the Serra di Pigno–Oletta gneisses, besides these minerals, garnet and jadeitic pyroxene occur. In another gneissic slice, near the Sant'Andrea di Cotone area (Fig. 1:☆), (Autran 1964, Caron *et al.* 1980), typical HP/LT metamorphic minerals indicate PT conditions estimated at 8 kbar and 300°C. This metamorphism was characterized by two parageneses developed during the deformation stages of our previously defined main phase.

In the ophiolites' basic sequence, HP associations, including eclogite, (e.g. near Albo) have been described (Ohnenstetter *et al.* 1976, Grupo Ofioliti 1977, Dal Piaz & Zirpoli 1979). According to Amaudric du Chaffaut *et al.* (1976 b) in the eastern part of the Cap Corse one can infer metamorphic conditions of about 5–6 kbar and 350–400°C. In the upper mafic units, HP parageneses are rare or even lacking. We admit therefore as a first approximation, neglecting large post-metamorphic shear motions, that metamorphic intensity decreases away from the main basal contact towards the top of the nappe.

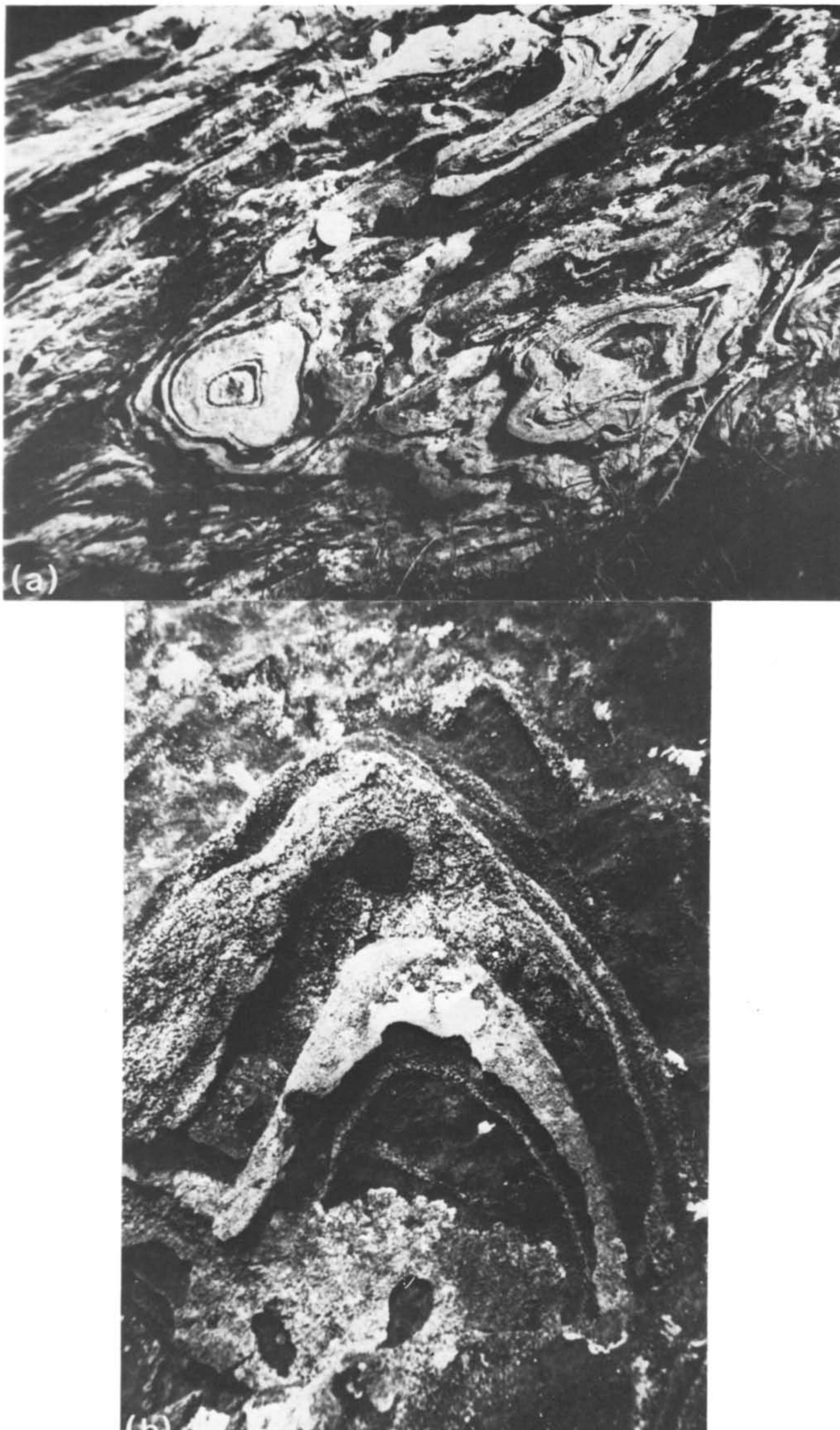

Fig. 6. (a) Outcrop in sedimentary series of quartzite and greenschist alternations (near Patrimonio) showing eyed-structure of sheath folds in a section approximately normal to the stretching lineation. (b) Sheath structure near Col de Teghime, well marked by thin siliceous layers in marbles, plane of view subparallel to the foliation. The L_1 lineation is poorly visible.

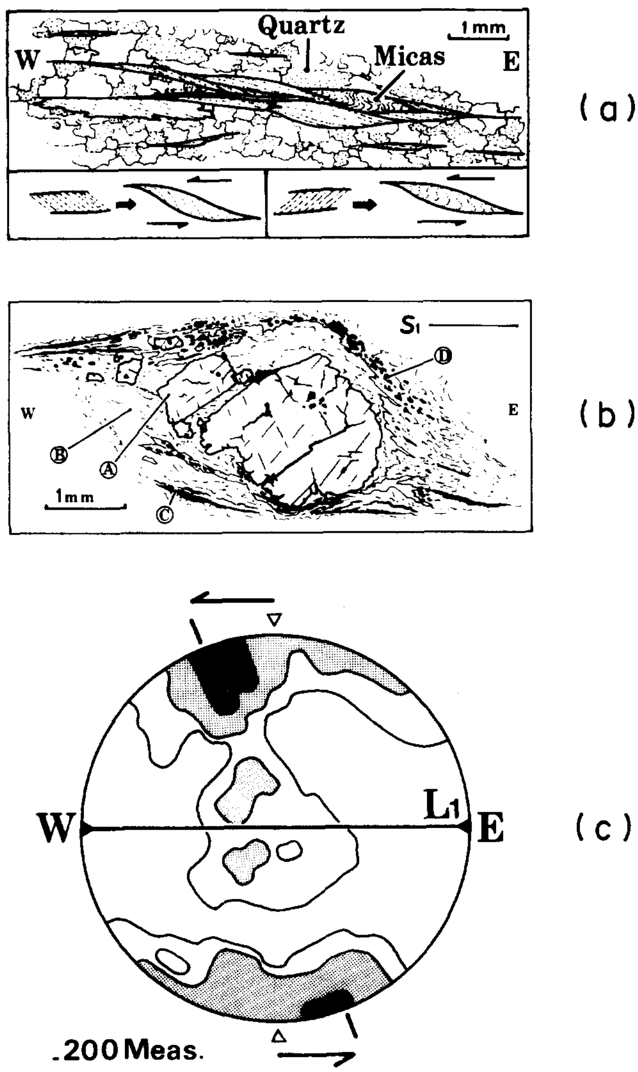

Fig. 5. Microscopic criteria for rotation. (a) Texture of quartzites in XZ section showing recrystallized quartz grains and sheared white-micas, according to the initial orientation of their (001) cleavages. (b) Microscopic rotational criteria showing; (A) sheared feldspar augen and asymmetric pressure shadow, (B) quartzo-feldspathic matrix, (C) mica, and (D) opaque minerals. (c) Quartz C-axis orientation diagram, the monoclinic symmetry being interpreted as due to westward shear. Quartzite near Farinole, 200 measurements, contours for 0.5, 2.0, 6.5 and 12.0% per 1% area.

THE STRETCHING LINEATION AND ITS TECTONIC MEANING

The L_1 stretching lineation is always well marked both in the autochthonous basement and in the tectonic slices of gneisses and sediments emplaced into the Schistes Lustrés nappe. In the ophiolitic sequence, L_1 is well expressed in gabbros and greenschists, it is less visible in the oceanic schists. Generally, in the whole area the macroscopic fabric is planolinear ($S > L$), nevertheless, in places, around the Col de Teghime, the rocks exhibit a strong linear fabric ($L > S$). The lineation is due to elongated mafic xenoliths in the gneisses and boudinaged pebbles in the sediments. On a microscopic scale L_1 is due to: (i) cataclasis where minerals with brittle behaviour (feldspars, pyroxenes) have been boudinaged and pulled apart; (ii) ductile strain where plastic minerals (quartz) have been elongated; and (iii) crystallization where pressure shadows or metamorphic amphiboles are aligned along L_1.

Finite strain ellipsoid

Following Nicolas & Poirier (1976) we assume that the foliation S_1 is parallel to the XY plane of the finite strain ellipsoid, and that the lineation L_1 corresponds to the maximum stretching direction X ($X > Y > Z$). The shape of the strain ellipsoid can be qualitatively approximated by relative size ratios of pebbles and phenocrysts (feldspars or pyroxenes), and by the development of pressure shadows (Choukroune & Lagarde 1977). Along X stretching is important, the apparent X/Y ratio ranges between 3 and 10, but extension along Y is limited (rare and short pressure shadows, no boudinage). In the Défilé du Lancone, 55 measurements of ellipsoidal spots with the same mineralogical composition as the prasinitic matrix (hence with negligible rheological contrast), give axial ratios of 3.4 : 1 : 0.6 ($K = 3.6$). These data suggest that the strain ellipsoid is located in the constriction field or in the vicinity of plane strain. L_1 remains constant in direction over large areas and transverse to the trend of the belt (Fig. 3). This is in agreement with the proposed interpretation that the stretching lineation (L_1) is parallel to the E–W nappe transport direction (Mattauer & Proust 1975, Mattauer *et al.* 1977). To confirm this view, an investigation of rotational criteria in the X/Z plane was carried out.

Deformation regime

Sigmoidal white-micas are widespread in the quartzites and contain evidence for shear (Eisbacher 1970, Burg & Laurent 1978). If the (001) cleavage is suitably oriented it acts as a slip plane, otherwise it is buckled (Fig. 5a). Brittle minerals (e.g. feldspars, pyroxenes, magmatic amphiboles) are cracked, faulted and some small pieces have been dragged by rotation of the clasts (Fig. 5b). Asymmetric pressure shadows at the ends of garnet, pyroxene, amphibole, feldspar and pyrite grains indicate non-coaxial strain (Fairbairn 1950, Zwart & Oele 1966, Choukroune 1971, Choukroune & Lagarde 1977).

The preferred orientation of quartz C-axes in quartzites and mylonitic gneisses unaffected by late phase deformation displays a monoclinic symmetry (Fig. 5c). Optical microstructures and T conditions (300°C) inferred from metamorphic assemblages are in agreement with deformation by an intracrystalline mechanism. The observed fabric diagrams suggest that basal slip is the dominant active slip system in quartz (Bouchez & Pecher 1976, Lister & Price 1978). Following Etchecopar's (1977) simulations the strong maximum (12%) displaced toward the west is in agreement with a non-coaxial strain and a shear directed to the west.

Locally the Tenda orthogneisses show decimetric-scale westward-translating ductile shear zones. The observed sheath folds, with axes parallel to the stretching lineation, are considered to have been initiated during intense (simple) shear (Carreras *et al.* 1977, Cobbold & Quinquis 1979, Faure & Malavieille 1980). In the same way, flame folds (Fig. 4c) overturned to the west are similar to those produced experimentally by Cobbold & Quinquis (1979). Besides, the overturning of F_{1c} microfolds is in agreement with the structural pattern.

All the rotational criteria briefly summarized above have been observed throughout the eastern margin of the Tenda Massif and the Oletta–Serra di Pigno zone. A small percentage of data conflict with a westward sense of shear: they may be related to either eastward motions caused by differential displacements along some shear contacts, or to anomalous mechanical behaviour of rotational markers as shown by their initial shapes and orientations with respect to the displacement direction. Therefore we consider that the microtectonic data reflect a general westwards motion, parallel to the L_1 lineation.

We propose that the ductile first deformation phase produced foliation, lineation, folds and shear contacts. The strain ellipsoid and rotational criteria suggest that a shear regime, approximately simple shear to satisfy the boundaries conditions, but locally more complex, was the dominant regime. Hence L_1 appears as the thrust direction (the *a* lineation) and the sense of shear is towards the west, that is in accord with other geological data (Escher & Watterson 1974, Mattauer 1975, Mattauer *et al.* 1977).

Despite the inference that the foliation in the gneisses developed before the microstructures concentrated along the thrust zones, we conclude that both can be accounted for by continuing strain during the main phase of deformation. Thus the gneissic slice of Oletta–Serra di Pigno may have acquired its foliation while it was still autochthonous and then became tectonically emplaced in the Schistes Lustrés nappe along ductile shear contacts.

CONCLUSIONS

The ductile deformation related to the studied ophiolitic obduction may be applied to a larger geodynamic model. As has been suggested elsewhere (Mattauer & Proust 1976, Mattauer *et al.* 1977), if obduction results from intraoceanic subduction blocked by underthrusting of continental crust beneath oceanic lithosphere, the plastic shear deformation contemporaneous with the HP/LT metamorphism occurs in the uppermost part of the sialic subducting basement, and in the lower part of the oceanic crust and sedimentary cover. Non-coaxial strain is therefore a direct consequence of tangential tectonics leading to the anomalous superposition of oceanic crust upon sialic basement. In this model, slices of basement gneisses and sedimentary cover are drawn to the subducting continent and transported large distances (> 20 km) (Fig. 7). This interpretation emphasises that deformation products are consistent on all scales from microstructures to megastructures and that they can all be explained by a simple mechanism. From this point of view the transverse stretching lineation and the rotational displacement provide constant and valuable markers.

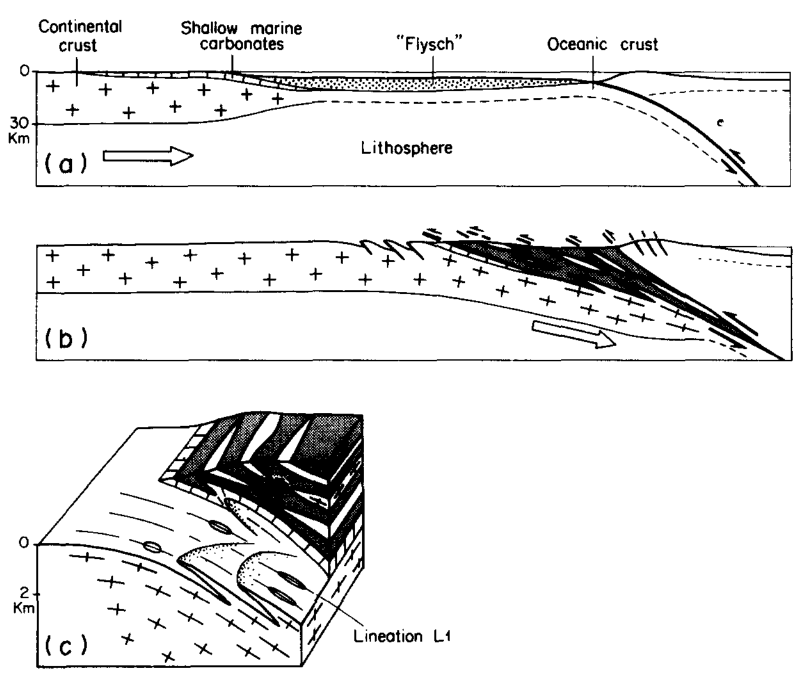

Fig. 7. Geodynamic interpretation of the obduction mechanism in Corsica. (a) Intra-oceanic subduction (Early Cretaceous). (b) Blocking of subduction through underthrusting of continental crust leading to crustal shearing associated with ductile deformation and HP metamorphism (Late Cretaceous). (c) Schematic block diagram showing a possible occurrence of large (kilometric-scale) sheath folds involving basement with an associated stretching lineation.

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