STRUCTURES AND MICROSTRUCTURES IN A THRUST-RELATED, GREENSCHIST FACIES TECTONIC MÉLANGE, VOLTRI GROUP (NW ITALY)

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ABSTRACT

The ophiolitic Voltri Group in the eastern part of the Ligurian Alps (NW Italy) is made up of a number of thrust sheets emplaced during Alpine collision. These thrust sheets include (1) the Voltri-Rossiglione calcschist unit of Mesozoic high-pressure calcareous micaschists, metavolcanics and slices of serpentinite, overlain by (2) the Beigua serpentinite unit, of mainly antigorite serpentinite and eclogitic metagabbro, in turn overlain by (3) the Erro-Tobbio peridotites. In the northern part of the Voltri Massif, a conspicuous mélange-type lithology occurs along the contact of the Beigua serpentinite unit and the Voltri-Rossiglione calcschist unit. In the vicinity of the contact, the structure in the hanging-wall serpentinites is dominated by kink-type crenulations. Towards the base of the serpentinite nappe these crenulations become intense, and veins and patches of talc + chlorite + tremolite + carbonate replace the original antigorite-dominated assemblage. The thrust itself is marked by a layer, at least several tens of metres thick, of intensely deformed and foliated antigorite-bearing talc-chlorite-tremolite schist, enclosing rounded and lense-shaped (phacoid) blocks, up to 25 metres across, of retrogressed eclogitic metagabbro, antigorite serpentinite, metabasic rock, calcschist and schistose micaceous marble. The main features of this chaotic lithology meet the descriptive criteria of a tectonic mélange. The structures and assemblages in the wall rock units and those in the mélange indicate that the mélange lithology developed at a relatively late stage of greenschist facies ductile thrusting, emplacing the Beigua unit onto the rocks of the Voltri-Rossiglione unit. The structures indicate that the blocks and lenses were formed during localized deformation in a relatively narrow zone along the thrust plane via intense stretching and boudinage of the various lithologies in the foot- and hanging wall. The development of talc-chlorite-tremolite-carbonate assemblages at the expense of the overriding antigorite serpentinites require significant calcium-metasomatism, hence extensive fluid activity, whilst the microstructures in the mélange matrix suggest that the talc-chlorite-tremolite-carbonate assemblage was mechanically weak. It is suggested that both fluid activity and the associated metamorphic reactions strongly facilitated ductile to semi-brittle deformation along the thrust, leading to progressive fragmentation and mixing of the different lithologies and development of a tectonic mélange.

INTRODUCTION

Lithologies called mélanges (French: mixtures) have been widely recognized in the geological record over the past decades, yet discussion continues on how these lithologies should be defined, how they are formed, and what the significance of mélanges is (e.g., Hsü, 1968; Raymond, 1984). Many mélanges seem to be associated with convergent plate margins, and it has been proposed that mélanges mainly develop in convergent tectonic settings (e.g., Cloos, 1984). In addition, most mélanges documented in the literature occur in Phanerozoic orogenic belts (Raymond and Terranova, 1984). However, before turning to the question how mélanges form and what their significance is in terms of tectonic processes, one is faced with the problem that mélanges are difficult to define.

In a comprehensive review of current classifications of mélanges and inherent criteria, Raymond (1984) elucidated how a variety of structures, from coherent formations to mélanges, may develop in response to processes ranging from purely sedimentary sliding to synmetamorphic ductile deformation. For the purpose of this paper, we largely follow Raymond's (1984) definition, i.e., a mélange is a mappable body of rock characterized both by the lack of internal continuity of contacts or strata and by the inclusion of fragments and blocks of all sizes, exotic and native, embedded in a fragmented matrix of finer grained material. Implicit in this and similar definitions by other workers is the notion that in order to form a mélange, processes are needed that allow the fragmentation of previously coherent strata or bodies and subsequent mixing of these fragments (e.g., Hsü, 1968). From a structural point of view, this clearly calls on some form of competence contrast between mechanically strong layers or bodies and a weaker matrix material. Fragmentation by boudinage, albeit possible in some sedimentary environments, is known to prevail where brittle-ductile movement zones affect heterogeneous lithologies with contrasting competence, whilst extensive mixing should clearly be promoted if these movement zones account for large-scale transport.

In this paper we study a mélange-type lithology associated with a major thrust in the ophiolitic Voltri Group of the Ligurian Alps in NW Italy (Fig. 1). The structures, and associated mineral assemblages indicate that this lithology developed during greenschist facies ductile thrusting. The mineral assemblages, moreover, suggest that the matrix material may have been weakened in response to reaction softening processes (White and Knipe, 1978). The concept of reaction softening refers to the mechanical weakening, expected when metamorphic reactions lead to the development of new minerals and mineral assemblages that are weaker than the precursor assemblage, either (1) because the reaction products are weaker, or (2) because the reaction products are finer-grained, thereby allowing an increased role of diffusion-assisted creep, or (3) because of increasing fluid activity triggered by dehydration reactions. The structures and fabrics of the rocks addressed in this study suggest that progressive syntectonic mineral transformations helped to enhance competence contrasts, facilitating fragmentation as well as the potential to mix fragments once they became separated from the adjacent wall rocks.

GEOLOGICAL SETTING

The Voltri Massif in the Ligurian Alps is the largest ophiolite massif in the Alps-Apennine system (Fig. 1). The

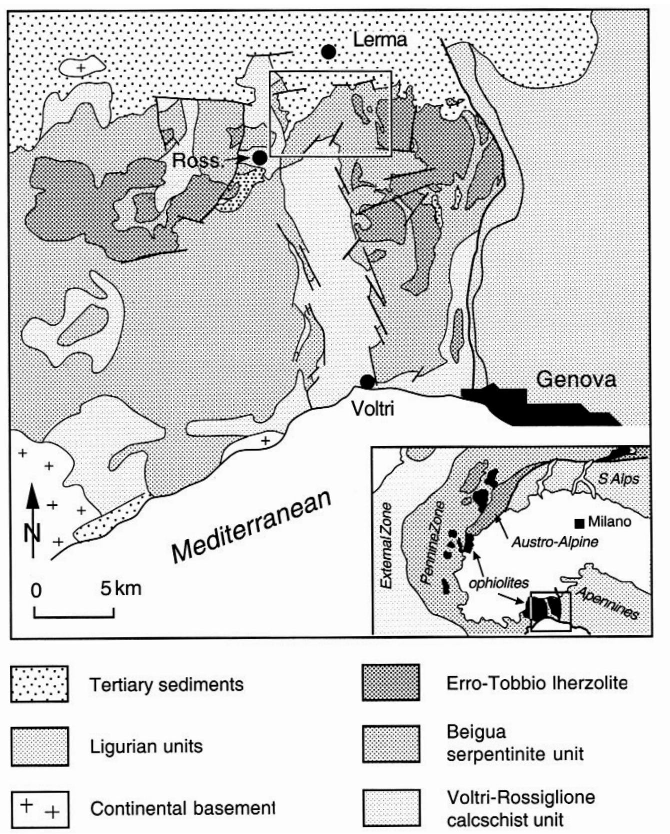

Fig. 1. Sketch map of the Voltri Massif and (inset) location of the Voltri Massif in the Alps. The area outlined is shown in Fig. 2. Ross.-Rossiglione.

structure of the massif is dominated by subhorizontal thrust sheets affected by polyphase deformation and metamorphism (Chiesa et al., 1975; Piccardo et al., 1977). Three main units are commonly distinguished, i.e., from bottom to top: (1) the Voltri-Rossiglione calcschist unit of blueschist- to eclogite-facies calcareous metasediments, metavolcanite and slices of serpentinite, (2) the Beigua serpentinite unit of heavily serpentinized ultramafic rocks enclosing small amounts of eclogitic metagabbro and locally metabasalt, and (3) the overlying lherzolite-dominated Erro-Tobbio peridotite. These units, also referred to as the Voltri Group (Chiesa et al., 1975), represent fragments of the subducted lithosphere of the Piedmont-Ligurian ocean, the Alps-Apennine part of the Mesozoic Tethys (Ernst and Piccardo, 1979; Lemoine et al., 1987). This oceanic basin, formed during the Middle and Late Jurassic, became involved in intraoceanic subduction and subsequent collision after the Early Cretaceous leading to imbrication and stacking in the Alpine suture zone and emplacement of oceanic fragments as ophiolites onto the European continental crust.

The rocks addressed in this study are exposed along the contact of the Beigua serpentinite unit and the underlying Voltri-Rossiglione calcschist unit in the northern part of the Voltri Massif, SSE of the village of Lerma (Figs. 1, 2). Outcrop conditions in the region are generally poor due to dense vegetation, but the Piota River (Fig. 2) provides excellent exposure in a domain where the contact of the two main units is subhorizontal. Below we first consider the structures and assemblages in the hanging-wall rocks of the Beigua serpentinite unit, followed by those in the footwall, i.e., the Voltri-Rossiglione calcschist unit. For present purposes, the description of these structures and associated metamorphism is limited to critical observations in the main rock types, with emphasis on their metamorphic evolution as deduced from the stability of key mineral assemblages and thermobarometry. We then proceed to the mélange-type lithology seen in the contact zone between the two units.

STRUCTURE AND METAMORPHISM IN THE WALL-ROCK UNITS

On the basis of outcrop- and microscale overprinting relationships, a sequence of deformational structures has been recognized in each unit (Hoogerduijn Strating, 1991) which forms the basis for the relative timing of different metamorphic minerals and mineral assemblages summarized in Figs. 3 and 4. All units of the Voltri Group show an eclogite, a blueschist-eclogite, and a greenschist facies stage of deformation. On the basis of correlation via eclogitic metagabbros in the Beigua serpentinite unit, Hoogerduijn Strating (1991) labelled these three tectono-metamorphic episodes D_2-M_2, D_3-M_2 and D_4-M_5. In addition, a pre-eclogitic stage (D_1-M_1) has been identified, whilst several of the rock types involved show evidence for a static greenschist facies recrystallization (M_4) in between tectono-metamorphic episodes D_2-M_2 and D_4-M_5. Late-stage growth of zeolite facies minerals associated with brittle, NW-directed thrusting (Hoogerduijn Strating, 1991) is not considered here.

Beigua serpentinite unit

The Beigua serpentinite unit is dominated by Ca-poor, harzburgite-derived antigorite serpentinite with up to 100 m

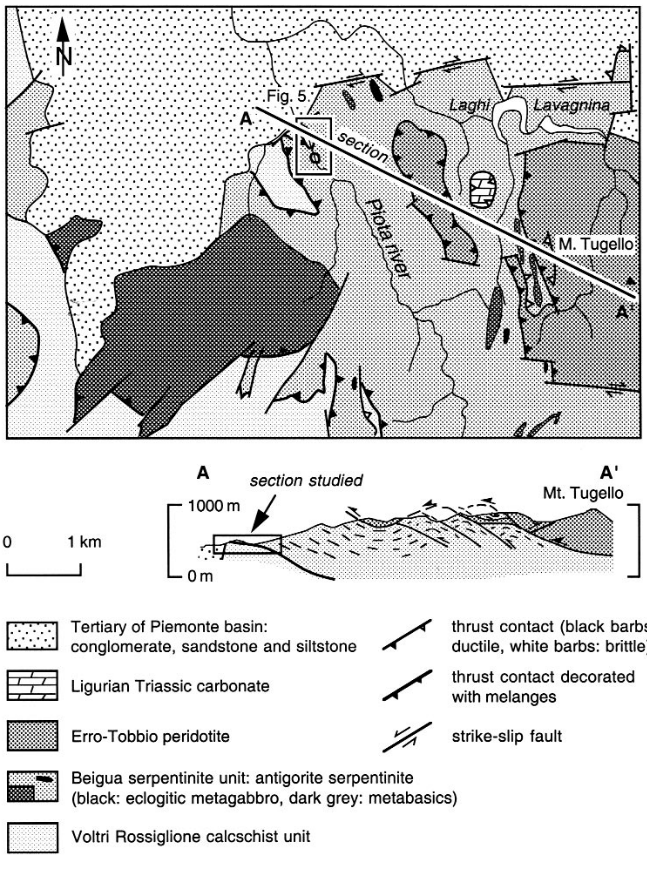

Fig. 2. Sketch map and cross section of the central northern Voltri Massif south of Lerma, showing location of mélange exposures in the Piota riverbed (area outlined).

scale lenticular bodies of eclogitic metagabbro and, locally, metabasalt. The earliest (D_1) fabric observed in the serpentinites is an intense foliation associated with isoclinal and possibly sheath folds. Gradual transitions from massive, virtually undeformed to strongly foliated serpentinite are common, suggesting that D_1 strain was heterogeneous at a length scale between 10 cm and at least 100 m. In many localities the early fabric involves a composite D_1-D_3 structure made up of a foliation (D_1) overprinted by narrowly spaced ($D_{2/3}$) shear bands or extensional crenulation cleavages (ecc's, Platt and Vissers, 1980). On the micro-scale, the D_1 foliation is defined by oriented antigorite, chlorite and magnetite (M_1), whilst in the $D_{2/3}$ shear bands this assemblage is replaced by fine-grained olivine + antigorite + chlorite + diopside + titanian clinohumite ($M_{2/3}$). The growth of these olivine-bearing assemblages is interpreted to result from synkinematic dehydration of antigorite in the shear bands, at temperatures of about 500°C (Hoogerduijn Strating and Vissers, 1991; Scambelluri et al., 1991). The mineral lineations in shear bands and asymmetric porphyroclast systems (Passchier and Simpson, 1986) indicate WNW-directed ductile thrusting.

The composite D_1-D_3 fabric is locally refolded by small-scale, WNW-vergent folds accompanied by a crenulation cleavage (D_4). These crenulations are most intensely developed close to the contacts with the underlying Voltri-Rossiglione calcschist unit and the overlying Erro-Tobbio peridotite, and often involve complete transposition of the D_1-D_3 fabric. D_4 crenulations are associated with growth of antigorite and magnetite at the expense of olivine whilst, close to the contact with the Voltri-Rossiglione calcschist unit, extensive replacement occurs to talc-chlorite-tremolite-carbonate-bearing assemblages (Fig. 3a) indicating greenschist facies conditions. These structures and associated transformations are considered in further detail below.

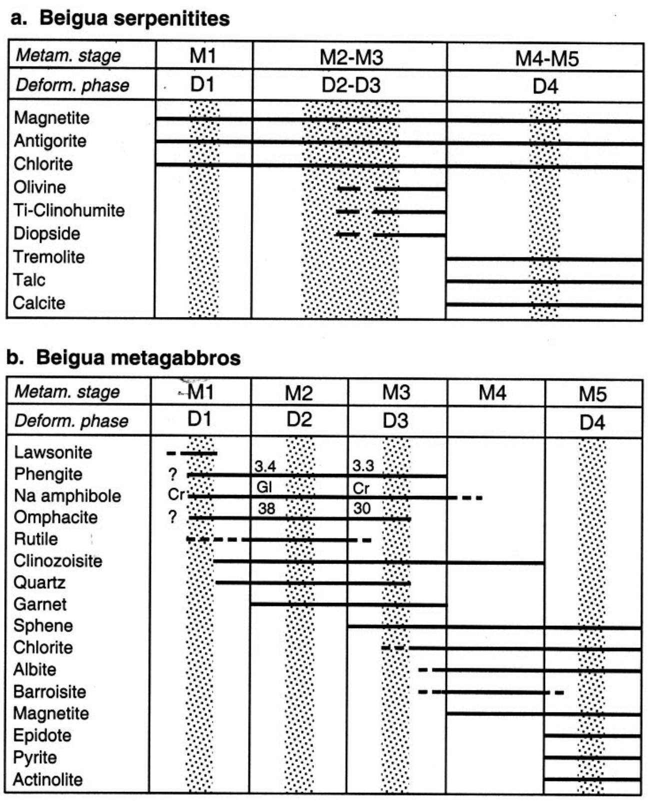

Fig. 3. Relationship between deformation and metamorphism in (a) the serpentinites and (b) the metagabbros of the Beigua serpentinite unit.

The structural and metamorphic history of the eclogitic (Mg and Fe-Ti) metagabbros in the Beigua serpentinite unit has been studied in detail (e.g. Messiga and Piccardo, 1974; Chiesa et al., 1975; Ernst, 1976; Messiga et al., 1983; Scambelluri, 1987; Hoogerduijn Strating, 1991; Messiga and Scambelluri, 1991). The oldest structure observed is a faint foliation defined by aligned clinopyroxene crystals, occasionally cut by metabasaltic dykes. No relics are preserved of the stable mineral assemblage during this deformation event, but the structures are remarkably similar to “oceanic” amphibolite facies mylonites predating basaltic dyke intrusion in some of the ophiolites in the Ligurian Apennines (e.g., Hoogerduijn Strating, 1988; 1991), and may well have formed during the oceanic stage.

The dykes and metagabbros are deformed in metre to hundred metre-scale shear zones, characterized by a penetrative foliation bearing omphacite (Jd^{38}), glaucophane, garnet, rutile, quartz, clinozoisite, phengite ($Si^{3.4}$) and apatite (D_2-M_2; Fig. 3b). This assemblage also developed in strain shadows of omphacite pseudomorphs (Jd^{28}) after pyroxenes presumably of magmatic origin. The foliation bends around these porphyroclasts which are locally rimmed by coronas of more sodium-rich pyroxenes. Olivine, only present in Mg metagabbros, is transformed into aggregates of talc, Na-clinopyroxene, clinozoisite, chlorite, Ca-clinoamphibole and, in few cases, chloritoid. Chloritoid is partially overgrown by talc and commonly occurs close to the contact with domains of originally plagioclase (cf. Kienast and Pognante, 1988). Thermobarometry of Mg (Messiga et al., 1983) and Fe-Ti metagabbros (Messiga et al., 1983; Hoogerduijn Strating, 1991; Messiga and Scambelluri, 1991) suggests synkinematic eclogitic conditions of 450-530°C and 1300-1500 MPa, whilst slightly higher P-T estimates (520-570°C, 1200-1600 MPa) were obtained from a metabasalt with a stable assemblage of omphacite (Jd^{38}), garnet, glaucophane, phengite ($Si^{3.6}$), rutile and quartz.

Some of the largest M_2 garnets in the metagabbros enclose aligned grains of crossite, paragonite, clinozoisite, Na-clinopyroxene and occasionally rutile, pointing to earlier deformation and crystallization under prograde blueschist facies conditions (D_1-M_1; Fig. 3b; Messiga and Scambelluri, 1991). In addition, rectangular pseudomorphs of clinozoisite + paragonite + quartz may indicate that lawsonite was also stable during this stage (Messiga et al., 1989).

The eclogitic foliation is locally overprinted by metre-scale shear zones with a foliation of crossite, clinozoisite, sphene, garnet, and sometimes omphacite (Jd^{30}), while crossite and phengite ($Si^{3.3}$) grew at the expense of omphacite porphyroclasts in the wall rock (D_3-M_3; Fig. 3b). These shear zones are inferred to have developed under blueschist to eclogite facies conditions (500-525°C, 800-1100 MPa).

Many of the eclogitic metagabbros show static (M_4) replacement of omphacite, glaucophane and crossite by barroisite in the presence of albite, clinozoisite, chlorite, sphene and magnetite. The stability of this assemblage and the crossite contents of the barroisite suggest recrystallization at 400-500°C and 500-700 MPa. This stage of static recrystallization is overprinted by the development of metre-scale shear zones and recumbent folds with axial-plane crenulation foliations associated with the synkinematic transformation (D_4-M_5; Fig. 3b) of barroisite to actinolite in the presence of albite, chlorite, epidote, sphene, magnetite and pyrite indicating greenschist facies conditions (350-450°C, 200-500 MPa).

Correlation between the early deformational structures in the serpentinites and metagabbros is difficult and therefore tentative but the mutual evolution towards temperatures in excess of 500°C at eclogite facies conditions suggests that the antigorite foliation in the serpentinites developed simultaneous with the blueschist- to eclogite-facies foliation preserved in M_2 garnets in the metagabbros. Progressive deformation of the serpentinites leading to the development of olivine-bearing shear bands probably postdate peak eclogite (D_2-M_2) and possibly also eclogite-blueschist facies (D_3-M_3) deformation in the gabbros (Figs. 3a and b), because there is evidence that bodies of eclogite with an internal eclogitic foliation are enclosed in serpentinites with a prograde antigorite foliation cut by olivine veinlets and olivine-bearing shearbands (Scambelluri, pers. comm.). Greenschist facies D_4 crenulations seen in small eclogitic lenses correlate with antigorite-bearing (i.e., olivine-free) D_4 crenulations in the surrounding serpentinite.

Voltri-Rossiglione calcschist unit

The dominant rock types of the Voltri-Rossiglione calcschist unit are calcareous micaschists with interbeds of quartzite and marble lithologically identical to the well-known “Schistes lustrés” of the Western and Central Alps. Lenticular bodies of metabasite, largely replaced by an albite-actinolite-epidote (prasinitic) assemblage, and serpentinite were emplaced into the metasediments along shear zones and faults. Occasionally preserved primary contacts between the metabasites and the metasediments show a stratigraphy reminiscent of the ophiolitic sequences in the Ligurian Apennines: from the bottom upward, the sequence consists of prasinite (meta-basalt), quartzite (meta-chert) sometimes associated with marble, calcschist and micaschist (meta-pelagics; Amendolia and Capponi, 1985).

From recent structural work (D’Antonio et al., 1984; Amendolia and Capponi, 1985; Capponi et al. 1986; 1987; Hoogerduijn Strating, 1991), an overall picture has emerged of the structural and metamorphic history of the Voltri-Rossiglione rocks. Deformation in the metasediments resulted in a generally 40-60° E dipping, penetrative foliation locally associated with isoclinal folds ($D_{1/2}$). Some of these folds are isoclinally refolded by D_3 folds and evolved progressively into D_3 sheath folds. The metasediments show intense syntectonic recrystallization. E-W to SE-NW trending mineral lineations on the foliation planes are ubiquitous, and shear bands or ecc’s overprinting the schistosity are common. Although early structures are often obscured by later compositional banding and transposition of the bedding and folds, kinematic indicators suggest that $D_{1/2}$ and D_3 deformation in the Voltri-Rossiglione calcschist unit involved essentially W- to NW-directed thrusting in a ductile shear regime.

A summary of the metamorphic mineral assemblages for the Voltri-Rossiglione calcschists is shown in Fig. 4a. Mineral assemblages associated with the earliest folds are rare, due to intense greenschist facies recrystallization (D_4-M_5). Locally, however, garnet, rutile, silica-rich phengite ($Si^{3.5-3.7}$; Cimmino and Messiga, 1979), paragonite, and zoisite occur, whilst paragonite breaks down during deformation (D_3), and chloritoid becomes stable with albite, sphene, occasional chlorite, and phengite with a lower silica contents ($Si^{3.3-3.5}$; Cimmino and Messiga, 1979). The stability of garnet, paragonite, zoisite and phengite ($Si^{>3.5}$) suggests $M_{1/2}$ eclogite-facies conditions (450-550°C, 1200-1500 MPa). The syn-D_3 ($M_{3/4}$) assemblage of phengite, chloritoid and albite points to

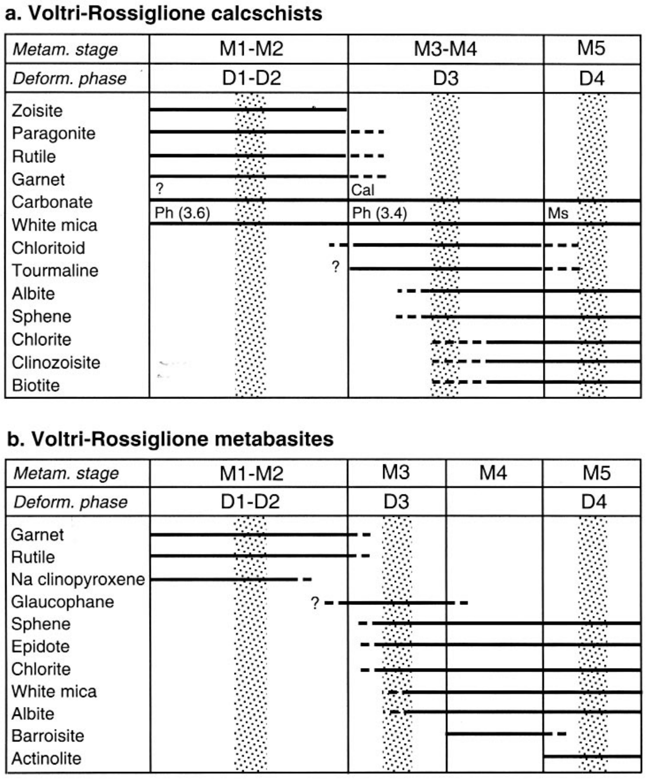

Fig. 4. Relationship between deformation and metamorphism in (a) the calcareous schists and (b) the metabasites of the Voltri-Rossiglione calcschist unit.

an evolution towards blueschist facies conditions (700-900 MPa, at temperatures exceeding 400°C), whilst the average Si content of phengite ($Si^{3.4}$) suggests that recrystallization may have started at pressures of about 1000 MPa.

The composite fabric described above is refolded in m-scale, open to tight, asymmetric W to NW facing D_4 folds associated with a fanning crenulation foliation. Generally, these folds are non-cylindric and have 40-60° E to SE dipping axial planes. Oblique grainshape fabrics in the quartzites as well as shear bands in the schists indicate that folding occurred during W- to NW-directed ductile thrusting (Hoogerduijn Strating, 1991). There is a synkinematic (M5) greenschist facies assemblage of chlorite, muscovite ($Si^{3.0-3.25}$; Cimmino and Messiga, 1979) and quartz (grown at the expense of chloritoid), with albite, biotite, clinozoisite and tourmaline (Fig 4a). Inferred P-T conditions are 200 to 400 MPa, at temperatures between 350 and 425°C.

The mineral chemistry of the metabasites intercalated in the calcschists has not been studied in detail, such that some uncertainty exists as to the equilibration conditions of the various assemblages observed. An early eclogitic stage ($M_{1/2}$-$D_{1/2}$) is indicated by the probably synkinematic growth of Na-clinopyroxene, garnet and rutile (Fig. 4b; Piccardo et al., 1979). Most metabasites have preserved a banded fabric, consisting of oriented glaucophane, chlorite, epidote, white mica, albite and sphene (M_3-D_3). This mylonitic fabric is tentatively correlated with the D_3 (sheath) folds in the metasediments. Barroisite, in the presence of sphene, epidote, chlorite, white mica and albite (M_4), has grown statically at the expense of glaucophane, garnet and Na-clinopyroxene. Simultaneous with open D_4 folding in the calcschists, a synkinematic greenschist facies (M_5) assemblage of actinolite, sphene, epidote, white mica and albite developed in the metabasites (Fig. 4b).

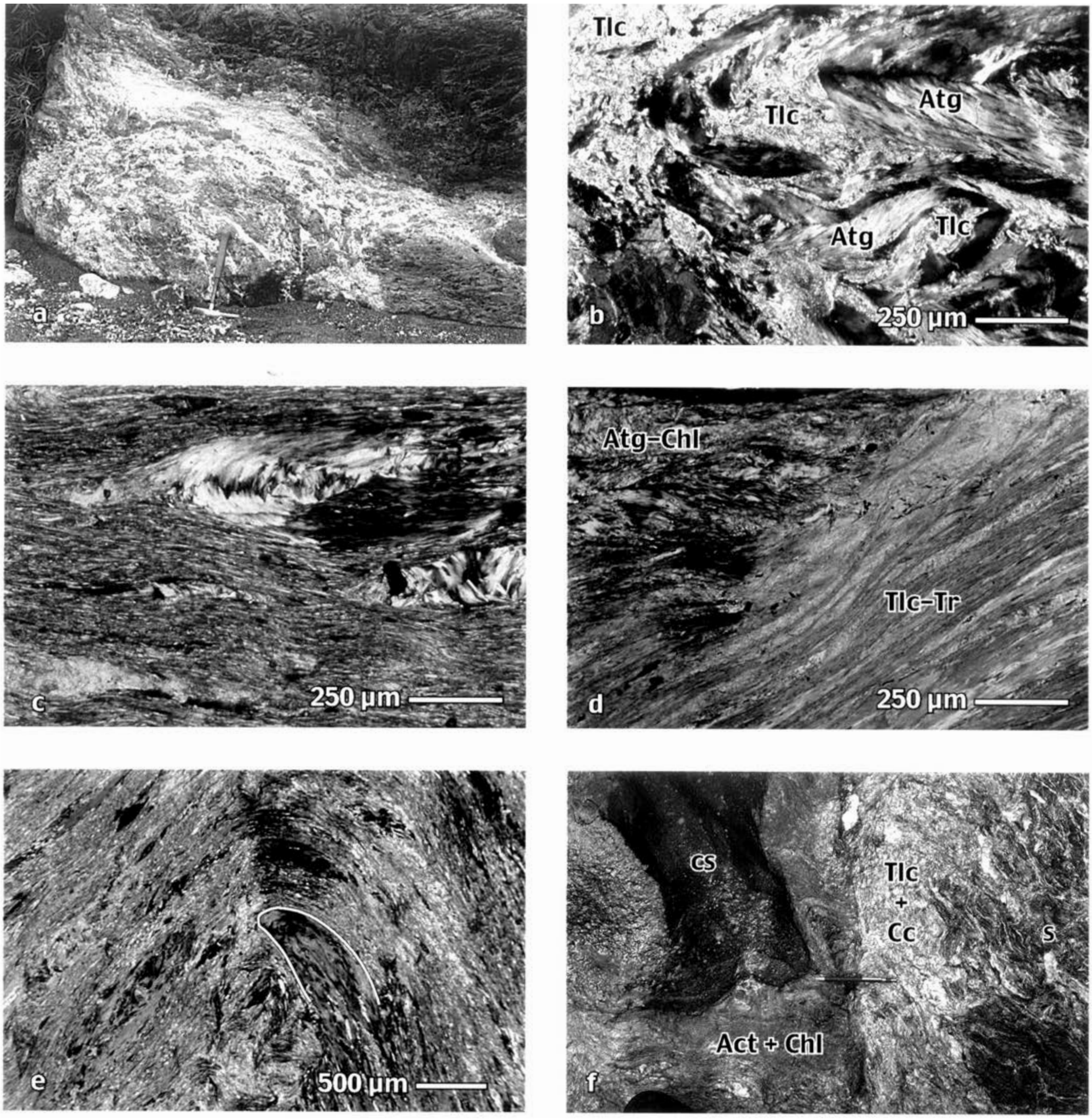

Plate 1 - Structures and microstructures of the mélange matrix. a) Exposure of hanging-wall serpentinites close to the mélange proper, showing numerous light-coloured patches and veins filled with talc-chlorite-tremolite-carbonate assemblages. b) Microstructure of intensely crenulated antigorite (Atg) showing extensive replacement by fine-grained talc (Tlc) in crenulation hinges and along the microfolded antigorite foliation. c) Microstructure of main foliation in mélange matrix made up of strongly oriented tremolite and talc warped around microfold relics mainly of Mg-chlorite. d) Detail of micro-scale shear zone, with oriented tremolite and talc (Tr-Tlc) in lower right corner, deforming main antigorite-chlorite (Atg-Chl) fabric in upper left corner. e) Late crenulation of mélange matrix foliation, showing refolding of earlier folds of Mg-chlorite (traced). f) Reaction zoning in mélange matrix in between calcschist (cs) and serpentinite (s) remnants. Calcschist patch is surrounded by layer of actinolite + chlorite, separated from the serpentinite remnant by layer of mainly talc + calcite.

STRUCTURES IN THE CONTACT ZONE: MÉLANGE STRUCTURES

The contact zone between the Beigua serpentinite and Voltri Rossiglione serpentinite units exposed in the Piota riverbed (Figs. 5 and 6) shows a bewildering chaos of lense-shaped (phacoidal) and rounded blocks of all sizes, up to 20 m across, in a penetratively foliated matrix. In terms of structure and composition, there are several types of blocks. These include eclogitic Fe-Ti and Mg gabbro commonly with coarse, flaser-type microstructures and rarely with finer-grained mylonitic fabrics, mostly greenschist-facies (prasinitic) but occasionally eclogitic metabasalt, massive and foliated serpentinite, calcschist, and calcareous marble. The matrix enclosing these different types of blocks is in most cases a serpentine- and often actinolite-bearing talc-chlorite-tremolite-carbonate schist, but gradual transitions occur to intensely foliated serpentinites as well as to more calcareous schist. There is some tendency for the serpentinitic matrix compositions to occur close to the hanging wall serpentinites of the Beigua unit, but in general there is no systematic zonation in matrix composition at scales larger than that of individual exposures.

Except for some local roads and tracks, the area immediately outside the Piota riverbed is in fact unaccessible, and the lack of any road exposure indicates that most of the region is covered by extensively vegetated soils and screes. This poses the problem that both the thickness and the lateral extent of the mélange-type lithology in the contact zone are difficult to assess. The riverbed section suggests a minimum thickness of the mélange-type lithology of some 75 m (Figs. 6, 7), but there is no control on the downward transition to relatively coherent Voltri-Rossiglione material. This transition may occur at shallow levels, immediately below the exposures found in the northern part of the riverbed section, or deeper down. A gradual transition from the hanging-wall serpentinites of the Beigua unit and the mélange lithology is well exposed, however. Below we first consider this transition and the allied development of the matrix material. We then describe the different types of enclosed blocks, with emphasis on their relationship with the structures and assemblages in the matrix.

Mélange matrix

In the southern part of the study area, coherent outcrops occur of the Beigua serpentinite unit. The structures in these serpentinites are dominated by the composite D_1-D_3 fabric made up of an early antigorite foliation and sets of shear bands described above. Northward along the section, i.e., structurally downward in the hanging wall, this composite fabric is overprinted by tight (D_4) crenulations (Figs. 7, 8a) with shallowly ESE dipping axial planes. Within the lowermost tens of meters of the hanging wall, the structure of the serpentinites is completely dominated by these crenulations. Synkinematic talc-bearing assemblages (talc with minor tremolite, chlorite and carbonate) are developed in the hinges of the crenulations, in irregular veins possibly originating from brittle cracks (Plate 1a) and, at a smaller scale, in thin crack-like veneers of tremolite and talc parallel to the crenulated antigorite foliation (Plate 1b). Downward in the hanging-wall serpentinite, layers and patches of these transformed serpentinites, several meters thick, become ubiquitous. The exposure is discontinuous, however, and the partly transformed hanging-wall sepentinites are separated from genuine mélange outcrops by steep ductile shear zones as well as brittle thrusts, both with an upthrust sense of movement to the NW.

The serpentinite matrix in the mélange lithology proper is often difficult to discriminate from patches and boudins of less transformed, intensely crenulated serpentinite material, and is pervasively deformed by anastomosing small-scale shear zones and single and conjugate sets of shear bands surrounding less deformed phacoidal domains (Fig. 8b). At the microscale, the dominant foliation is in many cases a strongly attenuated, transposed crenulation foliation (Plate 1c). The

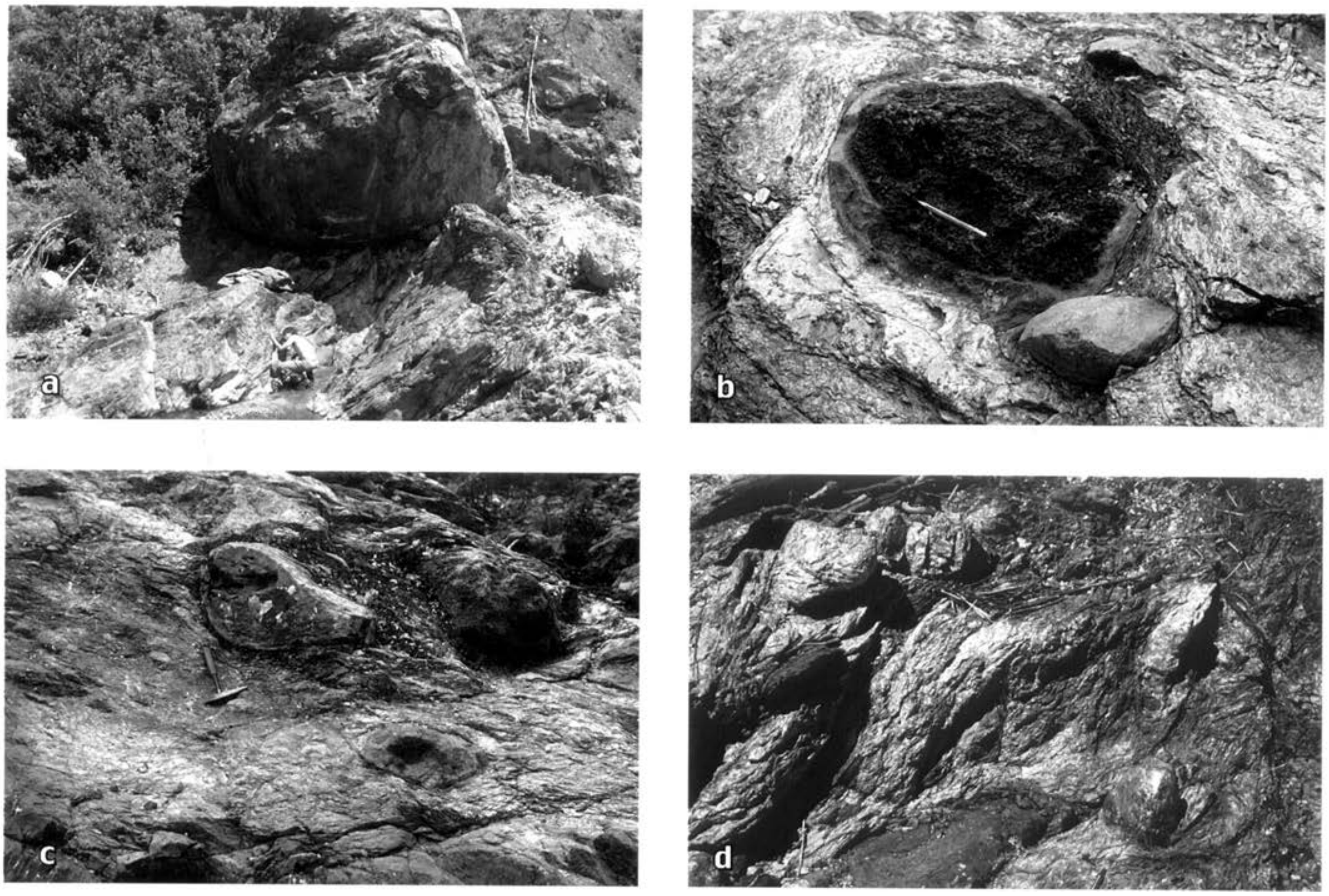

Plate 2 - Aspect of tectonic blocks in the Piota riverbed exposures. a) Rounded block of eclogitic metagabbro, resting in situ in largely eroded mélange matrix. Note geologist for scale. b) Largely retrogressed block of eclogite showing retrogressed rim of mainly albite+ actinolite + chlorite. c) Phacoidal boudins of metabasic rocks, with lighter coloured, chlorite-actinolite-rich rims. d) Lenses of less deformed and less transformed serpentinite in strongly sheared, talc-bearing serpentinitic matrix. Approximate width of exposure 1.5 m.

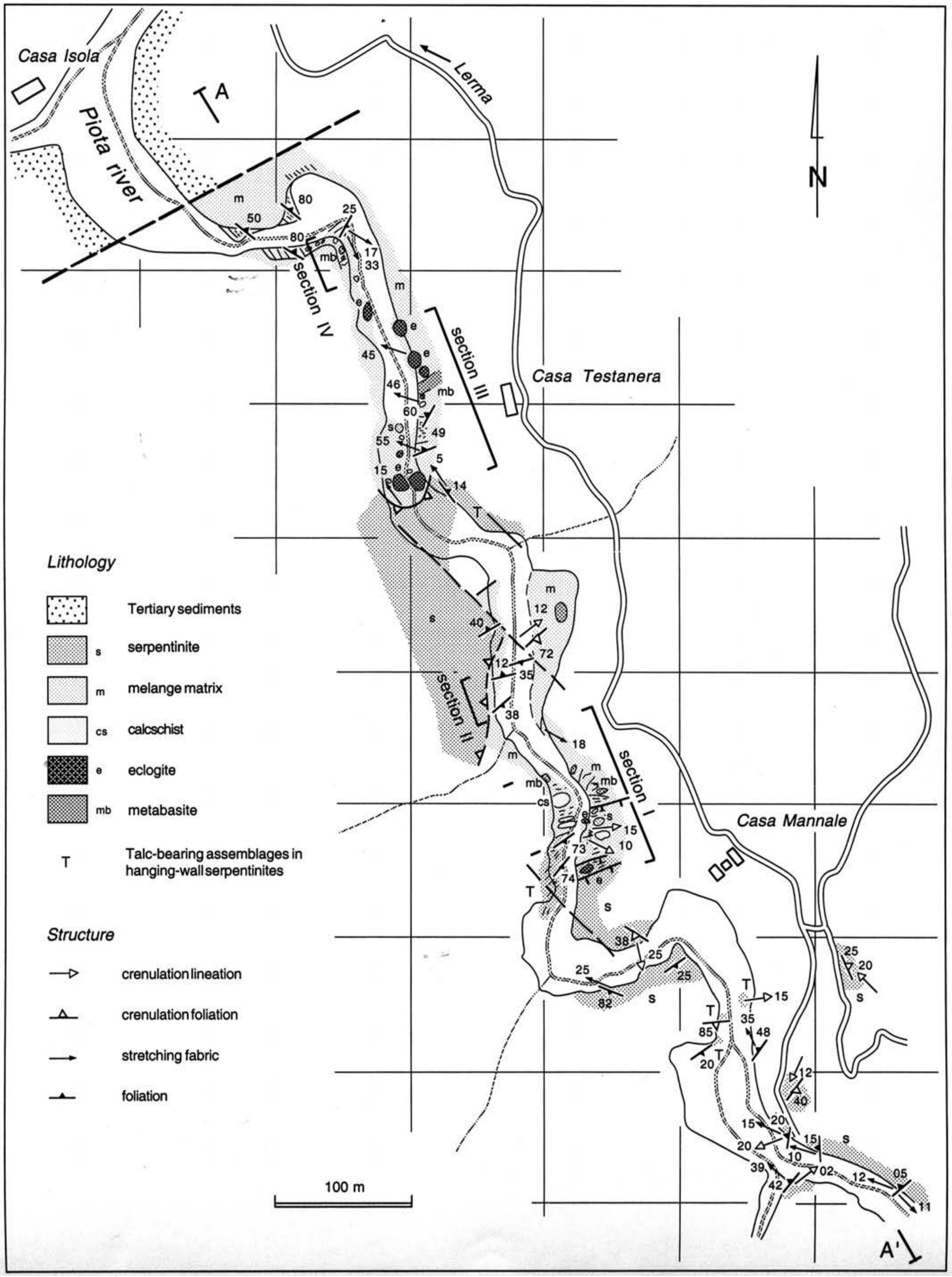

Fig. 5. Detailed map of mélange exposures in the Piota riverbed SSE of Lerma, with locations of sections shown in Figs. 6 (sections I-IV) and 7 (section AA').

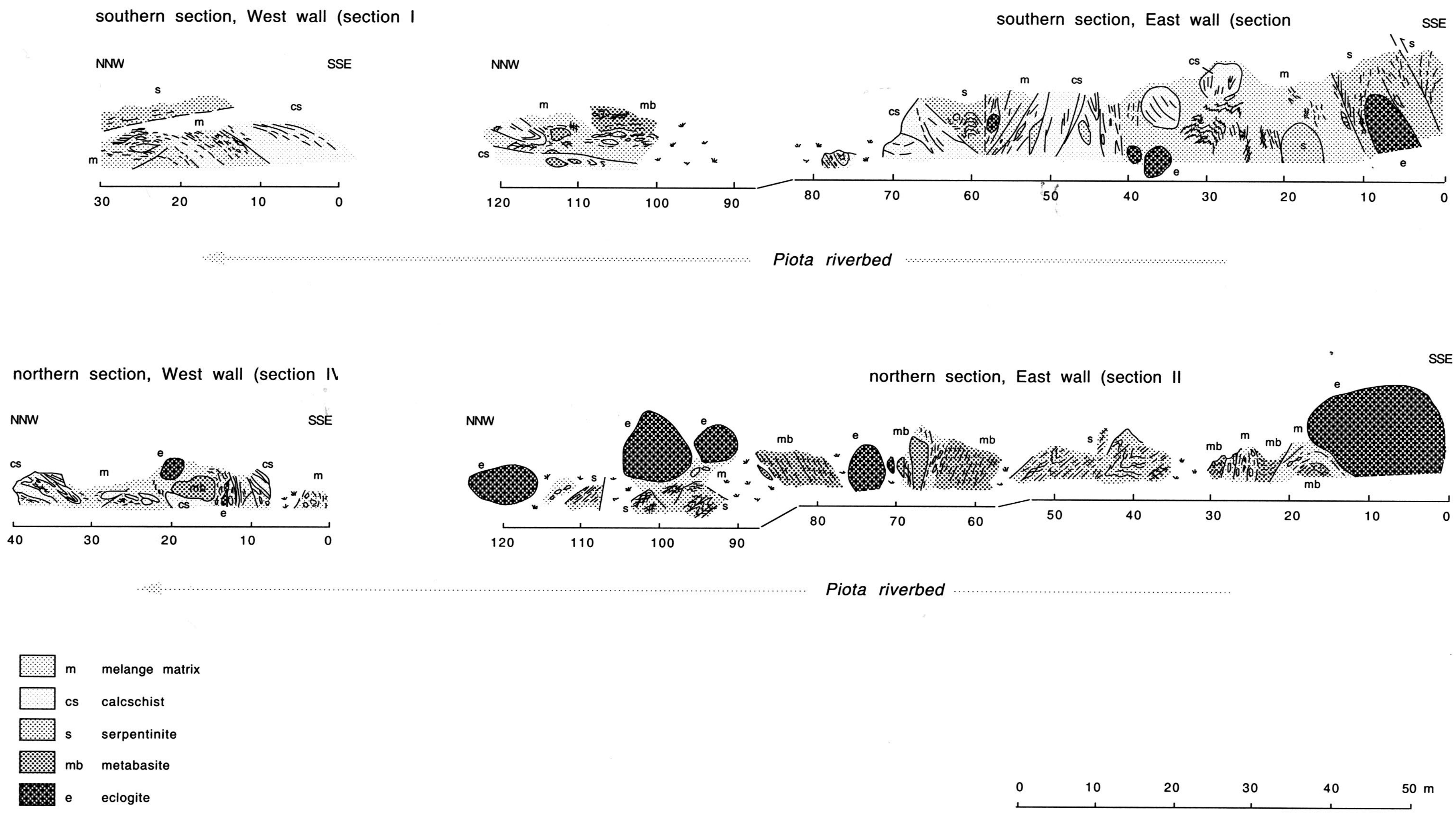

Fig. 6. Detailed sections across the mélange exposures of the Piota riverbed (location of sections shown in Fig. 5).

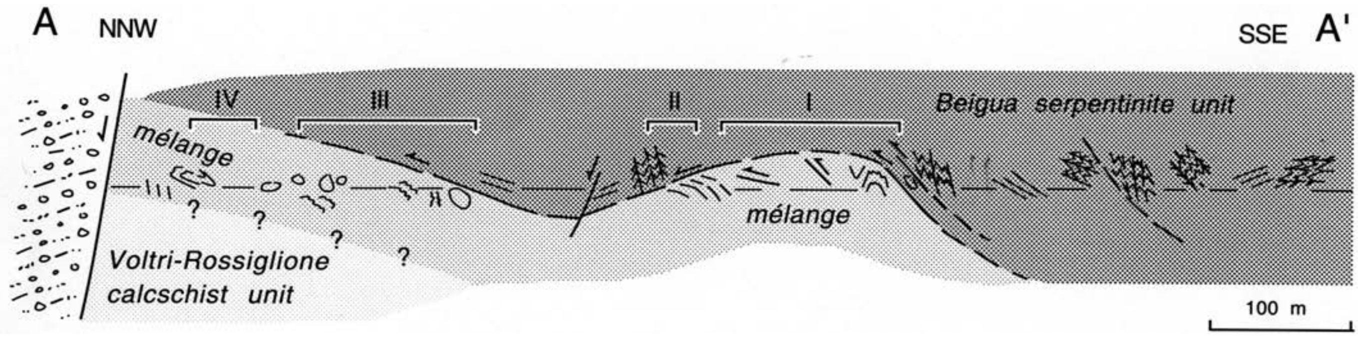

Fig. 7. General section across the basal contact of the Beigua serpentinite unit and the Voltri-Rossiglione calcschist unit, and the mélange lithology in between (location of section shown in Fig. 5; positions of detailed sections I-IV of Fig. 6 indicated).

shear zones and shear bands overprinting the dominant foliation are commonly decorated with fine-grained talc and tremolite plus carbonate, suggesting that the deformation became localized in these small-scale talc-bearing mylonites (Plate 1d).

At several localities in the mélange, the matrix lithology is dominated by strongly deformed calcschist equally showing ubiquitous evidence for intense shearing and stretching. In such locations gradual transitions are observed from discrete calcareous layers intercalated in a serpentinite-derived matrix to a more homogenous calcareous matrix. The relatively competent calcareous bands as well as mafic (possibly metabasaltic) layers show symmetric and asymmetric boudinage adjacent to anastomosing shear zones (Fig. 8c) such that boudin-like phacoid blocks of less deformed matrix material are brought about by the three-dimensional interplay of curved, anastomosing shear zones. These phacoids show elongate shapes parallel to the extension direction defined by oriented amphiboles. Aside the development of these phacoids, some calcareous bands are isoclinally folded with the dominant matrix fabric parallel to the axial plane (Figs. 8c, d).

Younger, non-penetrative upright folds and crenulations locally affect the sheared matrix fabric of anastomosing small-scale shear zones and extensional crenulations (Plate 1e). In places, such folds give rise to interference patterns with older, strongly flattened folds transposed to the plane of the dominant matrix foliation (Figs. 8e and f).

The chaotic nature of the lithology precludes a reliable analysis of the large-scale geometry through systematic study of the small-scale structures. Nevertheless, an overall top-to-the-NW movement sense can be inferred from shear zone geometries and small-scale asymmetric extensional crenulation cleavages, in combination with the orientations of stretching fabrics and long axes of phacoidal blocks (Fig. 9).

Tectonic blocks

Spectacular blocks, up to 25 m across, and smaller slices and phacoids are enclosed in the mélange matrix. The most striking of these are rounded blocks of eclogitic metagabbro (Plate 2a). Where erosion has provided sections across such blocks, they consistently show eclogitic cores, mostly with flaser structures, and dm-scale retrogressed rims (Plate 2b). The mineral assemblages seen in the cores of the blocks are identical to those described above in eclogitic metagabbros in the Beigua serpentinite unit, and allow to identify the M_1-M_4 stages of metamorphism. The rims of the blocks are clearly retrogressive and contain actinolite grown at the expense of barroisite in the presence of albite, chlorite, epidote, sphene, magnetite and pyrite, whilst on the contact with the surrounding matrix the assemblage may contain Mg-chlorite and tremolite. Notably, these retrogressive rims are discordant to the flaser structure in the cores of the blocks. The internal parts of the retrogressive rims may show static assemblages with little evidence of deformation whilst, in the outer few centimeters, the rims often show a distinct foliation passing into the main fabric of the mélange matrix (e.g., Plate 2b). In few localities an associated deflection of the foliation, from these foliated rims towards the matrix, seems consistent with the sense of shear inferred from small-scale shear bands in the surrounding matrix, but the rotational behaviour of the blocks is in many cases difficult to ascertain. The retrogressive assemblages in the rims are the same as those developed during the retrogressive greenschist facies stage (D_4-M_5) identified in the eclogitic metagabbros of the Beigua unit.

Slices and blocks of metabasic rocks (Plate 2c), ranging from a few dm up to 10 m size, commonly show greenschist facies assemblages dominated by actinolite, epidote and albite, frequently with relics of glaucophane partially transformed into barroisite. One block of about 2 m diameter contains relics of a fine-grained eclogitic assemblage of omphacite-garnet-rutile, retrogressively replaced via glaucophane- and barroisite-albite-epidote-bearing assemblages to an albite-epidote-actinolite-chlorite schist in the rim of the block. In terms of the metamorphic evolution seen in the adjacent Beigua and Voltri Rossiglione units, the core of the block again preserves the earlier (M_2-M_4) metamorphic stages whilst the rim is dominated by the M_5 greenschist facies assemblage.

Commonly phacoidal blocks of mostly foliated and occasionally massive serpentinite are ubiquitous. Their sizes range from a few cm to at least 10 m. The rims of the blocks often suggest a gradual transition from the serpentinite to the mélange matrix, in particular in serpentinitic matrix compositions. Many blocks in such cases show progressive replacement, in the rims, to a foliated talc-tremolite-carbonate-bearing assemblage. As outlined above, isolation of the serpentinite blocks was clearly associated with progressive localized shearing in the serpentinite protolith (Fig. 8b, Plate 2d) under greenschist facies conditions.

Blocks, slices and boudinaged layers of calcschist and schistose micaceous marble, ranging from a few dm to about 10 m size, are thoroughly intermixed within the serpentinitic talc-tremolite-carbonate matrix. The juxtaposition of calcschist material with serpentinitic blocks is locally associated with the development of conspicuous metamorphic reaction zones that enhance the compositional heterogeneity of the matrix. An example is shown in Plate 1f,

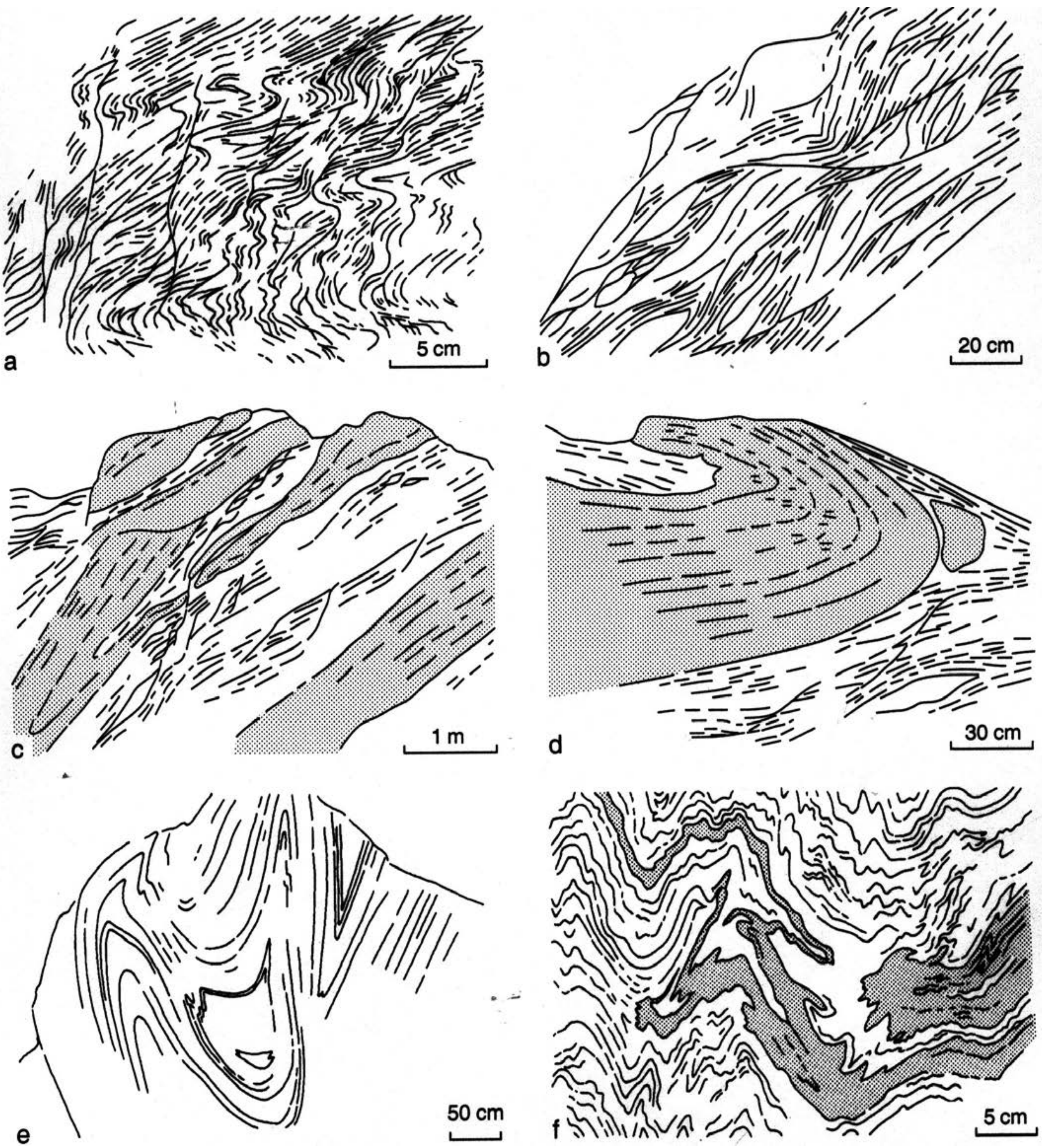

Fig. 8. Characteristic structures of the Piota River mélange. (a) Small-scale folds and crenulations in the hanging-wall serpentinites of the Beigua unit, affecting earlier composite fabric. (b) Network of anastomosing extensional shear zones in mélange matrix. (c) Field sketch of strongly boudinaged calcschist layers preserving isoclinal fold in lower left corner. (d) Layer of calcschist showing tight fold with faint axial-plane fabric apparently continuous with main foliation in the matrix. (e) Interference of early folds in calcschist layer with relatively late (upright) folding also seen in the mélange matrix. (f) Interference in mélange matrix of early crenulations and folds associated with the main mélange foliation, and late (upright) kink-type crenulations.

where a calcschist remnant is surrounded by a 1 dm thick actinolite-chlorite layer, in turn separated from a serpentinitic phacoid by a zone of dominantly talc + tremolite + carbonate. The development of such reaction zones clearly shows that metamorphic reactions were involved in, and contributed to the process of mélange development. The layers, lenses and blocks of calcschist and micaceous marble preserve early structures including folds and a compositional layering unrelated to the structure in the matrix. Some of the calcschists contain relics of the earlier metamorphic stages in the form of rectangular pseudomorphs, possibly after chloritoid, of albite, white mica and numerous tiny inclusions of carbonate, sphene and graphite. The dominant mineral assemblage, however, comprises chlorite, muscovite, carbonate and quartz, with albite, biotite, clinozoisite and tourmaline, consistent with the retrogressive,

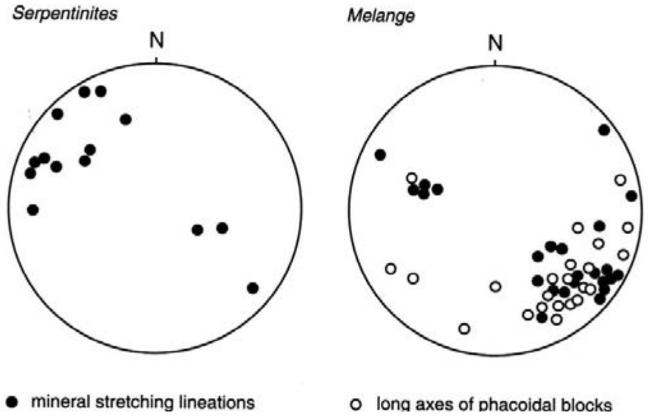

Fig. 9. Orientation data of mineral lineations in hanging-wall serpentinites and mélange matrix, and orientations of long axes of phacoidal blocks (equal area projections, lower hemisphere).

greenschist facies M_5 stage identified in the Voltri-Rossiglione calcschist unit.

DISCUSSION

Like many mélanges documented in the geological literature, the mélange-type lithology of the Piota riverbed invites to question its nature, origin and tectonic significance. In view of the many ambiguities surrounding mélanges we first discuss the main features of the Piota riverbed exposures in terms of mélange classifications. We then proceed to discuss the development of the mélange structures in the context of the structural and metamorphic history of the adjacent main units, and attempt to identify the principal processes and mechanisms involved.

The Piota lithology and mélange classifications

The mélange-type lithology of the Piota riverbed shows striking similarities with ophiolitic mélanges documented elsewhere. Analogous, serpentinite-matrix dominated mélanges have been described, e.g., from the Kamuikotan Zone in Japan (Ishizuka et al., 1983) and the Peleru Mélange in Sulawesi (Parkinson, 1996), both allegedly formed in subduction-accretionary systems, and from the thrust-fault related Puerto Nuevo Mélange, Baja California (Moore, 1986). Aside their gross similarity with these other mélanges, the exposures described here clearly meet the criteria implied by Raymond's (1984) general definition of a mélange regarding their lack of internal continuity of contacts and strata, and the inclusion of fragments and blocks of all sizes in a fragmented matrix. There are two problems, however, in the application Raymond's (1984) definition of a mélange to the mélange-type lithology studied here.

First, all tectonic blocks are either clearly derived from the adjacent wall rocks, or the pertinent lithologies are at least known to occur in the wall rock units. This suggests that the development of the mélange initiated along the thrust contact of the Beigua serpentinite unit over the underlying Voltri-Rossiglione calcschist unit, isolating blocks from the wall rocks (Fig. 10) whilst the serpentinitic hanging wall started to transform to greenschist facies assemblages. The consequence, however, is that none of the tectonic blocks can be regarded as truly exotic, nor are they exotic in the sense that the early eclogite-facies metamorphism recorded in the metagabbroic and metabasaltic blocks is known to have affected the adjacent units. On the other hand, the process of fragmentation and mixing involved rocks that have preserved to a variable extent the various stages of the structural and metamorphic history of the two adjacent, lithologically heterogeneous units, whilst on the basis of entirely descriptive criteria the resulting chaotic lithology should clearly be termed a mélange.

Secondly, the mélange-type lithology of the Piota riverbed does not seem to form a body at the scale commonly seen in mélange terrains. This may in part be due to the degree of exposure in the region. The Voltri-Rossiglione calcschist unit in particular is poorly exposed, but the unit is known to contain a variety of rock types including many, rather small outcrops of serpentinite. This indicates that the Voltri-Rossiglione unit must contain numerous movement zones emplacing these serpentinites amidst clearly crustal rock types, and it may be questioned if the unit as a whole should be regarded as a pervasively deformed mélange. Such an interpretation approaches that by Hsü (1989) who essentially considers the entire ophiolitic suture of the Alps as an ophiolitic mélange. The scale

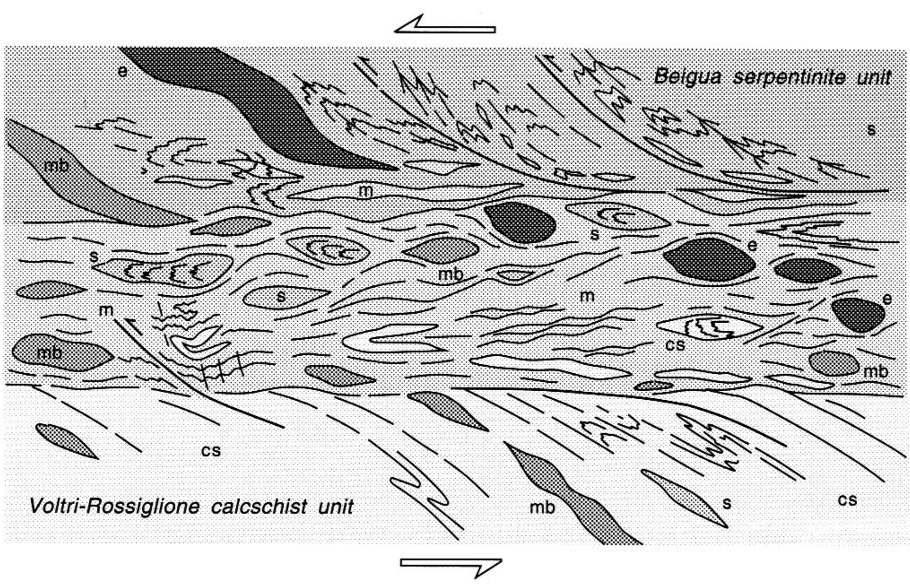

Fig. 10. Cartoon illustrating fragmentation and mixing of wall rock lithologies during development of the Piota River mélange. Legend and abbreviations as in Fig. 6.

of observation is crucial here, however. From structural mapping (Hoogerduijn Stating, 1991) it is known that the units of the Voltri Group are characterized by mappable and coherent, mostly ductile thrust structures, and the same applies to the Voltri Group as a whole (Chiesa et al., 1975). This implies that, at those scales, there is no need to describe these units, or the entire ophiolitic Voltri Group, as mélanges. On the other hand, and irrespective of its limited volume, the mélange-type lithology along the contact between the Beigua serpentinites and the Voltri-Rossiglione calcschists clearly shows the characteristics of many other ophiolitic mélanges. As discussed further below, the serpentinitic Piota mélange must have developed at a late stage of the tectono-metamorphic history of the Voltri Group. As matters stand, we feel that the Piota mélange is best interpreted as a syn-metamorphic, thrust-related tectonic mélange, spatially and compositionally related to the overriding Beigua serpentinites.

Piota mélange and tectono-metamorphic history of the Voltri Group

The structural and metamorphic data documented above in the mélange lithology and in the adjacent Beigua and Voltri-Rossiglione units clearly show that the mélange structures developed relatively late in the thermo-tectonic history.

Pre-mélange structures are seen in the hanging-wall serpentinites containing an early antigorite schistosity and shear bands decorated with fine-grained olivine-diopside-titanian clinohumite bearing assemblages. These early structures and mineral assemblages are also preserved in serpentinite blocks in the mélange. The blocks of eclogitic metagabbro contain early flaser-type structures as well as occasional mylonitic fabrics, and both developed at high-pressure conditions. Blocks and fragments derived from the Voltri-Rossiglione calcschist have preserved relics of early folds and a compositional banding. All of these features predate the development of the mélange structures.

The development of the mélange matrix foliation involved intense crenulation of earlier composite fabrics in the overriding serpentinites. In the lowermost part of the Beigua serpentinite unit the development of these crenulations, identified as a regional D_4 generation of deformational structures (Hoogerduijn Strating, 1991), is associated with the transformation from antigorite-dominated to talc-tremolite-chlorite-carbonate-dominated assemblages. We refrain from a thorough petrogenetic investigation of plausible mineral reactions that may have produced these assemblages, as such a petrological study lies beyond the scope of this paper. However, the transformations seen in the margins of eclogitic metagabbro blocks, often with a (D_4) foliated rim made up of (M_5) greenschist facies assemblages, and of metabasic blocks and lenses showing pervasive greenschist facies recrystallization clearly indicate that the talc-tremolite-chlorite-carbonate-dominated assemblages of the foliated matrix formed during the regionally identified phase of greenschist facies retrogression (M_5).

It follows that the Piota mélange was essentially formed during the D_4-M_5 stage of deformation and regional metamorphism. All of the mélange structures were further modified by relatively late structures, including late upright folds and crenulations of the mélange foliation, open folds of some phacoids of serpentinite and calcschist, and late brittle faults and thrusts.

Deformation mechanisms: fluid activity and transformation enhanced ductility

The structures and microstructures described above clearly show that the deformation associated with ductile thrusting of the Beigua serpentinite unit onto the Voltri-Rossiglione footwall was largely localized in the mélange lithology. This localization suggests that during ductile shearing the mélange persisted as a weak zone. Fragmentation and isolation of tectonic blocks in the mélange matrix was accomodated by the development of shear zones at all scales down to the microscale. In the mélange lithology proper, layers and bodies of calcschist as well as metabasaltic rocks, serpentinite phacoids and in part the eclogite lenses were intensely deformed by sets of anastomosing small-scale shear zones. This often led to disruption and complete isolation of lense-shaped blocks in the greenschist facies matrix, as well as to occasional folding with the matrix schistosity parallel to the axial planes. Concurrently, pervasive deformation in the mélange matrix was accommodated by the development of small-scale shears that invariably show either oriented or very fine-grained, hence probably syntectonic talc-tremolite-carbonate bearing assemblages. This raises the possibility that the development of these assemblages and, presumably, the presence of associated fluids helped to weaken the deforming lithology and to facilitate the imposed deformation.

At least three lines of evidence suggest the presence of hydrous fluids during the development of the Piota mélange. First, the ubiquitous growth of tremolite- and carbonate-bearing assemblages associated with the progressive development of the mélange matrix from an essentially Ca-poor (harzburgite-derived) serpentinite wall rock requires Ca metasomatism, which calls on extensive fluid activity. We speculate that the developing ductile thrust zone at the base of the Beigua serpentinite acted as a pathway for hydrous fluids containing Ca (and possibly also SiO_2) largely derived from the underlying Voltri-Rossiglione calcschist unit. Previous studies on retrograde fluid inclusions present in the Beigua eclogites (Vallis and Scambelluri, 1996) and in the Voltri-Rossiglione calcschists (Crispini and Frezzotti, 1998) indicate the presence of aqueous fluids with variable amounts of dissolved CO_2 component, with CO_2 more abundant in inclusions within the carbonaceous sediments. Such fluid compositions fit well with the one suggested here to produce the talc-, carbonate- and tremolite-bearing assemblages in the mélange matrix. Secondly, the development, in the crenulated serpentinites close to and in the mélange, of microscale veinlets and saddle-reefs with tremolite-carbonate-talc bearing assemblages seems impossible without the presence of a grain boundary fluid phase. Thirdly, although the onset of retrogression in the eclogitic blocks predates the development of the mélange lithology, the pervasive greenschist facies alteration seen in the rims of the blocks is again consistent with extensive fluid infiltration and hydration.

Both the presence of hydrous fluids and the development of the mélange matrix assemblages may have considerably weakened the material in the thrust zone. First, a high fluid activity should promote deformation by low-stress diffusive mass transfer processes. Secondly, the microstructures consistently indicate localization of the deformation in microscale zones dominated by the talc-tremolite-chlorite-carbonate assemblages suggesting that these assemblages were mechanically weak. This in turn must have enhanced the ductility contrast with the less transformed, mechanically stronger serpentinitic remnants of the developing phacoidal blocks. A weakened matrix would thus further promote fragmentation and boudinage of the stronger materials now preserved in the tectonic blocks. The lack of quantitative mechanical data preclude to unequivocally prove our inference that the talc-tremolite-chlorite-carbonate assemblages in the small-scale and microscale mylonitic shears were mechanically weak, hence that the associated transformations effectively weakened the developing matrix material. The consistent syntectonic development of these assemblages, however, in the most strongly deformed, sheared domains of the mélange matrix strongly suggests an enhanced ductility of these domains.

CONCLUSIONS

(1) The mélange-type lithology exposed in the northern Voltri Massif shows all characteristics of a mélange of tectonic origin. It is spatially associated with a major zone of overthrusting, the transition from the hanging-wall serpentinites to the mélange proper is essentially gradual, the matrix is pervasively affected by small-scale shear zones and extensional crenulations, and all enclosed blocks are derived from the hanging and footwall units.

(2) The structures associated with the development of the mélange matrix and fragmentation of the various lithologies were formed during a regionally identified, late greenschist facies retrogression of earlier HP metamorphic assemblages. The mélange structures are modified by late open folds and associated crenulations, and late brittle faults.

(3) The development of the mélange matrix was associated with syntectonic growth of talc-chlorite-tremolite-carbonate-dominated assemblages at the expense of Ca-poor, harzburgite-derived serpentinites, which clearly calls for significant Ca-metasomatism presumably derived from the calcareous rocks of the footwall. This Ca-metasomatism, pervasive at the scale of the mélange exposures, suggests extensive fluid activity in the developing thrust zone. The ubiquitous talc- and tremolite-bearing mylonites and microscale shears in the mélange matrix suggest localization of the deformation in mechanically soft domains of extensive serpentinite breakdown, and indicate that reaction-enhanced ductility of the matrix contributed to the progressive fragmentation and mixing in the developing mélange lithology.

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