THE ROLE OF EARLY MIOCENE THRUST TECTONICS IN THE STRUCTURAL ARRANGEMENT OF THE VOLTRI GROUP (LIGURIAN ALPS, ITALY): EVIDENCE FROM THE BANDITA AREA

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Keywords: *thrust fault, Erro-Tobbio Unit, Early Miocene tectonic phase, Voltri Group. Ligurian Alps, Italy.*

ABSTRACT

Geological mapping and structural analysis of the Bandita area in the northwestern sector of the Voltri Group (Ligurian Alps) revealed the occurrence of ductile shear zones and brittle thrust faults involving metamorphic rocks. This paper focuses on the brittle thrust faults and their role in the structural arrangement of a large metalherzolite body belonging to the Erro-Tobbio Unit.

Layers of fault rocks, mostly banded cataclasites and crush breccia, are associated with the brittle thrust faults and show a consistent top to the east-northeast sense of shear. The features of these brittle thrusts match those of structures related to the Early Miocene post-collisional tectonic phase known as the D_4 phase in the Voltri Group and "fase ligure III" (3^{rd} Ligurian phase).

In this area a major D_4-related thrust fault is the basal contact between the metalherzolites and the underlying serpentinites. Similar structural relationships of the metalherzolites to other Voltri Group rock types also occur in adjoining areas. However, at the regional scale, structural and metamorphic evidence supports an early coupling (i.e. pre-D_4) of the lherzolite with the serpentinite, metabasite and metasediment, indicating that the D_4-related thrust surfaces rework a pre-existing structural arrangement. We suggest that the Erro-Tobbio metalherzolites are frequently involved in the D_4 thrusting because the pre-existing contacts with the surrounding rock types, due to the competence contrast, acted as preferential sites for the nucleation of the D_4 shear surfaces.

INTRODUCTION

The main features of the structural evolution of the Voltri Group are described in the papers by D'Antonio et al. (1984), Amendolia and Capponi (1985), Capponi (1987; 1991), Hoogerduijn Strating (1991), Capponi et al., (1994a), Crispini (1996), Capponi and Crispini (1997), Crispini and Frezzotti (1998) and Crispini and Capponi (1997, in press). These papers describe the occurrence of multiple sets of superposed structures and point to a multiphase deformation history, with slight differences between the western and the eastern sector of the Voltri Group. In the western sector, where the study area is located, early recognizable structures consist of tight to isoclinal folds, developed in greenschist-facies metamorphic conditions and representing F_1/F_2 folds associated with the D_1/D_2 deformation phases. F_3 folds are parallel folds, gentle to open in shape, and locally associated with a rough spaced cleavage, but rarely with a schistosity. These deformations are linked to the exhumation of the subducted slabs during the Alpine orogenesis.

Late structures include thrust faults and large-wavelength folds, related to the D_4 deformation phase described in literature (Crispini, 1996 and Crispini and Capponi, in press). D_4 structures are locally accompanied by zeolite-facies recrystallization. The D_4 related structures involve not only the metamorphic rocks of the Voltri Group, but also the sedimentary rocks of the Tertiary Piedmontese Basin, as observed by many researchers at the western and northwestern borders of the Voltri Group. The major occurrences of such structures are in the areas of Santa Giustina, Rossiglione, and Bandita (Fig. 1). In these areas, metamorphic rocks are thrust onto Oligocene sedimentary rocks, which are locally folded and tilted to the vertical. The involvement of Oligocene sedimentary rocks in these structures points to D_4 as a post-Oligocene tectonic phase. From this point of view the Val Gorrini thrust, near Bandita (D'Atri et al., 1997; Capponi, Crispini, Piazza and Amandola, unpublished data), yields the best time constraint for the D_4 structures: the involvement of the Rocchetta Formation (Early to Late Oligocene) and the occurrence of the undeformed Burdigalian Visone Formation, onlapping the Val Gorrini thrust fault limits the timing of this tectonic event to the Early Miocene. On the regional scale, this event is correlated (D'Atri et al., 1997; Piana et al., 1997) with the phase of tectonic uplift linked to the Monferrato culmination, described as "fase ligure III" (3^{rd} Ligurian phase) by Mutti et al. (1995). At the sites where D_4 thrusts provide anomalous superposition of the metamorphic rocks of the Voltri Group onto the sedimentary rocks of the Tertiary Piedmontese Basin, they are quite evident and well constrained in age. By contrast, it is more problematic to correlate brittle thrust surfaces that involve only the metamorphic rocks to a definite deformation event.

The aim of this paper is twofold: to highlight the occurrence of the D_4-related thrust faults in the metamorphic rocks of the Voltri Group and to discuss their role in the structural arrangement of the metaperidotite of the Erro-Tobbio Unit, which is one of the units of the Voltri Group. To achieve this goal, we examined an area near Bandita (northwestern part of the Voltri Group), that is representative of the structural setting of the western sector of the Voltri Group.

GEOLOGICAL FRAMEWORK

The Voltri Group consists of a large meta-ophiolitic complex with metasediments, at the southeastern boundary of the Western Alps in Central Liguria (Fig. 1). Its main lithological associations consist of metamorphic lherzolite, serpentinite with metagabbro and eclogite bodies, and metasediment with metabasite. They derive from the Juras-

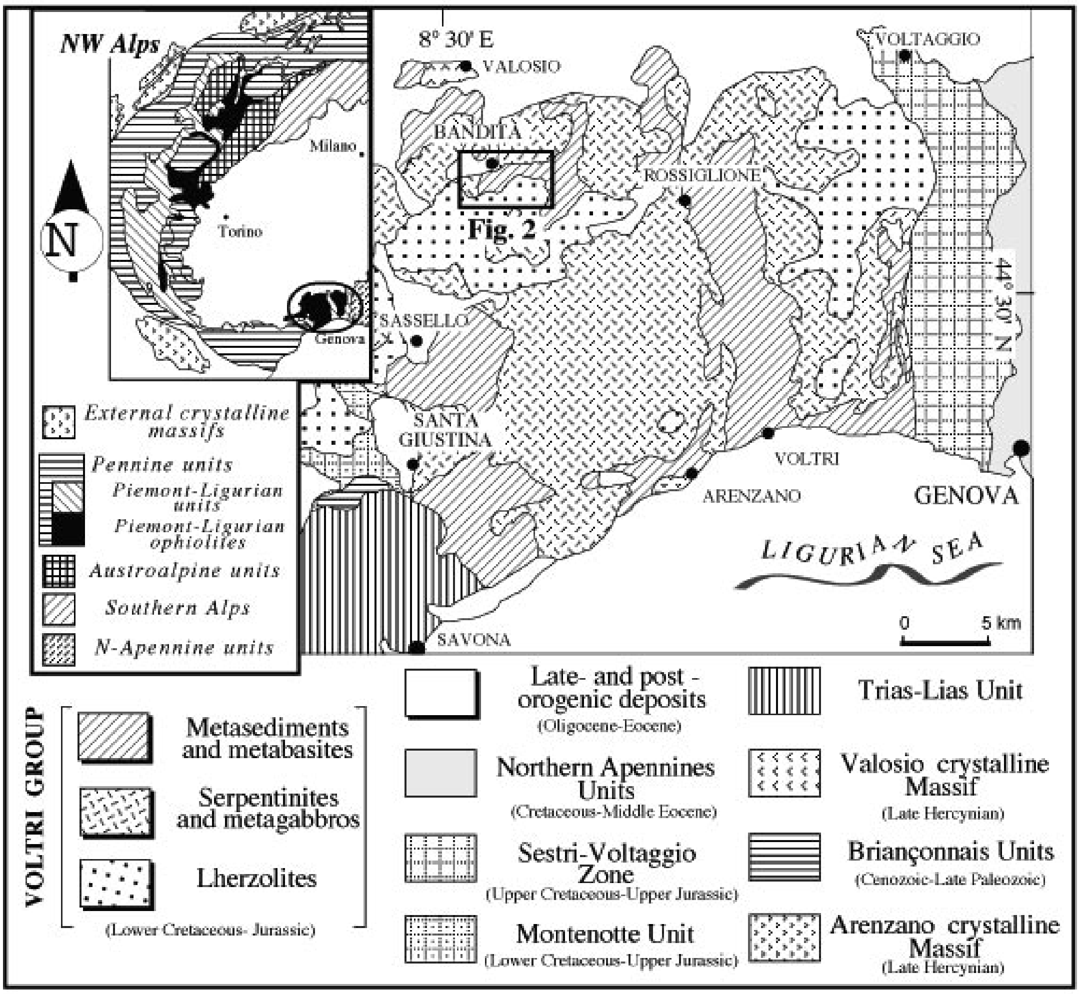

Fig. 1 - Structural sketch map of the Voltri Group and surrounding units.

sic-Cretaceous ophiolite sequence of the Piedmont-Ligurian ocean basin together with portions of subcontinental mantle exposed during the pre-Jurassic rifting (Scambelluri et al. 1995; Borsi et al., 1996). All these rocks were involved in the Cretaceous (Alpine) subduction events and underwent, at different stages, metamorphic re-equilibration under High Pressure-Low Temperature conditions (HP-LT), followed by decompression under greenschist facies conditions (Cortesogno et al., 1977a; Messiga et al., 1983; Piccardo et al., 1988, Messiga and Scambelluri, 1991). Presently the HP-LT assemblages are rarely preserved and the greenschist facies assemblages prevail on the regional scale. The Voltri Group comprises different tectono-metamorphic units (Chiesa et al., 1975); one of these is the Erro-Tobbio unit derived from portions of subcontinental mantle. The heterogeneous distribution of strain and metamorphism preserves huge bodies of the Erro-Tobbio peridotites from the Alpine overprinting, and in most cases magmatic features and mineral associations are still recognizable. The Erro-Tobbio metaperidotites derive mainly from an original lherzolite with minor gabbro and basalt intrusions, and minor harzburgite, pyroxenite and dunite bodies. Metaperidotites are often transformed into serpentinites; in these cases the distinction with the serpentinites of the other units of the Voltri Group may be problematic.

Up to the 1990's the Erro-Tobbio lherzolite was believed to be free from the Alpine metamorphic overprint and consequently many researchers hypothesized that the Erro-Tobbio unit was emplaced on the other units of the Voltri Group (Chiesa et al., 1975) by post-collisional thrusting. The recent discovery of eclogite parageneses in Erro-Tobbio rocks (Piccardo et al., 1988; Capponi and Crispini, 1990; Scambelluri et al., 1991) indicates their involvement in the Alpine subduction events, opening new scenarios for the Alpine tectonic evolution of this unit. However, an exhaustive analysis of the Erro-Tobbio metalherzolite structural arrangement is still lacking.

The Tertiary Piedmontese Basin is a late to post-orogenic basin spanning in age from Late Eocene (?) - Oligocene to Miocene; it can be defined as an epi-Mesoalpine basin (Mutti et al., 1995), developed on the Alpine Units already involved in the main Alpine tectonic phases.

FIELD DATA

The geological situation of the study area is depicted in the geological map of Fig. 2, simplified from an original 1:5000 mapping. Serpentinite, metabasite, metagabbro, and metasedimentary rocks are the lithologies of the Voltri Group that crop out in the central part of the map; these rocks represent the metamorphic substratum of the conglomerate that crops out in the northern sector; fault rocks occur at many places. A large body of metalherzolite occurs in the southern part of the map and is superposed on the serpentinite along a thrust surface (Fig. 3), which is exposed on

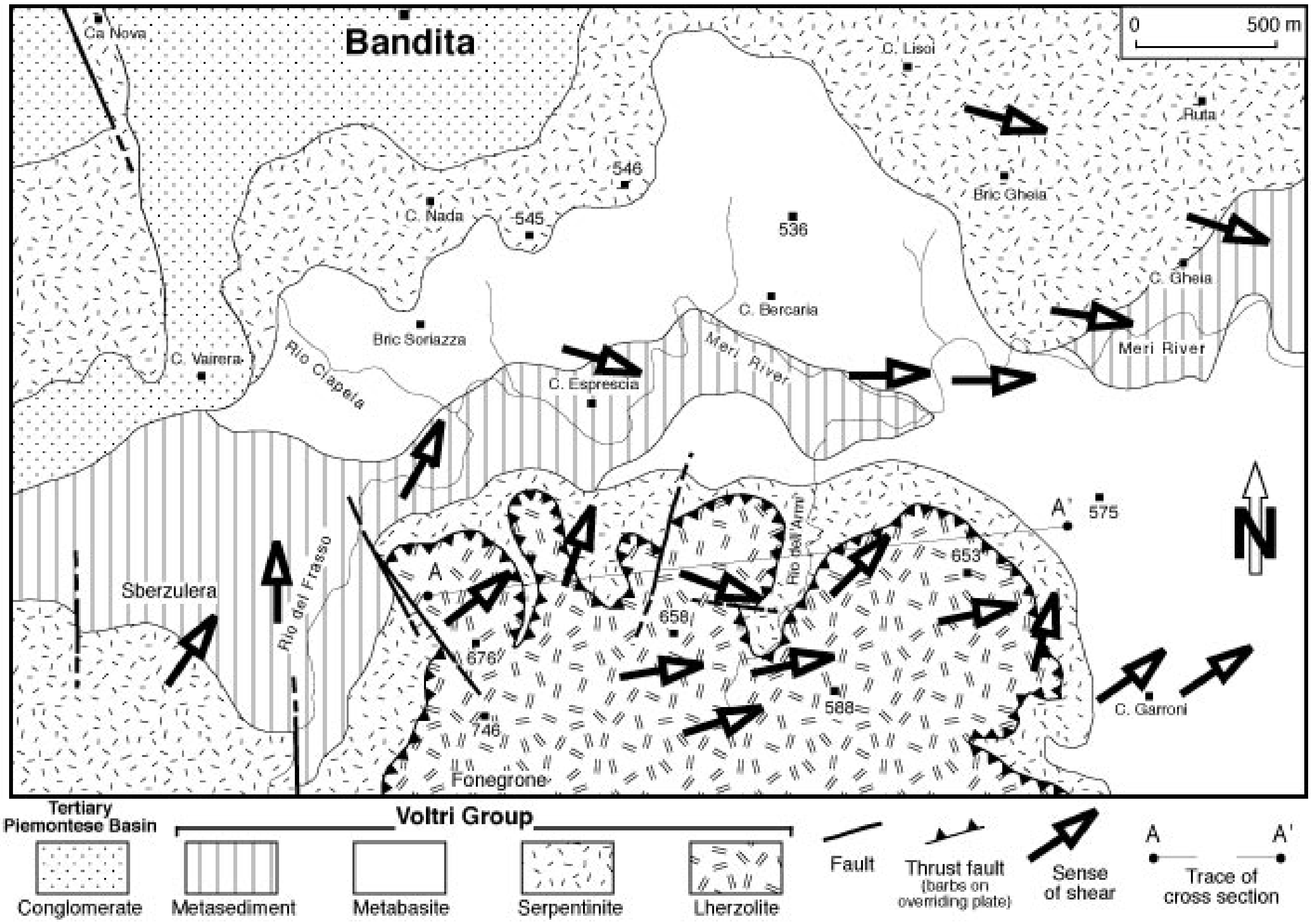

Fig. 2 - Geological map of the study area. Solid black arrows indicate sense of shear of the brittle thrust faults in selected sites.

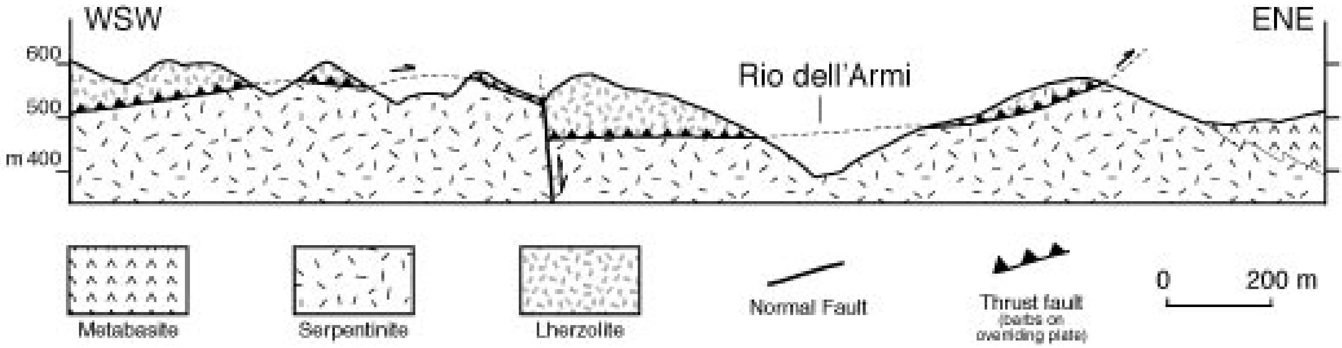

Fig. 3 - Geological cross section which outlines the brittle thrust at the base of the metalherzolites. Trace shown in Fig. 2.

the southern side of the valley of the Meri River.

The structural analysis of the Bandita area reveals a multiphase deformation history with multiple sets of ductile, brittle-ductile and brittle structures (Table 1). The features of early ductile structures match those broadly described in literature for the D_1/D_2 folding. The main foliation of the metamorphic rocks is a composite fabric that contains the lithological surface and the axial plane foliation of the D_1/D_2 folds. Lithological contacts occur along this foliation, which at most sites has a low to medium inclination (Fig. 4). Ductile shear zones and brittle(-ductile) thrusts are also related to D_1/D_2 folding and are deformed by the D_4 folds, which affect both the metamorphic rocks of the Voltri Group and the rocks of the Tertiary Piedmontese Basin and causes verticalization of the sedimentary in the northwestern part of the map, with a top to east vergence. The geometric arrangement of the horses, related to the attitude of the thrust surfaces, is a ubiquitous shear criterion, available almost on each outcrop. No evident structures related to the D_3 phase have been observed, although they are described in other sectors of the Voltri Group.

In this paper we focus on the brittle thrust surfaces (hereafter BTS), which occur in the metamorphic rocks. The BTS post-date the D_1/D_2 folding and also comprise the thrust contact at the base of the lherzolite body. In the field, the BTS were distinguished from D_1/D_2-related brittle-ductile thrust surfaces on the basis of structural style, P-T conditions of development, constrained by the associated fault

Table 1 - Relationships among structures, metamorphism, age and tectonic events in the Voltri Group and in the Bandita area.

Deformation phases and related folds in the Voltri Group	**Type of structures in the Bandita area**	**Tectonic event related to the Alpine orogenesis**	**Inferred Age**	**Metamorphism**
pre-D_1 pre-F_1	Mineralogical and structural relicts	Subduction	Cretaceous	Eclogite to Blueschist facies
D_1/D_2 F_1/F_2	Pervasive schistosity Isoclinal folds Ductile and brittle-ductile thrust faults	Exhumation - Uplift of the metamorphic units and nappes emplacement	Paleocene-Eocene	Na-amphibole Greenschist to Greenschist s.s. facies
D_3 F_3	*No structures*	Uplift of the metamorphic units and nappes emplacement	Eocene-Early Oligocene	Low greenschist facies
D_4 F_4	Open folds Brittle thrust faults	Post-collisional NE-vergent backthrusting “Fase ligure III”	Early Miocene	Zeolite facies

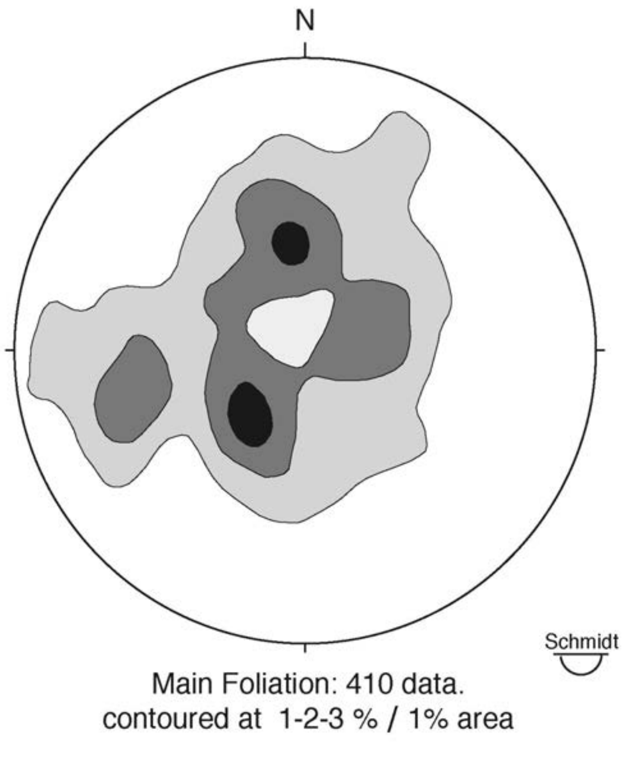

Fig. 4 - Stereographic projection of the poles to the main foliation (i.e., composite fabric that contains the nearly parallel lithological surface and axial plane foliation of the D^1/D^2 folds) in the metamorphic rocks of the Voltri Group. Schmidt net, lower hemisphere. The scattering of the orientation is due to the superposition of the D^4-related structures.

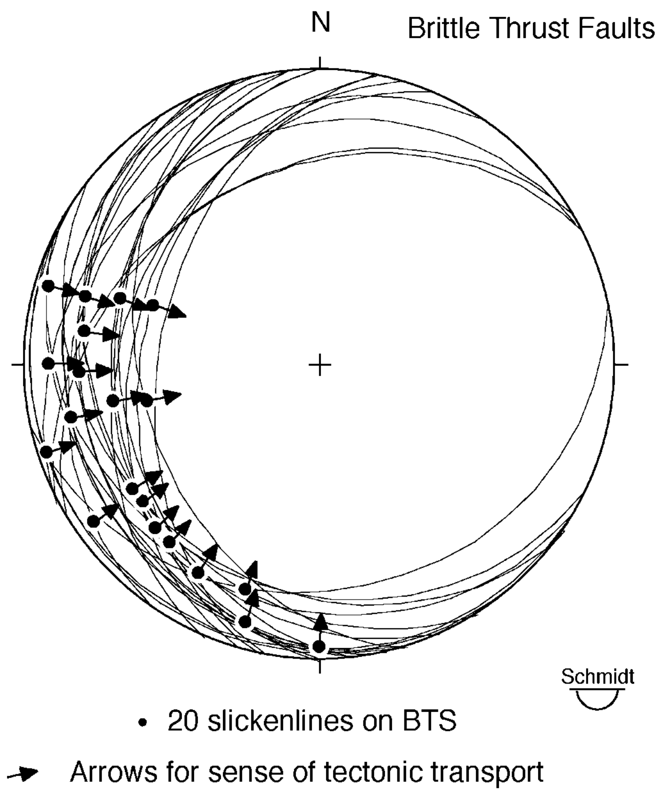

Fig. 5 - Stereographic projection (Schmidt net, lower hemisphere) of the brittle thrust surfaces with the related slickenlines (black point). Arrow on each point indicates sense of tectonic transport. The bimodal distribution of the directions is discussed in text.

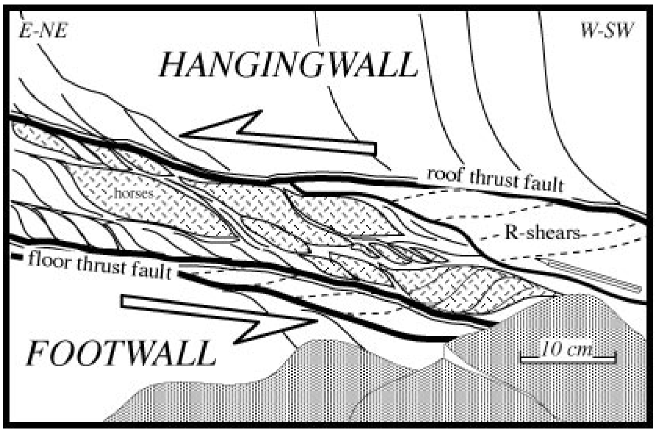

Fig. 6 - D_4-related brittle thrust fault in serpentinites of the Voltri Group. The section of the outcrop is nearly parallel to the direction of the slickenlines. Redrawn from a photograph.

rocks, and rarely on the intersection relationships. On the average the BTS gently dip to the west-southwest, with low to medium inclination (Fig. 5). A systematic study of the kinematic indicators on the outcrop and at the microscale gives us constraints on the kinematics of the BTS. Figs. 1 and 6 show data collected at 20 selected sites, where the sense of shear was unequivocal.

The fault rocks associated with the BTS have a thickness from 1 m up to 5 m; the thickest layers are in correspondence of the BTS at the base of the metalherzolite body, mostly on the hangingwall side. They are mostly crush-breccia, with minor crush microbreccia, protocataclasite and cataclasite, rarely pseudotachylyte (nomenclature of fault rocks after Sibson, 1977). Close to the roof- and the floor-faults banded cataclasite occur in cm-thick layers.

In most cases the rocks along the BTS are arranged in sigmoidal bodies, the geometrical organization of which matches a mesoscopic duplex structure; hence the sigmoidal bodies can be referred to as horses (Fig. 6). The small-scale reverse faults delimiting the horses dip in an opposite direction with respect to the tectonic transport and the duplex structure is a hinterland dipping duplex. In the lherzolite, the rims of the horses are transformed into serpentinite and/or chlorite-rich layers; in the metabasite the horses are surrounded either by chlorite schists or by a fine-grained matrix composed of metabasite microclasts and carbonates. The geometric arrangement of the horses, related to the attitude of the thrust surfaces, is a ubiquitous shear criterium, available almost on each outcrop. The slickenlines (movement striations and shear fibre lineations) on the main thrust surface and on the reverse faults delimiting the horses, supplied the average direction of tectonic transport.

In some outcrops the thrust faults cause the deflection of pre-existing schistosities of foliated rocks, such as metasediments and serpentinite-schists; however, the usual absence of related striations reduces the use of these shear criteria. R-Riedel shears are common on the outcrops where the thrust faults cut non-foliated rocks, such as metabasites or massive serpentinite and metalherzolite.

Striations such as grooves and overlapping slickenfibres made up of carbonates, serpentine group minerals, magnetite and chlorite occur on the thrust fault planes; the interpretation of these structures is sometimes ambiguous because of the occurrence of lineations belonging to different stages of tectonic movement.

The fault rocks near the thrust planes have also been analyzed at the microscale, particularly where the outcrop scale observations furnished ambiguous data. The analysis was performed on oriented thin sections; we could work on shear band cleavages, microfaulting or asymmetric boudinage of opaque minerals, and asymmetric porphyroclasts consisting of fragments of the footwall and, less frequently, of the hangingwall rocks. The direction of tectonic transport of the BTS spans from east to northeast (Figs. 1 and 6) and the lineations show an evident bimodal distribution.

The overall style of structures and the occurrence of crush breccia as prevalent fault rock testify to a dominant brittle deformation attained at relatively shallow crustal levels.

The reactivation of the original thrust surfaces as low-angle normal faults has been observed in a few sites, where the arrangement of the horses and the overlapping fibres give opposite sense of shear: the geometry and the arrangement of the horses point to thrusting with a top to northeast sense of shear and by contrast overlapping fibre systems point to a top to southwest sense of shear.

DISCUSSION

D_4-related thrusts in the metamorphic rocks of the Voltri Group

The direction of tectonic transport of the BTS spans from east to northeast (Figs. 1 and 6). Lineations show an evident bimodal distribution; this can be explained with a progressive non-coaxial deformation characterized by a gradual change in the movement trajectories; the observation of curved slickenfibres in three sites is in agreement with this hypothesis. A strike slip component of movement has also to be taken into account: some NE-SW oriented lineations (Fig. 6) do not fit the down-dip direction of the related thrust fault.

The structural style, direction and sense of tectonic transport of the BTS match those of the D_4-related thrusts described in adjoining areas.

The best-known D_4 structures that involve Oligocene sedimentary formations are at Santa Giustina, Rossiglione and in the Val Gorrini area, close to Bandita. In these areas, metamorphic rocks are thrust onto the Oligocene sedimentary beds, which are locally folded and tilted upright. At Santa Giustina, Pasquarè (1968) and Capponi and Giammarino (1982) described the superposition of blueschist facies metaophiolite (Montenotte Unit) on Late Oligocene sandstone and siltstone. At this site thrust-related folds suggest a top to the east-northeast sense of shear. The same direction of tectonic transport has been detected for the Rossiglione thrust (in the Gargassino Valley), where Forcella (1976) and Capponi et al. (in press) described the superposition of a lherzolite slab on the conglomerate of the Molare Formation (Early Oligocene). Other data from equivalent structures are summarized in Hoogerduijn Strating et al. (1991). The structure closest to the Bandita area is the Val Gorrini thrust (D'Atri et al., 1997; Capponi, Crispini, Piazza and Amandola, unpublished data), which also provides a top to the east sense of shear. The Bandita area, subject of this work, is directly to the south of the Val Gorrini (about 1 km), and the tilted sedimentary beds that occur in the northwestern part of the map in Fig. 2 belong to the km-scale structure of the Val Gorrini.

The above observations together with the conformity of the structural style, direction and sense of tectonic transport suggest that the BTS detected in the metamorphic rocks of Bandita, including the thrust contact at the base of the lherzolite body, are related to the D_4 phase. This deformation is linked to an Early Miocene tectonic phase (“fase Ligure III” in Mutti et al., 1995) and is responsible for the Val Gorrini thrust and the other anomalous superpositions of metamorphic rocks over the sedimentary rocks of the Tertiary Piedmontese Basin.

In the Ligurian Alps and Northern Apennines this tectonic phase is revealed by a thick-skinned thrust tectonics which is coeval to the rotation of the Corsica-Sardinia block (which ends at 19 Ma, Montigny et al., 1981); this tectonics leads to a general NE-vergent backthrusting, expressed by the emplacement of the Internal Ligurian Units onto the Sub-Ligurian and Tuscan domains and to the early N-vergent thrusts into the future Po Plain area.

The fault rocks associated with the BTS provide qualitative information on the structural level of deformation. The occurrence of crush breccia and cataclasites (Sibson, 1977) points to a deformation attained at shallow crustal levels. On the basis of the crystallization of zeolites along equivalent thrust surfaces at the base of the Erro-Tobbio lherzolite, Cortesogno et al. (1977b) suggested a temperature lower than 250 °C and very low pressure. In the study area, the presence in the breccia of fragmented pre-existing greenschist facies rocks, and the concurrent recrystallization of chlorite and carbonates on the slickensides provide evidence in agreement with the P-T estimate by Cortesogno et al. (1977b).

Role of brittle thrust tectonics in the structural arrangement of the Erro-Tobbio metalherzolite

In the study area it is apparent that the D_4-related BTS occur in all rock types; the thrust surface at the base of the lherzolite body is the most prominent and evident structure of this set. This is further evidence of what occurs elsewhere: similar situations are detected at many other sites of the Voltri Group, where the lherzolite rests tectonically on other lithologies along thrust faults, with a top to east-northeast sense of shear (e.g. Capponi et al., 1986). This highlights the role of the D_4-related thrusts in the control of the structural arrangement of the Erro-Tobbio lherzolite.

By contrast, the lherzolites also show different structural relationships with respect to the surrounding rocks: frequently, lherzolite bodies and pods are in contact with other rock types (in most cases serpentinite) along the regional foliation. Arrangements like this have been studied in the area of Monte Riondo (Capponi and Crispini, 1990), in the surroundings of Voltri (Capponi et al., 1994b), along the Gorzente River (Scambelluri et al., 1995), and in the area of Piani di Praglia (Capponi, Crispini, Federico and Garofano, unpublished data). These features suggest that the lherzolites were already coupled with the other rocks of the Voltri Group at the time of the development of the greenschist facies regional foliation. Hence the D_4 thrusts at the base of the lherzolite, observed in the study area and in many other sites, appear to have reworked a pristine structural arrangement. The strong contrast in rheological behaviour between lherzolite and the other rock types of the Voltri Group provided preferential sites for the nucleation of the D_4 shear surfaces; this explains the reason why the pre-existing contacts between lherzolite and the surrounding rocks were tectonically re-activated so extensively.

CONCLUSIONS

In the study area, east-northeast vergent thrust faults and folds are related to an Early Miocene post-collisional tectonic phase. Though the D_4-related thrusts are more evident where they provide anomalous superposition (i.e., metamorphic rocks on sedimentary rocks), such structures occur also in the metamorphic basement of the Voltri Group.

The Erro-Tobbio lherzolites are frequently involved in the D_4 thrusting as the high competence contrast with the surrounding lithologies causes the reactivation of the pre-existing contacts, which are preferential sites for the nucleation of the D_4 shear surfaces.

The study area is one of the sites of the Voltri Group where the emplacement of the lherzolite on the other lithologies is controlled by a major D_4 thrust fault. However, on the scale of the whole massif, structural and metamorphic evidence supports an early coupling (i.e. pre-D_4) of the Erro-Tobbio lherzolite with the other lithologies of the Voltri Group indicating that the D_4 thrust faults rework a pristine structural setting.

Acknowledgements

This manuscript was improved by constructive and thorough review by Y. Dilek. This work benefited from Ateneo funds from the University of Genova, Italy.

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Received, March 14, 1999
Accepted, May 25, 1999