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The thrust zone of the Ligurian Penninic basal contact (Monte Fronté, Ligurian Alps, Italy)

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ABSTRACT

This paper presents a geological map and interpretative cross-sections, which illustrate the structure of a major fault zone of the Alps, that is, the Ligurian segment of the Penninic Basal Contact (PBC), which led to the emplacement of the orogenic wedge onto the European crust. Chaotic deposits, whose origin is debated, characterize the footwall of this complex thrust zone. The lower part of the sequence containing chaotic deposits consists of low deformed paraconglomerates and exotic megablocks embedded with turbidites. Conversely, the highly deformed upper part of the sequence englobes fragments of substratum-derived succession and is bounded by thrust planes. The nature of these chaotic deposits suggests an origin by gravitational processes related to the unstable front of the advancing wedge associated with offscraping of tectonic slices during the thrusting of allochthonous nappes along the PBC thrust zone.

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Thrust zone; chaotic deposits; tectonic mélange; Alps; orogenic wedge; fault rocks

1. Introduction

Nappe stacking over a continental margin overlain by migrating foredeep basins triggers sedimentary and tectonic processes that produce chaotic rocks units, known as tectonic and/or sedimentary mélanges (e.g. Cloos, 1984; Festa, Pini, Dilek, & Codegone, 2010). Sedimentary mélanges (olistostromes, Flores, 1955) commonly form through mass transport processes along the unstable wedge front of accretionary complexes or orogenic wedges (Abbate, Bortolotti, & Passerini, 1970; Festa et al., 2010). Tectonic mélanges derive from tectonic processes, which may include offscraping and stacking of originally coherent sequences of the substratum under the base of the allochthonous nappe (e.g. Pini, 1999; Underwood, 1984). At the base of the advancing thrust sheet, the overprinting of tectonic deformation onto primary sedimentary mélanges may form sub-nappe tectono-sedimentary mélanges (olistostromal carpet, see Elter & Trevisan, 1973) by reworking and reorganizing the primary block-in-matrix fabric according to the imposed tectonic shearing (see Festa, Dilek, Pini, Codegone, & Ogata, 2012; Pini et al., 2004).

Several criteria have been proposed in the literature (e.g. Cowan, 1985; Festa, Dilek, Codegone, Cavagna, & Pini, 2013; Pini, 1999 and reference therein) to discriminate between the sedimentary and/or tectonic origin of the mélanges generated in front of an advancing orogenic wedge, such as: the existence of an erosional discontinuity surface at the base of the chaotic deposits, the occurrence of exotic blocks, the superposition of tectonic foliations onto primary stratigraphic surfaces, the block-in-matrix fabric (random vs. structurally ordered), the shape of blocks, the nature and internal fabric of the matrix (brecciate matrix), etc. Geological and structural mapping is the fundamental tool for reconstructing the relationships between stratigraphy and deformation and thus may help in better constraining the nature and tectonic setting of the formation of chaotic deposits. In the Ligurian Alps (Figure 1), chaotic deposits occur in the footwall of the Penninic Basal Contact (PBC) (Ceriani, Fugenschuh, & Schmid, 2001) separating the allochthonous nappes (the Helminthoid Flysch nappes) from the foreland basin succession developed onto the external European crust (Kerckhove, 1969). These deposits have been controversially interpreted as originating from sedimentary (Lanteaume, 1968; Lanteaume, Radulescu, Gavos, & Feraud, 1990; Perotti et al., 2012) or tectonic processes (Giammarino, Fanucci, Orezzi, Rosti, & Morelli, 2010; Lanteaume, 1962; Vanossi, 1991) mainly on the basis of the detection (or not) of major tectonic or stratigraphic discontinuities within or at the base of the chaotic bodies.

In this paper we present a geological map (Main Map) synthesizing stratigraphic and structural data from both the complex thrust zone of the Ligurian segment of the PBC and the associated chaotic deposits. The reconstructed structural framework and the definition of the nature of the recognized discontinuities allow characterization of the nature of the mélanges associated with this major thrust zone.
2. Methods

The geological map (Main Map) – at 1:10,000 scale – derives from field work including stratigraphic characterization of the lithologies and structural analysis. The topographic base maps used during the fieldwork are the ‘Carta Tecnica Regionale – Regione Liguria’ and the ‘Carta Tecnica Regionale – Regione Piemonte’. These topographic maps have been used to produce a new simplified version with 50 m contour interval, in order to allow clear data presentation. The description of lithostratigraphic units (Figure 2) follows previous fieldwork performed in the study area (Giammarino et al., 2010; Lanteaume, 1962; Lanteaume et al., 1990; Perotti et al., 2012). The main structural data – that is, the trace of thrusts and faults, the attitude of foliations and fold axes – are shown on the map. The integration of these data results in two interpretative sections across the PBC thrust zone and the associated chaotic deposits.

3. Geological setting

The Ligurian Alps are the southernmost segment of the western Alpine orogen (Figure 1). They formed in response to the Late Cretaceous-Neogene convergence and collision between European and Adria plates and the subduction of the interposed oceanic domain (Vanossi et al., 1986). The oceanic crust (Piedmont-Ligurian domain) and the European continental margin (Briançonnais domain) were involved into the Cretaceous-to-Eocene Alpine subduction phases and were affected by medium- to high-grade metamorphism (e.g. Bonini, Dallagiovanna, & Seno, 2010; Decarlis, Dallagiovanna, Lualdi, Maino, & Seno, 2013; Decarlis, Manatschal, Haupert, & Masini, 2015; Maino, Bonini, Dallagiovanna, & Seno, 2015; Seno, Dallagiovanna, & Vanossi, 1998, 2005; Vanossi et al., 1986). During the Late Eocene-Early Oligocene, the Alpine wedge, constituted by the Palaeo-Cenozoic succession of the Briançonnais and the Mesozoic ophiolites of the Piedmont-Ligurian units (internal zone of Figure 1(b)), approached the external European crust (Dauphinois-Provençal domain; the external zone of Figure 1(b)), where an outward migrating peripheral foreland basin was depositing (Bonini et al., 2010; Dallagiovanna, Gaggero, Maino, Seno, & Tiepolo, 2009; Decarlis et al., 2013, 2014; Maino, Dallagiovanna, Gaggero, Seno, & Tiepolo, 2012). The front of the wedge is represented by the Helminthoid Flysch nappes, previously obducted and transported from the oceanic realm toward more proximal portions of the European foreland. The Early Oligocene final thrusting of the Helminthoid Flysch nappes onto the foreland basin succession is constrained by biostratigraphic and thermochronometric dating (Ford, Lickorisch, & Kusznir, 1999; Maino, Casini et al., 2015; Vanossi, 1991).

Subsequent, Late Oligocene-Miocene deformation phases are characterized by transtensional/transpressional fault systems associated with the rifting of the Liguro-Provençal basin and the Corsica-Sardinia drifting, which induced a rotation of the Ligurian and internal SW Alps (Maino, Dallagiovanna, Dobson et al., 2012, 2013).

4. Stratigraphy

The study area is divided into two parts by the ~NW–SE trending PBC thrust zone, separating the allochthonous San Remo-Monte Saccomello Unit – part of the Helminthoid Flysch nappes – by a footwall represented by an Eocene-Early Oligocene (?) foreland basin succession overlying the Dauphinois Mesozoic sequence (Main Map). However, between the foreland basin succession and the PBC thrust, a thick succession comprising chaotic deposits occurs. This succession has been named with different terms on the basis of the interpretation of its (sedimentary and/or tectonic) nature: ‘Zone des Lambeaux de charriage’ of Lanteaume (1962), ‘Complexe olis-tostromatique’ of Lanteaume (1968) and Lanteaume et al. (1990), ‘Zona dei Lembi Interposti’ of Vanossi

Figure 1. (a) Location of the study area. (b) Tectonic sketch of the Western and Ligurian Alps, simplified after Ceriani et al. (2001) and Maino, Decarlis, Felletti, and Seno (2013). Tectonic units are grouped in Internal (Piedmont, Piedmont-Ligurian and Briançonnais) and External (Provençal-Dauphinois, Helvetic and External Massifs) domains. The yellow box shows the location of the Monte Fronte Thrust zone along the PBC. DB: Dent Blanche nappe (Austroalpine domain); E-U: Embrunais-Ubaye nappes; HF: Helminthoid Flysch nappes; TH-M: Torino hill and Monferrato high; TPB: Tertiary Piedmont Basin.
Tectonic Unit of Baiardo-Triora of Giammarino et al. (2010) and ‘Triora Olistostrome Member’ (TOM) of Perotti et al. (2012). Our fieldwork shows that this succession should be divided in two different structural units (Main Map; Figure 2): in fact, chaotic rocks stratigraphically overlay both the foreland basin succession and a substratum-derived tectonic sheet (the Rocca Barbone Unit), which is included between two thrust planes (the Monte Fronté Thrust and the Rocca Barbone Thrust) constituting the PBC. The description of the stratigraphy of each unit cropping out in the study area is reported below.

4.1. San Remo-Monte Saccarello unit

The San Remo-Monte Saccarello unit is mainly constituted by anchimetamorphic upper Campanian-Maastrichtian turbidites, resting on upper Hauterivian-upper Campanian basin plane varicoloured pelites, that is, the San Bartolomeo Fm., up to 300 m thick (Figure 2; Cobianchi, Di Giulio, Galbiati, & Mosna, 1991; Sagri, 1980, 1984). The turbiditic sequence begins with coarse to fine grained quartz-feldspatic sandstones interlayered with thin beds of marls or dark pelites (Bordighera Sandstones Fm. (BOR), up to 250 m thick; Figure 3(a)). These arkoses were deposited...
into submarine lobes after the erosion of the Variscan Corsica-Sardinia basement (Casini, Cuccurru, Maino et al., 2015, Casini, Cuccurru, Puccini et al., 2015). It follows a monotonous succession of limestones and marls that reach at least 1500 m thick (San Remo Flysch Fm.).

4.2. The foreland basin succession

The Alpine foreland basin succession was deposited in the outer zones of the Western Alps in response to the flexural subsidence of the European crust during the orogenic phases (Ford et al., 1999; Sinclair, 1997). In the study area, a typical foreland basin succession (Decarlis et al., 2014; Lanteaume, 1968) is constituted by (Figure 2):

1. upper Lutetian–lower Barthonian quartz-arenites and calcarenites with abundant nummulite bioclasts (Nummulitic Sandstones Fm. up to 120 m thick);
2. Barthonian-lower Priabonian blue-grey marls (Blue Marls Fm. up to 100 m thick);
3. the uppermost formation is represented by a thick succession (up to 400 m) of Priabonian-Early Oligocene (?) brownish sandstones and pelites resulting from deep-water turbidite sedimentation (Ventimiglia Flysch, which is part of the Gres d’Annot system). Quartz, feldspars, muscovite, chlorite and biotite associations form the grey-wacke sandstones.

The Eocene-Early Oligocene (?) sequence is exposed in the SW part of the study area where it rests upon the Late Cretaceous marls and marly limestones of the Trucco Limestones Fm. that are the uppermost term of the Dauphinois Mesozoic succession.

4.2.1. The ‘Triora olistostrome member’

At the top of the Ventimiglia Flysch, up to 400 m thick chaotic deposits are characterized by paraconglomerates and exotic megablocks interbedded within the normal turbiditic sequence (Figure 2; see Perotti et al., 2012). Paraconglomerates occur as dm- to m-thick beds without internal organization. These beds are constituted by intraformational and exotic clasts with variable shape (from rounded to subangular) deriving from the Priabonian-Early Oligocene (?) Ventimiglia Flysch or from a different lithostratigraphic unit as the upper Lutetian–lower Barthonian Nummulitic sandstones, Mesozoic carbonate rocks or Cretaceous limestones belonging to the Helminthoid Flysch nappes. The clasts of paraconglomerates are randomly

![Image](image-url)
disposed into a pelitic matrix with the same composition of clasts (Perotti et al., 2012).

The decametre to kilometre in size megablocks are embedded in a matrix consisting of paraconglomerates and pelites and consist of:

1. Jurassic-Cretaceous carbonate Dauphinois succession;
2. Late Cretaceous marly limestones analogous to the San Remo-Monte Saccarello carbonate turbidites and
3. Eocene nummulitic limestones.

These olistoliths have different shapes comprising rounded, lenticular, irregular and tabular blocks. In the lower part of the TOM they do not show any particular organization, whereas, approaching the thrust zone, their long axes are progressively aligned to the main foliation associated with the thrusting.

A Priabonian-Early Oligocene (?) age of these chaotic deposits can be derived from the fossil content of the paraconglomerate matrix that indicates reworking of un-lithified Eocene sediments (Perotti et al., 2012).

4.3. The Rocca Barbone unit

The Rocca Barbone Unit is constituted by a condensed Meso-Cenozoic succession comprising (Figure 2):

1. Triassic dolostones and limestones (Figure 3(b));
2. Middle Jurassic well bedded dark limestones characterized at the base by breccia and conglomerate layers containing Triassic to Middle Jurassic clasts (Figure 3(b) and 3(c));
3. light grey Late Jurassic limestones (Figure 3(b));
4. Late Cretaceous marly limestones;
5. Eocene polygenetic breccias characterized by Mesozoic carbonate clasts embedded within a calcareous matrix containing nummulite fragments (Figure 3(d)); these Eocene breccias rest below or are interlayered with and
6. up to 200 m thick brownish turbidites of mica-rich sandstones and pelites containing paraconglomerates and lenticular to phacoidal exotic olistoliths of Late Cretaceous to Paleocene (Lanteaume, 1962) marly limestones (Figure 2(e) and 2(f)) or Eocene Nummulitic Sandstones.

Items 1–5 of this succession have been classified (see the legend of the Main Map) as the identical stratigraphic units described in the Briançonnais units, which are characterized by a Triassic-Eocene mainly carbonate cover with a huge Late Triassic-Early Jurassic sedimentary gap (Bonini et al., 2010; Decarlis & Lualdi, 2011; Decarlis et al., 2013). The last item (6) is the equivalent to the TOM resting onto the foreland basin succession described above.

Until now, this Triassic-Eocene sequence has been interpreted as: (1) an association of olistoliths embedded within the TOM without any major tectonic contact separating it from the lower foreland basin succession (e.g. Perotti et al., 2012); (2) or as part of a larger tectonic unit comprising all the chaotic rocks between the San Remo-Monte Saccarello Unit and the foreland basin succession (e.g. Giammarino et al., 2010; Vanossi, 1991). In the following section, new structural data provide the required information to clarify the structural setting of this succession.

5. Structure

In the study area the Penninic Basal Thrust is constituted by a main, upper thrust – Monte Fronté Thrust – and a secondary, lower one – Rocca Barbone Thrust (Main Map and Figure 4(a) and 4(b)).

The Monte Fronté Thrust couples the Cretaceous sediments of the allochthonous San Remo-Monte Saccarello unit onto the Jurassic-Eocene chaotic deposits (Figure 5(b); Main Map and cross-sections A–A′ and B–B′). The NE-dipping turbiditic succession of the hanging wall (Figure 6(a)) shows SW-verging kink to close folds characterized by a discrete axial plane cleavage (Figure 5(a) and 5(c)). Extension fractures and calcite veins sub-parallel to bedding are common. Minor fault zones sub-parallel to the main thrust surface and related an en-echelon array of veins occur locally. The varicoloured pelites of the San Bartolomeo Fm. are characterized by disharmonic folding. Folds axes plunge mainly toward SE.

The secondary thrust (Rocca Barbone Thrust) is well exposed as a wide cataclastic zone at the base of the Triassic-Eocene Briançonnais succession (Figure 7(a) and 7(b); Main Map and cross-section B–B′) and identifies an isolated tectonic slice encompassed between this thrust and the Monte Fronté Thrust (i.e. the Rocca Barbone Unit; Main Map, cross-section A–A′ and B–B′ and Figures 2 and 4(b)). The occurrence of a Briançonnais sheet included between the San Remo-Monte Saccarello unit and the foreland basin succession suggests a translation of this portion of substratum from the internal zone of the Ligurian Alps (Briançonnais domain) toward the outer zone (Dauphinois domain). It explains that the Triassic-Eocene succession was tectonically off scrapped from the Briançonnais substratum and translated foreword during the Helminthoid Flysch nappe thrusting. This thrusting is constrained between ca. 34–29 Ma by zircon (U-Th)/He dating (Maino, Casini et al., 2015).

Both thrust zones consist of a main fault core and damage zones asymmetrically developed in the footwall/hanging wall (Figures 5(b) and 7(a) and 7(b)).

The Monte Fronté Thrust (Main Map and cross-section A–A′ and B–B′) shows a ~20–100 cm-thick fault core made of:
(1) pervasively foliated (scaly fabric) gouges and protocataclasites (sensu Woodcock & Mort, 2008) developed in the pelites, sandstones or marly limestones of the chaotic deposits;
(2) foliated gouges of San Bartolomeo Fm. pelites;
(3) a thin layer (<3 cm) of weakly foliated cohesive cataclastic chaotic breccias (sensu Woodcock & Mort, 2008) of the BOR (Figure 5(b)–(e)).

The hanging wall damage zone is represented by 2–7 m of extensively fractured and veined arkoses of the BOR. The damage zone develops for 10s m in the footwall rocks (Rocca Barbone Unit) and is characterized by alternation of foliated gouges, cataclastic breccias, folded strata and low deformed portions (Figure 5(b), 5(f)–5(h)). Exotic megablocks, found within the TOM, show a superposition of the thrust-related cleavage onto the primary stratigraphic boundaries (Figure 3(f)).

The Rocca Barbone Thrust is well exposed at the base of the Rocca Barbone section (Main Map and cross-section B–B’) where it shows a 0.4–1 m-thick core zone comprising foliated and veined cataclastic chaotic breccias (sensu Woodcock & Mort, 2008) of Middle Jurassic limestones and Middle Triassic dolostones, which are associated with plastically folded layers of limestones (Figure 7(a)–7(d)). The damage zone in the footwall develops as a wide transition zone into the TOM with a poor defined lower boundary, while in the hanging wall it shows up to
10 m-thick highly fractured and veined Mesozoic rocks (Figure 7(a) and 7(b)). Above this highly deformed zone, the Jurassic rocks of the Rocca Barbone and Rocca Goina sections appear quite undeformed and characterized by set of fractures (Main Map and Figures 3(b) and 4(b)). Both thrust zones show asymmetric folds, sigma-shaped pressure shadows, well-defined cleavage, Riedel fracture planes consistent with a top-to-the-southwest kinematics (Figure 5(d)–(h) and Figure 7(a)–(d)). Geometric measurements show that in the carbonate damage zone of the Rocca Barbone Thrust...

Figure 5. (a) Late Cretaceous arkoses and limestones of the San Remo-Monte Saccarello Unit (SSU) involved in SW-verging folding above the MFT; (b) The fault zone of the MFT at the contact between the Bordighera Sandstones (BOR) and the ‘TOM’; (c) detail of close folds within the BOR, close to the Monte Fronté Thrust; (d) detail of the core zone showing the developing S-C bands within the TOM; (e) C’ bands locally occurring within the TOM embedded in the fault core; (f) folds within a block of Late Cretaceous marly limestones from the fault damage zone; (g), (h) s-c bands and sigma-shaped clast of limestone with trails filled with calcite from the Eocene polygenetic breccias (PB) involved in the damage zone.
the main stylolitic cleavage (St) is oriented at 54° to the thrust plane (T), whereas in the fault core the main S planes are oriented 36° to the C fabric, which is sub-parallel to the thrust plane (Figures 6(b) and 7(b)). The entire fault zone is characterized by two, ca. perpendicular systems of veins (V and V2; Figures 6(b) and 7(b)). In the clay-rich damage zone of the Monte Fronté Thrust the main S fabric is oriented at 42° to the shear plane (C), while in the core zone the S planes are oriented 16° to the C plane (Figure 6(c)). Moreover, in the fault core, C’-type bands sometimes occur in the pelitic layers (Figure 5(e)). In both thrust zones, the main angles R-C range between 17° and 21°. These structural associations are compatible with a simple-shear-dominated deformation (Berthé, Choukroune, & Jegouzo, 1979) with the highest shear strain localized in the fault cores and particularly in the core of the Monte Fronté Thrust.

Strike-slip faults trending ∼NE–SW are also present (Main Map). Most of these faults bound the major outcrops of Eocene polygenetic breccias and can be considered original Eocene extensional structures (Bonini et al., 2010). During the thrusting phase they acted as tear faults. Minor NW-dipping normal faults (not indicated on the Main Map) cut the thrust damage zones (Figure 6(e)). These structures can probably related to post-thrusting, extensional phases, which occurred during the Late Oligocene (Maino, Dallagiovanna, Dobson et al., 2012, Maino, Decarlis, Felletti, & Seno, 2013).

The footwall rocks of the TOM appear less deformed, affected only by open to close folds and characterized by inhomogeneous cm- or mm-spaced dissolution cleavage in the arenaceous/calcareous or pelitic/marly levels, respectively. This cleavage becomes a continuous and penetrative foliation approaching the thrust zone. It is important to note that the cleavage cuts the primary sedimentary boundaries between the
exotic megablocks mantled in the turbiditic layers, thus confirming a sedimentary origin of these megablocks (Perotti et al., 2012).

6. Conclusion

The geological mapping of the Ligurian segment of the PBC in the Monte Fronté area allows better constraint of the tectono-stratigraphic evolution of a sector largely characterized by chaotic deposits associated with a major thrust zone. The geological map and the interpretative cross-sections integrate the collected stratigraphic and structural data and show that the chaotic rocks crop out into two different units. Paraconglomerates and olistoliths characterize the top of the sequence of both the foreland basin succession and the Rocca Barbone Unit. This last unit is characterized by a peculiar stratigraphic succession (with a Briançonnais affinity) and is structured as a tectonic slice bounded by thrust planes associated with the PBC thrust zone.

Collected data indicate that the origin of the Eocene-Early Oligocene chaotic rocks from both units was primarily achieved through sedimentary processes controlled by the gravitational instability of the advancing orogenic wedge. Conversely, the Triassic-Eocene sequence of the Rocca Barbone Unit should be interpreted as a tectonic slice offscraped by the Briançonnais substratum during the Late Eocene-Early Oligocene thrusting of the Helminthoid Flysch nappes.

In summary, the data presented show that the chaotic deposits resting below the Penninic Basal Thrust experienced a complex evolution coupling sedimentary and tectonic processes associated with the propagation of the Alpine orogenic wedge.

Software

The geological map was compiled using Esri ArcGIS 10.1 and refined using Adobe Illustrator. Sections and figures were constructed or modified using Adobe Illustrator. Stereonet plots were computed using Stereonet3D (Cardozo & Allmendinger, 2011).

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