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Breaking up continents at magma-poor rifted margins: a seismic vs. outcrop perspective. A discussion

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The contribution of Decarlis et al. (2018) focuses on the breakup of continents at magma-poor rifted margins, a topic which, as claimed by the authors, "… is a complex, yet little understood ….. accounting for intricate interactions between tectonic and magmatic processes". The authors use field observations of a classical Ligurian ophiolites exposure – the Bracco-Levanto - to compare it with the setting of the East Antartica margin analyzed by seismic survey and interpretations (Geoscience Australia Survey 228). The authors state that the overall aim is to combine detailed structural mapping and petrological data from the fossil exhumed example (Bracco-Levanto) with architectural features observed in seismic sections from present day OCTs.

Moreover, as explicitly mentioned in the title, the authors aim at discussing the implications of their analysis for the interpretation of the nature of seismic interfaces and of the character of rocks at ultra-distal margins. It also helps to constrain the timing and type of processes controlling lithospheric breakup and onset of steady state, localized seafloor spreading.

Actually, the three-dimensional complexity of the tectonic architecture of the Ligurian ophiolites, if not properly taken into account, can cause uncertainty in the analyses and projected goals; therefore, in the following pages I will complement and refine the geological information provided by Decarlis et al. (2018), with the purpose of helping future works on the subject. Moreover, my contribution aims to complete the references on the study area, providing further structural information and details and amending for some misinterpretations included in Decarlis et al. (2018).

Geology of the Bracco-Levanto area and its value in geological heritage

As recognized by Decarlis et al. (2018), the Bracco-Levanto area represents a key region for the studies of the Ligurian Tethys ophiolites having a special value in the history of modern geological knowledge. In the early '60s Bailey, Mc Callien (1960) analyzed the local geology following the problems related to the "Steinman Trinity" the original association of pillow lava, serpentinites and cherts (Bernoulli et al., 2003). Later on, Abbate (1969) and above all Decandia & Elter (1969) and Decandia & Elter (1972) addressed the peculiarity of the Ligurian ophiolites. They described a major unconformity between mantle rocks and overlying basalts, tectono-sedimentary breccias (ophicalcites and ophigabbros) and sediments. Moreover, Decandia & Elter (1969) for the first time envisaged the interpretation of mantle and gabbro tectonic fabrics as related to low-angle extensional shearing (cfr. Mattauer, in Perrin, 1976) and mantle exhumation connected with tectonic processes predating the emplacement of basalts, being therefore at the forefront of the concepts that are today proposed to understand continental breakup at magma-poor rifted margins and ultraslow ridge spreading center (Boillot et al., 1987; Manatschal & Muntner, 2009 and references therein). The Bracco-Levanto and nearby areas were furthermore the object of key papers on the petrology of mantle (Bezzi & Piccardo, 1971; Piccardo, 1977; Rampone et al., 1998; Piccardo et al., 2014 and ref.), geochemistry of ophiolitic magmatism (Ferrara et al., 1976; Serri, 1980; Beccaluva et al.,1980), of ocean-floor metamorphism (Spooner & Fyfe, 1973; Bonatti et al., 1976; Cortesogno et al., 1975; Cortesogno & Lucchetti, 1984; Cortesogno et al., 1994, Tribuzio et al., 2002; Zaccarini, Garuti, 2008 and ref.) and stratigraphy-sedimentology of ocean floor deposits and mineralizations and their connection with the tectonic enviroment (Bonatti et al., 1976; Barrett & Spooner, 1977; Folk & Mc Bride, 1978; Cortesogno et al., 1980; Barrett, 1982; Cortesogno et al., 1987).

The geology of the Bonassola-Levanto area is represented in the map of Figure 1 (to be compared with Figure 2 in Decarlis et al. 2018). All terms of the Ligurian-type ophiolite sequence are exposed in the area, they consist of a basement formed by serpentinised mantle peridotites intruded by up to km-scale MOR-type gabbroic bodies dated at 162-161 Ma (Tribuzio et al., 2016) and of a volcano-sedimentary cover (Abbate, 1969; Cortesogno et al., 1987). This latter is made up of basalt lava flows, with incompatible trace elements and Nd isotopic signature closely similar to that of modern N-MORB (Rampone et al., 1998; Renna et al., 2018). Beyond those basalts, the volcano-sedimentary cover includes sedimentary breccias (see below), Middle to Upper Jurassic radiolarian cherts and Cretaceous shales (Decandia & Elter, 1972; Cortesogno et al., 1987). The different kinds of ophiolitic breccias are mostly named from local sites (see Figure 1) of the investigated area: the Rossola Breccia mainly characterized by clasts of basalts, the M.Zenone Breccia mainly characterized by clasts of gabbros, and finally the Framura Breccia made up of clasts of peridotites in a serpentinite-rich matrix. The different types of breccia are collectively named Bonassola Breccia (Cortesogno et al., 1987).

Mantle peridotites and gabbros record a pre-orogenic deformation and retrograde-metamorphism which has been described since the seventies (Cortesogno et al., 1975; Piccardo, 1977), later re-addressed and analyzed by Hoogerdujin Strating, 1988; Molli, 1994; 1995, 1996; Menna 2009. This pre-orogenic history includes:

- shearing of the mantle section in hectometre to kilometre scale shear zones developed before the mantle reequilibration in plagioclase stability field (900-1000 °C, 0,5-0,7 GPa, Rampone et al., 1998; Piccardo, Guarnieri, 2010 and references);
- intrusion of gabbros within mantle rocks constrained to a maximum pressure of crystallization around 0,7-0,5 GPa e.g. 15-20 Km of depth (Cottin, 1984; Sanfilippo & Tribuzio, 2011 and ref.);
- deformation of peridotite and gabbro in retrograde metamorphic conditions from granulite to greenschist facies (Cortesogno et al., 1994) and related with serpentinization and exhumation of peridotites and gabbros to the sea floor. Relicts of these deformation structures can be found in a network of metre- to hectometre scale shear zones within gabbro bodies (e.g. Bracco and Bonassola gabbro), as well as in the uppermost part of peridotites where polyphasic fault rocks show an early mylonitic fabric overprinted by cataclastic deformation and fracturing due to hydrothermal and sea water-derived fluids interaction (Treves & Harper, 1994; Molli, 1996) producing the peculiar fault-rocks represented by the ophicalcites (and corresponding ophigabbros) which are related in current literature to the pre-orogenic extensional detachment faulting (Lemoine et al., 1987; Picazo et al., 2013 and references).

This deformation and magmatic history pre-dates the emplacement of extrusive magmatic rocks mainly made of massive and pillow basalts associated with sedimentary ophiolitic breccias (Cortesogno et al., 1987 and references).

Orogenic deformation structures in the Bonassola-Levanto area

As shown in the geological map of Figure 1 and cross-sections in Figure 2a, the whole ophiolitic sequence is involved in orogenic polyphase folding, thrusting and internal deformation including extensional faulting (Galbiati, 1970; Decandia & Elter, 1972; Barrett & Spooner 1977; Cortesogno et al., 1987; Hoogerdujin Strating & Van Wamel 1989; Hoogerdujin Strating, 1994; Molli, 1994). This is patently not in line with Decarlis et al. (2018) who claim that the "….Alpine deformation was mainly localized in the post-rift sedimentary cover..". The sentence is altogether wrong if referred to Barrett (1982), since this author (see also Barrett & Spooner 1977) clearly recognized the presence of orogenic structures affecting all the ophiolitic terms in the area.

Jurassic High Angle Faults and related basins

Since Decandia and Elter (1969), all the authors who have worked on the Bracco-Levanto ophiolites (e.g. Decandia & Elter, 1972; Principi, 1972; Gianelli & Principi, 1977; Barrett & Spooner, 1977; Abbate et al., 1980; Cortesogno et al., 1981; Cortesogno et al., 1987 and references therein) have recognized the peculiar character of the former oceanic Ligurian paleodomain as related to an irregular and rugged paleomorphology possibly connected to fault-related Jurassic paleoscarps. Nevertheless, no author (until now) has mapped those faults which, on the contrary, have been mainly inferred from the differences in thickness of the volcano-sedimentary cover in close areas, as well as at kilometre regional scale (e.g. Bracco-Levanto vs. Val di Vara - Rocchetta Vara occurences).

Decarlis et al. (2018) firstly report Jurassic high normal angle faults bounding, according to their interpretation, two semi-grabens (M.Rossola and M.Pastorelli, in their Figure 2f) which they consider as filled with different kinds of ophiolitic breccias such as the Bonassola (erroneously used as synonimous of the M.Zenone breccia) and Rossola breccias. The documentation of high angle Jurassic faults is pivotal in the issues supported by the paper, and therefore deserves some discussion.

The first comment is about the cartographic representation. The two Jurassic high angle faults in Figure 1 of Decarlis et al. (2018) are both reported as north-dipping in the map, whereas they are drawn antithetic in cross section b-b' of Fig 2e, as well as in the recostruction proposed in Fig. 2f. Only in the cross-section do these Jurassic high angle faults figure as partially reactivated during the orogenic deformation, whereas the map does not include such information (indeed the map also lacks the indication of M. Pastorelli peak, repeatedly recalled in the text).

Nevertheless, more importantly in drawing the Jurassic high angle faults the orogenic structures of the area are completely underestimated if not ignored at all.

As represented in the cross-sections of Figure 2 what Decarlis et al. (2018) describe as a graben is indeed developed between hinge to limb domains of a north-west plunging regional fold (D3 according to Hoogerdujin Strating & Van Wamel, 1989 and Molli 1994b), southern prolongation of the Montaretto syncline (Decandia, Elter 1972; Barrett, 1982; Cortesogno et al., 1987; Hogeerdujin Strating, 1994; Molli, 1994). High angle normal faults are indeed present as minor late orogenic structures (and therefore not represented in Figure 1), clearly post-dating the main fabric (D1 foliation) affecting the Framura breccias as well evident in the M.Pastorelli-M.Brino area (Fig.2d,e,f).

Due to the underestimation of the local orogenic structure of the area altogether with the oversimplified view of the different kinds of ophiolitic breccias (see the more complete and detailed description in Principi, 1973; Barrett & Spooner, 1977; Cortesogno et al., 1981; Cortesogno et al., 1987) Decarlis et al. (2018) fail to recognize the interference between the source areas of the different breccias and therefore the interconnections of the fault-related basins making an undocumented compartimentalization of the Jurassic high angle extensional framework. Figure 2b reports the retrodeformation of two representative cross-sections (a-a' and c-c') with a location of the Jurassic high angle faults, south of M.Brino to separate former close sectors characterized by differences in volcano-sedimentary sequences (cfr. with Figure 2f in Decarlis et al., 2018). The major characters of the former basin architecture and the major differences with the interpretation of Decarlis et al. (2018) may be underlined as follow:

- the rugged morphology of basement formed by gabbro and serpentinized peridotites ridges appear to be still present during the pillow basalts flow as documented by the irregular thickness of the basalts, by the Framura breccias interlayered within pillow basalts (Fig. 1), as well as by decameter-sized blocks of gabbro-mylonites within the pillow basalts observable along the coast line west of M.Brino (see Figures 1 and 3c);
- the high angle faults, which clearly postdate the detachment were still active during cherts deposition as testified by the variable thickness of the radiolarites and cherts at local (from 0 to 70 metres) and regional scale (up to 350 metres);

- the pillow basalts cannot, therefore, be considered as post-tectonic as claimed in Decarlis et al. (2018). On the contrary, pillow basalts and overlaying radiolarian cherts altogether with the different kinds of ophiolitic breccias (e.g. Framura, Rossola, Bonassola as whole) appear to be part of the volcano-sedimentary cover of peridotites and gabbros as well documented in cross section c-c' and in agreement with the existing literature (Cortesogno et al., 1987 and ref.);
- previous points collectively suggest that the end of tectonic extension is marked in the Bracco-Bonassola area by the post-rift layer represented by the Palombini shales instead of the pillow basalts as claimed in Decarlis et al. (2018).

To conclude, I completely agree with the interpretation of Ligurian ophiolites as related to a "embrionic oceanic lithosphere" (Decandia, Elter, 1969; Piccardo, 1977; Lombardo, Pognante, 1982; Lemoine et al., 1987; Molli, 1994, 1995; Manatschal & Nivergelt, 1997; Manatschal & Muntner 2009; Manatschal et al., 2011) formed as the result of magma-poor rifting, similar to what is described in the Iberia-Newfoundland OCT (Wilson et al., 2001; Montanini et al., 2006; Manatschal & Muntner, 2009 and ref.) and ultraslow spreading ridges (Piccardo, 2008; Sanfilippo & Tribuzio, 2011; Vissers et al., 2013 and ref.); therefore, the comparison with the proto-oceanic sector of the East Antartica margin appears fruitfully significant. Nevertheless, I disagree with the reconstructions of the geometries and compartimentalization of fault-related basins proposed by Decarlis et al. (2018) for the Bonassola-Levanto area. Field observations and data so far presented support a different structural and litological interpretation of the GA228-27 seismic section with a "correlation" of the post-rift sediments with the Ligurian Palombini shales and with the volcano-sedimentary sequence resting on an exhumed peridotite-gabbro basement exposed in the footwall of a previously developed low angle detachment as syn-tectonic with high angle normal faulting.

Acknowledgements

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Figure captions

Figure 1: Geological map of the Bonassola-Levanto area. Based on 1:5000 scale author's mapping (1990-1994) and Decandia & Elter (1972); Cortesogno et al. (1987).

Figure 2: a) Geological cross-sections of the investigated area; b) Recostructed interpretative sections of the former OCT during Cretaceous based on retrodeformation of the geological structures of the Bonassola-Levanto area. Vertical and horizontal scale based on observed thickness of lithologies and retrodeformation of the orogenic and late orogenic structures.

Figure 3: a) Tectonic breccia (ophicalcite) formed by angular-subangular clasts of serpentinite-mylonites within a fine grained serpentinite and carbonate rich-matrix. Relict domain of Ligurian Tethys detachment fault. Punta del Marmi, see Figure 1; b) S/C top-to-the east D3 thrust related fabric in ophicalcite. Cava dei Marmi (Bonassola) for location see Figure 2; c) decametre-sized block of gabbro-mylonites within pillow basalt observable along coast line west of Montaretto see Figure 1 for location; d) Framura breccia, north-west of M.Pastorelli, note the attitude of D1 fabric (see Figure 2 for picture location); e) typical exposure of Framura breccia, coast-line west of M.Pastorelli, note the attitude of D1 fabric (see Figure 2 for picture location); f) sheared primary contact between Framura breccia, decimetre thick layer of radiolarites and pillow basalts. Note the steep D1 fabric within the Framura Breccia. Punta dei Marmi (see Figure 2 for picture location).

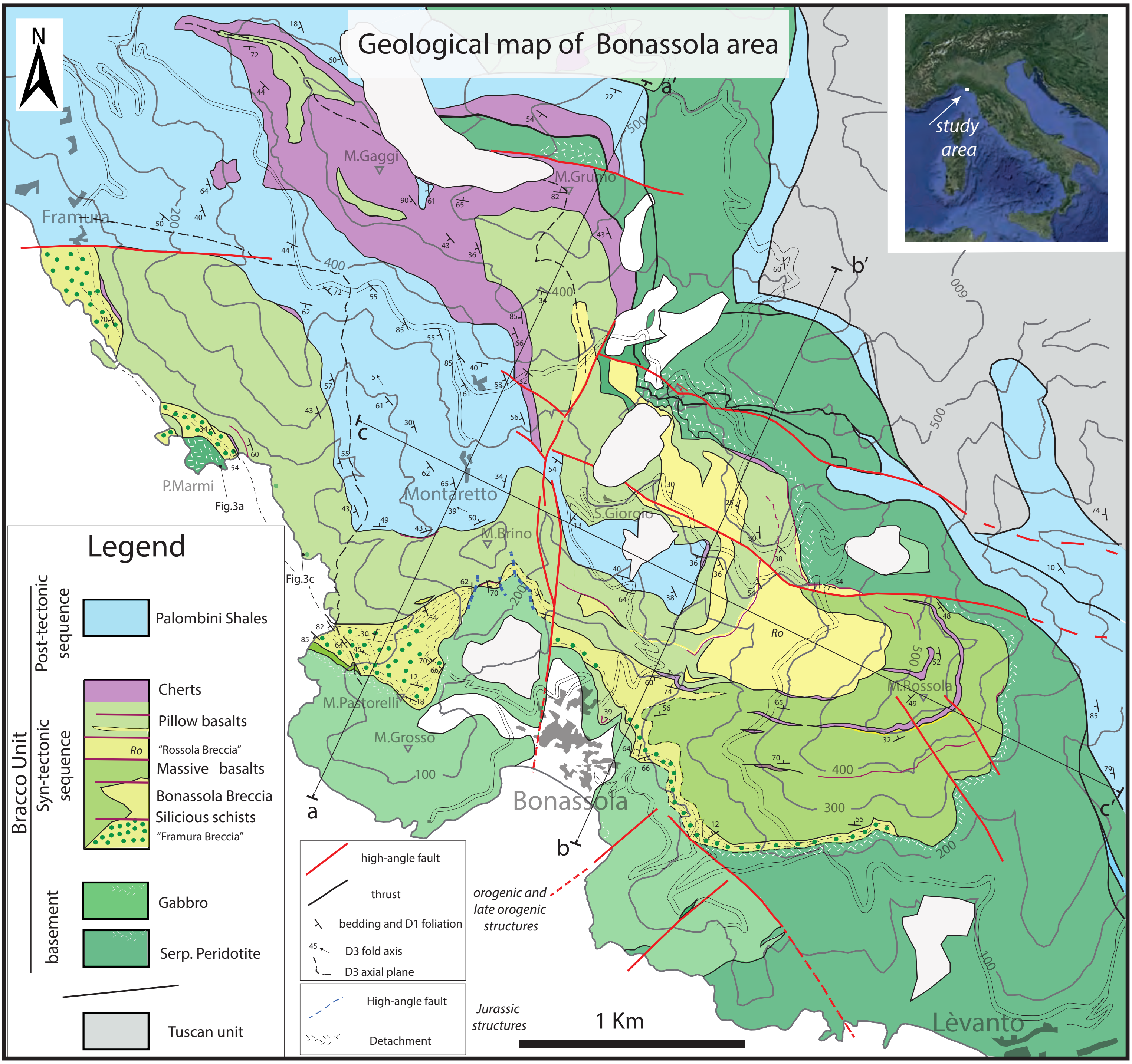
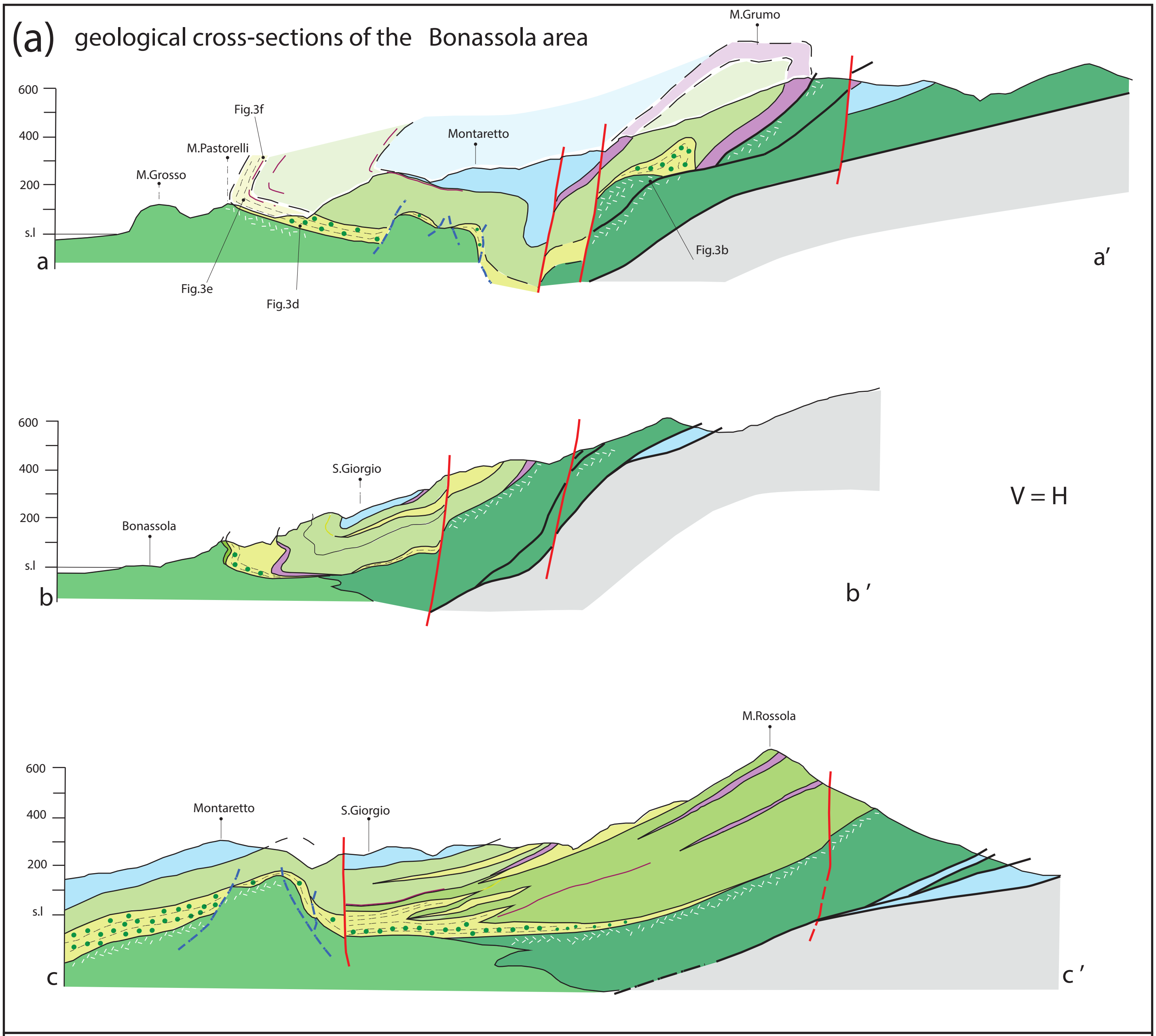
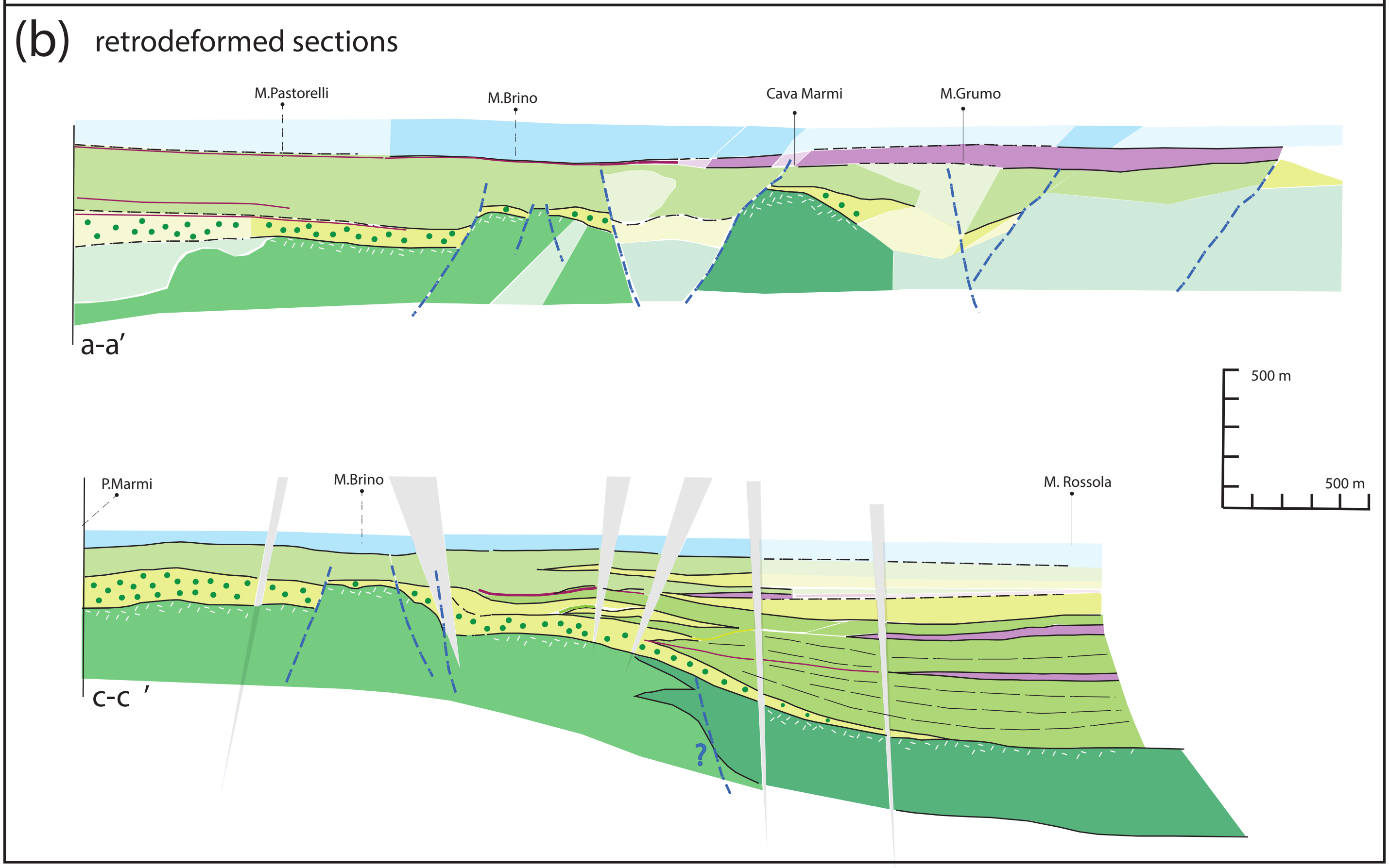


Figure 1 Molli Breaking up.......: a Discussion JGSL



(a) geological cross-sections of the Bonassola area



(b) retrodeformed sections

Figure 2 Molli Breaking up......: a Discussion JGSL

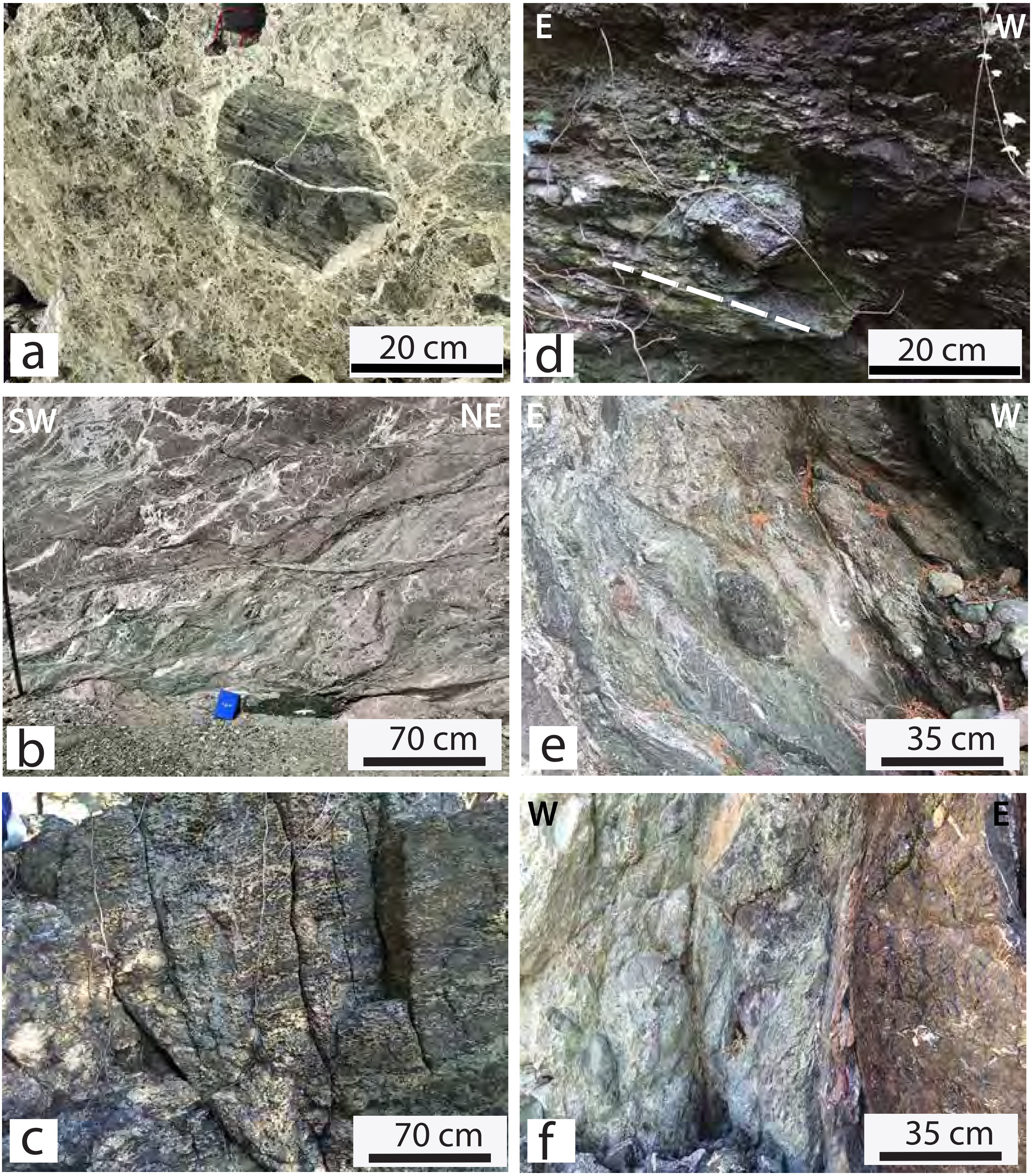


Figure 3 Molli Breaking up....... : a Discussion JGSL