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Kilometre-scale palaeoescarpments as evidence for Cretaceous synsedimentary tectonics in the External Briançonnais Domain (Ligurian Alps, Italy)

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ABSTRACT

In the central part of the External Ligurian Briançonnais in the Ligurian Alps (NW Italy), a large and diverse set of stratigraphic, sedimentologic and petrographic data provides evidence for the occurrence of Cretaceous kilometre-scale palaeoescarpments. These palaeoescarpments consist of irregular erosional surfaces more or less deeply incising a stratigraphic succession that ranges from Upper Jurassic limestones down to Permian volcano-sedimentary rocks; at present they are partly exposed and partly covered by Upper Cretaceous−Upper Eocene sediments, and patchily encrusted by authigenic minerals. Palaeoescarpments resulted from the remodelling of palaeofault planes by gravity-driven rock fall processes, whose products are represented by breccias and metre- to tens of metres-sized blocks of Upper Jurassic limestones either lying directly over the surfaces or embedded within onlapping sediments. Palaeofault-related tensional stresses are also documented by the occurrence of subvertical sedimentary neptunian dykes and tabular breccia bodies, interpreted as fault rocks and locally bearing evidence of the uprise of hot, overpressured fluids. Fault activity started during the Aptian, with most of the displacement - which locally reached several hundred metres - accomplished during the Late Cretaceous, resulting in deep morpho-structural depressions that, by Eocene times, were not yet levelled out. Two systems of kilometre-long palaeoescarpments are recognized and mapped, suggesting the existence of a Cretaceous kilometre-sized fault-bounded basin limited to the north and south by two main transcurrent zones, presently striking E−W and internally partitioned by N−S oriented east-dipping normal faults. This type of setting could be consistent with the Western Tethys tectonic context, in which the Ligurian Briançonnais Domain, close to the Early−Late Cretaceous boundary, was located at the easternmost end of a transcurrent belt connecting the Bay of Biscay to the Valais and Ligurian-Piedmont oceans.

*Keywords***:** palaeoescarpments, breccias, External Briançonnais, Ligurian Alps, syn-depositional faults, Cretaceous transtensional tectonics.

1. Introduction

Synsedimentary faults play a fundamental role in controlling the geometries of basins on extensional continental margins, and are commonly imaged on seismic profiles where their extension and 3D geometry can be depicted in detail (Péron-Pinvidic et al., 2007; Afilhado et al., 2008). In outcrop, synsedimentary palaeofaults are commonly inferred from variations in the thickness of sedimentary bodies and the co-occurrence of several features such as neptunian dykes (Montenat et al., 1991; Winterer et al., 1991; Winterer and Sarti, 1994), megabreccias (Böhm et al., 1995; Spence and Tucker, 1997; Aubrecht and Szulc, 2006) and soft sediment deformation (e.g. seismites: Montenat et al., 2007). Direct observation of palaeoescarpments - morphological features resulting from surface exposure and erosion of fault planes (Carminati and Santantonio, 2005) - is, however, more rarely reported (Surlyk and Hurst, 1983; Bice and Stewart, 1985; Surlyk and Ineson, 1992; Bosellini et al., 1993; Santantonio, 1993, 1994; Purser and Plaziat, 1998; Di Stefano et al., 2002; Montenat et al., 2002; Morsilli et al., 2002; Gill et al., 2004; Carminati and Santantonio, 2005; Rusciadelli, 2005; Bertok and Martire, 2009).

The aim of the present paper is to describe Cretaceous kilometre-scale palaeoescarpments, related to the activity of faults with vertical displacements in the order of hundreds of metres, that occur in the central part of the External Ligurian Briançonnais in the Ligurian Alps. The Ligurian Briançonnais is the southernmost sector of the Briançonnais Domain, a major palaeogeographical and tectonic unit in the Alpine orogen which has been interpreted as part of the northern continental margin of the Western Tethys (Faure Muret and Fallot, 1954; Amaudric du Chaffaut et al., 1984; Vanossi et al., 1984; Lemoine et al., 1986; Lemoine and Trümpy, 1987; Lanteaume et al., 1990). The Ligurian Briançonnais Mesozoic−Cenozoic stratigraphic succession reflects different evolutionary stages of an extensional margin, from its initiation up to its final involvement in the Adria - Europe collision. According to the literature (e.g. Boillot et al., 1984), the Ligurian Briançonnais was mainly structured during the Late Triassic−Early Jurassic rifting phase of the Western Tethys (which was characterized by intense extensional tectonics giving rise to a horst-and-graben structure) and was followed during the Middle−Late Jurassic and Cretaceous by a post-rift phase marked by thermal subsidence and the end of extensional tectonics. However, this scenario has recently been questioned by several authors who have documented the occurrence of extensional synsedimentary tectonics during the Middle−Late Jurassic (Claudel and Dumont, 1999; Bertok et al., 2011). In the present study, geometric, stratigraphic and sedimentologic evidence is provided at all scales, allowing the documentation of intense fault activity during the Cretaceous and the evaluation of the associated displacements. The significance of this Cretaceous extensional tectonic activity on a more regional scale and in the frame of the Western Tethys geodynamic evolution is also discussed.

2. Geological setting

The Ligurian Alps are a tectonic stack of four main groups of units which have always been assumed to correspond to four adjacent main Mesozoic palaeogeographical domains: the Dauphinois and Ligurian Briançonnais domains, which were part of the European continent; the Pre-Piedmont domain, which was the margin of the European continent; and the Piedmont-Ligurian domain, which represents the contiguous oceanic basin (Vanossi et al., 1984; Lemoine et al., 1986). These units were stacked since the Late Eocene by SW-verging Alpine thrusts, coeval with a subduction of continental crust along an intracontinental shear zone. In the present-day geometric setting, the Pre-Piedmont units rest on the Briançonnais units, which in turn are thrust onto the outermost Dauphinois Domain. Detached cover units of inner Piedmont-Ligurian domain (the so-called *Helminthoides* Flysch unit) overlie all these units (Vanossi et al., 1984; Seno et al., 2003, 2005; Bonini et al., 2010).

The Ligurian Briançonnais Domain can be subdivided into two main sectors: internal and external. The Internal Ligurian Briançonnais was involved in the subduction channel up to a maximum depth of about 30 km, developing high-pressure blue schist metamorphic parageneses (Messiga et al., 1982; Goffé, 1984). The External Ligurian Briançonnais was not involved in subduction and developed only low grade to anchizone metamorphism (Messiga et al., 1982; Seno et al., 2003, 2005; Piana et al., 2009; Bonini et al., 2010).

The study area is located in the Marguareis Alps (sensu Marazzi, 2005), and extends from Cima della Fascia to the NW, and Monte Mongioie and Colle del Lago dei Signori to the East and South, respectively. It belongs to the central part of the External Ligurian Briançonnais (Fig. 1), and is composed of kilometre-scale tectonic units which, although intensively strained at certain stratigraphic levels, did not experience significant transposition and/or mineralogical reorganization, so that primary sedimentologic features and original stratigraphic relationships are preserved at all scales (Piana et al., 2009). This effect is likely due to the low intensity of metamorphism (anchizone) and the localization of deformation along the Limone-Viozene deformation zone to the south and along the Verzera shear zone, that corresponds to the northern boundary of the External Ligurian Brianconnais, to the north. The Verzera and Limone-Viozene zones were active during all stages of Alpine deformation and mainly accommodated left-lateral movements in a transpressive regime (Piana et al., 2009).

The oldest rocks outcropping in the study area are volcanic and volcanoclastic rocks of Carboniferous−Permian age (Boni et al., 1971). These are overlain by a condensed Mesozoic−Cenozoic succession which is subdivided into several lithostratigraphic units systematically bounded by important hiatuses (Vanossi, 1963, 1972, 1974; Boni et al., 1971; Bertok et al., 2011) (Fig. 2).

The Quarziti di Ponte di Nava (QPN) (Upper Permian?−Lower Triassic?) comprises littoral conglomerates and cross-bedded quartz arenites, locally interbedded with shales (up to 110 m thick).

The Dolomie di S. Pietro dei Monti (DSPM) (Anisian−Ladinian) consists of peritidal dolomites and limestones (200−400 m thick). Lualdi and Bianchi (1990) proposed that the mainly calcareous Anisian lower portion be distinguished, as the Formazione di Costa Losera, from the Ladinian dolomites of the upper portion (DSPM s.s.). The top of the DSPM is truncated by an erosional surface corresponding to a hiatus which spans the Upper Triassic, Lower Jurassic and part of the Middle Jurassic.

The Calcari di Rio di Nava (CRN) (Bathonian) comprises monotonous dark micritic limestones, locally bioclastic in the lower portion, that are intensely laminated and nearly barren of fossils in the upper portion (about 50 m thick); conglomerates composed of Triassic dolomite clasts are present locally at the base. A restricted carbonate shelf environment may be inferred (Bertok et al., 2011). The top is truncated by an erosional surface, locally associated with an angular unconformity.

The Calcari di Val Tanarello (CVT) (Kimmeridgian?−Berriasian) consists of pelagic facies represented by crinoidal limestones at the base and massive light micritic limestones, locally exhibiting a nodular Ammonitico Rosso facies, in the upper part. The thickness of the CVT is variable (25−70 m).

The Formazione di Upega (FU) (Upper Cretaceous) consists of grey marly limestones lithologically equivalent to the "calcschistes planctoniques" of the Briançon area (Faure Muret and Fallot, 1954) and interpreted as slope hemipelagic sediments. These marly limestones are separated from the underlying CVT by a black crust of Fe-Mn oxides, glauconite and phosphates containing planktonic foraminiferal assemblages referable to the middle Albian−Cenomanian (Bertok et al., 2011). This mineralized hard ground documents a prolonged hiatus encompassing the Valanginian−Aptian interval and may refer to palaeoceanographic changes taking place at a regional scale. This gap is in fact widespread throughout the Briançonnais Domain (Lualdi et al., 1989; Barfety et al., 1996), but is also known in other Western Tethys sectors (e.g. Lozar, 1995). Within the FU, Lanteaume et al. (1990) have reported the presence of foraminiferal assemblages indicating a late Cenomanian−Campanian age. The FU is crossed by a pervasive foliation that documents a strong localization of the deformation, due to the rheological contrast with respect to the underlying, massive carbonate formations (Piana et al., 2009). For this reason the real stratigraphic thickness is hard to assess and may be only approximately estimated to several tens of metres.

The Calcari della Madonna dei Cancelli (CMC) (up to 30 metres thick) comprises foramol-type ramp massive bioclastic limestones, with abundant macroforaminifera that enable the formation to be dated to the Middle Eocene (early Bartonian; Rendinella, 2006). These are transitionally overlain by pervasively foliated dark marls with interbedded more calcareous and thin beds. They were dated to the Priabonian by Lanteaume et al. (1990). An important discontinuity surface is present at the base with a hiatus encompassing all of the Paleocene and part of the Eocene.

The Flysch Noir (FN) consists of dark argillaceous sediments, locally with turbiditic sandstone layers, that have been tentatively assigned to the late Priabonian (Guillaume, 1969; Michard and Martinotti, 2002).

In the last decade, two papers examining the Marguareis Alps have shown that extensional synsedimentary tectonics did not stop at the end of the Late Triassic−Early Jurassic rifting phase. Bertok et al. (2011) provided a large set of sedimentologic and stratigraphic data pointing to the primary role of tectonics in controlling sedimentation patterns throughout the Middle−Late Jurassic, whereas Michard and Martinotti (2002) hypothesized the occurrence of kilometre-scale N−S-trending normal faults active during the Late Cretaceous−Eocene time interval. The present paper focuses instead on evidence for palaeofault activity during the Cretaceous, and on the description and characterization of the related palaeoescarpments.

The Marguareis Alps have some favourable features for recognizing evidence of paleofault activity: very good exposure of rocks within a high altitude karstic landscape; a substantial preservation of the original, pre-Alpine, geometries of sedimentary bodies and their structural relationships; and a highly condensed Mesozoic stratigraphic succession that in a few hundred metres encompasses the Triassic to Upper Cretaceous interval, thus allowing the displacements of the syn-depositional faults to be highlighted.

3. Methods of study

Geological mapping at a 1:10.000 scale was performed in order to reconstruct the geometries of the sedimentary bodies and the structural setting. A detailed mesostructural analysis was then undertaken in order to distinguish the effects of the syndepositional tectonics from the Cenozoic Alpine deformation related to the build up of the mountain chain. Detailed outcrop observation was integrated with extensive sampling, mainly aimed at the breccia deposits that directly overlie the palaeoescarpments. Petrographic analyses of peels and thin sections, and cathodoluminescence (CITL 8200 mk3 equipment operating at 400−500 μA and 15−17 kV) enabled the nature and origin of clasts to be defined and the complex history of diagenesis, fracturation and cementation that has preceded and succeeded deposition to be unravelled. O and C stable isotope analyses were also carried out in order to constrain the nature of the fluids involved in the genesis of the breccia deposits.

4. Cretaceous palaeoescarpments

A large and diverse dataset illustrating the occurrence of palaeoescarpments onlapped by Upper Cretaceous sediments has been gathered. The most ubiquitous and compelling evidence is represented by stratigraphic contacts showing features such as unconformable relationships and/or an absence of lithostratigraphic units which normally occur in complete stratigraphic successions. The physical continuity of the palaeoescarpments is still recognizable and they can be traced over several kilometres. Four different palaeoescarpments are recognized: the E−W striking Chiusetta palaeoescarpment, and the N−S striking Passo delle Saline, Colle del Pas and Mongioie palaeoescarpments (Fig. 1). The following sections contain a description of several outcrops selected in order to provide a full picture of the main features of the palaeoescarpments.

4.1. Chiusetta palaeoescarpment

4.1.1. Vallone dei Maestri (outcrop 1 in Fig. 1)

In this region, located some hundreds of metres east of Colle del Lago dei Signori, the gently southward-dipping CVT limestones are cut by a surface dipping steeper than the bedding and incised for about ten metres (Fig. 3). This surface has a very irregular morphology and is locally covered by limited patches of a millimetre- to centimetre-thick mineralized crust - closely similar to that commonly topping the Calcari di Val Tanarello - at the unconformable but concordant boundary with the FU. The FU marly limestones onlap this surface, with beds becoming progressively thinner and steeper as they approach it (Fig. 4). Two blocks of CVT limestones, respectively a few metres and tens of metres in size, are entirely embedded within the FU a few metres above the bounding surface. The outer surface of the largest CVT block shows small scattered patches of a centimetre-thick mineralized crust. A few millimetre- to centimetre-sized cavities, with irregular morphologies and rounded edges, also occur (Fig. 5). The cavities' internal walls are uniformly covered by an isopachous rim of finely crystalline sparry calcite cement, and they are geopetally infilled with a graded micritic sediment and a zoned sparry calcite cement. The polarity indicated by the geopetal structures is not concordant with the present position; the blocks are also crossed by many millimetre- to centimetre-wide randomly oriented neptunian dykes infilled with a red micritic sediment.

4.1.2. Pian Ambrogi (outcrop 2 in Fig. 1)

The southernmost sector of the Pian Ambrogi area is characterized by a staircase arrangement of the CVT (Fig. 6), separated by a gentle grassy slope covering FU marly limestones. The horizontal distance between the two steps is about one hundred metres, corresponding to a height difference of some tens of metres. Looking closely at the boundary between the FU and the upper step, it can be observed that the subhorizontal CVT bedding planes are cut abruptly by a steep surface dipping southwestward; the latter presents a highly irregular morphology and is patchily covered by a centimetre-thick mineralized crust (Fig. 7). containing planktonic foraminiferal associations (*Ticinella primula*, *T. raynaudi, T. roberti, Muricohedbergella* sp., *Macroglobigerinelloides* sp., *Rotalipora subticinensis*) which point to a Middle to Late Albian age. The FU onlaps this surface with the same geometric relationships observed in the Vallone dei Maestri outcrop, and similarly metre-sized CVT blocks embedded within the FU have been observed. The boundary between the FU and the CVT at the top of the lower step is not exposed; however, the geometry of the FU allows to infer a tangential downlap relationship.

4.1.3. Discussion

At both sites described above, the CVT−FU contact is a primary stratigraphic boundary showing anomalous features, with the bounding surface - clearly highlighted by the authigenic mineral crust - markedly discordant with the CVT bedding planes. This surface represents a specific type of angular unconformity in which the erosional surface dips more steeply than the beds of the underlying rocks. Although the intense Alpine tectonic overprint masks primary bedding within the FU, the onlap of FU sediments onto this surface may be reconstructed. Fully embedded within the FU, the metre-sized masses of the CVT represent original blocks that fell into the marly limestones of the FU during the early stages of deposition. The occurrence of planktonic foraminifera within the authigenic mineral crusts highlights the submarine origin of the surface and allows it to be dated to the Albian. The occurrence of cavities filled with sediment and cement in the CVT blocks points to the opening of fissures associated with creep processes taking place within poorly consolidated levels of the CVT preceding the block fall.

The evidence observed at the Vallone dei Maestri and Pian Ambrogi sites documents the existence of a wide palaeoescarpment incised within the CVT limestones, which was generated during the Albian and then progressively covered by the Upper Cretaceous FU marly sediments, and affected by the collapse of metre-sized blocks of the exposed partly-lithified substrate.

4.2. Passo delle Saline palaeoescarpment

4.2.1. Gias Gruppetti (outcrop 3 in Fig. 1)

The stratigraphic succession between the DSPM and the FU outcrops spectacularly on the eastern side of Cima delle Saline, just a few hundred metres north of Passo delle Saline (Fig. 8), with beds dipping 30-40° toward the SW. In the lower portion of the slope a massive rock body is present, composed of CVT light micritic limestones 5−6 m thick and some hundreds of metres wide. This roughly tabular rock body rests on a relatively planar surface which dips about 30° toward the SE and is deeply incised within the DSPM. The body itself is in turn onlapped by marly sediments attributable to the upper part of the Eocene CMC (Fig. 9). Underneath the rock body, a 1.5 m-thick breccia body occurs locally, internally organized in erosionally-based 20−40 cm-thick beds (Fig. 10). The breccia is clast-supported and poorly sorted, with millimetre- to centimetre-sized clasts of dolomites and a fine grained matrix. Two main different textures may be recognized in the clasts, including finely crystalline (crystals smaller than 50 μm) and coarsely crystalline dolomite (crystals up to 2 mm). Locally, the fine-grained dolomite clasts also show irregularly-shaped patches with a coarser crystal size. These lithologies may be correlated with the upper part of the DSPM where homogeneous, finely crystalline beds alternate with beds in which shrinkage pores, dissolution vugs and/or collapse breccias are filled with a coarse dolomite cement. Most clasts are internally crossed by a complex framework of spar-filled veins. Different generations of mutually crosscutting veins, some of which display a fibrous aspect, may be recognized by cathodoluminescence analysis. The fine-grained matrix of the breccia shows a complex network of very thin dark laminae with branched geometries, interpretable as fluid escape structures.

4.2.2. Discussion

The spectacular outcrop conditions on the eastern side of Cima delle Saline allow the observation of anomalous stratigraphic and geometric relationships between Triassic to Eocene lithostratigraphic units. From this it is interpreted that the present eastern side of the mountain closely corresponds to a submarine palaeoescarpment irregularly covered by monomict breccias with Triassic dolomite clasts, and onlapped by Eocene marly sediments. In this context, the big slab of CVT represents a large olistolith which slid down from the edge of the palaeoescarpment.

The features displayed by the breccias point to a complex genetic process. The different systems of veins document repeated fracturing and cementation of the parent rock preceding its exhumation and erosion. The breccias were thus most likely derived from the erosion of a fault-rock exposed at the sea floor due to the downward displacement of the fault hanging-wall. After transportation for a short distance by gravity, the clasts were accumulated in local depressions of the underlying palaeoescarpment together with minor amounts of a fine-grained matrix. Breccia deposition was soon followed by the emplacement of a large block which provoked the sudden expulsion of intergranular fluids, as shown by the fluid escape structures within the matrix.

4.2.3. Vallone Saline (outcrop 4 in Fig. 1)

This outcrop is located in the southern part of the N−S-oriented Vallone delle Saline. Exposed on the right-hand side of the valley and exhibiting a westward dip, QPN sandstones are separated by a high-angle eastward-dipping fault plane from a large domain (several hundred metres in size) that is internally subdivided into three blocks tilted in a domino-like arrangement. The upper portions of the blocks are composed of CVT massive limestones, while the depressions between the blocks are filled with the FU (Fig. 11). Specific geometric and facies features of the CVT can be observed in each block (Fig. 12).

Within the easternmost block the bedding surfaces dip 20−30° westward and are cut by the eastward-dipping surface which bounds the block to the west. Close to this surface, decimetre-thick beds show millimetre- to centimetre-thick cavities. Elongated and aligned to the bedding, these cavities are very irregular in shape and are filled with micrite and a sparry calcite cement, and also contain geopetal structures. The cavity-bearing beds are frequently and abruptly crossed by centimetre- to decimetre-wide sedimentary dykes perpendicular to the bedding. The dykes are themselves filled with breccias composed of millimetre-sized clasts and a micritic matrix (Fig. 13).

The CVT limestones of the central block are characterized by a regular centimetre-spaced lamination. Many millimetre-wide sedimentary sills also occur parallel to the lamination, containing a mixed infilling of red micritic sediment and microcrystalline calcitic cement. Both sills and laminae dip 20−30° eastward, and are cut by a 40−50° westward-dipping surface which bounds the western edge of the central block and which is patchily covered by a mineralized crust, very similar to that which commonly covers the stratigraphic top of the CVT. A few sedimentary dykes occur parallel to the palaeosurface; these are slightly wider than the sills parallel to the bedding and are filled with a reddish partially-mineralized sediment which locally contains small fragments of the mineralized crust.

The western block is bounded to the east by a steep (50−60°) surface which dips eastward and abruptly cuts the bedding surfaces - which here dip to the west, as in the eastern block. This surface is covered by a discontinuous, millimetre- to centimetre-thick clast-supported breccia (Fig. 14) made up of millimetre- to centimetre-sized CVT clasts, an intergranular carbonate sparry cement and a fine-grained matrix. Locally within the clasts, millimetre-sized irregular cavities are recognizable which are filled with a non-luminescent sparry cement. Most clasts are also crossed internally by different generations of crosscutting veins (Fig. 15). The intergranular sparry cement of the breccia is zoned and overgrows small fragments of the same cement infilling the veins within the clasts. The textural and structural features of these breccias indicate a prolonged and polyphase history of syndepositional fracturing at a very superficial level, which can be schematically subdivided as follows:

1) Creep movements within partially-lithified CVT sediments, probably due to a gravitational instability along a slope, caused the opening of irregular cavities that were quickly filled with an early sparry cement.

2) Repeated fracturing events associated with active fluid circulation provoked the opening and cementation of different vein systems.

3) The ongoing fracturing processes resulted in the formation of a breccia composed of CVT clasts, vein fragments and micritic sediment.

4) An early cementation episode led to the growth of the sparry intergranular cement.

4.2.4. Discussion

The present geometric setting of the Vallone Saline outcrop is the product of an Early Cretaceous faulting that resulted in the formation of three blocks variously downthrown, rotated and separated by morphostructural depressions. This process is clearly confirmed by the occurrence of small patches of the crust of authigenic minerals that coated all exposed surfaces of the resulting rugged sea-floor topography, which was subsequently covered by FU sediments. This faulting was associated with different syndepositional tectonic and gravitational instability phenomena, whose expression largely depends on the degree of lithification of the involved stratigraphic units. The breccia bodies covering the high-angle locally-mineralized palaeosurfaces (western block) and the dykes parallel to the surfaces (central block) are the most superficial expression, occurring just below the sediment-water interface, of a polyphase fracture zone corresponding to normal faults. The creep cavities, the centimetre- to decimetre-wide sedimentary dykes perpendicular to bedding (eastern block), and the millimetre-wide sedimentary sills parallel to bedding (central block) all indicate the presence of tensional stresses oriented parallel to bedding and represent indirect evidence of the dislocation and tilting of the blocks.

4.3. Colle del Pas palaeoescarpment

4.3.1. Colle del Pas (outcrop 5 in Fig. 1)

The steep mountainside west of Colle del Pas is composed of massive Permian volcanic rocks overlain by QPN Lower Triassic quartzarenites which dip 30° westward; on the gentler slope to the east, the Upper Cretaceous-Eocene succession is exposed, dipping 20−25° westward. The Permian volcanic rocks are abruptly truncated by an erosional surface dipping 40° to the east, which is itself overlain by a 15 m-thick succession of well-bedded sediments (Figs. 16, 17). These sediments exhibit unique compositional and sedimentological features not observed anywhere else within the stratigraphic succession of the study area. Three intervals may be distinguished:

Interval 1 (6−7 m thick) is composed of 1−2 m-thick alternating purple and whitish beds, both of which display erosional basal bases, rapid variations in thickness and pinch-out terminations. The purple beds are composed of fine-grained breccias to arenites which locally exhibit a parallel lamination. Cathodoluminescence analysis enabled to distinguish three different kinds of grain:

1) Quartz crystals, showing a well-developed cathodoluminescence zonation, with bright blue cores and purple to red edges identical to the quartz phenocrystals of the Permian volcanic rocks.

2) Purple microcrystalline grains, with the same pale blue luminescence as shown by the groundmass of the Permian volcanic rocks. Veins, 100's μm-wide and filled with a dull brownish luminescent quartz, locally display a fibrous habit and are confined within the grains (Fig. 18).

3) Polycrystalline quartz grains, showing the same features as the above-described veins.

The white beds are composed of fine- to medium-grained sandstones of the same composition as the purple beds; the difference in colour is due to the greater abundance of quartz grains.

Interval 2 (0.5−1 m thick) is a yellowish massive bed made up of a clast-supported breccia with millimetre-sized limestone clasts and a partially dolomitized micritic matrix;

Interval 3 (2 m thick) is a light-coloured massive micritic limestone bed, with a basal polygenic clast-supported breccia containing millimetre- to centimetre-sized *Saccocoma*-bearing CVT clasts, dolomite clasts and polycrystalline quartz grains.

Interval 3 is bounded at its top by an irregular surface which is partly covered by discontinuous and thin beds of fine-grained limestone with scattered chert nodules and an ill-defined internal wavy lamination, which can be attributed to the FU formation.

Above interval 3, the outcrop conditions are poor, high-angle late Alpine faults cross the succession and thus sedimentary bodies cannot be traced laterally. However, some tens of metres to the east just above the FU, discontinuous portions of CMC are recognizable. The dip of the bedding planes, commonly 20−25° westward, quickly decreases to horizontal approaching the erosional surface that truncates the Permian volcanic rocks and thus it is possible to infer onlap relationships with the discontinuous levels of FU described above.

4.3.2. Discussion

Many authors (e.g. Faure-Muret and Fallot, 1954; Guillaume, 1969; Lanteaume et al., 1990) have pointed out the presence of a high-angle kilometre-long normal fault, passing through Colle del Pas with a N−S strike, and have related it to a late stage of Alpine orogenesis. The data set outlined above, however, leads to consider the geological setting of Colle del Pas as instead being the result of a Cretaceous fault-related palaeoescarpment, whose evolution can be tentatively reconstructed in a number of steps.

Starting from the Early Cretaceous, the Mesozoic succession and underlying massive Permian volcanic rocks were dissected by a high-angle N−S striking normal fault. Close to the main fault plane, Permian crystalline rocks were repeatedly and intensively fractured giving rise to a fault breccia, early cemented by silica-rich fluids.

Total fault displacement progressively increased to 600−700 m, leading to the exhumation of all stratigraphic units of the footwall, including the Permian volcanic rocks. The margin of the footwall block was then progressively exhumed and eroded, resulting in the formation of a steep escarpment. The lower portion of this escarpment was partially covered by coarse-grained sediments derived from the erosion of the margin - first of the quartz-cemented fault breccia and then of the carbonate breccias containing clasts of the Upper

Jurassic rocks. The occurrence of FU sediments resting on these sediments constrains the main phase of fault activity to the Cretaceous.

The morphological depression generated by the fault displacement was partially filled during the Middle−Late Eocene by the deposition of the CMC sediments. Alpine tectonic foliations later developed in all the lithostratigraphic units, but without any significant change of the primary stratigraphic relationships.

4.3.3. Colle del Pas North (outcrop 6 in Fig. 1)

Despite poor outcropping, scattered blocks were observed north of Colle del Pas along the northern portion of the Colle del Pas escarpment. In the area between Lake Ratoira and the Sestrera pass, a lozenge-shaped rock slice some hundreds of metres long, tens of metres thick and composed of Triassic and Jurassic carbonate rocks, is sandwiched between the Permian volcanic rocks to the west and the FU to the east. The boundary with the Permian rocks is represented by a N−S-oriented surface dipping about 30−40° to the east but the surface itself cannot be directly observed. The eastern boundary with the FU is locally well-exposed, and appears as an irregularly-shaped surface which dips on average 20−30° eastward draped by thin levels of FU in clear stratigraphic contact (Fig. 19). The elongated rock body is composed of different blocks - not in stratigraphic relationships - in which the typical lithologies of the DSPM, CRN and CVT are recognizable. In the largest block, a portion of succession including the top of the DSPM and the lower part of the CRN occurs. This site demonstrates that the breccia deposits with Permian volcanic clasts are discontinuous and that very large olistoliths of carbonate rocks may occur along the palaeoescarpment strike.

4.3.4 Valle del Pas (outcrop 7 in Fig. 1)

At this site, located several hundred metres south of Colle del Pas, the dolomitic limestones of the Costa Losera Formation are widely exposed, dipping slightly to the SW.

These limestones are abruptly truncated by a sharp surface which dips 20−30° towards the SE and which is characterized by an irregular morphology. This surface is discontinuously covered by centimetre- to decimetre-thick patches of a whitish clast-supported breccia composed of millimetre- to centimetre-sized dolomite clasts and a fine-grained matrix (Fig. 20). The textural and compositional features of the clasts are the same as those described in section 4.2.1 occurring in the breccia levels at Gias Gruppetti.

Breccia sediments also occur as infillings of sub-vertical fissures tens of decimetres wide, which strike nearly parallel to the NE-dipping surface. Just beneath this surface, the uppermost part of the dolomitic limestones consists of an ‘in-situ breccia’ defined by a network of millimetre- to centimetre-wide highly irregular veins filled with a calcitic sparry cement. Cavities one millimetre in width with a thin isopachous rim of finely crystalline calcite cement and a micrite infilling occur locally (Fig. 21). Cathodoluminescence shows that both cement and micrite, with their bright yellow luminescence, are markedly different from the surrounding dully luminescent dolomitic limestones and in fact closely resemble the matrix and cement of the breccias.

Most veins do not cross the overlying breccia deposit, indicating that deposition of the latter took place after the fracturing of the dolomitic limestones (Fig. 20). The intensity of this fracturing progressively decreases with depth, and after a few decimetres the veins become more spaced and eventually disappear.

A number of rock bodies composed of metres-thick CVT limestones with a tabular geometry and an areal extent ranging from tens to hundreds of metres, directly lean on the NE-dipping surface. Both the NE-dipping surface - which is patchily draped by the whitish breccia - and the large CVT rock bodies are in turn onlapped by Eocene marly sediments.

4.3.5. Discussion

The stratigraphic and geometric relationships observed at this locality perfectly match those described at Gias Gruppetti, and can thus be interpreted in the same way. At Valle del Pas the lower boundary of the breccias and the Triassic dolomitic limestones are well-exposed, with the rocks underlying the palaeoescarpment affected by intense fracturing. The occurrence of breccia-filled dykes and irregular cavities filled with the micritic matrix of the breccias further supports the interpretation of the escarpment as a depositional surface, and also documents the opening of the fissures in the underlying rocks after their denudation and exposure close to the sea floor. Two distinct stages of fracturing are recorded here. The first, occurring before palaeoescarpment formation, gave rise to a complex network of calcite- or dolomite-filled fractures within the rock mass. The second took place close to the surface after palaeoescarpment formation, and was possibly related to a mechanical relaxing of the dolomitic limestones (e.g. Jaeger et al., 2007).

4.4. Mongioie palaeoescarpment

At Bocchin dell’Aseo, close to Monte Mongioie (outcrop 8 in Fig. 1), the DSPM outcrops extensively, with bedding planes dipping slightly to the SW. These are truncated by an irregular surface which dips eastward by about 30° and is discontinuously overlain by breccias. The breccia deposits locally reach a total thickness of 80 cm and are internally subdivided into dm-thick beds. The texture and composition of the clasts are almost the same as those seen in the breccia levels at Gias Gruppetti and Valle del Pas, with the only difference being maximum clast size which reaches into the tens of centimetres at Bocchin dell’Aseo (Fig. 22). A metre-sized block of CVT lies directly on the surface and the breccia sediments, and is in turn covered by the Eocene marly sediments. A few tens of metres east of the surface, a larger, decametre–sized block composed of both CRN and CVT limestones is entirely embedded within the Eocene marly sediments. A palaeoescarpment also occurs in the

Mongioie area, exhibiting the same features and evolution as those at Colle del Pas and Saline.

5. Neptunian dykes and subvertical breccia bodies

Neptunian dykes infilled with Cretaceous sediments were observed in two different settings. In the southern part of Pian Ambrogi, a few tens of metres north of the Chiusetta palaeoescarpment, many vertical and horizontal neptunian dykes occur within the upper part of the CVT. A few centimetres to several decimetres in width, these dykes are filled with red sediments containing scattered centimetre- to decimetre-sized clasts of CVT (Fig. 23). The red sediment is a wackestone/packstone containing mineralized echinoderm fragments, bivalves, and benthic and planktonic foraminifera of generally Middle Albian-Late Cenomanian age (e.g. *Ticinella primula*, *Whiteinella aprica*, *Dicarinella* sp., *Rotalipora cushmani*). The local occurrence of clasts consisting of the same red sediment or of finer-grained similar breccias indicates a polyphase opening and infilling of the dykes (Fig. 24).

Close to the southern part of the Colle del Pas palaeoescarpment, two dykes with different infillings are recognized within the CVT. Subvertical, striking N−S and about 1 m wide, the first dyke is filled with the FU and locally contains decimetre-sized clasts of CVT. The dyke walls and the edges of the CVT clasts are patchily covered by a millimetre- to centimetre-thick mineralized crust. The second dyke is 20−50 cm wide, dips 40° northward and is directly observable for more than 100 m. The infilling sediment in this case is a red-coloured packstone containing mineralized echinoderm fragments, belemnites and small mineralized crust clasts. Outcrop conditions make it impossible to evaluate how deep the dykes penetrate the CVT.

A close resemblance to these neptunian dykes is displayed by breccia bodies occurring at a number of different sites in the Pian Ambrogi area within the CRN and CVT (Fig. 25). Ranging in thickness from a few decimetres to 2 m thick, these breccia bodies are characterized by tabular geometry and occur sub-perpendicular to bedding with a N−S strike. The breccias also exhibit textural features similar to those of the above-described breccia deposits which rest on erosional surfaces, being matrix-supported, strictly monomict breccias composed of millimetre- to centimetre-sized clasts of the enclosing formation (CRN or CVT) and a fine-grained matrix. The clasts are internally crosscut by different systems of veins infilled with a calcite cement, while many fragments of the same cement occur within the matrix (Fig. 26). Very thin veins, filled with both a sparry cement and fine-grained sediment, commonly occur in the matrix. These show complex branched geometries recalling fluid escape structures (Fig. 26). Locally, barite crystals occur among clasts within the sparry cement. Some O and C stable isotope analyses of the breccia have been undertaken (Table 1). The marked difference in $\delta^{18}O$ of clasts, matrix and cements clearly shows that, in spite of the Alpine deformation, neither recrystallization nor reequilibration has taken place since breccia formation. The strongly negative $\delta^{18}O$ values of the matrix and cements are therefore primary signals and document the involvement of hot fluids in the precipitation of the authigenic carbonates. The slightly negative $\delta^{18}O$ values of the clasts may relate to a limited contribution of strongly negative calcite precipitated in residual pores still present in the enclosing fine-grained sediments during breccia cementation. The $\delta^{13}C$ values, varying between 1.4 to 2.1 ‰ PDB, are in the range of normal marine waters and thus any contribution of organic matter or hydrocarbons to carbonate precipitation can be ruled out.

5.1. Discussion

The neptunian dykes fit the model of opening and sediment-filling of fissures close to the sea floor, well known from numerous western Tethyan examples (e.g. Wendt, 1971; Castellarin, 1972; Winterer et al., 1991; Winterer and Sarti, 1994). However, a similar process cannot explain the formation of the tabular breccia bodies. The strictly monomict nature of the breccias and the presence of different systems of veins within the clasts point to an in situ brecciation process occurring within a semi-lithified sediment. Polyphase veining and fracturing episodes took place and were most probably associated with a tensional regime. The fluid escape structures and isotope values indicate the important role of fluids - most probably overpressured and hot - in the production and cementation of the breccia.

6. Discussion

6.1. Evidence of palaeoescarpments

The anomalous contacts observed among different lithostratigraphic units - in some cases previously interpreted as tectonic - in fact represent primary stratigraphic boundaries (Fig. 27). These contacts consist of irregular erosional surfaces more or less deeply incising a stratigraphic succession that may range from Upper Jurassic limestones (CVT) down to Permian volcano-sedimentary rocks. Such surfaces are partly exposed and partly covered by Upper Cretaceous (Formazione di Upega) or Eocene (Calcari della Madonna dei Cancelli) sediments, with the localized occurrences of distinctive breccia deposits or crusts of authigenic glauconite, phosphates and Fe-Mn oxides identical to the those marking the normal stratigraphic CVT − FU boundary. No significant evidence of shear at the boundary is present. Moreover, metre- to tens of metres-sized blocks of Upper Jurassic limestones occur either directly overlying the surface or embedded within the Upper Cretaceous or Eocene sediments, indicating that these surfaces are palaeoescarpments that developed in submarine environments.

Four different kilometre-long palaeoescarpments (Chiusetta palaeoescarpment, striking E−W, and Colle del Pas, Passo delle Saline and Mongioie palaeoescarpments, striking N−S) have been recognized and mapped in the study area.

At present, the Chiusetta palaeoescarpment falls within a large polyphase post-Oligocene Alpine shear zone (Limone−Viozene deformation zone; Piana et al., 2009). Primary stratigraphic relationships and sedimentologic/diagenetic features are however still clearly recognizable, making it possible to define the nature and evolution of this palaeosurface that may be followed along strike for several kilometres. The N−S-striking palaeoescarpments (from west to east: Colle del Pas, Passo delle Saline and Mongioie) are also well-preserved. Not only is it possible to evaluate the original relief, in the order of hundreds of metres, as well as the geometric/stratigraphic relationships between the sedimentary bodies juxtaposed along these kilometre-long palaeoescarpments, but it is also feasible to investigate in detail the sedimentologic and petrographic features of distinctive deposits which adhere to the surfaces, such as breccias and authigenic mineral crusts.

6.2. Palaeoescarpments as remodelled palaeofault scarps

Two main mechanisms are usually called upon to explain the genesis of escarpments in marine settings: mass gravity flows - that leave a scar upslope - and faulting. Both the nature and rheological state of the rocks within which the studied palaeoescarpments were incised (mainly Permian volcanics and Triassic dolomites), as well as the degree of vertical displacement, enables submarine landslides to be excluded as the process responsible for the generation of the surfaces. The escarpments are instead morpho-structural elements resulting from the remodelling of palaeofault planes by gravity-driven block fall processes. Clast-supported yet fine-grained matrix-bearing breccias, locally organized in beds with erosional bases, blanket the escarpments fairly continuously and represent the first products of erosional processes to accumulate at the foot of the surfaces. The occurrence within the breccias of clasts characterized by polyphase vein systems suggests that they are related to the erosion of fault rocks and thus supports the fault-related escarpment hypothesis (Fig. 27).

The partially early-lithified Upper Jurassic limestones (CVT) occurred at the top of the sedimentary column crossed by the fault planes., The supposedly intense fracturing of these rocks, subjected to an extensional regime, then provided suitable conditions for the formation, detachment and sliding of metre- to tens of metres-sized blocks along the surfaces, just before or during the deposition of Cretaceous−Eocene sediments which onlapped the surfaces and filled the structural depressions.

Further evidence of tensional stresses active at the Early−Late Cretaceous boundary in the study area is provided by the occurrence of both sub-vertical sedimentary dykes and bed-parallel creep cavities within the Upper Jurassic CVT limestones. The tabular bodies of monomict breccias within the Middle and Upper Jurassic limestones may correspond to cataclastic zones parallel to the N−S-trending palaeofaults but characterized by minor amounts of vertical displacement. Such zones likely represented preferential conduits for the circulation of uprising fluids, whose hydrothermal origin is documented by negative $\delta^{18}O$ values. The multiphase evolution of the breccias may be related to high fluid pressure that led to hydraulic fracturation and cementation of the resulting breccias.

6.3. Age of faulting

Planktonic foraminiferal assemblages contained within the crust of authigenic minerals coating the top of the Upper Jurassic CVT and the uppermost portion of the E−W palaeoescarpment indicate an Aptian age for the beginning of the fault-related displacements (Fig. 27). The occurrence of FU sediments just above the whitish and red-purple conglomerates which rest directly on Permian volcanic rocks at Colle del Pas shows that most displacement took place during the Late Cretaceous. At other sites, the present level of erosion does not allow to observe the deepest parts of the escarpments in which the oldest onlapping sediments occur. An Early−Late Cretaceous age of scarp formation may also be the case for sites at which the palaeoescarpment is directly covered by Eocene sediments. The intense deformation and extreme scarcity of recognizable microfossils within the whole FU (except for the basal hardground) hinders a precise dating of the oldest sediments onlapping the palaeoescarpment, which could range from Cenomanian to Maastrichtian. The time span over which the total displacement of about 700 m was accomplished may accordingly range from a few to a maximum of 30 my. In any case, the average rates of fault displacement are in the order of some cm/ky, which is still much less than that observed along active faults in modern extensional settings such as the Gulf of Corinth (Lykousis et al., 2007).

The onlap of Eocene CMC marly sediments onto the escarpments and the occurrence of blocks of the Upper Jurassic CVT, fully embedded within the same Eocene sediments, both show that the topography relating to the activity of Cretaceous faults was not yet levelled during the Eocene, and thus blocks could fall from scarps in which Upper Jurassic limestone was still exposed.

6.4. Geodynamic context

The large dataset available with regards to the mid-western Mediterranean clearly documents the occurrence of significant tectonic activity close to the Early−Late Cretaceous boundary. This period in fact corresponds to a phase of geodynamic restructuration at the scale of the whole Western Tethys. Palaeogeographic reconstructions have shown that in the Early Cretaceous this area represented a complex junction zone crossed by regional strike-slip fault zones (Dercourt et al., 2000; Golongka, 2004). Major plate tectonic events taking place between the Hauterivian and the Cenomanian resulted in the break-up of the Newfoundland and Iberian margins, i.e. the opening of the N Atlantic, followed by the eastward transcurrent movement, in the order of 300−500 km, and counterclockwise rotation of Iberia away from Europe that led to the opening of the Bay of Biscay (Olivet, 1996; Gong et al., 2009; Lagabrielle et al., 2010). At the same time the eastern part of the Iberian/European margin was affected by the opening of the Valais Ocean (Stampfli, 1993; Stampfli et al., 1998; Handy et al., 2010; Loprieno et al., 2011), while an important transform system crossed the European continent in a roughly E−W direction, connecting the Bay of Biscay to the Valais and Ligurian-Piedmont oceans.

Evidence of a transcurrent tectonism is recorded in the Pyrenean realm, where it is associated with intense extensional deformation, crustal stretching and mantle exhumation (Lagabrielle and Bodinier, 2008; Jammes et al., 2009; Lagabrielle et al., 2010). In the southwestern French subalpine domain, extensional to strike-slip Early Cretaceous tectonics controlled the evolution of the boundary between the Provençal platform and the Vocontian Basin (Friès and Parize, 2003; Montenat et al., 2004). The associated regional fault activity is documented by the occurrence of fault scarps onlapped by Albian sediments, conglomerate beds and olistoliths (Dardeau and de Graciansky, 1987; de Graciansky et al., 1987; de Graciansky and Lemoine, 1988; Montenat et al., 1997; Montenat et al., 2004), and multiple stratigraphic hiatuses taking place within the Lower Cretaceous (Hibsch et al., 1992; Pasquini et al., 2004). A regional hiatus occurring during the Aptian−Albian is also documented within the Briançonnais Domain (Barfety et al., 1996), while Claudel et al. (1997) and Claudel & Dumont (1999) reported the incidence of two different synsedimentary extensional events in the Albian and Turonian, respectively.

The Ligurian Briançonnais Domain was located at the easternmost end of a regional transform system connecting the Bay of Biscay to the Valais and Ligurian-Piedmont oceans (e.g. Stampfli, 1993; Stampfli et al., 2002; Rosenbaum and Lister, 2005; Handy et al., 2010) (Fig. 28). In this tectonic context, the study area may be envisaged as a Cretaceous kilometre-sized fault-bounded basin bordered to the north and south by two main E−W transcurrent faults - in some way related to the present-day Verzera and Limone-Viozene transpressive zones - and internally partitioned by east-dipping normal faults (Colle del Pas, Passo delle Saline, Mongioie) with vertical displacement in the order of some hundreds of metres (Fig. 29). Locally, minor west-dipping normal faults give rise to small horst-and-graben structures with blocks downthrown by a few tens of metres (e.g. the Vallone Saline outcrop).

7. Conclusions

The main results of the present paper may be summarized as follows:

- Kilometre-scale palaeoescarpments have been recognized in the central part of the External Ligurian Briançonnais in the Ligurian Alps. They consist of irregular erosional surfaces more or less deeply incising the Permian to Upper Jurassic rock column and are onlapped by Upper Cretaceous−Upper Eocene sediments.
- The presence of discontinuous breccia bodies containing clasts of fault rocks and draping palaeoescarpments demonstrates that the latter resulted from the erosional sculpturing of normal fault planes exposed in a submarine environment. Large-scale rock fall processes then

caused the emplacement of olistoliths of Upper Jurassic limestones directly over the surfaces or embedded within onlapping sediments.

- The occurrence of subvertical sedimentary dykes and tabular in situ breccia bodies, related to cataclastic zones, further supports a tensional regime. Negative vein calcite $\delta^{18}O$ values and the fluid escape structures observed within the tabular breccias are both suggestive of hydraulic fracturing by upward flows of overpressurized, hot fluids.
- The biostratigraphic ages of the authigenic mineral crust, which coats the top of the CVT and localized areas of the uppermost parts of the palaeoescarpments, indicate that fault activity started in the Aptian; most displacement took place during the Late Cretaceous and gave rise to morphostructural depressions up to several hundred metres deep.
- The recognition of different systems of mappable palaeoescarpments suggests that, during the Cretaceous, the study area corresponded to a fault-bounded basin limited by E−W transcurrent zones and internally partitioned by N−S normal faults. This inferred geotectonic setting could be consistent with the palaeogeographic position of the Ligurian Briançonnais Domain; located at the easternmost end of a transform system that at the Early−Late Cretaceous boundary connected the Bay of Biscay to the Valais and Ligurian-Piedmont oceans.
- The results of this study are relevant in particular for geologists working in mountain chains where present-day geometric relationships between rock bodies are mainly interpreted as the result of contractional tectonics related to orogenic processes. The primary architecture of a sedimentary basin, controlled by syndepositional faults, can in fact be well-preserved even on a large scale, and within structural domains affected by polyphase deformation and very low grade metamorphism.

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FIGURE CAPTIONS

Fig. 1. A. Location of the study area. AM: Argentera massif; D: Dauphinois units; HF: *Helminthoides* Flysch unit; PP: Pre Piemontese units; LB: Ligurian Briançonnais units; TU: Colle di Tenda unit. B. Geological sketch map of the study area, with the four recognized palaeoescarpments (CP: Chiusetta palaeoescarpment; CPP: Colle del Pas palaeoescarpment; PSP: Passo delle Saline palaeoescarpment; MP: Mongioie palaeoescarpment) and the location of the described outcrops (1: Vallone dei Maestri; 2: Pian Ambrogi; 3: Gias Gruppetti; 4: Vallone Saline; 5: Colle del Pas; 6: Colle del Pas North; 7: Valle del Pas; 8: Bocchin dell'Aseo). VIDZ: Limone-Viozene deformation zone; VZSZ: Verzera shear zone. Modified after Piana et al. (2009).

Fig. 2. Simplified stratigraphic section of the External Ligurian Briançonnais succession. In the right column acronyms of the lithostratigraphic units, as used in the text, are reported.

Fig. 3. Panoramic view of the Vallone dei Maestri, showing the E−W oriented Calcari di Val Tanarello (CVT) − Formazione di Upega (FU) boundary (dashed line), corresponding to the Chiusetta palaeoescarpment. The black asterisk points to the Vallone dei Maestri outcrop. The Don Barbera hut (encircled) for scale is about 20 m long.

Fig. 4. Vallone dei Maestri outcrop (locality 1 in Figure 1). Picture and interpretive sketch of the mineralized surface incised within the Calcari di Val Tanarello (CVT), and onlapped by the Formazione di Upega (FU) sediments. At the base of the surface a metre-sized Calcari di Val Tanarello block (CVT b) is visible. Thin lines highlight bedding planes. Hammer for scale is 35 cm long. HG: mineralized crust.

Fig. 5. Vallone dei Maestri outcrop. A. Photomicrograph showing an irregular creep-related cavity occurring in a Calcari di Val Tanarello block. Note the isopachous calcite cement rim. The square indicates position of B. B. Close up of Figure A in cathodoluminescence, highlighting the geopetal infilling and the cathodoluminescence zonation of the cement.

Fig. 6. Staircase arrangement of the Pian Ambrogi outcrop, with two morphological steps made up of Calcari di Val Tanarello limestones (CVT) separated by Formazione di Upega sediments (FU). Dotted lines indicate the Calcari di Val Tanarello − Formazione di Upega boundaries. The black dot points to location of Fig. 7.

Fig. 7. Pian Ambrogi outcrop (locality 2 in Figure 1). Subhorizontal Calcari di Val Tanarello (CVT) bedding planes (white dotted lines) of the upper morphological step are abruptly truncated by a steep surface patchily covered by a mineralized crust (HG) and onlapped by the Formazione di Upega (FU). A graphic sketch of the geometric relationships is shown in the box at the upper left corner.

Fig. 8. Panoramic view of the eastern side of the Cima delle Saline, preserving large evidence of a submarine palaeoescarpment. The a-b line corresponds to the schematic cross section shown on Figure 9.

Fig 9. Schematic, not to scale, section across the eastern side of the Cima delle Saline showing stratigraphic and geometrical relationships. The section line (a-b) is shown in Figure 8 and is about 300 m long. DSPM: Dolomie di San Pietro dei Monti; CRN: Calcari di Rio di Nava; CVT: Calcari di Val Tanarello; CMC: Calcari della Madonna dei Cancelli; br: breccia sediments.

Fig. 10. Gias Gruppetti outcrop (locality 3 in Figure 1). Stratified breccia deposits (br) between the Calcari di Val Tanarello block (CVT) and the underlying palaeoescarpment, incised into the Dolomie di San Pietro dei Monti (DSPM).

Fig. 11. Vallone Saline outcrop (locality 4 in Figure 1). Calcari di Val Tanarello limestones are subdivided into three blocks (WB: western block; CB: central block; EB: eastern block) showing a domino-like arrangement. The depressions between the blocks are filled with Formazione di Upega (FU) sediments. Height of the cliff on the right side is about 50 m.

Fig. 12. Graphic sketch of Figure 11. All the mesoscopic and microscopic features described in the text are represented schematically. WB: western block; CB: central block; EB: eastern block; CVT: Calcari di Val Tanarello; FU: Formazione di Upega; HG: hard ground; ND&S: neptunian dykes and sills; br: breccias.

Fig. 13. Vallone Saline outcrop. Cavity-bearing beds within the eastern block. A. Cavities (Cc) are irregularly shaped, elongated and aligned to bedding. They are filled with a sparry calcite cement, locally showing geopetal structures. B. Polished slab showing cavities abruptly crossed by a sedimentary dyke (d) filled with a breccia. Hatched lines indicate bedding.

Fig. 14. Vallone Saline outcrop. A. A steep surface incising the Calcari di Val Tanarello (CVT) bounds to the east the western block and is onlapped by Formazione di Upega sediments (FU). Breccias (br) plaster the surface. Hatched white lines in the CVT indicate bedding planes. B. Close-up view of the surface, with the thin and discontinuos breccia (br).

Fig. 15. Thin section of the breccia of Figure 14, in transmitted light (A) and in cathodoluminescence (B). Clasts are internally crossed by different generations of veins.

Fig. 16. Panoramic view of the Colle del Pas southern side. The white asterisk points to the location of Figure 17. In the corresponding graphic sketch below, the boundaries between different lithological units are shown. V: Permian volcanics; QPN: Quarziti di Ponte di Nava; FU: Formazione di Upega; CMC: Calcari della Madonna dei Cancelli; br: breccia sediments.

Fig. 17. Colle del Pas outcrop (locality 5 in Figure 1). An erosional surface (hatched white line) dipping at medium angle to SE is incised into the Permian volcanic rocks (V) and is overlain by well-bedded breccia sediments.

Fig. 18. Photomicrographs of the fine-grained breccias of the Colle del Pas outcrop, Level 1, showing veins (v) filled with dull brownish luminescent fibrous quartz cement and confined

within microcrystalline volcanic grains (g), showing a pale blue luminescence. A. Transmitted light, crossed nicols. B. Cathodoluminescence.

Fig. 19. Colle del Pas North outcrop (locality 6 in Figure 1). Thin beds of Formazione di Upega sediments (FU) draping an irregular surface, abruptly truncating the Calcari di Val Tanarello limestones (CVT) of the elongated rock body. Black arrows point to the stratigraphic contact. Hammer for scale is 35 cm long.

Fig. 20. Valle del Pas outcrop (locality 7 in Figure 1). A thin layer of whitish clast-supported breccia drapes an irregular surface incised into the highly fractured dark dolomitic limestones of the lower part of the DSPM. Note that a thin vein in the dark dolomitic limestones (encircled) does not cross the overlying breccia.

Fig. 21. Valle del Pas outcrop. Photomicrograph of a cement-rimmed and micrite-filled cavity within the DSPM dolomitic limestones, just beneath the breccia. A. Transmitted light. B. Cathodoluminescence.

Fig. 22. Bocchin dell'Aseo outcrop (locality 8 in Figure 1). Breccia beds resting on the Mongioie paleoescarpment. Hammer for scale is 35 cm long.

Fig. 23. Pian Ambrogi. Vertical dyke (d) within the upper part of Calcari di Val Tanarello (CVT). Hammer for scale is 35 cm long. Dyke walls are marked by black lines.

Fig. 24. Detail of the infilling sediment of the dyke of Figure 23. Note that some clasts show a brecciated texture documenting polyphase fracturing and infilling.

Fig. 25. Tabular sub-vertical breccia body (black arrow) occurring within the subhorizontal Calcari di Rio di Nava (white arrow). The hammer head in the upper right is about 18 cm long.

Fig. 26. Photomicrographs of the breccia of Figure 25. The clast in the middle is crosscut by two different veins (I and II). Fragments of type II veins are also observable in the matrix.

Note the occurrence of very thin veins (tv) in the matrix showing branched geometries. A. Transmitted light. B. Cathodoluminescence.

Fig. 27. Sketch representing four steps in the evolution of Cretaceous palaeofaults and their remodelling into palaeoescarpments. For the sake of graphical simplicity, the Middle−Upper Jurassic limestones are represented as a tabular body although it was reported by Bertok et al. (2011) that thickness changes occur in the Middle – Upper Jurassic succession and palaeoescarpments were already present during its deposition. V: Permian volcanics; QPN: Quarziti di Ponte di Nava; DSPM: Dolomie di S. Pietro dei Monti; CRN: Calcari di Rio di Nava; CVT: Calcari di Val Tanarello; FU: Formazione di Upega; CMC: Calcari della Madonna dei Cancelli; HG: hard ground; br: breccia sediments; fr: fault rocks; ol: olistholith.

Fig. 28. Palaeogeographic map of the Western Tethys in the Aptian, showing the location of the Marguareis − Mongioie area (black asterisk). Redrawn after Handy et al. (2010) and Stampfli et al. (2002).

Fig. 29. Schematic plan-view and 3D sketch of the Cretaceous kilometre-sized fault-bounded basin. VIDZ: Limone-Viozene deformation zone; VZSZ: Verzera shear zone.

Table 1. Stable isotope data from the sub-vertical breccia bodies.

References

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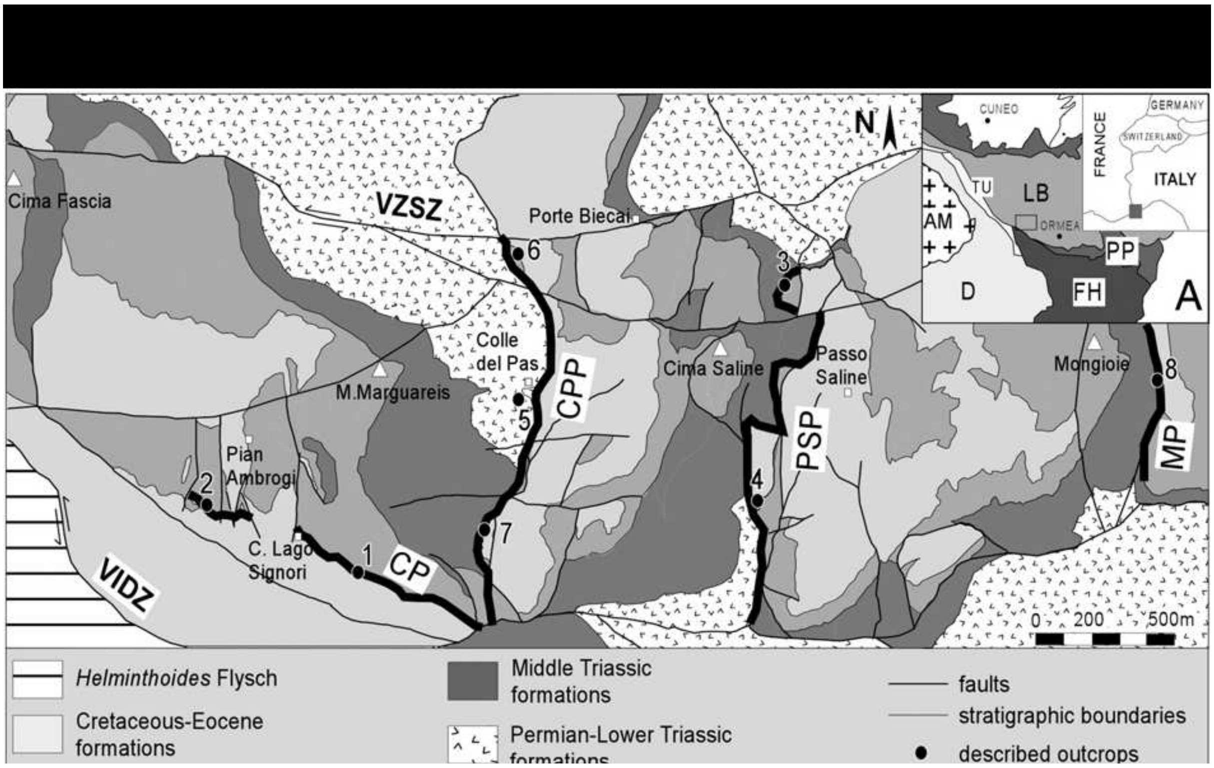

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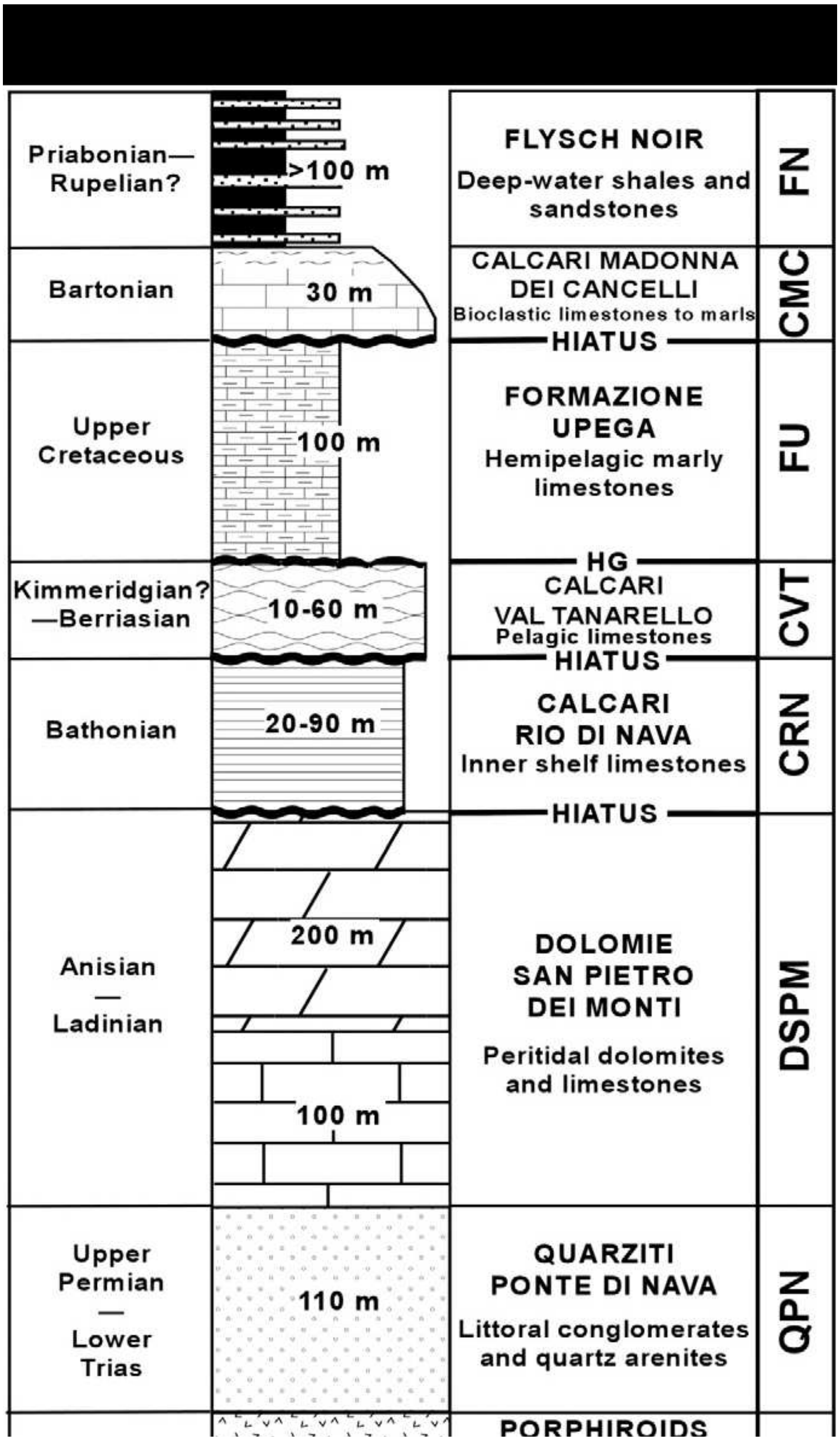
Fig. 1


Priabonian—
Rupelian?
>100 m
FLYSCH NOIR
Deep-water shales and sandstones
FN
Bartonian
30 m
CALCARI MADONNA DEI CANCELLI
Bioclastic limestones to marls
CMC
HIATUS
Upper Cretaceous
100 m
FORMAZIONE UPEGA
Hemipelagic marly limestones
FU
HG
Kimmeridgian?
—Berriasian
10-60 m
CALCARI VAL TANARELLO
Pelagic limestones
CVT
HIATUS
Bathonian
20-90 m
CALCARI RIO DI NAVA
Inner shelf limestones
CRN
HIATUS
Anisian
—
Ladinian
200 m
100 m
DOLOMIE SAN PIETRO DEI MONTI
Peritidal dolomites and limestones
DSPM
Upper Permian
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Lower Trias
110 m
QUARZITI PONTE DI NAVA
Littoral conglomerates and quartz arenites
QPN
PORPHIROIDS

Fig. 2

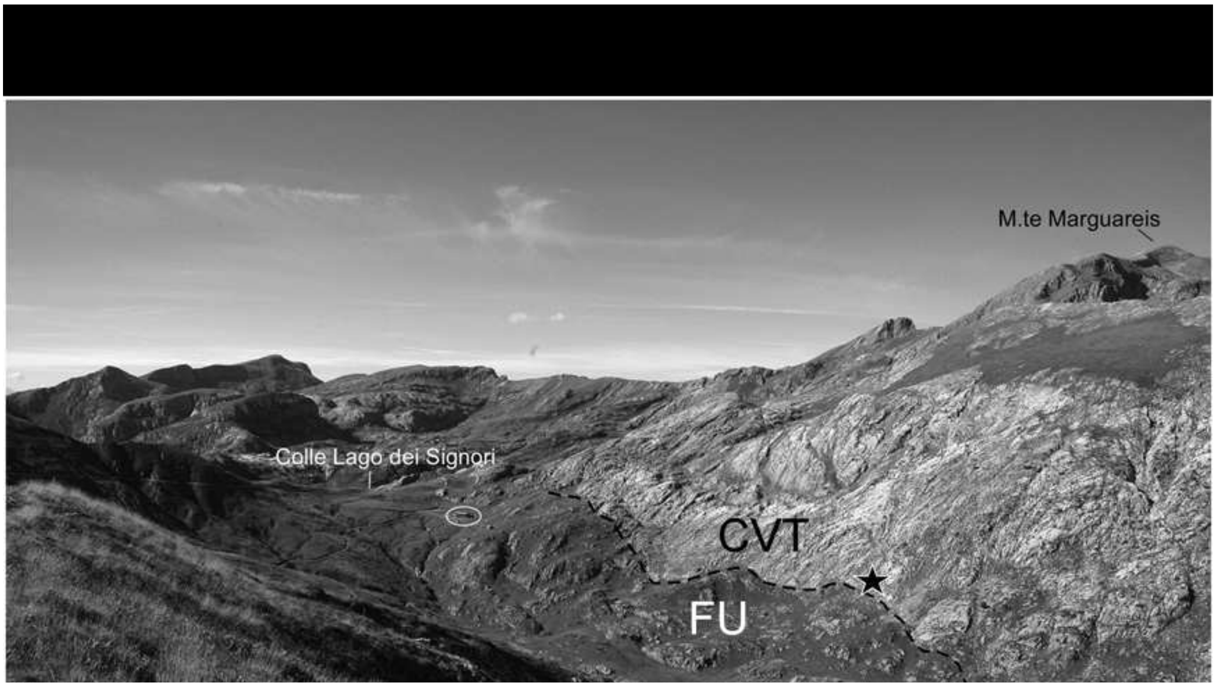

Fig. 3

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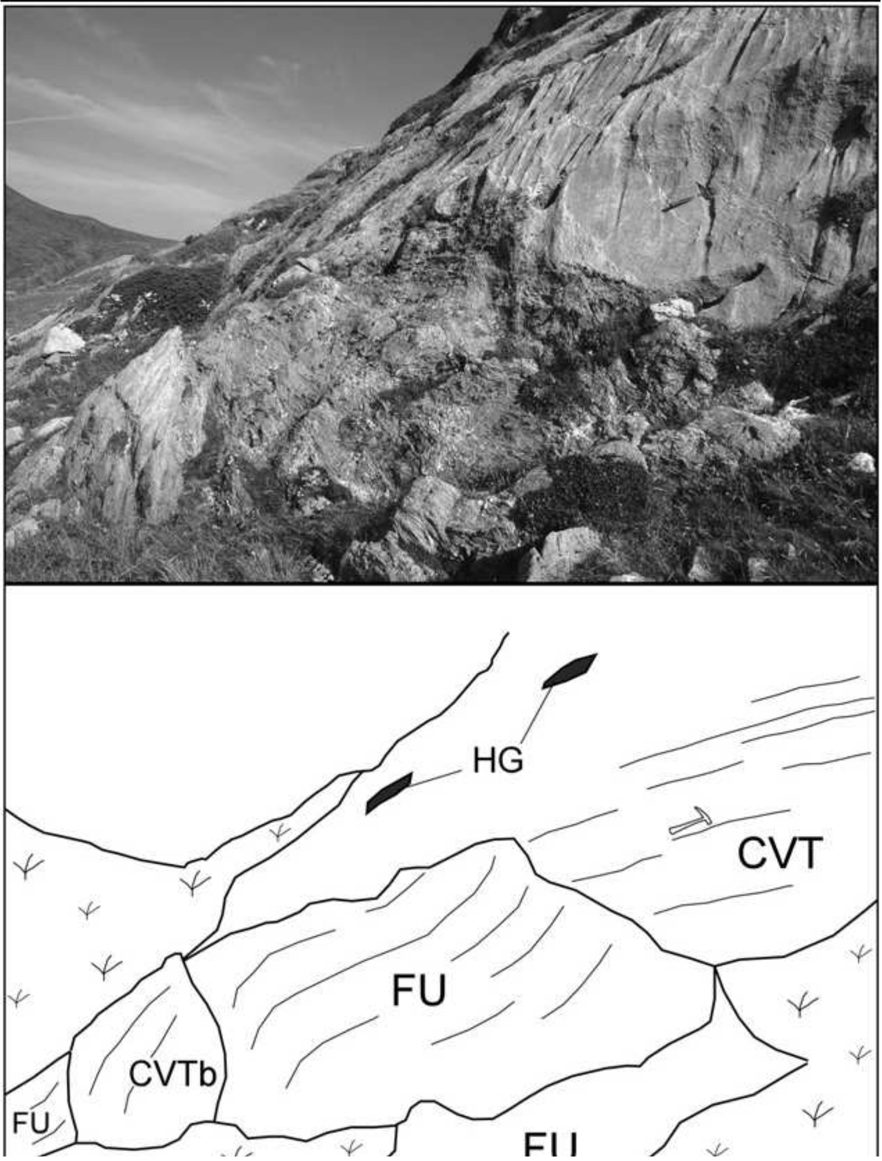

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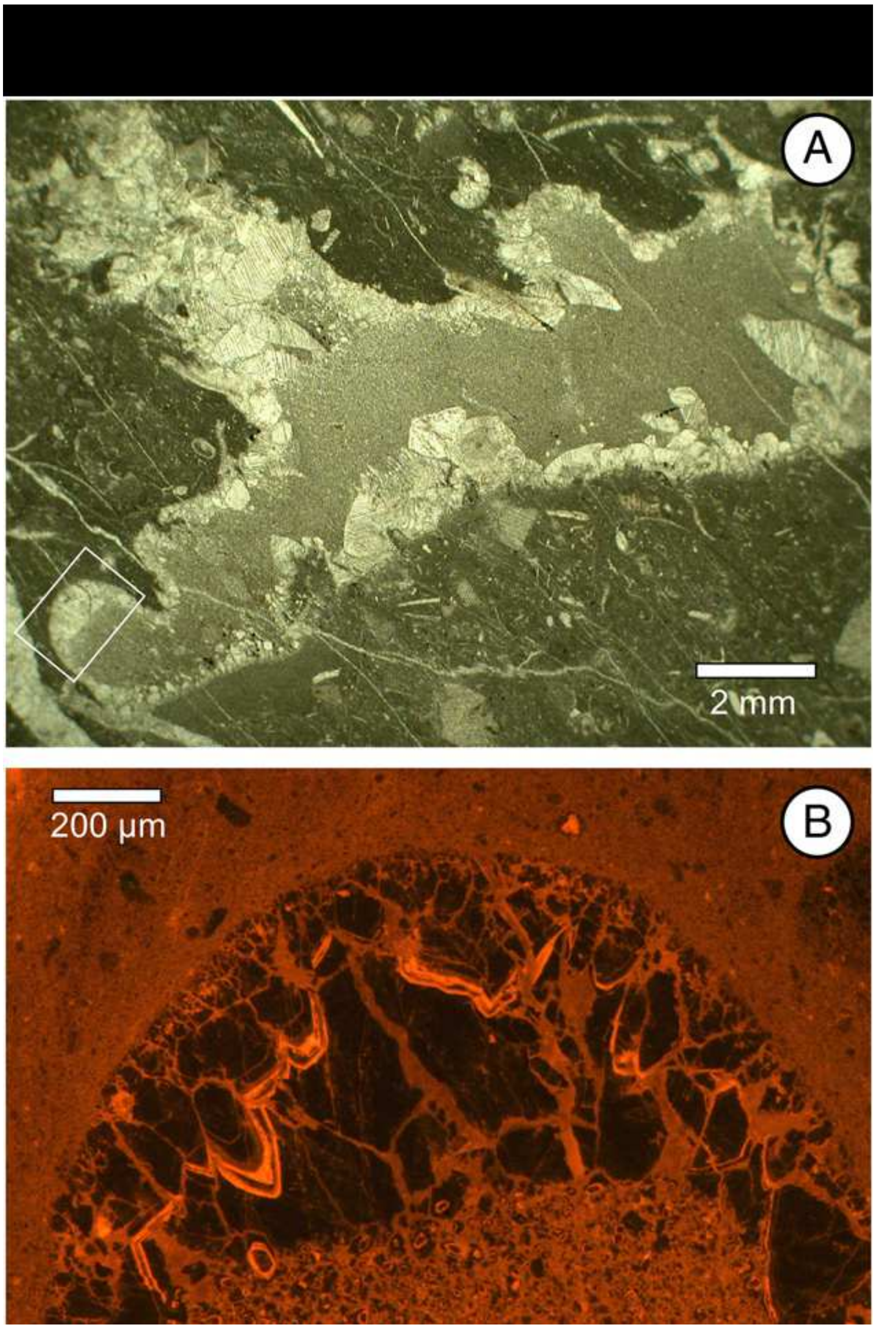

Fig. 5

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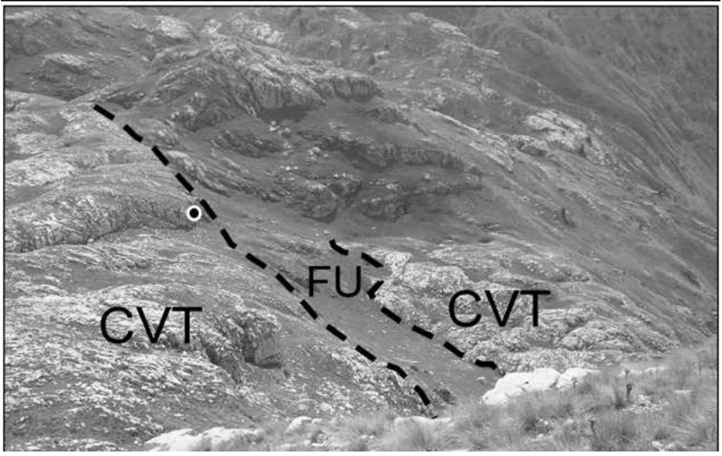

Fig. 6

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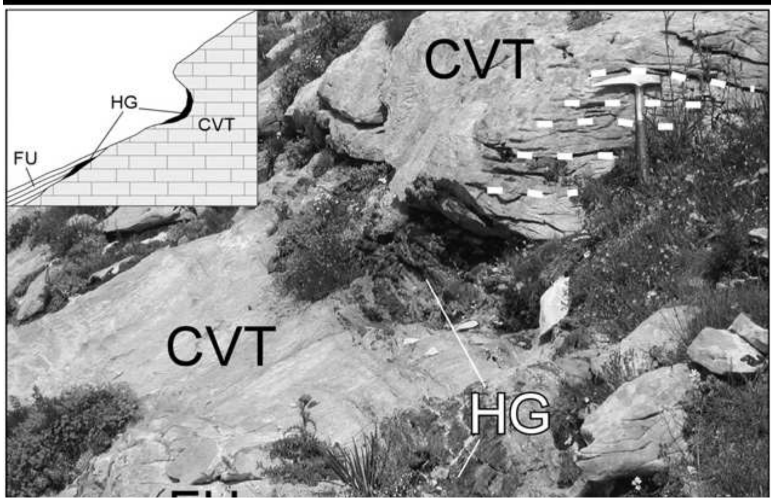

Fig. 7

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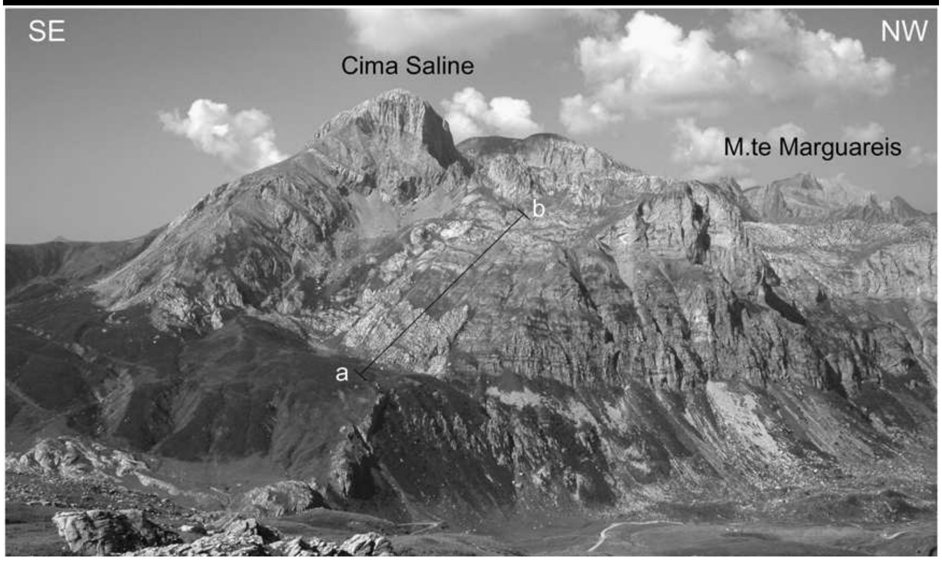

Fig. 8

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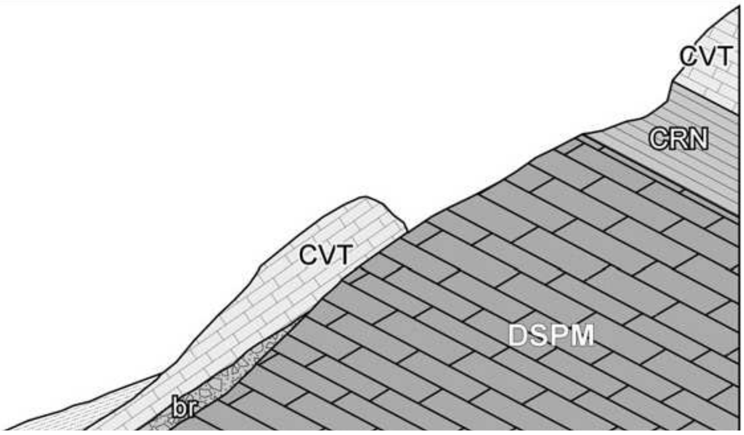
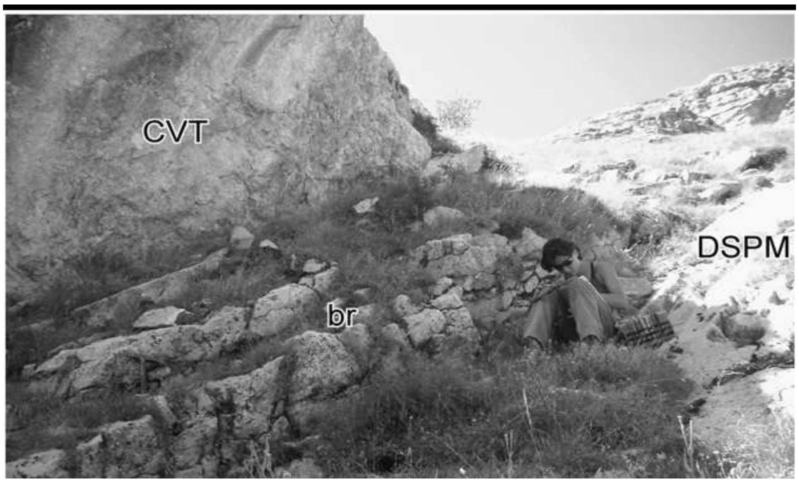


Fig. 9



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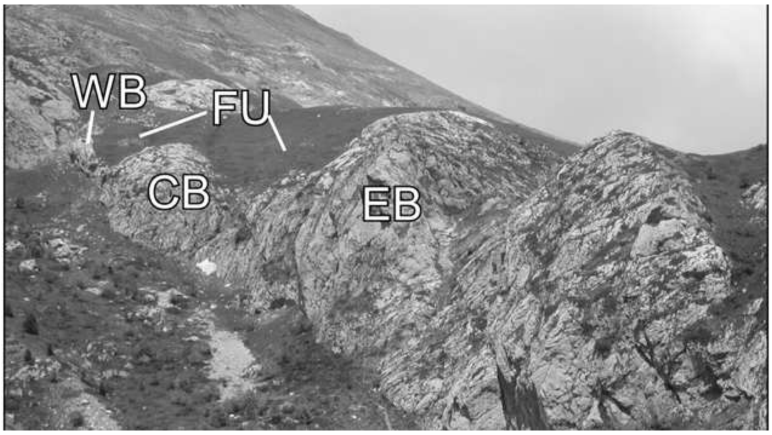
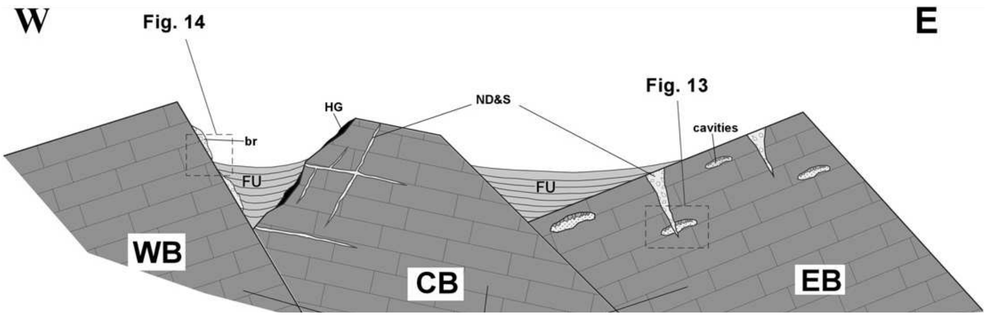


Fig.11



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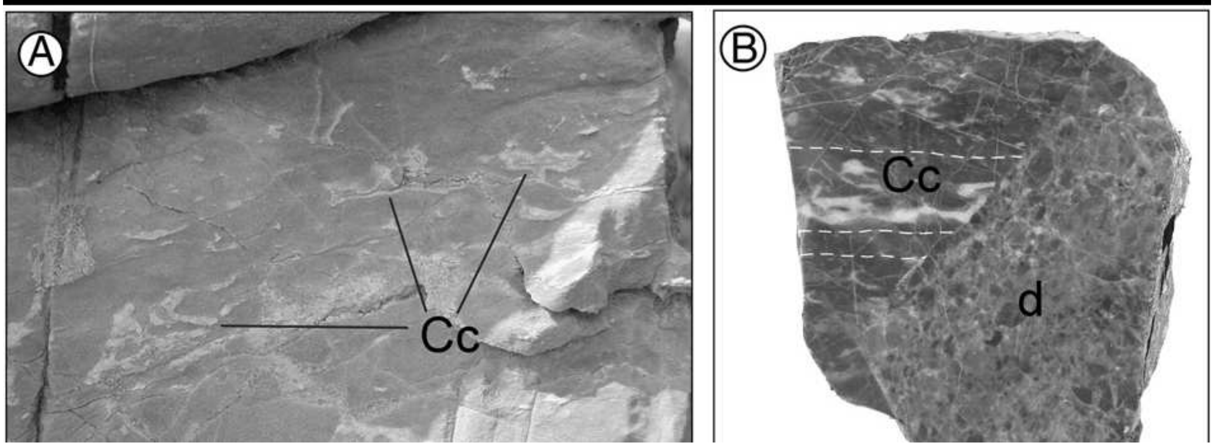

Fig. 13

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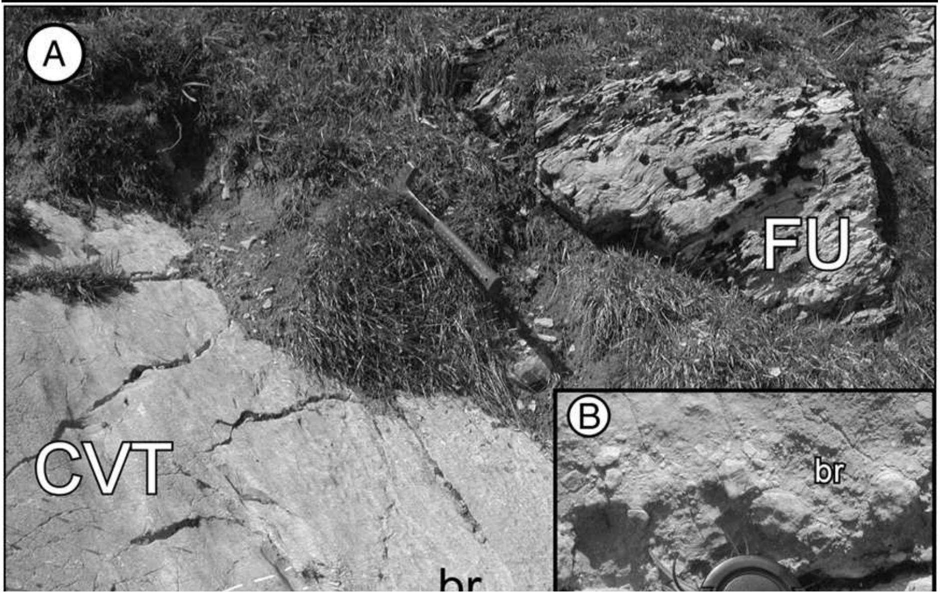
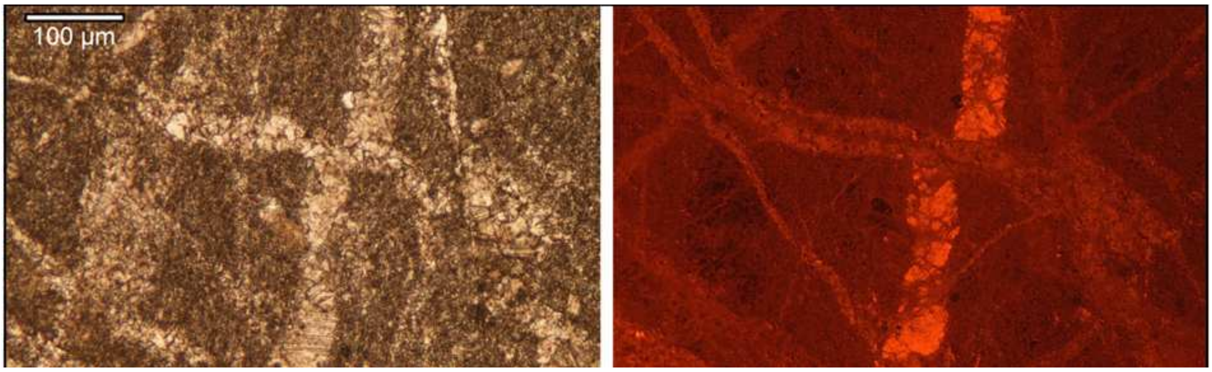


Fig. 14



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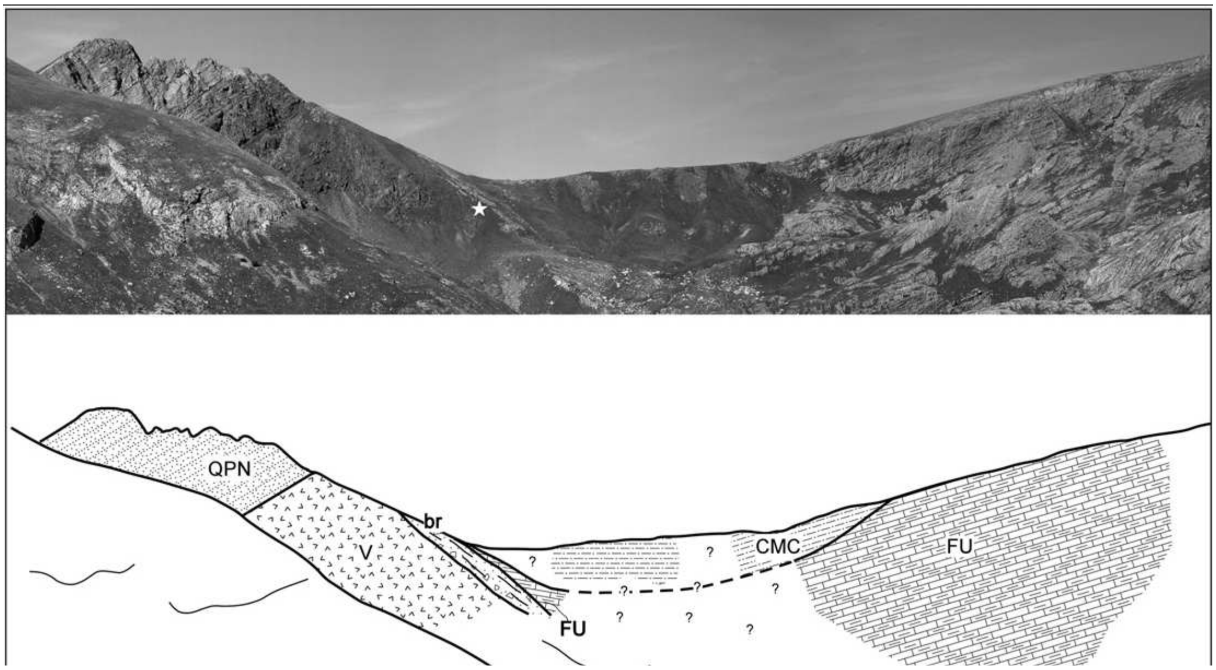
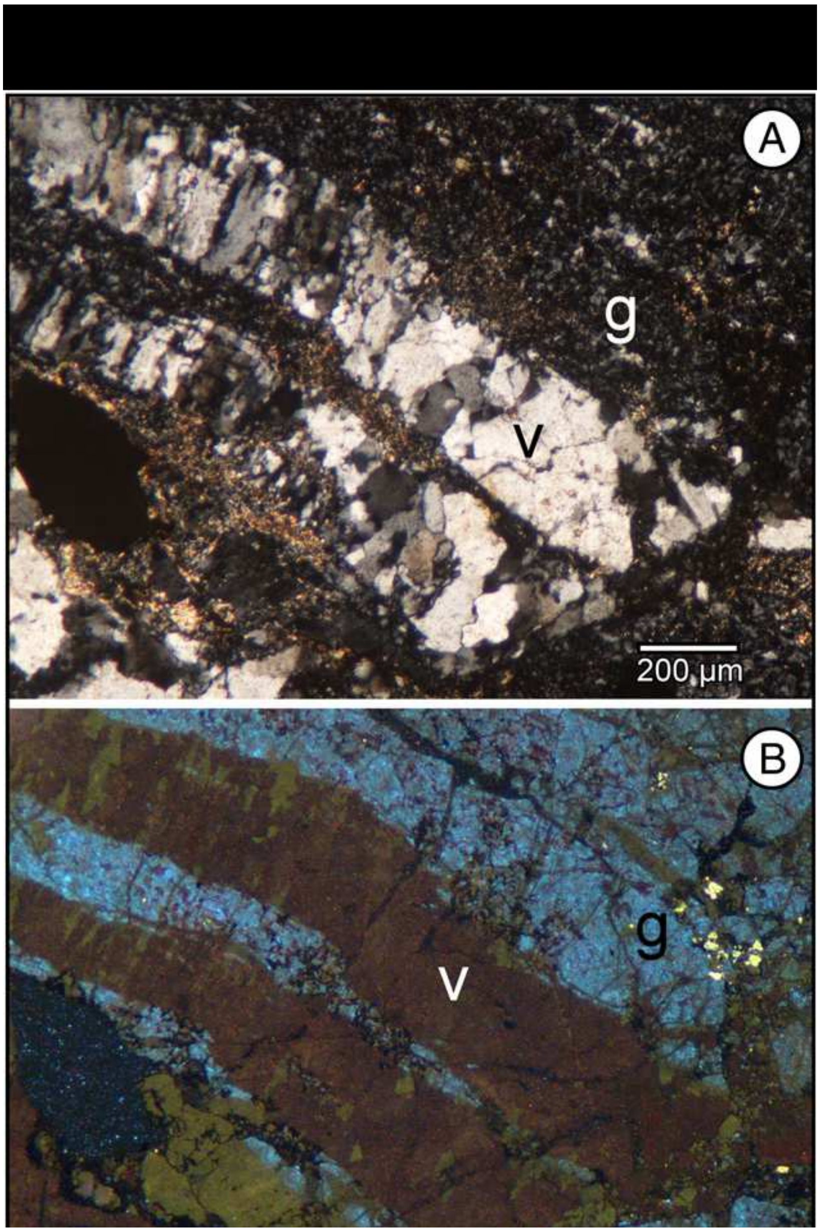


Fig. 16

Fig. 17



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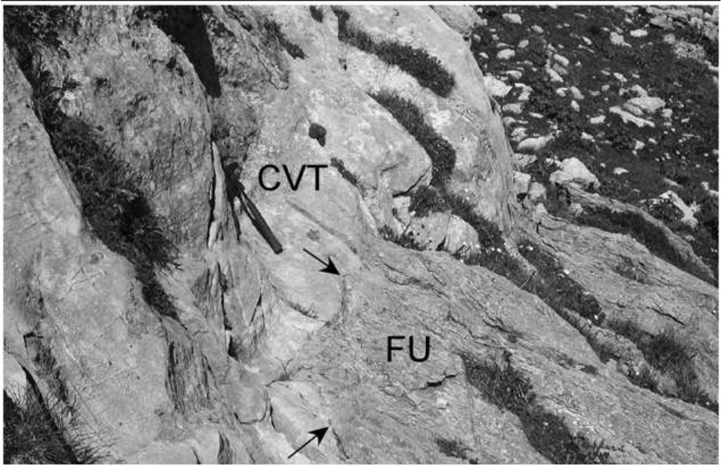

Fig. 19

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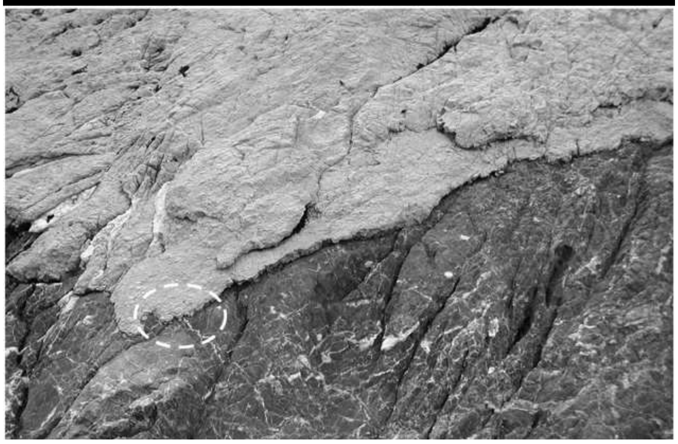

Fig. 20

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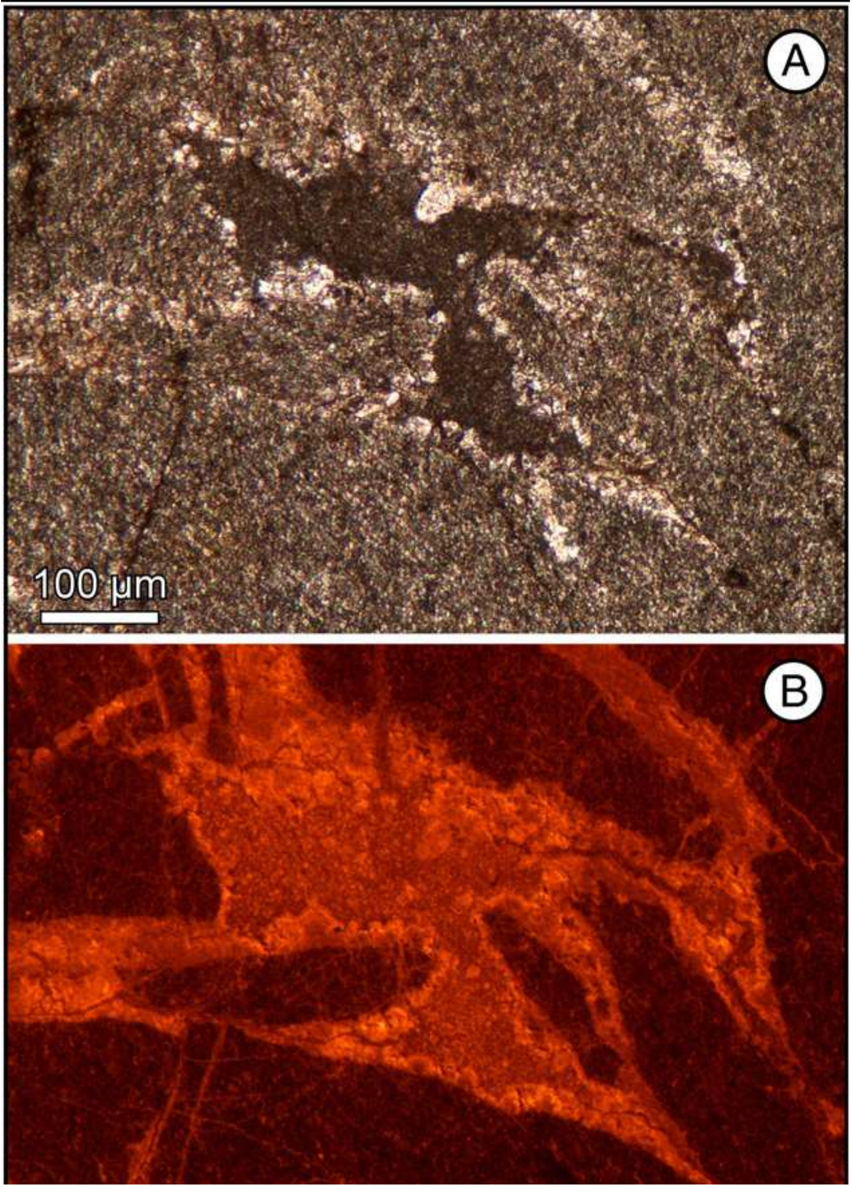

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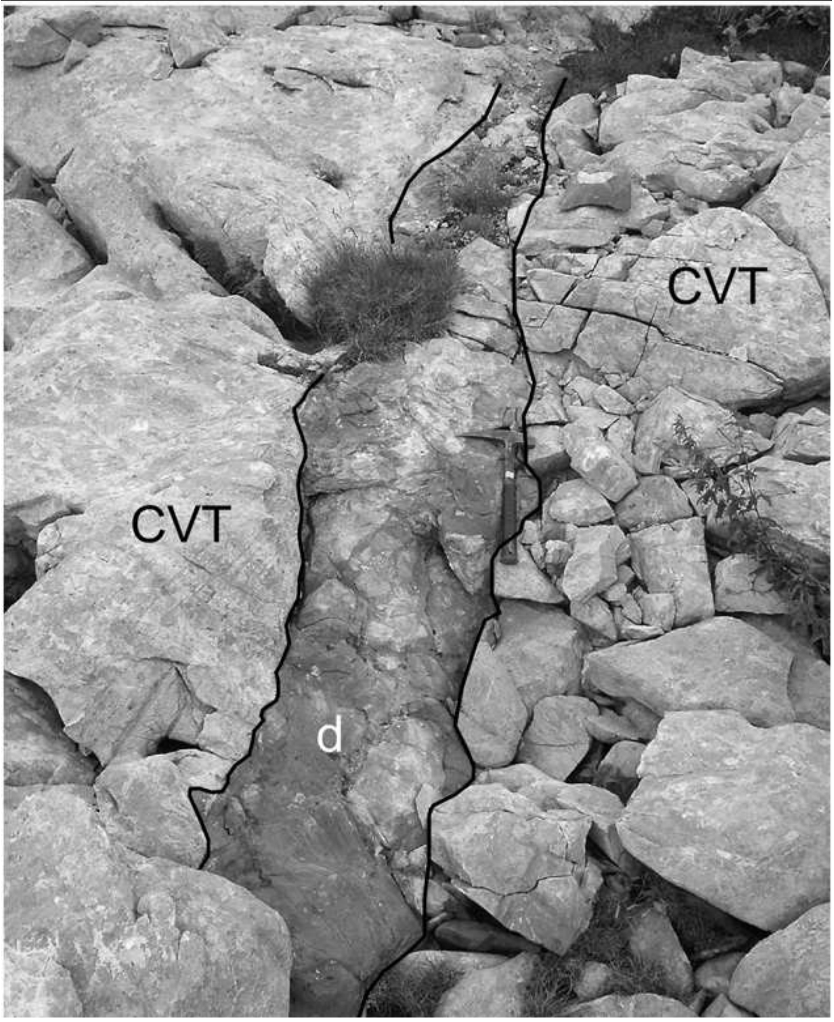

Fig. 23

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[redacted]

Fig. 25

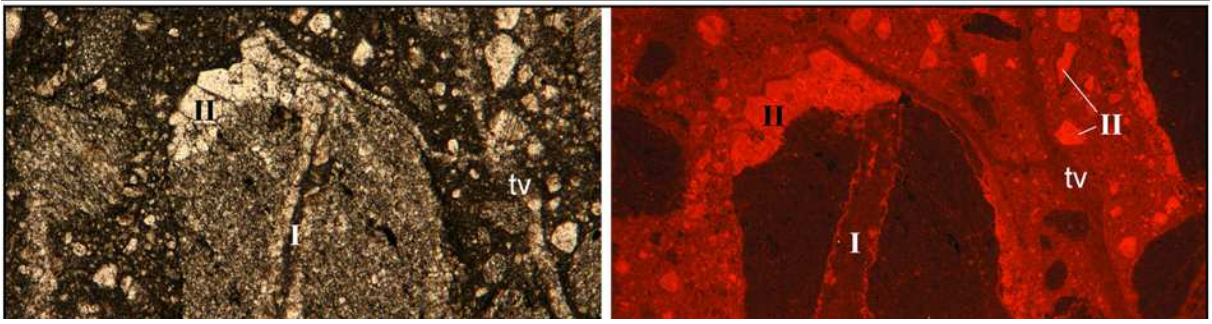

Fig. 26

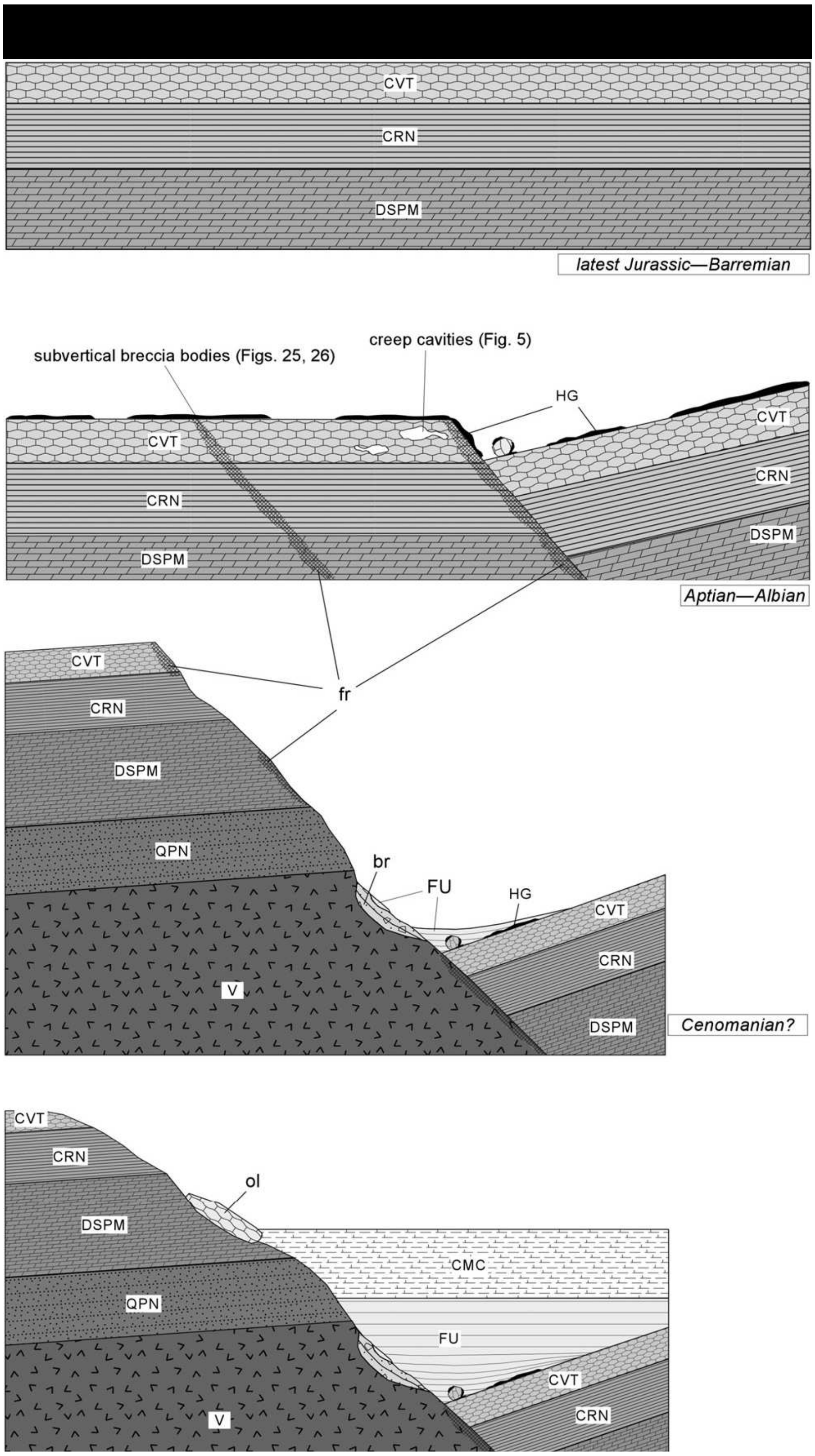
CVT
CRN
DSPM
latest Jurassic—Barremian
subvertical breccia bodies (Figs. 25, 26)
creep cavities (Fig. 5)
HG
CVT
CRN
DSPM
CVT
CRN
DSPM
Aptian—Albian
CVT
CRN
DSPM
QPN
fr
br
FU
HG
CVT
CRN
V
DSPM
Cenomanian?
CVT
CRN
ol
DSPM
CMC
QPN
FU
CVT
CRN
V

Fig. 27

[redacted]

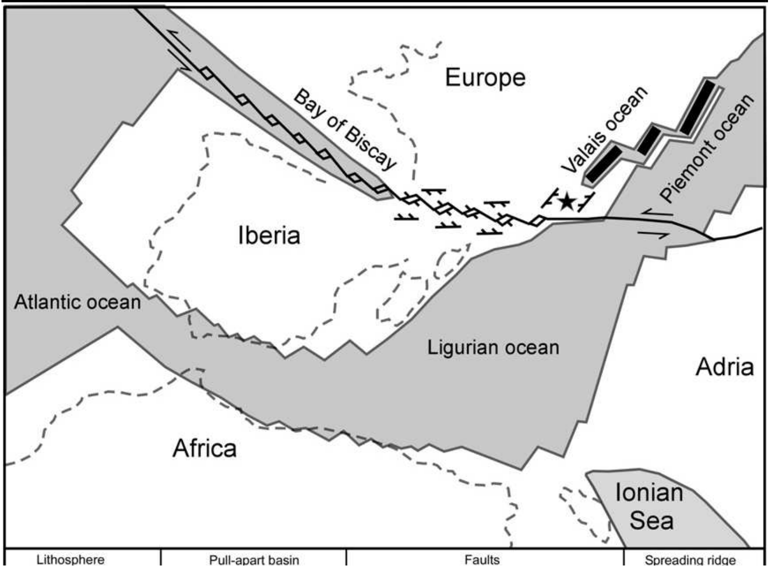

Fig. 28

[redacted]

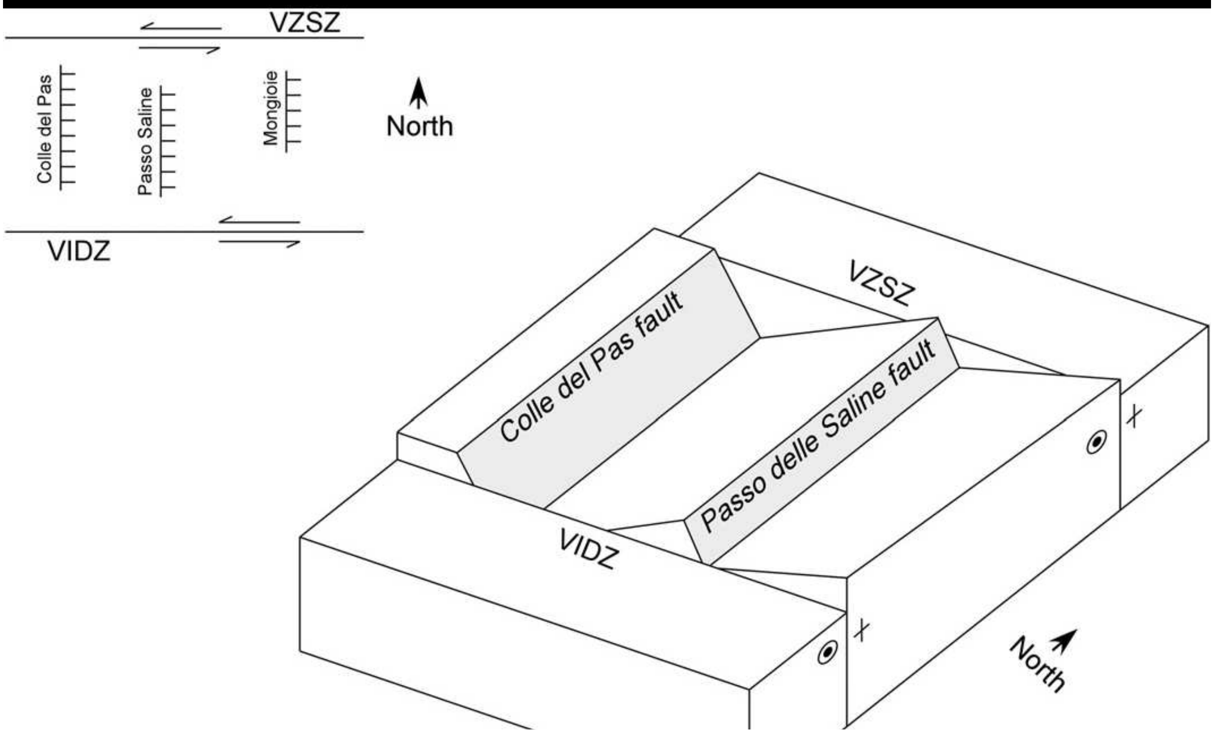

Fig. 29