New data on post-Eocene tectonic evolution of the External Ligurian Briançonnais (Western Ligurian Alps)

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Nuovi dati sull'evoluzione tettonica post-eocenica del Brianzonese Ligure Esterno (Alpi liguri occidentali)

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ABSTRACT

A new structural setting for the central part of the External Ligurian Briançonnais (CELB) is proposed. CELB is divided into km-scale tectonic units that still preserve pre-Alpine geological features at several stratigraphic levels. Macro-, meso- and microscale primary features, such as paleoescarpments, unconformities and depositional or diagenetic fabrics are thus well preserved and can be still mapped and studied in detail at many stratigraphic levels.

Significant transposition of bedding is recorded only in Upper Cretaceous and Eocene marly limestones and shales and in major km-long shear zones, where intense development of closely spaced tectonic foliations occurred.

Several features indicate that the CELB tectonic evolution took place at shallow crust levels: 1) strong localization of deformation along the weakest stratigraphic levels, 2) absence of diffuse recrystallization of rocks, 3) minor occurrence or absence of transposition of bedding, 4) kinematic evolution of fold axial plane foliations into frictional slip cleavages.

A gradual decrease in the intensity of deformation from the Internal Ligurian Briançonnais to CELB and Dauphinois Domain is observed, although the boundaries of these three domains correspond, in the study area, to several Km-long, transpressive shear zones whose kinematic role in the evolution of the southern termination of Western Alps should be carefully considered.

Key words: Ligurian Briançonnais Domain, Meso-Cenozoic carbonate succession, Alpine transpressive tectonics, palaeofaults.

RIASSUNTO

Dopo oltre un secolo di geologia alpina, nelle Alpi occidentali rimangono ancora ampie regioni nelle quali la conoscenza geologica di base, stratigrafica e strutturale, non è aggiornata alla luce delle moderne metodologie e del generale stato di avanzamento delle conoscenze. In tali regioni, inoltre, la cartografia ufficiale è ancora rappresentata dai rilevamenti di inizio ‘900. Il Brianzonese Ligure Esterno è una di queste regioni, in particolare per quel che riguarda il settore centro-occidentale compreso tra Ormea e il Massiccio dell’Argentera, nella zona del Colle di Tenda. Questa regione, caratterizzata dalla presenza di molte delle unità paleogeografiche e strutturali alpine che in essa si rastremano, è cruciale per l’interpretazione dell’assetto e dell’evoluzione geologica cenozoica della parte meridionale delle Alpi occidentali.

Recentemente un progetto di revisione stratigrafica e strutturale basato su rilevamenti di dettaglio alla scala 1:10.000 è stato intrapreso nel settore centrale del Brianzonese Ligure Esterno (CELB) tra il Monte Mongioie e la Cima della Fascia, avendo come punti di riferimento i lavori di Vanossi (1972, 1974), Vanossi *et alii* (1984) e Gosso *et alii* (1983) e per quel che riguarda l’adiacente settore interno del Brianzonese Ligure i recenti lavori di Seno *et alii* (2003, 2005b). Gli studi condotti hanno permesso la ridefinizione dell’assetto strutturale macroscopico del CELB e hanno portato all’individuazione di sottounità geometriche bordate da faglie e zone di taglio frizionali, all’interno delle quali i caratteri stratigrafici e sedimentologici primari appaiono ben preservati, a differenza di quanto riportato in letteratura per l’adiacente Brianzonese Ligure Interno. Gli effetti della deformazione alpina, localizzati in corrispondenza di alcuni livelli stratigrafici e in particolari contesti strutturali, non corrispondono a significative e/o generalizzate trasposizioni o riorganizzazioni geometriche, né a diffusi fenomeni di ricristallizzazione o dissoluzione delle rocce. Gli effetti di dissoluzione per pressione, seppur ampiamente diffusi nella successione sedimentaria, sono confinati lungo superfici stilolitiche discrete (clivaggi spaziati) che non obliterano la struttura primaria delle rocce. Solo all’interno di domini strutturali compresi nelle principali zone di taglio, gli effetti della dissoluzione per pressione sono concentrati in più ampi volumi rocciosi, senza tuttavia determinare una completa ricristallizzazione delle rocce. Il buon grado di preservazione delle successioni sedimentarie ha permesso di osservare in maniera ubiquitaria, a tutte le scale e a quasi tutti i livelli stratigrafici, numerose strutture sedimentarie

deposizionali e diagenetiche quali superfici di stratificazione e di discordanza, filoni sedimentari, laminazioni da corrente, cavità da disseccamento, zonature composizionali in cementi calcitici, dettagli morfologici in macro- e microfossili. Inoltre, è stato possibile riconoscere una paleoscarpata di faglia, estesa a scala chilometrica e associata a rigetti di ordine ettometrico, lungo la quale sedimenti del Cretacico superiore poggiano direttamente sulle vulcaniti permiane con un contatto stratigrafico primario solo in minima parte riattivato in età alpina. La localizzazione della deformazione, l'assenza di ricristallizzazione delle rocce e di una significativa trasposizione delle superfici di stratificazione, e l'evoluzione frizionale delle foliazioni di piano assiale dei principali sistemi plicativi indicano che l'evoluzione alpina del CELB si è realizzata a livelli crostali superficiali. Il CELB mostra quindi un grado di deformazione intermedio tra il Dominio Delfinese da un lato e il Dominio Brianzonese Ligure Interno dall'altro, e rappresenta un settore di transizione tra questi due domini dai quali è separato da importanti zone di taglio transpressive.

Termini chiave: Dominio Brianzonese Ligure, successione carbonatica meso-cenozoica, tettonica transpressiva alpina, paleofaglie.

INTRODUCTION

Even if the Western Alps are commonly considered one of the best known geological regions of the world, large domains within this chain are still poorly studied and modern reconstructions of their paleogeographical and structural evolution are still lacking. The External Ligurian Briançonnais is one of these domains (fig. 1a): its stratigraphic-sedimentological framework dates back to the 70's (CAMPREDON *et alii*, 1967; LANTEAUME, 1968; VANOSSI, 1970), while recent structural analyses are limited to few contributions on its central sector (GOSSO & CARMINATI, 2000; CARMINATI, 2001; MICHARD & MARTINOTTI, 2002).

In order to reduce this gap of knowledge, new multidisciplinary studies based on 1:10.000 scale geological mapping have been carried out on the External Ligurian Briançonnais (ELB). These studies have brought new detailed information on the stratigraphic and structural setting of this domain, allowing new interpretations of its geological history.

This work provides the evidence for the occurrence of km-scale low-strain units in the ELB, whose primary stratigraphic and sedimentological features are still well preserved since they lack significant transposition or even geometrical reorganization of the stratigraphic succession. These units thus did not undergo severe effects of Alpine deformation although they belong to the Briançonnais Domain, that in literature is thought to be a domain largely involved in Alpine subductive and collisional events.

The ELB low-strain units are separated from the internal units of Ligurian Briançonnais on one side and from the *Helminthoides* Flysch units and Dauphinois Domain on the other, by different types of faults and regional shear zones.

Two main implications are here discussed:

- all the tectonic units of the Ligurian Briançonnais Domain do not share the same structural evolution;
- the role of the ELB during the Alpine orogenic cycle and its relationships with both the internal Ligurian Briançonnais, the *Helminthoides* Flysch units and Dauphinois Domain must be reconsidered.

The original data and interpretations of this work therefore contribute to the wide present-day discussion on the significance of the large tectonic and paleogeographic units of the western Alps and possibly offer a clue for a critical reanalysis of their meanings.

GEOLOGICAL FRAMEWORK

TECTONIC EVOLUTION OF LIGURIAN ALPS

The Ligurian Alps are a tectonic stack of four main groups of units, which have always been assumed to correspond to four adjacent main paleo-geographical domains: the Dauphinois and Ligurian Briançonnais domains as parts of the European continent; the Pre-Piedmont domain as the margin of the European continent; the Piedmont-Ligurian domain as the contiguous ocean (LEMOINE *et alii*, 1986; VANOSSI *et alii*, 1984). These units have been stacked during the principal Eocene SSW-wards Alpine tectonic event (D1) coeval with an ensialic subduction along an intra-continental shear zone dipping towards the more internal domains. During these processes, the units incorporated in the orogenic wedge were affected by metamorphism, increasing from the external to the internal units. Post-D1 deformational events did not significantly change the previous geometrical order of the tectonic units: the almost coaxial backfolding event (D2) simply induced further NE-SW shortening and the development of back-vergent contractional structures, while the D3 phase generated open folds nearly orthogonal to the D1 and D2 regional folding axes (GOSSO *et alii*, 1983; LANTEAUME *et alii*, 1990; SENO *et alii,* 2003, 2005b). In the present-day geometrical setting (figs. 1a, 1b), the Pre-Piedmont units rest onto the Briançonnais units, which in turn are thrust onto the outermost Dauphinois Domain. The *Helminthoides* Flysch units, which constitute the detached original cover of inner Ligurian oceanic units, overlie all these units and locally conceal the Briançonnais-Dauphinois transition (VANOSSI *et alii*, 1984; SENO *et alii,* 2003, 2005b).

THE EXTERNAL LIGURIAN BRIANÇONNAIS

The Ligurian Briançonnais Domain can be subdivided into two main sectors:

- the Internal Ligurian Briançonnais (ILB), that was involved in the subduction channel up to a maximum depth of about 30 km, developing high-pressure metamorphic parageneses (blue schists: MESSIGA *et alii*, 1982; GOFFÉ, 1984) and becoming part of a hinterland-dipping duplex bounded at its roof by Pre-Piedmont and Piedmont-Ligurian units, while its lower surface runs within the basement;

- the External Ligurian Briançonnais (ELB), that was not involved in the subduction and developed only a low grade to anchizone metamorphism (MESSIGA *et alii*, 1982; SENO *et alii,* 2003, 2005b).

The stratigraphic succession of the ELB (fig. 2) consists of Permo-Carboniferous volcanic rocks and volcanoclastites, Lower Triassic conglomerates and littoral cross bedded quartz arenites and Middle Triassic peritidal dolomites and limestones, bounded at the top by a Late Triassic to Middle Jurassic stratigraphic hiatus due to a prolonged subaerial exposure. Above, a thin (few hundred meters), discontinuous and condensed Jurassic to Paleogene succession was deposited. This is made up of Mid Jurassic outer platform carbonate deposits and Upper Jurassic pelagic limestones, locally showing a Rosso Ammonitico facies, followed by another important stratigraphic hiatus (hard-ground in fig. 2) and by Upper Cretaceous hemipelagic sediments. A last unconformity corresponding to an important hiatus bounds at the base Middle Eocene Nummulitic limestones followed by hemipelagic and flysch sediments (CAMPREDON & PORTAULT, 1971; LANTEAUME, 1968; LANTEAUME *et alii*, 1990). Such Meso-Cenozoic succession is the result of a complex evolutionary history that started with Triassic continental rifting, continued with the formation of the paleo-European passive margin, during the Jurassic opening of the Ligurian branch of Alpine Tethys ocean, and ended with the beginning of the continental collision in the latest Cretaceous-Paleogene (BOILLOT *et alii*, 1984; CRAMPTON & ALLEN, 1995).

The tectonic evolution of the ELB underwent the same tectonic stages of the other sectors of the Ligurian Briançonnais Domain. Anyway, less amount of finite deformation, translation and transposition is recorded in ELB with respect to inner Ligurian Briançonnais units.

Although the ELB units were already described (VANOSSI, 1972, 1974; VANOSSI *et alii,* 1984) as the less deformed part of Ligurian Briançonnais domain, a detailed discussion about their kinematic evolution and heterogeneity of their deformation have not yet given. This work describes in detail the central part of the ELB (CELB), where distinct low strain units have been recognized, as well as the nature of its boundaries.

THE STRUCTURAL SETTING OF THE CENTRAL PART OF THE EXTERNAL LIGURIAN BRIANÇONNAIS (CELB)

The central part of the External Ligurian Briançonnais, here labelled as CELB, underwent the same tectonic stages experienced by the more internal units of the Ligurian Briançonnais Domain, albeit with less intensity and with a strong heterogeneity of deformation. Consequently, the CELB is characterized by the same correlative structural surfaces, plus an older pervasive foliation (S0), less or not preserved in the more intensively deformed units of Ligurian Briançonnais Domain.

CELB PENETRATIVE FOLIATIONS

Several foliations were recognized in the CELB:

- *S0***,** the oldest correlative foliation generated by dissolution processes generally sub-parallel with bedding (Ss); since it is not related to any well known macroscale structural feature, it is inferred to be the result of diagenetic processes resulting from non-oriented lithostatic load (figs. 3b, 4a, 7a, 7c);
- *S1*, axial-plane foliation related to SW-vergent narrow to isoclinal folds (F1) that, although locally developed in the CELB, largely characterize the adjacent internal Ligurian Briançonnais units (as reported by MENARDI-NOGUERA, 1988; GOSSO & CARMINATI, 2000; CARMINATI, 2001) (figs. 4b, 7g,);
- *S2*, pervasive axial-plane foliation related to widespread NE-vergent centimetre to metre folds (F2). It consists of mm to cm-spaced discrete crenulation cleavage mainly generated by pressure dissolution and well developed in the Upper Cretaceous and Eocene marly limestones and shales (figs. 5a). Within these lithotypes, the S2 foliation shows a relatively constant attitude at regional scale (figs. 3c, 7b, 7c);
- *S2sh*, slip cleavage related to shearing evolution of F2 folding event that induced the reactivation of the S2 foliation (fig. 5b). The shear deformation reoriented and frictionally

reactivated as shear planes not only the S2 surfaces but also all the pre-existent pervasive surfaces (fig. 5c).

The last deformational event (F3), probably associated with the development of SW-verging thrusts and open folds, did not develop any pervasive foliation but only spaced cleavage mainly localized along reactivated faults.

CELB LOW-STRAIN UNITS

The CELB has been subdivided into eight low strain units named: Jurin, Moglie, Brignola, Carsene, Mongioie, Ormea, Fascia and Marguareis-Saline (fig. 3a). These units, that have been defined on the basis of 1:10.000 scale geological mapping, are bounded by different types of tectonic discontinuities and gathered into three main groups characterized by a decreasing degree of preservation of their primary features:

- the Fascia and Marguareis-Saline units (Group 1) where primary features are well preserved;
- the Carsene, Mongioie, Ormea units (Group 2) that show an intermediate degree of preservation;
- the Jurin, Moglie, Brignola units (Group 3) where primary features are poorly preserved.

The low strain units are bounded by different types of discontinuities: a) regional shear zones, b) low angle faults, c) individual steep faults and d) reactivated paleofaults (fig. 3a).

The N-NE CELB boundary is a regional long-lived brittle shear zone (Verzera shear zone, VZSZ) that juxtaposed the Internal Ligurian Briançonnais metamorphic units with the CELB non-metamorphic rocks. It is about 15 km long and several hundred meters thick; its internal geometry is dominated by linked, mainly steep, discrete faults that isolate strongly aligned tectonic slices made up of Permian to Eocene rocks.

The S-SW CELB boundary is a regional deformation zone, here named Viozene deformation zone (VIDZ), whose thickness ranges from some hundred meters in the western part to 5-6 km in the eastern one (fig. 1). It is a composite deformation zone that involves slices of Permian volcanoclastic rocks, partially affected by greenschist facies metamorphism (CORTESOGNO *et alii*, 1982), *Helminthoides* Flysch units and Meso-Cenozoic Briançonnais units. The VIDZ is bounded on its northern and southern sides by two km-long fault zones: the Chiusetta (CHFZ) and the Upega (UPFZ) fault zone respectively (figs. 1, 3a). The VIDZ includes a km-scale low strain unit (Upega-Nava unit) made up of Briançonnais Meso-Cenozoic carbonate rocks not yet studied in detail, and two slices of Permian volcanic rocks corresponding to the Carnino and Viozene units described by VANOSSI (1972). The attitude of bedding and tectonic foliation of the VIDZ are mostly steep or sub vertical (fig. 6b) even in its less deformed parts, suggesting an important internal geometrical reorganization that led to a marked alignment of the tectonic slice elongation axes and of pervasive foliations since the first tectonic stages (fig. 6c). The strong along-strike alignment of VIDZ internal tectonic elements indicates a prevalent strike-slip kinematic during the evolution of the deformation zone, as also suggested by kinematic indicators on Chiusetta and Upega boundary fault zones.

The SE boundary is the Caprauna-Armetta low-angle fault, that is responsible of the superposition of the Caprauna-Armetta unit, belonging to Internal Ligurian Briançonnais, onto the CELB (VANOSSI, 1974; MENARDI-NOGUERA, 1988).

The CELB western boundary is a poorly known geological feature, here named S. Giovanni fault, that juxtaposed the CELB with the western part of the ELB (WELB in figs. 1a, 3a), represented as an undifferentiated domain in the present work, since the analysis of its stratigraphic and structural feature are still in progress.

The Verzera shear zone and the Viozene deformation zone are the most important tectonic boundaries of CELB, because they are the most laterally persistent structures marking the largest differences in strain and metamorphism. For these reasons they are described in detail as follows.

VERZERA AND VIOZENE SHEAR ZONES

The VZSZ and VIDZ are mature, long-lived shear zones, active during all stages of Alpine deformation, but during the latest stages of their history accommodated a left-lateral transpressive shearing as shown by kinematic indicators on individual fault planes. Anyway, despite their common strain history, the meaning of the VZSZ and the VIDZ is quite different:

- the VZSZ corresponds to a metamorphic gap between high pressure metamorphic units (MESSIGA *et alii*, 1982; GOFFÉ, 1984) to the north, and anchimetamorphic to non-metamorphic units to the south, and in this sense it can be considered the boundary between ILB and ELB units (see above);
- the VIDZ corresponds to the outer boundary of ELB; although slices of metavolcanic rocks are involved in the eastern part of the VIDZ (Carnino and Viozene units in fig. 3a), this deformation zone presently juxtaposes three non-metamorphic domains (ELB, HF and DD in fig. 1a) and thus it does not mark significant changes in deformational regime and metamorphic grade at a regional scale.

It is here remarked that, independently from the amount of the metamorphic grade gap observed across VZSZ and/or VIDZ and despite they include tectonic slices made up of metamorphic rocks, the main correlative structural surface of both shear zones presently corresponds to a pervasive non-metamorphic foliation mostly parallel to the shear zone main boundaries.

The morphological (*sensu* POWELL, 1979) and kinematic characters of this foliation depend on the involved rock-type:

- in Permian non-metamorphic volcanoclastic rocks, the main correlative foliation corresponds to a spaced anastomosed slip-cleavage defined by the preferred orientation of silicate layers. At the micro scale, anastomosed sericite-rich differentiated levels constitute a foliation overprinted on the detrital texture of the rock (fig. 8e);
- in Permian metavolcanics, it corresponds to a mesoscale crenulation cleavage which deforms a pre-existing metamorphic foliation;
- in Jurassic massive limestones, it corresponds to a spaced fracture cleavage;
- in the Cretaceous and Eocene marly and shaly rocks, all the tectonic foliations, as well as bedding, are generally sub-parallel to the main shear zone boundaries and are often reactivated to form a composite slip cleavage (figs 3b, 3c, 6c, 7d, 7e, 7f, 7h).

The VIDZ internal foliations formed by development of stylolitic surfaces (fig. 8a, 8b) and slip cleavages that reactivated the diagenetic foliation S0 (fig. 8c, 8d) or by pressure dissolution cleavages originated in response to folding and or shearing events. In any case, these foliations, although penetrative within the VIDZ, did not induce significative recristallization of the rocks. The primary texture, only partially affected by re-orientation and crushing of grains, is often well preserved (figs. 8a, 8b, 8c) and it is still recognizable even in the more deformed rock slices (fig. 8d). This suggests that deformation occurred at relatively shallow levels, as confirmed by widespread occurrence of cataclasis and/or discrete cataclastic flow processes, aided by diffuse pressure dissolution of carbonate minerals and showing localized growth of authigenic quartz.

The VIDZ and VZSZ are here interpreted as transpressive shear zones. They maintained this kinematic feature through most part of their tectonic evolution (at least during F1 and F2 deformational events), as suggested by the orientation of the main axes of the finite strain ellipsoid. The latter can be derived by the present orientation of the syn-F1 and syn-F2 structural elements, such as folds, cleavages and veins (fig. 9). The macroscale “flower-structure” arrangement of the main correlative foliation within the VIDZ, since to confirm this interpretation (fig. 6a). Minor pure contractional kinematics seems to have characterized the F3 deformational stage, while a later frictional reactivation as an oblique left-lateral fault system successively occurred, as testified by striation and grooving on the VIDZ discrete foliations and boundary faults (fig. 9).

MARGUAREIS-SALINE LOW STRAIN UNIT

Although the CELB consists of eight low-strain units, in this work only the best-preserved unit (MSU) is described in detail.

STRATIGRAPHIC FEATURES

The Marguareis-Saline unit (MSU) geographically ranges from Passo delle Saline to the east to Cima della Fascia to the west (fig. 3a) and stratigraphically spans the Permian to Eocene interval. In the MSU the stratigraphic polarity is basically normal since overturned sequences do not occur.

At a large scale, the MSU is substantially subdivided into two portions, arranged in west-dipping homoclines, by a north-south complex geological feature that can be continuously mapped for more than 2 km. This feature has been recently interpreted as a paleoescarpment representing the morphological expression of a paleofault (figs. 3a, 10) with displacements of several hundred metres and sealed by Upper Cretaceous sediments (BERTOK, 2007). Along the paleoescarpment peculiar and anomalous stratigraphic, sedimentological and geometrical relationships can been observed:

- anomalous stratigraphic contact of Upper Cretaceous marly limestones directly overlying in angular unconformity the Permian volcanics or the Middle Triassic dolomite limestones;
- erosional nature of the above described contact, testified by irregular geometries, occurrence of draping stratified breccias with clasts of the substrate, and authigenic mineral crusts;
- occurrence of metre- to decametre sized blocks mainly of Upper Jurassic massive limestones leaning on the surface and covered by the Upper Cretaceous marly limestones.

The preservation of such km-scale continuous syn-sedimentary feature demonstrates that the MSU did not suffer any significant volumetric reorganization neither diffused transposition phenomena. This is also confirmed, at most stratigraphic level, by ubiquitous preservation of:

- bedding that still shows its primary characteristics and is locally underlined by mm- to cm-thick mineralized hard grounds of Fe-Mn oxides and phosphates. Erosional features are also preserved as well as their associated lag of clasts; angular unconformities are locally still recognizable (fig. 11a);
- different kinds of stratigraphic and sedimentological structures:
  - ✓ neptunian dykes and sills cutting across Jurassic limestones and showing different generations of sedimentary infillings, cm-sized flame structures within the Permian volcanoclastic levels, internal laminations, graded bedding in sandstones, desiccation shrinkage pores and dolomite pseudomorphs of gypsum crystals in the Middle Triassic dolomite limestones (fig. 11b), bioturbations;

- ✓ depositional and diagenetic features that are not stretched and preserve their original shape such as pebbles in Lower Triassic conglomerates (fig. 11c), sub-angular clasts in Middle Jurassic breccias, chert nodules in Middle Triassic dolomite limestones, and calcareous nodules in Upper Jurassic pelagic limestones;
- ✓ macro- and microfossils that still preserve their finest morphological details (i.e. shell structure in larger benthic foraminifera or cellular tissue in red algae, fig. 11d);

- rocks that did not underwent significant recrystallization:
  - ✓ Permian rhyolite rocks where the porphyric structure and a concentric compositional zoning in quartz phenocrystals are still recognizable;
  - ✓ hard grounds where authigenic minerals (glauconite, amorphous phosphate, pyrites) are generally not replaced by other minerals and preserve delicate mm-sized stromatolite structures (fig. 11e);
  - ✓ Jurassic limestones, where primary diagenetic zoning of pore-filling calcite cements occur (fig. 11f).

All these micro- and mesoscale observations testify a high degree of preservation of primary features and thus suggest the absence of any metamorphic transformations and of widely diffused carbonate dissolution processes.

STRUCTURAL FEATURES

The MSU is characterized by the same penetrative structural features of the other CELB units (see above) and is dissected by a complex fracture network resulting from the interconnection of several sets of discontinuities such as pervasive fold axial plane foliations, spaced slip cleavages along major shear zones, fractures associated with major individual faults and others. Nevertheless, most part of MSU still preserve its primary stratigraphic and sedimentological features due to heterogeneity of rock mechanical properties, that play a fundamental role in controlling strain localization. In fact, a large amount of strain is mainly localized in the Upper Cretaceous and Eocene marly limestones and shales, whilst the Permian to Lower Cretaceous siliceous rocks and massive limestones are only slightly deformed. Furthermore, it must be stressed that preservation of original stratigraphic relations, lithosome geometries and microscale diagenetic structures is also due to the nature of the deformational processes related to the generation of the main pervasive foliations. These are in fact mostly represented by discrete pressure-dissolution processes that did not obliterate the primary fabric of the rocks.

Summarizing, the differences of the tectonic history of the MSU, and more in general of the CELB, with respect to the Internal Ligurian Briançonnais are:

- a minor amount of the whole finite strain;
- a strong localization of the deformation, that made the preservation of primary stratigraphic and sedimentological features possible over relatively large areas and several stratigraphic levels.

DISCUSSION

The new stratigraphic and structural data on the External Ligurian Briançonnais Domain discussed in this paper pointed out that its central part (CELB) is represented by km-scale low-strain units, separated from the metamorphic internal units of Ligurian Briançonnais on one side and the Dauphinois domain and *Helmintoides* Flysch units on the other by two non metamorphic regional shear zones, the Verzera shear zone (VZSZ) and the Viozene deformation zone (VIDZ), respectively. Although the CELB low strain units experienced the same tectonic stages of the more internal Briançonnais units, they escaped metamorphic transformations and significant geometrical reorganizations (transposition) as on the contrary occurred in the Internal Ligurian Briançonnais (SENO *et alii*, 2003, 2005a, 2005b), where the total amount of strain was definitely higher. Within the less deformed unit of CELB (Marguareis-Saline unit) primary features of the sedimentary succession are still well preserved, and Mesozoic syn-depositional tectonic features, such as km-long paleoescarpments, are still well recognizable and traceable on maps (figs. 3a, 10). Preservation of primary features was determined by a strong localization of the deformation that is mainly confined within the Upper Cretaceous and Eocene marly limestones and shales, and allowed by the nature of the deformational processes, mainly represented by pressure-dissolution along discrete structural surfaces. These arguments suggest that in post-Eocene times the CELB always stayed at shallow crustal levels and underwent the same type of deformation processes that were active in the same time span in the adjoining Dauphinois Domain (BURGISSER & FORD, 1998) where, however, a lesser amount of finite deformation is observed. The CELB thus can be considered as a tectonic slice, representing the remnant of a wider "transition zone" placed between the inner part of the Ligurian Briançonnais and the Dauphinois Domain. During the Alpine collisional event, important transpressive shear zones (VIDZ and VZSZ) caused the fragmentation and partial obliteration of this original "transition zone", which presently can be recognized only in the CELB (figs. 1, 3a). During this stage the VIDZ and VZSZ also involved the *Helminthoides* Flysch units previously overlaid onto the Briançonnais Domain.

The CELB boundary shear zones (VIDZ and VZSZ) could represent the surface expression of a megascale roughly sinistral E-W shear zone that, as inferred by many Authors in the last twenty years, should have bounded the Western Alps arcuate front to the south at least since Early Oligocene (*i.e*. Stura Couloir, RICOU & SIDDANS, 1986; GIGLIA *et alii*, 1996; COLLOMBET *et alii*, 2002).

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This paper is published despite the effects of the Italian law 133/08. This law drastically reduces public funds to public Italian universities, which is particularly dangerous for scientific free research,

and it will prevent young researchers from getting a position, either temporary or tenured, in Italy.

The authors are protesting against this law to obtain its cancellation.

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FIGURE CAPTIONS

Fig. 1 - a) Geological sketch of Ligurian Alps; *b)* Schematic NE-SW section (AA') across the Ligurian Briançonnais and Dauphinois domains in the inset the study area. The grade of metamorphic imprint, increasing from NE to SW, is represented in the crossbar placed in the lower part of the section AA'. PQD: Plio-Quaternary deposits; TPB: Tertiary Piedmont Basin; ILB: Internal Ligurian Briançonnais; WELB: western part of External Ligurian Briançonnais; CELB: central part of the External Ligurian Briançonnais; EELB: eastern part of External Ligurian Briançonnais; CTU: Col di Tenda Unit; AM: Argentera Massif; CM: Calizzano Massif; PPU: Pre-Piedmont Units; HF: *Helminthoides* Flysch; DD: Dauphinois Domain; VIDZ: Viozene deformation zone; CHFZ: Chiusetta fault zone; UPFZ: Upega fault zone; VZSZ: Verzera shear zone (modified from SENO *et alii*, 2005a).

- a) *Schema geologico delle Alpi Liguri;* b) *Profilo schematico NE-SW (AA') attraverso il Dominio Brianzonese Ligure e il Dominio Delfinese. L'impronta metamorfica, che aumenta progressivamente da NE a SW, è rappresentata nel riquadro nella parte inferiore del profilo AA'. PQD: depositi plio-quaternari; TPB: Bacino Terziario Piemontese; ILB: Brianzonese Ligure Interno; WELB: settore occidentale del Brianzonese Ligure Esterno; CELB: settore centrale del Brianzonese Ligure Esterno; EELB: settore orientale del Brianzonese Ligure Esterno; CTU: Unità del Colle di Tenda; AM: Massiccio dell'Argentera; CM: Massiccio di Calizzano; PPU: Unità Pre-Piemontesi; HF: Flysch ad* Helminthoides*; DD: Dominio Delfinese; VIDZ: Zona di deformazione di Viozene; CHFZ: Zona di faglia della Chiusetta; UPFZ: Zona di faglia di Upega; VZSZ: Zona di taglio della Verzera (modificato da* SENO et alii*, 2005a).*

Fig. 2) - Simplified stratigraphic section of the External Ligurian Briançonnais succession (modified from BRIZIO *et alii*, 1983).

- *Sezione stratigrafica semplificata della successione del Brianzonese Ligure Esterno (modificata da* B*RIZIO* et alii*, 1983).*

Fig. 3 - a) Sketch map of the study area representing the central External Ligurian Briançonnais (CELB) low-strain units, related boundaries and main discontinuities. ILB: Internal Ligurian Briançonnais; WELB: western part of External Ligurian Briançonnais; HF: *Helminthoides* Flysch; DD: Dauphinois Domain; CHFZ: Chiusetta fault zone; UPFZ: Upega fault zone; VZSZ: Verzera shear zone; *b, c)* Maps view of the S0 (b) and S2 (c) regional attitude inside and outside the VIDZ. Note the difference between the angular relations of S0 and VIDZ macrostructural boundaries, with respect to those observed between S2 and VIDZ.

- a) *Schema strutturale dell'area in studio in cui sono rappresentate le unità a basso grado di deformazione del settore centrale del Brianzonese Ligure Esterno (CELB), i relativi limiti e le principali discontinuità. ILB: Brianzonese Ligure Interno; WELB: settore occidentale del Brianzonese Ligure Esterno indifferenziato; HF: Flysch ad* Helminthoides*; DD: Dominio Delfinese; CHFZ: Zona di faglia della Chiusetta; UPFZ: Zona di faglia di Upega; VZSZ: Zona di taglio della Verzera;* b, c) *carta schematica delle foliazioni S0 (b) e S2 (c) all'interno e all'esterno della VIDZ. Si osserva la differenza delle relazioni angolari tra S0 e VIDZ e S2 e VIDZ.*

Fig. 4 - Kinematic evolution of the Marguareis-Saline unit as recorded by mesoscale structural associations. *a)* diagenetic foliation (S0) formed subparallel to bedding (Ss) and is evidenced by compositional and/or textural changes; *b)* folding event F1 generates S1 fold axial plane foliation. Cross cutting relations between S0 and S1 foliations can be observed only in F1 hinge zone and rarely occur in the Marguareis-Saline unit.

- *Evoluzione cinematica dell'unità Marguareis-Saline registrata dalle associazioni mesostrutturali;* a) *la foliazione diagenetica (S0) è subparallela alla stratificazione (Ss) che è evidenziata da variazioni composizionali e/o tessiturali;* b) *l'evento plicativo F1 genera la foliazione di piano* *assiale S1. Le relazioni di intersezione tra le foliazioni S0 e S1 possono essere osservate solo nelle cerniere F1 e si ritrovano solo di rado nell'unità Marguareis-Saline.*

Fig. 5) - Shearing evolution of F2 folding event of MSU. *a)* F2 folding event generates the S2 axial planar foliation and fold bedding (Ss) and composite foliation (S0+S1); *b)* S2 surfaces evolve from an axial plane foliation to a slip cleavage (S2sh); *c)* the shear localization induces a strong parallelism of all the preexisting surfaces (Ss, S0+S1, S2).

- *Evoluzione per taglio dell'evento plicativo F2.* a) *L'evento plicativo F2 origina una foliazione di piano assiale S2 e piega la stratificazione (Ss) e la foliazione composita diagenetica (S0*+ *S1);* b) *le superfici S2 evolvono da superfici di piano assiale a* slip cleavage *(S2sh);* c) *la localizzazione della deformazione per taglio induce un forte parallelismo di tutte le superfici preesistenti (Ss, S0+S1, S2).*

Fig. 6 a) Landscape East-ward view of VIDZ. The main macroscale correlative foliation depicts a divergent structure. See also fig 7; - *b)* Eastward view of the Chiusetta fault zone *(*CHFZ*)*. White dashed lines mark subparallel fracture sets representing the macroscale evidence of the composite foliation (Cf) shown in fig. 6c*. c)* cross cutting relations between Ss+S0 and S1+S2 composite foliations. Where shear deformation was more intense, all sedimentary and tectonic foliations became parallel and a comprehensive composite foliation (Cf) developed. S1+S2 compositive foliation is locally dragged by syn-F3 S-vergent reverse planes (F3C).

- a) *vista verso Est della VIDZ. La principale superficie di correlazione macrostrutturale presenta una configurazione geometrica divergente(vedi anche Fig. 7); b) vista verso Est della zona di faglia della Chiusetta (CHFZ). Le linee bianche tratteggiate sottolineano sistemi di fratture sub-paralleli corrispondenti all'evidenza macroscopica della foliazione composita (Cf) di fig. 6c.* c) *relazioni di intersezione tra le foliazioni composite Ss+S0 e S1+S2. Dove la deformazione per taglio è più intensa le foliazioni tettoniche e sedimentarie diventano coalescenti a generare una foliazione* *composita (Cf). La foliazione S1+S2 è localmente riorientata da piani di taglio inversi S-vergenti coevi alla fase deformativa F3.*

Fig. 7 – a, b, c, d, e, f) stereoplots representing the attitude of the S0 and S2 foliations outside and inside the VIDZ; *g, h)* axial planes and axes of F1 and F2 folds outside and inside the VIDZ. Note that F1 folds are clockwise rotated and steepened by F2 folding event.

- a, b, c, d, e, f) *proiezioni stereografiche delle foliazioni S0 e S2 all'interno e all'esterno della VIDZ;* g, h) *assi e piani assiali delle pieghe F1 e F2 all'interno e all'esterno della VIDZ. Si osserva la rotazione in senso orario e la verticalizzazione delle pieghe F1 da parte dell'evento plicativo di fase 2 (F2).*

Fig. 8) – Microstructural features of the VIDZ. Different shapes and degrees of progressive deformation are represented. *a)* isolated microfractures developed in Eocene hemipelagic fine-grained sediments with Globigerinids involved in VIDZ; *b)* localization of deformation into discrete levels occurs by rock grain reduction and cataclastic flow that induces fragmentation, alignement and rotation of bioclasts of fine-grained levels of Nummulitids-rich ramp limestones; *c)* within the more intensively foliated rock portions of VIDZ, remobilization of the diagenetic S0 foliation gives origin to regularly spaced stylolitic surfaces showing high concentration of clay minerals; *d)* crenulation of microscale stylolitic foliation induces the formation of a new set of dissolution surfaces developed in the axial zone of the crenulation folds. This deformation stage represent the more intense strain condition recorded by the sedimentary rock slices involved in the VIDZ. A major degree of recrystallization, with respect to microphoto 8a, 8b and 8c, is observed; *e)* despite of cataclastic processes affecting the rock, the primary detritic texture of Permian volcanoclastic levels are preserved, in the eastern sector of VIDZ (crossed polars view); *f)* an anostomosed sericite-bearing foliation overprints the cataclastic texture of Permian volcanoclastic levels involved within the VIDZ (crossed polars view).

– Caratteri microstrutturali della VIDZ. Sono rappresentati differenti stadi e gradi di deformazione progressiva. a) *sviluppo di microfratture isolate in sedimenti emipelagici eocenici ricchi in Globigerinoidi coinvolti nella VIDZ;* b) *localizzazione della deformazione in livelli discreti, sottolineata dalla riduzione di grana e dal flusso cataclastico che induce, nei livelli a grana fine dei calcari ricchi in Nummulitidi, la frammentazione, l'allineamento e la rotazione dei bioclasti;* c) *all'interno della VIDZ, nelle rocce maggiormente foliate, la rimobilizzazione della foliazione diagenetica S0 origina superfici stilolitiche spaziate e regolari, sottolineate da un'alta concentrazione di minerali argillosi;* d) *alla microscala, la crenulazione della foliazione stilolitica induce la formazione di un nuovo set di superfici da dissoluzione che si sviluppano in corrispondenza della zona assiale delle pieghe. Questo stadio rappresenta il più intenso grado di deformazione registrato dalle scaglie di rocce sedimentarie coinvolte nella VIDZ; si osserva un maggiore grado di ricristallizzazione rispetto alle microfoto 8a, 8b e 8c;* e) *nei settori più esterni delle VIDZ, nonostante la roccia sia interessata da processi cataclastici, i livelli vulcanoclastici permiani preservano ancora la loro originaria tessitura detritica (microfoto a nicols incrociati);* f) *all'interno della VIDZ la foliazione anastomosata a sericite si sovrappone alla tessitura cataclastica dei livelli vulcanoclastici permiani (microfoto a nicols incrociati).*

Fig. 9 – Strain distribution within the VIDZ. The shape of the 3D rectangular grey box is roughly consistent with the orientation of the finite-strain ellipsoid, as inferred by the distribution of the main field structural elements (folds, extensional lineations and foliations). Later frictional reactivation of VIDZ is testified by meter-scale grooves and slickenlines on the main S2 foliation, indicating strike-slip to oblique movements.

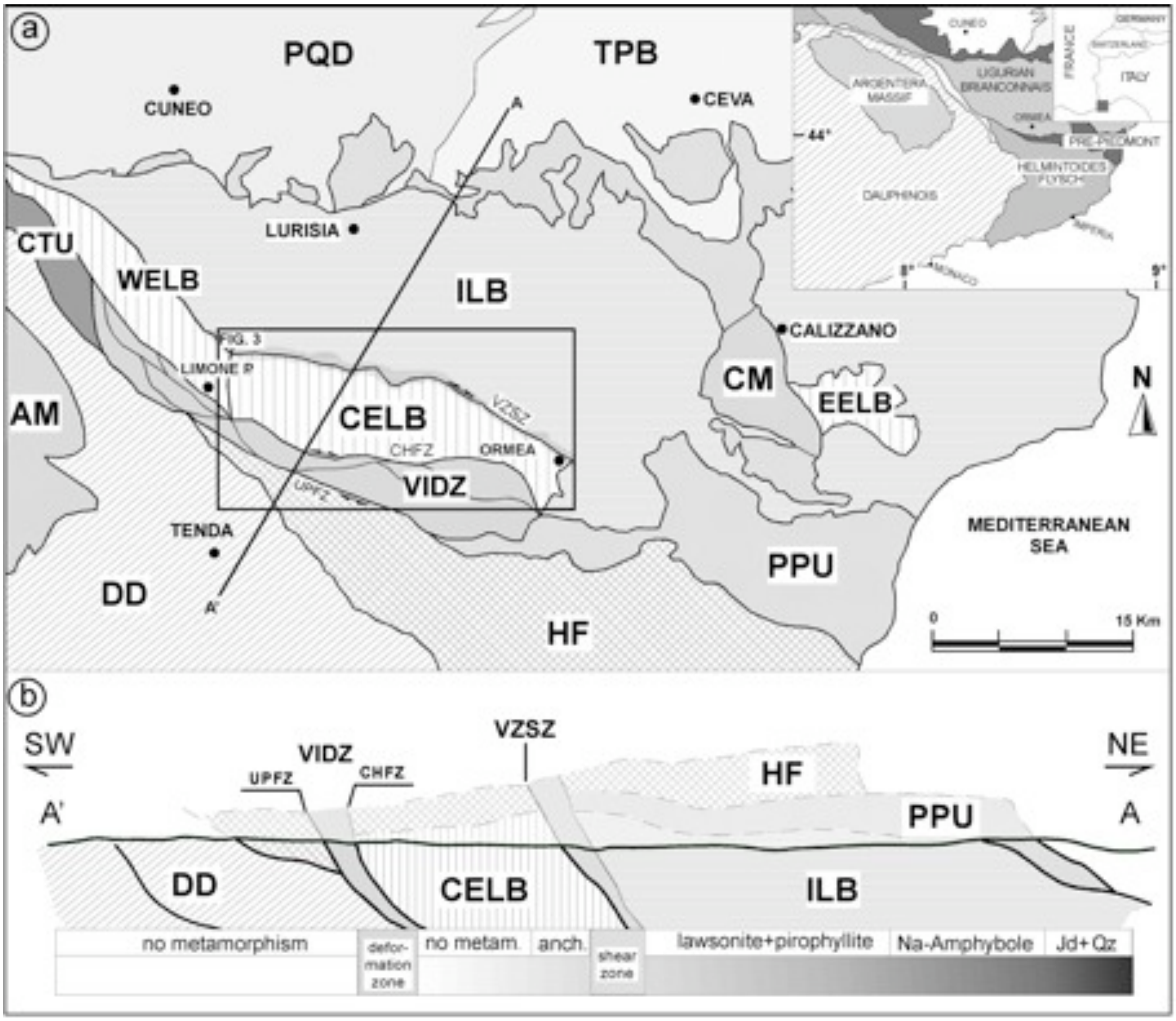
- distribuzione della deformazione all'interno della VIDZ. La forma del parallelepipedo è indicativa dell'orientazione dell'ellissoide dello strain finito, come sottolineato dalla distribuzione dei principali elementi mesostrutturali (pieghe, lineazioni estensionali e foliazioni). La recente riattivazione frizionale della VIDZ è testimoniata dalla presenza di grooves e strie meccaniche a scala metrica che indicano movimenti trascorrenti sulle superfici di foliazioni S2.

Fig. 10 - Panoramic view of the central sector of the Marguareis-Saline unit, crossed by a N-S Km-scale complex tectonic feature corresponding to a paleoescarpment (thick dashed white lines and squared hatches) sealed by Upper Cretaceous sediments and variously reactivated by recent faults (thin continuous white lines). Thin continuous black lines mark stratigraphic boundaries. Pv: Permian volcanics; LTqa: Lower Triassic quartz arenites; Tdl: MiddleTriassic dolomitic limestones; M-UJl: Middle and Upper Jurassic limestones; UC-Es: Upper Cretaceous- Eocene succession.

- *Vista panoramica del settore centrale dell'unità Marguareis-Saline, tagliata da una complessa struttura N-S a scala chilometrica che corrisponde ad una paleoscarpata (spessa linea bianca tratteggiata e quadrettato bianco) sigillata da sedimenti del Cretacico superiore e riattivata da faglie recenti (sottili linee bianche continue). Le sottili linee nere continue indicano i limiti stratigrafici. Pv: vulcaniti permiane; LTqa: quarzoareniti del Trias inferiore; Tdl: calcari dolomitici del Trias medio; M-UJl: calcari del Giurassico medio-superiore; UC-Es: successione del Cretacico superiore-Eocene.*

Fig. 11 – a) angular unconformity between Middle Jurassic limestones (MJ) and Upper Jurassic nodular limestones (UJnl) highlighted by pinch out of Upper Jurassic crinoidal limestones (UJcl). Thin continuous lines mark bedding; dashed lines mark the MJ/UJcl and UJcl/UJnl boundaries; *b)* dolomite pseudomorphs of gypsum crystals in Middle Triassic dolomitic limestones; *c)* primary shape of quartz pebbles preserved in Lower Triassic conglomerates; *d)* larger benthic foraminifera (*Nummulites* (n), *Discocyclina* (d)) and a well preserved rodolith (*Solenomeris* encrusted by *Sporolithon*, r). Eocene limestones (micrograph); *e)* stromatolite structure in Lower Cretaceous hard ground (cathodoluminescence micrograph): alternation of very thin phosphate laminae (non luminescent) and calcite laminae (luminescent) is well recognizable; *f)* primary diagenetic zoning of pore-filling calcite cements in Jurassic limestones (cathodoluminescence micrograph).

- a) *discordanza angolare tra i calcari del Giurassico medio (MJ) e i calcari nodulari del Giurassico superiore (UJnl) evidenziata dalla chiusura dei calcari encrinitici del Giurassico superiore (UJcl). Le linee sottili e continue indicano la stratificazione; le linee tratteggiate evidenziano i limiti tra MJ/UJcl e UJcl/UJnl;* b) *pseudomorfi di dolomite su cristalli di gesso nei calcari dolomitici del Trias medio;* c) *forma originaria dei ciottoli di quarzo preservata nei conglomerati del Trias inferiore;* d) *esemplari di macroforaminiferi (*Nummulites *(n),* Discocyclina *(d)) e un rodolite ben preservato (*Solenomeris *incrostato da* Sporolithon, *r). Calcari eocenici (microfotografia);* e) *struttura stromatolitica nell'hard ground del Cretacico inferiore (microfotografia in catodoluminescenza): l'alternanza di sottili lamine fosfatiche (non luminescenti) e calcitiche (luminescenti) è chiaramente riconoscibile;* f) *zonatura diagenetica primaria di cementi calcitici all'interno di una cavità presente nei calcari giurassici (microfotografia in catodoluminescenza).*



a
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TPB
CUNEO
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ILB
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FIG. 3
LIMONE P.
CM
EELB
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ORMEA
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CELB
ILB
no metamorphism
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shear zone
lawsonite+pirophyllite
Na-Amphybole
Jd+Qz

Fig. 1

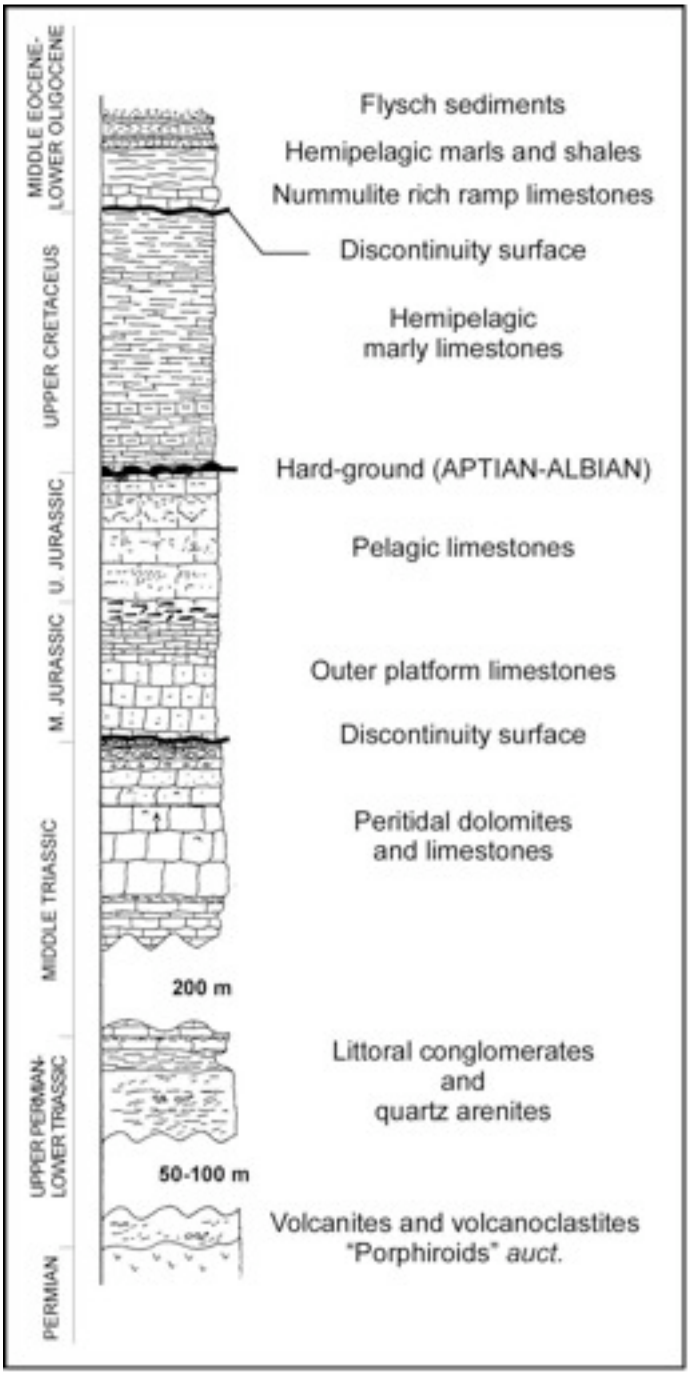

MIDDLE EOCENE-
LOWER OLIGOCENE
UPPER CRETACEUS
U. JURASSIC
M. JURASSIC
MIDDLE TRIASSIC
UPPER PERMIAN-
LOWER TRIASSIC
PERMIAN
Flysch sediments
Hemipelagic marls and shales
Nummulite rich ramp limestones
Discontinuity surface
Hemipelagic
marly limestones
Hard-ground (APTIAN-ALBIAN)
Pelagic limestones
Outer platform limestones
Discontinuity surface
Peritidal dolomites
and limestones
200 m
Littoral conglomerates
and
quartz arenites
50-100 m
Volcanites and volcanoclastites
"Porphiroids" *auct.*

Fig. 2

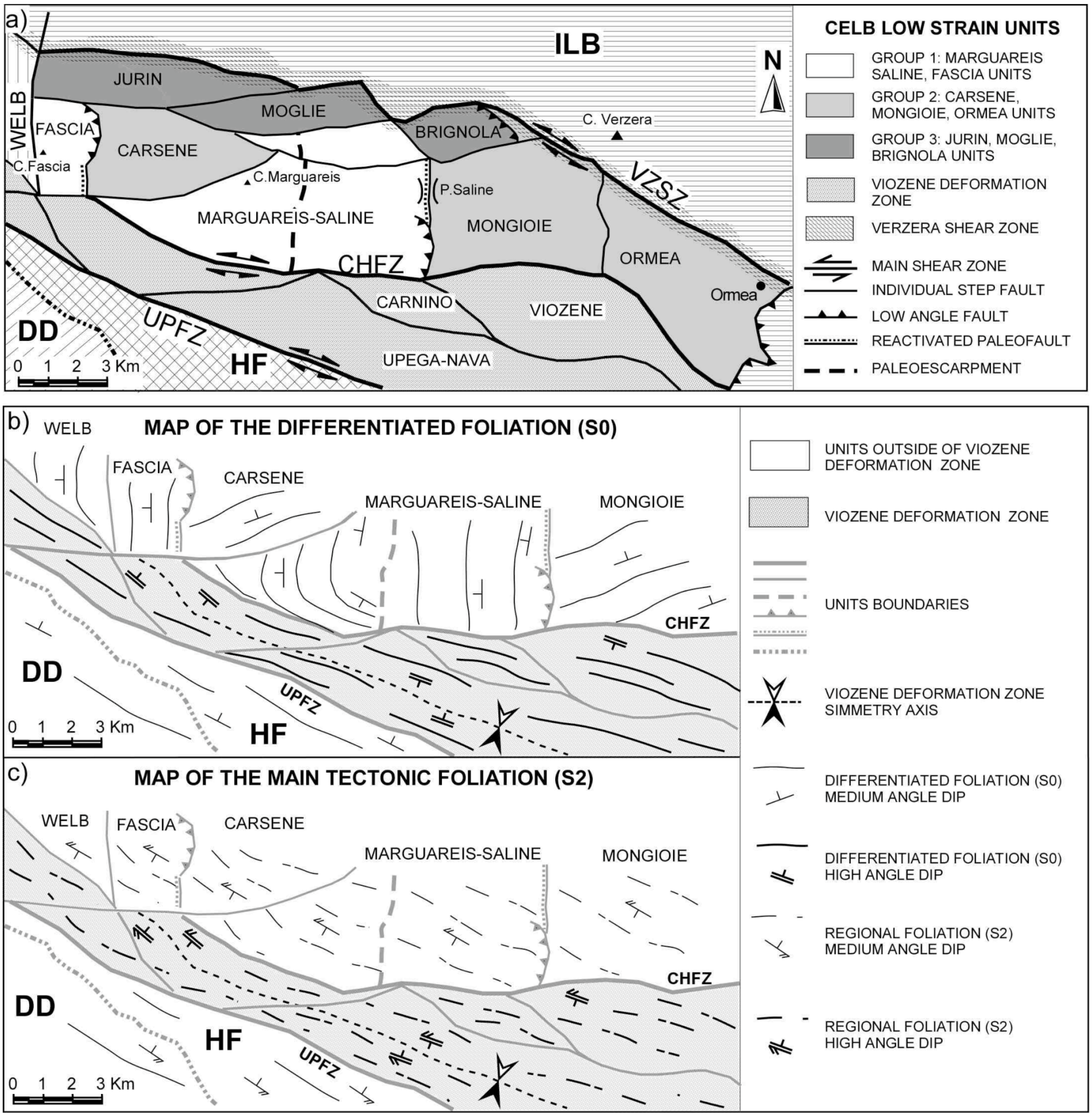

a)
ILB
JURIN
MOGLIE
BRIGNOLA
WELB
FASCIA
C.Fascia
CARSENE
C.Marguareis
C. Verzera
VZSZ
P.Saline
MARGUAREIS-SALINE
MONGIOIE
ORMEA
CHFZ
CARNINO
VIOZENE
Ormea
DD
UPFZ
HF
UPEGA-NAVA
0 1 2 3 Km
N
CELB LOW STRAIN UNITS
GROUP 1: MARGUAREIS SALINE, FASCIA UNITS
GROUP 2: CARSENE, MONGIOIE, ORMEA UNITS
GROUP 3: JURIN, MOGLIE, BRIGNOLA UNITS
VIOZENE DEFORMATION ZONE
VERZERA SHEAR ZONE
MAIN SHEAR ZONE
INDIVIDUAL STEP FAULT
LOW ANGLE FAULT
REACTIVATED PALEOFAULT
PALEOESCARPMENT
b)
MAP OF THE DIFFERENTIATED FOLIATION (S0)
WELB
FASCIA
CARSENE
MARGUAREIS-SALINE
MONGIOIE
CHFZ
DD
UPFZ
HF
0 1 2 3 Km
UNITS OUTSIDE OF VIOZENE DEFORMATION ZONE
VIOZENE DEFORMATION ZONE
UNITS BOUNDARIES
VIOZENE DEFORMATION ZONE SIMMETRY AXIS
DIFFERENTIATED FOLIATION (S0) MEDIUM ANGLE DIP
DIFFERENTIATED FOLIATION (S0) HIGH ANGLE DIP
REGIONAL FOLIATION (S2) MEDIUM ANGLE DIP
REGIONAL FOLIATION (S2) HIGH ANGLE DIP
c)
MAP OF THE MAIN TECTONIC FOLIATION (S2)
WELB
FASCIA
CARSENE
MARGUAREIS-SALINE
MONGIOIE
CHFZ
DD
HF
UPFZ
0 1 2 3 Km

Fig. 3

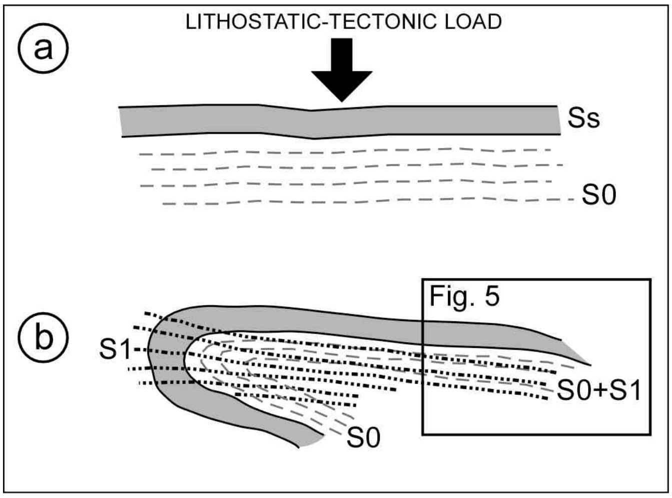

a
LITHOSTATIC-TECTONIC LOAD
Ss
S0
b
Fig. 5
S1
S0+S1
S0

Fig. 4

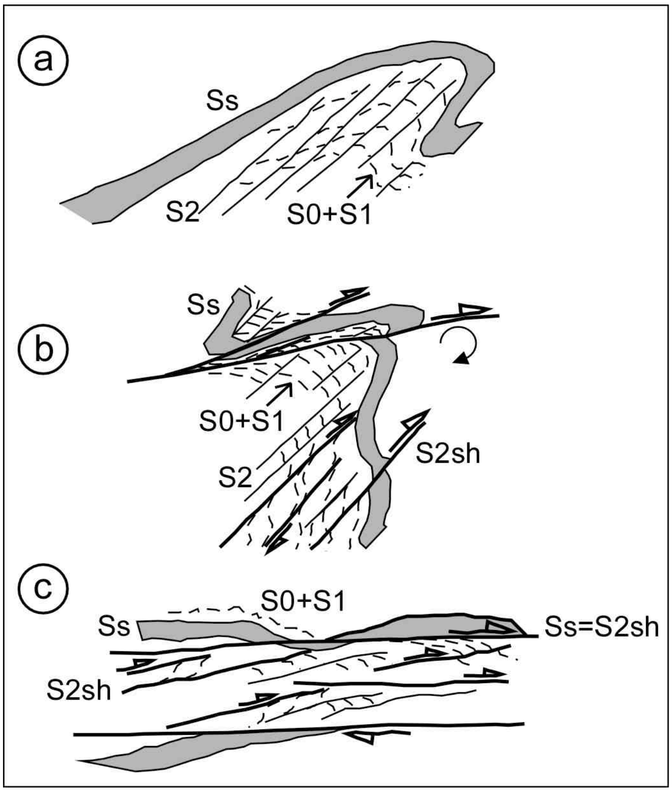

a
Ss
S2
S0+S1
b
Ss
S0+S1
S2
S2sh
c
S0+S1
Ss
Ss=S2sh
S2sh

Fig. 5

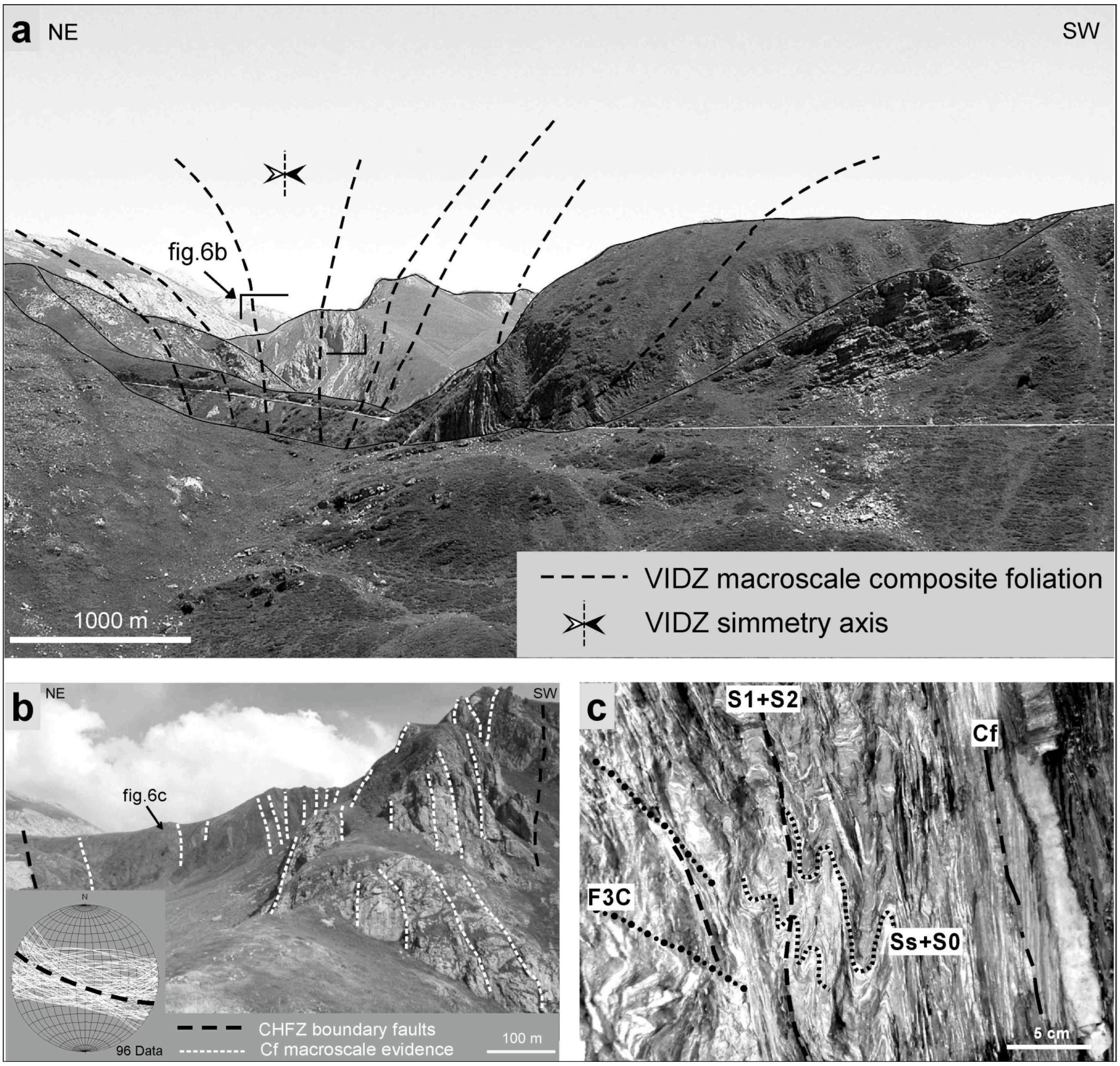

a
NE
SW
fig.6b
VIDZ macroscale composite foliation
VIDZ simmetry axis
1000 m
b
NE
SW
fig.6c
N
96 Data
CHFZ boundary faults
Cf macroscale evidence
100 m
c
S1+S2
Cf
F3C
Ss+S0
5 cm

Fig.6

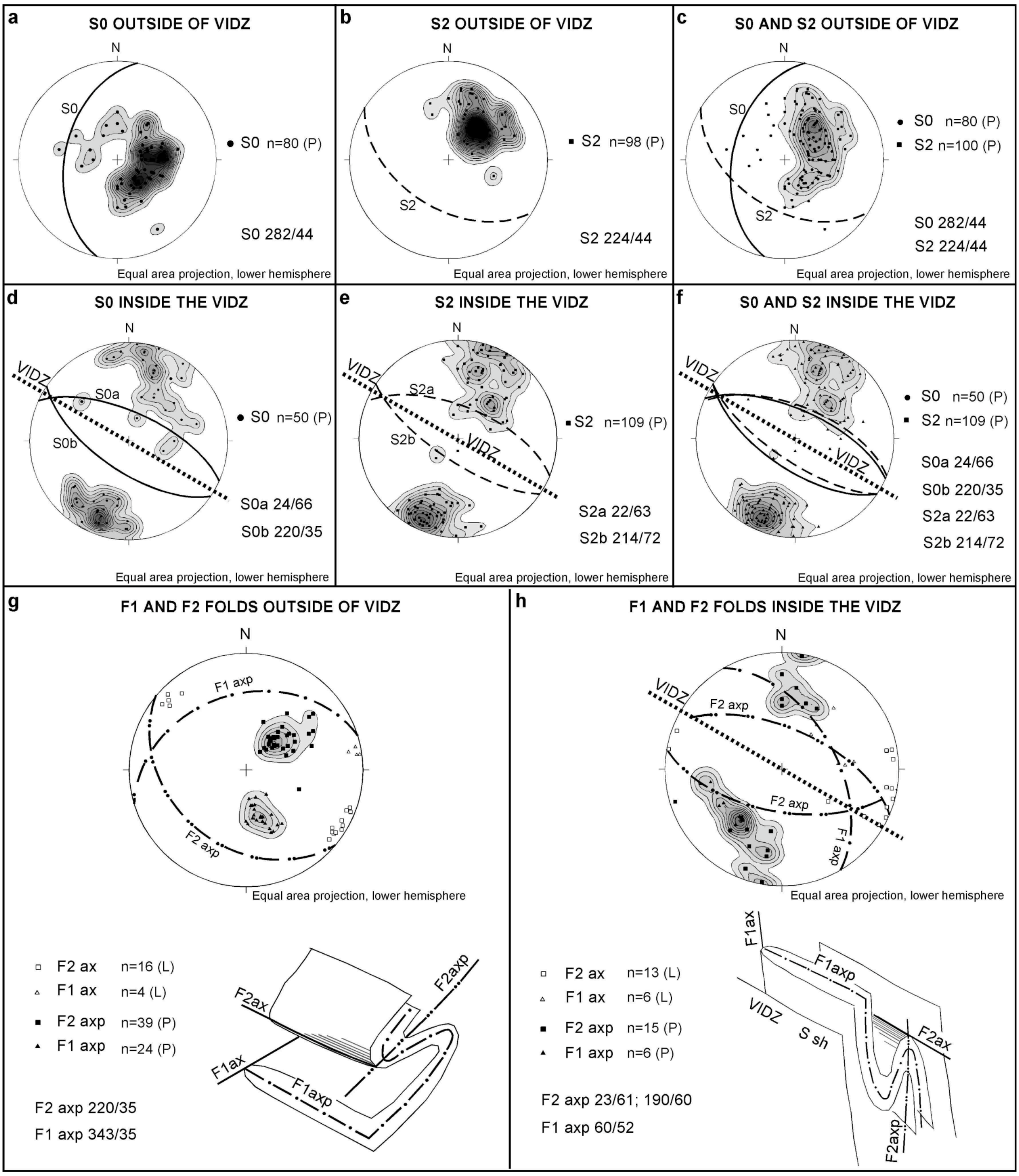

a
S0 OUTSIDE OF VIDZ
N
S0
S0 n=80 (P)
S0 282/44
Equal area projection, lower hemisphere
b
S2 OUTSIDE OF VIDZ
N
S2 n=98 (P)
S2
S2 224/44
Equal area projection, lower hemisphere
c
S0 AND S2 OUTSIDE OF VIDZ
N
S0
S0 n=80 (P)
S2 n=100 (P)
S2
S0 282/44
S2 224/44
Equal area projection, lower hemisphere
d
S0 INSIDE THE VIDZ
N
VIDZ
S0a
S0b
S0 n=50 (P)
S0a 24/66
S0b 220/35
Equal area projection, lower hemisphere
e
S2 INSIDE THE VIDZ
N
VIDZ
S2a
S2b
VIDZ
S2 n=109 (P)
S2a 22/63
S2b 214/72
Equal area projection, lower hemisphere
f
S0 AND S2 INSIDE THE VIDZ
N
VIDZ
VIDZ
S0 n=50 (P)
S2 n=109 (P)
S0a 24/66
S0b 220/35
S2a 22/63
S2b 214/72
Equal area projection, lower hemisphere
g
F1 AND F2 FOLDS OUTSIDE OF VIDZ
N
F1 axp
F2 axp
Equal area projection, lower hemisphere
F2 ax n=16 (L)
F1 ax n=4 (L)
F2 axp n=39 (P)
F1 axp n=24 (P)
F2 axp 220/35
F1 axp 343/35
F2ax
F2axp
F1ax
F1axp
h
F1 AND F2 FOLDS INSIDE THE VIDZ
N
VIDZ
F2 axp
F2 axp
F1 axp
Equal area projection, lower hemisphere
F1ax
F1axp
VIDZ
S sh
F2ax
F2axp
F2 ax n=13 (L)
F1 ax n=6 (L)
F2 axp n=15 (P)
F1 axp n=6 (P)
F2 axp 23/61; 190/60
F1 axp 60/52

Fig. 7

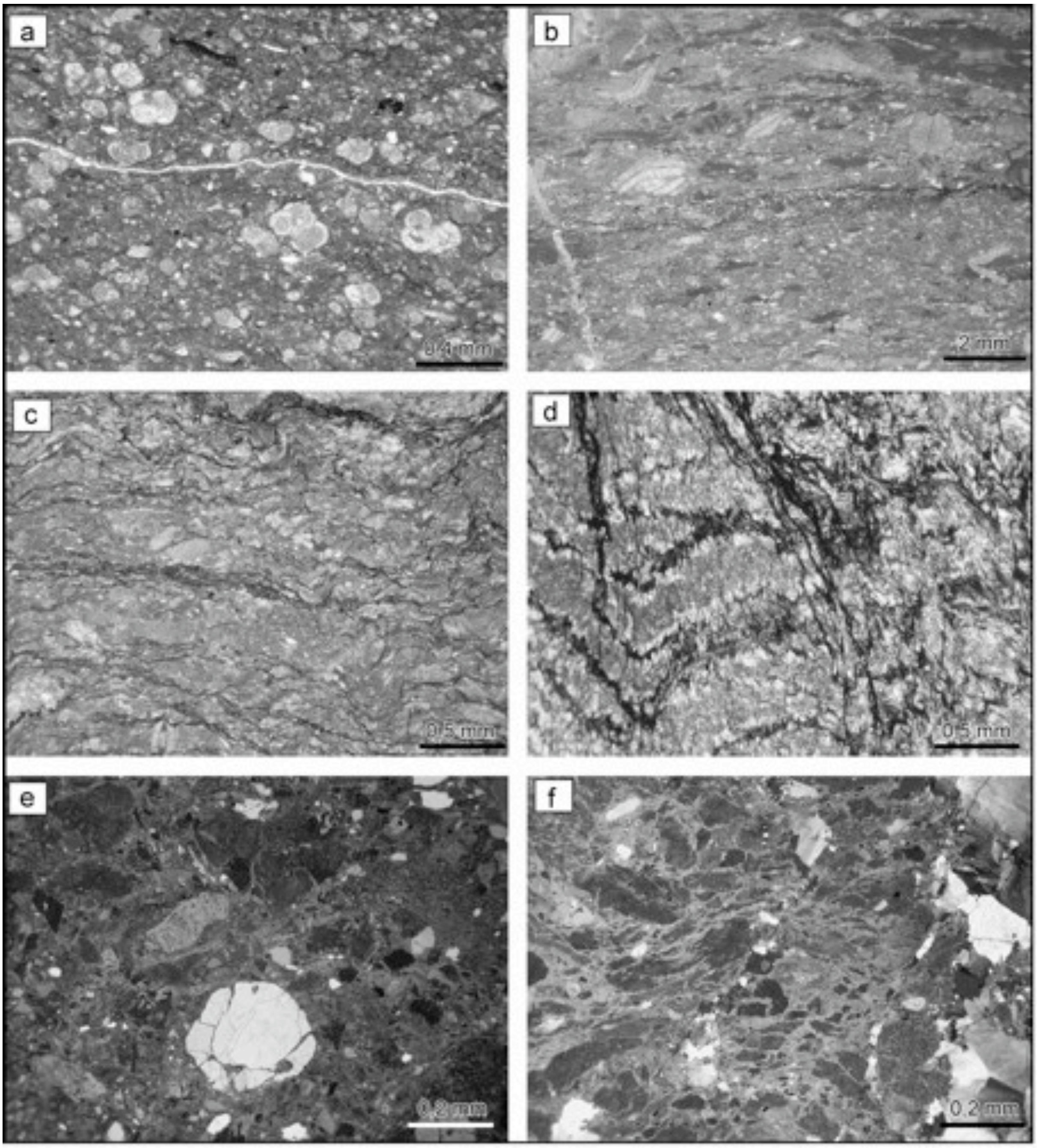
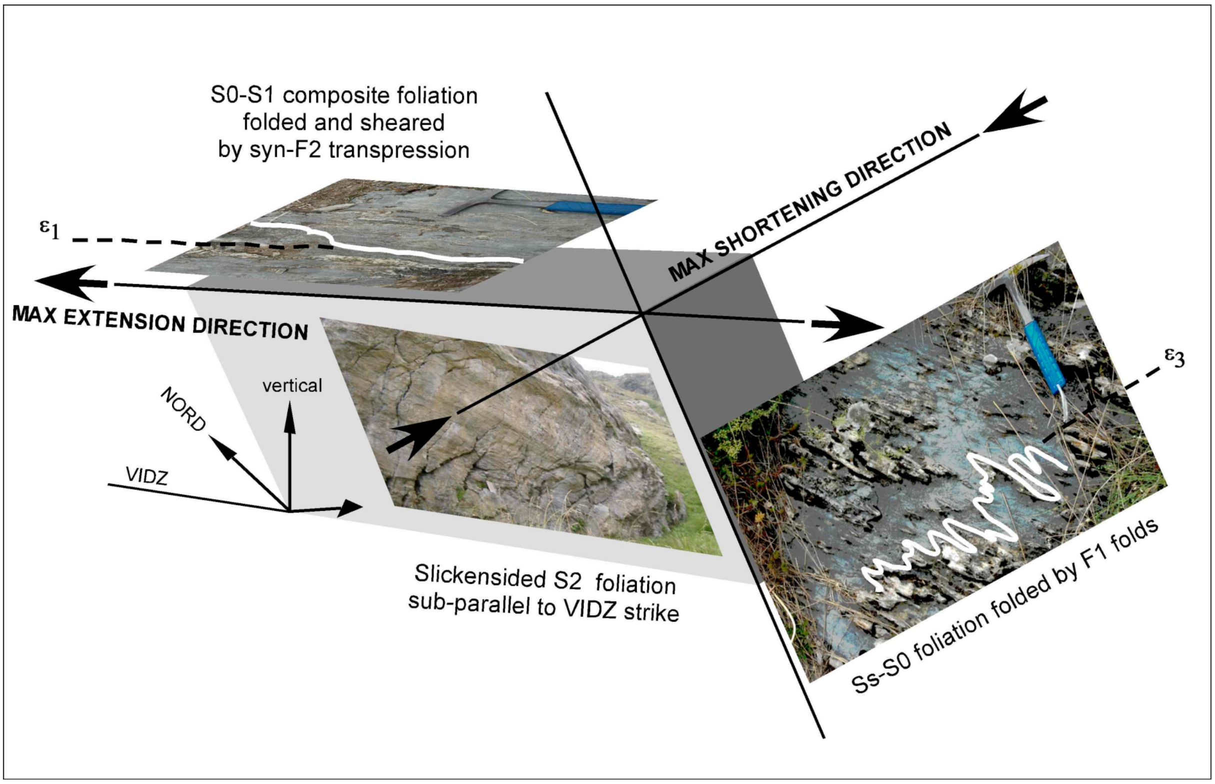
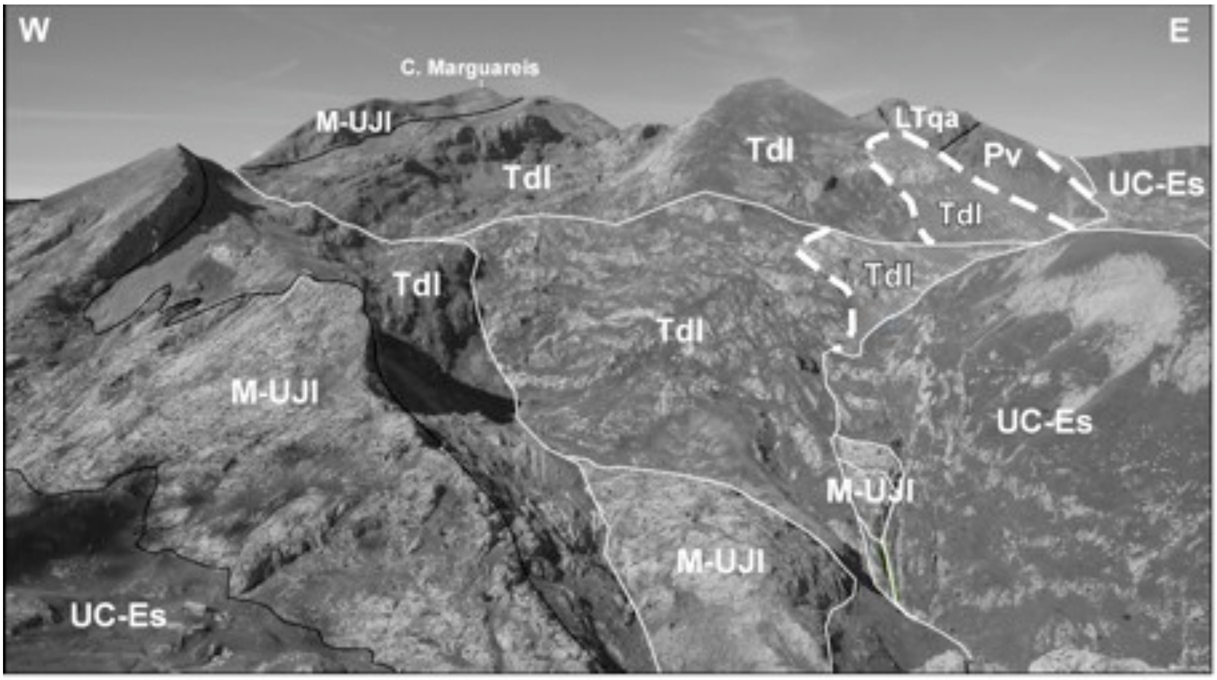


Fig. 8



S0-S1 composite foliation
folded and sheared
by syn-F2 transpression
ε1
MAX EXTENSION DIRECTION
MAX SHORTENING DIRECTION
ε3
vertical
NORD
VIDZ
Slickensided S2 foliation
sub-parallel to VIDZ strike
Ss-S0 foliation folded by F1 folds

Fig. 9



W
E
C. Marguareis
M-UJl
Tdl
LTqa
Pv
UC-Es
J
M-UJl
UC-Es

Fig. 10

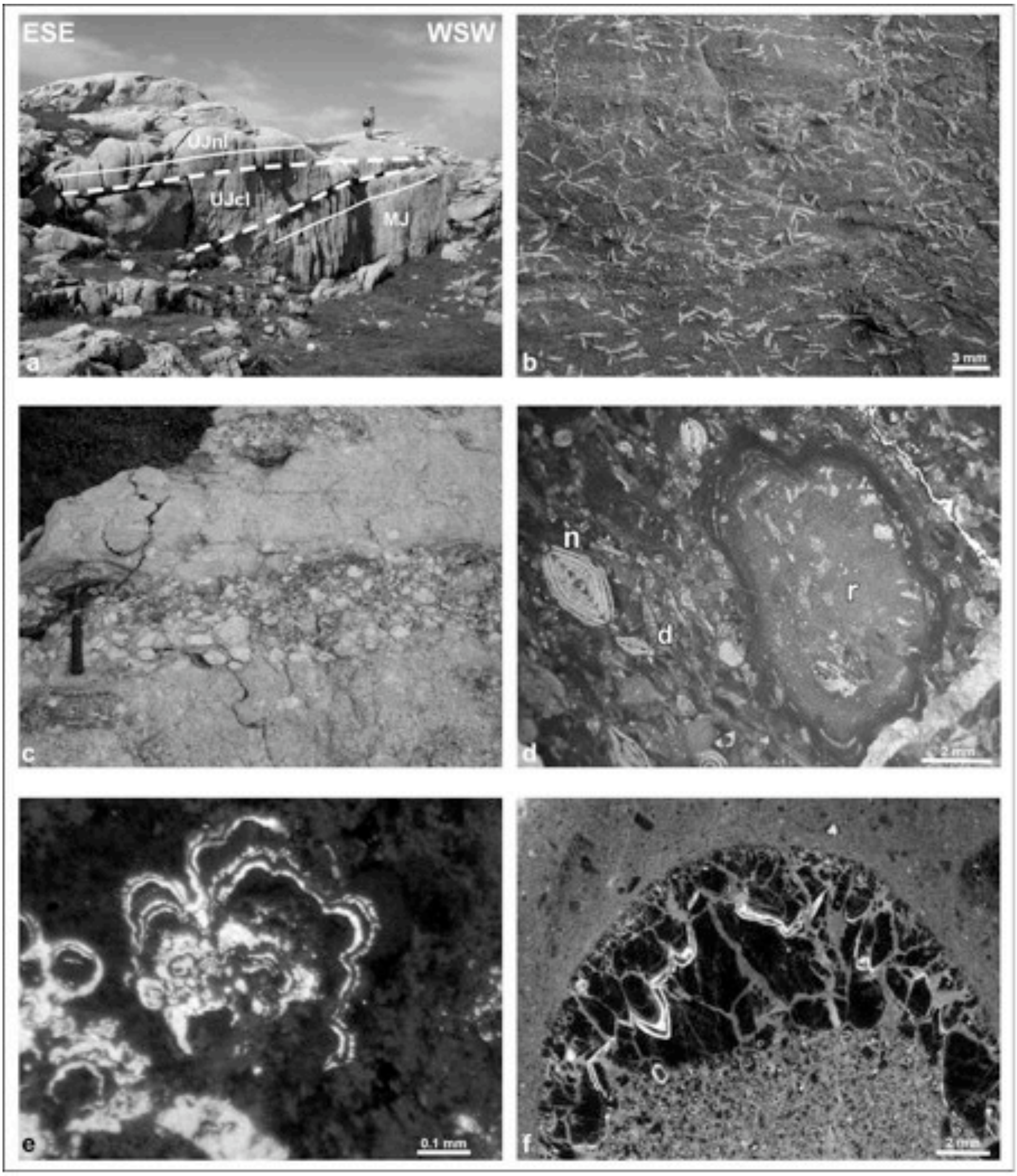


Fig. 11