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## **Subduction interface processes**

**recorded by eclogite-facies shear zones (Monviso, W. Alps)**

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## **Abstract**

The Monviso ophiolite Lago Superiore Unit constitutes a well-preserved, almost continuous upper fragment of oceanic lithosphere subducted at c. 80 km depth, thereby providing a unique opportunity to study mechanical coupling processes and meter-scale fluid-rock interactions occurring at such depths in present-day subduction zones. It is made of (i) a variably thick (50-500m) section of eclogitized basaltic crust (associated with minor calcschist lenses) overlying a 100-400m thick metagabbroic body and of (ii) a c. 1km thick serpentinite sole. We herein focus on the three major eclogite-facies shear zones found at the top of the unit, at the boundary between basalts and gabbros, and between gabbros and serpentinites, respectively. Strain localization occurred at lithological interfaces, irrespective of material strength. While ductile deformation dominates along the shear zones, local brittle behaviour is demonstrated by the existence of numerous eclogite breccias of Fe-Ti metagabbros and widespread garnet fractures, possibly linked with intermediate-depth eclogite-facies (micro)seismicity. These m- to hm-sized fragments of Fe-Ti metagabbros were later sheared and disseminated within serpentinite schists along the gabbro-serpentinite boundary (Lower Shear zone; LSZ). Pervasive and focused fluid flow is attested in the LSZ by significant alteration of bulk rock compositions, weakening of the rocks and widespread crystallization of hydrous parageneses. By contrast, the Intermediate Shear zone (ISZ) shows evidence for more restricted, short-range fluid flow. The activity of both the ISZ and LSZ ceased during early lawsonite eclogite-facies exhumation, when deformation localized deeper within the serpentinite sole, allowing for the detachment (and preservation) of this large ophiolitic fragment.

**Keywords:** *Subduction channel, shear zone, eclogite, fluids, Monviso ophiolite*

## 1. Introduction

Characterisation of subduction interface dynamics is crucial to understand lithospheric-scale coupling between plates, vertical movements, material recycling and to better assess seismic hazard. The subduction interface is the target of numerous geophysical (e.g., Zhao et al., 2002; Oncken et al., 2003; Ranero et al., 2003; Abers et al., 2006; Raimbourg et al., 2007; Hilairet et al., 2007) and numerical modelling investigations (e.g., Gerya et al., 2002; Yamato et al., 2007). A wealth of field observations constrain mechanical processes occurring along the seismogenic zone at depth where megathrust earthquakes occur (15-35km; Toyoshima, 1990; Ikesawa, 2003; Rowe et al., 2005; Bachmann et al., 2009; Meneghini et al., 2010; Fig. 1). In comparison, mechanical processes taking place deeper (>30-40 km) along the subduction interface, such as episodic tremor and slip events (Rogers and Dragert, 2003) or intermediate depth seismicity, are still poorly known due to the scarcity of well-preserved fault planes and shear zones within exhumed fragments detached beyond such depths (e.g. Austrheim and Andersen, 2004; John and Schenk, 2006; Healy et al., 2009; Fig. 1).

Large-scale, fossil shear zones from exhumed portions of subducted lithosphere may preserve the record of subduction interface processes (such as dynamic recrystallization, fluid flow and mass transfer) and shed light on interplate mechanical coupling and past seismic activity (e.g., White et al., 1980; Kirby, 1985; Handy et al., 1999; Montési and Hirth, 2003; John et al., 2009; Platt and Behr, 2011). However, contrary to eclogite facies shear zones from deeply subducted continental crust studied in the Norwegian Caledonides (e.g., Boundy et al., 1992; Fountain et al., 1994; Terry and Heidelbach, 2006; Raimbourg et al., 2007), few examples exist on large-scale, deeply subducted oceanic lithosphere remnants liable to give information on mechanisms acting during long-lived oceanic subduction (e.g., Philippot and Van Roermund, 1992; Hermann et al., 2000).

This paper aims at filling this gap and focuses on eclogite-facies shear zones formed at c. 80 km depth during oceanic subduction, which are found in the Monviso ophiolite, a well-preserved fragment of Tethyan oceanic lithosphere (W. Alps, Italy; Lombardo et al., 1978; Lagabrielle and Lemoine, 1997; Groppo and Castelli, 2010; Spandler et al., 2011; Angiboust et al., 2011).

We herein present detailed petrological and deformation data, from the kilometer scale to the mineral scale, on the three largest shear zones found in the Monviso ophiolite, as identified from previous mapping and recently published P-T determinations (Angiboust et al., 2011). The field relationships and petrography, mineralogy and chemistry of the three major shear zones are successively presented and a detailed petro-tectonic evolution is then proposed. We then discuss implications for fluid-flow, strain partitioning and subduction dynamics, and for the detachment and migration of km-scale fragments along the subduction interface.

## **2. Geological setting and structure of the Lago Superiore Unit**

The Western Alps result from successive subduction, accretion and collision between the European and Apulian/African plates from the Cretaceous to the Oligocene (Coward et al., 1989; Polino et al., 1990; Agard et al., 2002; Rosenbaum and Lister, 2005). The internal Western Alps represent the W-verging stack of continental and oceanic nappes formed during subduction and (partial) exhumation of the Jurassic Tethyan seafloor and associated European thinned margin below the Apulian plate (e.g., Bearth, 1967; Dal Piaz et al., 1972; Agard et al., 2002; Rubatto and Hermann, 2003; Oberhänsli and Goffé, 2004; Angiboust et al., 2009; Beltrando et al., 2010). Remnants of this slow-spreading ocean form the Liguro-Piemontese domain, now sandwiched between the Penninic front and eclogitized portions of the European continental margin (e.g., Dora Maira, Gran Paradiso; Fig. 2, inset). Eclogitized portions of the Liguro-Piemontese oceanic lithosphere are found 200 km along-strike, from the Zermatt-Saas area (in the north) to the

Monviso area (in the south), and constitute some of the largest and deepest ophiolitic slices detached from a subduction zone (Reinecke, 1998; Bucher et al., 2005; Angiboust et al., 2009).

The southern extent of the Liguro-Piemontese domain can be divided in two main tectono-metamorphic domains. To the west (Queyras area), the external Liguro-Piemontese zone corresponds to a fossil accretionary wedge, the Schistes Lustrés domain *s.s.*, where m- to hm-sized blocks and lenses of mafics and ultramafics are embedded in blueschist-facies, late Mesozoic metasedimentary rocks (e.g., Lagabrielle et al., 1984; Deville et al., 1992; Schwartz et al., 2000; Agard et al., 2001, 2002; Tricart et al., 2004; Fig. 2, inset). To the East, the Monviso ophiolite forms the structural base of the Liguro-Piemontese domain and is separated from the adjacent Schistes Lustrés *s.s.* domain by an extensional shear zone (Ballèvre et al., 1990). The Monviso ophiolite is in turn separated from the underlying continental Dora Maira massif (Sampeyre and Dronero units) by another extensional shear zone (Blake and Jayko, 1990; Fig. 2a,b). These deep tectonic contacts, originally thrust planes, were thus reactivated as detachment zones during the Monviso exhumation history (e.g. Philippot and Van Roermund, 1992).

Based on tectono-stratigraphy, the Monviso ophiolitic massif was earlier divided into six units separated by W-dipping ductile tectonic contacts (Lombardo et al., 1978; Schwartz et al., 2001). All the rocks of the massif show evidence for recrystallization under eclogite-facies conditions followed by retrogression under epidote-blueschist facies and greenschist facies (Lombardo et al., 1978; Blake et al., 1995). Ages for eclogitization of the ophiolite range between 50 and 40 Ma (Monié and Philippot, 1989; Duchêne et al., 1997; Cliff et al., 1998; Rubatto and Hermann, 2003). Several studies suggested variable maximum P-T conditions for the Monviso ophiolite (from *c.* 450°C/12 kbar to 620°C/24 kbar; Blake et al., 1995; Messiga et al., 1999; Schwartz et al., 2001) and argued for the presence of a deep subduction mélange where tectonic slices detached from different depths accumulated in a weak serpentinized subduction channel (e.g., Guillot et al., 2004). However, Angiboust et al. (2011) recently demonstrated that the Monviso ophiolite can be divided in two main coherent tectono-metamorphic units (Fig. 2b): (i)

the Monviso Unit to the W, which reached *c.* 480°C/ 22 kbar and (ii) the Lago Superiore Unit to the E, which recrystallized within lawsonite eclogite facies close to the coesite stability field (*c.* 550°C/ 26 kbar; similar estimates were obtained on a lawsonite-eclogite assemblage by Groppo and Castelli, 2010). These two units are separated by a ductile shear zone named “Upper Shear Zone” (USZ) in this study (Fig. 2).

The Lago Superiore Unit is a well-preserved, relatively undisturbed section of oceanic lithosphere, cut across by two major shear zones (referred to as the “Intermediate” and “Lower Shear Zones”: ISZ and LSZ; Fig.2b; Philippot and Kienast, 1989; Angiboust et al., 2011). The upper portion of the section is composed of a variably thick and heterogeneous, dominantly mafic sequence containing (i) metabasalts and associated interpillow material (60-80%), (ii) metadiabases and Fe-Ti metagabbro layers (10-20%) and (iii) calcschists (5-10%; Fig.2b). The middle part of the section is composed of a 200-300m thick Mg-Al metagabbro capped by a discontinuous (generally 5-20m thick) layer of Fe-Ti metagabbros. The bottom of the sequence is mainly composed of serpentinites derived from hydrothermally altered abyssal peridotites (Monviso, 1980; Hattori and Guillot, 2007; Figs.2b, 3a).

### **3. Field observations in the three major shear zones**

The three main shear zones, which cut across the Monviso ophiolite, are either localized at the boundary between units with different P-T histories (USZ) or along major lithological boundaries (ISZ, LSZ; Figs. 2b, 3). By contrast, m-sized shear zones found in the field show limited spatial continuity and lack well-developed mylonites or blocks embedded in serpentinite. For the sake of clarity, field observations for each of the shear zones are summarized in Table 1 and detailed geological maps of the shear zones are given as Supplementary material 1.

#### **3.1 *The Upper Shear Zone (USZ)***

The USZ can be followed over 15 kilometers from Colle Armoine in the north to south of Passo Gallarino in the south (Fig. 2a). This USZ is lined up by a variably thick (between 1 and 30m) serpentinite sliver, in which m-sized flattened lenses of Fe-Ti metagabbros are randomly dispersed, together with rare Mg-Al gabbro lenses and metasediments (dominantly calcschists). Metabasaltic rocks forming the lower margin of the USZ are commonly dragged and sliced along the shear zone. Meter-sized mylonite serpentinite slivers are also interleaved with strongly retrogressed metabasalts in the vicinity of the USZ. Importantly, eclogitic lenses found along the USZ do not record evidence for strong and pervasive eclogite-facies mylonitization as for other shear zones deeper in the ophiolite pile (see below). The USZ was intensively reactivated as an extensional detachment zone during later exhumation stages, as testified by the formation of ubiquitous W-dipping shear bands and L-tectonites at the transition between epidote blueschist facies and greenschist facies conditions (9kbar, 420°C; Schwartz et al., 2000).

### 3.2 *The Intermediate Shear Zone (ISZ)*

The ISZ, which is more limited spatially than the other two, is well expressed in the Lago Superiore area and pinches out southwards in the Viso Mozzo area and northwards (Fig. 2a, Fig. 3a). In the Lago Superiore area (Supplementary material 1a), Mg-Al metagabbros, which constitute the bulk of the sequence, are capped by a 2-50 meter-thick discontinuous sequence of dark Fe-Ti metagabbros (ISZ-17; Fig. 3a) exhibiting a mylonitic foliation sub-parallel to the ISZ. The absence of large porphyroblasts in the mylonitic foliation, however, prevents identification of the dominant sense of shear.

These eclogites are heterogeneously deformed, showing an alternation of highly and intermediately strained samples at the outcrop scale (Philippot and Kienast, 1989). Intermediate to highly strained mylonites represent over 90 % of the volume outcrop in the Lago Superiore area.



High strain, non-coaxial deformation and folding interferences led to the formation of N-S trending cigar-shaped boudins (10m x 1m) in the Lago Superiore area (Philippot, 1987). Tensile fractures with fibrous omphacite perpendicular to the vein walls (and with the mylonitic foliation only occasionally deflected around these veins) represent a few percents of the rock volume (Philippot and Kienast, 1989). The different generations of omphacite epitaxial fillings along these veins were interpreted as marking successive incremental crack-seal processes associated with mylonitization and cm-scale, fluid-assisted mass transfer (Nadeau et al., 1993).

Several metabasaltic lenses, and to a minor extent metasediments, are found along the ISZ within serpentinite mylonites, lying subparallel to the main gently dipping foliation (~N005 15-30° W). P-T estimates show that these rocks underwent a metamorphic history similar to that of the walls of the shear zone (Angiboust et al., 2011). The apparent meter-scale structural complexity therefore results from a tectonic juxtaposition of rocks constituting the walls of the ISZ together with variably thick serpentinite slivers (0-10m; Table 1). The presence of an allochthonous serpentinite sliver between gabbros and basalts (Fig. 2a, Lago Superiore Area) indicates that the ophiolitic sequence was disrupted along the ISZ. Retrogression under epidote blueschist-facies is attested by the formation of glaucophane, chlorite, epidote and albite instead of garnet and omphacite). It dominantly affects the metabasalts from the hanging wall, whereas mylonitized Fe-Ti metagabbros are remarkably well-preserved.

### 3.3 *The Lower Shear Zone (LSZ)*

The LSZ runs at the base of the main Mg-Al gabbro body, at the boundary with the underlying serpentinite sole, and can be traced over 15 km in the studied area from Rocce Fons in the north to Colle di Luca in the south (Fig. 2a). The LSZ ranges in thickness from 40 to 150 m (Supplementary material 1b, c, d). The upper boundary of the LSZ is well defined by the Mg-Al gabbro interface but its lower margin, towards the serpentinite sole, is much more diffuse.

Finite deformation linked to the activity of the LSZ is characterized by (i) a W-dipping foliation (generally 20-30°) and the flattening of the Mg-Al gabbros of the hanging wall and (ii) an extremely pervasive schistosity in serpentinites. This serpentinitized tectonic contact is lined by many irregularly dispersed lenses and aggregates of metagabbroic and metasedimentary rocks (Fig. 2b; Table 1). Rare lenses of metasediments (mainly calcschists, carbonates and garnet-chloritoid quartzites) are intercalated within serpentinites and metagabbro aggregates in the LSZ. Most of these flattened lenses are generally meter-sized except a large lens located at the southeast of the Lago Superiore reaching several hundred meters in length and ca. 50m in thickness (Supplementary Material 1d, Fig.2a; Fig. 3a) showing slightly higher maximum temperatures than adjacent rocks ( $T_{max}=550-570^{\circ}\text{C}$  vs.  $530-550^{\circ}\text{C}$ , respectively; see Angiboust et al., 2011). Rare meter-sized blocks of jadeitite (Compagnoni et al., 2007) after plagiogranite and rodingite veins (Lombardo et al., 1978; Castelli et al., 2002) are found in blocks and veins in the LSZ and within the underlying serpentinite sole, respectively. Metabasalts were neither observed within the LSZ nor within the serpentinite sole.

Fe-Ti metagabbros generally constitute large (10-20m-sized) rounded aggregates, internally made of several independent, rounded blocks (Fig. 3b-d), wrapped by a mixture of antigorite schists, tremolite schists and talcschists. The abundance of these small rounded fragments (0.1-0.5m sized), dispersed within the serpentinite in the vicinity of the major aggregates decrease away from the aggregate core. Importantly, small (<20cm) angular mylonite fragments are dispersed upon the rough block surface (Fig. 3b) and cemented by an omphacite-rich matrix.

Some of the meter-scale blocks are made of eclogitic breccias (Fig.3e,f), where internal rotation is attested by the strong variability in strike and dip of the main mylonitic foliation planes (Fig. 3f) and omphacite cementation is also conspicuous.

Fe-Ti eclogitic blocks expose remarkably well-preserved peak mylonitic assemblages and underwent only minor and very localized retrogression under epidote blueschist-facies and

greenschist facies (Table 1). These rocks are characterized by the ubiquitous presence of whitish layers or patchy aggregates (up to 1cm in length) of pseudomorphs after lawsonite, which is now dominantly replaced by epidote and paragonite (e.g. Lombardo et al., 1978; Fig. 4). They occur either along the mylonitic foliation (Fig.4a,d) but also as porphyroblasts associated with omphacite or as vein-filling material (Fig.4a,b,c; Table 1). In locality LSZ-21 (Fig. 2a), a block exhibiting a mylonitic fabric is wrapped by a banded eclogite mainly composed of strongly folded, milky (0.5 to 2 cm-thick) layers of pseudomorphed lawsonite and foliated fined-grained omphacite (Fig. 4d). Primary crack-seal omphacite-bearing fractures similar to those from the ISZ near Lago Superiore, are locally preserved and commonly associated with pseudomorphed lawsonite veins (Fig.4a,c). Textural relationships with the mylonitic fabric are often erased by later ductile deformation.

#### **4. Mineralogy of shear zones eclogites**

Eighteen samples from the three main shear zones (Fig. 2a) were selected from a set of 75 samples collected across the study area. We focus below on the eclogitic Fe-Ti gabbro with well-preserved peak assemblages and the extent to which they record the activity of these shear zones beyond 50 km depth. The detailed peak rock paragenesis are presented in Table 2. Analytical methods used to track mineralogical and compositional changes are described in Appendix A.

##### *4.1 Upper Shear Zone eclogites (USZ)*

Rare lenses of eclogitized Fe-Ti gabbros, locally retrogressed under blueschist-facies conditions, are dispersed throughout the USZ serpentinites. One characteristic sample was collected at the south of rifugio Sella (USZ-69; Fig. 2a, 5a). The texture of these low strain Fe-Ti

metagabbros consists of former corona features with garnet growing at the boundary of pseudomorphed magmatic crystals (see also Lombardo et al., 1978, Pognante and Kienast, 1987, Philippot and Von Roermund, 1992). Clinopyroxene porphyroblasts in sample USZ-69 have been rotated, fractured and disseminated along the foliation plane. Plastic deformation is suggested by the elongated shape of recrystallized omphacite crystals. Garnet porphyroblasts are only rarely fractured (but not healed) and always show a typical “alpine” zoning pattern (i.e. Mn-Ca rich cores and Fe-Mg enriched rims; Fig. 5b; Supplementary material 2). Phengite is randomly dispersed in the clinopyroxene matrix and dismembered rutile ribbons after magmatic ilmenite define a crude foliation together with clinopyroxene. Brecciated garnet and eclogite-facies mylonites such as those described hereafter for the other shear zones have not been observed along the USZ.

#### 4.2 *Intermediate Shear Zone eclogites (ISZ)*

These eclogites are characterized by a marked grain size reduction of omphacite down to 5-10  $\mu\text{m}$  and a relatively strong crystal preferred orientation within the foliation plane, interpreted as the result of plastic dynamic recrystallization by dislocation creep (Lardeaux et al., 1986; Philippot and Kienast, 1989; Philippot and Van Roermund, 1992). Brittle deformation is attested by the presence of fractured, 10 to 300 $\mu\text{m}$  large garnet porphyroblasts (Figs. 5d-f; initially part of coronitic structures: Pognante and Kienast, 1987). Omphacite-cored atoll garnet commonly occurs along the mylonitic foliation (Fig. 5c) but is systematically absent from low-strained Fe-Ti metagabbros. Phengite and glaucophane are rare (<0.5 vol. %) and generally aligned between omphacite crystals along the foliation. Pseudomorphs after lawsonite (much smaller than those from LSZ eclogites) generally occur as millimeter-sized ribbons or aggregates dispersed along the mylonitic foliation (sample ISZ-17, Fig. 5c).

Zoning patterns in garnet from ISZ mylonitic eclogites show embayments and healed fractures, suggesting a combination of dissolution and cementation (Fig. 5d). In the least fractured garnets, the original pattern with Ca/Mn-rich cores and Fe/Mg enriched rims is preserved. In addition, a sharp depletion in grossular content commonly occurs towards garnet rims, associated with a marked increase in pyrope content (Fig. 5e,f). The outermost parts of garnet rims are slightly enriched in Mn compared to garnet mantles (see Angiboust et al., 2011, for further chemical data on these garnets). Garnet filling the fractures, which are generally 5-10µm wide, is marked by a sharp enrichment in pyrope content too (from 8 mol. % to 16 mol. %; Supplementary material 3) and a slight depletion in grossularite and almandine contents. Some samples (ISZ-36a, ISZ-49) exhibit very small truncated garnet fragments with limited evidence of post-fracturing healing.

#### *4.3 Lower Shear Zone eclogites (LSZ)*

The LSZ contains numerous blocks of Fe-Ti metagabbros, some almost identical to those found in the ISZ. It nevertheless displays a much wider diversity of rock types than along the ISZ, suggesting a somewhat different post-mylonitic metamorphic history. A common feature to those diverse rock types only encountered in the LSZ is the presence of large and widespread hydrated mineral phases (Fig. 4b). By contrast, eclogites similar to those found in the ISZ will be referred here to as "dry" eclogites.

Within dry eclogites showing textural affinities with the highly strained ISZ eclogites (i.e., brecciation, cementation and grain-size reduction), some display a marked banding exemplified by almost monomineralic layers of garnet and omphacite (e.g., samples LSZ 52d and LSZ-21; Figs. 3d, 4d). Garnet-rich layers consist of over 75 vol. % of coalesced (50-100 µm-sized) garnet crystals with intergranular spaces filled by very fine grained omphacite (c. 10-30 µm).

Omphacite-rich layers contains less than 5% vol. garnet and preferentially host millimeter-sized aggregates of pseudomorphs after lawsonite (Fig. 3d).

Hydrated eclogites, which are found only in the LSZ (Figs 3b-f), can be grouped in two main categories:

- *lawsonite-bearing eclogites (LSZ-17, 18, 21, 42 and 44)*

Lawsonite-bearing eclogites occur on the rims of the blocks of Fe-Ti metagabbros, with centimetric (Figs. 4b,d) or millimetric lawsonite fringes along the mylonitic foliation (Fig. 4a). The rims of the smaller block fragments typically comprise garnet and omphacite-bearing layers with variable amounts (0-30 vol.%) of variably-sized euhedral lawsonite pseudomorphs (from 10 $\mu$ m to up to 1cm in length; Fig. 4b). Fragments scattered at the block surface are cemented by an omphacite-lawsonite+/-garnet assemblage that ranges from weakly (Fig. 4a,b) to highly strained (Fig. 4c). Garnet diameter ranges from 20 $\mu$ m up to 1cm (Fig. 4b). A complex fracture network is generally preserved within garnet, as in ISZ eclogites. These garnet crystals exhibit 10 to 20  $\mu$ m-wide chemical oscillations associated with dissolution-precipitation processes (showing striking similarities to “cloudy” garnets described in Martin et al., 2011). One sample (LSZ-42; Fig. 5h) shows large phengite laths (0.5-4mm in length; Si<sup>4+</sup> = [3.6-3.7 p.f.u]) in apparent textural equilibrium with subidioblastic garnet and fine grained omphacite aligned along the mylonitic foliation. Phengite has not been observed included within garnet cores. Small lawsonite pseudomorphs (c. 100 $\mu$ m long) are preferentially scattered in the phengite-rich layers (Fig. 5h).

- *chlorite and talc-bearing eclogites (LSZ-06, LSZ-23 and LSZ-58)*

Talc- (LSZ-06) and chlorite-bearing (LSZ-23; LSZ-58) eclogites randomly occur on the rims of Fe-Ti metagabbro blocks. They exhibit garnet crystals with two distinct generations intensively fractured and healed by a pyrope-rich garnet. Talc or chlorite (up to 10 vol.%) occur as elongated laths along the foliation between omphacite and garnet but have not been observed as inclusion within garnet cores. Talc-bearing domains are often associated with glaucophane shear bands and chlorite aggregates cutting across and postdating the mylonitic foliation.

Complex fracture patterns are found in the garnets. As an example, five successive tectono-metamorphic events were recorded by a single garnet grain from a chlorite-eclogite (sample LSZ-23; Fig. 6a,b). The boundary between garnet I and garnet II is lined by an embayment rich in Mn and Ca (respectively up to 10 mol. % and 25 mol. %). Pyrope content increases rimwards within garnet II, from c. 15 mol. % to 25 mol. %. Several “fossilized” fracture networks lined by a slightly Mg-enriched composition can also be identified (Fig. 6a,b).

## 5 Chemical variations in shear zones eclogites

Shear zones have been long recognized as a preferred locus for fluid-assisted mass transfer leading to bulk rock chemical alteration, as well as isotopic mixing (White and Knipe, 1978; Austrheim, 1987; Dipple and Ferry, 1992; Keller et al., 2004). In order to evaluate the degree of fluid circulation, the major element compositions of all rock-types encountered in the ISZ and LSZ were compared. The procedure used to obtain reliable compositions is given in Appendix B and detailed compositions are available in Supplementary material 4.

Figure 7a shows that low-strained and dry mylonitized Fe-Ti eclogites compositions (whether from the ISZ or the LSZ) plot in the middle of the ACF diagram. “Dry” mylonitized Fe-Ti metagabbros generally have a bulk composition which lies very close to the Lago Superiore area eclogites studied by Schwartz et al. (2000). By contrast, lawsonite-rich hydrated eclogites (dominantly cropping out in the LSZ) exhibit a striking depletion in FeO (-8 wt. %; Fig. 7a). This feature is also observed for lawsonite and omphacite-bearing veins sampled between brecciated fragments, whose composition largely differs from that of the undeformed Fe-Ti metagabbro (Fig. 7a).

Mg-chlorite and talc-bearing mylonites, where pseudomorphed lawsonite has not been observed, are significantly enriched in MgO: talc-bearing mylonites range from 9 to 16 wt.% MgO (Fig. 7a; low strained Fe-Ti metagabbros typically contain 6 wt.% MgO). Similar bulk rock

estimates for the phengite-bearing Fe-Ti metagabbro (LSZ-42) show that the K<sub>2</sub>O bulk rock content of this sample is close to 1.5 wt.%, *i.e.* more than 5 times higher than the average K<sub>2</sub>O content of Monviso Fe-Ti metagabbros (see Lombardo et al., 1978 and Schwartz et al., 2000).

A striking depletion in FeO is also recorded by garnet rims from LSZ eclogites (Fig. 7b), which are systematically depleted in almandine content, and corresponds to the transition between GrtI and GrtII (Fig. 6a). Garnet rim values for all samples are surprisingly similar (Fig. 7b) and generally trend towards 55% of almandine content. Such a trend is absent from the ISZ (and USZ) samples (Fig. 7b).

## **6. DISCUSSION**

### **6.1 Petrological evolution during shear zone activity at 80 km depth**

Our data (field relationships and petrography, mineralogy, chemical trends) suggest that eclogite-facies deformation of Fe-Ti metagabbros and fluid infiltration led to the formation of various mylonite types. Their relative timing of formation is presented in figure 8a and set back against P-T conditions (taken from Angiboust et al., 2011). We stress that the four steps described in figure 8a successively took place between 70 and 80 km depth under lawsonite eclogite facies conditions, as testified by the presence of lawsonite pseudomorphs all along the textural evolution (as porphyroblasts and/or in veins). Steps 2 to 4 occurred in a relatively narrow P-T range as demonstrated by similar thermobarometric estimates obtained on these texturally different assemblages (detailed calculations given in Angiboust et al., 2011).

“Dry” mylonites (Fig.8a-step2) are common along the ISZ and also occur in the LSZ. By contrast, the presence in the LSZ of strongly hydrated parageneses and extensive bulk rock alteration demonstrates that the blocks of Fe-Ti metagabbros dispersed along this shear zone recrystallized in a much more fluid-rich environment. Chemical data (Fig. 7a,b) indicate



contrasting degrees of bulk rock alteration, ranging from slightly (in the ISZ) to strongly altered (in the LSZ). Similarities in terms of rock types, P-T conditions and textures (garnet zoning and brecciation; lawsonite pseudomorphs) between the ISZ and LSZ suggest that the LSZ recorded a broadly coeval (i.e., at the same depths) yet slightly longer tectonic history than the ISZ, with marked fluid and mass transfer. This is consistent with the much more intense fragmentation of eclogite blocks and the larger spatial extension of the LSZ in the field (Figs. 2a, 3b,c). These additional stages of deformation and fluid influx, mostly recorded in the LSZ, are shown in figure 8a, as steps 3 (compare with Figs. 3e-f) and 4 (compare with Fig. 4d).

We finally point out that the presence of eclogitic breccias (Fig. 3e), garnet fractures (Fig. 6a) and block boudinage (Fig. 4d) attests to switches between brittle and ductile deformation, as shown in steps 2 through 4 (Fig. 8a). In the following sections, we use this petro-tectonic evolution to provide critical information on deformation patterns, fluid-rock interactions and rheological processes occurring within the eclogitized oceanic lithosphere, down dip in the subduction zone.

## **6.2 Contrasting ranges of fluid flow**

The above data suggest a contrasting amount of fluid flow for the ISZ and the LSZ (Figure 8b), whose spatial extent is further discussed here.

The detailed analysis of ISZ garnets shows a complex zoning pattern (overgrowths, oscillations; Fig. 5f, supplementary material 2; see also Spandler et al., 2011), suggesting chemical system opening and deformation-assisted fluid circulation. Manganese, which is strongly partitioned within garnet cores, may have been dissolved during fracturing of garnet cores and subsequently precipitated after advective transport (for examples of garnet embayment within an ISZ eclogite, see Angiboust et al., 2011; their Fig. 3g). However, undeformed Fe-Ti

metagabbros and “dry” ISZ mylonite samples are chemically indistinguishable (Fig. 7a). Moreover, garnet rim almandine content from ISZ Fe-Ti eclogites is similar to that of undeformed, unaltered samples (Fig. 7b). Even if a very local infiltration of external fluid is possible (Spandler et al., 2011), our results support the predominance of relatively short range (i.e. meter-scale) fluid flow along the ISZ, as first inferred for Lago Superiore area eclogite mylonites from the presence of omphacitic crack-seal veins (e.g., Philippot and Selverstone, 1991; Nadeau et al., 1993; Table 1; Fig. 7a). Sharp interfaces between (omphacite filled) tensile cracks and mylonitized wall rock also suggest short-lived, incremental fluid-rock interaction and short vein lifetime (Philippot and Van Roermund, 1992).

In the LSZ, by contrast, our data point to larger-scale fluid flow and substantial metasomatism (Fig. 7a; with noticeable chemical potential gradients in H<sub>2</sub>O, SiO<sub>2</sub> and FeO; e.g., Ferry, 1979) between the serpentinite matrix and the blocks of Fe-Ti metagabbros (see Fig. 8a, steps 3-4). Dissolution figures and associated overgrowths (Figs. 6a,c) show that the garnet surface was successively enriched in Mn-Ca then in Mg. This sharp boundary between Grt I and Grt II in LSZ eclogites (Figs. 6a,c; Fig.7b) requires the advection of elements (and chemical system opening) close to peak conditions. The decrease of garnet almandine content within core-rim profiles for all LSZ samples towards a similar value (Fig. 7b) strongly suggests a buffering and input of Mg by the adjacent thick serpentinite sole (Figs. 2b,3b).

Eclogite porosity is generally limited to microfractures, isolated pores, cleavage planes and mineral boundaries (e.g. Mibe et al., 2003), connectivity is presumably very limited (Watson and Brenan, 1987; Davies, 1999) and eclogite permeability is estimated at six orders of magnitude lower than for serpentinite mylonites ( $10^{-18} \text{m}^2$ ; Morrow et al., 1984). We thus suggest that serpentinite-bearing shear zones, particularly the LSZ, acted as true conduits for fluid flow, despite the fact that the relatively low permeability of the blocks possibly deflected most of the flow through the matrix and limited deep infiltration into the blocks (Ague, 2007).

Whether fluids channelized within the LSZ originate from antigorite breakdown (which occurs close, yet slightly deeper than estimated peak conditions: ~650°C, 25-30kbar; Scambelluri et al., 1995; Ulmer and Trommsdorff, 1995) or derive from dehydration of the adjacent Mg-Al gabbro body during prograde reactions remains uncertain (see also the discussion on ISZ veins by Spandler et al., 2011). Chemical exchange and the formation of metasomatic rinds in any case facilitated the transposition of fabrics and enhanced fragment disaggregation, as observed on the block rims along the LSZ (Fig. 3c; for similar blackwall examples: Bebout and Barton, 2002; Catlos and Sorensen, 2003; Breeding et al., 2004).

### **6.3 Rheology of the subducting lithosphere and strain localization at depth**

The Lago Superiore Unit provides a unique opportunity to document deep deformation processes occurring in subducted oceanic lithosphere, from the kilometer scale to the mineral scale, and to compare it with theoretical rheological parameters derived from rock flow laws based on experimental data (e.g., Kirby, 1983).

#### *6.3.1 Rheological behaviour at the kilometer scale*

Bulk cumulative strain inferred from field observations is shown in figure 9b (and set back against the cross-section of figure 9c). This profile shows that the main shear zones are preferentially located along the major lithological contrasts, i.e. at the boundary between materials with significantly different strengths and viscosities. In agreement with theoretical studies of multilayered media (e.g., Stromgard, 1973; Treagus, 1981), this confirms that interfaces between rocks with different competencies are the loci of maximized shear strain.

For the sake of comparison, we tentatively evaluated the strength of each layer of the column using available dislocation creep flow laws for similar materials (Fig. 9a). This profile has

been calculated using a constant strain rate of  $10^{-14} \text{ s}^{-1}$ . Other details of the calculation method are given in Appendix C. Our field observations (Fig. 9b) qualitatively strengthen the rheological envelope inferred from laboratory experiments (Fig. 9a) in showing that gabbros are indeed stronger than the overlying metabasaltic sequence under peak conditions (in agreement with preliminary observations; Burg and Philippot, 1991). However, the geometry of the whole system (stack of layers) implies that the different shear zones were active for the same range of shear stresses, a statement at variance with the very large strength contrasts derived from dislocation creep flow laws (Fig. 9a). In particular, in spite of the presence of a thick serpentine sole supposedly so weak as to accommodate all the deformation, not only the shear zones (where serpentinite slivers are commonly found) but also the bulk of the metabasalt unit was pervasively deformed. This relative weakness of eclogites, not well reflected in experimental flow laws (Fig. 9a), could be related to their high water content, as rock strength is known to be significantly reduced by the presence of dissolved water (“hydrolytic weakening”; Griggs, 1967; Rybacki and Dresen, 2000; Zhang and Green, 2007), particularly within omphacite (whose  $\text{H}_2\text{O}$  content commonly reaches 1000 ppm in natural eclogites; e.g. Katayama et al., 2006).

Although ductile deformation dominates the deep evolution of this ophiolite, brittle deformation is apparent in veins (Fig. 5g) and in the breccia structures on the rims of the blocks of the LSZ (Fig 3c-e; Fig.4c). These observations are consistent with the experimental results describing a “semi-brittle” mode of deformation, in particular for clinopyroxene (Kirby and Kronenberg, 1984; Rutter, 1986; Philippot and Van Roermund, 1992). It should be noted that the “clasts” of these breccia are mylonite fragments, and that the whole breccia is generally reworked by ductile deformation, i.e., brecciation is bracketed by two phases of mylonitization (Fig. 8a, step4). Pseudotachylites marking brittle rupture (Austrheim and Boundy, 1994; Andersen and Austrheim, 2006) have not been observed within the Lago Superiore Unit, despite extensive investigations. This could be due to the fact that pseudotachylites preferentially develop in

extremely water-poor protoliths (John et al., 2009), whereas the Lago Superiore Unit shear zones show ample evidence for abundant fluid circulation.

### 6.3.2 *At the cm-scale: phase segregation and garnet fracturing*

Phase segregation between omphacite and garnet (Fig. 3d, Fig. 4d, Fig. 8a-step 2) was described in shear zones from the Tauern, Dabie Sulu, Caledonides (Holland, 1979; Ji et al., 2003; Terry and Heidelbach, 2006) and in experimentally deformed eclogites under high shear strain (Zhang and Green, 2007), but at temperatures much higher than those reported for Lago Superiore eclogites. Mechanisms invoked for phase segregation include mineral reactions, deformation-related processes such as dynamic recrystallization associated with grain size reduction (Philippot and Van Roermund, 1992; Mauler et al., 2000; Terry and Heidelbach, 2006) and/or the presence of a free fluid phase (e.g., Essene and Fyfe, 1967; Holland, 1979; Schliestedt, 1990; Selverstone et al., 1992).

We suggest that the segregation of garnet (otherwise behaving as rotating rigid spheres in a matrix of weaker omphacite) into lenses or layers may well explain their fracturing (Fig. 8b) as a result of indentation at garnet-to-garnet contacts. This does not preclude the contribution of other processes, such as hydraulic fracturing (Spandler et al., 2011), but does not require the presence of a very high pore fluid pressure. In principle, with increasing strain such angular fragments can be disseminated along the foliation by cataclastic flow (e.g., Tullis and Yund, 1987). This is locally observed in some very dry eclogite mylonites along the ISZ (ISZ-49; Fig.2a), but most garnet fractures, within both ISZ and LSZ samples, are healed without evidence of relative displacement (Fig. 5d, Fig. 6a). Fast healing of garnet requires efficient element mobility, which is fostered by a free fluid phase (Erambert and Austrheim, 1993) and by grain size reduction (Rutter and Brodie, 1995). The preservation of an almost undisturbed garnet I shape at the core of garnet II also suggests the existence of a stress drop after fracturing (Fig. 6d), since garnet fragments would

otherwise have been disseminated by ongoing strain. This result is consistent with the very large minimum stress drops associated with very small earthquakes, inferred from pseudotachylytes of Corsica (Andersen et al., 2008). These observed deformation and growth patterns thus potentially relate to co-seismic deformation and intermediate-depth coupling processes (see also Erambert and Austrheim, 1993). On the other hand, phase segregation and healed fractures also point to a key contribution to small-scale deformation processes from dissolution-precipitation, in addition to creep. Dissolution-precipitation may indeed be an important deformation mechanism within omphacite-rich domains, which are particularly subject to channelized fluid circulation (Piepenbreier and Stöckhert, 2001), or within garnets (as shown by the propagation of crack-tips; Prior, 1993).

#### **6.4 Implications for km-scale, geodynamic processes at the subduction interface**

Our results demonstrate that the Lago Superiore ophiolite was affected by intense shearing dominantly accommodated along three major shear zones defined by eclogite-facies mylonites and/or serpentinite slivers (Fig. 8b). Lenses and blocks dispersed along these shear zones, as well as the whole of the Lago Superiore, display similar P-T conditions (Angiboust et al., 2011), suggesting spatially limited tectonic mixing. The error bar associated with the thermobarometric methods used here (i.e.  $\pm 20^{\circ}\text{C}$  and  $\pm 1.5$  kbar) implies that less than c. 12 km of cumulative displacement occurred along these shear zones (considering a dip of  $45^{\circ}$  for the plate interface). The slightly hotter temperatures reported in a calcschist lens embedded within the LSZ (Fig. 3a;  $560\text{-}570^{\circ}\text{C}$ ; Angiboust et al., 2011) may reflect the fact that the lower portion of the ophiolite reached slightly greater depths ( $\leq 3$  km deeper) than the overlying portions of the Lago Superiore ophiolite (Fig. 10a). These shear zones, particularly the LSZ, represent an example of network widening (in the sense of Schrank et al., 2008, for example) and not a subduction *mélange* formed by extensive mixing along the subduction interface (Blake et al., 1995; Guillot et al., 2004). The

above description of deformation patterns within the Lago Superiore ophiolite thus suggests that caution is needed before interpreting former eclogite-facies shear zones as serpentinite mélanges, particularly in areas with limited surface exposures (e.g., Voltri; Brouwer et al., 2002; Federico et al., 2007).

We emphasize that mylonitized Fe-Ti metagabbros blocks found dispersed within serpentinite in the LSZ originate from the ISZ for two reasons: (i) the main source of Fe-Ti gabbros is structurally located at the top of the Mg-Al gabbroic body (Figs.3a, 8b) (ii) mylonitization of such eclogites cannot happen once the blocks are embedded within the rheologically much weaker serpentinite. Such Fe-Ti metagabbros thus constitute markers of the relative displacement along the shear zones. The blocks from the LSZ successively underwent mylonitization along the ISZ (Fig. 10a), shearing and detachment from the ISZ by a ball-bearing mechanism before being embedded in the serpentinites schists of the LSZ (Fig. 10b). Note that displacement of eclogitic blocks from ISZ to LSZ through the gabbroic body could have been facilitated by the presence of an inherited structural weakness (such as bending-related faults; e.g. Ranero et al., 2003), tectonically reactivated as a thrust during deep shearing.

The final detachment of the Lago Superiore ophiolitic slice as a whole implies that deformation migrated towards the base of the serpentinite sole (Fig. 10c). Strain localization within the ultramafic section of the lithosphere probably occurs at the transition between highly and mildly serpentinitized peridotite (i.e., at depths of a few hundred meters to a few km below the oceanic Moho; Minshull et al., 1998; Iyer et al., 2010). It is likely that from this stage onwards (Fig. 10c) both the ISZ and LSZ were less active, and consequently preserved from extensive overprinting.

The behaviour of the Lago Superiore ophiolite after detachment remains somewhat speculative but is closely linked (as discussed by Agard et al., 2009) with the upward, buoyancy-driven exhumation of light continental material ( $\rho \sim 2700 \text{ kg.m}^{-3}$ ) dragging these dense ( $\rho = 3300\text{-}3400 \text{ kg.m}^{-3}$ ; e.g. Stern, 2004; Lapen et al., 2007; Angiboust and Agard, 2010) portions of

eclogitized oceanic lithosphere along the subduction interface. Accordingly, younger peak ages recorded in the adjacent, continental Dora Maira internal crystalline massif (c. 35-40 Ma v. 40-45 Ma for Monviso; Tilton et al., 1991; Duchêne et al., 1997; Rubatto and Hermann, 2001) would imply that the ophiolite remained at depth for ~5 My before being dragged upwards by the Dora Maira unit. In the meantime, the Lago Superiore slice may have remained buoyant enough thanks to the buoyant serpentinite sole at the base of the section (300-500m;  $\rho=2900 \text{ kg.m}^{-3}$ ; Schwartz et al., 2001; Guillot et al., 2004) and/or to the overall fluid content in the mafic section (Angiboust and Agard, 2010). Further geochronological data are now required to better constrain the relative timing of deformation and deep thrusting processes responsible for detachment and exhumation of the Monviso ophiolite and its relationships with the underlying Dora Maira unit.

## 6. Conclusions

The Lago Superiore Unit, which exposes a very well-preserved lithospheric-scale tectonic ophiolitic slice returned from c. 80 km depth in the Alpine subduction zone, is crosscut by a network of three km-scale shear zones. It therefore provides a unique opportunity to study strain localization and rheological weakening in the subducting lithosphere. Our results show that:

- (i) Strain was strongly localized within eclogite-facies shear zones at the interface between layers presenting rheological contrasts (i.e. between basalts, gabbros and serpentinites).
- (ii) Dominantly short-range fluid flow occurred at the basalt-gabbro boundary (ISZ) through repeated fracturing processes associated with mylonitization of the shear zone. By contrast, we identified a longer-lived, pervasive deformation-enhanced fluid pathway at the gabbro-serpentinite interface (LSZ) leading to strong metasomatism, mechanical weakening and dismembering of the block fragments within serpentinite schists.



- (iii) The presence of eclogite “breccias”, preserving numerous healed fractured garnet crystals, suggest a local brittle behaviour of the oceanic crust, possibly associated with co-seismic deformation.
- (iv) The activity of both the ISZ and LSZ stopped during early lawsonite eclogite-facies exhumation when deformation localized deeper within the serpentinite sole, allowing for the detachment (and preservation) of this large ophiolitic fragment.

## **Appendix A**

### *Analytical methods:*

Mineral abbreviations used in this work are after Whitney and Evans (2010).

The mineral analyses were performed using a Cameca SX100 electron microprobe (Camparis, Univ. Paris 6; a Cameca SX50 was also used for additional conventional analyses). Classical analytical conditions were adopted for spot analyses [15 kV, 10 nA, wavelength-dispersive spectroscopy (WDS) mode], using  $\text{Fe}_2\text{O}_3$  (Fe),  $\text{MnTiO}_3$  (Mn, Ti), diopside (Mg, Si),  $\text{CaF}_2$  (F), orthoclase (Al, K), anorthite (Ca) and albite (Na) as standards. Chemical maps of garnet were obtained at the SX100 electron microprobe using 15 kV, 20 nA and a counting time of 100ms. Quantifications were derived from the automated Cameca ZAF quantification procedure.

Chemical composition of microdomains (~3mm x 1.5mm) studied for bulk rock composition analysis were obtained at the Geology Laboratory of the Ecole Normale Supérieure (Paris) using a Zeiss Sigma field-emission-gun SEM with an X-max Oxford detector (50 mm<sup>2</sup>), an acceleration voltage of 20 kV and a counting time of 1 minute per domain.

Three additional whole-rock chemical analyses were undertaken at the SARM (CRPG Nancy) from c. 5 cm<sup>3</sup> of each representative rock sample (ISZ-17, sole-55 and LSZ-18-2). The major elements were analysed by inductively coupled plasma-optical emission (ICP-OES) spectroscopy after fusion with LiBO<sub>3</sub> and dissolution in HNO<sub>3</sub>. More details on the method are given in Carignan et al. (2001). H<sub>2</sub>O content was determined by loss on ignition.

## **Appendix B**

### *Bulk rock composition analysis:*

Chemical composition of fifteen thin sections from USZ, ISZ and LSZ were calculated either by averaging of several surface compositions scans using a FEG-SEM (average between 2 and 5 surface analyses) or by a combination of visual percentage estimated modes (Terry and Chilingar, 1955) and averaged EMP chemical analyses. Detailed chemical compositions, average values and sampling GPS coordinates are given in Supplementary material 4.

## **Appendix C**

### *Construction of the rheological profile*

In order to compare rheological properties of the materials, fixed value of 10<sup>-14</sup> s<sup>-1</sup> has been chosen for the calculation. Note that integrated strain rates for subduction zones, generally between 10<sup>-13</sup> and 10<sup>-14</sup> s<sup>-1</sup> may be substantially higher along shear zones (between 10<sup>-9</sup> and 10<sup>-12</sup> s<sup>-1</sup>; Sibson, 1986; Stöckhert, 2002; Burg and Gerya, 2005), leading to significant increase of rock strength and a marked decrease of rock viscosity

For the basaltic upper section (Fig.9a), we use an omphacite power law creep rheology (Zhang, 2006) to describe its behaviour because omphacite appears to be the dominant (c. 75%) mineral under eclogite-facies conditions. This assumption is justified by the fact that garnet (less than 15 vol.% in the eclogitized basaltic crust) does not exhibit a strong fabric and generally behaves as a rotating rigid body during plastic deformation of eclogite (e.g. Mainprice et al., 2004). For Fe-Ti

metagabbros, where the relative amount of garnet locally reaches 40 vol.%, an eclogite flow law is considered to be more appropriate (Jin et al., 2001). We also consider that Mg-Al gabbro is rheologically similar to diabase, whose mineralogy is also composed of a Ca-rich plagioclase and clinopyroxene (Mackwell, 1995). As Fe-Ti metagabbros are included in the uppermost portion of the Mg-Al metagabbro, the whole gabbroic unit is believed to behave as a coherent body (Fig. 9). Serpentine exhibits a viscosity which is over 4 orders of magnitude lower than metagabbros (following the flow law for antigorite from Hilairet et al., 2007).

Experimental parameters for the eclogite flow law (calculated for 50% garnet, 40% omphacite, and 10% quartz; Jin et al., 2001) yield an unrealistic rock strength of 7 GPa for Fe-Ti metagabbros under these relatively cold conditions ( $T=550^{\circ}\text{C}$ ; Fig. 9a). This value will likely be lowered in our samples since garnet, considered as responsible for strengthening of the eclogites in the dislocation creep regime (Jin et al., 2001) represents only 25–30 vol.%. Pervasive ductile deformation of metagabbros contrasts with the presence of omphacite-bearing crack-seal veins (earlier reported in eclogite-facies mylonites from the Lago Superiore Area; Philippot, 1987), which constitute one of the rare examples attesting to local brittle behaviour of oceanic crust under HP-LT conditions.

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### **Figure captions**

**Figure 1:** Sketch showing a typical subduction zone and some of the key processes occurring along the plate interface. Mechanical coupling is maximum along the seismogenic zone (between 10-35km) where the plate boundary is possibly sealed (Audet et al., 2009). Episodic tremor and slip events (ETS) generally occur at the base of the seismogenic zone. Decoupling is believed to occur below due to fluid transfer across the plate interface and serpentinization of the overlying mantle wedge. Note that the oceanic mantle is also believed to be partially serpentinized before entering the trench.

**Figure 2: a.** Geological map of the working area showing the location of the main shear zones, the position of the units and the location of samples mentioned in text (modified after Lombardo et al., 1978 and Angiboust et al., 2011). The inset localizes the Monviso ophiolite within the Western Alps. **b.** Section across the Monviso ophiolite showing the disposition of the main tectonic units and tectonic relationships between them (dotted transect on Fig. 2a).

**Figure 3: a.** Field view of the Lago Superiore Unit showing the various lithologies and the location of the three main shear zones (USZ, ISZ, LSZ: upper, intermediate and lower shear zones, respectively) together with samples mentioned in the text. Deep shear zones (in red) are marked as thrusts on the picture. The USZ, reactivated as a major detachment zone during late exhumation processes, is lined by dark black rectangles. **b.** Field view of a rounded block of Fe-Ti metagabbro embedded within LSZ serpentinites (Punta Forcione: N 44° 40' 38.1"; E 07° 07'

39.8"). **c.** Drawing illustrating a disaggregated block and associated disseminated fragments within a serpentinite/taleschist matrix (Punta Murel: N 44° 39' 00.5"; E 07° 07' 55.4"). **d.** A strongly foliated mylonite where omphacite (Omp) and garnet (Grt) have been clearly segregated in two distinct domains (hammer for scale). Note that whitish pseudomorphs after lawsonite (Ps. Lws) are concentrated in omphacite domains. **e.** Picture of typical eclogite breccias found at the surface of blocks embedded within the Lower Shear Zone (LSZ), showing variably sized and oriented fragments of eclogite facies mylonites cemented by omphacite. **f.** Drawing of the foliation trend within an eclogite-facies breccia from Colle di Luca (Fig. 2a) emphasizing the rotation of the fragments at the block surface.

**Figure 4:** **a.** Contact between a mylonitized eclogite fragment and a vein filled by omphacite and pseudomorphs after lawsonite at the surface of a brecciated eclogitic block from the LSZ (N 44° 39' 52.8"; E 07° 07' 50.3"). **b.** Lawsonite eclogite sample occurring in a low-strained domain at the block surface showing remarkably large lawsonite pseudomorphs (up to 1cm in length) in a weakly deformed matrix (Punta Murel; Fig.2a). **c.** A mylonitic foliation consisting of garnet, omphacite and rutile (right) crosscut by a vein (left) filled by lawsonite and omphacite (lawsonite is now pseudomorphed by epidote and paragonite). **d.** Boudinaged mylonitic fragment wrapped within a later foliation consisting of omphacite, garnet and lawsonite (LSZ). Mineral abbreviations as in figure 3.

**Figure 5:** **a.** Scanned thin section of a moderately strained eclogite from a block embedded within serpentinite from USZ (Fig. 2a), showing relatively well preserved relicts of omphacite porphyroclasts (after augite) embedded within an omphacite-rich foliated domain. **b.** Quantified chemical map of a garnet crystal magnesium content (wt.%) of sample USZ-69, showing a typical zoning pattern (enrichment in Mg towards the rims) and the absence of healed fractures. **c.** Back-scattered Electron (BSE) view of an Fe-Ti metagabbro mylonite from Lago Superiore Area

showing pseudomorphs after lawsonite growing along the omphacitic foliation. Dismembered rutile ribbons underline the foliation. **d.** BSE picture of a garnet showing two distinct garnet generations with a clear Ca-rich core and a dark Mg-rich rim. A dark complex network of healed Mg-rich fractures connected on the garnet rim crosscuts the garnet core. Garnet chemical composition across the fracture (transect a-b) is given in Supplementary material 3. **e.** Chemical map of Mg content (counts) of the mylonitic matrix from sample ISZ-17. **f.** Chemical map of Mg content (wt.%) of a garnet from sample ISZ-49 exhibiting a very complex pattern of Mg-enriched healed fractures. **g.** Scanned thin section of a mylonitic sample showing the mylonitic foliation deflected around an omphacite-filled crack-seal vein. **h.** Scanned thin section of sample LSZ-42 (courtesy of D. Waters) showing numerous phengite and pseudomorphed lawsonite crystals along the eclogitic foliation. Abbreviations after Whitney and Evans (2010).

**Figure 6:** **a.** Chemical maps of a garnet from a chlorite-eclogite sample from the LSZ (LSZ-23). **b.** Sketches depicting the successive steps of garnet growth. A first garnet (Garnet I) generation is fractured and healed by a Mn-Ca rich garnet composition (white dotted line square). A second fracturing episode is attested by the presence of a very complex fracture pattern cemented by a Mg-rich composition (Garnet II). **c.** Core to rim zoning profiles of the garnet composition. **d.** These successive events can be interpreted in terms of cyclic variation of relative shear stress associated with movement along the shear zone. See discussion for details.

**Figure 7:** **a.** Plot of the bulk rock composition in the ACF triangle (with F=FeO) for the mylonites sampled in the Intermediate (ISZ) and Lower (LSZ) Shear Zones distinguishing the different types of mylonites identified on petrographic observation and the trend in FeO depletion associated with water-saturated mylonitization (growth of lawsonite). **b.** Smoothed, normalized garnet core-rim transects for eleven samples from the three different shear zones. Iron depletion is



systematically observed at the rim of garnet from LSZ while it is absent within garnet from unaltered or ISZ samples. The red arrow localizes the relative position of incipient depletion.

**Figure 8: a.** Relative chronology of events (and associated P-T position) observed on eclogite Fe-Ti metagabbro mylonites boudins along the ISZ and LSZ. Igneous texture (step 1) is progressively blurred by mylonitization processes (step 2) leading to grain size reduction, garnet fracturing and phase segregation. Variable amounts of hydrous phases crystallized depending on the amount of water available during mylonitization. Eclogite facies breccias (step 3), commonly found along the LSZ are generally cemented by omphacite +/- lawsonite +/- garnet. These brecciated fragments (Fig. 3f) may be embedded as boudins in a later lawsonite eclogite-facies foliation (step 4). The P-T diagram at the background shows the P-T path for the LSU ophiolite, the location of the main metamorphic facies and the relative position of the four steps identified. Note that the presence of lawsonite (now pseudomorphed by epidote), omphacite and garnet in all textural positions constrains these events to the lawsonite-eclogite facies. **b.** Schematic drawing at the scale of the Lago Superiore unit, showing the location of the different shear zones and the location of the four steps mentioned above. Our results indicate that substantial fluid flow occurred along the LSZ, whereas only short range localized fluid flow within the ISZ.

**Figure 9: a.** Plot of differential strength (thick line) and viscosities (dotted line) against the same cross-section using the following flow laws: calcschists (micaschist: Shea and Kronenberg, 1992), basalts (omphacitite: Zhang et al., 2006), gabbros Fe-Ti (eclogite: Jin et al., 2001), gabbros Mg-Al (diabase: Mackwell et al., 1995), serpentinite (serpentinite: Hilairet et al., 2007) at 550°C and with a strain rate of  $10^{-14}$ . More details on the construction of the profile are given in Appendix C. **b.** Finite strain envelope across the described section, inferred from field observations and strain markers, showing that strain is strongly localized along the shear zones. **c.** Section across the Lago Superiore Unit showing the lithologies and the location of the three main shear zones. Arrows

along the shear zones represent normal movement during late exhumation processes (Philippot and Van Roermund, 1992).

**Figure 10:** **a.** Sketch representing the Lago Superiore ophiolite slice at the onset of mylonitization. Deformation is first localized on the ISZ, at the boundary between basalts and gabbros (red dotted line). **b.** Ongoing shearing along the plate interface is responsible for dismembering and fragmentation of eclogite blocks detached from the ISZ. **c.** The whole Lago Superiore unit finally detaches from the downgoing slab and the bulk of the deformation is now localized at the base of the serpentinite sole. Monviso unit, which detaches from the slab at c. 65-70km is not represented here. **d.** P-T paths from Angiboust et al. (2011) for both Monviso and Lago Superiore Units. **e.** Eclogite facies shear zone activity is restricted to the vicinity of peak conditions (i.e. 550°C, 26 kbar). Juxtaposition with the adjacent Monviso Unit occurs in the epidote blueschist facies during exhumation in the subduction channel (Schwartz et al., 2000). The relative timing of shear zone activity is based on the intensity of metamorphism recorded by the rocks from the different shear zones.

**Table 1:** Summary of field, structural and petrological observations with emphasis on the lenses and/or blocks dispersed within the three main shear zones. Thermobarometric results are from Angiboust et al. (2011).

**Table 2:** Synthesis of peak paragenesis and relative phase abundances in the selected set of samples from the three shear zones described in the text.

**Supplementary material 1:** Detailed geological maps of selected areas along the ISZ and LSZ. Position of these close-up views is shown in Figure 2.

**Supplementary material 2:** Chemical map comparing garnet zoning pattern from USZ and ISZ. A “classical” (i.e. a smooth decrease in Ca-Mn garnet content from core to rim) undisturbed zoning pattern is observed for the sample embedded within the USZ serpentinites (USZ-69). Garnet from a mylonite from ISZ exhibits two distinct generations: the core of Grt I is enriched in Mn-Ca while the rim (Grt II) is enriched in Mg-Fe. An intense fracture network, characterized by healing with Mg-enriched Grt composition, crosscuts Grt I.

**Supplementary material 3:** Garnet end-member molar fraction from EMP chemical analyses for the transect a-b (Fig. 5d) across a healed fracture showing a clear enrichment in Mg along the fracture.

**Supplementary material 4:** Summary of bulk-rock estimates performed for this study and average composition obtained for each rock type. GPS coordinates of each sample are also given.

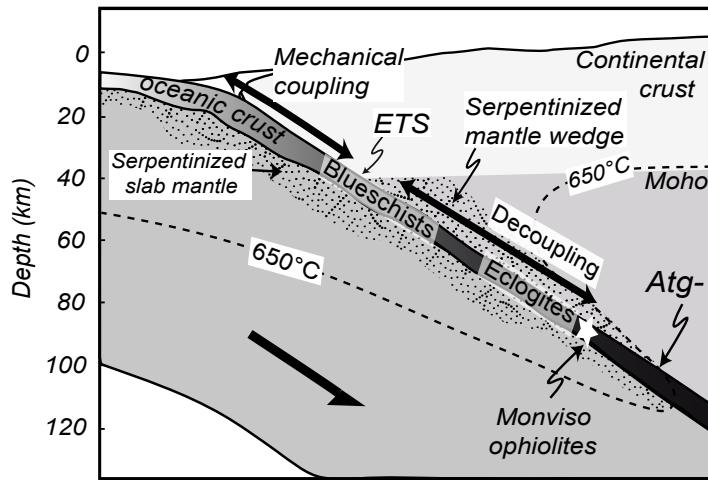
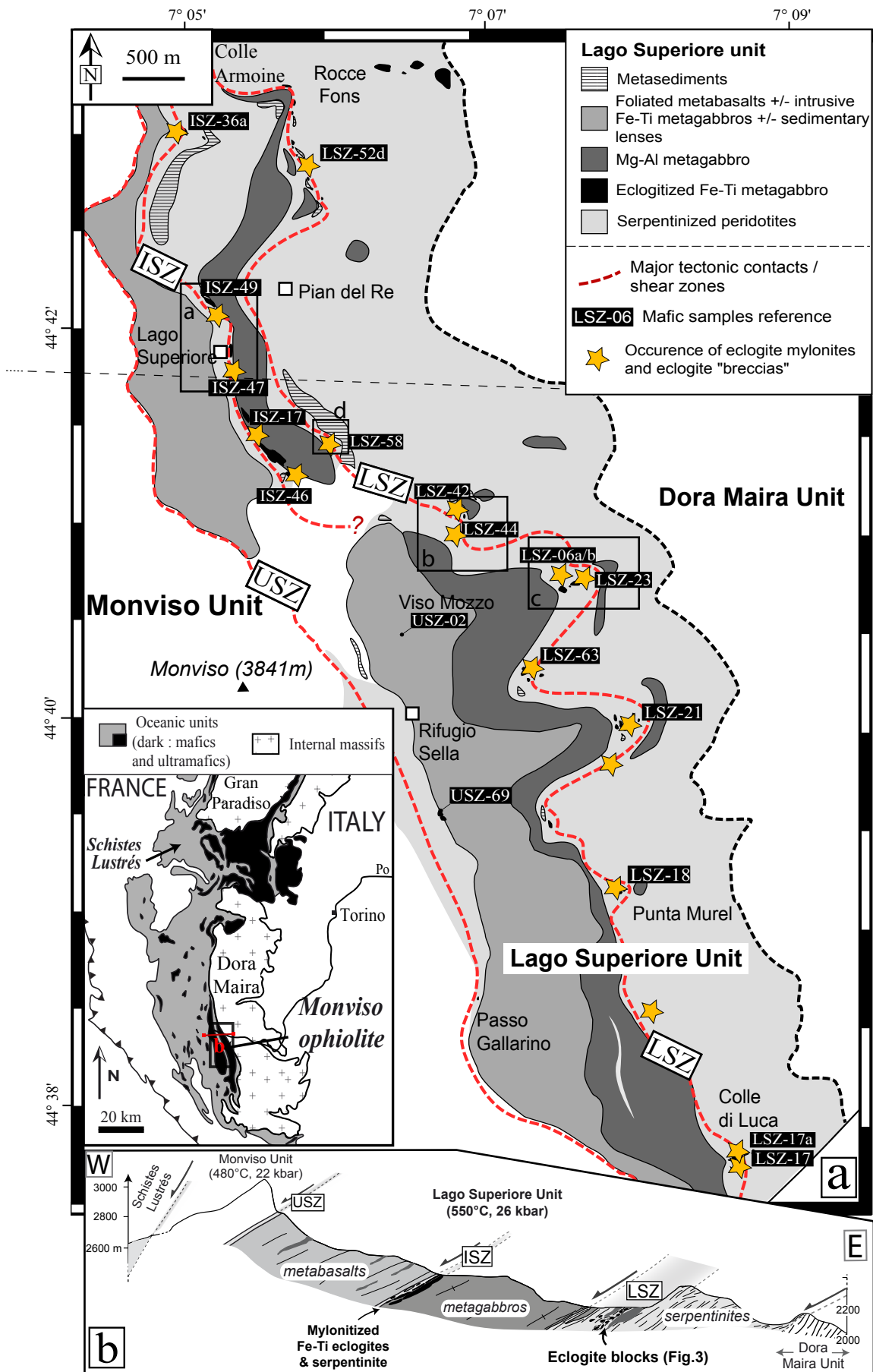


Figure 1





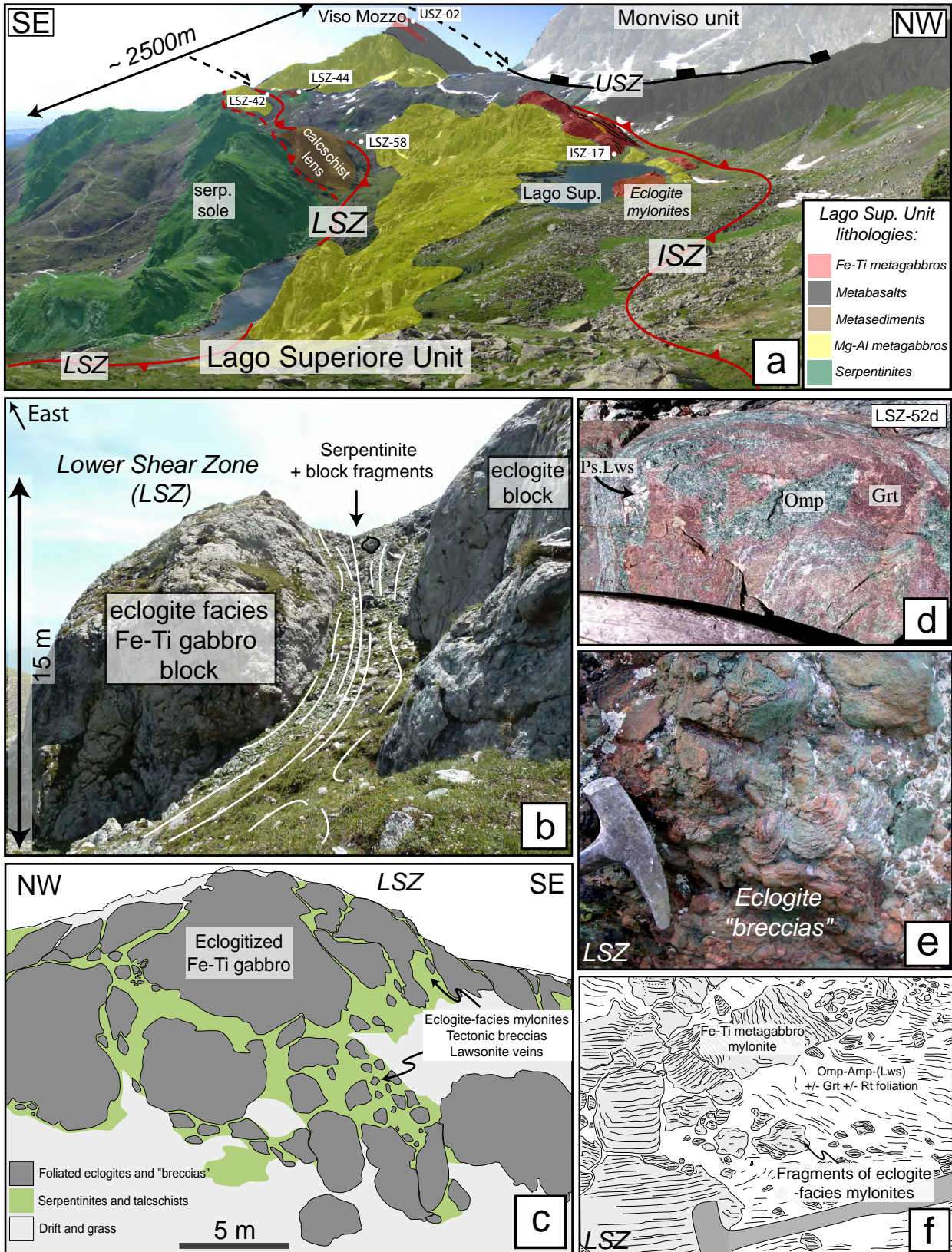


Figure 3



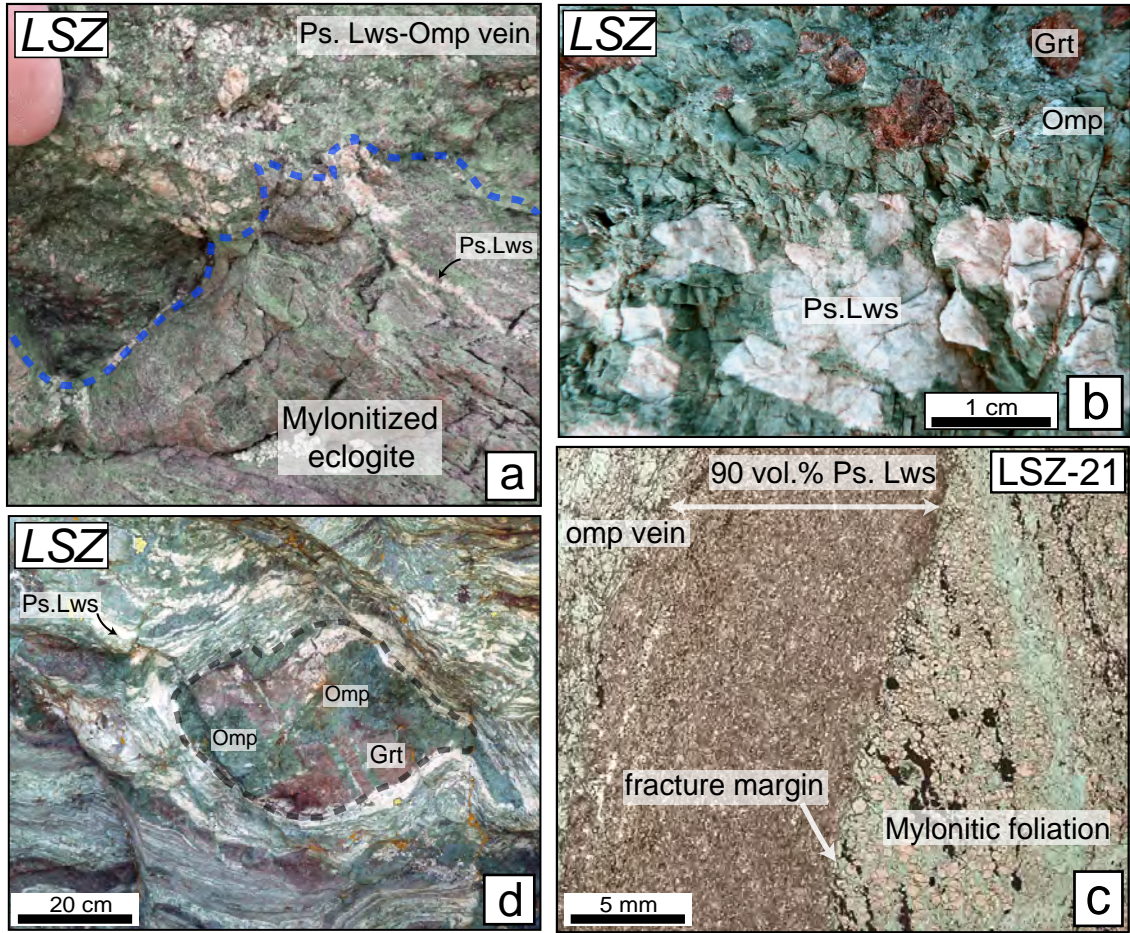


Figure 4



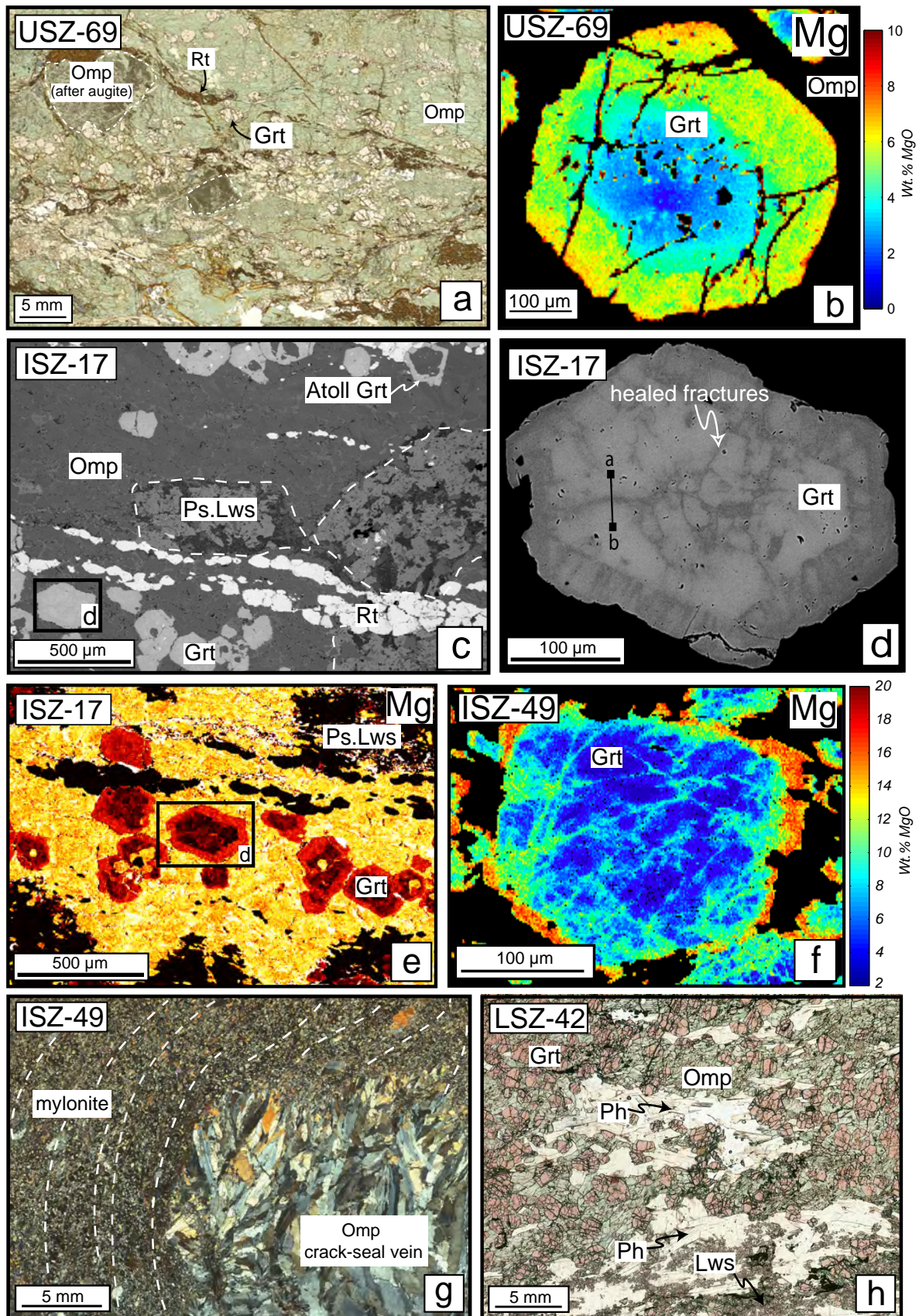


Figure 5



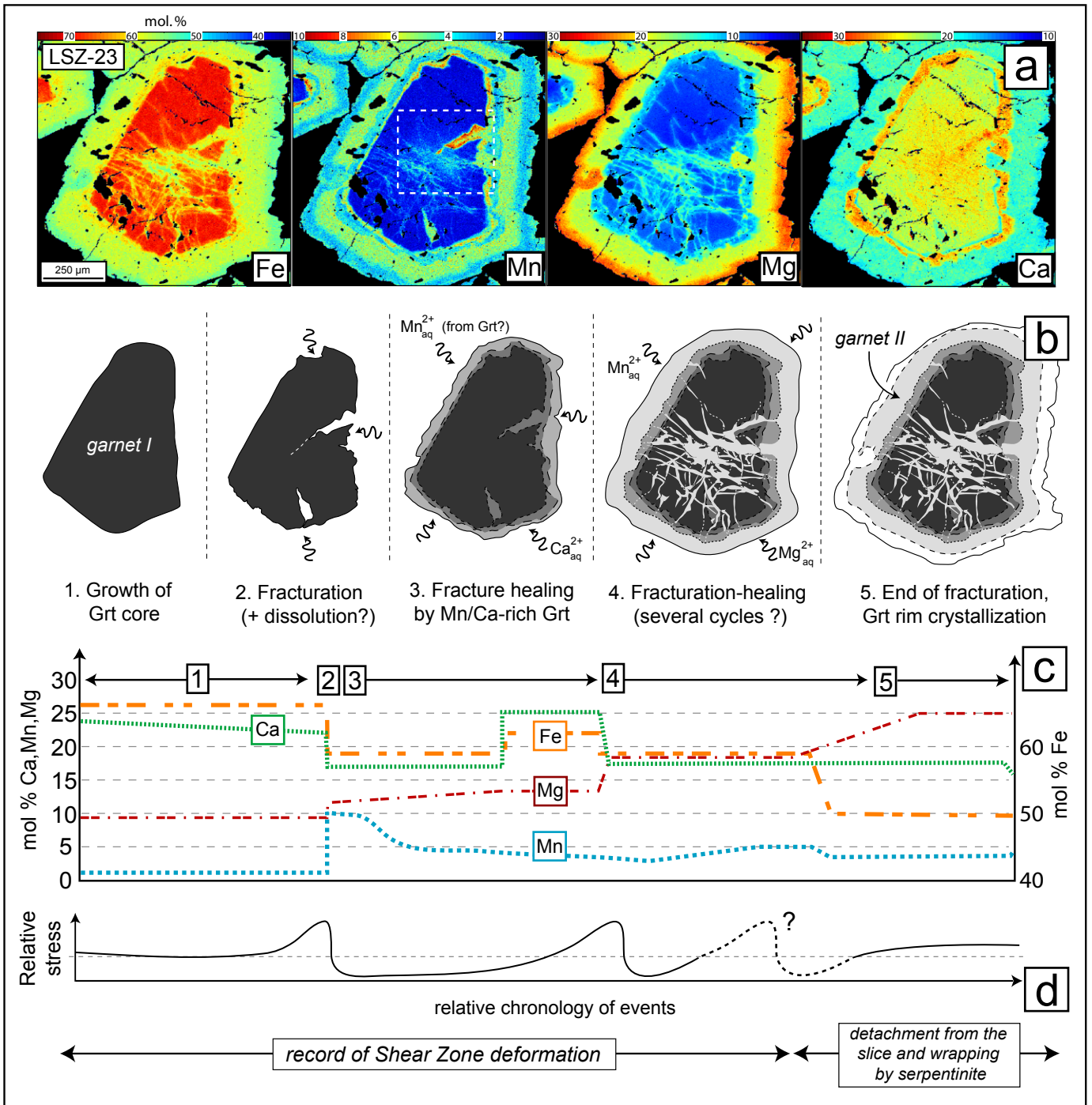


Figure 6

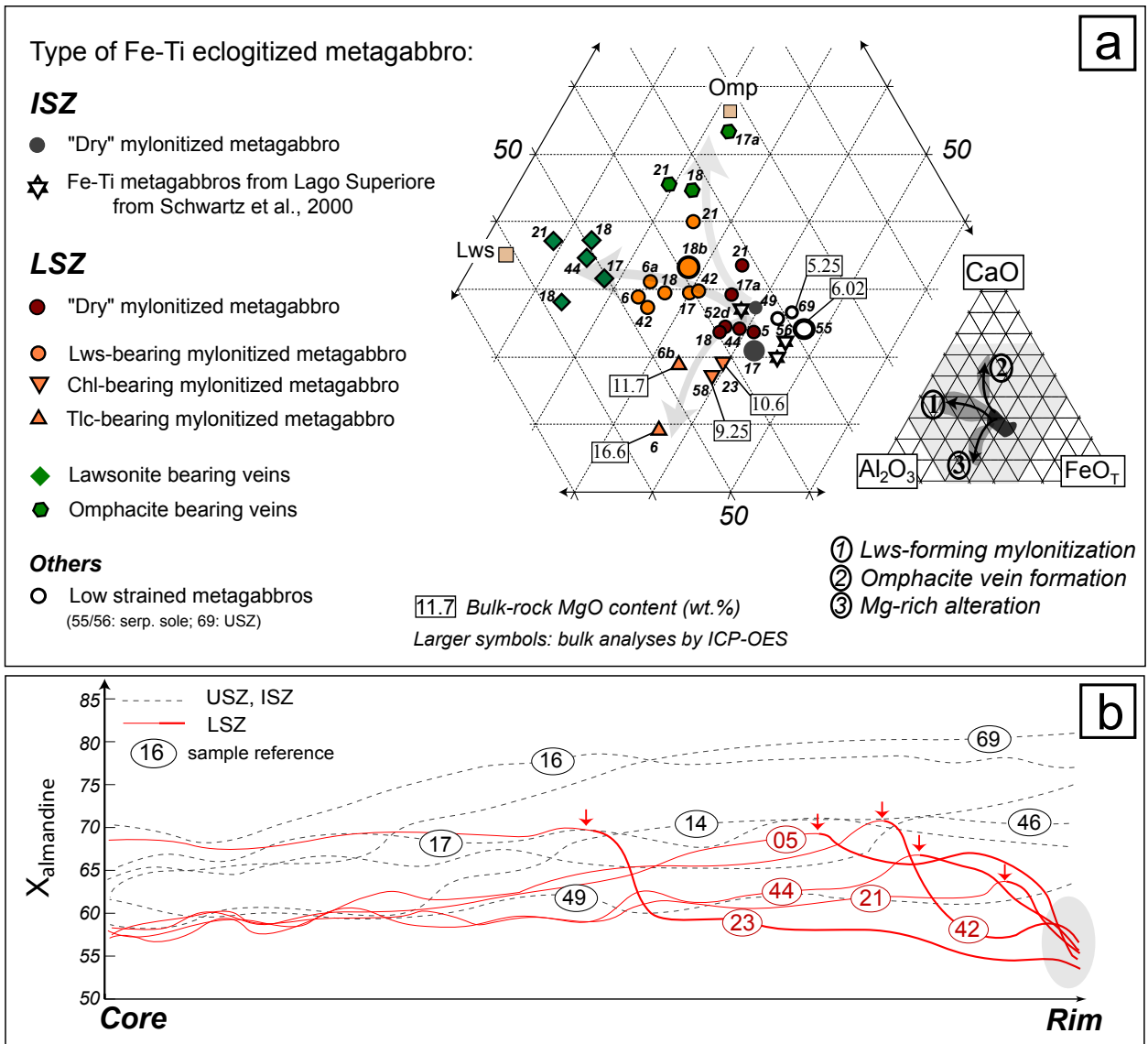


Figure 7

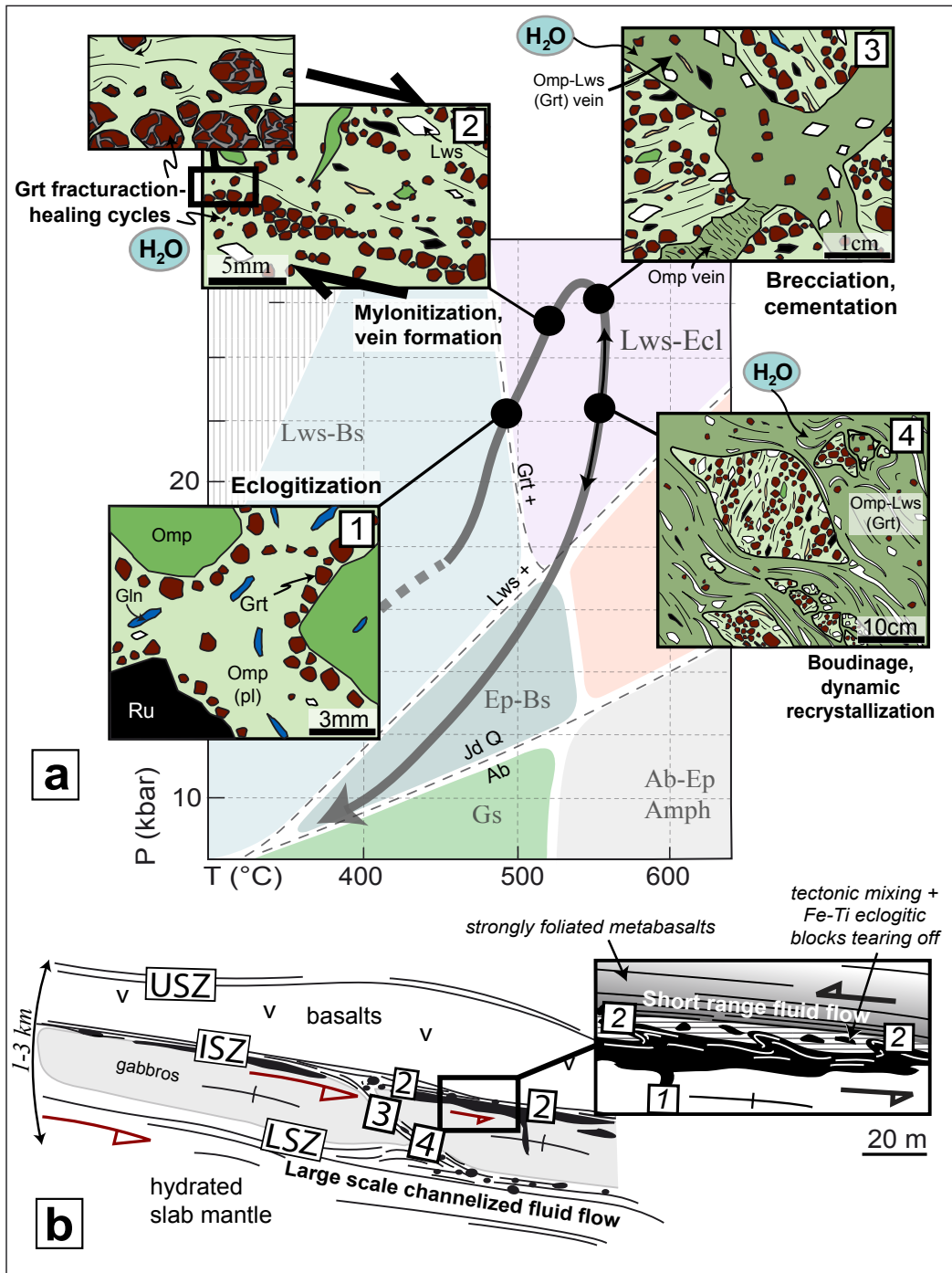


Figure 8

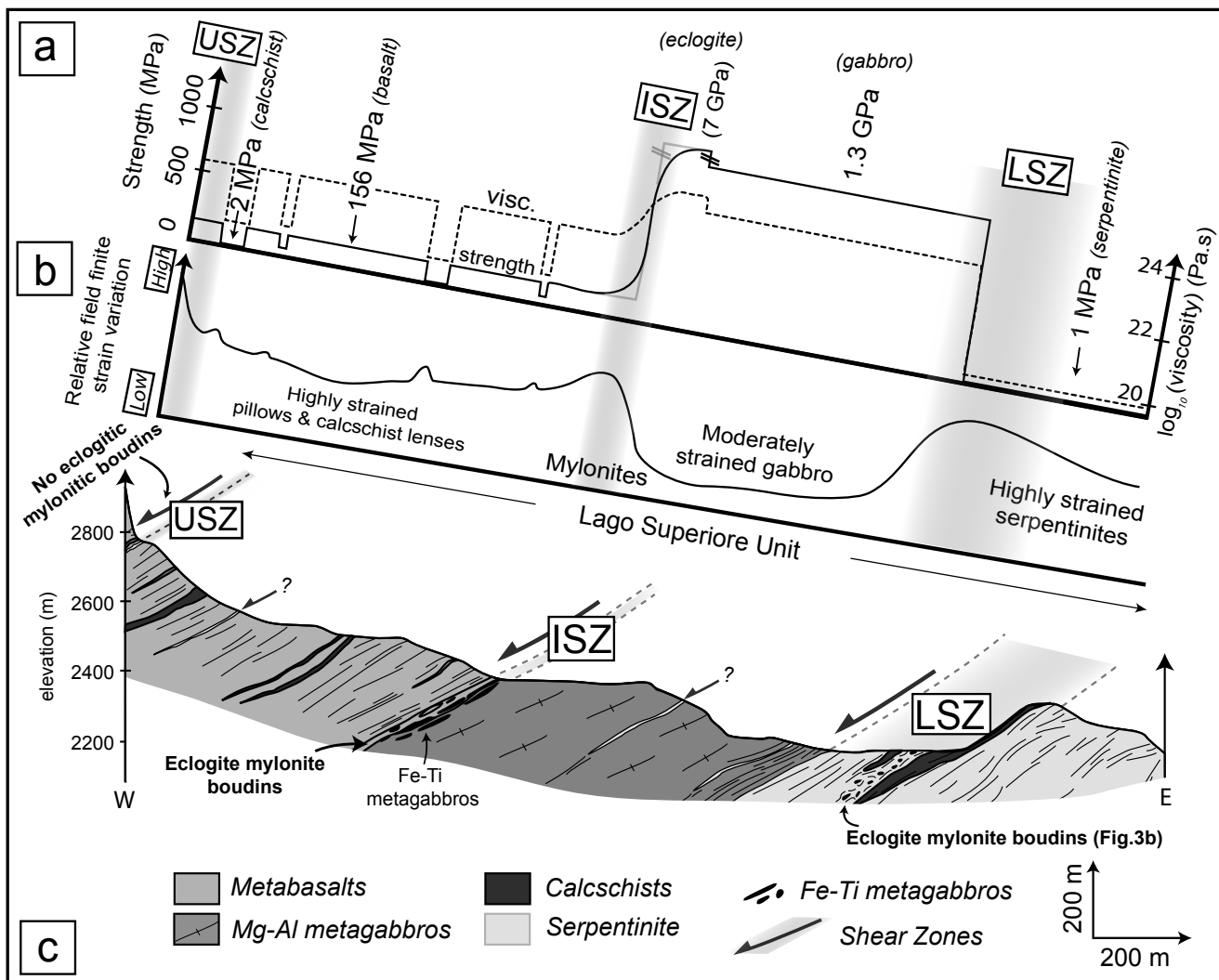


Figure 9

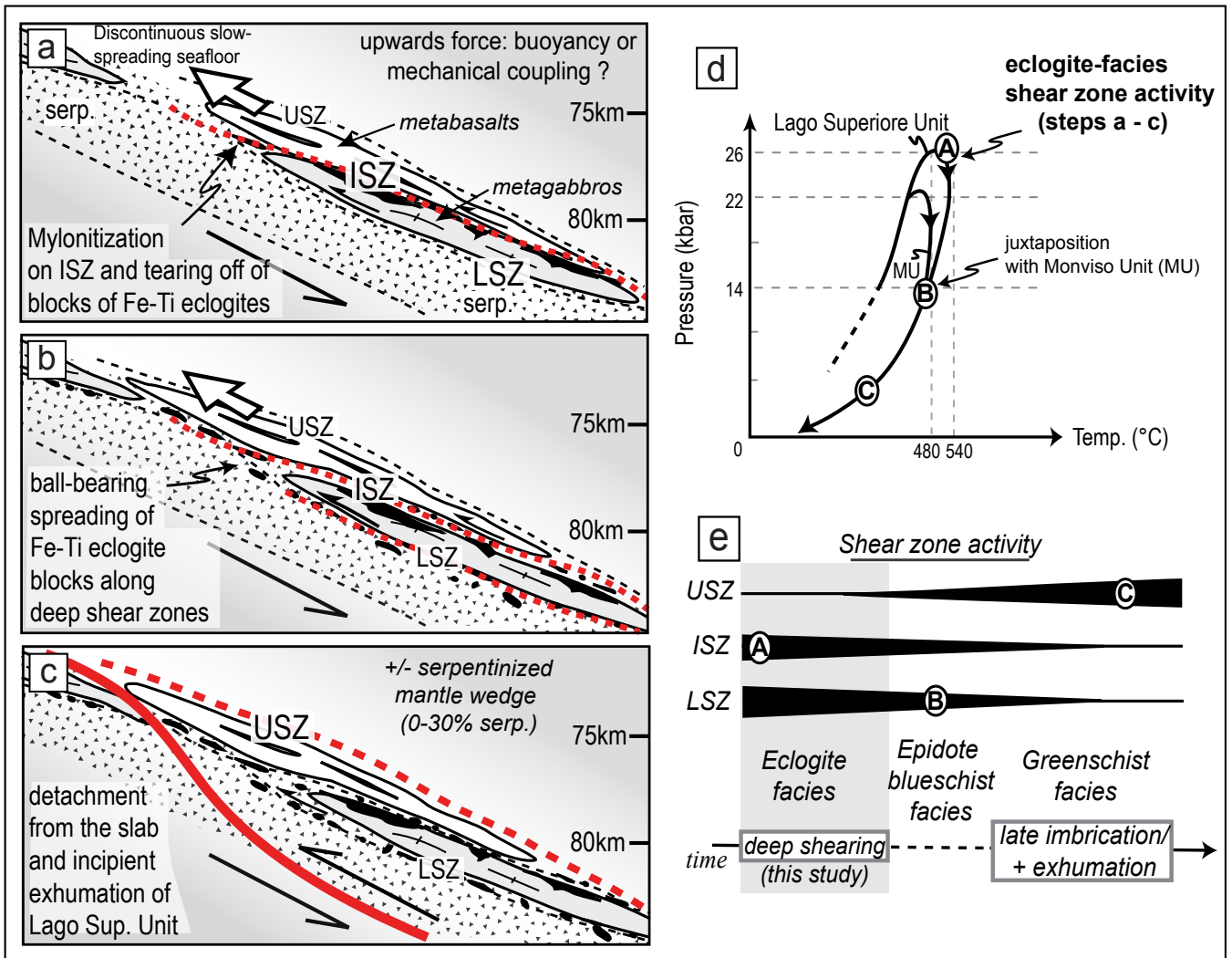


Figure 10