Geological map of the Monviso massif (Western Alps)

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(Article begins on next page)

1. Introduction

The geological map of the Monviso massif encompasses an area of the inner Western Alps where different tectonic units that belong to the Monviso Meta-ophiolite Complex (MO) are discontinuously covered by different Quaternary deposits. The MO is an important remnant of the Mesozoic Tethyan oceanic lithosphere, that was dragged at depth during the Alpine subduction, exhumed and stacked in the axial sector of the Western Alps (Ballèvre, Lagabrielle, & Merle, 1990; Philippot, 1990; Lardeaux et al., 2006). It is tectonically superposed on the carbonate Mesozoic cover of the Paleozoic Dora Maira Unit (Sandrone et al., 1993), that is part of the European continental margin involved in the continental collision, and is overlain by the Mesozoic Queyras Schistes Lustrès (Lemoine & Tricart, 1986), a tectonic stack of blueschist to greenschist-facies carbonate metasediments. The MO is made up of serpentinized peridotites, metagabbros, metabasalts and metasediments that were metamorphosed under eclogitic conditions and heterogeneously re-equilibrated under blueschist to greenschist facies conditions (Lombardo et al., 1978; Schwartz et al., 2000). In the Monviso massif (i.e. the central sector of the MO) six N-S striking and W-dipping tectonostratigraphic units were distinguished from bottom to top by Lombardo et al. (1978): the Basal Serpentinite Unit (BS); the Lago Superiore Mg-Al metagabbro Unit (LS); the Viso Mozzo Unit (VM), that is mainly made up of basalt-deriving metabasites; the Passo Gallarino Unit (PG), that consists of Fe-Ti metagabbros and serpentinites; the Costa Ticino Unit, that was renamed Forciolline Unit (FO) by Castelli and Lombardo (2007) and corresponds to an overturned sequence of metagabbros, metabasalts and metasediments; the Vallanta metabasite Unit (VA). The inner structure of the MO was re-interpreted by Angiboust et al. (2012a) who describe two tectonometamorphic units: the Lago Superiore Unit, a preserved ophiolite sequence that encompasses the BS, LS, VM and PG units, and the overlying Monviso Unit, that consists of two superposed sub-units (the FO and VA units).

Different sector of the Monviso massif was previously mapped at 1:100,000 scale, in the Pinerolo sheet (Mattirolo et al., 1913) and in the two editions of the Argentera-Dronero sheet (Franchi &

Stella, 1930; Carraro et al., 1971) of the Geological Map of Italy, and at 1:50,000 scale by Lombardo et al. (1978), Lagabrielle & Polino (1987) and Tricart et al. (2003). The aim of the map given here is to extensively and completely represent the lithological, structural and geomorphological features of the Monviso massif, as already done for the northern sector of the MO (Balestro, Fioraso, & Lombardo, 2011).

2. Methodology

The map is at 1:25,000 scale and encompasses an area of 61 km^2. Data were *i*) collected through an original fieldwork at 1:10,000 scale, *ii*) stored in a GIS database (Coordinate System WGS 1984 UTM Zone 32N) and *iii*) represented on a vector topographic map that derives from the CTRN (Carta Tecnica Regionale Numerica, vector50 series, sheet 190 Barge). The newly-collected lithological, structural and geomorphological mesoscale information was integrated with microscale data about composition of rocks given by Cavallera (1978) and by Lombardo et al. (1978). Structural analysis was performed by stereographic projections (equal-area lower-hemisphere) and based on the main regional foliation (Sp), that allows objective distinction of coeval (syn-Sp fold axes), pre-existing (pre-Sp foliations) and subsequent (post-Sp fold axes and axial planes) structural elements. The glacial and post-glacial Quaternary deposits have been mapped by original fieldwork, whereas geomorphological analysis was supported by photointerpretation of aerial images (2000 colour 1:15,000/1:19,000 scale) of the Regione Piemonte. The tectonostratigraphic units (sensu Dela Pierre, Lozar, & Polino, 1997) are represented in the tectonic sketch map. The two generations of tectonic discontinuities distinguished in the map correspond to *i*) syn-metamorphic shear zones (i.e. the tectonic contacts that bound the tectonostratigraphic units), and *ii*) late- to post-metamorphic (brittle) faults that crosscut the previous ones.

3. Tectonostratigraphy

The four tectono-stratigraphic units and the main shear zone distinguished in the map (Figures 1, 2a and 2b), are from bottom (east) to top (west), *i*) the Basal Serpentinite Unit (BS), *ii*) the Lago Superiore Shear Zone (LS), *iii*) the Viso Mozzo Unit (VM), *iv*) the Forciolline Unit (FO) and *v*) the Vallanta Unit (VA).

The Basal Serpentinite Unit

The BS Unit continuously crops out from the Colle della Gianna area (where it is 1000 m thick) to the Punta Rasciassa area (where it is roughly 500 m thick), and corresponds to the lowest unit of the MO. The top of the underlying Dora-Maira Unit consists of marbles, dolomite marbles and calcschists of supposed Middle Triassic to Early Jurassic age, and of quarzites and micaschists of Permian age (the Sampeyre Ensemble of Vialon, 1966).

The BS Unit consists of serpentinites that host m- to hm-sized bodies of Mg-Al metagabbros and of eclogitic Fe-Ti metagabbros. The serpentinites are covered by an overturned metasedimentary sequence that particularly crops out in the SE sector of the map (the Roccenie Complex of Mondino et al., 2004). The serpentinites are medium-grained, pervasively foliated and mainly made up of antigorite and magnetite. The original peridotite mineral assemblage is preserved only as textural relics of pyroxenes in more massive varieties. The Mg-Al metagabbros have been mapped as more abundant greenschist-facies Mg-Al metagabbros made up of albite, clinozoisite and actinolite, and minor eclogite-facies Mg-Al metagabbros that are "smaragdite"-bearing and more or less retrogressed into greenschist-facies. Eclogitic Fe-Ti metagabbros particularly occur at the base of the serpentinites between Colle della Gianna and Punta Sea Bianca. They show a pegmatitic texture, with well-preserved plagioclase-clinopyroxene igneous sites, that is progressively replaced by a banded texture with omphacite-garnet-rutile and Na-amphibole-rich bands. The serpentinites also host m-sized dykes of rodingitized metagabbro, omphacitite and rare jadeitite (Compagnoni, Rolfo, & Castelli, 2012). The metasedimentary sequence crops out between Rocca Nera and Punta Rasciassa, and is made up of calcschists. The latter consists of different amounts of calcite, white mica and quartz, and host dm- to m-sized levels and bodies of metabasite (Figure 3a). The occurrence of meta-ophicalcites (NE of Colle Armoine, NE of Costa Pelata and SE of Punta Rasciassa) at the contact with serpentinites, suggests that these metasediments originally covered the mantle peridotite rocks.

The Lago Superiore Shear Zone

The LS Shear Zone bounds at the top the BS Unit and its thickness varies between 800 m in the Colle Armoine area to roughly 250 m in the Punta Forcion area. It corresponds to a tectonic mélange (sensu Festa et al., 2010) wherein a “matrix”, made up of pervasively foliated antigorite schists, encloses *i*) bodies of Mg-Al metagabbro and eclogitic Fe-Ti metagabbro, *ii*) masses of metaperidotite, *iii*) sheets of metasediment and *iv*) rodingite dykes (Figure 3b).

The “smaragdite”-bearing Mg-Al metagabbros are medium-grained and essentially pervasively foliated (Figure 3c). They consist of two main NNW-SSE elongated lenticular sheets (up to 400 m thick) that crop out in the Lago Superiore and Lago Bulè areas respectively, and are characterized by the occurrence of m-sized levels of serpentinite and metaperidotite. The eclogitic Fe-Ti metagabbros are mainly made up of garnet and omphacite (Figure 3d), and consist of both dam-sized masses associated to the Mg-Al metagabbros (NW of Lago Chiaretto) and m-sized rounded bodies scattered in the antigorite schists. Peculiar blocks of brecciated eclogites that occur at Punta Forcion, SW of Testa Rossa and at Colle di Luca, have been interpreted as fault-rocks resulting from deep intra-slab seismicity (Angiboust et al., 2012b). The metaperidotites show well-preserved relics of pyroxene, and particularly consist of a minor m-sized level interlayered in the Mg-Al metagabbros (SW of Lago Fiorenza), and a major dam-sized body (E of Colle Armoine) embedded in the antigorite schists. The latter, at the bottom, are characterized by the occurrence of calcite-bearing serpentinites, that presumably derive from original ophicalcites, mylonitic calcschists and garnet-bearing micaschists. Other metasediments locally cover the Fe-Ti metagabbros (NW of Lago Chiaretto) and the serpentinites (NW of Lago di Alpetto), and consist of lawsonite-bearing calcschists with levels of metabasites that originate from detrital ophiolite-derived sediments. Sheets of metasediments are also embedded in the antigorite schists S of Lago Fiorenza, at Monte Ghincia Pastour and Punta Forcion, and consist of calcschists with m-sized levels of micaceous marbles and of phengite- and garnet-bearing metacherts.

The Viso Mozzo Unit

The VM Unit is made up of basalt-deriving metabasites, Mg-Al metagabbros and metasediments. It is southward thinning and at most 1200 m thick, and is bounded at the top by a shear zone that is mainly defined by the occurrence of chlorite- and talc-bearing antigorite schists. This shear zone is m-sized both in the N sector and in the S sector of the map, whereas between Colle dei Viso and Passo Gallarino is roughly 100 m thick and is associated with more massive serpentinites and with Fe-Ti metagabbros (i.e. the Passo Gallarino Unit of Lombardo et al., 1978). The latter particularly occur in the Passo Gallarino area and show a mylonitic structure that is defined by strongly iso-oriented garnet-omphacite- and Na-amphibole mineral assemblages.

The metabasites show a medium-grained banded texture (Figure 3e), that consists of alternate albite- and epidote-rich levels, and Na-amphibole and actinolite-rich levels. Brecciate and pillowed textures are locally preserved (e.g. SE of Rifugio Quintino Sella). The Mg-Al metagabbros are “smaragdite”-bearing and crop out at the bottom of the metabasites between Truc Bianco and the area W of Lago Bulè. SE of Viso Mozzo, the top of the Mg-Al metagabbros is characterized by the occurrence of fine-grained eclogites that presumably derive from original basaltic dykes.

The metasediments occur at the top of the VM Unit and stratigraphically cover the basalt-deriving metabasites. In the S sector of the map they consist of minor m-sized layer of mylonitic calcschists, whereas in the N sector of the map (Rocce Alte, Monte Meidassa) they are m- to dam-sized sequences, interlayered in the metabasites, consisting of calcschists (Figure 3f) with levels of micaceous marbles, quartz-rich garnet-bearing micaschists, phengite- and garnet-bearing metacherts (Monte Meidassa).

The Forciolline Unit

The FO Unit is roughly 900 m thick along the E ridge of Monviso (Figure 2a), and is bounded to the W by the overlying Queyras Schistes Lustrés. The FO Unit is an overturned sequence of metagabbros and basalt-deriving metabasites, with minor metasediments.

Most of metabasites are characterized by a metamorphic layering with yellowish epidote-rich levels and dark-green Na-amphibole and actinolite-rich levels. Massive aphyric and porphyritic metabasalts, and brecciated and pillowed metabasalts (Figure 3g), widely occur in the area between Punta Barracco, Punta Michelis and Laghi delle Forciolline. Between the SE ridge of Monviso and Rocce di Viso, massive metabasites are overlain by a major, lens-like body of coarse-grained Mg-Al metagabbro. The latter is mostly massive, and shows a well-preserved magmatic fabric with relics of pyroxene, pseudomorphs on olivine in a groundmass of altered plagioclase. The metagabbros are further characterized by the occurrence of layered metatroctolites (N and S of Punta Fiume), dam-sized rafts of serpentinized metaperidotites (E of Punta Caprera) and dm-sized metabasalt dykes (Figure 3h). The metasediments are interlayered with the metabasites in the lowest part of the FO Unit and consist of m-sized levels of phengite- and garnet-bearing metacherts (NE of Punta Gastaldi, E of Passo delle Sagnette), quartz-rich garnet-bearing micaschists and calcschists.

The Vallanta Unit

The VA Unit is topographically and tectonically the highest of the MO, and consists of two capping slabs that respectively extend between Monviso and Viso di Vallanta (Figures 2a and 2b), and between Punta Caprera and Rocce di Viso. The tectonic contact with the underlying FO Unit is defined by the discontinuous occurrence of antigorite schists and of a m-sized layer of calcschist that crops out S of Punta Caprera. The VA Unit is made up of eclogite-facies metabasites. The latter, in the upper part, are reddish, massive and with relics of pillow textures, whereas in the lower part are banded, and the garnet-omphacite and Na-amphibole mineral assemblage is partially re-equilibrated to greenschists facies compatibilities.

4. Structures

The lithological contacts and the syn-metamorphic shear zones (i.e. the tectonic contacts; Figures 1, 2a and 2b) that bound the W- to SW-dipping units, are parallel to the main pervasive foliation (i.e. the Sp). The latter is a composite surface that results from reorientation of a syn-eclogitic early foliation (i.e. the pre-Sp; Figure 4a) and synkinematic recrystallization under blueschist-facies conditions. The Sp foliation is mostly NW-SE striking and SW-dipping (Figure 4b), and corresponds to the axial plane of non-cylindrical tight to isoclinal syn-Sp folds (Figure 3f) whose axes are scattered in the NW and SW quadrants (Figure 4c). Map scale hinge zones of syn-Sp folds particularly occur in the LS Unit and at the top of the VM Unit, where pre-Sp structures are folded but not fully transposed.

Post-Sp folding (Figures 4d and 4e) can be related to two different generations of open to gentle folds (Figure 3e). The older ones are characterized by E-dipping axial planes and consist of W-verging and N-S trending folds that particularly occur in the upper part of the MO (i.e. the FO and the VA units) and are well exposed in the Vallanta valley. They are interpreted as drag folds coeval with top-to-W extensional structures (Schwartz et al., 2000) and they presumably accommodate the major late-metamorphic fault (i.e. the West Viso Detachment; Tricart et al., 2004), that separates the MO from the overlying Queyras Schistes Lustrés. Other post-Sp folds (i.e. the younger generation) are poorly defined at field scale and characterized by gently NW-plunging axes, and by steeply both N- and S-dipping axial planes. At map scale, these folds are roughly asymmetric with W-dipping long limbs and SSW-dipping short limbs, and are more pervasive in the lower part of the MO.

Syn- and late-metamorphic structures are crosscut by post-metamorphic normal to transtensive faults (Figure 3f), that are NE-SW striking and characterized by dam-sized throws. A major NE-SW striking post-metamorphic fault that seems to crosscut both lithological contacts and syn-metamorphic shear zones has been inferred in the SE sector of the map (Rio Bulè Valley) and is characterized by a hm-sized throw.

5. Quaternary deposits and geomorphology

The overall morphology of the Monviso massif results from the interaction between the lithostructural features of the bedrock and the glacial erosion active during the Pleistocene glaciations. In the mapped area glacial deposits related to the Last Glacial Maximum (LGM) and subsequent post-LGM glacier retreat are extensively preserved at the head of the Po Valley and tributary basins. Glacial tills are made up of chaotic and unsorted angular block deposits with sandy-silty matrix (ablation till) and subordinate diamicton with silty-sandy matrix containing faceted, smoothed and striated clasts and boulders (lodgement till). In many cases glacial till forms impressive lateral or end moraine systems (more than 50-70 meters high as in the case of the moraine visible on the eastern slope of Monte Grané) related to the LGM or to temporary halts in post-LGM glaciers retreat.

After the almost complete deglaciation occurred during the Holocene Climate Optimum (between about 9000 and 6000 years B.P.) a new advances of glacier fronts occurred during the Little Ice Age (LIA) between A.D. 1350 and 1850. With an overall area of 1.62 km^2, LIA glaciers were located at the base of the eastern and western slopes of the Visolotto - Punta Roma ridge, around the Monviso peak and on the northern slope of Punta Dante. The maximum extent of glaciers during the LIA are highlighted by a well developed end moraine system (Figure 5) with blocks characterized at present by an incipent lichen cover. Glacial tills related to the LIA are made up of diamicton with abundant silty-sandy matrix containing clasts and boulders, blanketed by a thin layer of supraglacial debris made up of unsorted angular blocks and rock fragments. At present day only a few glaciers survive on the NE and W Monviso faces, covering 0.14 km^2 on the whole.

A combination of morphological and climatic factors was responsible for the collapse of the Upper Coolidge Glacier which took place July 6, 1989 (Mortara & Dutto, 1990; Dutto, Godone, & Mortara, 1991): the ice avalanche originated at 3190 m a.s.l. involving 200,000 m^3 of ice mixed with glacial debris and till. The ice avalanche had crossed the LIA terminal moraines of the Lower Coolidge Glacier and after a vertical drop of 900 m came to rest in the Chiaretto Lake (2265 m a.s.l.) which was partially filled up with a mixture of ice and debris up to 8-10 m thick.

In the Monviso massif several rock glaciers have been identified, some of them (4) are currently active. Rock glaciers are up to one km long (1.3 km in the case of the rock glacier E of Passo delle Sagnette), 100-400 m wide and cover an area of less than 0.75 km^2. Rock glaciers tipically show lobate or tongue-shaped morphology in plan view with a complex system of longitudinal and transverse arcuate ridges and furrows. They are localized mainly on NW to NE slopes, although some are S-facing (i.e. the rock glacier of Rocce Sbiasere). Inactive rock glacier fronts are localized between 1720 and 2870 m a.s.l., whereas fronts of active rock glaciers range in elevation between 2490 and 2830 m a.s.l. Rock glaciers are primarily localized at the base of massive rock slopes (i.e. metabasites and metagabbros of the MO) and where rock breakdown is particularly active due to frost shattering.

Mountain slopes were affected by a variety of gravitational phenomena: rock falls (i.e. the historical landslide originated on the north-west wall of the Punta Caprera that buried the terminal moraine of the Caprera Glacier), rock flows (i.e. the large landslide originated along the northern slope of the Monte Ghincia Pastour, south of Pian Melzé) and rock slides (i.e. the Costa Pelata landslide in the Rio Bulé valley, Figure 6). Landslide deposits are composed of chaotic accumulations of angular blocks with scanty or abundant sandy-silty matrix (rock falls and rock flows respectively) or large loosened portions of bedrock (rock slides).

The Colle Armoine – Colle della Gianna ridge and the Costa Pelata - Punta Rasciassa ridge are involved by deep seated gravitational slope deformations (DSGSD; Figure 1) that give rise to impressive morphologies such as antislope scarps and threnches up to one kilometer long. DSGSDs, rock flows and rock slides are mainly localized within the BS Unit and the LS Shear Zone, and are mainly composed of antigorite schists. All gravitational processes have developed subsequently to the glacial retreat (post-LGM) after the debuttressing processes involving rock slopes adjacent to glaciers.

6. Conclusions

The geological map of the Monviso massif aims to give a complete representation of the geology of the central sector of the MO and of the geomorphological evolution of the massif during the Quaternary age. Detailed geological mapping particularly allowed to

- provide new lithological and structural data,
- update the interpretation of the tectonostratigrapy of the MO,
- reconstruct the ice-flow pattern of glaciers during the LGM,
- define the terminal moraine systems related to the LIA advance.

The lithological and structural information given here may also support further geodynamic reconstructions of the MO and field investigations in the adjoining areas.

Software

The map database was built with ESRI® ArcGIS 9, whereas the final map layout was assembled by Adobe® Illustrator 10. Structural data were plotted by StereoNett.

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Figure captions

Figure 1. Tectonic sketch map of the central sector of the Monviso Meta-ophiolite Complex.

Figure 2. Views of the tectonic units of the Monviso Meta-ophiolite Complex (BS: Basal Serpentinite Unit; LS: Lago Superiore Shear Zone; VM: Viso Mozzo Unit; FO: Forciolline Unit; VA: Vallanta Unit) and related tectonic contacts (black lines); (**a**) photo taken from Colle Armoine, view looking S; (**b**) photo taken from Punta delle Guglie, view looking NW.

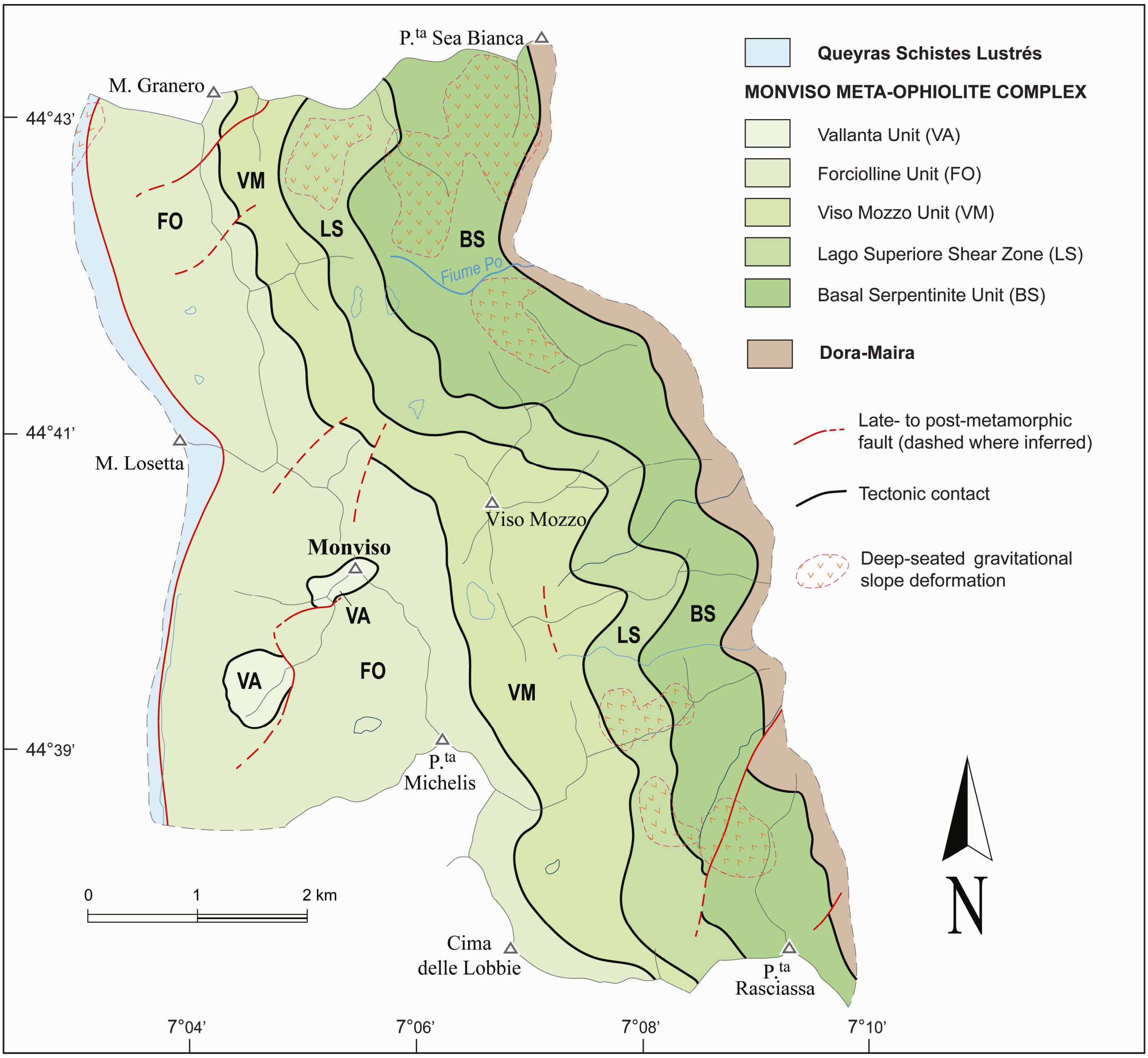
Figure 3. **a**) Level of metabasite (mb) in the calcschists (cs) of the BS Unit (NE of Punta Rasciassa, 2,260 m a.s.l.); **b**) rodingite dyke (rd) in the serpentinites (sp) of the LS Shear Zone (SW of Punta Forcion, 2,350 m a.s.l.); **c**) cm-sized level of eclogite (ec) in the "smaragdite" Mg-Al metagabbro (mg) of the LS Shear Zone (Lago Superiore, 2,340 m a.s.l.); **d**) eclogite-facies Fe-Ti metagabbros of the LS Shear Zone (S of Monte Ghincia Pastour, 2,450 m a.s.l.); **e**) banded metabasite of the VM Unit weakly deformed by post-Sp folds (SW of Viso Mozzo, 2,650 m a.s.l.); **f**) syn-Sp folds and late fault in micaschists (ms) and calcschists (cs) of the VM Unit, (E of Colle delle Traversette, 2,880 m a.s.l.); **g**) pillowed metabasalt of the FO Unit (block below Cima delle Lobbie, 2,900 m a.s.l.); **h**) metabasalt dyke (mb) in the coarse-grained Mg-Al metagabbros (mg) of the FO Unit (E of Punta Fiume, 3,200 m a.s.l.).

Figure 4. Stereographic projections of the structural features of the Monviso Meta-ophiolite Complex.

Figure 5. The NE slope of the Monviso (photo taken from the Chiaretto Lake at 2320 m a.s.l., view looking SW). The white lines highliht the moraine ridge of the Little Ice Age glaciers. The dashed

line separates the post-LGM glacial deposits (Ug) from the Little Ice Age glacial deposits (Ul). UCG: Upper Coolidge Glacier.

Figure 6. Frontal view of Costa Pelata complex rock slide (photo taken from the E ridge of Rocca del Lu at 2200 m a.s.l., view looking SE). Dashed lines separate the different portions of the landslide (Ld – landslide deposits). In foreground, on the right, is visible the alluvial deposit (Fl) of Alpe Bulè due to valley damming caused by the emplacement of the rock slide.



P.ta Sea Bianca
M. Granero
44°43'
44°41'
44°39'
M. Losetta
Monviso
Viso Mozzo
P.ta Michelis
Cima delle Lobbie
P.ta Rasciassa
FO
VM
LS
BS
VA
Fiume Po
0
1
2 km
7°04'
7°06'
7°08'
7°10'
N
Queyras Schistes Lustrés
MONVISO META-OPHIOLITE COMPLEX
Vallanta Unit (VA)
Forciolline Unit (FO)
Viso Mozzo Unit (VM)
Lago Superiore Shear Zone (LS)
Basal Serpentinite Unit (BS)
Dora-Maira
Late- to post-metamorphic fault (dashed where inferred)
Tectonic contact
Deep-seated gravitational slope deformation

Figure 1

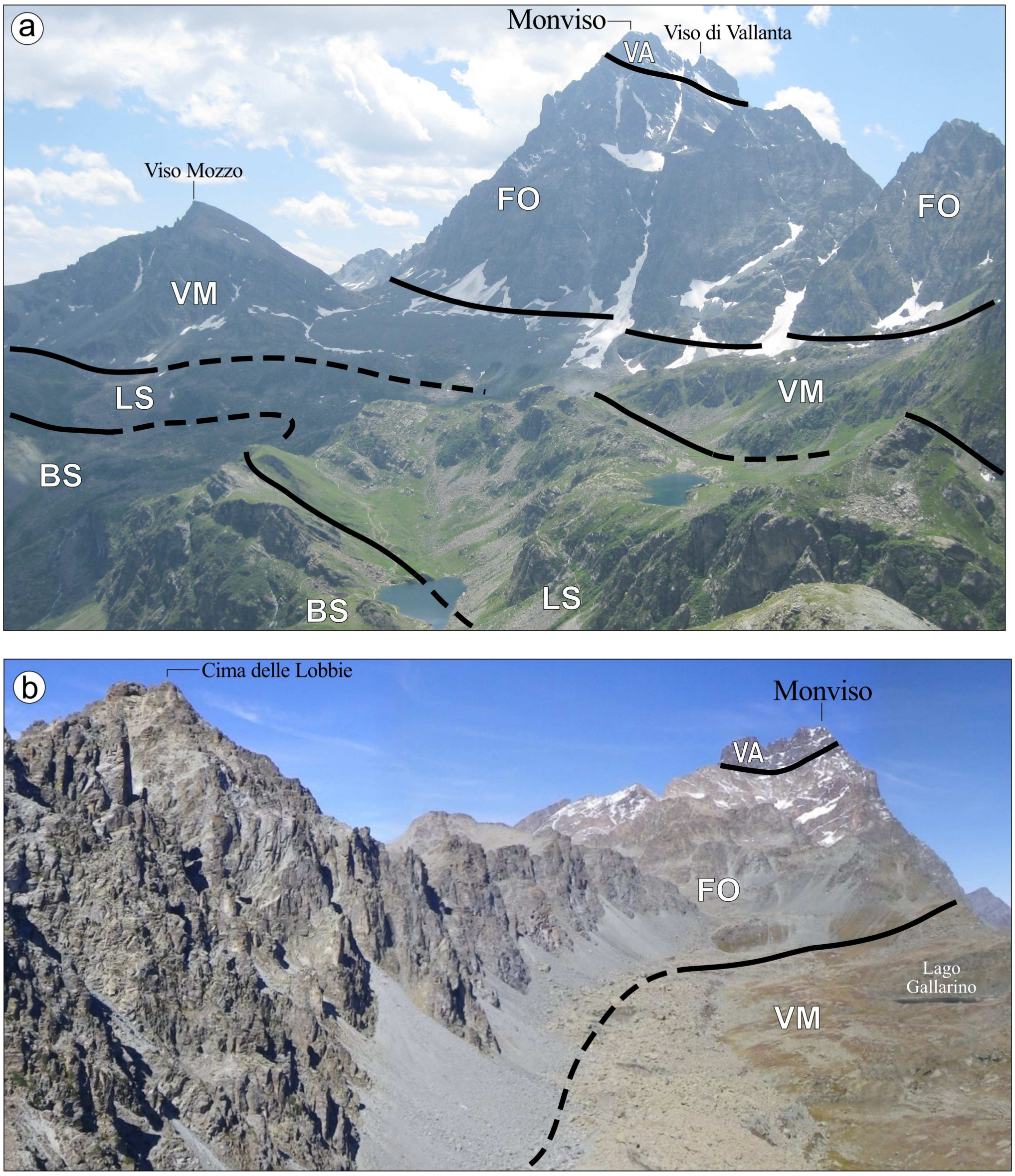

a
Monviso
Viso di Vallanta
VA
Viso Mozzo
FO
FO
VM
LS
VM
BS
BS
LS
b
Cima delle Lobbie
Monviso
VA
FO
Lago
Gallarino
VM

Figure 2

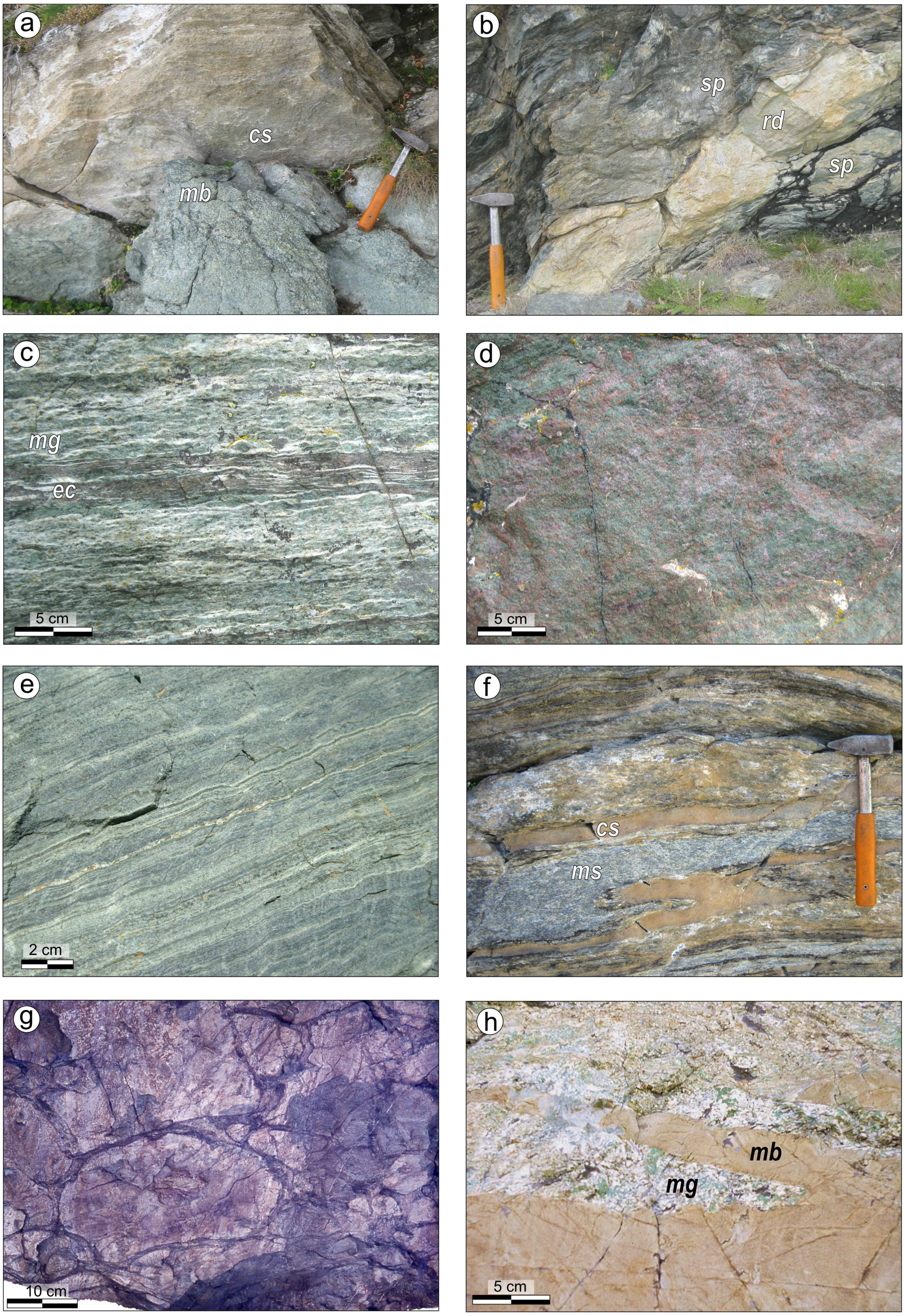


Figure 3

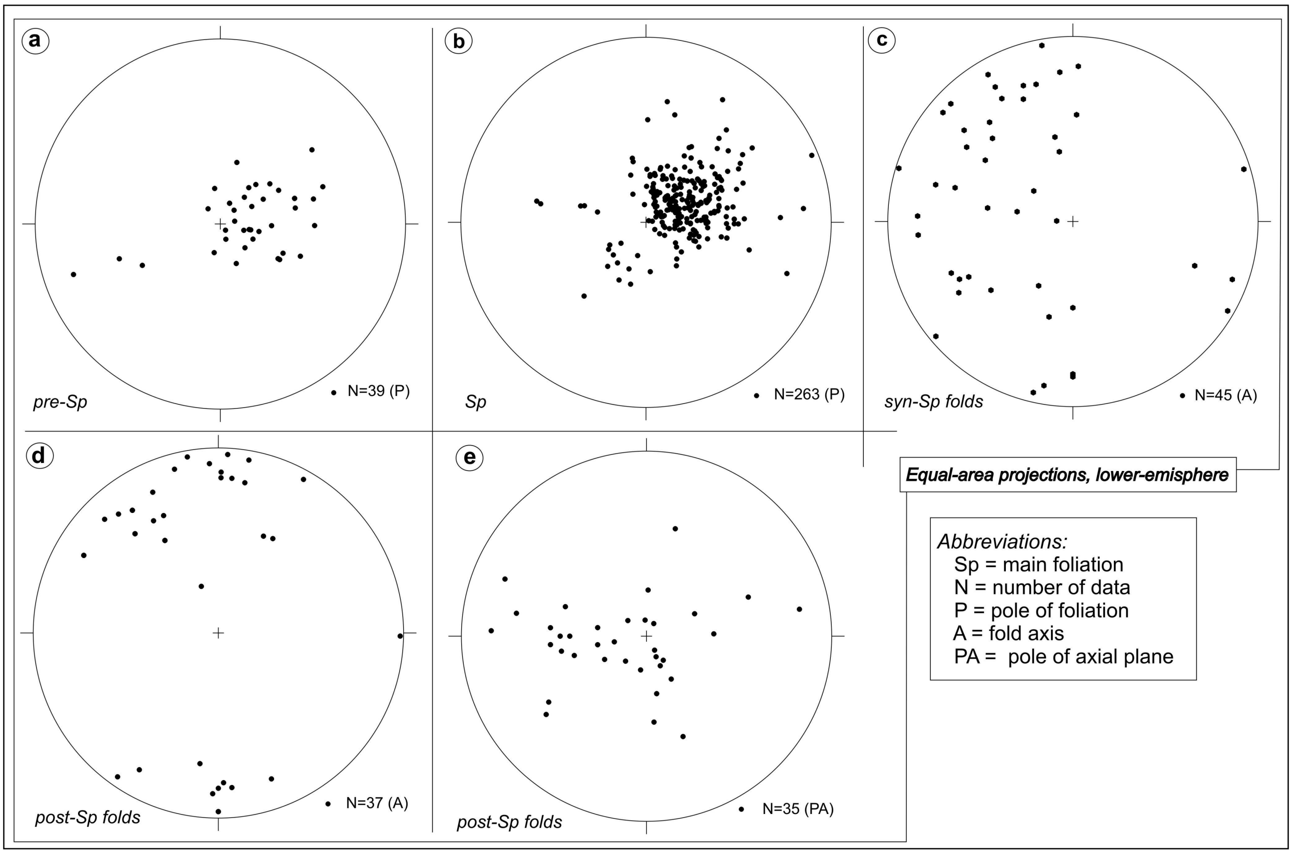

a
pre-Sp
N=39 (P)
b
Sp
N=263 (P)
c
syn-Sp folds
N=45 (A)
d
post-Sp folds
N=37 (A)
e
post-Sp folds
N=35 (PA)
Equal-area projections, lower-emisphere
Abbreviations:
Sp = main foliation
N = number of data
P = pole of foliation
A = fold axis
PA = pole of axial plane

Figure 4

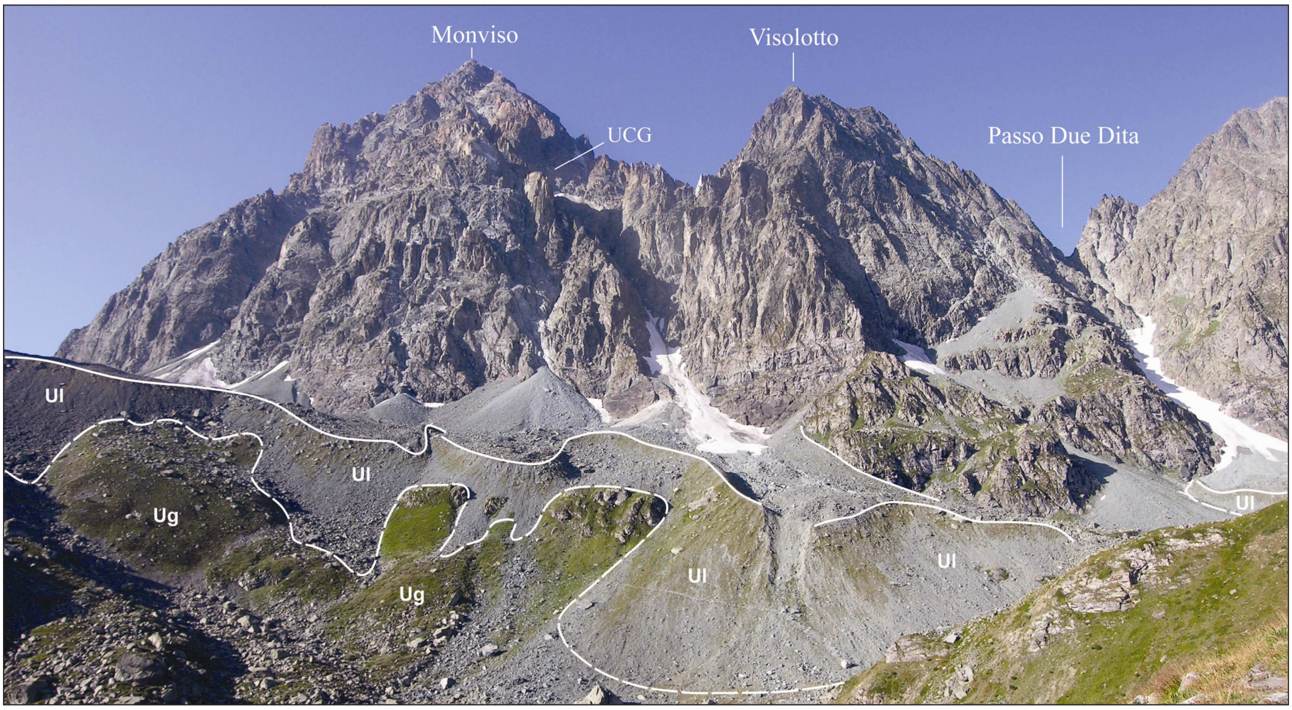


Figure 5

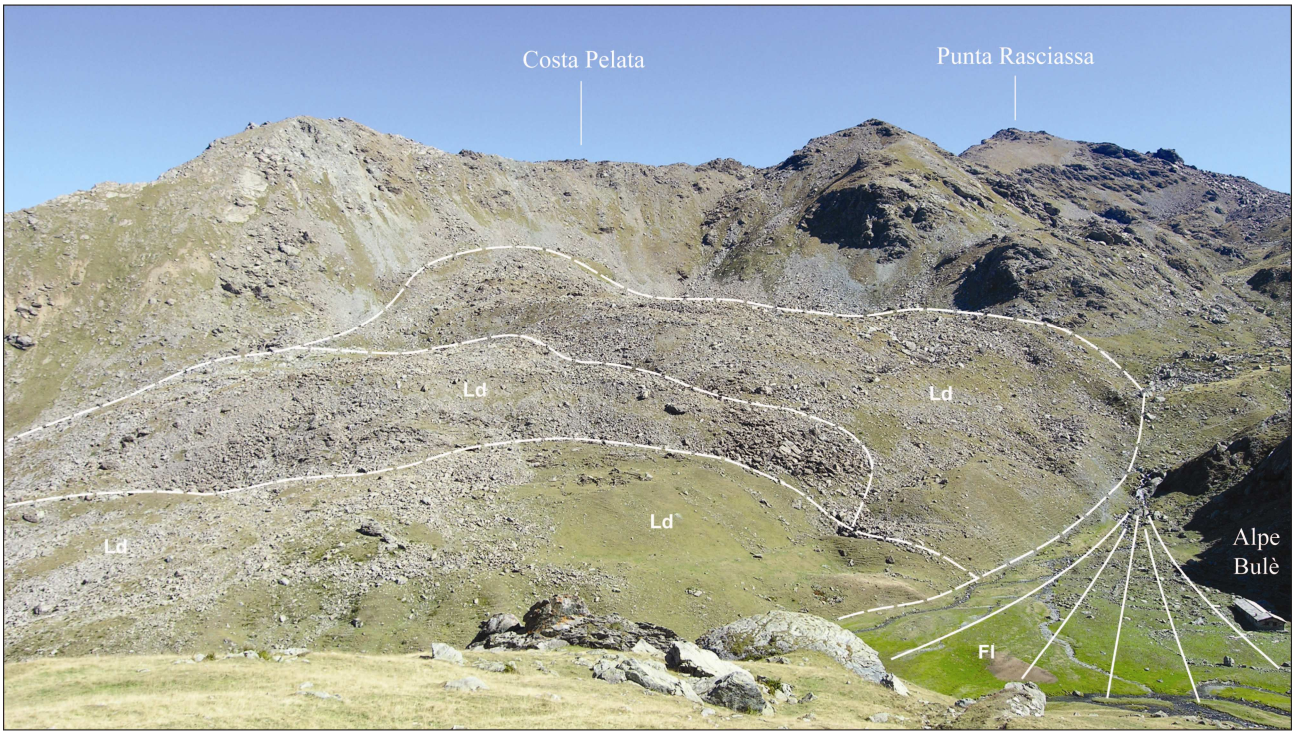


Figure 6