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ABSTRACT
In this work, we present the geological map of the San Pellegrino pass, inserted in the spectacular scenario of the Dolomiti region (Southern Alps, Italy), at a scale of 1:10.000 and accompanied by geological cross-sections. The detailed distinction of lithological thin units allowed to achieve a consistent interpretation of the local structural setting by drawing brittle and ductile Alpine tectonic deformations. The differential deformation and structural styles within the geological map are the result of the different rheological nature of volcanic and sedimentary rocks, as well as of the superimposition of compressional Alpine tectonics over Permo-Mesozoic extensional tectonic phases, and consequent reactivation of inherited structures.

1. Introduction

Within the worldwide-famous Dolomites region, in the Italian Southern Alps, the San Pellegrino pass is well frequented by tourists in winter and summer seasons. During the winter, it offers a unique ski arena with tens of kilometres of fantastic slopes, while in the summer numerous trekking paths can be followed within the scenery of the Dolomites, which since 2009 has been included in the World Heritage List (http://whc.unesco.org/en/list/1237). Their dramatic vertical and pale colored peaks in a variety of distinctive sculptural forms are extraordinary and with a unique geological value. These are notably the evidence of Mesozoic carbonate platforms, which preserve their depositional geometric relationships with the surrounding basins and provide information on the evolution of reef builders after the end-Permian mass extinction.

The geological values of the Dolomites as a World Heritage site in part exist because post-depositional tectonic deformation was weak enough to preserve complex vertical and lateral stratigraphic relationship between Permo-Triassic sedimentary units. Nevertheless, the tectonics of the Dolomites bears a complexity that should not be neglected (Doglioni, 1987), featuring multiple phases of deformation under stress fields of varying type and orientation (see chapter 4).

The western Dolomites region, including San Pellegrino pass, is part of the Southern Alps of Italy, a south-verging portion of the Alpine orogen (Figure 1). This region contains clear evidence of Middle Triassic volcanism and intrusive magmatic activity in the form

of km-scale magmatic intrusions (Predazzo and Monzoni), sub-volcanic sills and dikes, and submarine as well as subaerial lava flows and pyroclastic deposits (e.g. Vardabasso, 1931a).

The geological mapping of the Dolomites is not homogeneous. The first known geological survey is reported in the 1:75.000 map attached to the study 'Die Dolomitriffe von Südtirol und Venetien' by von Mojsisovics (1879), afterwards major contributions were by Castiglioni, Cornelius Furlani, and Vardabasso (1930), Vardabasso, Cornelius Furlani, and Castiglioni (1930), Vardabasso (1931a, 1931b), Klebelsberg (1935), Castiglioni (1939), Leonardi (1961, 1967), Leonardi et al. (1970), Dal Piaz (1970), Rossi et al. (1977). The geological mapping of the Triassic volcanic complex of Predazzo and Monzoni was performed by Vardabasso et al. (1930), Vardabasso (1931a, 1931b).

The last national geological mapping project at a scale 1:50.000 (CARG Project – Carta Geologica d'Italia alla scala 1:50.000 – ISPRA – http://www.isprambiente.gov.it/Media/carg/) has until now produced incomplete covering of the Dolomites region, and the area of San Pellegrino pass is not covered yet. The Servizio Geologico of the Provincia Autonoma di Trento has published online a geological map including the study area at a scale of 1:10.000 ('Carta Geologica della Provincia Autonoma di Trento – Cartografia geologica – Protezione Civile – Provincia Autonoma di Trento,' 2017 – http://www.protezionecivile.tn.it/territorio/Cartografia/Cartografiageologica/-CartageologicaPAT/pagin
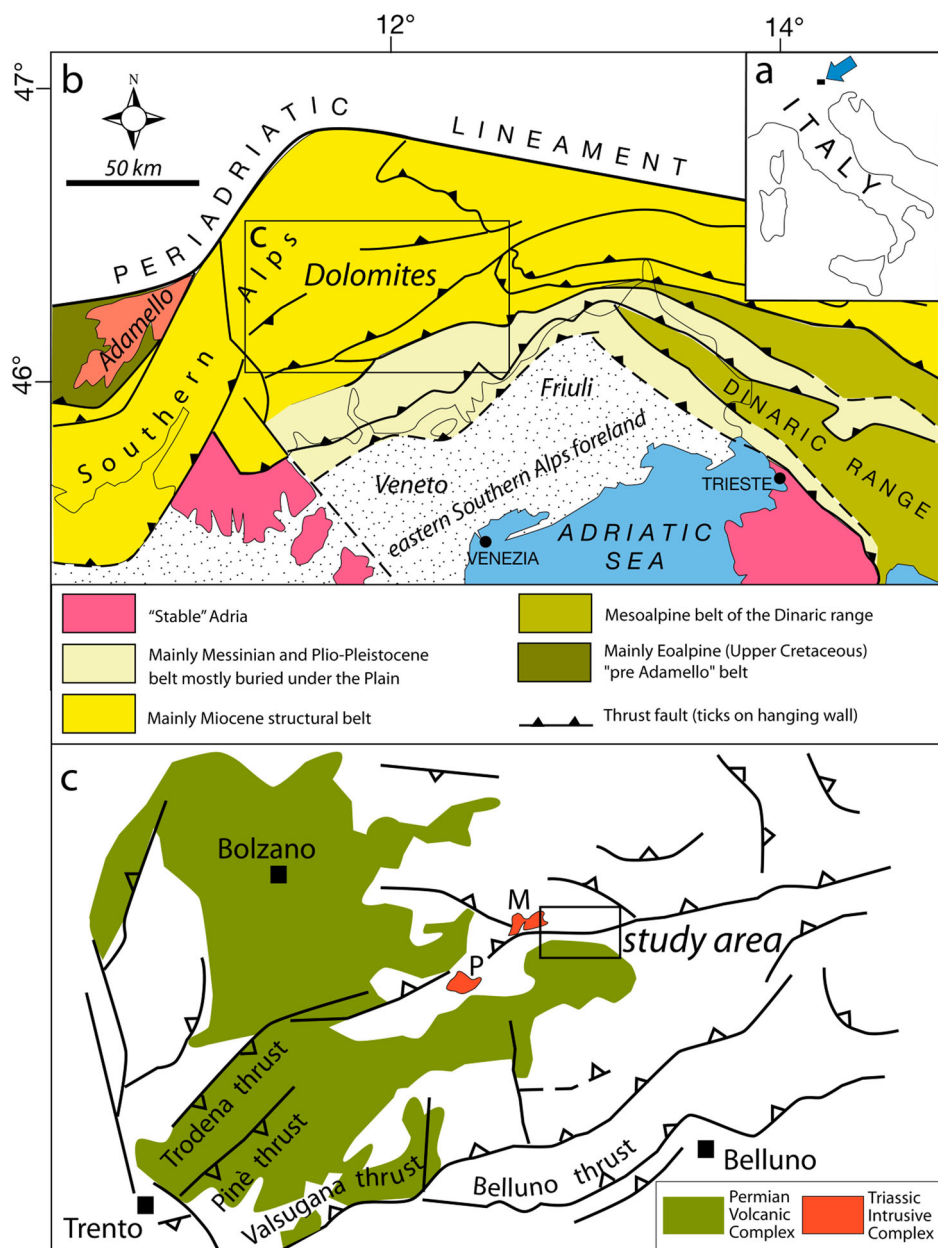
Figure 1. Structural sketches and location of San Pellegrino pass. (a) Localization of the study area in North-eastern Italy. (b) Geological structural sketch of the Southern Alps. The Dolomites belong to the Southern Alps, which are a Neogene-Present SSE-verging thrust and fold belt, which foreland basin (Veneto-Friuli) is shared with the Paleogene Dinaric chain. (c) Close-up on the Dolomites with an inset of the study area, which is located at the eastern border of the Permian tectonic depression where the Athesian Volcanic complex accumulated and close to the Middle Triassic intrusive complex (M = Monzoni, P = Predazzo).

a14.html). Unfortunately, the maps of the Trento Province were produced from a heterogeneous database, which imply that the tracing of regional-scale structures has been done, often after mapping, on the base of data of various provenances and resolutions. As of September 2018, last time the authors retrieved the maps, this still resulted in an uneven detail of outcrops distribution and in structural elements (i.e faults) that often do not preserve their original vergence, and orientations which may locally vary in an unlikely wide range of patterns. Furthermore, folds are not mapped and no cross-sections are provided. This strongly limits the value of this map for geologic and structural interpretation.

Despite their great value as a tool for regulatory purposes, these maps are not intended for tectonic reconstruction.

Here, we present a geological map of the San Pellegrino pass at a scale of 1:10.000, in which the tracing of tectonic structures and boundaries has been performed directly and on the basis of a homogeneous set of field data. Hence, the map deeply integrates the work of the Trento Province with new original surveys, and is intended for an audience of researchers working on the geology of the Dolomites. It includes a consistent interpretation of the local structural setting in the framework of the tectonics of the Dolomites. Indeed,

the accurate mapping of thin lithological units at large scale allowed to recognize folding and dislocations that remained unidentified in previous works, and to draw brittle and ductile Alpine tectonic deformations with unprecedented detail.

2. Methods

The San Pellegrino pass map is an outcome of the field-work performed over the last ten years during the Geological Mapping course of the Bachelor degree in 'Geological Sciences' at University of Padova (Italy). Small patches of maps produced by the students have been merged, thoroughly revised and integrated by several instructors of the University of Padova (T. Abbà, A. Breda, M. Massironi, N. Preto, D. Zampieri) and by Dolomiti Project (G. Piccin, T. Trentini). The geological map has been realized by means of a detailed geological survey at 1:10.000, on the regional topographic base (CTR – Carte Tecniche Regionali) produced by Trentino Alto Adige and Veneto. The stratigraphic units, their abbreviations and the style of the legend were chosen in agreement with the direction of the Italian program of geological mapping CARG, albeit the higher scale of the geological map allowed us to use much more distinctions within the lithological units.

Direct field surveying (using analogical altimeters and global positioning system receivers), were followed by detailed topographic observations performed on a DTM (digital terrain model) with 1 m^2 resolution obtained from an aerial LIDAR survey with resolution of ca. 5 points per m^2. The use of this high resolution DTM was particularly important in the accurate tracking of structural and geomorphological elements.

3. Lithostratigraphy

The lithological succession in the study area is summarized in the stratigraphic inlet of the Main Map (see supplementary materials). The oldest units (IGG, LRE1, ORA in the map) belong to the Athesian Volcanic Complex and are made of extrusive volcanics emplaced in the Early Permian. Less than 1 km thick Lower Permian volcanics are exposed at San Pellegrino pass, but the Athesian Volcanic Complex may attain a thickness of over 2 km in the Dolomites region (Carta Geologica della Provincia Autonoma di Trento - Cartografia geologica - Protezione Civile - Provincia Autonoma di Trento, 2017). The units cropping out in the study area are lapilli tuffs and ignimbrites of rhyolitic (Ora Formation – ORA) and rhyodacitic (IGG – Gargazzone Formation) composition. LRE1 (Regnana Formation, San Pellegrino Member) is instead a dome of andesitic lava flows in the north-western part of the map.

An Upper Permian to Lower Triassic succession lies on the Athesian Volcanic Complex through an erosional unconformity surface (Massari & Neri, 1997). Above the unconformity, the Upper Permian sedimentary units formed during a transgression are sandstones to siltstones deposited in a dryland river system (Val Gardena Sandstones – AVG) passing upward and eastward to dolomites, dolomitic marls and gypsum deposited in a coastal mudflat and sabkha, and then to dark limestones of a marginal marine environment (*Bellerophon* Formation – BEL). Within the geological map, these Upper Permian units (AVG and BEL) account for ca. 250 m of sedimentary deposits.

A sharp conformity surface marks the base of the Werfen Formation (Broglio Loriga, Masetti, & Neri, 1983), a well-bedded continental to shallow marine unit that may achieve a thickness of more than 300 m in this region. The first few meters of the formation (Tesero Member), made of white oolitic grainstone, belong in part to the Upper Permian, while the remaining part of the formation is Early Triassic in age. The Werfen Formation is subdivided into 9 members with alternating carbonate (limestone, marly and silty limestone) and siliciclastic (shale, siltstone and fine sandstone) lithologies and colors that may vary from gray to greenish, yellow, red and violet. The last member of the Werfen Formation (the San Lucano Member) is always missing in this area.

The Late Anisian to Ladinian sedimentary units rest on the Werfen Formation through an angular unconformity surface (Bosellini, 1968). Above the unconformity, an Upper Anisian conglomerate made of limestone and siltstone pebbles from the underlying Werfen Formation (Richthofen Conglomerate) discontinuously occurs and fills former topographic lows. Above, the Anisian succession continues with nodular gray limestones (Morbiac Limestone) and massive white limestones (Contrin Formation) with dasycladacean algae. These three units have been mapped together (CON in the map) because the first two are discontinuous, and may attain a maximum thickness of ca. 200 m in the area.

The top of the Contrin Formation is a sharp drowning unconformity. Above it, in the western part of the map, a succession of up to 60 m of prevailing nodular limestone with chert beds (Livinallongo Formation – LIV), bearing thin shelled bivalves and radiolarians, deposited in a deep basin of Late Anisian to Early Ladinian age. In the eastern part of the map, above the drowning unconformity on top of the Contrin Formation, a ca. 600 m thick massive limestone unit (Sciliar Formation – SCI) deposited as clinoforms, *i.e.* beds with a primary inclination of up to 30°. This unit formed the submarine slopes of high-relief microbial carbonate platforms (e.g. Leonardi, 1967) heteropic with, and prograding over LIV; its age is also Late Anisian to Early Ladinian.

Finally, the sedimentary succession is cut by Upper Ladinian mafic sills and dikes, mostly of basaltic composition. Upper Ladinian subvolcanic bodies have roughly the same age of the Monzoni intrusive complex (MON: pirossenite, gabbro, gabbrodiorite and monzogabbro) that crops out on the western margin of the map. A metamorphic contact aureola formed around the Monzoni intrusion, and is identified in the field by the formation of hornfelds at the expense of the Permo-Triassic sedimentary succession.

The Permo-Triassic units are locally covered by Quaternary deposits. Upper Pleistocene glacial deposits pertaining to the Last Glacial Maximum and the Late Glacial are widespread, both as moraines and extensive covers (Glacial Unit – GLA). Talus deposits and landslides lie at the foot of the main rock walls, while large rock glaciers, formed after the downwasting of local glaciers, reach further downslope (Postglacial Unit – PTG).

4. Tectonic framework

Most of the exposed structural features in San Pellegrino Pass are dominated by compressional Alpine structures with ENE-WSW trend and southern vergence (e.g. the folds of the Lower Triassic sedimentary sequence in the eastern part of the map, cross-sections C-C' and D-D'), whereas the previous extensional tectonic phases are only poorly preserved. In particular, no structures can be unambiguously related to the Mesozoic events related to the opening of the Neothetys ocean (e.g. Bertotti et al., 1993; Doglioni, 1992) and only a few Permian faults were detected. Nevertheless, pre-Alpine tectonic activity is testified by faults and dramatic contrasts in thickness of the Permian volcanic and sedimentary units.

A NW-trending fault exposed on the southern slope of the Colifon (f1 in the structural sketch, main map) is sealed by the AVG and implies the tectonic juxtaposition of the ORA tuffs and ignimbrites against the LRE1 lava flows. This sealed fault is an example of a non-reactivated Lower Permian fault. East of it, a ca. N-trending fault (f2) links southwards with a major NNE-trending fault depicted in the B-B' cross-section (f3). While f3 must have been a strike-slip movement during Alpine compression (it dislocates thrusts t2, t3 and t7 at least), the N-trending one is interpreted as a reactivated Permian fault, which confines the ORA tuffs and ignimbrites to the West. The different thickness of the BEL unit on the two sides of f2 may suggest an Upper Permian normal activity, with subsidence of the eastern block. On the other hand, the Alpine activity of f2 is shown by the offset of the SCI unit at the northernmost end of the fault.

The Lower Permian stiff volcanics of the Athesian Volcanic Complex are tapering toward the east and disappears just outside this map, in the Falcade area, where the eastern margin of the basin containing the Permian volcanic products was likely located (Castiglioni, 1939; Vardabasso et al., 1930). Volcanic sequences in fact are thinning eastward, most likely due to the activity of a series of west dipping syn-volcanic normal faults, which controlled the development of the basin where the huge pyroclastic deposits of the Athesian Volcanic Complex accumulated (e.g. Rottura et al., 1998; Selli, 1998). Also the late Permian sedimentary cover is affected by severe changes in thickness across normal faults, that were then sealed by Triassic units (e.g. Cassinis and Perotti, 2007; Massari and Neri, 1997).

It can be thus shown that the Alpine deformation has been controlled by the geological framework inherited from Permian and Mesozoic events, since the Alpine compression interested a net of pre-existing faults, and a juxtaposition of lithologies with different strength and rheological behaviors. Some of the N-S structures, represented in the geological map as wrench faults of Neo-Alpine age, were likely Permian normal faults, extended and reactivated with strike-slip movements during the Alpine compression. It is possible that these faults modulated also the Middle Triassic sedimentation, as seen in many other areas of the Dolomites (e.g. Blendinger et al., 1986; Preto et al., 2011).

As a consequence of the uneven thickness of the lower Permian volcanics, the weak Permo-Triassic sedimentary cover dominates in the eastern sector of the region, whereas in the westernmost sector the sedimentary cover sits on a thick pile of stiff volcanics, and it is hardened by the contact metamorphism associated to the Middle Triassic Monzoni intrusion (MON in the map). This was the geological framework as the Alpine compression took place and developed in the Miocene.

An accurate field mapping gave us the chance to compare the different deformations, which affected the sedimentary sequence during the Alpine shortening. In particular, comparing cross-sections B-B', C-C' and D-D' an eastward increase in shortening of the Werfen Formation becomes evident. Cross-section D-D' is affected by numerous south-vergent thrusts (t3, t4, t5) and folds highly duplicating the Werfen Formation (Figure 2), cross-section C-C' is characterized by gentle folds and fewer thrusts and cross-section B-B' is virtually unaffected by deformation, except for tilting. This differential deformation is consistent with the concept of inversion tectonics proposed by Doglioni (1992) for the Dolomites, albeit we here suggest that the compressional Alpine stress field inverted not only the rifting-related Mesozoic extensional faults, but also older, Permian faults.

Hence, while the eastern sector of the geological map shows a relevant shortening of the sedimentary

Figure 2. Panoramic view of the eastern part of the study area corresponding to cross-section DD': (a) from the east and (b) from the west. Note the intense deformation of the Permo-Triassic sedimentary succession, characterized by three S-vergent thrusts and folds. For a detail of the deformation style in the upper Permian *Bellerophon* Formation, see Figure 5.

cover (sections C-C' and D-D'; Figure 2), in the western sector most of the Alpine deformation is exclusively focused within the Athesian Volcanic Complex. Here a thrust and a couple of back-thrusts are present underneath the Quaternary deposits of the San Pellegrino Pass and at the base of the Iuribrutto-Col Margherita crest respectively (t7, t8 and t9 in the main map, structural sketch; cross-sections A-A' and B-B'; Figure 3). In particular, our geological map suggests a triangular structure underneath the glacial deposits of the pass where a south-vergent thrust faces a north-vergent back-thrust (t7 and t8 in the main map, structural sketch; cross-sections A-A' and B-B'). These buried structures have been formerly interpreted by Doglioni (1984) as Ladinian transpressive faults, but the clear moderate dip angle and the reverse kinematics of the Iuribrutto-Col Margherita back-thrust inferred from the anticlinal fold of the hangingwall (Figure 4) point in favor of a thrust tectonics of Alpine age possibly reactivating inherited structural features (sections A-A'). Indeed, the north-vergent Iuribrutto-Col Margherita back-thrust (t9), spectacularly duplicating the Gargazzone series (cross-section A-A'; Figure 4), poses the intriguing question on how the Alpine deformation did not concentrate in the weaker sedimentary series in this location but focused along a limited series of faults mostly within the hard Permian volcanics. A possible explanation is that inherited structures within the Athesian Volcanic Complex were reactivated preventing the nucleation of new SSE-vergent faults in the sedimentary succession. These faults later became the preferred sites of strain because they were optimally oriented with respect to the Alpine NNW-SSE contraction. The existence of such weak inherited discontinuities could have prevented the nucleation of new SSE-vergent faults in the sedimentary sequence of the western sector of the analyzed region, where the Permian volcanic series are thicker. A similar behavior of Permian ENE inherited anisotropies has been hypothesized also in other sectors of the Dolomites, as at the southern margin of the Athesian Volcanic Complex along the Valsugana Line (Selli, 1998). The retro-vergence of such thrusts in an otherwise dominant SSE-vergent tectonic domain may be forced from the possible inherited Permian faults attitudes and geometries and could be another element supporting this hypothesis, which however needs further structural investigations to be proved and consolidated.

In the Dolomites, the localization of the décollements along thrust faults in the sedimentary series was controlled by the rheology of the stratigraphic succession (Doglioni, 1987, 1992). The deepest and main décollement surface corresponds to the evaporites of the lower *Bellerophon* Formation (BEL). Metric to decametric asymmetric folds occur in this unit, producing a consistent thickening in the eastern sector (see cross-sections C-C', D-D' and Figure 5). The absence of Alpine thrust faults and folds affecting the sedimentary succession in the western part of the study area accounts for the smaller thickness (ca. 70 m) of BEL in this area with respect to the eastern part of the map, where BEL was thicker and has been duplicated by tectonic faulting and folding.
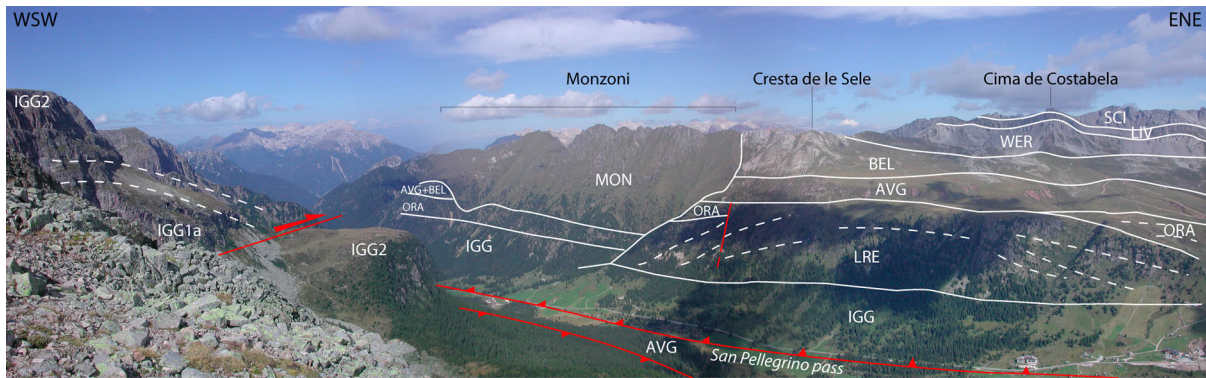
Figure 3. Panoramic view of the western part of the study area from the south. Note the faults affecting the Athesian Volcanic Complex and the Val Gardena Sandstones (AVG), with a thrust and two back-thrusts concentrated south of the Monzoni intrusion.

The Middle Triassic extension associated with the growth of carbonate platforms and the emplacement of magmatic intrusive and extrusive bodies (e.g. Bechstädt et al., 1978; Gramigna et al., 2013; Preto et al., 2011) has not been documented in the map, although the study area lies just to the east of the Monzoni intrusive body.

5. Conclusions

The San Pellegrino area in the Italian Southern Alps is a key sector for understanding how inherited fault geometries and juxtaposition of rocks with different rheological behavior, might affect later deformations.
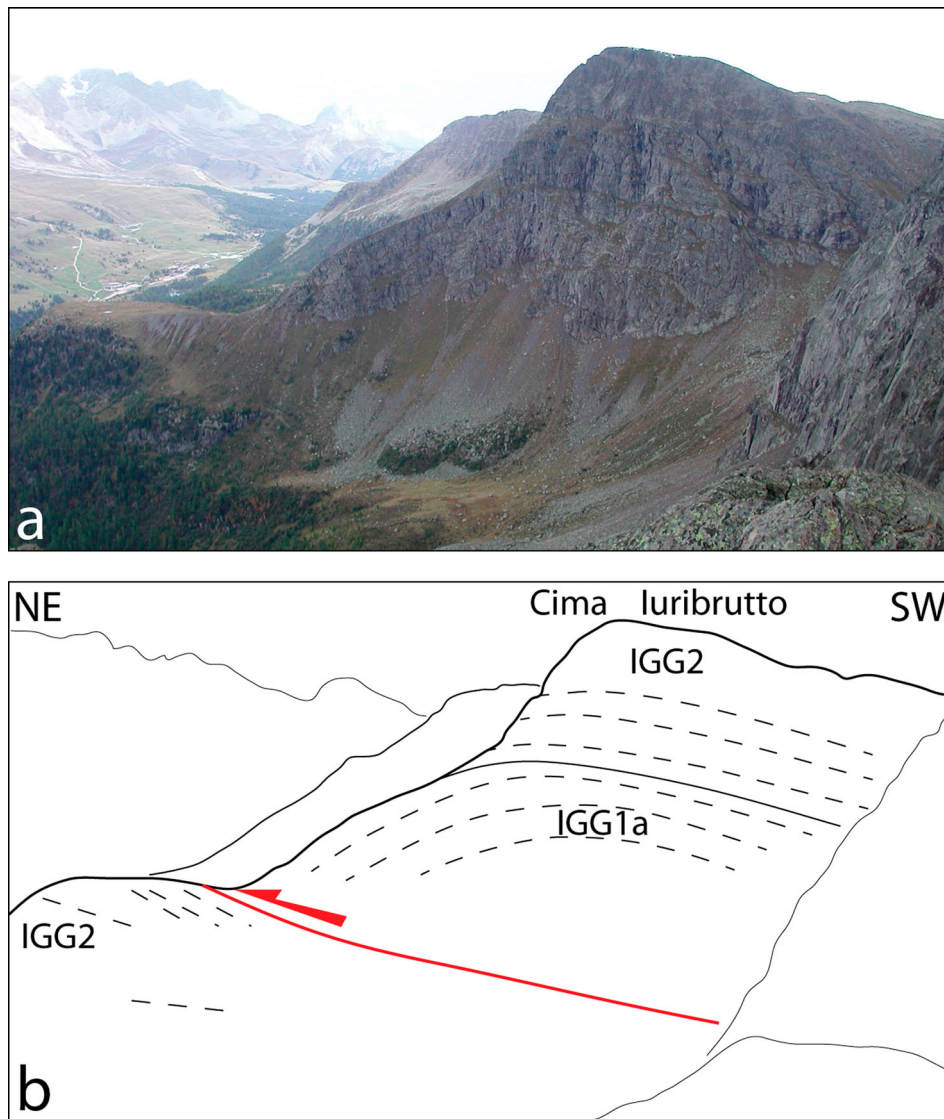
Figure 4. Panoramic view (a) and structural sketch (b) of Cima Iuribrutto as seen from the north-west. The Iuributto-Col Margherita back-thrust and the related hanging-wall anticline folding the Athesian Volcanic Complex are visible.
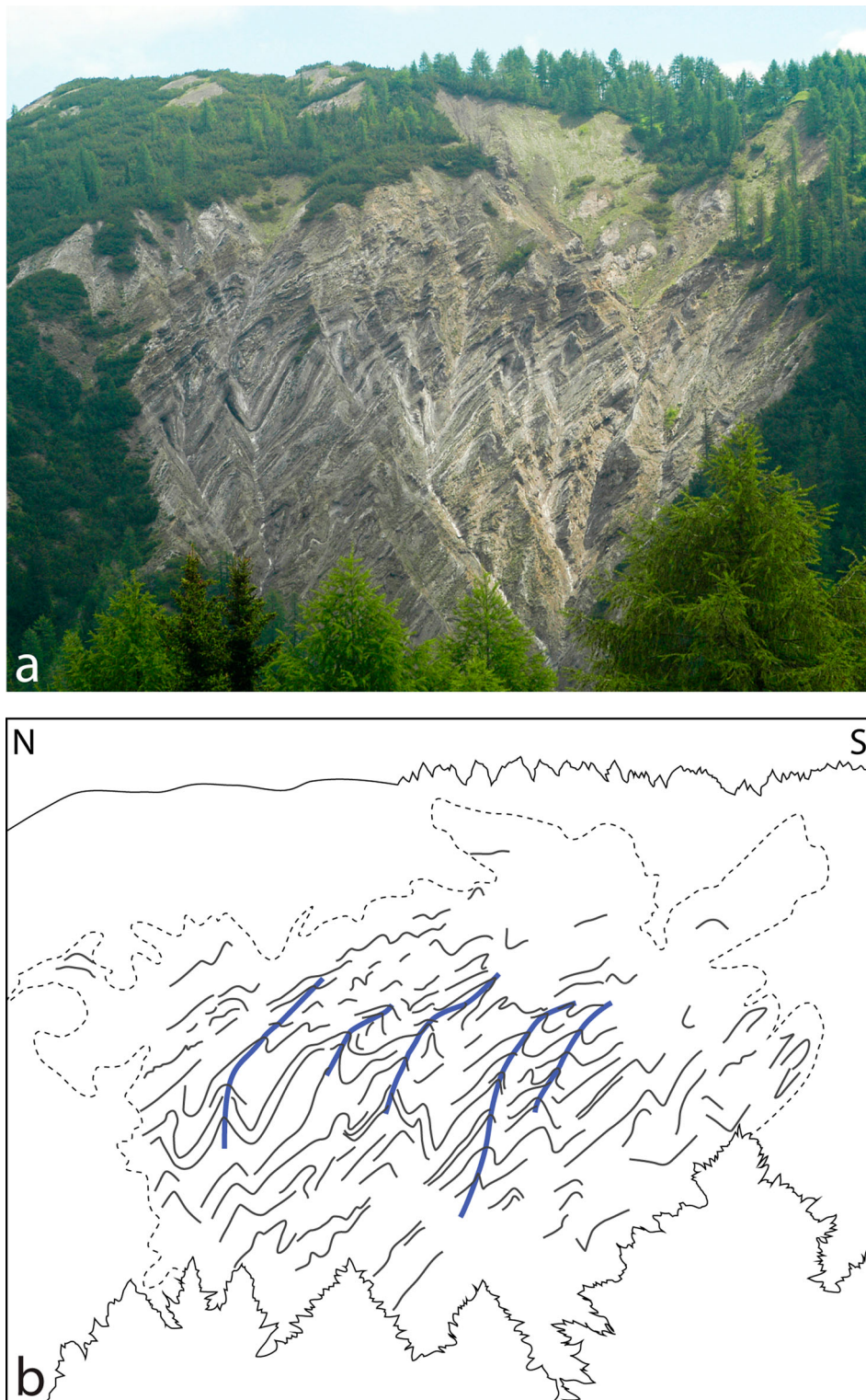
Figure 5. Panoramic view (a) and structural sketch (b) of the *Bellerophon* Formation in the south-eastern part of the map (see location in Figure 2). Note the intense folding with steep, north-dipping axial planes (blue line traces).

Specifically, a weak Permo-Mesozoic sedimentary succession is here juxtaposed to hard volcanics of Permian age or to the Triassic Monzoni intrusion. Most of this complex framework was likely inherited from the Permo-Mesozoic tectonic events that affected the entire South Alpine domain and was already in place when the later Alpine deformation occurred. Our geological survey has shown that ENE trending Alpine tectonic compressive structures are the dominant elements in this area. Some of these structures are possibly inherited by pre-Alpine deformational phases, but their original kinematics cannot be reconstructed. A few N-S oriented high-angle faults still retain characters of pre-Alpine extensional phases. Such hints of a Permo-Mesozoic tectonic history hidden by the subsequent Alpine deformation have been highlighted

with a detailed structural mapping of folds and faults affecting thin geological units. This allowed to perceive a change of structural style, with the shortening of sedimentary series decreasing from E to W. In places, a counter-intuitive behavior of strain partitioning is observed, with un-deformed weak sedimentary rocks in direct contact with faulted hard volcanic successions. We interpreted this counter-intuitive strain partitioning as a further evidence of the influence of inherited structural grain onto later deformational events.

Software

The geological dataset was implemented within Esri ArcGIS 10.0 (https://www.esri.com/en-us/arcgis/about-arcgis/overview). The geometric primitives and alphanumeric attributes of interest for map generation were produced as a shape file in Esri geodatabase and then exported into the Adobe Illustrator (www.adobe.com/Illustrator) for the final layout of geological map and sections. The ArcGIS project uploaded into Adobe Illustrator loses any descriptive information, hence all the layers of the maps have been reestablished as Adobe Illustrator levels. The LIDAR-DTM panoramic view, inserted within the map has been produced using the Arc-Scene package of ArcGIS 10.0 software.

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Acknowledgments

Disclosure statement

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