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SCIENCE

Deciphering large-scale superposed fold systems at shallow crustal levels in collision zones: insights from the Marguareis Massif (southwestern Alps)

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ABSTRACT

We present and discuss the results of a field-based approach including accurate geological mapping and micro- to map-scale structural analysis to highlight the finite strain pattern recorded in Marguareis Unit, a massif deformed at shallow crustal levels at the boundary between Maritime and Ligurian Alps. We describe superposed tectonic structures developed under low-grade metamorphic conditions during the Alpine collision and nowadays exceptionally well recorded in the area of interest. We demonstrate that the structural frame of the Marguareis Unit results from superposition of fourfold systems, later segmented, but without significant displacements, by brittle faults.

1. Introduction

At shallow structural levels of orogenic belts (i.e. orogenic suprastructure, De Sitter & Zwart, 1961) continental and/or oceanic-derived tectonic units are deformed under low- and very low-grade metamorphic conditions and can partly preserve their original lithostratigraphy. Consequently, they are generally considered for the reconstruction of the pre-collisional paleogeography and/or for estimation of bulk horizontal shortening during the continental collision (Davis et al., 1983; Ford et al., 2006; Gidon, 1972).

These units, being involved in collisional systems, are characterized by the development of large-scale penetrative and continuous tectono-metamorphic fabrics, but their finite strain pattern might easily be underestimated. However, the excellent preservation of their original lithostratigraphy allows the implementation of a high-resolution structural mapping and enhancement of large-scale, sometimes geometrically complex, fold-thrust structures.

We discuss the results of field investigations and map updating that revisit a sector of the Marguareis Massif located in the southern termination of the Western Alps, at the boundary between Maritime and Ligurian Alps (Figure 1) along the French-Italian border. A new 1:10000 scale map of the southwestern sector of the Marguareis massif is presented; it synthesizes structural and lithostratigraphic field results. The aim is to focus on the relative deformation chronology of tectonic events concealed within the Marguareis Unit characterized by a typical Meso-Cenozoic sequence of the Briançonnais Domain showing a low-grade metamorphic imprint. The excellent exposures of multi-scale structures, from foliations to kilometer-size polyphase fold systems make the Marguareis Massif a privileged area where to unravel histories of sedimentary and tectonic episodes, broadly assisted by well-known solid sedimentological and paleontological supports (i.e. Brizio et al., 1983; D'atri et al., 2016; Lanteaume, 1962; 1968; Sanità et al., 2020; Vanossi, 1972).

2. Geological frame

The Marguareis Massif consists of a tectonic pile of Briançonnais Units where the Marguareis Unit is the topmost one (Figure 1). These units are deformed and metamorphosed and then thrusted by the Helminthoid Flysch during the building up of the Western Alps starting from middle Eocene age during an overall southwestward movement (i.e. Carminati, 2001; Sanità et al., 2020). Recently, Sanità et al. (2020) documented a polyphase deformation history during which the Helminthoid Flysch Unit is thrust before onto the already exhumed Briançonnais Units that subsequently are superposed over the Helminthoid Flysch Unit by an out-of-sequence thrust. The result of this history is the present-day position of the Helminthoid Flysch lying between the
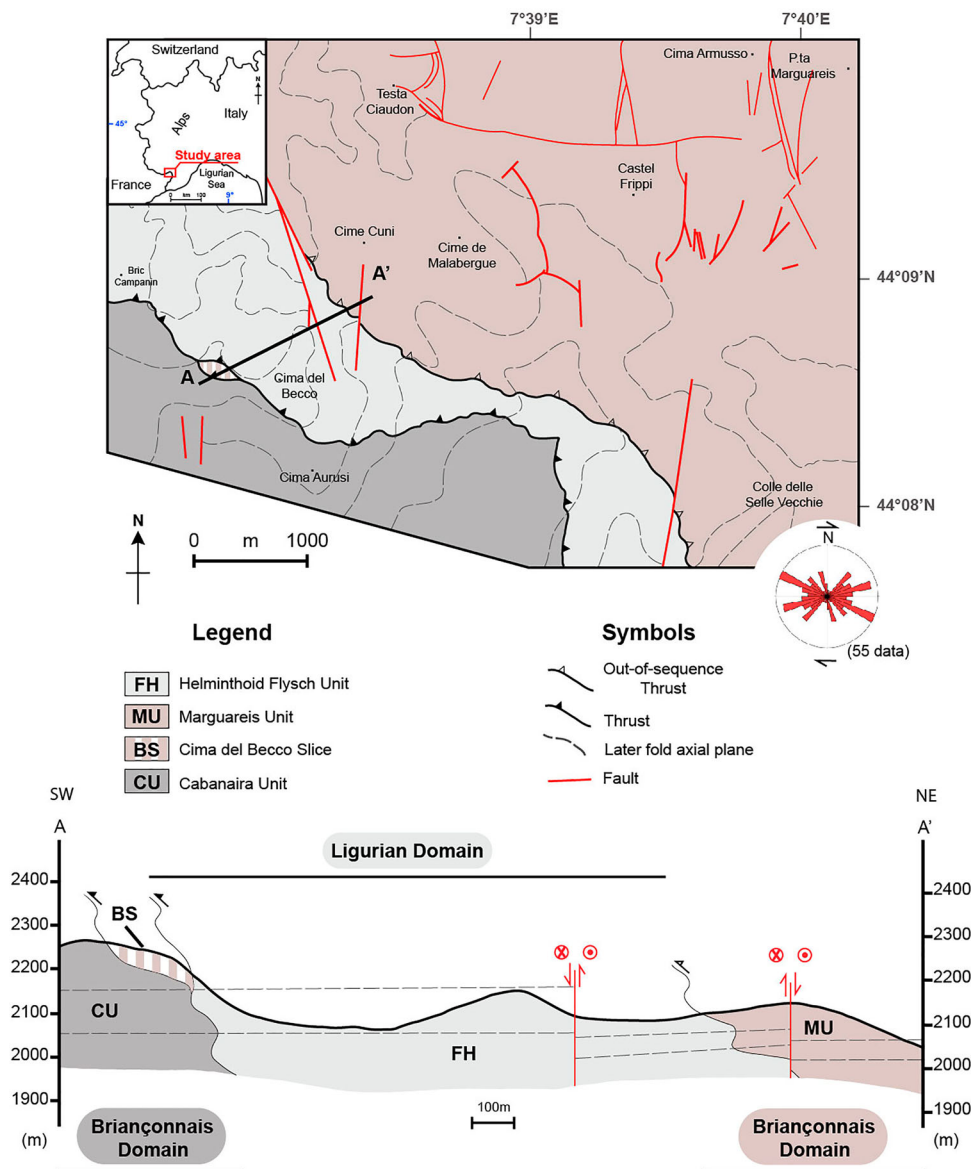
Figure 1. Tectonic sketch of southwestern sector of Marguareis Massif showing the relationships between different units. Geographic location of the study area and geometrical distribution of faults are reported.

Briançonnais Units (Figure 1), separated by two *top-to-SW* thrusts (Figure 1).

A different interpretation was proposed by Bertok et al. (2018). The authors describe an intricate high-angle fault-network separating different tectonic units showing different P-T conditions (Piana et al., 2014). The same authors, in accordance with D'atri et al. (2016), proposed that the fault-network is part of an E–W-direct shear zone active during the Alpine collision. This faults-network played a key role in the structural configuration of the Marguareis Massif.

The Helminthoid Flysch Unit shows a Late Cretaceous non-metamorphic sedimentary succession. It consists of basin plain deposits that pass upward to deep-sea fan turbidites. The Briançonnais Units consist of Meso-Cenozoic cover rocks here represented (Figure 2) by the Marguareis Unit, including the Cima del Becco Slice and the Cabanaira Unit (for a

discussion about the stratigraphy of other units, see Sanità et al., 2020 and quoted references).

3. The Marguareis Unit: stratigraphy

The succession (Figure 2) of the Marguareis Unit is coherent with the sedimentary evolution of the European passive continental margin, generated during Mesozoic continental thinning initiated in late Permian (Filippi et al., 2020) and that, since Late Cretaceous, was involved in a convergent setting (Decarlis et al., 2013).

The Marguareis Unit is constituted by a Middle Triassic peri-tidal dolostones (San Pietro dei Monti Dolostone, SPDM; Vanossi, 1972). The SPDM are separated by a Late Triassic-Middle Jurassic hiatus from the overlaying Middle Jurassic platform carbonates (Rio di Nava Limestone, RNL; Boni et al., 1971)
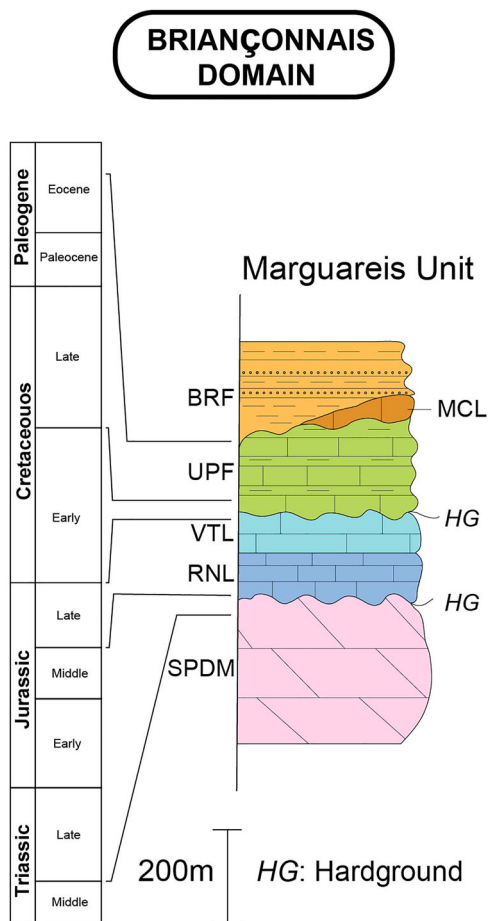
BRIANÇONNAIS DOMAIN

Figure 2. Stratigraphic log of Marguareis Unit (modified and re-draw from Brizio et al., 1983).

showing a transition to massive to nodular pelagic limestones (Val Tanarello Limestone, VTL, cf. *Marbres de Guillestre* of Fallot & Faure-Muret, 1954). An Early to Late Cretaceous mineralized hardground with stromatolites marks the boundary between the Jurassic deposits and the hemipelagic marly limestones of Late Cretaceous age (Upega Formation, UPF, cf. *Calcshistes Planctoniques* of Fallot & Faure-Muret, 1954). The topmost deposits (Figure 2) are represented by middle(?) Eocene *Nummulite*-rich limestones (Madonna dei Cancelli Limestone, MCL; Vanossi, 1972) and turbidites. The latter are represented by deep-sea fan siliciclastic turbidite interlayered with chaotic deposits (Boaria Formation, BRF, cf. *Flysch Noir* of Lanteaume, 1968). This formation unconformably overlies both on the UPF and MCL.

4. Methods

In order to display the finite strain pattern recorded in Marguareis Unit, we performed a geological mapping according to classical techniques of geological field survey. The fieldwork uses a 1:10,000 scale topographic map. To obtain the final version of the 1:10,000 geological map (hereafter called Main Map),

our structural data were combined with a revisiting and updated of datasets of Brizio et al. (1983) and Carminati and Gosso (2000). High-definition mapping relies on minimizing interpretation giving privilege to factual geometric evidences and omitting surmised portraits of stratigraphy, folds and faults. Central question for quality structural map turns on the systematic fitting of deformation scales, e.g. fold systems related to grain-scale deformation (i.e. foliations) leading to firmly establish the connection of repeated folding and coeval foliation histories by kinematic data. In Main Map, geometric and kinematic compatibilities of folds and foliations support the attribution of the synchronous origin of these two fabric elements; ubiquitous indicators, as axial plane traces and, foliations overprints, support firm comprehension of deformation of mapped units and provide relatively dated foliations for rewarding laboratory work. Microstructural analysis was performed on samples collected during fieldwork in key areas where the superposition relationships between the different deformation phases have been observed. Stereographic plots of fold axes and axial planes express synoptically their spatial relationships, graphically distinguished as relative ages all over the map.

5. The finite strain pattern of the Marguareis Unit

The Marguareis Unit records a polyphase deformation history characterized by the superpositions of folding and faulting events (see Sanità et al., 2020 and quoted references). Labeling of deformation times matches the one used in Sanità et al. (2020). Since that this paper is focused on the Marguareis Unit strain pattern, the deformations detected in this unit will be labeled with a simplified nomenclature (for more details see Sanità et al., 2020).

5.1. D1 phase

5.1.1. Meso- and micro-scale features

The oldest deformation phase recorded in the Marguareis Unit is testified by a pervasive continuous S1 foliation (Figure 3(a)) showing NW–SE to WNW–ESE strike with both SW and NE dip (Figure 4). Under the microscope (Figure 3(b)), the S1 foliation is, in the fine-grained rocks, a slaty cleavage with thin lenticular aggregates of oriented calcite and quartz grains, detrital and syn-metamorphic white micas. In the marly carbonate rocks, S1 is marked by differentiated foliation consisting of calcite, white micas, quartz and plagioclase grains surrounded by levels consisting of syn-metamorphic white micas and oxides. The grain-scale deformation mechanisms include re-crystallization, passive rotation of phyllosilicates and the pressure solution, which is
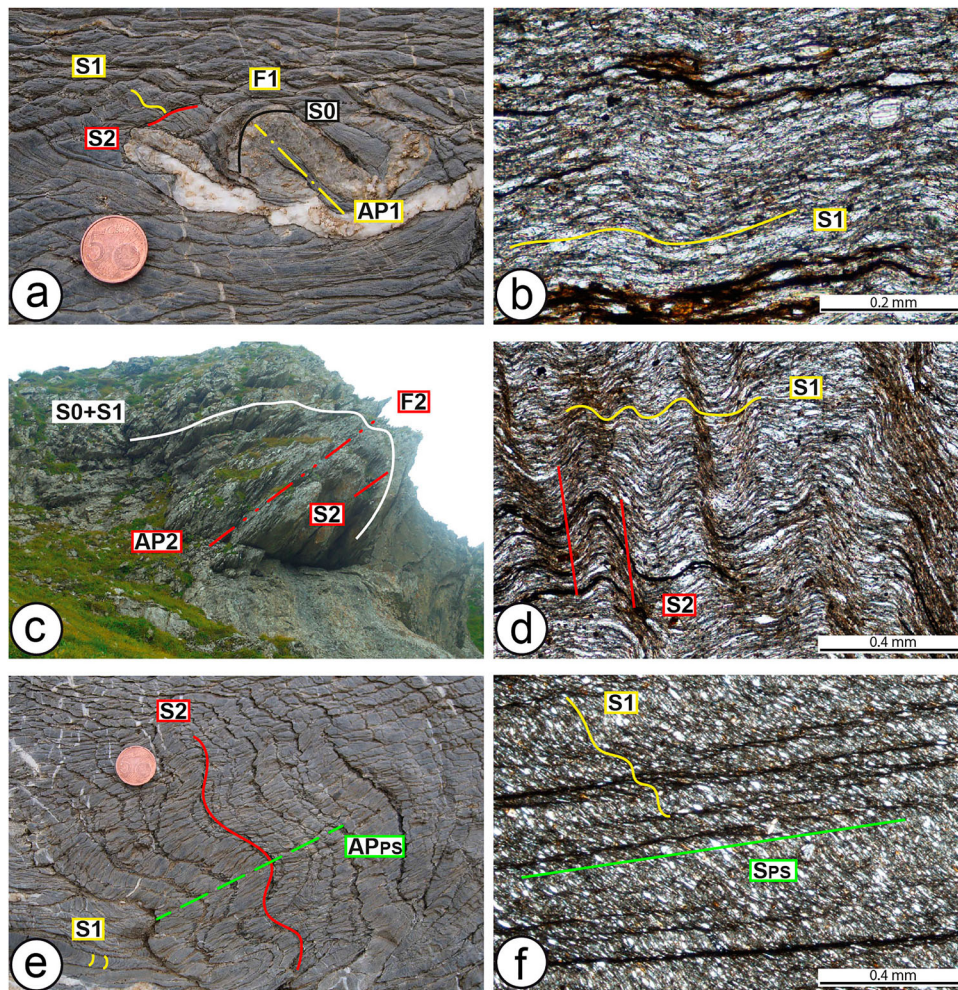
Figure 3. Outcrop- and micro-scale structural features in the Marguareis Unit. (a) F1 fold with AP1 axial plane and S1–S2 overprint; (b) S1 foliation; (c) F2 fold which folds the S0–S1 surface. AP2 axial plane and S2 foliation are indicated; (d) S1–S2 interference pattern at the microscale; (e) S1 and S2 foliations folded by AP_{PS} axial plane; (f) S_{PS} foliation which folds the S1. S0: bedding.

predominant over the other mechanisms. The S1 foliation, parallel to axial planes (AP1) of F1 folds, is well-developed from micro- to meso-scale in the fine-grained rocks (i.e. marly limestones, Figure 3(a,b)). The F1 folds show a similar geometry with thickened and rounded hinges, thinned limbs sometimes with boudinaged layers and scattered A1 fold axes with the main trend-oriented NW-SE (Figure 5). The thickness of the formations located along the limbs are thinner compared with those placed in hinge zones, it is also due to boudinage of more competent lithotypes. The AP1 shows a strike ranging from NW–SE to WNW–ESE with both NE and SW dip (Figure 4).

5.1.2. Map-scale structures

Map-scale F1 folds occur in the Cima Armusso-Punta Straldi ridge and Vallon de Malabergue (see Main Map) areas. In these areas, the major F1 folds are testified by synclines with the Upega Formation at the core. The Cima Armusso syncline continues in the Pian Ambrogi area, but the quaternary deposits and the low-quality outcrops do not allow its accurate reconstruction in this area. In the Vallon de Malabergue area, F1 folds are testified by flat-lying synclines and anticlines developed in the Jurassic and Late Cretaceous deposits (Val Tanarello Limestone and Upega Formation). Moving from NE to SW in the Marguareis Unit, the S1 and AP1 attitudes show a change in dip from gently dipping toward NE, in Cima Armusso-Punta Straldi ridge, to sub-horizontal attitude in the Vallon de Malabergue area (Figures 4 and 6).

5.2. D2 phase

5.2.1. Meso- and micro-scale features

The D2 phase is defined by the S2 foliation well-preserved in fine-grained rocks (i.e. Boaria Formation). In fine-grained rocks, S2 foliation is a penetrative crenulation cleavage, whereas in coarse-grained ones it corresponds to a disjunctive cleavage marked by dissolution surfaces (Figure 3(a,c)). The S2 foliation strikes NW–SE and dips toward SW or NE (Figure 4). Under the microscope, the S2 foliation is a crenulation cleavage overprinting the previous S1 foliation (Figure 3(d)). The S2 cleavage domains are marked
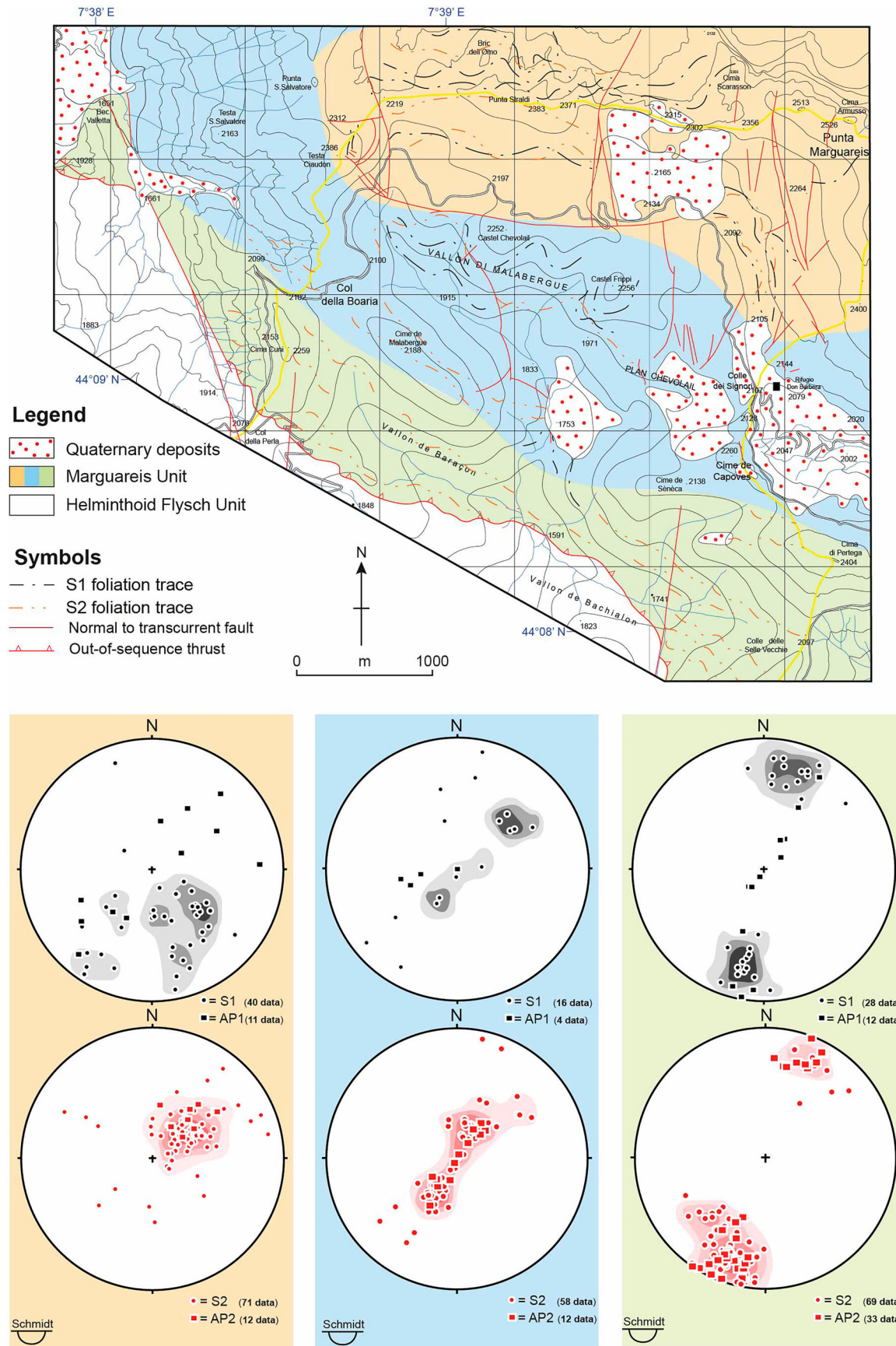
Figure 4. Structural sketch of the Marguareis Unit. Different colors indicate structural domains with different attitudes of F1 and F2 folds. Stereoplots of their structural planar features are reported.

by oxide-rich stylolitic surfaces and both detrital passively rotated and syn-kinematic white micas. The main deformation mechanism appears to have been the pressure solution. The F2 folds are common in the Boaria and Upega formations whereas in the Val Tanarello Limestone, Rio di Nava Limestone and

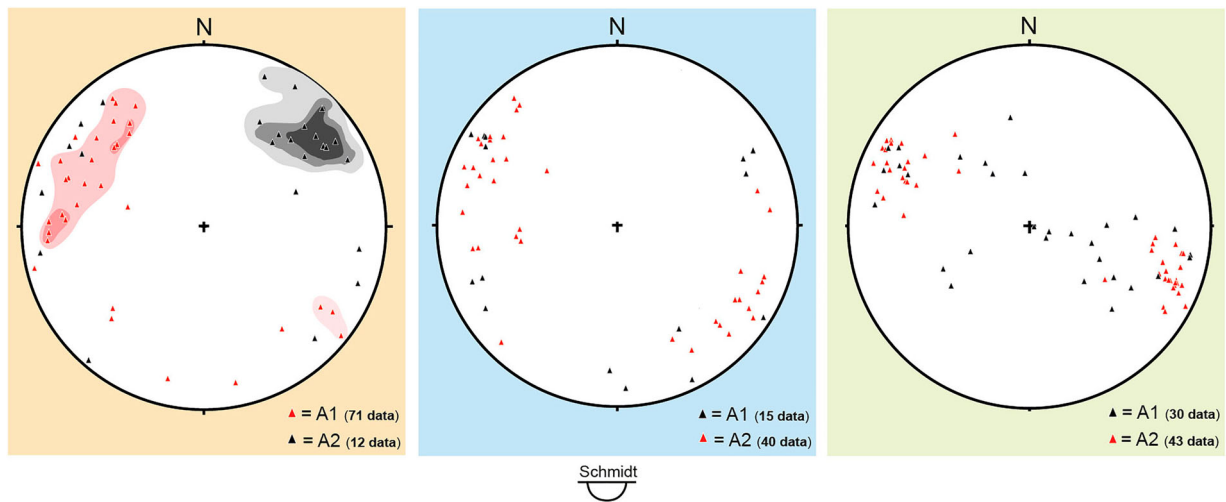**Figure 5.** Stereographic plots od D1- and D2-related fold axes for each structural domain reported in Figure 4.
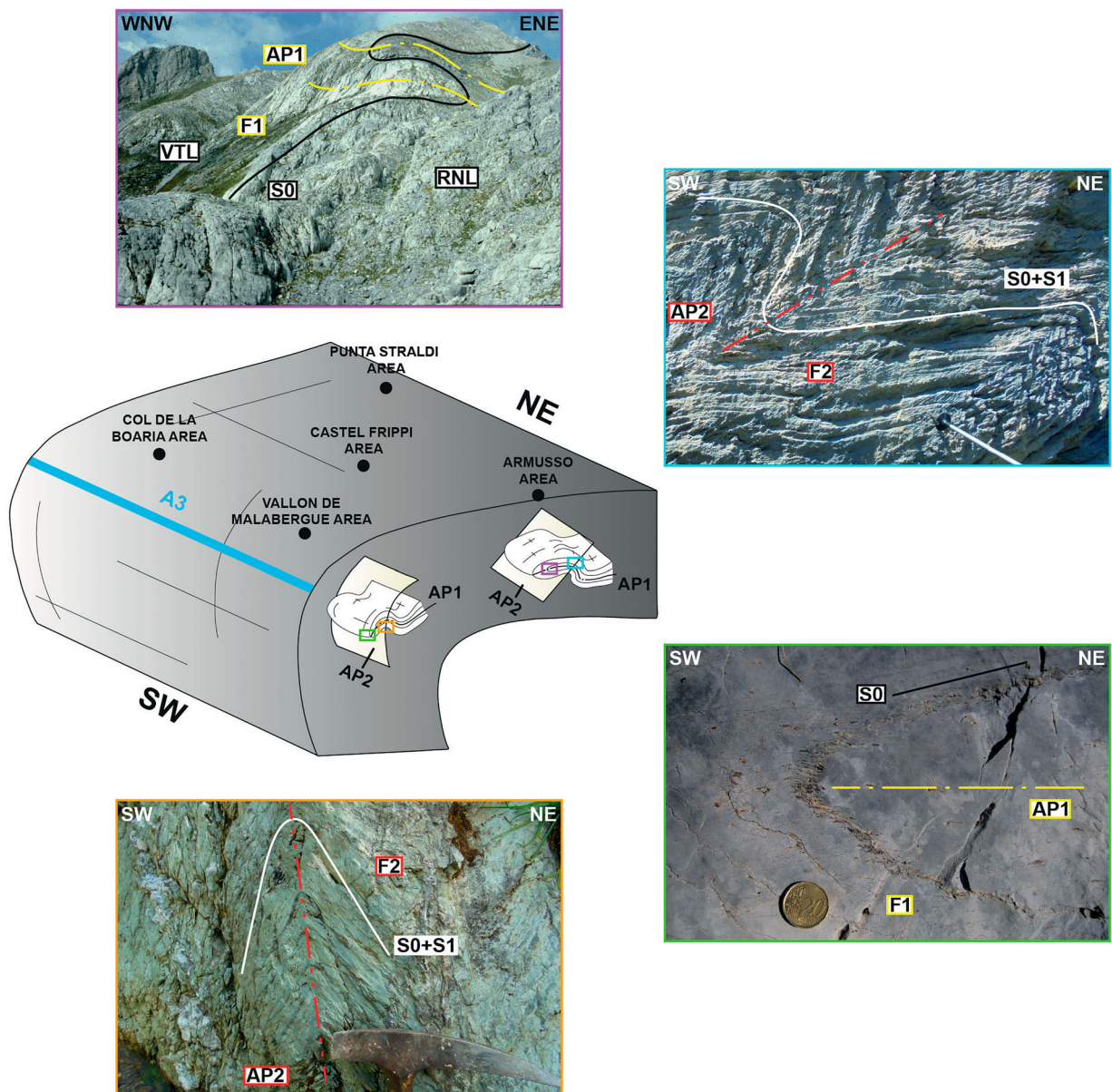

Figure 6. 3D sketch showing the D3 folding on previous structural features. The D1- and D2-related folds attitudes are reported.

San Pietro dei Monti Dolostone, the F2 folds have been recognized at the decametric- to kilometric-scale only. The F2 folds show parallel geometry (Figure 3(c), F2 folds with similar geometry are locally present) with thickened and rounded hinges. The A2 fold axes show a clear NW–SE trend and plunge toward NW or SE (Figure 5). The AP2 axial planes show an NW–SE strike with a dip toward SW or NE (Figure 4).

5.2.2. Map-scale structures

Map-scale F2 folds are represented by the Col de La Boaria and Colle delle Selle Vecchie Synform and Cime di Pertega Antiform (Main Map). The Boaria Formation occurs at the core of the synforms, whereas the core of the antiform is made of Val Tanarello Limestone (Main Map). The Boaria Synform is probably prosecuted in the Colle dei Signori area (eastern sectors of Main Map), where the Boaria Formation crops out at the core of a synform.

Note that the S2 and AP2 dip changes moving from NE to SW (Figure 4). In fact, from Cima Armusso-Punta Straldi ridge to Cime de Malabergue areas, the AP2 and S2 dip progressively change from gently dipping to SW up to sub-vertical in the Col de la Boaria area, and dipping to NE in the Vallon de Malabergue area (Figure 4). The overprint between F2 and F1 fold systems produces a type 3 interference pattern (Ramsay, 1967), from meso- to map-scale, deriving from the superposition of twofold systems with axial planes at high angles and roughly co-axial fold axes. The best examples of this interference are provided by Cima Armusso-Punta Straldi ridge (Main Map). In this area, D1 and D2-related antiforms and synforms structures are continuous northwestward for about 3 km.

5.3. D3 phase

5.3.1. Meso- and micro-scale features

The D3 phase (Figure 6) is testified by the folding of the D1 and D2-related structural elements (i.e. axial planes and foliations) and by the development of NW–SE strike unit-bounding thrusts which are responsible for the coupling of the units (Sanità et al., 2020). These are marked by cataclastic high-strain decametric shear zones showing kinematic indicators point to SW. The F3 folds and the associated S3 foliation are generally developed in the fine-grained rocks. The F3 folds are better appreciable at the map scale.

5.3.2. Map-scale structures

The D3 phase produced a map-scale knee-shaped F3 fold showing NW–SE trending fold axis and axial plane with NW–SE strike and with a dip toward NE (Figure 6). The trend of A3 fold axes, the strike of the AP3 and the attitude of the unit-bounding thrust are sub-parallel suggesting their coeval development (Sanità et al., 2020, see B-B' cross-section). The sub-vertical limb of the F3 fold is developed along the thrust separating the Marguareis Unit from the underlying Helminthoid Flysch Unit, whereas the normal sub-horizontal limb can be observed in its central and northern sectors (see B-B' cross-section).

5.4. Late structures

All the previously described structures are deformed in turn by late post-stacking (PS) fold (according to Sanità et al., 2020) and subsequent brittle faults. PS folds developed from micro- to map-scale show parallel geometry, axial planes (AP_{PS}) gently dipping toward SW (Figure 3(e)) and NW–SE trending A_{PS} fold axes (see Main Map). The S_{PS} foliation has been observed only in the less competent layers as spaced disjunctive cleavage. Under the microscope, the S_{PS} is marked by stylolitic surfaces without metamorphic re-crystallization (Figure 3(f)). In the central and southwestern sector of the Marguareis Unit, the over-printing relationships between the F_{PS} and F2 folds produce a type 3 interference pattern (Ramsay, 1967). This setting derives from the overprint of two folding systems both with NW–SE trending axes and high-angle axial planes.

The last deformation event is represented by sub-vertical strike-slip to normal faults. The geometrical distribution of the fault planes detected a Riedel system composed of three fault arrangements (N110-120, N050-070 and N160-170, Figure 1) coherent with an E–W-direct dextral shearing as proposed by Sanità et al. (2020).

6. Discussion and conclusion

The presented 1:10,000 scale geological map shows how multi-scale analysis of structures contributes to investigate finite deformation pattern of low- and very low-grade tectonic units in a portion of the external part of collisional belts. The complex structural frame of the Marguareis Unit originates from super-position of different folding (F1, F2, F3 and post-stacking folds) and faulting events made evident in clear interference patterns. F1 and F2 fold systems are confined to the Marguareis Unit, whereas the sub-sequent deformation was acquired during (F3 folds) and after (PS folds and faults) the coupling of the units (as proposed in Sanità et al., 2020).

Complexities of fold systems currently coincide with overprinting fold patterns, later crossed by faults that segmented the whole tectonic pile without erasing the previous structures. The fault system cuts at high-angle all the previously described structures and only
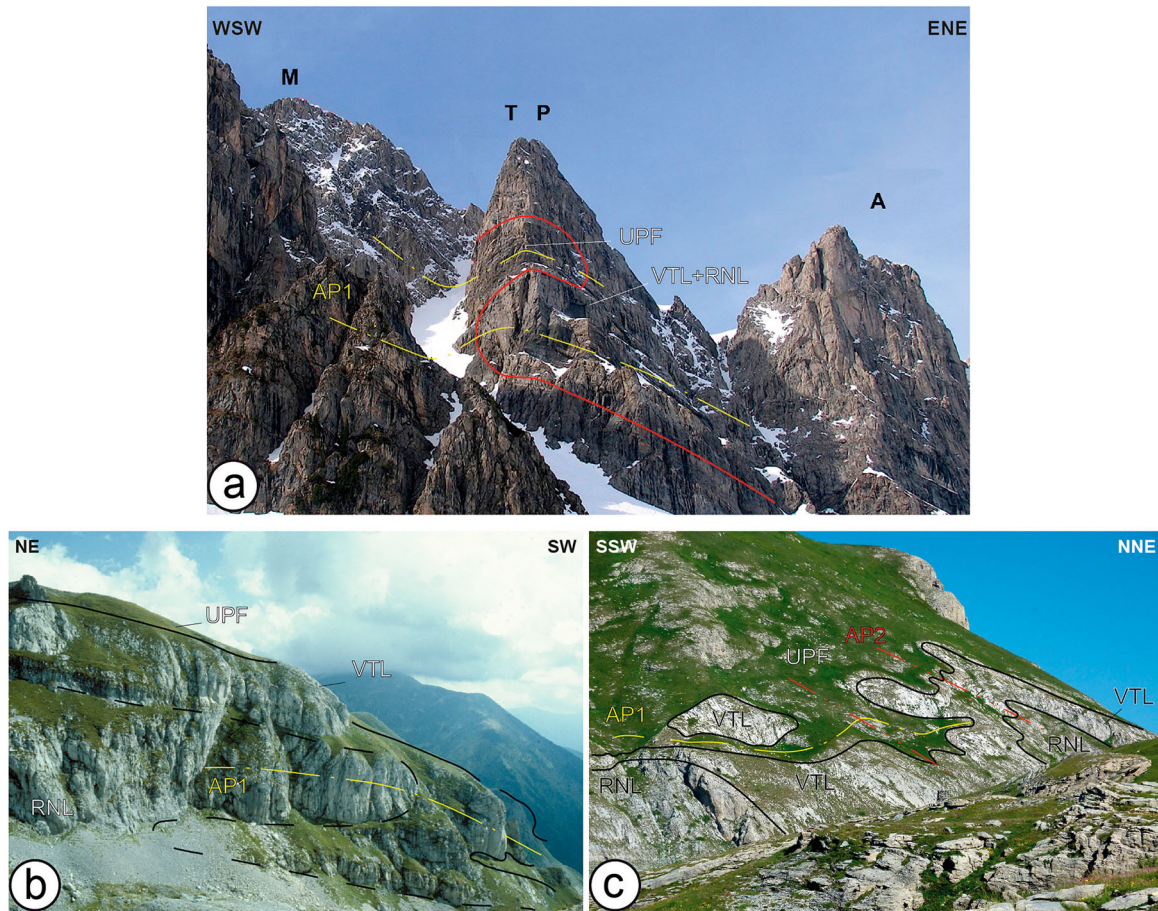
Figure 7. (a) View due southwest of north wall of Punta Marguareis (M)-Tino Prato (TP)-Armusso (A) ridge; the 90° faces of TP dihedron display F1 isoclinal fold stack; red line = bedding. (b) Hinge zone of F1 isoclines at the northern margin of Vallon de Malabergue. View due southeast of Castel Frippi western slope. Black solid line = bedding; black dotted line marks the cherty levels near the top of Rio di Nava Limestone (RNL). (c) F1–F2 folds interference pattern west of Morgantini hut. Black solid line = bedding. UPF: Upega Formation; VTL: Val Tanarello Limestone.

locally juxtaposes different tectonic units. In contrast with Bertok et al. (2018), we retain that the reworking caused by the fault-network did not substantially modify or obscure the previous structural configuration.

The apparently intricate fold and foliation clusters are mapped where lithostratigraphy is clear.

Disharmonic fold wavelengths, contact strain zones and faulting-related brecciation are the main structural configurations determining the local assemblages of structural imprints, or tectonic style; most of these patterns are functions of rock competence contrast, generally active between carbonates and marls. The diffused competence contrast, i.e. between SPDM dolostones and RNL-VTL limestones, markedly induces extreme disharmonic folding in the latter, generating a sort of super thick pile of F1 isoclinal folds (steep slope above Conca delle Carsene and north Punta Marguareis-Cima Armusso ridge and Castel Frippi areas, Figure 7(a,b)). A similar markedly rheologic contrast happens between RNL + VTL and UPF limestones, generating F1 isoclinals nearly parallel to basal more competent VTL levels (W of Capanna Morgantini, Figure 7(c)).

Since the D1 phase characteristics documented in this work, the remarkable thickness variation of the Marguareis Unit formations is probably the result of the D1-related deformation history rather than their stratigraphic pattern. The D1 and D2 phase-related folds are re-oriented during the D3 phase, developed during the coupling with the underlying unit. Structural dataset for the Marguareis Unit allowed us to differentiate three structural domains moving from NE to SW. Each of these is characterized by a different attitude of the F1 and F2 folds, as testified by stereoplots (Figure 4). The F3 folding is thus responsible of an important re-orientation moving from NE to SW of the pre-existing structural elements. This interpretation is clearly supported by the dip of the S2 foliation and AP2 axial planes, which change moving from NE to SW (Figure 4). In this structural setting, F1 and F2 folds show, respectively, flat-lying and northeastward-dipping axial planes if observed along the sub-vertical limb of the F3 fold. In contrast, the same structural elements are characterized, respectively, by northeastward-dipping and southwestward-dipping axial planes if observed along the normal limb (Figure 6).

The first two phases took place at a relatively deeper collisional tectonic level, under conditions ensuring diffuse granular plasticity (intense foliations of fine-grained rocks) and related isoclinal folding up to km-scale amplitude. The third phase caused thrusting of Marguareis Unit over Helminthoid Flysch, at shallower crustal depth, being unable to assist small-scale folding and diffuse granular reworking. The latest deformations are shared by all the units and developed at very shallow structural levels; they overprint all the previously described structures, including the unit-bounding thrusts and F3 mega-fold (see Main Map). The post-stacking (PS) folds are well developed in the southern and central sectors of the Marguareis Unit, where nearly vertical layerings dominate. The late structures, including the fault system, can be the result of extensional tectonics (according to Sanità et al., 2020) affecting also others areas of the Alpine belt.

Software

The Main Map, tectonic sketch, cross-section and pictures were drawn using Illustrator. The stereoplots were constructed with Allmendiger Stereonet.

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Disclosure statement

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Data availability statement

Data available from the authors on request.

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