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Title: Tectono-metamorphic evolution of the European continental margin involved in the Alpine subduction: new insights from the Alpine Corsica, France.

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Keywords: Continental subduction, polyphase exhumation, P-T-d paths, HP metamorphism, Alpine Corsica

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Abstract: In Corsica, continental units (the Lower Units) affected by high-pressure metamorphism represent the remains of the European margin deformed during the Alpine orogeny. In order to document how Alpine deformation and metamorphism changed along the European margin involved in the Alpine subduction, we selected three key areas: Corte, Cima Pedani and Ghisoni transects. The three transects show a broadly similar lithostratigraphy. They are characterized by a Variscan basement intruded by Permo-Carboniferous metagranitoids, and by a sedimentary cover including Mesozoic carbonates and Middle to Late Eocene breccias and sandstones. The three transects recorded a similar deformation history with three deformation phases. Thermo-baric estimations instead, reveal that each unit was exhumed along an independent retrograde path within the orogenic Alpine wedge. In particular, the lowest units of the Lower Units stack were exhumed along an isothermal path whereas those located at upper structural levels experienced progressive heating.

Cover Letter

Dipartimento di Scienze della Terra
Università di Pisa

July 24th, 2018

To the Editor of the Comptes Rendus Geoscience

Dear Editor,

we hereby submit the manuscript titled "Tectono-metamorphic evolution and stratigraphy along the European continental margin involved in the Alpine subduction: new insights from the Alpine Corsica, France" by Di Rosa Maria, Frassi Chiara, Meneghini Francesca, Pandolfi Luca, Marroni Michele and De Giorgi Alberto for its publication in your journal.

The Alpine Corsica is regarded as a fragment of the Alpine collisional belt isolated from the Western and Ligurian Alps since the Late Oligocene, when the opening of the Liguro-Provencal oceanic basin started. According to this picture, the Alpine Corsica provides a picture of the structure of the Alpine collisional belt not affected by the more recent Miocene-Quaternary deformations that are instead well developed inland. This setting of the Alpine Corsica provides thus an exceptional opportunity for the study of the tectono-metamorphic features of the first stages of the continental collision in a time span ranging from Late Eocene to Early Oligocene. This period is crucial in the evolution of the collisional belt mainly due to a change of the plate convergent rate and geothermal gradient, both producing a modification in deformation style and metamorphic conditions. These changes produced also exhumation of HP continental rocks with mechanisms different than those detected in the subducted oceanic fragments.

Similarity to what documented in the western Alps, continental units with high-pressure metamorphic imprint crop out in the Alpine Corsica. These units derived from the thinned European continental margin that has been deeply involved in the tectono-metamorphic events that characterize the transition from continental subduction to continental collision. These units (i.e. Lower Units) crop out along a north-south trending line that runs from Ile Rousse, in the north, to Corte and Ghisonaccia, in the south.

In this paper three selected areas of the Alpine Corsica (i.e. Cima Pedani, Corte and Ghisoni) are compared, in order to constrain the behavior of the Lower Units during their subduction/exhumationm and their relationships with the Hercynian Corsica (i.e. the European margin not involved in subduction) and the others unit of the Alpine Corsica stack (i.e. the Schistes Lustrés Complex and the Upper Units). The good exposures and the smooth topography have allowed an integrated approach that uses geological mapping, mesoscale structural analyses, microfabrics investigations and P-T path determination by mineral chemistry. A full reconstruction of the tectono-metamorphic history of several tectonic units belonging to the Lower Units group is thus presented.

In Cima Pedani (the geological map and the PT paths of this area are under revision in another journal) the Lower Units occur in a tectonic window below the Schistes Lustrés Complex (i.e. the MP-to HP/LT oceanic units) and the Upper Units (i.e. the undeformed oceanic and continental units located at the top of the stack). In Corte (one of the two PT paths of this area has been already published in Di Rosa et al., 2017a; the geological map here presented is part of the geological chart published in the Journal of Maps by Di Rosa et al., 2017b) the Lower Units are stacked above the Hercynian Corsica together with slices of Schistes Lustrés Complex. Lastly, in Ghisoni (all the data related to this area are new and are proposed in this work for the first time) the Lower Units are represented by a single tectonic unit, sandwiched between the Hercynian Corsica and the Schistes Lustrés Complex.

The results gather information about the polyphasic deformation history acquired during the exhumation of this unit at the transition from continental subduction to continental collision.

Even if part of the data actually occurs in the other papers, the data related to Ghisoni are here first presented and the general aim of the work, as well as the discussions and conclusions, totally differ from those of the paper under revision in the other journal.

I would like to inform you that an early version of this paper has been submitted in November 2017 to the Italian Journal of Geosciences for the special volume "Integrating multiple techniques to constrain the evolution of basement Geology". The first reviewer - Federico Rossetti - suggested minor revisions whereas the second – probably Alberto Virale Brovarone - suggested moderate revisions. Despite the positive reviews, we asked to the editor of the IJG to block the acceptance , due to disagreements about the modifications requested. However, we take the chance of the two revisions already done by Rossetti and Vitale Brovarone to improve this new version.

The authors belong to the italian research group of the Università di Pisa that consists of four reserchers with a consolidated experience (MM, LP, FM and CF) a Ph.D. student (MDR) and a young researchers (ADG). They work together long since; focused on the Corsica geology, the last papers they published are:

Malasoma A., Marroni M., Musumeci G. & Pandolfi L. (2006) *High-pressure mineral assemblage in granitic rocks from continental units, Alpine Corsica, France.* Geol. J., 41, 49-59. DOI: 10.1002/gj.1032

Pandolfi, L.; Marroni, M.; and Malasoma, A. (2016). *Stratigraphic and structural features of the Bas-Ostriconi Unit (Corsica): paleogeographic implications*. Compt. Rend. Geosci. 348:630-640.

Di Rosa M., De Giorgi A, Marroni M. & Vidal O. (2017a) *Syn-convergence exhumation of continental crust: evidence from structural and metamorphic analysis of Monte Cecu area, Alpine Corsica (Northern Corsica, France).* Geol. J. DOI: 10.1002/gj.2857

Di Rosa M., De Giorgi A., Marroni M. & Pandolfi L. (2017b). *Geology of the area between Golo and Tavignano Valleys (Central Corsica): a snapshot of the continental metamorphic units of Alpine Corsica*. Journal of Maps, 13(2):644-653. doi: 10.1080/17445647.2017.1351900.

We should be very grateful if you would consider this paper for publication in Comptes Rendus Geoscience
We look forward to hearing from you.

Sincerely,

Maria Di Rosa (corresponding author)

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***Detailed Response to Reviewers**

Ms. Ref. No.: GEOSCIENCE-D-18-00145

Title: **Tectono-metamorphic evolution of the European continental margin involved in the Alpine subduction: new insights from the Alpine Corsica, France.**

CR Geoscience

Dear Editors,

We have considered all the comments and we have inserted the suggested corrections. The line-by-line corrections are also reported (in blue are pasted the sentences/comments of the editors). In the attached file of the text, all the modified/added sentences are marked in red. We hope that this new version can be accepted for the publication in your journal.

Best wishes,

Maria and Co-authors.

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ASSOCIATED EDITOR – ISABELLE MANIGHETTI

General comments

At first glance, the paper seems too long, especially as it contains nine figures and one table. Please remind that the CRG articles can be no longer than 10 pages (text, figures, and references included), with each page counting no more than 5500 characters and one half-page figure representing 2750 characters. I thus invite you to shorten the text and reduce the number of figures, moving some of them to the available Electronic Supplements.

As suggested by the editor, we have moved the Fig.8 and the Tab.1 to the Supplementary Material. In order to comply with the standards of the journal, we have prepared an informal draft (sent by email to the associated editor I. Manighetti and to the graphic editor H. Paquet) in which the revised text and the figures (sized as though by the authors) are assembled using the format of the CR Geosciences. This draft is not longer than 10 pages, as required by the CR Geoscience author guidelines. In any case, we are available for an additional payment for further 2 pages.

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REVIEWER 1 – ANDRE' MICHARD

General comments

I made a lot of English corrections and comments in the submitted ms

The text has been revised in order to correct every linguistic error.

References: the list is almost complete, but the BRGM maps and notices must appear. Idem, please cite Pulcinelli & Perelli who made possible dating the Cima Pedani "Jurassic breccias" from the Eocene. Idem, Rossetti et al 2015, which is directly in your topic. Idem Cavazza et al 2007, and Ferrandini et al 2003 for stratigraphy (see Comment P11).

All the papers suggested by the reviewer are now cited In the paper.

Geological setting: at a larger scale, it seems useful to cite Frizon de Lamotte et al 2011. Also please enlarge the point of view when describing the Hercynian Domain (see Comment P9).

Done.

Please be more clear about the age of the onset of subduction (Comments P4 and P10).

Done, see “Correction paragraph by paragraph”.

On the other hand, the importance of the "CCSZ" is probably exaggerated; the recent structural map by Gueydan et al (2017) does not show this alleged "major" wrench fault, which is not so impressive in the maps and cross-sections of the ms itself.

We believe that the importance of the CCSZ in the studied areas is crucial, as shown in the maps and related cross sections (Figs. 3-6). In Pedani area, it bounds the SW side of the tectonic window through a deformation zone in which pieces of Lower Units, Schistes Lustrés Complex and Upper Units are juxtaposed. In Corte area, the main sinistral strike-slip system of the CCSZ is located toward E and forms structures similar to those of Cima Pedani immediately S of Corte (Botro area, unpublished data); only dextral antithetic faults are recognizable in the map of Fig.4. The Ghisoni area is puzzled by at least two systems of strike-slip faults related to the CCSZ; the lineations found indicate a complex kinematics, with a clear normal sense of shear that predates a strike-slip one. Gueydan et al. (2017) in their interesting work recognized many normal fault systems that roughly fit with the CCSZ, even if some important sectors (e.g. between Caporalino and Corte villages in the valley where the road T20 is located), in which the sinistral strike-slip kinematics is easily observable, are not discussed. In their valid interpretation, that connects the activities of these faults with the deposition of the Miocene deposits, Gueydan et al (2017) did not consider the Francardo Basin (Burdigalian), whose relation with the CCSZ is established by several toher works (e.g. Ferrandini & Loye-Pylot, 1992, Géol.Alpine; Cubelles et al., 1994, Géol. Méditerr. and Malasoma, 2006, Ph.D. thesis).

Being the three areas distant from each other (Pedani and Ghisoni there are ~ 40 km apart), we believe that the CCSZ should have a regional importance in the Oligocene tectonics and, in particular, in the late stage of exhumation of the Lower Units. Unfortunately, data related to the entire CCSZ (structural features, age, …) are missing and thus its role within the Alpine Orogeny in Corsica needs to be fully clarified. For these reason, we have decided to present the CCSZ “on the data scale”, i.e. showing it in the maps and cross sections and briefly interpreting it in the geodynamic evolution of the area.

Moreover, references to the "CCSZ" description are not clear in the ms (comment P8).

According to the comment of the reviewer, the first description of this fault is given by Maluski in 1973, whereas, the name “Central Corsica Fault Zone” was attributed for the first time by Waters, 1990. Thus, all these papers are now cited in addition of Lacombe and Jolivet, 2005.

1) Quite generally, what are the admitted error margins for the Chl-Phg equilibria method for T and P, respectively? (See Comments P31, P33)

Following the recommendation of Vidal and Parra (2000), the error admitted by the Chl-Phg-Qtz-Wt method is of $\pm$ 0.2 GPa and $\pm$ 30°C.

2) Concerning your regional analysis of the subduction, how it is possible to decide that two "phases" occurred during the development of the S1 foliation? In the ternary diagrams of Fig. 8, the clusters of points do not allow us to distinguish two phases. It seems only that we deal with a continuous process. The main foliation is S0+(transposed S1)+S2 (Comment P18).

As described in the text, The S1 foliation is almost completely transposed by the S2 foliation. Only in the hinges zoned of the F2 folds it is possible to recognize relics of S1 foliation preserved within microlithons of S2 foliation. As a consequence, all the selected microareas used for thermobarometric estimations are located where the S1 foliation is optically distinguishable by the S2 foliation, i.e. in the F2 hinges zones. The selection based on the microstructural features (as recommended by Lanari et al., 2014) allowed us to clearly distinguish two foliations (S1 and S2). Through an accurate image analysis of these microareas (i.e. EPMA elemental micromaps), many variations in the phases compositions have been observed within the S1 domain, for example Fe-Mg substitution in chlorite and K-vacancy substitution in phengite. So, we agree with the comments of the reviewer about the identification of two phases during the D1 phase as a continuous process. For this reason, we have discussed in the text the variation of P and T values estimated for the D1 phase as a progressive and continuous process characterized by a P-peak and a T-peak. This feature has been emphasized in the text.

Additional illustrations (micrographs) are needed to support the S2 description (Comments P19-22).

As required by the reviewer, we inserted a new figure showing more in detail the S2 features. For length problems, we inserted it in the Supplementary Material (Fig.1s).

Discussion and Conclusions: The synthesis here proposed should be compared precisely with other synthesis dealing with the same topic, at least for Corsica (Gueydan et al 2017) and for the Western Alps (e.g. Le Bayon et al., 2006, J. Metam. Geol. 24; Manzotti et al 2015, J. Metam. Geol., and ref. therein).

Given the journal's rules we decided to concentrate the contents of our manuscript on our data, avoiding treating topics too wide that would require too long discussion. In addition, the tectonic model proposed by Gueydan et al. (2017) is related to the final (extensional) exhumation of the Alpine Corsica, whereas our paper describes the-subduction/exhumation processes related to the initial (compressional) stages. However, to follow the reviewer's suggestion,-we inserted a new section in the revised manuscript in which some considerations devoted to the comparison with the Western Alps are made.

Corrections paragraph by paragraph

<u>Title</u>

Line 1: substitute "in" with "of".

Done.

<u>Abstract</u>

Line 25: substitute "continental-affinity" with "continental".

Done.

Lines 26 and 27: substitute "alpine" with "Alpine".

Done.

Line 27: remove "lithostratigraphy, the".

Removed.

Line 29: substitute "broad" with "broadly".

Done.

Line 29: remove "and tectonic evolution".

Done.

Lines 30-31: remove "meta".

Done.

Line 33: substitute "indipendently" with "indipendent".

Done.

Lines 34-35: to which transect are you referring?

The words "of the Lower Units stack" have been added to better defined the concept.

<u>Keywords</u>

Line 39: "Lower Units" is not a keyword, I guess. Better add HP metamorphism.

Done, the keyword has been substituted.

1. Introduction

Line 49: add "and subsequent exhumation of granitic and metasedimentary rocks".

Done.

Line 52: substitute "by" with "of" and "from".

Done.

Line 53: add "Lacombe and Jolivet, 2005" and "Frizon de Lamotte et al., 2011".

Done.

Line 54-55: substitute "since Paleocene" with "Eocene". I suggest to change "Paleocene" into "Eocene" (or even "Late Eocene") according to the discussion by Vitale Brovarone and Herwartz 2013 (p. 187) and Rossetti et al 2015 (Lithos). *The latter paper must be cited, it is directly in your topic!* See also Frizon de Lamotte et al., 2011 (Tectonics) for a more general framework.

Done.

Line 56: add "Brunet et al., 2000; (…) Vitale Brovarone et al., 2013; Rossetti et al., 2015; Gueydan et al., 2017". Please avoid to list here only italian researchers from Pisa and Firenze.

Done.

Lines 60-61: remove "new" and substitute "with data from two studied area (Cima Pedani and Corte) (…) located along the thinned European continental margin involved in the Alpine subduction and now exposed in Corsica Island" with "three transects across the western border of the Corsica Alpine tectonic prism, i.e., from north to south (Fig.1), the Cima Pedani, Corte and Ghisoni transects".

Done.

2. Geological setting

Line 66: substitute "can be considered as a boudin" with "is a piece " and "by" with "between". This comparison is inappropriate. A boudin Is stretched longitudinally, and Corsica trasversally…

Done.

Line 68: substitute "This lithospheric boudin preserves" with "The island exposes".

Done.

Line 70: remove "strongly" and "and reworked".

Removed.

Line 71: CCSZ is not defined under this name in Lacombe and Jolivet 2005. Of course, they define this shear zone, after Maluski et al 1973. It seems this fault zone is not taken in consideration by some authors (i.e., Gueydan et al 2017). Anyway, please rephrase (pour "rendre à César ce qui est à César").

Done (see general comments for more explaination). The sentence has been rewritten in this way: "… (CCSZ; Waters, 1990). This tectonic boundary, first described by Maluski et al. (1973), ideally marks the thrust zone of the Alpine Corsica onto the Hercynian Corsica Domain".

Line 74: substitute “Hercynian Corsica Domain, that occupies the south-western portion of the island” with “latter domain”.

Done.

Lines 74-77: (*the Variscan domain*) Not only (*metamorphic rocks*): there are also nonmetamorphic Paleozoic series well described in Rossi et al 2009. Likewise, the post-Variscan cover does not consist only of “sedimentary deposits”: remember the Permian volcanics and clastics. So, please rephrase more exactly this paragraph, probably using two or three sentences instead of only one, which is too long. The most important for a foreign reader is to understand that the Corsica-Sardinia basement was part of the Southern Variscan realm (Matte, 2001).

The paragraph has been rewritten according to the comments of the reviewer.

Line 78: substitute “sector” with “part” and “in analogy” with “Similar”.

Done.

Line 80: change the position of “Molli and Malavieille, 2011”.

Done.

Lines 82 and 101-102: remove “Late Cretaceous”. I agree that subduction began in the Late Cretaceous on the Sesia transect, but this is not so clear in the Corsica transect. Possibly note “Late Cretaceous (?)-Late Eocene

Removed.

Line 83: substitute “the subsequent” and “continental” with “of the European margin. This process was succeeded by the W-dipping subduction of the Adria margin and the incipient collision”.

Done.

Line 85: move “Molli and Malavieille, 2011” and add “Vitale Brovarone and Hewartz, 2013”.

Done.

Line 87: add “related to the Adria slab southeastward retreat”.

Added.

Line 89: remove “before”.

Removed.

Line 92: remove “the”.

Removed.

Line 95: Please also refer to Cavazza et al Basin Res. 2007, and to Ferrandini et al 2003, BSGF. The stratigraphic data are also important!

The references have been uploaded.

Line 96: substitute “geometrical relations” with “reciprocal contacts”.

Done.

Lines 99 and 103: substitute “quoted” with “references therin”.

Done.

Line 102: add “Gueydan et al., 2017”.

Added.

Line 104: substitute “Early Tertiary” with “Eocene”.

Done.

Line 105: reorder the references.

Done.

Line 106: substitute “2017a; 2017b” with “2016; 2017”.

I think there has been a misunderstanding. There are two Di Rosa et al., 2017: the first is published in the Geol. J., that was already available online in 2016 but in fact it has been published in 2017; the second one is those of the J. of Maps, always published in 2017. For this reason we refer “Di Rosa et al., 2017a“ to the paper of the Geol. J. and “Di Rosa et al., 2017b” to the paper of the J. of Maps (text+map). There is no Di Rosa et al., 2016.

Line 112: add “Gueydan et al., 2017”.

Added.

3. <u>Methods</u>

Lines 116-119: The BRGM maps have been probably important when you began there, isn’t it?

Yes, they were. The BRGM maps are now cited in the text.

Line 123: remove “(Fig.2)” and substitute “EPMA analysis with “Electron probe microanalysis… apparatus”.

Done.

4. <u>Tectono-metamorphism and stratigraphy of the Lower Units in the Cima Pedani, Corte and Ghisoni areas</u>

    4.1 <u>Tectono-stratigraphy</u>

Line 141: remove “sedimentary”.

Removed.

Lines 144, 466: remove “(Figs.1 and 3; Di Rosa et al., submitted”. Not accepted reference. Please delete from the Reference list, which must contain only published or accepted titles.

Removed.

Line 148: substitute “by” with “of” and add “covered”.

Done.

Line 149: add “in turn”.

Added.

Line 150: move “the”.

Moved.

Line 150, 162, 164, 165, 168: Fms." with capital letter.

Substituted.

Line 153: remove "the".

Removed.

Line 157: remove "Fig. 4".

Removed.

Lines 157, 298, 299, 351: 2016b (the map itself) is not referenced in the Reference list. In fact, it is useful to distinguisch a and b, since b (the map) is merely supplementary material of a.

See comment on line 106.

Line 158: I would prefer "Slivers" as an equivalent to "Ecailles". Please check, or leave " Ecailles de Corte". Anyway, this is not important for me...

"Corte Slices" has been substituted with "Ecailles de Corte".

Line 159: substitute "Hercynaian" with "Hercynian".

Done.

Line 165: moove "overlies".

Moved.

Line 168: remove "the".

Removed.

Line 176: remove "the".

Removed.

Line 178: substitute "metagranitois" with "metagranitoids".

Done.

4.2 Structural analysis

Line 184: remove "Since the geometrical features of the different structural elements are similar in each unit, the features of each phase are presented in a dedicated paragraph". Unclear, not useful. Substitute with "described in the following sub-sections".

Done.

Line 200: In Fig. 7a, I think the main foliation of the rock cumulates S0+S1+S2, except in the P2 hinges (more or less your fig. 7b) and likely in S2 microlithons along the limbs, where S1 is mostly transposed in S2. So you can use "S0+S2" for the main foliation at the macroscopic scale, keeping in mind the above remarks.

Done.

Line 207: add "The D2 phase is responsible for", "this phase" and "also".

Added.

Line 209: We would appreciated an illustration, this is important.

A supplementary figure with meso and micrograph has been added to the supplementary material (Fig.1s).

Line 210: remove “Fig. 7b”.

Removed.

Line 212: substitute “that” with “than”, “both” with “either”, “and” with “or” and “Analogous to” Together with”.

Done.

Line 213: substitute “plane” with “planar”.

Done.

Line 213: remove “Fig. 7a”.

Removed.

Line 213: substitute “it dips variably to W and E” with “showing dips either to W or E”.

Done.

Line 215: remove “a”.

Removed.

Lines 217-218: Here again, a microphotograph would have been appreciated.

A supplementary figure with meso and micrograph has been added to the supplementary material (Fig.1s).

Lines 222, 228: Reference, please.

The reference “Passchier and Trouw, 2005” has been added.

Lines 223: Illustrations, please.

A supplementary figure with meso and micrograph has been added to the supplementary material (Fig.1s).

Line 223: remove “and” and substitute “fish” with “fishes”.

Done.

Line 230: substitute “wrap” with “wraps”.

Done.

Line 234: substitute “ration” with “ratio”.

Done.

Lines 235: Compared to what in the other units?

The sentence has been rephrased: “The strongest aspect ratio (Rxz) and parallelism are observed in GHU, where quartz and feldspar reached Rxz max = 13:3 and 9:3, respectively.”.

Lines 242: Bulging: wht’s that?

Bulging recrystallization, or low temperature grain boundary migration, is the process with which grain boundaries bulge into the new crystal with high dislocation density and form new, independent small crystals. Please see Microtectonics of Passchier and Trouw, 2005, p.42.

Lines 243: How did you estimate quartz lattice orientation?

With the optical microscope using the lambda plate. "determined with lambda plate inserted in an optical microscope" has been added to the text.

Lines 244: Figure is lacking for this point.

A supplementary figure with meso and micrograph has been added to the supplementary material (Fig.1s).

Lines 249: more precisely?

"<400°C" has been added.

Lines 250: Why S-C' and not S-C? Here again these details are not illustrated with appropriate figures.

A supplementary figure with meso and micrograph has been added to the supplementary material (Fig.1s).

Line 256: substitute "to a" with "with".

Done.

4.3 P-T equilibrium conditions

Lines 269: Please develop the mineralogical abbreviations somewhere. What about the intermediate compositions??? Did you really tries to randomly measure proportions all over the thin sections? I guess you simply choosed the areas to analyse according to the structural pertinence. So Please rephrase.

The sentence has been rephrased.

Lines 275, 276, 287, 293: substitute "grew" with "grown".

Done.

Line 278: remove "Fig. 8a,b".

Removed and "See supplementary material" has been added.

Line 282: Please indicate the accepted error margin.

"(according with Vidal and Parra (2000), the admitted error for P and T calculated with this method is 0.2 GPa and 30°C, respectively)" has been added.

Lines 282: substitute "calculates" with "allows us calculating".

Done.

Lines 284: substitute "three" with "we measured (…) from different chlorite-phengite couples in order to".

Done.

Lines 286: add "of recrystallization".

Added.

Lines 287, 294: How can you recognize two generations in the same S1 micas and chlorite? Please explain more clearly your rationale. Why not a continum?

See in general comment section “2)”.

Lines 290: tendency: which one?

“tendency” has been substituted with “the three equilibrium conditions”.

Lines 293: substitute “articulated” with “complicated”.

Done.

Lines 294: substitute “grew along” with “associated with” and “generation” with “generations” and added “foliation”.

Done.

Line 299: remove “of”.

Removed.

Lines 302: substitute “grew along” with “related to”.

Done.

Line 303: remove “Table 1”.

Removed.

5. Discussion

5.1 Stratigraphy

Lines 309-311: What did they consider that you do not accept? Please be more precise.

A sentence about this point has been added.

Line 312: substitute “lacking” with “lack”.

Done.

Line 314: substitute “covers” with “sequence”.

Done.

Line 316: This paragraph is merely the repetition of the Geological setting. This reconstruction is quite classical, indeed. Please rather discuss Amaudric du Chaffaud interpretation more precisely – and other interpretations if any.

“In our reconstruction” has been substituted with “As postulated by Durand-Delga (1984)”. As regard Amaudric du Chaffaut please see the comment on lines 309-311.

Line 320: remove “unconformably above the Variscan cycle”.

Removed.

Line 324: substitute “continue” with “continues”.

Done.

Line 330: substitute “unconformably” with “unconformable”.

Done.

Line 333: substitute “by” with “from”.

Done.

Line 335: substitute “to” with “toward”.

Done.

5.2 The Lower Units from subduction to exhumation: the D1 and D2 phases

Line 340: add “Fig. 9”.

“Fig.8” has been added.

Line 340: remove “strongly”.

Removed.

Line 342: remove “a” and “by”.

Removed.

Line 344: add “the earlier D1”.

Added.

Line 345: add “only”.

Added.

Line 346: substitute “chlorites and phengites” with “chlorite” and add “-“.

Done.

Line 349: substitute “and” with “or”.

Done.

Line 350: substitute “unit” with “units”.

Done.

Line 351: substitute “what documented in Corte” with “those documented in the Corte area”.

Done.

Line 353: substitute “grown” with “growth of the” and add “occurred”.

Done.

Line 354: add “and” substitute “implying” with “This implies”.

Done.

Line 356: substitute “chlorites and phengites” with “chlorite and phengite” and remove “and it is in equilibrium.

Done.

Line 357: substitute “were” with “have been”.

Done.

Line 360: substitute “indicate” with “indicates”.

Done.

Line 362: remove “c.”.

Removed.

Line 363: add “the” and “the”.

Done.

Line 364: Assuming what thermal gradient?

“that assuming an average crustal geobaric gradient of 30 MPa/km (Best, 2003) is estimated from c. 27 to c. 4.3 km.” has been added.

Line 367: substitute “with the obtained for GHU” with “to the GHU”.

Done.

Line 368: add “laid”.

Added.

Line 369: remove “Corsica”.

Removed.

Line 373: remove “from deepest to shallower structural levels”.

Removed.

Line 378: substitute “(i.e. …)” with “from the”.

Done.

Line 379: add “the overlying”, “to the equivalent PPU from the Corte area” and “-“.

Added.

Line 381: remove “CAU and PEU” and add “temperature”.

Done.

Line 382: substitute “at” with “by”.

Done.

Line 382: add “However”.

Added.

Line 384: unclear. What is a re-cooling of a gradient?

The sentence has been rephrased: “that implies the re-cooling of CAU”.

Line 385: substitute “with” with “to” and add “to”.

Done.

5.3 <u>The final stage of exhumation of the Lower Units: the D3 east-verging deformation</u>

Line 399: Please recall which ones.

“The crystallization of only calcite” has been added.

Line 400: About how much km?

“shallow” has been substituted with “at depth at most 10 km”.

Line 406: substitute “Since” with “The” and “were” with “has been”.

Done.

Line 407: substitute “during” with “and dated from”

Done.

Line 408: add “In line with these authors”.

Added.

Line 410: substitute “anticlockwise rotation of the Corsica-Sardinia block” with “Adria roll-back”

Done.

Line 410: remove “Brunet et al., 2000”.

Removed.

Line 411: “combining” is not explained clearly. Please clarify your rationale.

The entire paragraph has been rephrased and the rationale has been explained.

Line 414: Southern only?

“southern” has been substituted with “south-western”.

6. Conclusions

Line 578: remove “crucial”.

Done.

Lines 580-581: add “Lower Units of the Alpine Corsica tectonic prism from the”.

Done.

Line 583: “… evolved from shallow to pelagic marine to a foredeep, from Triassic to Late Eocene” is unclear and poorly informative; the erosion of the bulge is overlooked.

This sentence has been modified according to the comments of the reviewer.

Line 590: substitute “anticlockwise rotation of the Corsica-Sardinia block” with “Adria slab roll-back”.

According to the comments of reviewer 2 we have deleted the sentence.

Acknowledgements

Line 596: substitute “italian” with “Italian”.

Done.

References

The reference of the papers suggested (Cavazza et al., 2007; Ferrandini et al., 2003; Frizon de Lamotte et al., 2011; Matte, 2001; Puccinelli et al., 2012; Rossetti et al., 2015; Rossi et al., 1994; 2012) has been added.

Line 617: substitute “2017a” with “2016”.

See the answer to the comment of Line 138.

Line 620: substitute “2017b” with “2017a”.

See the answer to the comment of Line 138.

Line 623: A submitted paper is not a Reference. You have to wait for its potential acceptance to cite it here. Better avoiding to draw attention on this coeval publication on the same topics...

This reference has been deleted from the text and the reference's list.

Line 635: substitute "Rotation" with "rotation".

Done.

Line 641: substitute "Pyreneeses" with "Pyrenees".

Done.

Line 691: Please considered also the paper by Vitale Brovarone et al., 2012 in Earth Sci.Rev., 116, 35-56.

We added "and reference therein" to Vitale Brovarone and Hewartz, 2013 at line 57.

Captions

Line 702: substitute "cross" with "cross-" and add reference.

Done. The reference required has been added.

Line 704: remove "Di Rosa et al., submitted".

Removed.

Line 729: substitute "Field" with "Mesoscopic" and "occurrence" with "aspects".

Done.

Line 730: What kind of rock? Please explain the mineralogy of the white/grey layers. I think the main foliation of this rock cumulates S0+S1+S2, except in the P2 hinges (your fig. 7b). However, in the elongated and flatenned limbs of these folds, S1 is transposed in S2. So you can use "S0+S2", keeping in mind the above remark.

The sentence has been modified in this way: "Macrophotograph of S0+S2 foliation in the Metabreccia Fm. (CPU, Corte area),…". "S0+S1" has been removed from the Fig.7a and substituted with "F2".

Line 732: from which rock, from what part of its structure?

The words "microlithon in the F2 hinge zone of the Metasandstone Fm., PPU, Corte area, sample CM32C." have been added.

Line 746: remove "CAU, PEU and SCU are after Di Rosa et al., submitted), those of".

Removed.

Line 747: substitute "2017a" with "2016" and explain Bs and Gs.

Regarding the citation, see the answer to the comment of Line 138. Bs and Gs are now explained in the reference of the new Fig.8 (ex Fig.9).

Figures

Fig.1 Please enlarge a bit the insert, delete the political indication Italy and instead add the Alpine belt.

Done.

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REVIEWER 2 – JAQUES MALAVIEILLE

Corrections paragraph by paragraph

2. Geological setting

Line 66: substitute “boudin” with “piece”.

Done.

Line 103: add “Mattauer et al., 1981; Faure and Malavieille, 1981”.

Done.

4. Tectono-metamorphism and stratigraphy of the Lower Units in the Cima Pedani, Corte and Ghisoni areas

4.1 Tectono-stratigraphy

Lines 132-135, 143, 145, 146, 146, 156, 160, 161, : all the formational names and Fm./Fms. (capital letter) have to be checked.

Done.

Line 171: “metagabbros” emplaced in the continental crust? Or in the hyperextended margin?

“within the continental crust” has been added.

4.2 Structural analysis

Line 177: substitute “analogous” with “similar”.

Done.

Line 205: substitute “range” with “ranges”.

Done.

Line 239: substitute “shape preferred orientation” with “shape of preferred orientation”.

The sentence has been substituted with the more correct form: “…the preferred orientation of grain shape..”

Line 252: substitute “plain” with “plane”.

Done.

Line 259: substitute “phyllosilicates” with “phyllosilicate”.

Done.

4.3 P-T equilibrium conditions

Line 266: substitute “respect to” with “with respect to”.

Done.

Line 288: substitute “generation” with “generations”.

Done.

5 Discussion

5.1 Stratigraphy

Line 303: remove “by” before Amaudric du Chaffaut et al.

Done.

Line 322: substitute “in Alps” with “in the Alps”.

Done.

5.2 The Lower Units from subduction to exhumation: the D1 and D2 phases

Line 343: the concept “subduction channel” must be clarified in the relation with your Alpine setting.

Done.

Line 345: substitute “documented” with “is documented”.

Done.

Line 346: substitute “generation” with “generations”.

Done.

5.3 The final stage of exhumation of the Lower Units: the D3 east-verging deformation

Lines 402-404. I am not certain that overthickening of the Corsican wedge is the driving mechanism for the extensional regime during Oligocene. Extensional tectonics is mainly driven by the slab rollback and allows the belt to collapse. As the belt was probably immature and narrow in Corsica, buoyancy forces stored in the crust by over thickening was probably insufficient to induce extensional collapse… this paragraph need to be clarified.

The sentence about the mechanism that driven the extensional tectonics has been modified according to the comments of the reviewer. We have not inserted a complete discussion about the exhumation because a complete discussion about this point requires a more complete (and long….) paragraph.

References

All the corrections reported by the reviewer (Lines 437, 438, 441, 443, 461, 491) have been done.

The reference of the two papers suggested (Line 103) has been added.

Captions

Line 537: substitute “are also” with “is”.

Done.

Lines 560 and 561: substitute “modify” with “modified”.

Done.

Line 582: “CDU” is not in the figure.

“CDU” has been removed from the caption.

Figures

Fig.2: insert “extended margin”, “W and E” and “oceanic domain”. Add “approximate scale”.

Doen

Figs. 3-5: the text in the legend is too small, as well as the cross section traces.

The text of the three legends and the cross sections traces have been enlarged.

Fig.9: stacking before final exhumation?

Yes. The sentence “The stacking of the Lower Units occurred in the Late D2 phase” has been added to the caption of this figure.

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*Manuscript

Tectono-metamorphic evolution of the European continental margin involved in the Alpine subduction: new insights from the Alpine Corsica, France.

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ABSTRACT

In Corsica, continental units (the Lower Units) affected by high-pressure metamorphism represent the remains of the European margin deformed during the Alpine orogeny. In order to document how Alpine deformation and metamorphism changed along the European margin involved in the Alpine subduction, we selected three key areas: Corte, Cima Pedani and Ghisoni transects. The three transects show a broadly similar lithostratigraphy. They are characterized by a Variscan basement intruded by Permo-Carboniferous metagranitoids, and by a sedimentary cover including Mesozoic carbonates and Middle to Late Eocene breccias and sandstones. The three transects recorded a similar deformation history with three deformation phases. Thermo-baric estimations instead, reveal that each unit was exhumed along an independent retrograde path within the orogenic Alpine wedge. In particular, the lowest units of the Lower Units stack were exhumed along an isothermal path whereas those located at upper structural levels experienced progressive heating.

Keywords: Continental subduction, polyphase exhumation, P-T-d paths, HP metamorphism, Alpine Corsica

1. Introduction

The exposure at the earth's surface of continental units affected by (ultra-) high pressure (U)HP metamorphism indicates that continental crust can move along the plates interface reaching depth greater than 50 km (Guillot et al., 2009 and references therein). The preservation of these units testifies the crucial role played by subduction processes in the growing and recycling of continental crust and help to solve fascinating and challenging problems, such as the understanding of the tectonic processes responsible for the subduction and subsequent exhumation of granitic and metasedimentary rocks.

The Alpine Corsica, cropping out in the north-eastern sector of the Corsica Island, is a key area to studying continental-derived units affected by HP metamorphic conditions. The Alpine Corsica is made of continental- and oceanic-affinity units, derived from the thinned European margin and the Western Tethys Ocean (Durand-Delga, 1984; Lacombe and Jolivet, 2005; Malasoma et al., 2006; Molli et al., 2006, Frizon de Lamotte et al., 2011), buried during the Eocene subduction of the European margin and subsequently affected by syn-convergent exhumation (Brunet et al., 2000; Malasoma and Marroni, 2007; Molli and Malavieille, 2011; Vitale Brovarone and Herwartz, 2013 and references therein; Rossetti et al., 2015; Gueydan et al., 2017).

To constrain the processes responsible for the continental crustal recycling and the exhumation of HP rocks and to understand how (and if) these processes change along the continental margin, we compare tectono-metamorphic and stratigraphic data from three transects across the western border of the Corsica Alpine tectonic prism, i.e. from north to south (Fig. 1) the Cima Pedani, Corte and Ghisoni transects.

2. Geological setting

The Corsica Island is a piece of continental lithosphere isolated between two Tertiary back-arc basins: the Liguro-Provençal basin, to the west, and the Tyrrhenian basin, to the east. The island exposes two geological domains separated by NNW-SSE-trending tectonic boundary (e.g. Durand-Delga, 1984): the Alpine and the Hercynian Corsica domains. Although locally obliterated by the Late Eocene - Early Oligocene sinistral strike-slip fault zone (Maluski et al., 1973), known as the Central Corsica Shear Zone (CCSZ; Waters, 1990), this tectonic boundary ideally marks the thrust zone of the Alpine Corsica onto the Hercynian Corsica Domain (Fig. 1).

The latter domain, that is widely exposed in the south-western of the Corsica and in the Sardinia islands, represents the Southern Variscan realm (Matte, 2001). It consists of Pan-African and Variscan metamorphic rocks (Rossi et al., 2009) intruded by Permo-Carboniferous magmatic rocks. The Permo-Mesozoic covers are represented by Permian rhyolites, volcanics and volcanoclastics and sedimentary deposits (conglomerates, arenites and pelites, Rossi et al., 2009) and Mesozoic carbonates, unconformably topped by Middle to Late Eocene deposits (Durand-Delga, 1984).

The Alpine Corsica is exposed in the north-eastern part of the island. In analogy to the Western Alps, it consists of a stack of units derived from the Ligure-Piemontese oceanic basin and the neighbouring Adria and Europe continental margins (Durand-Delga, 1984; Molli and Malavieille, 2011; Maggi et al., 2014; Marroni et al., 2017; Saccani et al., 2015). These units are metamorphosed and deformed during the Late Cretaceous (?)-Late Eocene E-dipping subduction of the Ligure-Piemontese oceanic lithosphere and of the European margin. This process was succeeded by the W-dipping subduction of the Adria margin and the incipient continental collision (Malavieille et al., 1998; Marroni et al., 2004; Molli and Malavieille, 2011; Vitale Brovarone and Herwartz, 2013; Marroni et al., 2017). In the Early Oligocene, the convergence-related processes were replaced by large-scale extension related to the Adria slab south-westward retreat that induced the collapse of the thickened orogenic wedge, as well as the opening of the Liguro-Provençal basin and then of the Tyrrhenian (Brunet et al., 2000; Gueydan et al., 2017).

The present-day tectonic setting of the Alpine Corsica Domain consists of a stack of three groups of tectonic units known as, from top to bottom, the Upper Units, the Schistes Lustrés Complex and the Lower Units (Durand-Delga, 1984; Malavieille et al., 1998; Molli and Malavieille, 2011; Pandolfi et al., 2016). The Miocene (Burdigalian–Langhian) deposits of the Saint-Florent and Francardo basins (Cavazza et al., 2001; 2007; Ferrandini et al., 2003) seal their reciprocal contacts.

The very low-grade metamorphic Upper Units (i.e., Nappes supérieures of Durand-Delga, 1984), include Middle to Late Cretaceous ophiolitic units associated with slices of Late Cretaceous carbonate turbidites (Pandolfi et al., 2016 and references therein). The Schistes Lustrés Complex consists of ophiolitic and oceanic-continental transitional sequences deformed under eclogite to blueschists facies conditions during Late Cretaceous (?) to Late Eocene subduction (Vitale Brovarone and Herwatz, 2013; Gueydan et al., 2017 and references therein). The Lower Units represent fragments of the European margin affected by Late Eocene HP-LT metamorphism acquired during their subduction below the Adria margin (Mattauer et al., 1981; Faure and Malavieille, 1981; Bezert and Caby, 1988; Malasoma and Marroni, 2007; Molli and Malavieille, 2011; Di Rosa et al., 2017a, 2017b).

The stack is lately affected by the brittle deformations related to the CCSZ (Lacombe and Jolivet, 2005; Di Rosa et al., 2017a), and during the Early Miocene time, the Alpine Corsica underwent a generalized extension (Cavazza et al., 2001; Danisik et al., 2007) leading to the development of basins, like those of Francardo and Saint-Florent (Fig. 1). The ramp-flat geometry of the normal faults is responsible of large-scale rollover anticlines and synclines, probably like that documented in the Castagniccia dome (Gueydan et al., 2017).

3. Methods

The 1:50,000 scale geological maps published by BRGM, France (Rossi et al., 1994; 2012) were used as a first cartographic base for geology of the Cima Pedani, Corte and Ghisoni regions objects of this study (see the Corte and Bastelica sheets of the BRGM maps database). Detail geologic mapping (scale 1:5,000) was achieved during our work in the three areas, coupled with mesoscopic structural analyses were conducted in the three areas. Detailed microstructural investigations were performed on metapelites and on late Variscan metagranitoids. P-T conditions were estimated using the chlorite-phengite multi-equilibrium thermodynamic technique (Vidal and Parra, 2000) for each tectonic unit. The Electron probe microanalysis analyses were acquired on the JEOL JXA apparatus of the IsTerre (Grenoble, France) equipped with five wavelength-dispersive spectrometers and treated with XMapTools 2.1.3 (Lanari et al., 2014) and ChlMicaEqui softwares. We estimated the P and T conditions for phengite-chlorite pairs grown in different microstructural domains elaborating pressure-temperature-deformation paths for each tectonic unit. To corroborate our results, we also used classical geobarometer and geothermometers (See Supplementary Material).

4. Tectono-metamorphism and stratigraphy of the Lower Units in the Cima Pedani, Corte and Ghisoni areas

4.1. Tectono-stratigraphy

The Lower Units consist of Variscan metamorphic rocks (i.e., Roches Brunes Fm.) and Permo-Carboniferous magmatic and volcanics products (metagranitoids and Metavolcanic and Metavolcaniclastic Fm., Fig. 2). The post-Paleozoic sequence consists of Mesozoic platform-type metacarbonates and Middle to Late Eocene metasandstones and metabreccias, unconformably lying on both the Variscan basement and the Permo-Mesozoic sequence (Fig. 2).

4.1.1. Cima Pedani area

In the Cima Pedani area, the Lower Units (Canavaggia Unit - CAU, Pedani Unit - PEU and Scoltola Unit - SCU) crop out in a tectonic window delimited by the Schistes Lustrés Complex (i.e., Lento Unit - LEU) and the Upper Units (i.e., Serra Debbione Unit - SDU and Pineto Unit - PIU) (Figs. 3 and 6).

CAU is made of metagranitoids intruded in the Roches Brunes Fm., covered by the Permian metavolcanics and metavolcaniclastics, in turn unconformably covered by the Metabreccia and Metasandstone Fms. (Fig. 2, Puccinelli et al., 2012). The Mesozoic sequence is missing in CAU whereas in the PEU, it is well represented at the top of the Permian Metavolcanic and Metavolcaniclastic Fm. (Fig. 2). The SCU is represented exclusively by the Metasandstone and Metabreccia Fms..

4.1.2. Corte area

In the Corte area (Figs.1, 4 and 6; Rossi et al., 1994; Di Rosa et al., 2017a; 2017b), the Lower Units (i.e., the "Ecailles de Corte": Castiglione-Popolasca Unit - CPU, Croce d'Arbitro Unit - CDU and Piedigriggio-Prato Unit - PPU) are sandwiched between the Hercynian Corsica Domain and the Schistes Lustrés Complex (i.e., Inzecca Unit - IZU). The CPU is made by Mesozoic dolostones to limestones lying above the Roches Brunes Fm. and unconformably covered by the Metabreccia and Metasandstone Fms. (Fig.2). In the CDU, the Variscan basement is topped by the Permian Metavolcanic and Metavolcaniclastic Fm. and by the Mesozoic sequence (i.e., Laminated Metalimestones Fm.). The Metabreccia and the Metasandstone Fms. overlies unconformably both the Paleozoic and Mesozoic Fms. The PPU has the more complete succession (Fig. 2). It consists of the Roche Brunes Fm., the Permian Metavolcanic and Metavolcaniclastic Fm., a complete Mesozoic succession and the Metabreccia and Metasandstone Fms. Moreover, the Middle Eocene angular unconformity crosscut the Mesozoic sequence down to the Norian Metadolostone Fm. (Fig. 2).

4.1.3. Ghisoni area

In the Ghisoni area (Figs. 1 and 5; Garfagnoli et al., 2009), the Lower Units are sandwiched between the Hercynian Corsica Domain and the Schistes Lustrés Complex (i.e., Inzecca Unit - IZU) and are strongly overprinted by the CCSZ (Fig. 6). They are represented by the Ghisoni Unit (GHU) that consists from bottom to top by: the Roches Brunes Fm., the epidote-bearing metagabbros (emplaced within the continental crust during the oldest Permo-Carboniferous intrusive pulse), the late Paleozoic metagranitoids and the Permian Metavolcanic and Metavolcanoclastic Fm. (Fig. 2).

4.2. Structural analysis

In the studied transects, the Lower Units recorded a similar deformation history with three deformation phases (D1- D3) described in the following sub-sections. The microscopic description of foliations was performed taking as reference the Permian Metavolcanic and

Metavolcaniclastic Fm. and the metapelitic layers in the Eocene Metabreccia and Metasandstone Fms., where the P-T paths were calculated, whereas quartz microstructures were investigated in the Permo-Carboniferous metagranitoids.

In the field, the pervasive foliation documented in the metagranitoids is parallel to the main foliation documented in the post-Variscan covers (i.e., the S2 foliation). As a consequence, we described the meso and microscopic feature of the metagranitoids foliation within the D2 phase section.

Considering the goal of this paper, the data presentation and their discussion will be focused on the three deformation phases documented in the field. Post-D3 tectonics is not described and discussed.

4.2.1. D1 phase

The structural elements produced during the oldest deformation phase (D1) are rarely observable at the mesoscale. They are represented by F1 sheath folds in Laminated Metalimestone Fm. and by an S1 foliation preserved in the hinge zones of F2 folds (Fig. 7a, 7b). At the microscopic scale, S1 foliation is often preserved within D2 microlithons as a continuous, coarse-grained schistosity marked by the syn-kinematic growth of chlorite, phengite, albite, quartz and calcite (Fig. 7b). No relics of an earlier foliation were documented within D2 microlithons in the metagranitoids.

4.2.2. D2 phase

The D2 phase is responsible for the main structural elements documented at the mesoscale (Fig. 7). This phase produced F2 isoclinal and similar folds associated to a S2 axial plane foliation, and also top-to-W shear zones, located within the units or close to the tectonic contacts between them. The trend of the A2 axes ranges from NE-SW in Cima Pedani area

(Fig. 3), to NNE-SSW in the Corte area (Fig. 4) and to SE-NW in the Ghisoni area (Fig. 5), always plunging less than 30° either toward N or S. Together with the A2 trending axes, the S2 axial planar foliation changes from NE-SW in Cima Pedani area, to NNE-SSW in Corte area and to NNW-SSE in Ghisoni area, showing dips either to W or E probably as a result of later D3 folding. The S2 foliation bears mineral and stretching L2 lineations that generally show a rough E-W trend with variable plunge. Along the limbs of the F2 folds, the S2 foliation is classified as a continuous foliation whereas in the hinge zone of F2 folds, it can be classified as a gradational to discrete spaced crenulation cleavage.

The S2 foliation represents the main structural element documented at the microscopic scale (Fig. 7b, d). In metapelites it is marked by recrystallized albite, quartz, calcite, chlorite and phengite. Within the D2 shear zone, metamorphic phyllosilicates fill asymmetric tails of σ and δ type porphyroclasts (Passchier and Trouw, 2005) of quartz and feldspar pointing to a top-to-W sense of shear. Additional kinematic indicators are S-C/C' fabrics, mica fishes and bookshelf structure in feldspar.

Metagranitoids samples from CAU (Cima Pedani), CPU (Corte area) and GHU (Ghisoni area) have the same protoliths consisting of quartz + k-feldspar + plagioclase + white micas (±biotite). They show poorly developed protomylonitic fabrics in the CAU and protomylonitic to ultramylonitic fabrics (Passchier and Trouw, 2005) in CPU and GHU. Discontinuous layers of recrystallized white mica (up to 100 μm) ± biotite, and granoblastic layers of fine-grained recrystallized quartz ± plagioclase (albite) mark the mylonitic foliation. It generally wraps cm-sized feldspars and quartz grains, aggregates of quartz + feldspar, and lenses of very fine-grained (less than 6 μm) recrystallized quartz and feldspar. In CPU, feldspar and quartz grains show nearly sub-euhedral geometry whereas in CAU they are weakly elongated with the main axis parallel to the mylonitic foliation. The strongest aspect ratio (Rxz) and parallelism are observed in GHU, where quartz and feldspar reached Rxz max = 13:3 and 9:3, respectively.

In CAU, quartz and feldspar crystals often show angular shape and reduction grain size produced by microcraking and microfaulting indicative of a late to post-foliation cataclastic event. Calcite crystals filling syn-tectonic veins, show type IV deformation twins (Ferrill et al., 2004) indicative of deformation temperatures greater than 250°C.

In GHU and CPU, cm-sized quartz crystals are affected by undulatory extinction, deformation lamellae, deformation bands (developing frequently as conjugate sets) and bulging (e.g. Passchier and Trouw, 2005). The biggest crystals show conjugate bands of recrystallized grains (4-8 μm) oriented at low- and at high-angle respect the mylonitic foliation. Crystal preferred orientation, determined with lambda plate inserted in an optical microscope, is weak and the preferred orientation of grain shape is limited to the asymmetric tails in σ- porphyroclasts. Locally, quartz crystals are strongly elongated and partly recrystallized indicating that incipient subgrain rotation recrystallization mechanisms occurred. Rare deformation twins are also present. These microstructures indicate that dislocation creep represents the main deformation mechanism in quartz during the development of the main foliation, suggesting deformation temperature of ~400°C. Feldspar shows features typical of low-temperatures conditions (<400°C) such as undulatory extension, microfaulting and boudinage. S-C' fabric, σ-type porphyroclasts of feldspar showing asymmetric tails of recrystallized quartz and/or white micas, and bookshelf structures in feldspar represent the main kinematic indicators pointing to a top-to-W in both GHU and CPU.

4.2.3. D3 phase

The D3 phase produced open to close gently inclined F3 folds associated with a spaced and sub-horizontal S3 axial plane foliation (Fig. 7c). The A3 axes trend changes in the studied transects from ENE-WSW in the Cima Pedani area to NNE-SSW in the Corte and Ghisoni areas. At the mesoscopic scale, F3 folds affected both the tectonic contacts within the Lower Units and those separating the Lower Units from the Schistes Lustrés Complex and the Upper Units (Fig. 6). At the microscopic scale, the S3 foliation can be classified as spaced crenulation cleavage associated to minor metamorphic recrystallizations of calcite, Fe-oxides and quartz. In the metagranitoids, D3 phase was documented exclusively in the thicker phyllosilicate rich-layers as symmetric microfolds (Fig. 7d).

4.3. P-T equilibrium conditions

4.3.1. Chlorites and phengites characterization

The chlorite (Chl) and phengite (Phg) end-members proportions in the analysed micro-areas of the samples are reported in the Supplementary Material. All the samples are characterized by Chl enriched in the clinochlore (Cl) and daphnite (Da) end-members. Chl in CAU, PEU and SCU show a higher amesite (Am) content with respect to the other units, suggesting that they have reached higher temperature conditions (Vidal et al., 2001). In all the studied samples, Phg composition is intermediate between celadonite (Ce) and muscovite (Mu) end-members, with a pyrophyllite (Py) content always lower than 35%, suggesting high P conditions (Vidal and Parra, 2000). The composition of the Phg grown along the S1 ranges between Ce and Mu end-members of 40-60% and 30-60% respectively; whereas those grown along the S2 foliation are characterized by an increasing Py content observable in all the units. Inside this general trend, several small-scale differences in end-members proportions can be recognized.

4.3.2. Multi-stepped P-T paths

The Chl-Phg-quartz-water multiequilibrium method (Vidal and Parra, 2000) allows us calculating the P-T equilibrium condition for each selected couple of Chl-Phg (according with Vidal and Parra (2000), the admitted error for P and T calculated with this method is 0.2 GPa and 30°C, respectively). In all the analysed samples, we measured different equilibrium conditions from different Chl-Phg couples in order to determined: (1) the baric (P-max) peak, (2) the thermic (T-max) peak and (3) the lower P-T conditions of recrystallization. The P-max and T-max conditions are obtained from two different generations of Chl and Phg grown along the S1 foliation, whereas the couples of Chl and Phg in equilibrium at lower P-T conditions grown along the S2 planes.

Although the three equilibrium conditions have been observed in all samples, the absolute P and T estimates in each sample vary in a range of 0.3 GPa and 100°C (See Supplementary Material). The P-T-d (pressure-temperature-deformation) paths obtained for each unit show two different trends: a straight path (GHU and CPU) and a more complicated trend (PPU, SCU, CAU and PEU) (Fig. 8). In GHU, the two generations of chlorite and phengite associated with the S1 foliation are in equilibrium at P = 0.81-0.72 GPa and T = 245-250 °C and at P = 0.68-0.39 GPa and T = 263-243 °C, respectively. In CPU, the first generation is in equilibrium at P = 1.22-1.10 GPa and T = 250-330°C whereas the second at P = 0.82-0.56 GPa and T = 320-350 °C (Fig. 8) (Di Rosa et al., 2017a). The rest of the units are characterized by variable P-T conditions related to the P-peak and a subsequent reverse trend of increasing of T and decreasing P. The differences between the samples in the P-T conditions related to the T-peak are smaller than those of the P-peak. The evolution from the second generation (i.e., T-peak) and the third generation (i.e., related to the S2 foliation) of Chl-Phg couples is associated with an abrupt cooling of ca.100°C.

5. Discussion

5.1. Stratigraphy

Differently from the lithotypes classification of Amaudric du Chaffaut et al. (1983) who defined a different stratigraphy in each study-area, we propose a unique stratigraphic evolution during the Permian - Late Eocene time span along the European margin. Minor differences within the units are mainly due to (Fig. 2): (1) the presence/lack of the Variscan basement and the Permian sediments, (2) the presence/lack of the Mesozoic sequence, (3) if present, the thickness of the Mesozoic sequence (4) if present, the thickness of the Middle to Late Eocene sequence and the position of the angular unconformity at its base.

As postulated by Durand-Delga (1984), the entire European continental margin is characterized by two main sedimentary cycles divided by a regional angular unconformity: the Variscan cycle and the Alpine cycle. The former consists of Devonian to Early Carboniferous low- to medium grade metamorphic rocks (i.e., the Roches Brunes Fm. *Auctt*). The Alpine cycle is characterized by two stratigraphic sequences, separated by an angular unconformity located at the base of Middle Eocene. The older sequence starts with the intrusion of the Permo-Carboniferous monzogranites and the deposition of Permian volcanics and volcaniclastic sediments (Metavolcanic and Metavolcaniclastic Fm.) and continues with the deposition of Jurassic-Triassic carbonate sequences. The younger alpine cycle instead, is represented by the Eocene foredeep sequence (i.e., Metabreccia and Metasandstone Fms.) crosscutting not only the carbonates of the first cycle, but also the Variscan sequence (Fig. 2).

As documented in the Alps (e.g. Michard and Martinotti, 2002), subduction-related peripheral bulge can produce or enhance local uplift with the consequent erosion of the forebulge and the deposition of unconformable foredeep sequences. In our reconstruction, the same processes may have occurred when the European plate reached the Eocene subduction zone. The angular unconformity documented inside the Alpine cycle (i.e., separating the Paleozoic-Mesozoic passive margin from the Middle to Late Eocene foredeep deposits) in all the studied Lower Units represents a regional surface produced by erosion processes affecting the continental lithosphere during its approach toward the subduction zone.

5.2. The Lower Units from subduction to exhumation: the D1 and D2 phases

The Lower Units exposed in the Cima Pedani, Corte and Ghisoni areas share the same deformation history but record different P-T exhumation paths (Fig. 8). The main ductile event preserved in all the units is the D2 phase. It is a non-coaxial deformation phase characterized by isoclinal folds, penetrative S2 foliation and top-to-W shear zones (i.e., top-to-the foreland shearing, considering the E-dipping subduction plane reconstructed for the Alpine evolution of this sector of Corsica). Relics of the earlier D1 deformation phase are scarce and preserved in D2 low-strain domains.

The thermo-baric estimates obtained by chlorite-phengite pairs grown during the D1 and D2 phases in the Lower Units exposed in the Ghisoni area constrain only the retrograde path recorded in the Lower Units during their exhumation up to shallower levels along the base of the Alpine Corsica wedge, today represented by the Schistes Lustrés Complex. No prograde path related to the underthrusting of the unit and to their transfer at the base of the Alpine Corsica wedge is recorded. These results corroborate what those documented in Corte (Di Rosa et al., 2017a).

In detail, three generations of phyllosilicates were documented in the Ghisoni samples. The growth of the first two, documented along the relics of S1 foliation, occurred during pressure, then temperature peak conditions, respectively. This implies that the D1 phase occurred from HP-LT to LP-HT metamorphic conditions (Fig. 8). A third generation of Chl and Phg grown along the S2 foliation and it is in equilibrium at lower P and T conditions. Even if the three generations of Chl-Phg pairs have been documented in all the units, the P-T conditions at which they were in equilibrium differ suggesting that each unit followed an independent trajectory of exhumation until the end of the D2 phase.

The straight path documented in the GHU and CPU indicates that their exhumation during the D1 and D2 phases occurred under almost isothermal paths. GHU shows a maximum change in temperature during the D1 phase between P-peak and T-peak of less than 20 °C, and between the D1 phase T-peak and the D2 phase of c. 60°C (Fig. 8). This trend indicates that GHU, stationed shortly in the deepest position, was quickly exhumed, that assuming an average crustal geobaric gradient of 30 MPa/km (Best, 2003) is estimated from c. 27 to c. 4 km. CPU recorded greater differences in pressure and temperature during the D1 phase and between D1 and D2 phase (Fig. 8). It records a trend broadly comparable to the GHU P-T path, suggesting probably analogous fast exhumation. This trend could be explained considering that both units are the lowest units of the Alpine tectonic pile laid directly above the Hercynian Domain. On the contrary, SCU (Cima Pedani area) and PPU (Corte area) occupy the uppermost positions in the tectonic stack of the Lower Units. Despite the different P-T estimates registered during the D1 phase, both units show comparable P-T paths. The progressive warming from the P-peak to the T-peak suggests that these units, during their exhumation, experienced progressive heating due to the re-equilibration of the isothermic field. This implies that, during their exhumation in the D1 phase, and differently from what described for GHU and CPU, SCU and PPU stationed for some time between 45 and 17 km and between 35 and 17 km, respectively. During the D2 phase, the P-T trends of SCU and PPU are comparable with that of CPU, although with higher P-T values.

CAU and PEU from the Cima Pedani area show D1-related trends similar to those of the overlying SCU and to the equivalent PPU from the Corte area, except for the relative low-P conditions of the P-peak registered in CAU, that causes the almost isobaric heating between the P-peak and the T-peak. Similarly to what described above for SCU and PPU, temperature 430°C in CAU and PEU at the end of the D1 phase. However, the transition from the D1 to the D2 phase in these units is characterized by an almost isobaric cooling that implies the re-cooling of CAU. A similar path during the cooling phase has been described in other orogens as related to the thrusting of initially warmer over cooler material (Chamberlain and Karabinos, 1987; Wakabayashi, 2004). Although the base of CAU is unknown, we can therefore postulate that CAU was juxtaposed over cooler units. A first possibility is that CAU overthrust directly onto the Hercynian Corsica Domain: in this case the observed temperature gap would be justified by the fact that CAU is in contact with a portion of the European margin that never underwent subduction. Alternatively, we could postulate an overthrusting of CAU over other, unexposed Lower Units. If so, we could argue, similarly to the scenario depicted for CPU in the Corte area, that these units experienced a much faster exhumation than CAU, because of their westernmost position (i.e., closer to the Hercynian Corsica Domain) in the units pile.

5.3. The final stage of exhumation of the Lower Units: the D3 east-verging deformation

In the three selected areas, the D3 phase is represented by gently inclined F3 folds characterized by eastward or south-eastward vergence. The crystallization of only calcite associated to the S3 axial plane foliation indicates their development at depth at most 10 km.

Contrary to the orientation of S3 foliation, the trend of A3 axes varies in the three areas, from NNE-SSW in the Corte and Ghisoni areas to ENE-WSW in the Cima Pedani area. The simplest explanation is that the changing in the A3 axes orientation documented in Cima Pedani area is the result of a passive rotation around a vertical axis during the sinistral strike-slip tectonics of the CCSZ.

The D3 extensional top-to-the-E shear zone has been described in the rest of the Alpine Corsica and dated from the Oligocene (Brunet et al., 2000) or the Late Oligocene-Early Miocene (e.g. Malasoma et al., 2006). In line with these authors, we interpret the D3 phase as produced during an extensional tectonics, mostly developed as consequence of the Adria slab roll-back (Gueydan et al., 2017).

Considering the differences within the P and T estimates obtained for the D1-D2 phases in GHU and in the Lower Units exposed in the Corte and Cima Pedani areas (Di Rosa et al., 2017a) and that the tectonic contacts between the Lower Units and the Schistes Lustrés Complex are folded during D3 event, it is supposed that the stack in the south-western Alpine Corsica occurred during the late D2 phase.

6. Conclusions

This study provides stratigraphic and tectono-metamorphic constraints to depict the involvement of the European continental crust in the processes of subduction and exhumation during the Alpine orogeny in Corsica. The data collected in the Lower Units of the Alpine tectonic prism from the Cima Pedani, Corte and Ghisoni areas indicate that:

1) the stratigraphy of the Lower Units indicates that from Triassic to Late Eocene the sedimentation above the European continental margin evolved from shallow to pelagic

marine. Starting from the Eocene, the deposition of breccias and sandstones is controlled by the erosion of the bulge, formed immediately before the subduction of the continental crust.

2) the Lower Units preserved only the retrograde migration path within the orogenic wedge;

3) P-T estimates indicate that each unit has an independent exhumation trajectory with different exhumation rate in function of their position within the orogenic wedge;

4) the exhumation processes started during convergence-related processes (D1 and D2 phase) and continue during extensional tectonics (D3 phase) driven by both the overthickening of the orogenic wedge and the Adria slab roll-back.

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CAPTIONS

Fig. 1. (a) Tectonic sketch of the Alpine Corsica; the location of the three studied areas (i.e., Figs. 3-5) is indicated. (b) Schematic cross-section of the Corsica Island (modified after Malavieille et al., 1998).

Fig. 2. Stratigraphic logs of the Lower Units in Cima Pedani, Corte and Ghisoni areas (green star indicates the metapelitic lithotype sampled and used for the study of the metamorphism). dc RB: Roches Brunes Fm.; pc γ: metagranitoids; pc ν: epidote-bearing metagabbros; pc γa: dykes complex; p VV: Metavolcanic and Metavolcaniclastic Fm.; t CV: Cavernoso Metalimestone Fm.; t DO: Lower Metadolostone Fm.; t CG: Metaconglomerate Fm.; t LD: Metalimestone and Metadolostone Fm.; j LM: Lumachella Metalimestone Fm.; j DO: Upper Metadolostone Fm.; j LL: Laminated Metalimestone Fm.; j CB: metacarbonate breccia; j CL: Cherty Metalimestone Fm.; j DL: Detritic Metalimestone Fm.; e BR: Metabreccia Fm. and e SS: Metasandstone Fm.

Fig. 3. (a) Geological map and stereographic projections of the main structural elements documented in the Cima Pedani area. (b) Tectonic sketch of the area.

Fig. 4. Geological map and stereographic projections of the main structural elements documented in the Corte area. (b) Tectonic sketch of the area. Modified after Di Rosa et al. (2017a; 2017b).

Fig. 5. (a) Geological map and stereographic projections of the main structural elements documented in the Ghisoni area. (b) Tectonic sketch of the area.

Fig. 6. Geological cross-sections of (a) Cima Pedani, (b) Corte (modified after Di Rosa et al., 2017a; 2017b) and (c) Ghisoni areas. See Figs. 3, 4 and 5 respectively, for locations.

Fig. 7. Mesoscopic and microscopic aspects of the studied rocks. (a) Macrophotograph of S0+S2 foliation in the Metabreccia Fm. (CPU, Corte area), F2 isoclinal folds and F3 folds in Metabreccia Fm., Corte area (CPU). A.P.2: F2 axial plane; A.P.3: F3 axial plane. (b) Photomicrograph of S1 foliation (S1) preserved within D2 microlithon in the F2 hinge zone of the Metasandstone Fm., PPU, Corte area, sample CM32C. S2: S2 foliation; Wm: white mica; Chl: chlorite. Metabreccia Fm., Corte area (CDU, sample CM24C). (c) cm-sized F3 fold in foliated metagranitoids, Ghisoni area (GHU). (d) Photomicrograph of metagranitoids, Ghisoni area (GHU, sample GHI21). The granoblastic layer consists of recrystallized quartz (Qtz) affected by incipient subgrain rotation recrystallization mechanism. ng: new grain of quartz; og: old grain of quartz; Wm: white mica.

Fig. 8. Summary of the pressure-temperature-deformation (P-T-d) paths of the Lower Units in the three selected areas. P-T-d paths of CPU and PPU are after Di Rosa et al. (2017a). The stacking of the Lower Units occurred during the late D2 phase. Bs: blueschist facies; Gs: greenschist facies.

SUPPLEMENTARY MATERIAL

Fig. 1s. Additional mesoscopic and microscopic pictures of the deformation history of the Lower Units. (a) S-C' fabric in the Detritic Metalimestone Fm., Castiglione-Popolasca Unit, Corte area (C': shear plane; S2: S2 foliation); (b) S-C' microfabric in the Metavolcanic and Metavolcaniclastic Fm., sample CMD51, Ghisoni area; crossed Nicols (C': shear plane; S2: S2 foliation; ulmy: ultramylonite layer); (c) S2 mylonitic foliation in metagranitoids, GHI22, Ghisoni area, crossed Nicols (S2: S2 foliation; Wm: white micas; Qtz: quartz; Pl: plagioclase); (d) σ-type amphibole porphyroclast in the epidote-bearing metagabbros, Ghisoni Unit, sample GHI18, parallel Nicols.

Fig. 2s. Ternary diagrams showing the proportion in each sample of chlorite (a) and phengite (b) end-members. (c) Si-intensity map acquired with EPMA. (d) P-T equilibria conditions of the three generations of Chl-Phg couples (the error of each cross is ±0.2 GPa and ±30°C). Dots in the maps indicate the sampled microareas from which the P-T estimates were obtained.

Tab. 1s. Representative electron microprobe analysis of the Chl-Phg pairs selected in the samples of metapelites.

Tab. 2s. P-T estimates for the three generations of Chl-Phg pairs in the 6 studied units. P-T estimates of CPU and PPU are after Di Rosa et al. (2017a). The results (Chl-Phg 1st, 2nd and 3rd generation) obtained with the Chl-Phg-quartz-water multiequilibrium approach (Vidal and Parra, 2000) are compared with classical thermobarometric methods (P max and T max).

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Fig.1

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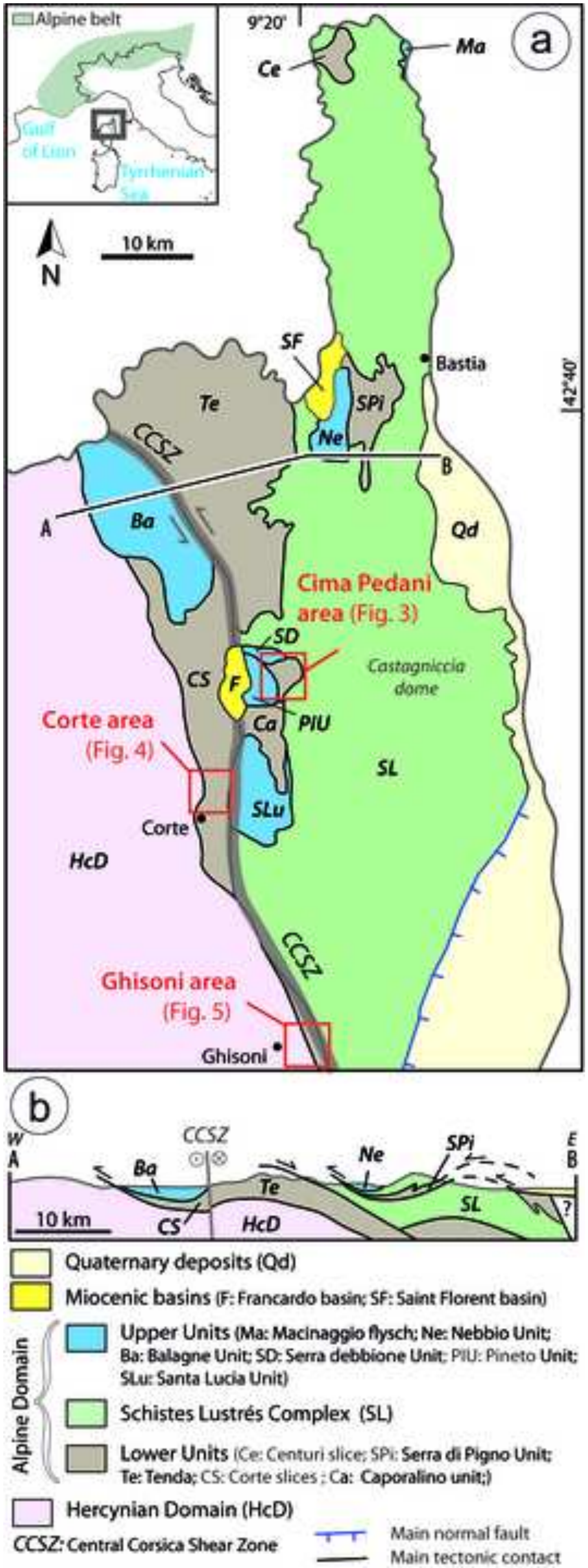

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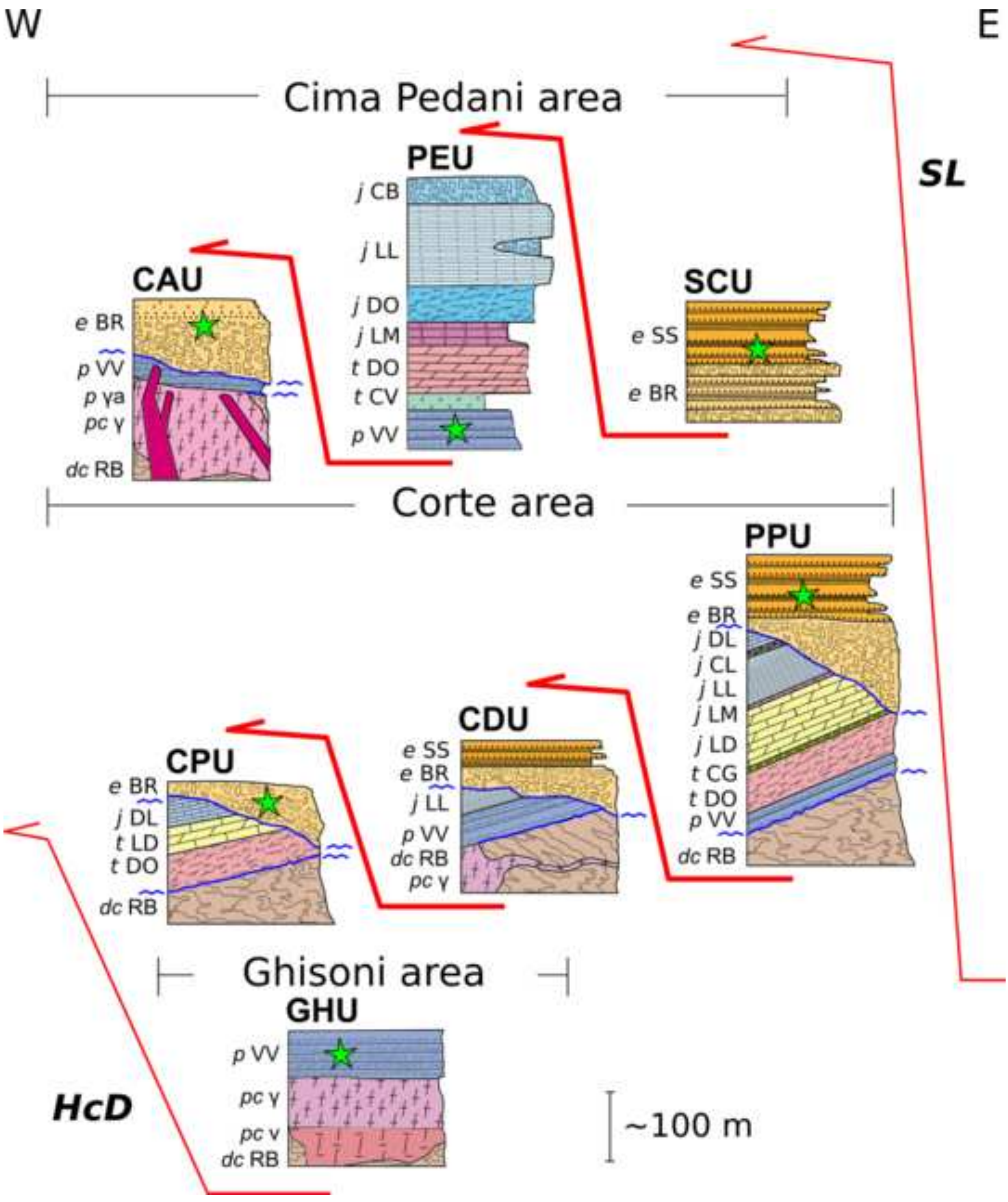

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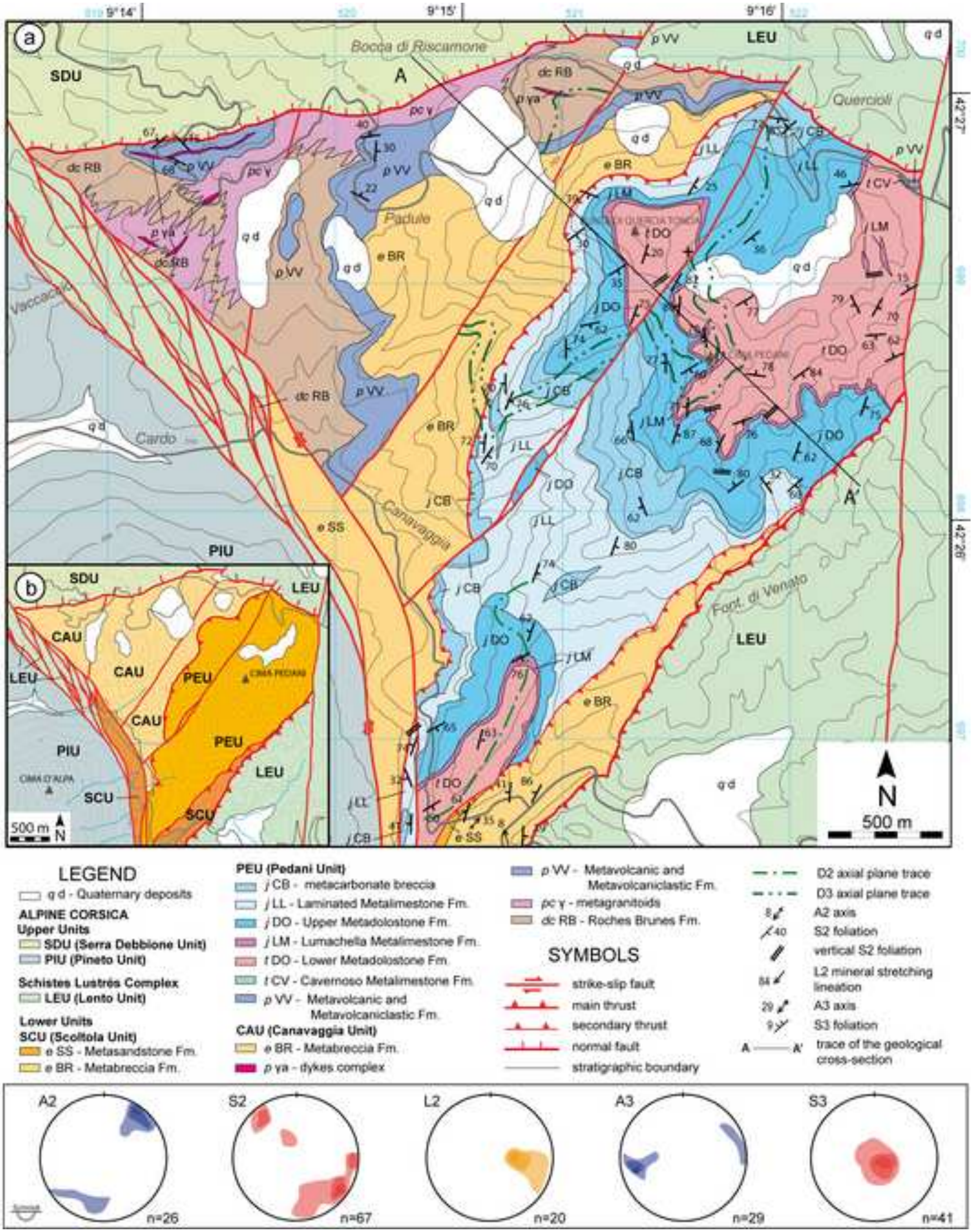

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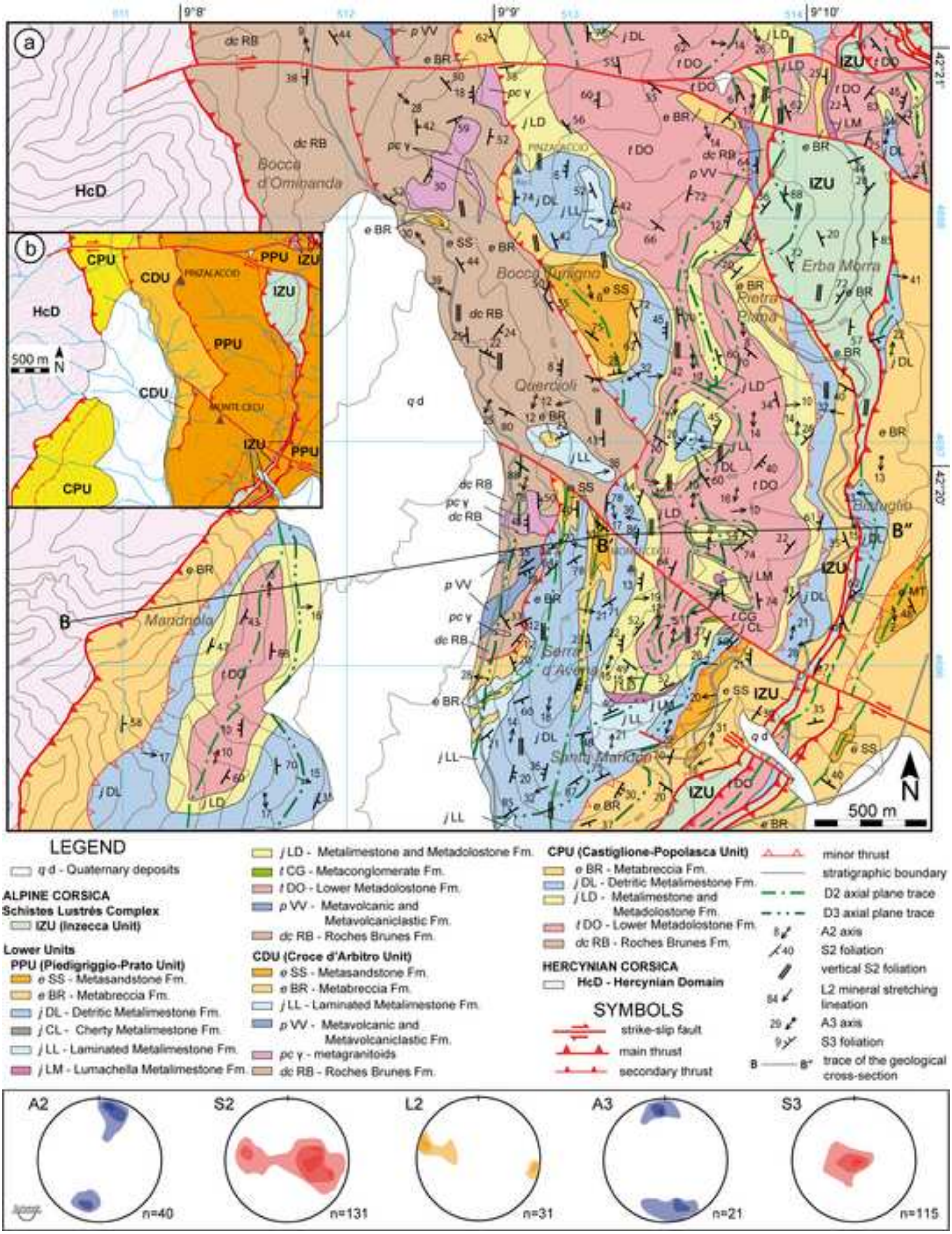

Fig.5

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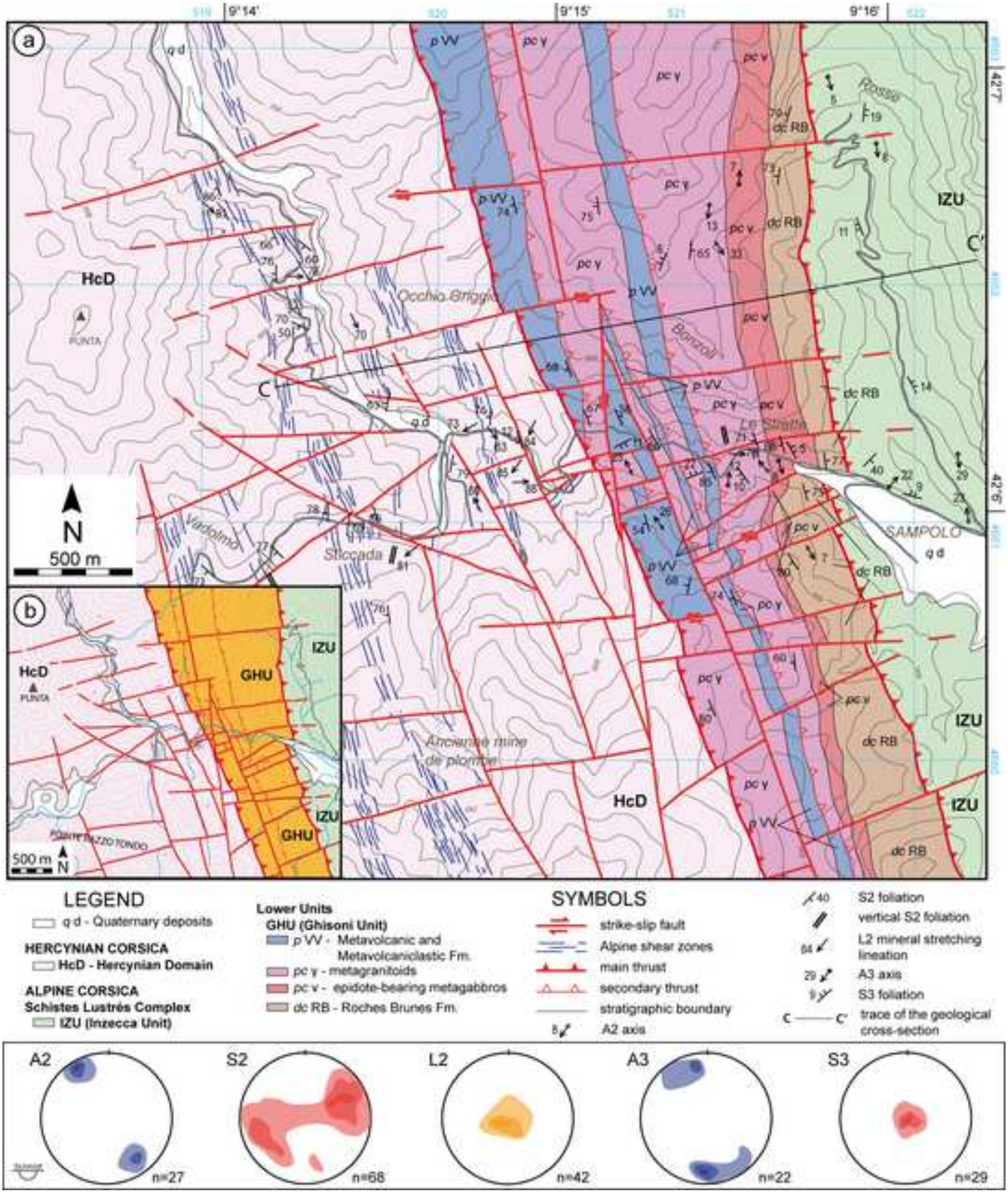

Fig.6

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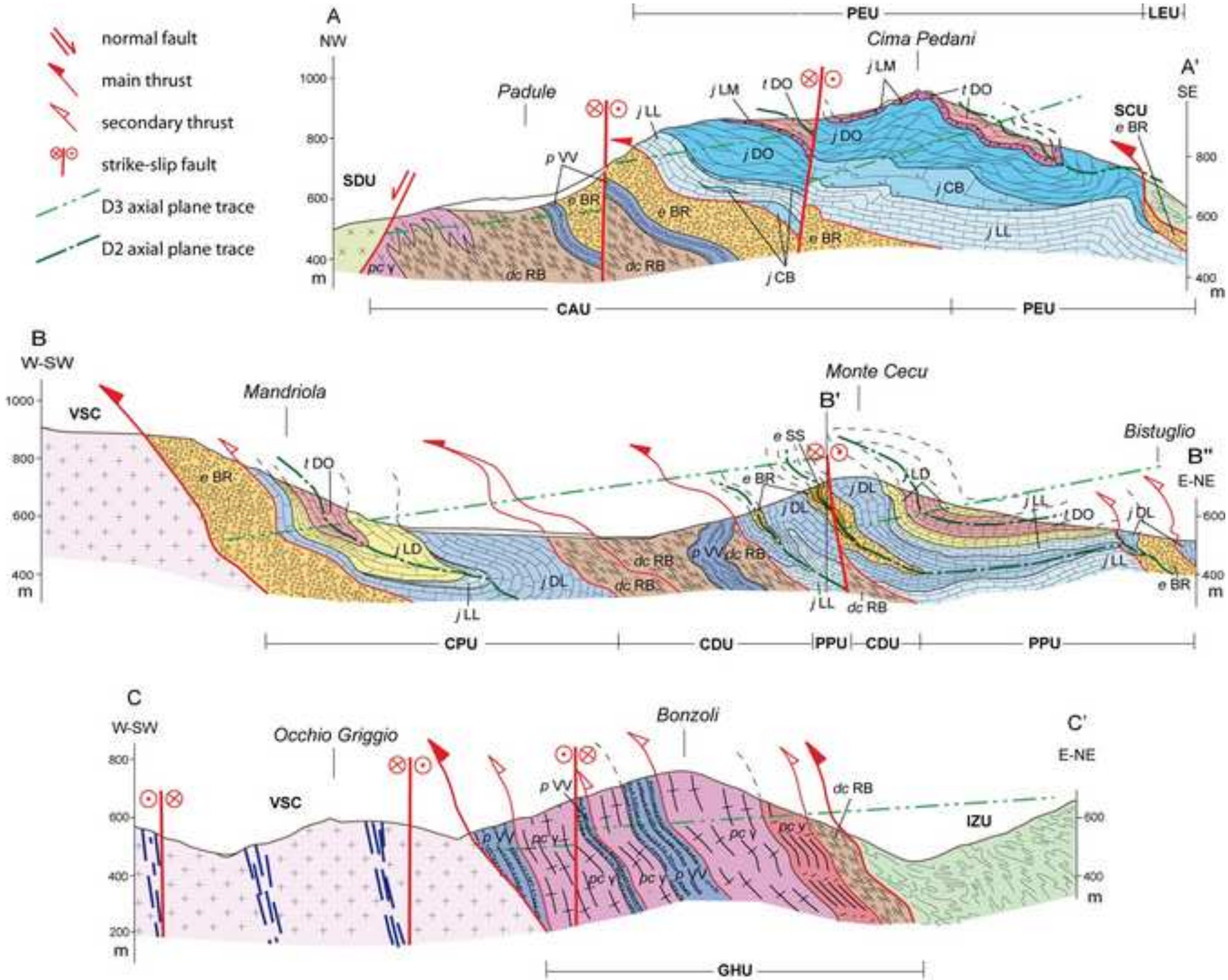

Fig.7
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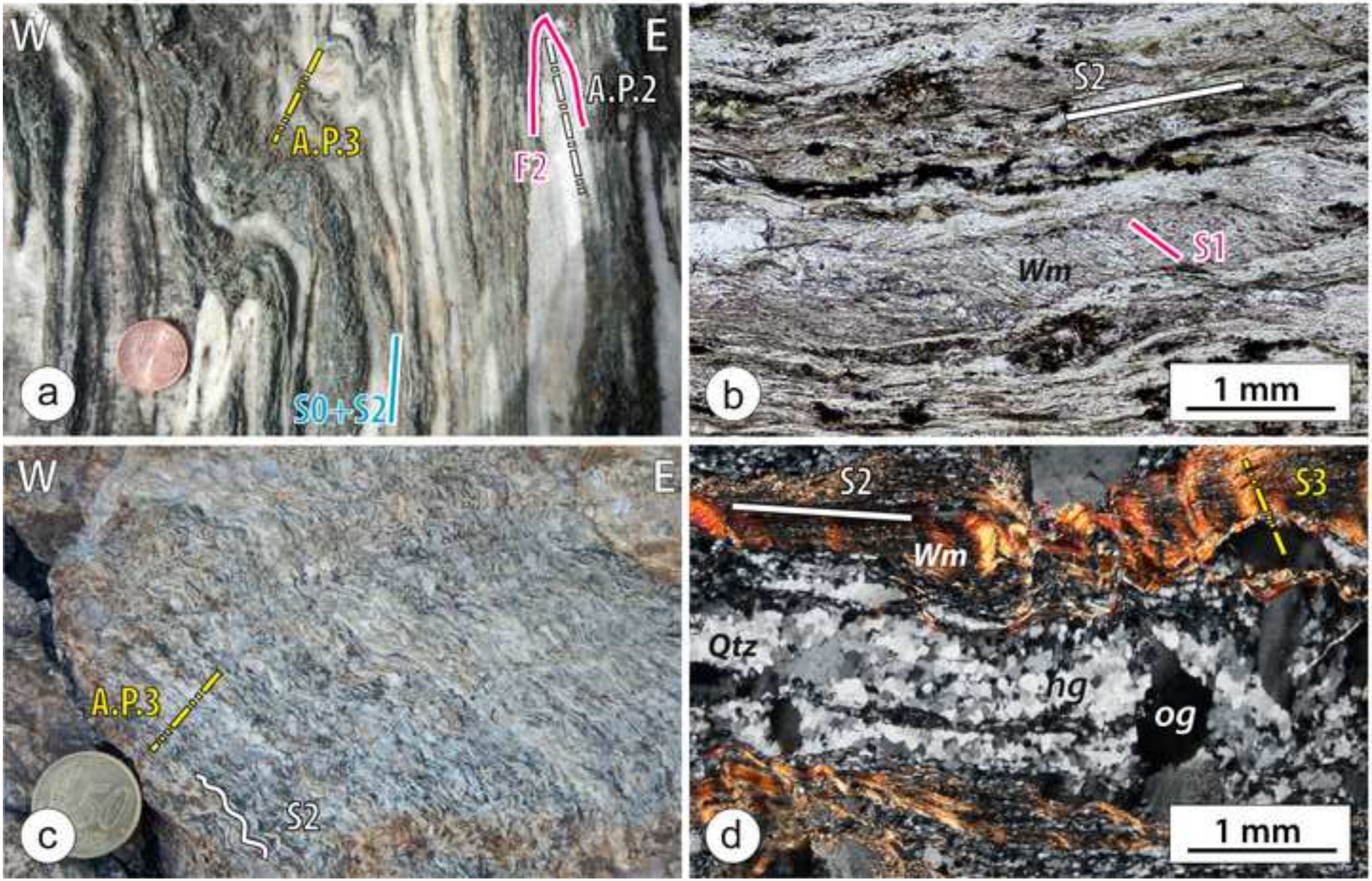

Fig.8

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