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Lateral displacement of a thermally weakened pluton overburden (Campiglia Marittima, Tuscany)

--Manuscript Draft--

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Abstract:	The ascent and emplacement of magmas in the upper crust modify the local pre-existing thermal and rheological settings. Such changes have important effects in producing anomalous structures, mass displacement, rock fracturing, and, in some conditions, hydrothermal mineralizations. In the Campiglia Marittima area, detailed field mapping led to the reconstruction of a local deformation history that overlaps, chronologically and spatially, with regional extension. This local deformation was triggered at the Miocene-Pliocene boundary by the intrusion of a monzogranitic pluton beneath a carbonate sedimentary sequence. The emplacement of the pluton produced a perturbation in the rheological behaviour of the carbonate host rocks, producing transient ductile conditions in the very shallow crust. The carbonate rocks were thermally weakened and flowed laterally, accumulating downslope of the pluton roof, mainly toward the east. As the thermal anomaly was decaying, the brittle-ductile boundary moved progressively back towards the pluton, and large tension gash-shaped volumes of fractured marble were generated. These fractured volumes were exploited by rising hydrothermal fluids generating sigmoidal skarn bodies and ore shoots. This work presents the Campiglia Marittima case study as a prime example of structural interference between regional extensional structures and local, lateral mass displacement in a transient ductile rheological regime triggered by pluton emplacement.

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Dear Editor,

we are submitting the revised version of the manuscript “Lateral displacement of a thermally weakened pluton overburden (Campiglia Marittima, Tuscany)” (IJES-D-17-00043). We appreciated the reviewers’ comments and changed the manuscript according to their comments/suggestions. In the following pages our replies to their main recommendations and comments are reported. We think that the paper is now substantially improved and we hope it can now be accepted for publication in *International Journal of Earth Sciences*.

Thank you for your consideration.

The corresponding author

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Reviewer #1

General points

Repetition: There is a general concern on repetition of information. It seems to stem from two issues. First, ideas about interpretation have been included in Section 3, but must be presented again in full in Section 4. Second, material need in Section 3 sometimes is unnecessarily repeated in Section 4 when the reader doesn't really need to be reminded (they just read it).

We did change sections with repetitions, generally making them more synthetic and avoiding any repetition.

Figures: Figures 2, 3 and especially 7 seem to have been prepared as presentation slides such that there may be too much duplication between text in the slides and text in the figure caption. Including such bold and inclusive titles for each segment of a figure may be unnecessary.

We have modified the figures as suggested by both reviewers.

Gravity: "Gravity" shows up in the key words, but not again until L318 where you write "Finally, the intrusion of the latest felsic dyke marked the end of the pluton-assisted gravity sliding, turning back to a dominant role of the extensional regional tectonics." It is true that "Gravitational" shows up in a header on L249, but the next mention is 68 lines later and it is noting the end of it. Section 4 needs to lay out your basic idea about how the emplacement of the pluton "assisted" the siding. The reader needs to know that the material in those 68 lines is dealing with that sliding. On L381, you switch to gravity-assisted sliding rather than pluton-assisted gravity sliding; That second one should just be gravity sliding.

AND

On L378, the gravity sliding is declared over. When reading this, my notes indicate that this process that spanned a period of the history, needs to be handled differently. Back when the section started (L249), the idea needs to be clearly stated. Then the pieces all the way up to L378 need to be phrased as presenting the evidence to support the notion.

We did not make use anymore of the term "gravity" which was only sparsely used.

Minor points:

L89: the range of meanings for "elision" is too great, and understanding of that term is so limited that it should be replaced. Perhaps "omission" or "loss"

We replaced "elision" with "omission"

L139: Your reference to Fig. 1 and to the Vezzoni paper has me confused. If you are referring to Fig. 1 of the new manuscript, the reader doesn't know which dike is the Ortaccio dike in that figure, and no dikes appear to cut across "all" the other magmatic units (especially the pluton as presented on the map – Fig. 7 shows a question mark at the deep end of that dike as well). On the other hand, if you are referring to a figure in the 2016 paper, that's awkward because the reader doesn't necessarily have it available.

We have modified the manuscript deleting the reference to Fig. 1

L184-187: It is not exactly sure what you are trying to say. Plunge refers to lines rather than planes, but I assume you are trying to convey the parallelism of the foliation and the intrusive contact of the roof. As for the last sentence, you need to express this more completely and clearly; it might need two sentences. Your phrase " – from the top of the pluton –" I think means relative to the thickness at the top compared to on the flanks. You are also drifting into interpretation/discussion which results in repeating information later.

We have changed the sentence. The phrase “is clearly linked …” was removed and drifting it to discussion

L15: … regime. Such changes have important consequences on …
L17: … mineralization.
L18: … mapping led to …
L21 and 23: use “carbonate” rather than “carbonatic”
L23: … host rocks, producing …
L25: … and flowed laterally … mainly toward the east.
L27: … back toward the pluton.
L29: This work presents the …
L31: delete “among”
L43-44: This is due, in part, to the general lack of evidence of the pathways followed by magmas and fluids once …
L51: … 2004), and fossil …
L57-58: … 20 km of mining tunnels, associated with deep …
L60: … succession, the thermal …
L69: … motions of the Adria …
L70: … in the late …
L74: … continental margin and consisting …
L76: … Early Jurassic to Early Cretaceous …
L77: … Late Oligocene/Early …
L81-82: … by no greater than very low-grade metamorphism (….
L124-125: … Nappe, with temperatures as high …
L127: I recommend that “carbonate” replace the term “carbonatic” throughout (18 times in the text, figures and cations).
L128: Many more …
L136: … or by filling …
L161: … is elongated N-S, with …
L162: Why wouldn’t you make the ratio 1:2?
L165: … thanks to mining …
L171: … 7 km in the N-S direction and 2.5 km in the E-W direction.
L179: … pluton bulge, to 500 …
L191-192: Fig. 3 doesn’t appear to show the outward sense of motion, or if it does, it’s not clear how to see it.
L195: … generally gently dipping …
L202: when you say “highlighted” do you mean “defined”?
L214: … than the ductile …
L225-227: If the Temporino skarn is a distal skarn, I think that should be noted.
L227-230: This starts by indicating that there is more than one Temperino skarn body. When you get to L229, it is not clear what is or are plunging. And again, plunge refers to lines, so it seems dipping is more correct since you describe the body as tabular.
L227: add a comma: … sub-vertical, sigmoid-tabular …
L236-243: The reader senses that they just read too much of this text back around L135. Try to reduce duplication
L258: … available for the whole …
L266: It looks like Fig. 2 is the one that shows the contact asymmetry.
L271: I don’t see the folds and boudins showing sense of shear in Fig. 2 (or any other). If it’s intended to do so, it needs to be made clearer.
L271-273: This sentence is awkward and unclear.
L278-279: Fig 2 doesn’t show the white encased in the older gray.

L282: I can’t see how the top-to-the-east sense of shear is indicated. If it is, guide the reader to it more specifically.
L284: What is meant by “culmination”? Would “exposure” be clearer?
L284: Replace “for” with “to”
L288-289: … be explained by original …
L293: … pluton, a condition more consistent with …
L299: … is a common …
L300: … of the thermal …
L301: … from a ductile back to a brittle …
L302: … in the brittle …
L308-310: Fig. 6 and text referring to it are problematic in that it is the Earle skarn body (Temperino mine) and the Temperino skarns seem to be used synonymously. Also, what’s the argument that top-to-NE is the sense of motion? It’s not until Fig. 7 that we see a cross-section, and there the sense is not defended.
L311: question: … magmas were emplaced …
L313-314: … exploited the feeder structures …
L317: Here’s the first mention of pluton-assisted gravity sliding, and it assumes that it is true without having directly presented the argument
L339-340: … experimental studies have shown that …
L341: … 2005), further …
L345: … intrusive deformation is recorded in other carbonate contact aureoles (e.g. …
L350: … dominantly toward the east, …
L352: … eastward-dipping, low-angle faults …
L352-353: Therefore, gravity ruled (i) …
L363: … in analogue studies …
L369-370: … traps that drew in hydrothermal fluids, and replaced …
L372: … recently described for the …
L376: … attesting to the persistence of a top-to-the-east …
L380: … late fault system.
L381: … emplacement allows us …
L388-389: … intrusion. Line of evidence in both cases indicate …
L390: … pluton overburden at Campiglia …
L391: …. displacement that occurred …
L396-397: In contrast, the pluton intrusion into carbonate formations in the Campiglia case generated …
L400-401: … outwardly squeezed aureole.
L409: … model that starts with the …
L412: … can be linked to …
L413: … and makes the case for reevaluation …
L416: … rocks did exploit …
L420-421: … mega-tension, gash-like fractures in marble volumes were able to …
L422-423: … sources. The potential for such anomalous …
L428-429: … active contribution of the shallow-level emplacement of a pluton on tectonic processes.
L436: … regime was re-established …
L721: … dykes. Rose diagrams …
L722: (a) and (b)
L726: delete “, respectively.”
L738: delete (n=218)
L740 and L742 delete “The” and start “Green …”
L744: delete (n=129)

L746: start "Yellow …"
L748: … movement with respect to …
L753: … Marmi mine; human with orange hard hat for scale).
L755: This caption and the small figures are the only ones with uppercase letters. Shift to (a), (b), etc.
L756: … host-rock; note fold completely replaced by skarn.
L768: … drill logs, and SW-NE …
L770: delete (n=54)
L772: start "Red …"
L777: (a) Emplacement of …
L788: replace "testify" with "constrain" (or another word)
We have accepted all the minor comments and modified the text accordin to them.

Fig 1c. change volcanites to volcanics
Done

Fig. 4. You might want to insert an arrow to draw attention to the scale
Done

Reviewer #2

The paper by Vezzoni et al. "Lateral displacement of a thermally weakened pluton overburden (Campiglia Marittima, Tuscany)" is an interesting paper dealing with a timely theme, having a great fallout on ore deposits and geothermal exploration science. It means that the theme is of broad interest for an international readership and therefore it deserves of publication in the International Journal of Earth Sciences. Nevertheless, there are some issues of the papers that have to be improved. In fact, data are good but are not well illustrated and framed in the present geological setting. The geological setting, as well as the structural framework, has to be better described even if deriving from literature. The discussion is a little dispersive and repetitive in some parts. Conclusions appear to be speculative without the appropriate geological and structural framework (that has to be well presented and discussed).
Here below more specific comments

Geological outline: This introductive part needs improvements: the authors refer the Northern Apennines geological evolution to a model, one of many. The authors do not explain why they prefer one model respect to the others proposed in the literature and have to add references for the model they propose.
We believe that a comprehensive discussion of the geological models is outside the aim of this work. The present work illustrates a local evolution in a short time period (between ca. 5.7 Ma and 4.3 Ma). Therefore, we refer to review papers as Platt (2007) and Molli (2008) and reference therein.

The general part is weak and lacks of a description of the stratigraphic units hosting the pluton. This part is fundamental in order to better understand the geological setting and the deformational evolution of the whole area during the emplacement of the magmatic body. In fact, within the text there are several indications (e.g red-nodular limenstone, massive limestone…) to rocks and/or formations but these are not described in the text. The reader that is not so much familiar with the southern Tuscany cannot understand correctly. In this view, I suggest to the authors to spend more lines in the description of the Tuscan Nappe succession, giving few and concise information on its stratrigraphic succession. At the same time, the tectonic framework has to be described mainly

addressing on the structures that characterise the Tuscan Nappe before the intrusion, during the intrusion and after the intrusion.
We have improved the description of the tectonic units exposed at Campiglia (with particular care for the Tuscan Nappe). Furthermore, we have added in Fig. 1 a scheme of the Apennine tectonic pile and its relationships with magmatic rocks exposed at Campiglia (see also comments on the Fig. 1).

An other problem is the gravitational induced lateral squeezing. Authors refer to such a setting the interplay between extension + gravitational sliding. This is also sketched in the Fig. 7. Take in mind that gravity plays a role on the whole rock masses exceeding the geoid surface. Below the geoid surface, the gravity cannot play any role… It means that the squeezing can be only induced by tectonic processs (regional or local), but these have to be discussed.
Gravitational potential energy likely played a role at Campiglia also below the geoid surface as reported in several papers for different geological processes (e.g., Glazner, 1994; Liu, 2001; Gerya et al., 2002; Gemmer & Houseman, 2007; Currie et al., 2008; Currie et al., 2014). Nevertheless, the main topic of this work is the description of a lateral sliding of pluton overburden developed during a local transient peak of ductile regime. For this reason, we have modified the manuscript according to the reviewer's suggestions deleting the use of the term gravity.

Brittle deformation: in this sub-paragraph the authors describe skarn bodies and their geometrical setting instead of brittle deformation and related structures. I suggest change the title to such a paragraph but anyway some basic information on the faults geometry and kinematics should be done… also because these information are crucial for the conclusion of this paper.
We showed that the skarn and porphyritic dykes developed in brittle regime and the morphologies of skarn and magmatic bodies can be used to reconstruct the local stress field during skarn formation and magma emplacement. We underline that the morphologies of skarn and magmatic bodies have never been previously investigated in detail. On the other, fault geometry and kinematics are the subject of specific papers referenced to (e.g., Giannini, 1955; Acocella et al., 2000; Rossetti et al., 2000). Anyway, we have improved this section following the reviewer's suggestions and changing its title.

Paragraphs 3.1, 3.2 and 4.1 report information on the deformational features with repetitions. In my opinion, in the paragraphs 3.x the authors have to describe firstly the geometry of the contact, the main faults geometries and fist-order tectonic feature like the foliation attitude. Secondly, they have to describe the minor structures as folds, fracture systems…. All these data have to be discussed in a paragraph that should be the paragraph 4. Nevertheless, what is reported in the paragraph 4.1 is (in part) a repetition and it is only in part a discussion; the structural elements have to be discussed in the framework of both evolution and emplacement of the magmatic body and geological setting of the area. In addition, just a curiosity: how informative is the asymmetry of the folds in order to reconstruct the shear sense? Take in mind that in this kind of settings, sheat folds have to be expected; I think this issue has to be discussed.
Line 190 - which kind of kinematic indicators? Please specify
Line 193-194 - When carbonate rock masses are intruded by magmatic rocks and they deform in a ductile field, we can imagine also the occurrence of sheath folds. If this is the case, folds vergence and structural facing lose significance…
We did change these paragraphs deleting repetitions and generally making them more synthetic and comprehensive. Furthermore, we improve the description of the asymmetric folds and the data about the sense of transport (line 201-213).

Data on the geometry of the skarn-bodies are very important and is one of the most intriguing issue of this paper. I suggest to better describe (and discuss) the skarn-bodies geometry in relation with

the LANFs and/or later faults, also described in the literature.
We have improved the description of the skarn geometries in relation with the LANFs (line 377-381).

Data on faults should be added to the paper: paragraph 4.2 reports in the title: "Kinematics and evolution of brittle deformations" but this paragraph does not deal nor with kinematics, neither with brittle deformation.
We have modified the paragraph 4.2 improving the description of the brittle deformation.

Just a part discuss about the possible interpretation of en-echelon segments to be developed in a strike-slip tectonics or, alternatively, in relay zones of east-dipping normal faults, but this part is highly speculative without geometric and kinematic data of faults. I think that all this discussion has to be reorganized and titled in a different way… Nevertheless, why the authors think that the described setting is better reconciled in a normal fault setting instead of a strike-slip one? Which are the data on which the authors are basing their hypothesis. If these data are from literature, authors have to better illustrate this setting.
The reviewer refers to the geometry of the Ortaccio felsic dyke, the only geological body described with en-echelon structure. We observed that the dyke shows a systematically arranged with a left-lateral en-echelon pattern in the southern half of the dyke, while a right-lateral en-echelon pattern in the northern half of the dyke. These features make the dyke emplacement inconsistent with a strike-slip setting. In fact, the examples of dyke emplacement in strike-slip settings have simple (right- or left-) en-echelon pattern (as reported in e.g., Glazner et al., 1999; Dini et al., 2008). However, in the Ortaccio case, the different, systematic arrangement point to a different setting. Walsh et al., 2003 described similar structures in faults and they interpret them in an extensional faulting system as relay ramp structures.

Section of figure 2 shows the contact separating the magmatic body from the hosting rocks. I can see that the contact is sub-parallel to the stratigraphic boundaries and it is hosted within the Rhaetavicula contorta Fm. Do you think the evaporite level could have played a role during the emplacement?
Evaporite levels are not reported in outcrop or drill cores in the Campiglia area.

Line 31 - among or between…?
Between

Line 41-42 - …focusing magmas and fluids in structural traps… probably is better "storing" instead of "focusing"
We stuck to “focusing” which better describe the process of concentrating and driving both fluids and magmas, and, to clarify the concept, we added “paths” to “traps”.

Line 47 - why back arc? … During Late Miocene-Quaternary the subduction process was interrupted; the opening of the Tyrrhenian sea and the whole extensional tectonics that dismantled the hinterland of the Northern Apennines was the consequence of another geodynamic process… so I would be more prudent
Several authors (e.g., Innocenti et al., 1997; Faggioni et al., 1998; Dini et al., 2005; Cadoux & Pinti, 2009) described the opening of the Tyrrhenian Sea in an ensialic back-arc setting. However, for the purpose of this work, describing the extensional tectonic setting is sufficient and we did not make use of the term “ensialic back-arc” anymore.

Line 51 - Bellani 2004 (in the reference list is reported Bellani et al., 2004) is not the appropriate reference… Batini et al. 2003 (Episodes) as a review is probably better; references have to be added

also for the examples of hydrothermal systems and different types of ore deposits… There is a broad literature that has to be, at least in part, mentioned.
Done, we changed Bellani et al. 2004 with Batini et al., 2003.

Line 72-73. This part is not correct. Take in mind the also the metamorphic successions are involved in the tectonic units of the Northern Apennines.
Line 81 - 82. Which one? Please specify or delate this sentence
Line 83 - are you sure on the age of the collision?
We have changed the manuscript to better describe the relationships between the different tectonic units. The age of collision is reported as from Molli (2008).

Line 83-85 - this is just one hypothesis on the Neogene-Quaternary geodynamic evolution of the Tyrrhenian area.. You have to specify the authors and why you prefer this one with respect to the other ones.
Line 87-88 - are you right that extension started in the Late Oligocene??
For a specific discussion on the geodynamic evolution of the Tyrrhenian area, we refer to review papers as Platt, 2007 and Molli, 2008.

Line 88-89 - Age of the extensional tectonic in southern Tuscany, as well as the extensional styles and faults setting/geometry, have been revised in last decade: cf Brogi, 2004 (Geod. Acta); Brogi et al. 2005 (JVGR); Brogi and Liotta, 2008 (Tectonics); Brogi 2011 (Tectonophysics); Brogi et al., 2014 (Journal of Geodynamics)… I know, it seams a horrible self-citation but it is not my fault if anyone worked on such a argument in the last decade….
We have enriched the literature referring to several of these papers (e.g., Brogi and Liotta, 2008; Brogi et al., 2014; Brogi, 2016).

Line 90 - the term "serie ridotta" was used for the first time by Trevisan 1950.. This is the right reference instead of Carmignani et al. 2001..
Done. However, we prefer to maintain also Carmignani et al. 2001. Carmignani et al. 2001 reported and summarized the different extensional phases that affected the inner Northern Apennines.

Line 106 - I would change the title of such a sub-paragraph in "The Campiglia Marittima magmatic complex and hydrothermalism". In fact this part is only focussed on the magmatic and hydrothermal system. If you want to maintain the same title, then you need to go deeper in the description of rocks, succession and tectonic setting. Nevertheless, some information (basic) on the stratigraphy of the hosting rocks is necessary independently by the title of the sub-paragraph
We have changed the title and we have added a brief description of the stratigraphic succession of the different tectonic units.

Line 249 - This title is not pertinent to the content of the sub-paragraph. I suggest to change.
We have changed the title.

Figure 1
(b) the blu rectangle doesn't indicate the enlargement of figure 2;
Fixed.
(c) it is a simplified geological map (not a geological-structural).
We have changed the figure caption.
Mommio et al. 2010 is not present in the reference list.
Actually it is (the whole correct name is Da Mommio et al., 2010).
Nevertheless, also the CARG (Geological map of Tuscany, scale 1:10.000) should be acknowledged.

The CARG 1:50000 do not yet cover the study area, so we refer to the Regione Toscana geological map 1:10000, Sezioni 305080 and 305120 (Cerrina Ferroni, 2007a and b).
I suggest to insert the stratigraphic columns of the exposed tectonic units and to describe, in the text, their successions. See also the general comments.
We have inserted a scheme of the tectonic pile and its relationships with the magmatic rocks exposed at Campiglia.

Figure 2 - This figure is very important and shows the depth of the magmatic body. Nevertheless, details reported in such a figure is specific and the reader cannot realize correctly where the relations with the geological setting are. I suggest add an additional geological map (as indicated in Fig. 1b) with an appropriate detail and with the same size of the present map reported in figure 2. The present figure 2 should be placed on the right of the geological map integrating the geological information. The rose diagrams do not show the % of counting.
A detailed geological map is not necessary for the purpose of this paper, and we think the map reported in Fig. 1 is sufficient. The % of counting was added at the rose diagrams.

Figure 3 - which is the meaning of the grey colour? Which kind of limit is that one separating the blue colour from the grey one? Photographs are too much small. I suggest enlarge these photographs in a better organised figure.
We modified the figure (following also suggestions of reviewer1).

Figure 5 - Photographs show very interesting details that deserve a more visibility. I suggest enlarge these pictures. 2 photographs for line are better.
Done.

Figure 6 - This body should be indicated in a geological map (fig. 2?).
Done.

Figure 7 - It is the core figure. It is well illustrative but gravity induced movements can be excluded at that depth! Gravity in not a process that is able to play below the geoid. See the general comments on the text.
Fig. 7 was modified (see also the reply to the specific comment above).

Line 15 - "thermal and rheological settings"… instead of "regime"
Line 18 - "detailed field mapping" … instead of "detailed mappimg work"
Line 41 - … "activated"…. Permeability cannot be activated.. it can be improved
Line 59 - "morphologies" has to be changed in "geometries".
Line 93-94 - Please add some references
Line 97 - Please delete Apennine
Line 100 - For the Elba Island add also Duranti et al., 1992
Line 104 - Please add Liotta et al., 2015 reference (Tectonophysics).
Line 108 - substitute "extensional" with "normal".
We have accepted all the minor comments and modified the text accordin to them.

Lateral displacement of a thermally weakened pluton overburden (Campiglia Marittima, Tuscany)

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ABSTRACT

The ascent and emplacement of magmas in the upper crust modify the local pre-existing thermal and rheological settings. Such changes have important effects in producing anomalous structures, mass displacement, rock fracturing, and, in some conditions, hydrothermal mineralizations. In the Campiglia Marittima area, detailed field mapping led to the reconstruction of a local deformation history that overlaps, chronologically and spatially, with regional extension. This local deformation was triggered at the Miocene-Pliocene boundary by the intrusion of a monzogranitic pluton beneath a carbonate sedimentary sequence. The emplacement of the pluton produced a perturbation in the rheological behaviour of the carbonate host rocks, producing transient ductile conditions in the very shallow crust. The carbonate rocks were thermally weakened and flowed laterally, accumulating downslope of the pluton roof, mainly toward the east. As the thermal anomaly was decaying, the brittle-ductile boundary moved progressively back towards the pluton, and large tension gash-shaped volumes of fractured marble were generated. These fractured volumes were exploited by rising hydrothermal fluids generating sigmoidal skarn bodies and ore shoots. This work presents the Campiglia Marittima case study as a prime example of structural interference between regional extensional structures and local, lateral mass displacement in a transient ductile rheological regime triggered by pluton emplacement.

Keywords: Extensional tectonics, Magmatic rocks, Skarn, Mass sliding, Northern Apennines

1. Introduction

The mobility of magmas and hydrothermal fluids in the upper crust plays a key role in geological processes such as volcanic eruptions, ore deposition, and activation of geothermal systems. The required country rock permeability is commonly enhanced by tectonic activity, focusing magmas and fluids in structural paths and traps. However, the active contribution to tectonics by magma emplacement at a local scale is still to be assessed in full. This is due, in part, to the general lack of evidence for the pathways followed by magmas and fluids once emplacement processes are over, so that geometries and textures of igneous and hydrothermal bodies represent the only witness to those pathways.

The late Miocene-Quaternary extensional setting of southern Tuscany offers the possibility to investigate at different crustal levels the interplay between processes that led to the generations of the Tuscan Magmatic Province (Serri et al. 1993), active high-enthalpy geothermal fields (Larderello-Travale and Monte Amiata: Batini et al., 2003), and fossil hydrothermal systems (Dini et al. 2008a; Mazzarini et al. 2011), as well as different types of ore deposits (Fe-oxides, pyrite, base metals, and Sb-Hg ores; Tanelli 1983). In detail, the study area of Campiglia Marittima (hereafter Campiglia) was affected by igneous activity during the latest Miocene-early Pliocene, linked with generation of metasomatic rocks and ore bodies exploited since Etruscan times (Barberi et al. 1967; Da Mommio et al. 2010). Here, detailed mapping and analysis of a cumulative 20 km of mining tunnels, associated with deep boreholes data and geophysical interpretative maps, allowed us to reconstruct the tridimensional geometries, textures and relative chronology of the magmatic units, their host sedimentary succession, the thermal metamorphic aureole and ore bodies. The evolution of the magmatic-hydrothermal system thus reconstructed (Vezzoni et al. 2016) is evidence for migration of fluids and emplacement of ores driven by the lateral displacement of the thermally weakened carbonate overburden of a pluton.

2. Geological outline

2.1. Tuscany and the Northern Apennines

The geological setting of Tuscany results from the relative motions of the Adria (Africa) and Sardinia-Corsica (Europe) plates, whose convergence started in the Late Cretaceous leading to Oligocene-Miocene continental collision with formation of the Apennine mobile belt (Molli 2008; Platt 2007). The Apennine tectonic units stacked onto the metamorphic Paleozoic-Triassic basement are, from bottom to top: (i) the Tuscan Units, formed onto the Tuscan continental margin, and including both metamorphic (Tuscan Metamorphic Complex) and non-metamorphic successions (Tuscan Nappe); (ii) the Sub-Ligurian units, deposited onto the transition zone between the oceanic and continental crust, and consisting of Cretaceous-Oligocene arenaceous and calcareous turbidite, and (iii) the Ligurian units, composed of a Jurassic oceanic lithosphere overlain by a Cretaceous-Oligocene sedimentary cover (Molli 2008 and references therein).

In the Campiglia area, the studied pluton host rocks belong to the Tuscan Nappe. Its sequence here lacks of the basal late Triassic evaporites (Burano Fm.), and consists of late Rhaetian grey platform carbonates (Calcari a *Rhaetavicula contorta* Fm.), early Jurassic massive white reef limestone (Calcare Massiccio Fm.) and red nodular, ammonite-bearing limestone (Calcare Rosso Ammonitico Fm.). This carbonate succession is overlain by an early Jurassic to early Cretaceous carbonatic-siliciclastic sequence (Calcare Selcifero, Marne a *Posidonomya*, Diaspri, and Maiolica formations) related to the deepening of the continental platform. The uppermost part of the Tuscan Nappe is composed of Cretaceous to late Oligocene/early Miocene foredeep detrital clayey-turbiditic succession (Scaglia Toscana and Macigno formations).

After the early Miocene collision, the rollback of the Adria slab, coupled with the eastward retreat of the subduction zone, drove the eastward migration of the compressional front, generating extensional structures in the inner Northern Apennines with strongly thinned continental crust in southern Tuscany (20 to 25 km; Piana Agostinetti and Amato 2009). This crustal extension went through two main phases: (i) an early to late Miocene stage with extension exceeding 120% on low-angle faults, and leading in southern Tuscany to omission of parts of the Tuscan Nappe stratigraphic sequence ("Serie Ridotta"; Carmignani et al. 2001; Trevisan, 1950); (ii) a late Miocene to Present stage, characterized by high-angle NNW-SSE and N-S normal faulting, producing horst-and-graben structures, with a total extension less than 10% (e.g., Carmignani et al. 1994; Decandia et al. 2001; Giannini, 1955; Rossetti et al. 2000; Brogi and Liotta, 2008; Brogi et al., 2014; Brogi, 2016). These extensional structures are cut by transversal tectonic SW-NE oriented lineaments (e.g., Livorno-Sillaro Line).

The extensional phase is characterized by magma production from crustal and mantle sources, leading to volcanic activity and emplacement of intrusive bodies into the metamorphic Paleozoic-Triassic basement and the overlying tectonic units (Innocenti et al. 1992; Serri et al. 2001). These intrusions generated HT-LP metamorphism in their host rocks (e.g., Campiglia - Barberi et al. 1967; Leoni and Tamponi 1991; Castel di Pietra - Franceschini et al. 2000; Elba Island – Duranti et al., 1992; Rossetti et al. 2007; Larderello - Rossetti et al. 2008; Giglio Island - Rossetti et al. 1999). The igneous centres are distributed along SW-NE lineaments, on which magmatic ages decrease eastward. These structures have been interpreted as transfer zones triggering extraction, rising and emplacement of magmas (Dini et al. 2008b; Liotta et al., 2015; Fig. 1b).

2.2. The Campiglia Marittima igneous-hydrothermal complex

The area of Campiglia is characterized by a N-S trending horst, mainly made of carbonate units of the Tuscan Nappe, bounded by high-angle normal and strike-slip faults (Acocella et al. 2000; Rossetti et al. 2000; Fig. 1c). During the late Miocene-Pliocene, the Campiglia area has been repeatedly affected by magmatic and hydrothermal events (Barberi et al. 1967).

The igneous sequence started with the emplacement of the Botro ai Marmi monzogranite pluton at ca. 5.7 Ma (Borsi et al. 1967; Rossetti et al. 2000). Its primary paragenesis consists of quartz, K-feldspar, plagioclase and biotite, along with accessory cordierite, tourmaline, apatite, and zircon. The monzogranite is affected by intense hydrothermal potassic alteration with replacement of plagioclase by K-feldspar (Lattanzi et al. 2001). The granite and its contact with the host-rock are well exposed in an open-pit mine for raw ceramic materials over as little as ca. 0.5 km^2 near the western border of the Campiglia horst. Nevertheless, drilling logs (Grassi et al. 1990; Samim S.p.A. 1983a, b; Stella 1955, 1938) and geophysical data (Aquater S.p.A. 1994) are evidence for a larger, N-S elongated pluton. The magma intruded below the Rhaetian grey platform carbonate at a depth corresponding to ca. 0.10-0.15 GPa, and producing an N-S elongated thermal aureole in the carbonate rocks of the Tuscan Nappe, with temperatures as high as 500-550 °C at the contact with the pluton (Leoni and Tamponi 1991). A small, irregular exoskarn body is found between the granite and the carbonate host rock (Barberi et al. 1967). Several, more voluminous skarn bodies are found ~0.5-1 km above the buried eastern limb of the pluton, hosted by a white marble derived from contact metamorphism of pure, homogeneous, massive early Jurassic reef limestone. The skarn consists essentially of hedenbergite and ilvaite, associated with Cu-Pb-Zn(-Ag) sulphide ores exploited mainly in the Temperino and Lanzi mines from Etruscan times to 1979 (Capitani and Mellini 2000; Corsini et al. 1980; Vezzoni et al. 2016).

The skarn is crosscut by three small intrusive units, all affected by potassic alteration. First, the mafic Temperino porphyry magma intruded the Temperino skarn bodies as small dykes or by filling skarn pockets. Second, the felsic Coquand porphyry dykes crosscut both the skarn and the mafic Temperino porphyry. Third, the felsic Ortaccio porphyry dyke crosscut both the skarn and all the other magmatic units (Vezzoni et al. 2016). The age of the latter intrusive event is constrained by a whole-rock K-Ar date of 4.30±0.13 Ma (Borsi et al. 1967), interpreted as the age of the potassic alteration (Barberi et al. 1967). The final igneous event in the area was the extrusion of the peraluminous San Vincenzo rhyolitic magmas (Ferrara et al. 1989; Ridolfi et al. 2015) at 4.38±0.04 Ma (sanidine ^{40}Ar-^{39}Ar age; Feldstein et al. 1994).

3. Results: deformation styles and geometries around the pluton

3.1. Roof morphology of the Botro ai Marmi pluton

In the Campiglia area, the geometric characteristics of the rock bodies and their deformation styles are clearly spatially related to the location and shape of the Botro ai Marmi pluton and its thermal metamorphic aureole. Intensity of deformation decreases with distance from the pluton, and deformation type changes accordingly, with records of both ductile and brittle styles. Therefore, reconstruction of the 3D morphology of the pluton-host rock surface is crucial to the understanding of local strain evolution during the development of the Campiglia magmatic-hydrothermal system.

The size and shape of the Botro ai Marmi pluton (Fig. 2) has been reconstructed on the basis of geological surveys (this work; Cerrina Feroni 2007b; Giannini 1955), exploratory boreholes (Grassi et al. 1990; Samim S.p.A. 1983a, b; Stella 1955, 1938), and reflection seismics, as well as gravimetric interpretive maps and sections (Aquater S.p.A. 1994). The pluton's roof is elongated N-S, with length/width ratio between 3 and 6, and an E-W strongly asymmetric profile, with the western side dipping > 70°, opposed to a mean slope of 25-30° on the eastern and southern flanks. The outcropping portion of the pluton is at the top of a bulge, exposed mostly thanks to mining activity for raw ceramic materials. As a whole, the minimum area covered by the pluton can be estimated at about 18 km^2, with a minimum N-S length of 9 km (Fig. 2).

3.2. Ductile deformation

The early Jurassic carbonate host rocks of the Botro ai Marmi pluton were metamorphosed, and the thermal aureole crops out for about 7 km in N-S direction and 2.5 km in the E-W direction (Fig. 3). The aureole thickness varies from ca. 300 m in the south (Monte Valerio; Stella 1938) to at least 900 meters in the eastern Temperino mining area, as attested by field, borehole and geophysical data (Fig. 2). Also the thicknesses of carbonate units of the Tuscan Nappe vary significantly. The

Rhaetian grey carbonate unit in direct contact with the pluton thickens outward from the pluton outcrop, from about 200 m in the east to 450 m in the south. The overlying reef limestone shows an impressive difference in thickness from about 150 m on top of the pluton bulge, to 500 m in the south, to >1000 m in the eastern side (Fig. 2).

The metamorphosed carbonate units, even those that were originally massive, are pervasively foliated. The foliation defines a broad antiform with a NE-SW to N-S sub-vertical axial plane, coexisting with minor antiforms and synforms (Fig. 3). Overall, the foliations are roughly parallel to the pluton roof, although the dip of the foliation planes decreases with distance from the underlying pluton roof. The carbonate units progressively thickens from the top of the pluton toward the flanks (Fig. 2).

The antiformal structure is accompanied by small-scale folds, whose geometries vary with distance from the pluton. The first meters from the pluton contact are characterized by decametric folds with non-cylindrical geometry, small inter-limb angle (tight to isoclinal), as well as by disharmonic folds with variably oriented axes and sheath folds (Fig. 4), with sense of transport difficult to determine. At the top of pluton’s bulge, also asymmetric folds and boudins are not coherently oriented, making it difficult again to determine any sense of transport. On the other hand, moving laterally outward from the top of the pluton, asymmetric folds and boudins indicate an outward sense of movement (Fig. 3). The axial planes of these folds are generally gently dipping and sub-parallel to the contact with the pluton. The limbs of the main folds are characterized by minor cm-sized isoclinal folds. These features are highlighted by the different shades of grey of the layers implicated in the ductile deformation.

Further away from the pluton, in the eastern side of the contact aureole, the overlying carbonate formations of the Tuscan Nappe show a different style of east-verging folding, characterized by asymmetric shape and variable inter-limb angle, defined by the foliation developed in the metamorphosed reef limestone. Furthermore, close to the contact with the overlying red nodular limestone, metric-sized lenses of red limestone, oblate parallel to the white marble foliation, are encased into the older early Jurassic reef limestone (Temperino and Lanzi mines; Fig. 2). Similar fold structures are described in the eastern side of the pluton aureole (Cerrina Feroni 2007a, b). In the eastern side of the Campiglia horst, the foliation/bedding structure is characterized by minor synforms and antiforms with N-S sub-vertical axial planes, with overall distribution irrespective of the pluton roof attitude (Figs. 2 and 3).

3.3. Brittle deformation, skarn bodies and magma intrusions

Brittle deformation overprints ductile deformational features. The brittle structures are less prominent than the ductile ones, and are found as minor features in metasomatic rocks at the pluton contact, in large distal isolated ilvaite-hedenbergite skarn bodies, in mafic and felsic dykes, and in rocks distal from the pluton.

Endo- and exoskarn occur near the contact between Botro ai Marmi monzogranite and the metamorphosed Rhaetian carbonate rock. Endoskarn veins, mostly made of diopside and scapolite, cut the monzogranite and are connected with the exoskarn, made of diopside, garnet, phlogopite, scapolite, vesuvianite, and wollastonite. The exoskarn occurs as a massive metric-sized volume at the contact with the pluton or as a selective replacement of folded beds of the Rhaetian carbonate, thus mimicking the geometries of the isoclinal folds (Figs. 4 and 5a, b, c, d). The Campiglia skarn bodies are distal skarn, made of ilvaite and hedenbergite and they are found along a N-S belt paralleling the unexposed eastern, E-dipping pluton roof at a distance of 500-1000 m. The Temperino skarn bodies have a sub-vertical, sigmoid-tabular shape, akin to mega-tension gashes, with maximum thickness in their central part (> 40 m; Earle body). The skarn-marble contact is elongated in SE-NW direction and steeply dipping to the NE, crosscutting the marble foliation. These bodies taper out at the upper and lower terminations toward SW and NE, respectively (Fig. 6; Vezzoni et al. 2016).

Three intrusive events followed the formation of the skarn. First, the mafic Temperino porphyry magma intruded the sigmoid-shaped skarn bodies. Second, the felsic Coquand porphyry dykes intruded in the middle of sub-vertical skarn bodies, following both their NW-SE trend (Fig. 3) and their attitude at depth (sigmoid-tabular shape in vertical sections; Fig. 6). Third, the felsic Ortaccio porphyry dyke is characterized over its 8-km length, by several steps and bridges, that are systematically arranged in a NNW-SSE left-lateral en-echelon pattern in the southern half of the dyke, while in the northern half they are arranged in a N-S rigth-lateral en-echelon pattern (Figs. 2 and 3).

4. The Campiglia lateral mass displacement

The Campiglia area represents an ideal case study for understanding the deformative-metamorphic-hydrothermal processes induced by pluton emplacement at shallow crustal levels thanks to (i) the lack of any pre-intrusion regional metamorphic imprint, so that the reconstruction of syn- to post-intrusion metamorphic-deformational effects on the host rock is straightforward, (ii) the large extent of the contact metamorphic aureole, that is also mappable in underground works, providing a three-dimensional structural-mineralogical record, (iii) the short time span (< 1.4 Ma) available for the whole sequence of pluton emplacement, thermal metamorphism, host rock deformation, hydrothermal circulation, and emplacement of porphyritic dykes and rhyolites (Vezzoni et al. 2016).

4.1. Kinematics and evolution of ductile deformations

Ductile deformations are spatially linked with the Botro ai Marmi pluton (Fig. 2). In fact, at the very top of the pluton, recrystallization of carbonate rocks is accompanied by development of transposition foliation, isoclinal folding and widespread boudinage, owing to a nearly coaxial, vertical shortening linked to pluton vertical inflation. Similar ductile asymmetric folds and boudins are observed on the western and eastern flanks of the contact aureole, with top-to-the-west and top-to-the-east sense of shear, respectively (Fig. 2). These geometries are consistent with a centrifugal -mostly eastward- increasing extent of non-coaxial deformation.

The role of non-coaxial deformation is emphasized by the relationships and geometries of the contacts between the different formations of the Tuscan Nappe involved in the thermometamorphic aureole (from bottom to top: grey platform carbonate, white reef limestone, red nodular limestone): (i) slices of white reef limestone are found encased into the older grey platform carbonate formation adjoining the pluton contact (Fig. 2), and (ii) slices of red nodular limestone are found encased into the older white reef limestone. In the eastern part of the contact aureole, sigmoidal red limestone slices/lenses (Cerrina Feroni 2007a; Figs. 2 and 3) invariably indicate a top-to-the-east sense of movement. The progressive change in fold geometry, from tight to open, recorded at increasing distance from the pluton, testifies to the eastward decreasing intensity of deformation, thus pointing out a main role of the pluton emplacement in ruling ductile deformation.

The eastward concomitant thickening of both the carbonate units and the metamorphic aureole could be explained by original variabilities of stratigraphic thicknesses (e.g., Bernoulli 2001) and/or tectonic boudinage of the Tuscan nappe as typically occurring in southern Tuscany (Brogi and Cerboneschi 2007; Carmignani et al. 2001). However, such explanations do not account for the asymmetric shape and displacement of the thermal aureole, with maximum thickness occurring distally with respect to the pluton, a condition more consistent with the lateral eastward mass transport and accumulation of thermally weakened marble triggered by the pluton emplacement dynamics.

4.2. Kinematics and evolution of brittle deformations

Overprinting of ductile structures by brittle deformation characterized by the same overall geometries is a common occurrence in the Botro ai Marmi thermal metamorphic aureole. During the waning stage of the thermal anomaly, the pluton host rock experienced a transition from a ductile back to a brittle rheological regime. Exoskarn bodies and endoskarn veins developed at the pluton-host contact in the brittle regime. In fact, exoskarn bodies cut the marble foliation and replaced the ductilely folded carbonate host rocks (Fig. 5a, b, c). Also, the endoskarn veins that fed the exoskarn are observed to follow brittle fractures in the Botro ai Marmi pluton (Fig. 5d). Slightly distal from the pluton, deformation in the brittle regime led to fracturing of sigmoidal marble volumes, akin to mega-tension gashes, drawing up hydrothermal fluids and thus generating the sigmoidal Temperino skarn bodies (Fig. 6; Vezzoni et al. 2016). The shape of these skarn bodies indicates a top-to-NE sense of shear.

After skarn generation, magmas were emplaced in tight spatial/geometric relationships with skarn metasomatic rocks, suggesting similar ascent mechanisms for metasomatic fluids and magmas. In detail, mafic magma exploited the feeder structures of skarn and filled into the primary porosity of skarn (residual skarn pockets), while felsic magma intruded as segmented dykes through the sub-vertical sigmoidal skarn bodies (Fig. 6; Vezzoni et al. 2016).

Finally, the intrusion of the latest felsic dyke marked the end of the lateral eastward mass transport, turning back to a dominant role of the extensional regional tectonics. Indeed, the apparently contradictory structural pattern of the Ortaccio dyke (Fig. 2), can be reconciled in a normal, east-dipping extensional system, where the dyke segment arrays are connected by relay ramps. Walsh et al. (2003) reported similar structures in segmented normal faults. In the external part of the igneous-hydrothermal system, this final extensional event is recorded by high-angle, large-throw, normal faults with NW-SE strike in the east and N-S strike in the west (see also Acocella et al. 2000; Rossetti et al. 2000; Giannini 1955).

4.3. A unifying scenario

At Campiglia, the active regional extensional tectonic regime interplayed with the local magma-induced tectonics and fluid transfer. A unifying model for all these intertwined events is therefore proposed (Fig. 7) to shed light on a series of significant geological processes in a contact aureole around a pluton, that could be difficult to be understand if tackled as single, isolated phenomena.

The first magmatic event was the emplacement of the Botro ai Marmi monzogranite pluton at ca. 5.7 Ma. This crustal melt emplaced below the Tuscan carbonate units, that were thermally metamorphosed to marbles (T up to 500-550 °C and P ~0.10-0.15 GPa; Leoni and Tamponi 1991). In these conditions, experimental studies have shown that marbles have a ductile behaviour (e.g., Fischer and Paterson 1989; De Bresser et al. 2005), further enhanced by the presence of fluids (in this case even at temperature <400°C; Liu et al. 2002). The rheological characteristics of Campiglia marbles, coupled with pluton volume growth, led to development of disharmonic, non-cylindrical folds in the contact aureole. Comparable highly plastic, ductile, syn-intrusive deformation is recorded in other carbonate contact aureole (e.g., Adamello pluton, Italy: Delle Piane et al. 2008; Serifos Island, Greece: Ducoux et al. 2016). The inflation of the intrusion induced a nearly coaxial, vertical shortening of the host-rock mainly localized at the very top of the pluton, and resulting in the lateral “squeezing” of the rheologically weakened marble units. The lateral mass displacement occurred dominantly toward the east, the direction of easiest accommodation (Wilson 1952) due to both the asymmetric shape of the intrusion roof and the overall extensional regime with eastward-dipping, low-angle faults. Therefore, pluton emplacement ruled (i) the mass sliding on the eastward dipping slope of the pluton-marble contact, resulting in attenuation of the original thickness of the carbonate units above the pluton and their anomalous thickening toward the east, (ii) the generation of disharmonic, east-verging folds in the marble at the pluton contact, (iii) the tectonic mixing of marble slices within grey, white, and red carbonate units and their sigmoidal deformation, and (iv) the development of foliation/bedding antiforms and synforms in the carbonate rocks.

Deformation becomes less intense and less ductile with distance from the heat source, leading to the formation of asymmetric chevron folds with sub-horizontal, NW-SE hinge lines (Acocella et al. 2000). This scenario has been well modelled in analogue studies (Merle and Vendeville 1995), thus accounting for magma-induced local compressional structures in a regional extensional regime.

The eastward displacement of carbonate material came to an end as the thermal anomaly was decaying, so that brittle deformation overprinted previous ductile structures progressing from the outermost zones towards the pluton. The main effect of the eastward displacement of material was the fracturing of sigmoid-shaped large volumes of the thermometamorphic marble. These porous volumes acted as a structural path/trap that drew in hydrothermal fluids replacing the carbonate host to generate the sigmoidal Temperino skarn bodies (Vezzoni et al. 2016). The sigmoid-shaped volume of marble indicate a local top-to-the-east displacement zone developed soon after pluton emplacement. The absence of any clay gouge or cataclasite associated with the Campiglia lateral displacement, its end-of-Miocene timing, rules out any relationships with the regional Miocene low-angle normal faults system, which, additionally, is never observed to affect the massive reef limestone (e.g., Brogi and Cerboneschi, 2007).

Similar structures have been recently described also for the Serifos skarns with en-echelon arrangement during the activity of detachment faults (Ducoux et al. 2016). Mafic magma intruded the main skarn bodies (Temperino mine), then a felsic melt intruded as porphyry dykes (Coquand porphyry) in the middle zone of the main skarn bodies (Vezzoni et al. 2016), attesting to the persistence of a top-to-the-east displacement process.

Finally, with the end of lateral mass sliding, the Ortaccio felsic dyke was emplaced parallel to the western horst-bounding fault, with a geometry coherent with the normal, east-dipping extensional late fault system. The Ortaccio dyke emplacement allows us to constrain the time interval in which the lateral mass sliding was active. In fact, the deformation regime reversed back to regionally-controlled before the emplacement of the Ortaccio dyke, constraining the sliding process between emplacement of the pluton (ca. 5.7 Ma) and the late Ortaccio dyke (>4.3 Ma). To further constrain this time interval, a comparison can be made with the thermo-rheological evolution of the host rocks modeled for the nearby Monte Capanne pluton, Elba Island (Caggianelli et al. 2014), suggesting that the ductile-brittle transition could have occurred in less than 500 ka after pluton intrusion. Lines of evidence in both cases indicate a short time interval to complete the whole process.

The eastward lateral displacement of pluton overburden at Campiglia is paralleled by another prominent displacement that occurred in Tuscany above the 7 Ma Monte Capanne intrusion (Elba Island, Westerman et al. 2004). However, in Elba Island the crustal slice was displaced by about 8 km as a thick, coherent, brittle body, similar to the Serifos detachment system (Ducoux et al. 2016) or the larger Markagunt gravity slide occurred ~21-22 Ma in SW Utah above an igneous intrusion (Hacker et al. 2014). In contrast, the pluton intrusion into carbonate formations in the Campiglia case generated a lateral mass displacement in ductile regime, changing to brittle movements with increasing distance and time. Thus, the resulting displaced material in Elba Island preserved its tectono-stratigrafic and intrusive layout, whereas in Campiglia the original stratigraphic sequence of the carbonate units has been partly disrupted and their thicknesses reduced onto the pluton bulge and accumulated outward, to the east.

4.4. Implications

The proposed model can account for the compressional structures observed in the SW-NE trending belt at Campiglia, such as the isoclinal folds in the marble near the pluton contact, the foliation/bedding antiforms and synforms and the chevron folds in the easternmost reaches of the Campiglia horst. These structures, that would be anomalous in the overall deformation frame of the uppermost Apennine tectonic units, are well explained in our unifying model that starts with the emplacement of the Botro ai Marmi pluton during the Apennine postcollisional extensional phase. This scenario thus points out some of the multiple ways how local compressional structures can be linked to active magmatism in a regional extensional setting, and makes the case for reevaluation of similar local structures found in the vicinity of shallow igneous intrusions in Tuscany, and whose origin is still matter of debate (e.g., Brogi et al. 2005; Brogi 2016).

Finally, ore bodies and magmatic rocks did exploit similar tectonic paths and traps in southern Tuscany (e.g., Elba Island - Dini et al. 2008b; Liotta et al. 2015; Gavorrano - Rossetti et al. 2001; Monte Amiata - Brogi et al. 2010, 2011; Roccastrada - Brogi and Fulignati 2012). At Campiglia, a more specific investigation refines this scenario, pointing out that the formation of very large, tension gash-like fractures in marble volumes were able to enhance permeability in the shallow crust and draw-in hydrothermal fluids and magmas from deeper sources. The potential for such anomalous tectonic structures should be taken into account in ore and geothermal exploration.

5. Conclusions

The Campiglia area offers the possibility to investigate the active contribution of the shallow-level emplacement of a pluton on tectonic processes. Based on field evidence, a unifying model linking the extensional regional tectonics and the local magmatic, hydrothermal and deformational features observed at Campiglia is proposed. The emplacement of the Botro ai Marmi monzogranite pluton induced (i) transient, thermal-induced rheological weakening of the carbonate host rocks, (ii) coaxial, vertical shortening at the top of the pluton, (iii) lateral mass sliding (mainly eastward) of the overburden, and (iv) once the shallow crustal brittle regime was re-established, generation of fractured volumes of carbonate rocks acting as traps for hydrothermal, ore-generating fluids. This work contributes to the knowledge of the mechanisms by which magma can affect local tectonics and create structural traps for ore-forming fluids, with implications for natural resources exploration.

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Figure captions

Figure 1 – (a) Location map of the investigated area. (b) Sketch map of the northern Tyrrhenian region and distribution of the main magmatic centres of the Tuscan Magmatic Province; green dashed belts are geological and geophysical lineaments with transversal orientation to the Apennine chain (modified after Dini et al. 2008b). (c) Simplified geological map of the Campiglia Marittima area (modified after Da Mommio et al. 2010; Cerrina Feroni, 2007a, b). (d) Schematic tectonic pile of the northern Apennines (modified after Carmignani et al. 2001) exposed at Campiglia and relationships with the Campiglia magmatic rocks.

Figure 2 – Morphologies of the roof of the of Botro ai Marmi pluton and the contact between Rhaetian grey limestone/marble and Hettangian white limestone/marble, as reconstructed by means of (i) field, boreholes, and geophysical interpretive maps and sections in the area around the pluton outcrop, (ii) geophysical interpretive maps and sections in the northern area, and (iii) borehole data in the southern area. Also reported are the spatial relationships with the outcropping skarn bodies and porphyritic dykes. Rose diagrams show the directions of the felsic Coquand (a) and Ortaccio (b) dykes: the dykes were split into 1122 segments, of ten meters length, whose strikes are reported in the length proportional to frequency rose diagrams (for method details see Dini et al. 2008b). Lines A-A' and B-B' indicate the geological cross sections oriented transversally and longitudinally with respect to the elongation of the Botro ai Marmi monzogranite pluton. Schematic stratigraphic sequence simplified after Brogi and Cerboneschi (2007). Note the asymmetric pluton roof morphology and the strong thickness variation of the host rocks, that progressively thicken away from the Botro ai Marmi outcrop. Furthermore, the thickness of the contact aureole shows strong variation from southern to eastern side.

Figure 3 – (a) Foliation/bedding attitude in the carbonate succession and related ductile deformation structures in the Campiglia horst (foliation and bedding attitude data from this work; Cerrina Feroni 2007a, b; Giannini 1955; Rossetti et al. 2000). The surface extension of the metamorphic thermal aureole is highlighted with a green dashed area (modified after Aquater 1994). (b) Stereographic projection of the foliation/bedding planes measured on the limbs of the main antiform, compared to the great circles representing the attitudes of the two sides of the pluton roof below the same areas (Wulff net, lower hemisphere). Green and red poles represent the attitude of the foliation/bedding planes in the western and the eastern sides, respectively. The green and red great circles represent the average of the pluton roof attitude in the western and the eastern sides, respectively. (c) Stereographic projection of the bedding planes measured on the limbs of minor distal antiforms in the eastern part of the Campiglia horst (Wulff net, lower hemisphere). Yellow great circle represents the average of the pluton roof attitude below the same area. (d) Ductile deformational structures and kinematic indicators with centrifugal sense of movement with respect to the main pluton's bulge indicate by the white arrows (white capital letters in black circles refer to the location of pictures as in Fig. 3a).

Figure 4 – Ductile deformational structures in the Campiglia area: panoramic view of folds in the metamorphosed Rhaetian grey limestone near the contact with the Botro ai Marmi pluton (Botro ai Marmi mine; red arrow points to a person for scale).

Figure 5 – Brittle structures in the Campiglia area. (a.) Metric-sized exoskarn mass between Botro ai Marmi pluton and marble host-rock; note a folded carbonate layer completely replaced by skarn. (b.) Exoskarn snake-shaped body selectively replacing non-cylindrical folds in Rhaetian platform carbonate unit close to the contact with Botro ai Marmi pluton (detail of Fig. 4). (c.) Exoskarn cutting the marble foliation. (d.) Endoskarn veins in Botro ai Marmi pluton. (e.) Small-size tension gash in marble (Lanzi mine). The photo shows an apparently right-lateral displacement, yet the displacement is actually left-lateral owing to the shooting of the photo from below in a mining tunnel. (f.) Normal fault located at the eastern border of Campiglia horst displacing white Hettangian reef limestone and red nodular Early Jurassic pelagic limestone.

Figure 6 – (a) 3D reconstruction of a sigmoid-tabular skarn body (Temperino mine) based on geological surveys and drill logs, and SW-NE oriented cross-section of the skarn body, showing also the S-shaped felsic Coquand dyke morphology. (b) Stereographic projection of the skarn-marble contact surfaces representing the attitudes of the contact at different mining levels (Wulff net, lower hemisphere), showing evidence for the sigmoidal shape of the skarn-marble contact.

Figure 7 – Schematic model for the magmatic-hydrothermal system at Campiglia. (a.) Emplacement of Botro ai Marmi pluton during the regional extensional phase produced a thermal anomaly changing the rheological characteristics of the carbonate host rocks. This event triggered lateral mass displacement (“squeezing”). Note the lateral thickness variation of the carbonate units, the asymmetric shape of the thermal aureole (upper boundary defined by the red dashed line), the isoclinal non-cylindrical folds at the contact with the pluton and the asymmetric folds and lenses in the eastern side of the pluton aureole. (b.) During the waning stage of the thermal anomaly, in sigmoid volumes affected by brittle fracturing, skarn bodies formed, followed by emplacement of mafic Temperino porphyry and felsic Coquand dykes. The shapes of these bodies recorded the local stress field (e.g., sigmoid-tabular shape) with a top-to-the-east sense of movement. (c.) The felsic Ortaccio dyke and the high-angle normal faults constrain the end of the lateral mass displacement of the rheologically weak carbonate material, with return back to regional extension.

Figure 1

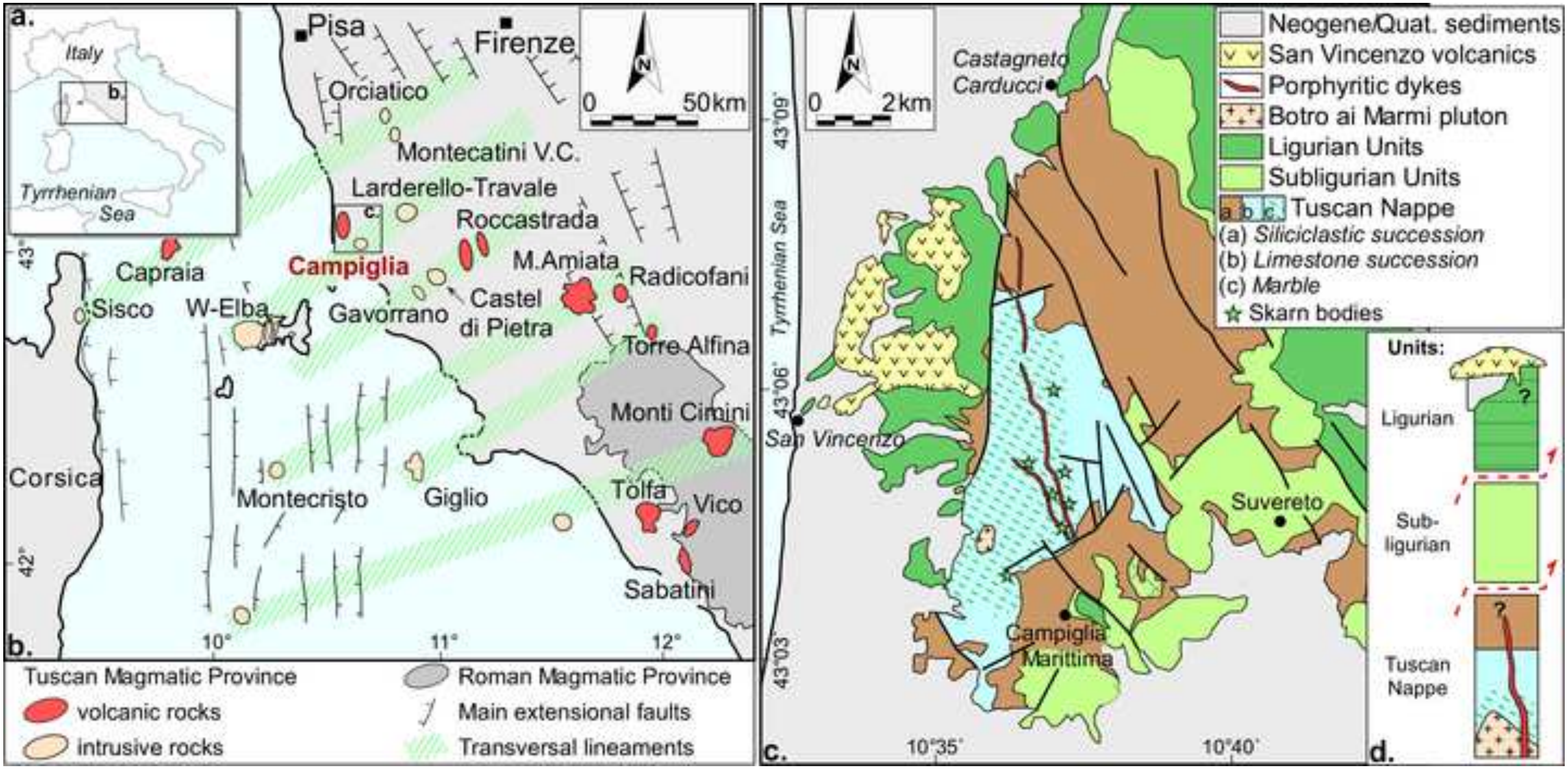

a.
Italy
b.
Tyrrhenian Sea
Pisa
Firenze
0
50km
N
Orciatico
Montecatini V.C.
Larderello-Travale
c.
Roccastrada
Campiglia
M.Amiata
Radicofani
Castel di Pietra
Gavorrano
Capraia
Sisco
W-Elba
Torre Alfina
Monti Cimini
Corsica
Montecristo
Giglio
Tolfa
Vico
Sabatini
43°
42°
10°
11°
12°
b.
Tuscan Magmatic Province
volcanic rocks
intrusive rocks
Roman Magmatic Province
Main extensional faults
Transversal lineaments
0
2km
N
Castagneto Carducci
Tyrrhenian Sea
San Vincenzo
Suvereto
Campiglia Marittima
43°09'
43°06'
43°03'
10°35'
10°40'
c.
Neogene/Quat. sediments
San Vincenzo volcanics
Porphyritic dykes
Botro ai Marmi pluton
Ligurian Units
Subligurian Units
a b c Tuscan Nappe
(a) Siliciclastic succession
(b) Limestone succession
(c) Marble
Skarn bodies
Units:
Ligurian
Sub-ligurian
Tuscan Nappe
?
?
d.

Figure 2

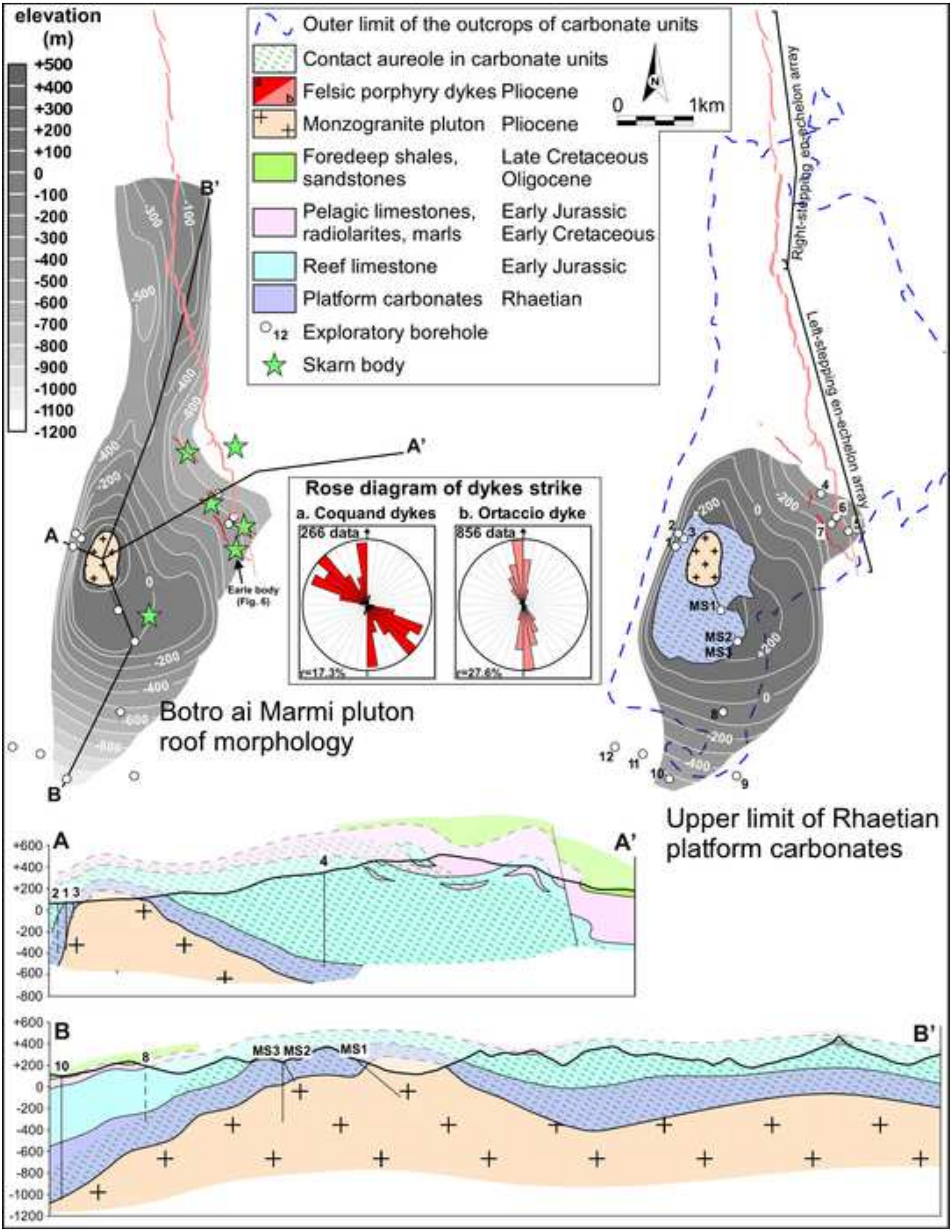
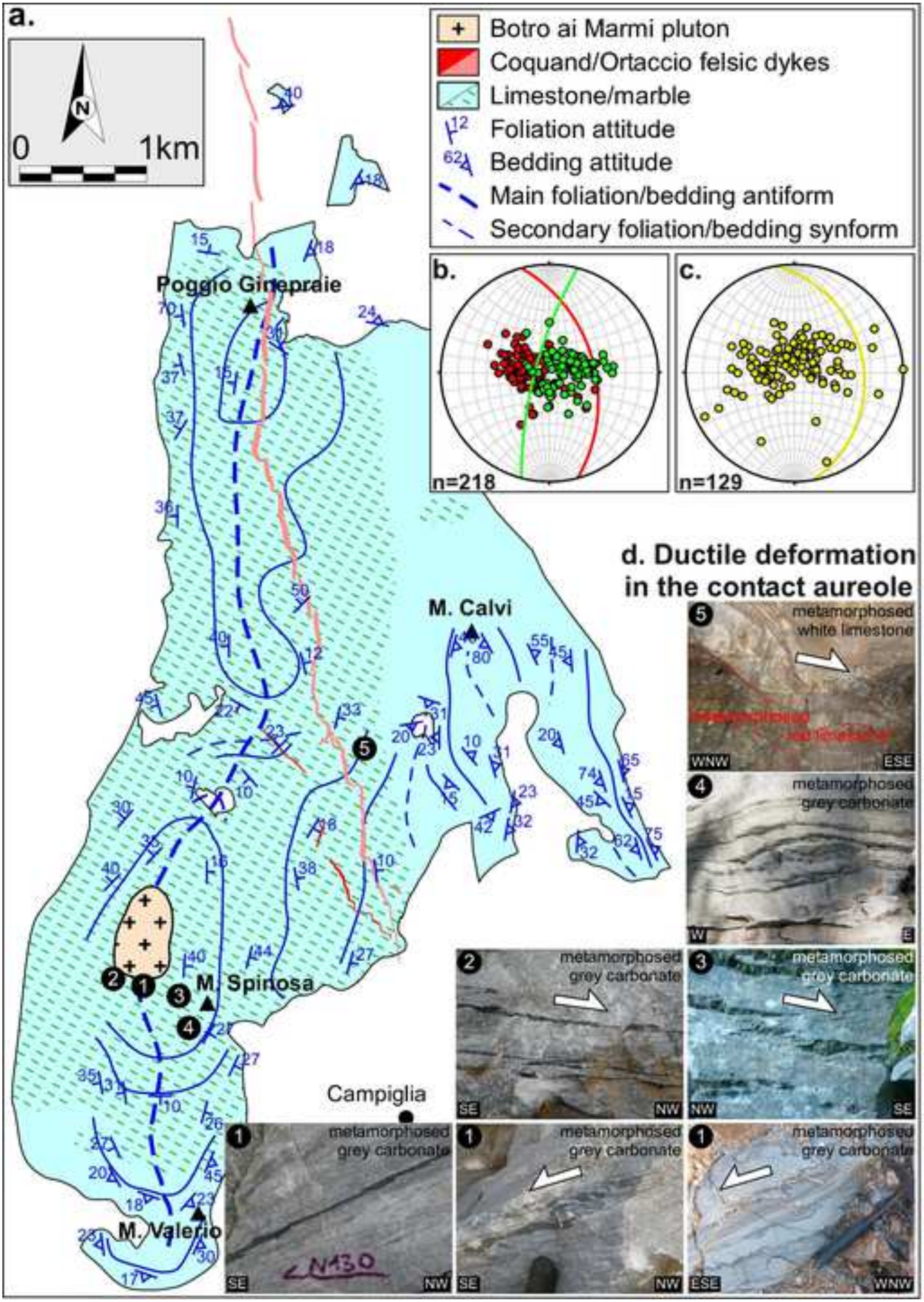
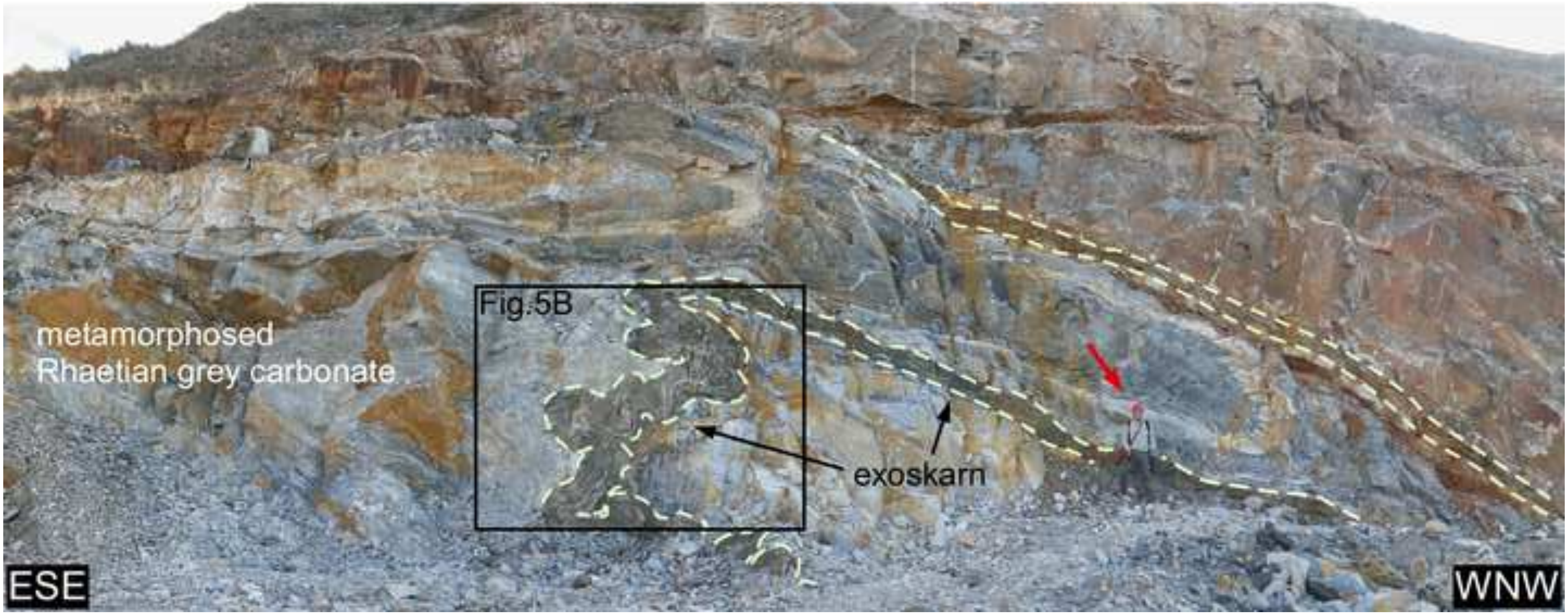

elevation (m)
+500
+400
+300
+200
+100
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
Outer limit of the outcrops of carbonate units
Contact aureole in carbonate units
Felsic porphyry dykes Pliocene
a
b
Monzogranite pluton Pliocene
Foredeep shales, sandstones Late Cretaceous Oligocene
Pelagic limestones, radiolarites, marls Early Jurassic Early Cretaceous
Reef limestone Early Jurassic
Platform carbonates Rhaetian
12 Exploratory borehole
Skarn body
N
0
1km
Right-stepping en-echelon array
Left-stepping en-echelon array
B'
A'
A
B
Earle body (Fig. 6)
Rose diagram of dykes strike
a. Coquand dykes
b. Ortaccio dyke
266 data
856 data
r=17.3%
r=27.6%
Botro ai Marmi pluton roof morphology
Upper limit of Rhaetian platform carbonates
1
2
3
4
5
6
7
8
9
10
11
12
MS1
MS2
MS3
+600
+400
+200
0
-200
-400
-600
-800
-1000
-1200
2 1 3
4
10
8
MS3 MS2
MS1

Figure 3


a.
N
0
1km
Botro ai Marmi pluton
Coquand/Ortaccio felsic dykes
Limestone/marble
Foliation attitude
Bedding attitude
Main foliation/bedding antiform
Secondary foliation/bedding synform
b.
n=218
c.
n=129
Poggio Ginepraie
M. Calvi
M. Spinosa
Campiglia
M. Valerio
d. Ductile deformation in the contact aureole
5 metamorphosed white limestone
WNW
ESE
4 metamorphosed grey carbonate
W
E
2 metamorphosed grey carbonate
SE
NW
3 metamorphosed grey carbonate
NW
SE
1 metamorphosed grey carbonate
SE
NW
N130
1 metamorphosed grey carbonate
SE
NW
1 metamorphosed grey carbonate
ESE
WNW


metamorphosed
Rhaetian grey carbonate
Fig.5B
exoskarn
ESE
WNW


S
relict fold structure
N
exoskarn
marble
Botro ai Marmi pluton
a.
marble
exoskarn
carbonate relict
marble
b.
foliation
exoskarn
marble
c.
Botro ai Marmi pluton
endoskarn veins
d.
S
marble
N
ilvaite + hedenbergite
e.
SW
NE
normal fault
pelagic red limestone
platform white limestone
f.

Figure 6

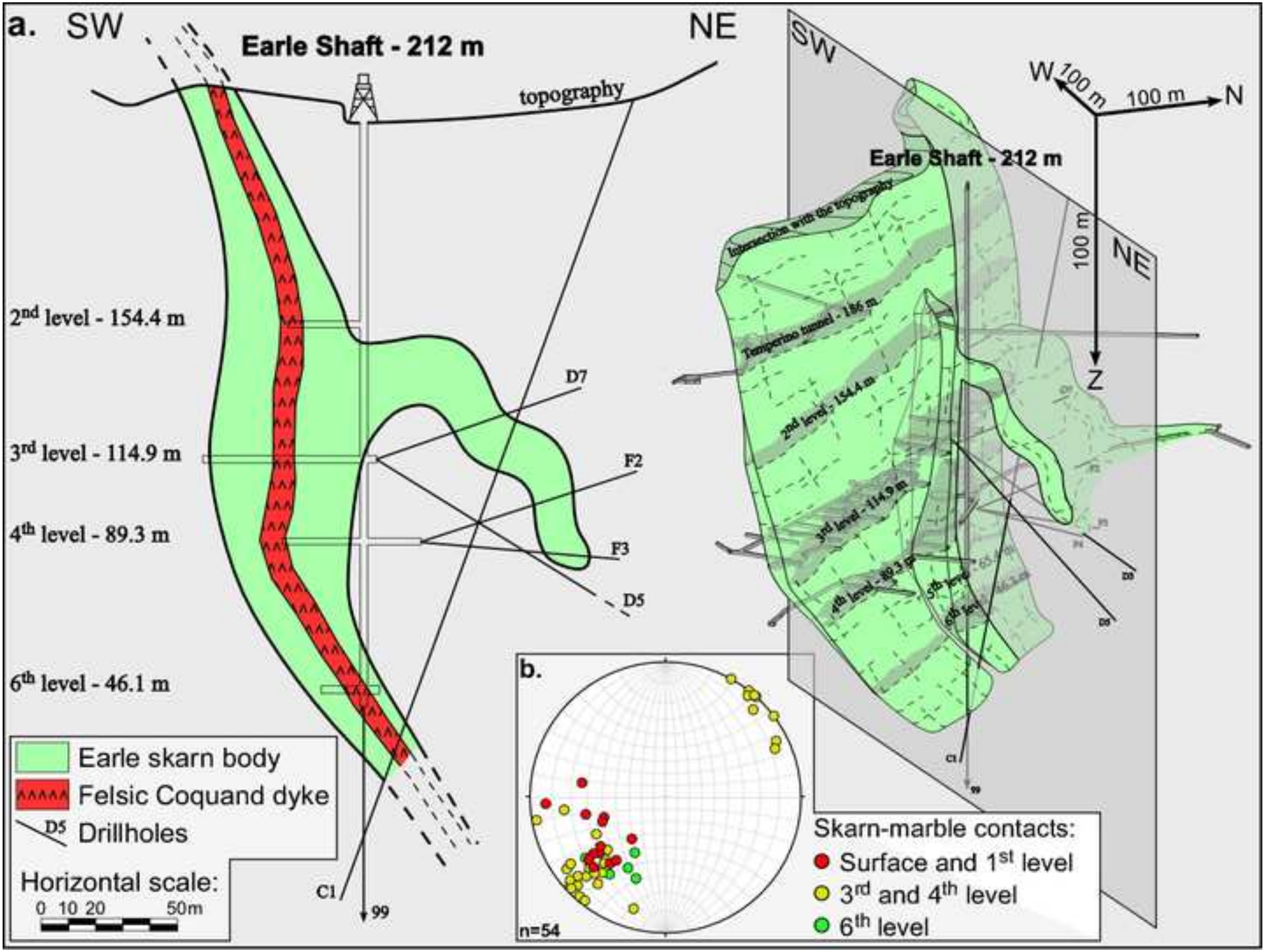
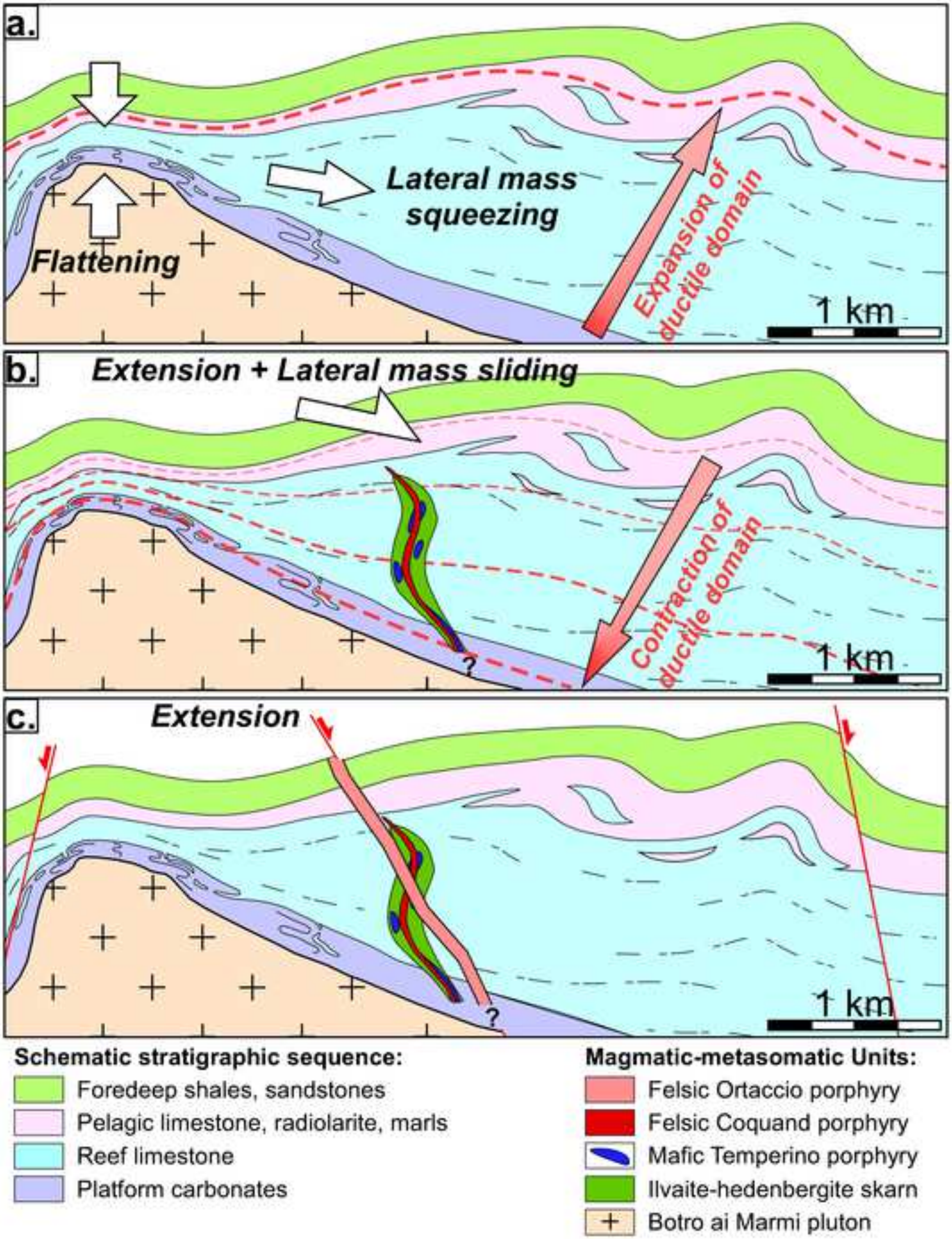

a.
SW
NE
Earle Shaft - 212 m
topography
2nd level - 154.4 m
3rd level - 114.9 m
4th level - 89.3 m
6th level - 46.1 m
D7
F2
F3
D5
C1
99
Earle skarn body
Felsic Coquand dyke
D5 Drillholes
Horizontal scale:
0 10 20 50m
SW
NE
W 100 m
100 m N
100 m
Z
Earle Shaft - 212 m
Intersection with the topography
Temperino tunnel - 186 m
2nd level - 154.4 m
3rd level - 114.9 m
4th level - 89.3 m
5th level
6th level
b.
n=54
Skarn-marble contacts:
● Surface and 1st level
● 3rd and 4th level
● 6th level

Figure 7


a.
Flattening
Lateral mass squeezing
Expansion of ductile domain
1 km
b.
Extension + Lateral mass sliding
Contraction of ductile domain
?
1 km
c.
Extension
?
1 km
Schematic stratigraphic sequence:
Foredeep shales, sandstones
Pelagic limestone, radiolarite, marls
Reef limestone
Platform carbonates
Magmatic-metasomatic Units:
Felsic Ortaccio porphyry
Felsic Coquand porphyry
Mafic Temperino porphyry
Ilvaite-hedenbergite skarn
Botro ai Marmi pluton