

## Manuscript Details

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### Abstract

In the Dolomites (Eastern Southern Alps, Italy), a diffuse Middle Triassic igneous activity is now present mostly as lava flow and pyroclastic successions, with rare shallow-depth intrusive bodies cropping out at Predazzo, Monzoni and Cima Pape areas. In this work, the emplacement modes of the Predazzo and Monzoni bodies were investigated by means of petrographic and anisotropy of magnetic susceptibility (AMS) data coupled with a field geological study. The presence of intrusive rocks in between these two bodies and the continuity of the metamorphic aureola from west of the Predazzo to east of the Monzoni body suggest that they are parts of a ~20 km wide SW-NE oriented continuous pluton, sub-parallel to Ladinian strike-slip faults. AMS and petrographic data from the Predazzo body are consistent with a multistage ring-dyke emplacement mode, with areas of upward flow of the magma located in the NE and SW part of the intrusion, whereas in the southern sector of the pluton our data suggest prevalently horizontal flows. In general, the Predazzo sheets indicate either upward magma flow or along-strike lateral magma transport, and the round shape suggests no influence of Ladinian tectonic structures. On the contrary, the ENE-WSW elongated shape of the Monzoni body was controlled by the occurrence of strike-slip faults associated with Ladinian-tectonics, the feeder being likely located at the NE edge of the body. However, the absence of deformation at the field- and micro-scale is consistent with a post Ladinian-tectonics timing of emplacement, as for the Predazzo pluton.

<b>Keywords</b>	Dolomites, anisotropy of magnetic susceptibility, pluton, Predazzo, Monzoni, mode of emplacement
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<b>Suggested reviewers</b>	Carles Soriano, Teresa Román-Berdiel, Nereo Preto, Hannah Pomella

## Submission Files Included in this PDF

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Abbas et al-reply letter.doc [Response to Reviewers]

Abbas-Highlights.docx [Highlights]

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DIPARTIMENTO DI SCIENZE DELLA TERRA  
UNIVERSITA' LA SAPIENZA - ROMA

Roma, 9<sup>th</sup> May 2018

Dear Editor of *Journal of Structural Geology*,

please consider the revised manuscript "**Emplacement modes of the Ladinian plutonic rocks of the Dolomites: insights from Anisotropy of Magnetic Susceptibility**" by Hassan Abbas and coauthors.

Please send correspondence to:

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I thank you in advance for kind attention.

Yours sincerely

Eugenio Carminati

To the kind attention of  
Prof. Ian Alsop  
Editor of Journal of Structural Geology

Dear Editor,

We thank you and the reviewers (Teresa Román-Berdiel and an anonymous referee) for your efforts to improve the quality of our manuscript, providing constructive criticisms. Below it follows how we answered to the criticisms and suggestions of the reviewer. We fulfilled all the requests. The answers to the reviewers' comments are in bold.

We are confident that this revised version of the manuscript will satisfy the standards required by the Journal of Structural Geology.

Best regards

Eugenio Carminati\*

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**Reviewer #1** Teresa Román-Berdiel

In this manuscript, the authors present the structural study of two intrusive bodies by means of AMS analysis and petrographic observations in thin section.

This is a new study based on AMS technique, and its interest lie in the use of AMS to decipher the mode of emplacement of intrusive bodies in the Dolomites. The paper is a new evidence of the validity of the method for unravel the mode of emplacement of igneous bodies with no evidences of strain or mineral preferred orientation in outcrop. The paper is the international interest in the field of AMS technique and for the knowledge of this region of the Alps.

**We thank the reviewer for her positive comments.**

The article is clear and well organized. However, I do not end up agreeing with the interpretation. There are some points that can be clarified and improved, mainly concerning the illustration of petrographic description. A new figure with photographs of thin sections is necessary to illustrate the petrographic description (section 4.1 and Appendix). Some aspects of the description of the results should also be improved. Do you observe preferred orientation of minerals in thin section? This should be described and showed in some photograph. This is a clue point in the interpretation of AMS results. The mineralogy of the described rocks (Appendix) is dominated by paramagnetic minerals, and the preferred orientation of these minerals must be compared with paramagnetic fabrics obtained. The preferred orientation of paramagnetic minerals must be coherent with the mode of emplacement proposed. Opaque minerals occur as subhedral occupying interstitial position (Appendix). If ferromagnetic and paramagnetic subfabrics do not agree there is most probably that opaque (ferromagnetic) minerals crystallize latter and can be interpreted in other terms, given information regarding a late event in the emplacement process.

**We improved the petrographic description, as also asked by reviewer 2, and added a figure (figure 6 in the revised manuscript) showing preferred orientation of minerals.**

Description of results about scalar parameters and their relationship ( $P'$ , Km) must be described in the result section. I recommended to add the diagram Km- $P_j$  in figure 7.

**We added  $P'$ -km plot in Figure 7 (T- $P'$  was removed).**

Below I indicate a series of comments that I consider necessary to improve the final presentation of this article. Please see also the annotations made directly in the text.

**All the requests were satisfied.**

Line 87 - Is "Stava line" in figure 2? It should be.

**Stava line has been labelled.**

Please use the standard symbol for thrusts in figure 2.

**Done**

Line 154 - Bellerophon Formation does not appear in figure 3, it should be, if possible.

**Done**

Line 193 - Stava, Trodena and Cavalse Lines should be in figure 2, if possible.

**Stava line has been labelled. We added a simplified tectonic map (Fig. 2a in the revised manuscript) showing Trodena and Cavalese lines, not included in the original Fig. 2 (now 2b).**

Line 206 - Can we see radial pattern of Ladinian mafic volcanic dykes in any figure?

**The radial pattern can be seen in Fig. 2 around the Predazzo body and in fig. 4a.**

I recommended to include a new figure with field photographs showing the main types of rocks sampled and described in sections 2.3 and 2.4

**We included new field pics (Figs. 6a and 6b in the revised manuscript) showing the elongated shape of the Monzoni pluton and anisotropic fabric in granite.**

Lines 244-251 - Please refer to figures in section 2.5

**OK Done**

Please add in Table I standard deviation for Km and put all Km values in the same power of 10 (normally  $10^{-6}$  SI).

**We added the standard deviation for Km but we didn't use the same power for all the sites because the range of magnetic susceptibility values is too big.**

Please add in table caption of Table I "std: standard deviation"

**Done**

Line 273 - How many thin sections has been analyzed? Please indicate the number.

**The number (29) is now indicated.**

Line 338 – PR 10? Do you mean PA10?

**Yes thanks.**

Line 346 - Do you observe preferred orientation of minerals in thin section? This should be described and showed in some photograph.

**Yes, we observed preferred orientation of minerals, as shown in the new Fig. 6c,d,e,f and now discussed in the text.**

Add “a” and “b” for each part of figures in figures 4 and 5.

**We corrected the figures adding “a” and “b”**

In figure 5 – Please add “Monzoni” in the map Hassan, please correct the figures

**We added “Monzoni” in the map.**

In figure 8 there are two “i” and the “l” is missing.

**OK, corrected**

In figure 9 add a hyphen to separate the site number from the sample number.

**Done**

In general, I advise to refer to the figures more precisely in the text.

**Thanks to the suggestions of the reviewer we quoted the figures mor precisely.**

Homogenize when writing the name of monzonitic units. Always write with uppercase or lowercase, in section 2 it is write in lowercase, in section 4 it is write in uppercase.

**OK, done**

Homogenize also: M1, M2, M3 or 1, 2, 3 (in section 2 it is write monzonitic unit M1, M2, M3; in section 4 it is write Monzonitic Unit 1, 2, 3; in figure 4 it is write Monzonitic unit 1, 2, 3).

**OK, done**

Lines 427-429 – Author explain that in samples where the HF-paramagnetic fraction is significant (>50%) there is a good correlation between low-field and high-field (ferromagnetic and paramagnetic) magnetic ellipsoids. The high-field paramagnetic sub-fabric obtained in samples where paramagnetic fraction is lower must be also interpreted in terms of emplacement mode.

**Unfortunately, in samples where the paramagnetic fraction is very low, its orientation cannot be determined with the necessary accuracy (this is now specified in the text). Unfortunately, the request of the reviewer cannot be fulfilled.**

Line 451 – Do you refer to Monzonitic unit 3? Does site PA11 belong to the Predazzo pluton?

**Yes, it belongs to the Predazzo pluton. The text is now corrected accordingly.**

Line 517 - It is the first time do you described results about P parameter. This information must be described in results section.

**We added a sentence in text (result section).**

Table 1 - Use one of the two scalar parameters (P or Pj), preferably Pj. One is enough.

**We removed P (and related standard deviation) from the table**

Line 521 - Information about relationship between Km and Pj must be described in results section before.

**We added a sentence in text (results section).**

I recommended to add the diagram Km-Pj in figure 7.

**Done**

Replace P' by Pj in diagram Pj-T of figure 7.

**Done**

Line 523 – “...the orientation of dykes (mainly trending NNW-SSE) crosscutting intrusive rocks ...” In section 2.3 you described mainly radial pattern for dykes, please clarity.

**We have clarified the text. The radial pattern was postulated by Doglioni (1983). This is now clearly explained. As shown in Fig. 4, the dykes around the Predazzo pluton show variable orientations, with a prevalence of NNW-SSE oriented. This is our observation, as specified in the text.**

531-534 –A final figure showing a scketch of the emplacement model can help.

**A final figure with the emplacement models have been added (new Fig. 11).**

**Reviewer #2**

Dear authors, dear editors

I went carefully throughout the manuscript entitled “Emplacement modes of the Ladinian plutonic rocks of the Dolomites: insights from Anisotropy of Magnetic Susceptibility”, focusing mainly on regional geology, correlation and the stratigraphy related to this study. My main research field is not structural geology nor it is igneous petrology, thus, I cannot comment too much on these two aspects.

This work is relevant with respect to a long-lasting debate on the nature of Triassic syndepositional tectonics and volcanism in the Dolomites. Despite decades of studies, this debate is far from settled, and the application of a new method of investigation (the study of magnetic anisotropies in plutonic rocks) brought to a true and welcome addition of completely new data.

With this new approach, the authors were able to pin down firmly that (1) the emplacement of the plutons followed the main Triassic tectonic phase, and (2) there were no strike-slip movements along the main Triassic tectonic lineage since the Late Ladinian (age of plutons emplacement). In my view, these results are very relevant for the reconstruction of the geologic history in a key area for the Triassic, and bear relevance for the still largely incomplete understanding we have of the geodynamic evolution of the western Tethys area during the Mesozoic.

Overall, I found the manuscript well written and easy to read. I have annotated some inconsistencies or formal problems in the way biostratigraphic or lithostratigraphic units are described, but these are things that can be easily fixed. Instances of incorrect nomenclature are marked in the commented manuscript.

**We thank the reviewer for his/her positive comments.**

In terms of the overall manuscript organization, I have only a few comments.

**(1) meaning of Ladinian tectonics.**

In the introduction, a nice, complete and synthetic explanation of the many ways the Triassic syndepositional tectonic structures of the Dolomites were interpreted is given. Later on (chapter 2.2 Ladinian tectonics in the Dolomites) only the sinistral strike-slip interpretation is considered as a base for data interpretation. This is illogical and at the same time hard to follow. If it is the author's point that only this interpretation of the Ladinian tectonics of the Dolomites is acceptable, it must be discussed somewhere, and other models should be excluded with some argumentation. If otherwise all other interpretations are outdated, there would have been no point in listing them in the introduction, and the whole problem could be dismissed by means of a few references.

This is quite important for the logical flux of the text. Later on (e.g., line 498), locally extensional features (open fractures filled by magmatic dykes) are related to strike-slip tectonics, but the reader cannot understand why other possible tectonic models are being discarded at this point, where no direct evidence of strike-slip is given. Other similar instances occur later in the text.

**We agree with the reviewer. In the introduction, after introducing all the proposed models, we explain that models involving subduction (2,4,9) are not coherent with the geological context of the Southern Alps that shows no evidence of volcanic arcs or oceanic subduction. The other models are consistent with geodynamic scenarios involving extensional tectonics, either controlled by rifting or strike-slip tectonics. The recognition of Middle Triassic NE-SW strike-slip faults in the Dolomites (e.g., Doglioni 1984a) testifies for the importance of wrench tectonics in this period. This should help the reader to understand the following of the paper.**

**(2) Separation of data and discussions**

Albeit a clear separation of background information, data and interpretations is kept in the manuscript, some mixing sneaked in into the discussions.

- The opening statements (“The AMS technique provides a quick and accurate determination...”) may better fit into the introductory or methods chapters.

**We agree. The statement has been moved to the methods section.**



- Microstructures are described as purely magmatic in the discussion as a premise to the interpretation of magnetic foliations – lineations, but these microstructures are not shown and the reader could not understand why they should be magmatic and not younger. Information on this may be inferred indirectly from the sample descriptions in the appendix, but this description and inference should be in part moved into the main text, along with a selection of images from thin sections.

**As also suggested by reviewer 1 we better explained this point (moving some info from appendix to text in the results section) and added a figure (Fig. 6 in the revised manuscript) including photographs of magmatic structures at the meso- and micro-scale.**

In summary, this is a welcome and new contribution to the understanding of the Western Tethys region. This region was tectonically active for hundreds of million years between the Variscan and Alpine orogeneses, but so far there isn't a universally accepted geodynamic model. This work provides strong evidence about the temporal relationships between magmatic activity and tectonism. My evaluation of the manuscript is overall positive.

**Thanks to the reviewer for the time spent evaluating our manuscript and providing constructive criticisms.**

- Emplacement of Triassic Predazzo and Monzoni plutons (Dolomites) is investigated
- Petrographic and anisotropy of magnetic susceptibility (AMS) data are used
- Middle Triassic structures controlled plutons emplacement modes
- Predazzo body was emplaced as a multistage ring-dyke complex
- Monzoni emplacement was controlled by a Ladinian strike-slip fault

1 **Emplacement modes of the Ladinian plutonic rocks of the Dolomites: insights**  
2 **from Anisotropy of Magnetic Susceptibility**

3

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26 **Abstract**

27

28 In the Dolomites (Eastern Southern Alps, Italy), a diffuse Middle Triassic igneous activity is now  
29 present mostly as lava flow and pyroclastic successions, with rare shallow-depth intrusive bodies  
30 cropping out at Predazzo, Monzoni and Cima Pape areas. In this work, the emplacement modes of  
31 the Predazzo and Monzoni bodies were investigated by means of petrographic and anisotropy of  
32 magnetic susceptibility (AMS) data coupled with a field geological study. The presence of  
33 intrusive rocks in between these two bodies and the continuity of the metamorphic aureola from  
34 west of the Predazzo to east of the Monzoni body suggest that they are parts of a ~20 km wide SW-  
35 NE oriented continuous pluton, sub-parallel to Ladinian strike-slip faults.

36 AMS and petrographic data from the Predazzo body are consistent with a multistage ring-dyke  
37 emplacement mode, with areas of upward flow of the magma located in the NE and SW part of the  
38 intrusion, whereas in the southern sector of the pluton our data suggest prevalently horizontal flows.  
39 In general, the Predazzo sheets indicate either upward magma flow or along-strike lateral magma  
40 transport, and the round shape suggests no influence of Ladinian tectonic structures.

41 On the contrary, the ENE-WSW elongated shape of the Monzoni body was controlled by the  
42 occurrence of strike-slip faults associated with Ladinian-tectonics, the feeder being likely located at  
43 the NE edge of the body. However, the absence of deformation at the field- and micro-scale is  
44 consistent with a post Ladinian-tectonics timing of emplacement, as for the Predazzo pluton.

45

46 **Keywords:** Dolomites, anisotropy of magnetic susceptibility, pluton, Predazzo, Monzoni, mode of  
47 emplacement

48

## 50 **1. Introduction**

51 The Middle Triassic igneous activity in the Dolomites (eastern Southern Alps, Italy; Figs. 1 and 2)  
52 is well known from nearly two centuries (e.g., von Richthofen, 1860; Hansel, 1878). The Dolomites  
53 represent a worldwide reference area for the relationships between magmatism, sedimentation and  
54 tectonics (e.g., Ogilvie-Gordon, 1902, 1903; Hörnes, 1912; Penck, 1911; Vardabasso, 1929, 1930;  
55 Leonardi, 1967; Castellarin et al., 1982, 1982b; Visonà, 1997). The igneous activity of the  
56 Dolomites is part of a more widespread magmatism developed during Middle and early Late  
57 Triassic in the western Tethys comprising the Southern Alps, Dinarides, Transdanubian Range and  
58 Austroalpine (Lucchini et al., 1982). In the Dolomites area, Middle Triassic igneous rocks are  
59 mostly pyroclastic, but abundant submarine and subaerial lava and dyke swarms also occur, with  
60 magma chambers eroded to shallow-depth intrusive body levels, cropping out at Predazzo, Monzoni  
61 and Cima Pape (Fig. 2).

62 Several contrasting geodynamic/tectonic models were proposed to explain Middle Triassic  
63 igneous activity in the Southern Alps: 1) An aborted continental rifting, based on the association of  
64 extensional structures and volcanism (Bechstädt et al., 1977); 2) Northward subduction and  
65 delamination of lower continental crust in the upper mantle, based on the calcalkaline and  
66 shoshonitic magmatic association and on local compressional structures of Middle Triassic age  
67 (Castellarin et al., 1980, 1988; Casetta et al., 2017); 3) Sinistral strike-slip tectonics associated with  
68 local compressional and extensional structures (“rhomb-horsts” and “pull-apart basins”) generating  
69 magma extrusion and subsidence as result of the collapse of magma chamber roofs (Blendinger,  
70 1985; Doglioni, 1987, 1988); 4) Marginal back-arc basin associated with the post-Variscan  
71 evolution of the Alpine sector (Marinelli et al. 1980; Viel, 1982); 5) Partial melting of a mantle  
72 source modified during the preceding Variscan orogeny and contaminated by the incorporation of  
73 large portions of crustal material (Crisci et al., 1984; Sloman, 1989; Bonadiman et al., 1994); 6)  
74 Intra-Pangea dextral megashear system with lithosphere-scale extension enabling hybridization  
75 between mantle melts and lower crust lithologies (Brandner and Keim, 2011); 7) Rifting related

76 with the opening of the Neotethys (Beltran-Trivinõ et al., 2016; Brandner et al., 2016); 8) Active  
77 upwelling of hot asthenospheric mantle due to the insulating thermal effect of the huge Pangea  
78 landmass (Stahle et al., 2001); 9) Subduction of a small Permian back-arc oceanic (Garzanti 1985;  
79 Zanetti et al. 2013). The models involving subduction (2,4,9) are not coherent with the geological  
80 context of the Southern Alps that shows no evidence of volcanic arcs or oceanic subduction. The  
81 other models are consistent with geodynamic scenarios involving extensional tectonics, either  
82 controlled by rifting or strike-slip tectonics. The recognition of Middle Triassic NE-SW strike-slip  
83 faults in the Dolomites (e.g., Doglioni 1984a) testifies for the importance of wrench tectonics in this  
84 period.

85 The Predazzo, Monzoni and Cima Pape Middle Triassic intrusive bodies in the Dolomites crop out  
86 close to Middle Triassic NE-SW strike-slip faults (e.g. Stava line; Fig. 2), suggesting a potential  
87 role for strike-slip tectonics in the emplacement of these plutons. The generation, ascent and  
88 emplacement of magma through the crust and its relation to strike-slip faulting are still matter of  
89 debate (Castro 1987; Tikoff and Teyssier 1992; Paterson and Fowler 1993; Román-Berdiel et al.  
90 1997; Rosenberg 2004). The emplacement of intrusive bodies can be considered either as controlled  
91 by regional tectonics (syntectonic) if the magmatic fabric is consistent with the regional strain field,  
92 or caused by the internal dynamics of the magma chamber if the magmatic fabric patterns are  
93 independent from the regional tectonic structures (Hutton, 1988; Paterson et al., 1998; Rosenberg,  
94 2004).

95 In the past years, several structural studies on intrusive bodies have been carried out using the  
96 anisotropy of magnetic susceptibility (AMS) technique (e.g., Van der Voo and Klootwijk 1972;  
97 Bouchez et al. 1990; Raposo and Gastal 2009, Cifelli et al., 2012). The magnetic fabric in a pluton  
98 is affected by several factors, such as the flow of the magma, the changes in its effective viscosity  
99 and the finite deformation it undergoes before complete crystallization. Assuming a direct  
100 relationship between mineral and magnetic fabrics (e.g., Graham 1954), the analysis of the AMS in  
101 igneous bodies can be used to define the relationship between magma emplacement and tectonics.

102 This is particularly crucial for rocks that often appear isotropic and where magmatic foliation and  
103 lineation are difficult to observe and measure at the outcrop scale, such as granites (e.g., Knight and  
104 Walker, 1988, Tarling and Hrouda 1993).

105 In this study, we investigate the space and time relationship between the Ladinian Predazzo and  
106 Monzoni plutons and Middle Triassic strike-slip faulting in the Dolomites using AMS techniques,  
107 coupled with petrographic and field studies. In addition to this regional significance, our work can  
108 contribute to the understanding of magma migration and emplacement in the upper crust. A few  
109 exposed subvolcanic and caldera-related plutons have been reported and magma-plumbing systems  
110 of active volcanic areas cannot be directly studied. Therefore, developing and testing models for the  
111 emplacement mechanisms of the ancient exposed sheet intrusions can contribute to the assessment  
112 of volcanic hazard and risk in active volcanic areas (Sparks, 2003; Tibaldi and Pasquarè, 2008;  
113 Cashman and Sparks, 2013).

114

## 115 **2. Geological setting**

116 The Dolomites (Figs. 1 and 2) are located in the central-eastern portion of the Southern Alps, a  
117 south-verging fold-and-thrust belt that belongs to the much larger Alpine Orogeny (Carminati et al.,  
118 2010b; Handy et al., 2010). The Southern Alps (Fig. 1) are located south of the dextral Neogene  
119 Periadriatic Line (also known as Insubric Line) and represent the retro-wedge of the double-vergent  
120 Alpine Chain (Doglioni, 1987; Castellarin et al., 1998; Castellarin and Cantelli, 2000; Bosellini et  
121 al., 2003; Doglioni and Carminati, 2008). The Southern Alps consist of a well-preserved Mesozoic  
122 passive continental margin inverted during the Alpine orogeny (Doglioni, 1987, 2007; Handy et al.,  
123 2010).

124 The area of the Dolomites testify several tectonic and magmatic events recorded in the  
125 stratigraphic succession, including: 1) Permian extensional tectonics and massive acid magmatism  
126 (Barth et al., 1993; Schaltegger and Brack, 2007; Visonà et al., 2007; Brandner et al., 2016) that  
127 induced a lithospheric anisotropy that significantly influenced the Triassic and Alpine evolution; 2)

128 Middle Triassic tectonics, associated with differential subsidence and uplift and diffuse magmatic  
129 events during the late Ladinian (Fig. 3); 3) A rifting, started in the Late Triassic (Fig. 3), evolved  
130 into the western Tethys spreading during Early Jurassic times (Carminati et al., 2010); 4) Several  
131 superimposed phases of compressional Alpine deformation including the Eo-Alpine, Mesoalpine  
132 and Neoalpine phases (Castellarin et al., 2004, 2006).

133 The dolomitic area was a wide shallow sea during Late Permian and Early Triassic times, but  
134 started to differentiate at the beginning of early-middle Anisian (Brandner, 1984; Doglioni, 1984a,  
135 1987; Masetti and Trombetta, 1998; Bosellini et al., 2003). Later, a sudden increase in subsidence  
136 combined with a strong sea level rise (Gianolla et al., 1998) drove to a general deepening,  
137 associated with the formation of high-relief carbonate buildups and retreat of the siliciclastic  
138 shoreline (De Zanche et al., 1993; Brack et al., 2007; Stefani et al., 2010; Marangon et al., 2011).  
139 Subsidence rates reached a climax during late Anisian, when the paleogeography of the Dolomites  
140 featured numerous small isolated microbial carbonate platforms (Sciliar Formation) surrounded by  
141 a deep basin (Buchenstein Formation). During Middle Triassic (Ladinian) the Dolomites witnessed  
142 a short-lived massive magmatic event, associated with a strong and localized tectonic activity  
143 (Assereto et al., 1977; Viel, 1979; Bosellini et al., 1982; Castellarin et al. 1988). Magmatic edifices  
144 such as Predazzo, Monzoni and Cima Pape (Fig. 2; Castellarin et al., 1982b; Sarti and Ardizzoni,  
145 1984), now eroded to subvolcanic to epi-pluton levels, developed during significant tectonic  
146 displacement and huge accumulation of megabreccia and chaotic mass-flow deposits (Caotico  
147 Eterogeneo, Fernazza Formation). The volcanic sequence (both submarine pillow lava and pillow  
148 breccias and subaerial lava flows) is composed of alkali olivine basalt to latite association  
149 (Castellarin et al., 1982b; Visona, 1997) and huge volumes of tuffs and volcanoclastics (Fernazza  
150 Formation). Rare quartz syenitic and much more common shoshonitic dyke swarms cut the  
151 sedimentary cover and intrude the magmatic edifices (Vardabasso, 1930; Castellarin et al, 1982b;  
152 Doglioni, 1983). Volcanic activity is also associated with the formation of evaporitic diapirs  
153 (sourced in the Upper Permian evaporitic Bellerophon Formation) that deform sedimentary covers



154 in areas adjacent to volcanic centers. The syn-volcanic age of these structures is documented by the  
155 fact that they are often cut by the magmatic dykes (Castellarin et al., 1998b). The volcanic activity  
156 ceased in upper Ladinian time and large volumes of volcanic material were dismantled and  
157 deposited as delta and turbiditic sequences in the surrounding basins (Wengen Formation). From  
158 late Ladinian to early Carnian, the subsidence rate decreased, resulting in the progradation of the  
159 southern shoreline and a general shallowing of the basins. This regressive trend culminated in the  
160 late Carnian, with a strong north-eastward shift of the coastline and complete flattening of the  
161 palaeotopography restoring a relative homogeneity in sedimentary palaeoenvironments, as  
162 documented by the Heiligkreuz and Travenanzes Formations (Stefani et al., 2010). A new  
163 transgression in the latest Carnian allowed the deposition of the thick peritidal succession of the  
164 Dolomia Principale (Stefani et al., 2010), which records a huge regional platform that extended for  
165 hundreds of kilometres from north to south and east to west. Widespread carbonate platforms then  
166 characterised the Southern Alps for several million years, from the late Carnian to (at least) the late  
167 Norian.

168

### 169 ***2.1 Age and duration of the Ladinian magmatic event.***

170 The age of the igneous activity is well constrained by biostratigraphy and geochronology. The first  
171 tephra horizon (Fig. 3) with a mafic mineral association (clinopyroxene, plagioclase and olivine) is  
172 recorded in the Acquafredda Fm. (*longobardicum* ammonoid subzone; Viel., 1979; De Zanche and  
173 Gianolla, 1995; Gianolla et al., 1998 ) and in the coeval Buchenstein Fm. (*sensu* Brack and Rieber,  
174 1993 ). The main phase of volcanic activity is recorded by the Fernazza Fm. (*neumayri* and early  
175 *regoledanus* ammonoid subzones) while the often unconformably overlaid post volcanic unit  
176 (Wengen Fm.) is assigned to the *regoledanus* ammonoid zone (Stefani et al., 2010; Mietto et al.,  
177 2012). Absolute ages from ash layers of the Seceda section (Brack et al., 1996, 1997; Brack and  
178 Muttoni, 2000; Wotzlav et al., 2018) suggest that the first evidence of mafic activity (tuffs, lava  
179 flows or submarine debris flow with lava blocks) is younger than  $239.04 \pm 0.04$  Ma (U-Pb

180 geochronology, Wotzlaw et al., 2018) and possibly coeval with the Upper Pietra Verde  
181 volcanics, where an ash layer (close to the *longobardicum/neumayri* subzones boundary)  
182 showed an age of  $238.0 \pm 0.05$  Ma (Mundil et al. 1996). The age of the termination of the  
183 paroxysmal effusive phase, is given by a tuff from the area of Alpe di Siusi (Mietto et al., 2012),  
184 where an ash layer, few meters above the top of the pillow-lava, gives an age of  $237.77 \pm 0.05$  Ma  
185 (U-Pb geochronology).

186 These ages confine the duration of the paroxysmal phase of Ladinian volcanism in the Dolomites  
187 to a time interval no more than 0.7 Myr long (considering all analytical errors) and are in agreement  
188 with the absolute age from the Predazzo intrusion, where zircons from the granitic phase were dated  
189 to  $237.3 \pm 1.0$  Ma (Mundil, 1996; Brack et al., 1997) and thus confirming a short-lived Upper  
190 Ladinian magmatic Event.

191

## 192 **2.2 Ladinian tectonics in the Dolomites**

193 During Middle Triassic time, the Dolomites were affected by N 70°-90°E trending strike-slip  
194 faulting (along the Stava, Trodena and Cavalase Lines), which locally was associated with  
195 transtensional and transpressional structures. These faults cut basement and sedimentary succession  
196 up to lower-middle Ladinian rocks (Doglioni, 1984b; Doglioni, 1987; Doglioni and Carminati,  
197 2008). These structures are concentrated along the alignment of the Stava Line – northern limb of  
198 the Cima Bocche Anticline – where flower structures suggest a sinistral kinematics.

199 Middle Triassic compressional structures were locally documented in the Dolomites and consist of  
200 folds and reverse faults (Bechstadt et al., 1977, Pisa et al., 1980, Bosellini et al., 1982; Castellarin et  
201 al., 1982; Doglioni 1982, 1984a, 1984b, 1985, 1987; Doglioni and Carminati, 2008). In addition,  
202 diapiric structures (originating from the Upper Permian evaporitic Bellerophon Fm.) elongated  
203 along N70E axis and dated to the Middle Triassic crop out in the central Dolomites (Doglioni,  
204 1984a). These Middle Triassic compressional structures were interpreted as related to N70E  
205 sinistral transpressional tectonics (Doglioni 1984a, 1984b, 1987, 2007), resulting from the sinistral

206 relative movement between Africa and Europe (Doglioni 1984b). According to Doglioni (1983)  
207 Ladinian mafic volcanic dykes in Dolomites show a radial pattern, which was interpreted as related  
208 to a domal uplift induced by coeval magmatism, possibly inheriting previous structures.

209

### 210 ***2.3 The Predazzo intrusive complex***

211 The Predazzo intrusive complex (Fig. 4) is ring-shaped, ~4 km in diameter and covers an area of  
212 ~13 km<sup>2</sup>. It has been subdivided into four intrusive units on the basis of magma chemistry,  
213 geometry and relative geochronology (Menegazzo et al. 1995; Visonà 1997). Monzonitic unit M1  
214 represents the first intruded unit and forms the outer part of the ring with mainly monzonitic  
215 composition associated with ultramafic rock types (pyroxenites). These ultramafic bodies are  
216 generally small, tabular and vertical with sinuous sharp contacts. Monzonitic unit M2 is intruded  
217 into the Middle Triassic volcanic rocks and into the Monzonitic unit M1 and cut them with short  
218 dykes. This unit crops out in the western part of the igneous complex and is mainly composed of  
219 quartz monzonite with subordinate leuco-quartz monzonite and quartz monzodiorite. In more recent  
220 studies, M1 and M2 units were merged into a single shoshonitic silica-saturated (SS) series (Casetta  
221 et al., 2017). Monzonitic unit M3 is mainly located in the eastern part of the pluton and intrudes  
222 both volcanic rocks and Monzonitic unit M1. It consists of monzodiorite to syenite, both quartz- or  
223 foid-bearing. The granite unit is located in the central part of the pluton and cuts both volcanic  
224 rocks and Monzonitic units M1 and M2. It consists of two separate lithotypes: a) biotite granite, b)  
225 tourmaline leuco-granite (Visonà, 1997). In Fig. 4 we observe variably (mainly NNW-SSE)  
226 oriented systems of basaltic to trachytic dykes that cut the entire intrusive complex together with the  
227 surrounding volcanic products, which in total cover an area of ~25 km<sup>2</sup> (Casetta et al., 2017).

228

### 229 ***2.4 The Monzoni intrusive complex***

230 The Monzoni intrusive complex (Fig. 5 and 6), located 8 km to the NE of the Predazzo complex  
231 (2) is a NE-SW elongated pluton with a length of <5 km covering an area of ~8 km<sup>2</sup>. The Monzoni

232 pluton played a central role not only for the study of the Middle Triassic magmatism but also in the  
233 development of petrography, being the type locality for monzonitic rocks (Brogger, 1895). The  
234 intrusion comprises a series of basic to intermediate plutonic rocks, which consist of gabbroic rocks  
235 (gabbro, olivine gabbro, monzogabbro), cropping out in the north-eastern part of the complex  
236 together with clinopyroxenite, while monzonites and monzodiorites constitute the western part of  
237 the intrusion (Del Monte et al., 1967; Bonadiman et al., 1994; Gallien et al., 2007) (Fig. 5). The  
238 Monzoni complex and its thermo-metamorphosed Permian to Triassic host-rocks are cut by quartz  
239 syenitic and shoshonitic dyke swarms (Bonadiman et al., 1994).

240

## 241 ***2.5 Intrusions' host rocks***

242 The country rocks of the Ladinian plutons include (Castellarin et al, 1982b) lower Permian acidic  
243 volcanic rocks of the Athesian Volcanic Group (mostly rhyolites; Marocchi et al., 2008), a  
244 succession of volcanites up to >2 km thick, the Upper Permian fluvial red beds of Val Gardena  
245 Sandstones (~100 m thick; Figs. 4, 5), the Upper Permian marls and evaporites of the Bellerophon  
246 Fm. (~300 m; Fig. 4), the Lower Triassic clastic-carbonate Werfen Fm. (~280-500 m; Figs. 3, 4),  
247 the middle Anisian mixed carbonate-siliciclastics units (from Richthofen to Contrin Fm.; ~150-200  
248 m; Figs. 3, 5), the Sciliar carbonate platform (~800 m) and the mainly cherty limestones of  
249 Buchenstein Fm (max 80 m).

250 The sedimentary cover is overprinted by contact metamorphism around the plutons (Vardabasso,  
251 1929,1930; Ferry, et al., 2002, Gallien, et al., 2007), and exhibit strong evidence of regional  
252 tectonic deformation. The area around the intrusions is characterized also by significant collapses of  
253 the sedimentary cover (Vardabasso, 1930; Castellarin et al., 1982b) with vertical displacements of  
254 several hundred meters (e.g., Monte Agnello area) and platform-block tilting (e.g., Vallaccia area).

255

## 256 **3. Sampling and Methods**

### 257 ***3.1 Sampling***

258 Sampling for petrographic and AMS analyses was carried out both in the Predazzo and Monzoni  
259 plutons (Table 1). In the Predazzo intrusive body, 14 sites were sampled and 107 cylindrical cores  
260 were collected for AMS analysis (Fig. 4a). In the Monzoni intrusive body, 10 sites were sampled  
261 for a total of 84 cylindrical cores (Fig. 5a). At each site, cores were drilled using an ASC 280E  
262 petrol-powered portable drill and oriented *in situ* by a magnetic compass, corrected to account for a  
263 local  $\sim 2^\circ$  magnetic declination according to the NOAA National Geophysical data center. The  
264 geographic distribution of the sampling was influenced by the difficulty to find accessible outcrops  
265 in many areas, preventing the possibility to make a homogeneously distributed sampling throughout  
266 the two intrusive bodies.

267

### 268 **3.2 Petrographic analysis**

269 The collected samples were cut with a diamond-disc saw to obtain 29 thin sections for  
270 petrographic study and the reminder parts were grounded in a steel mill to about mm-scale  
271 fragments. The petrographic description of the thin sections was accomplished using an optical  
272 polarizing microscope.

273

### 274 **3.3 Magnetic mineralogy**

275 The AMS technique provides a quick and accurate determination of igneous rock fabric. The  
276 magnetic fabric (lineation and foliation) data obtained from AMS measurement can record the  
277 primary magma flow in magmatic sheet intrusions (Polteau et al., 2008; Petronis et al., 2013,  
278 Andersson et al., 2016; Magee et al., 2016), although magnetic fabric data are sometimes complex  
279 and in some cases subject of controversy. The precise knowledge of the magnetic mineralogy is an  
280 important aspect to use AMS for tectonic purposes because the preferred orientation of different  
281 magnetic minerals reflects the deformation history of the rock (e.g., Rochette et al. 1992; Hrouda et  
282 al. 1997). Magnetic mineralogy analyses were carried out in order to characterize which are the  
283 main magnetic minerals in the sampled sites. The variation of magnetic susceptibility with

284 temperature was measured on powders from 24 representative samples, one for each site, by means  
285 of the same Agico KLY-3 Kappabridge used for LF-AMS measurements, equipped with a CS-2  
286 furnace, at the paleomagnetic laboratory of the Department of Sciences of Roma Tre University.  
287 Samples were heated up to 700 °C and cooled back to 40 °C to estimate the Curie/Néel range of  
288 temperatures, according to the inverse susceptibility method proposed by Petrovský and Kapička  
289 (2006), and to examine any possible mineralogical change associated to the heating process in air.  
290 Moreover, the hysteresis properties of powders from 21 representative samples were measured on a  
291 Princeton Measurements Corporation 3900 vibrating sample magnetometer (VSM), in field up to 1  
292 T. The powders have been placed in pharmaceutical gel caps suitable for vibrating in the VSM, in  
293 order to determine, after subtracting the high field linear trend, the coercive force ( $B_c$ ), the  
294 saturation remanent magnetization ( $M_{rs}$ ), as well as the saturation magnetization ( $M_s$ ). The  
295 coercivity of remanence ( $B_{cr}$ ) values have been extrapolated from backfield remagnetization curves  
296 up to -1 T, following forward magnetization in a +1 T field. These measurements were carried out  
297 in the Istituto Nazionale di Geofisica e Vulcanologia (INGV, Rome).

298

### 299 ***3.4 Anisotropy of low-field magnetic susceptibility (LF-AMS)***

300 AMS is defined by a second rank tensor and represented geometrically by an ellipsoid in which  
301 the greatest intensity of magnetization is induced along the long axis  $k_1$  and the weakest intensity  
302 along the short axis  $k_3$  (with the principal axes  $k_1 > k_2 > k_3$ ). Since the pioneering work of Graham  
303 (1954), a close correlation between the directions of the main axes of AMS ellipsoid ( $k_1, k_2, k_3$ ) and  
304 the petrofabric strain axes ( $\lambda_1, \lambda_2, \lambda_3$ ) has been widely demonstrated. Several parameters have been  
305 defined both for the quantification of the magnitude of anisotropy and for defining the shape of the  
306 ellipsoid (Table; Jelinek, 1981; Hrouda, 1982). The mean susceptibility values  $k_m$  have been  
307 computed as  $k_m = (k_1 + k_2 + k_3)/3$ . The magnetic lineation is computed by  $L$  ( $k_1/k_3$ ) and has an  
308 orientation defined by the orientation of  $k_1$ , while the magnetic foliation is computed by  $F$  ( $k_2/k_3$ )  
309 and it is defined as the plane perpendicular to  $k_3$ .  $T$  is the shape parameter and range from -1

310 (perfectly prolate ellipsoid with  $L \gg F$ ) to +1 (perfectly oblate ellipsoid with  $F \gg L$ ) with zero  
311 values corresponding to a triaxial shape ( $F \sim L$ ). The anisotropy degree is computed by the  
312 parameter  $P_j$  (Jelinek, 1981), which is obtained considering all the three principal susceptibility  
313 values.

314 Measurement of the anisotropy of low-field magnetic susceptibility (LF-AMS) represents a rapid  
315 and non-destructive technique for the characterisation of the mineral fabric in rocks (Hrouda, 1982).  
316 In this study, the LF-AMS was measured on about 200 specimens, with an Agico KLY-3S  
317 susceptibility bridge (Jelínek and Pokorný, 1997) in the paleomagnetic laboratory of the  
318 Department of Sciences of Roma Tre University. The anisotropy measurements at both the  
319 specimen and the site scale were evaluated using Jelínek's statistics (Jelinek, 1977).

320

### 321 ***3.5 Anisotropy of high-field magnetic susceptibility (HF-AMS)***

322 As the LF-AMS is the sum of the contribution from all minerals, which include ferromagnetic,  
323 paramagnetic and diamagnetic phases (Rochette et al., 1983), we measured high-field AMS (HF-  
324 AMS) on 13 selected samples in order to discriminate the relative contribution of ferromagnetic and  
325 paramagnetic minerals to the magnetic anisotropy (e.g., Martin Hernandez and Hirt, 2001). HF-  
326 AMS measurements were carried out, using magnetic fields up to 1500 mT. These fields are strong  
327 enough to saturate all ferromagnetic minerals except hematite (not present in the analyzed samples),  
328 and allow the separation of paramagnetic and ferromagnetic contribution to the magnetic anisotropy  
329 (e.g., Hrouda and Jelínek, 1990). Measurements were made with a high-field torque magnetometer  
330 (Bergmüller et al., 1994) in the Laboratory of Natural Magnetism of the Institute of Geophysics  
331 ETH in Zürich.

332

## 333 **4. Results**

### 334 ***4.1. Petrographic description***

335 A complete petrographic description of the samples (Table 1) is provided in Appendix A. Here a  
336 summary is presented.

337 In the Predazzo pluton, lithologies vary from cumulitic clinopyroxenite (samples PA12, PA11a, b,  
338 c) to cumulitic gabbro (PA10), diorites (PA06), monzonite (PA02, PA10), monzodiorite (PA08,  
339 PA14c, PA09), monzogabbro (PA12) albitized granite (PA01, PA04, PA05, PA17) and biotite  
340 granite (PA07, PA03, PA13). We found evidence of hydrothermal alteration in samples from the  
341 northern part of granite body of the Predazzo pluton (PA01, PA04, PA05, and PA17).

342 The samples from Monzoni pluton are classified into two main groups: gabbroic rocks and  
343 monzonites. Gabbroic rocks are mainly located in the north-eastern sector of the pluton and consist  
344 of monzogabbros (PA21), non-cumulitic gabbros (PA16) cumulitic gabbros (PA15) and olivine  
345 gabbros (PA20, PA18). Monzonites (PA22, PA22a, PA23, PA24) are mainly located in the south-  
346 western sector of the pluton and represent the most widespread rock type.

347 As accurately described in the appendix, the samples from both plutons show purely magmatic  
348 structures (for most of lithologies hypidiomorphic inequigranular medium- to coarse-grained  
349 textures with anhedral, to euhedral crystals) with undeformed feldspar, clinopyroxene, and  
350 amphibole. In few cases, kinked biotite occurs. Quartz does not show any or very limited  
351 undulatory extinction, and no or rare sub-grains.

352

#### 353 ***4.2 Magnetic fabric results***

354 The magnetic susceptibility and main anisotropy parameters of the analyzed sites are listed in  
355 Table 1. The orientation of the magnetic foliation and magnetic lineation has been reported in pre-  
356 tilting coordinates, on the base of the regional structural evolution and geological mapping, which  
357 show a 10° of tilting toward NE in the Predazzo area and 15° toward N in the Monzoni area. In the  
358 Predazzo pluton, a bimodal distribution of  $k_m$  values is observed, which reflects the lithological  
359 differences of the analyzed samples (Table 1). Samples taken from granites show low values, in the  
360 range of  $E^{-03}$ - $E^{-05}$  SI, whereas samples from clinopyroxenites, gabbros and diorites show higher



361 values (up to  $1.63 \text{ E}^{-01}$  SI), qualitatively suggesting a major contribution of ferromagnetic minerals  
362 to the magnetic susceptibility in these latter lithologies. These data are consistent with the  
363 occurrence of magmatic foliation (Fig. 6b) both at meso- and micro-scale. In the Monzoni pluton,  
364 monzonites and gabbroic rocks show similar values of  $k_m$ , in the range of  $\text{E}^{-02}$  SI, suggesting a  
365 strong contribution of ferromagnetic minerals (Table 1) consistent with preferred orientation of  
366 minerals observed in thin sections (Fig. 6c,d,e,f). The susceptibility vs. temperature heating-cooling  
367 curves indicate that low-Ti content titanomagnetite and magnetite are the main ferromagnetic  
368 minerals both in the Pradazzo and Monzoni intrusive bodies. A slight to moderate step around 350  
369 °C is attributed to the presence of a small amount of maghemite which converted to hematite as  
370 confirmed by the slightly lower susceptibilities recorded along the cooling curves (Fig. 7 a-d). Also,  
371 a well-defined Hopkinson peak has been recorded in few samples, before a sudden drop in  
372 susceptibility which might correspond to a partially oxidized titanomagnetite (Fig. 7 c and d).  
373 Hysteresis loops (Fig. 7 e-h), isothermal remanent magnetization (IRM) acquisition curves and  
374 backfield applications are well defined, due to the relatively high values of the concentration  
375 dependent magnetic parameters. The results are mainly consistent with a prevailing low-coercivity  
376 component, as evidenced by Bcr values, which are lower than 40 mT (Fig. 7 i-l).

377 In most of the sites, the magnetic foliation is well developed and its values (F) are greater than  
378 those of the magnetic lineation (L; Table 1 and Fig. 8). Magnetic shape factors (T) in most of the  
379 samples show a dominant oblate shape, and for few samples, it shows prolate and triaxial shape  
380 (Table 1). The degree of anisotropy (Pj) values do not show significant difference between  
381 monzonite and granites and vary between 1.01 and 1.15 (Fig. 8b Table 1).

382 In the Predazzo intrusives, the Monzonitic Unit M1 has been sampled in different sites along the  
383 southern (PA08, PA09, PA10), the south-western (PA06) and north-western (PA02) borders of the  
384 plutonic body (Fig. 4a). In all these sites AMS shows a well-defined magnetic foliation, which  
385 ranges from moderately dipping ( $25^\circ$ ) to vertical ( $89^\circ$ ) and strikes almost parallel to the intrusive  
386 borders. In particular the magnetic foliation is oriented WSW-ENE at sites PA08, PA09, and PA10,

387 WNW-ESE at site PA06, and N-S at site PA02 (Figs. 4b and 9a, e, f). Furthermore, we sampled a  
388 site (PA12) in one of the mafic bodies that outcrop along the western part of the intrusive. The  
389 magnetic foliation dips outward the intrusive body at sites PA02, PA09 and PA10 and toward the  
390 boundary within Monzonitic Unit M2 at sites PA06, PA08 and in the mafic body site PA12. The  
391 magnetic lineation shows gentle to sub-horizontal dipping, and is variably oriented respect to the  
392 intrusive body, ranging from sub parallel to the boundary (PA02, PA06, PA08, PA09) to orthogonal  
393 to it (PA10) to disperse around a great circle (PA12). The Monzonitic Unit M3 has been sampled at  
394 one site (PA11), located in the eastern part of the intrusive. In this site, magnetic foliation is very  
395 well defined and is sub-vertical with a WSW-ENE direction, parallel to the elongation of this unit.  
396 Magnetic lineation is also well defined and sub-vertical (Figs. 4b and 9d).

397 The granite intrusion has been sampled in 7 sites, located in the north-western (PA01, PA04,  
398 PA05 and PA17), in the south and south-western (PA03, PA07 and PA08) boundaries of the body  
399 (Fig. 4a). The magnetic foliation is well defined in all the sites, but in site PA01 where it shows a  
400 significant dispersion around an E-W direction. In the north-western part of the intrusion magnetic  
401 foliation is oriented NNE-SSW at sites PA04 and PA05, where it is sub-vertical and dips toward the  
402 internal and the external border of the intrusive body, respectively (Figs. 4b and 9b, c), whereas at  
403 site PA17 the magnetic foliation is E-W oriented and dips toward the north. In the south-western  
404 part of the granitic body, the magnetic foliation is also parallel to the border of the intrusion, being  
405 W-E oriented at site PA03 and NW-SE at site PA07. In both sites, the foliation is dipping toward  
406 the external part of the intrusion. The magnetic lineation is very poorly defined at sites PA01 and  
407 PA07, whereas is sub-vertical at sites PA04 and PA05. At sites PA03 and PA17 the magnetic  
408 lineation is poorly grouped with a sub-horizontal E-W orientation (Figs. 4 and 9a-f).

409 In the Monzoni pluton we sampled mafic rocks in the eastern part of the intrusive, and monzonite  
410 units in the western part of the body (Fig. 5a). In the monzonite sites (PA22, PA23, and PA24), the  
411 magnetic foliation is well defined, with a W-E orientation and a sub-vertical attitude. In these sites,  
412 the magnetic lineation is well defined and mostly shows sub-vertical dip (Figs. 5b and 9j). In the

413 mafic units, the magnetic foliation is well defined and varies from gently dipping toward the SE  
414 (PA18) to a sub-horizontal attitude (PA19, PA20, PA21). In all these sites, the magnetic lineation is  
415 well defined with a WNW-ESE orientation (Figs 5b and 9i, k, l). At sites located in the eastern part  
416 of the pluton, the magnetic foliation is well defined at sites PA15 and PA16, where it shows a NE-  
417 SW orientation and a steep dipping to NW. At site PA14 the magnetic foliation is poorly defined,  
418 being dispersed in a E-W direction. Magnetic lineation is well defined at sites PA14 and PA16,  
419 where it is sub-horizontal and N-S oriented respectively, whereas it is poorly defined at site PA15.  
420 (Figs. 5b and 9g-h).

421 HF-AMS measurements indicate that, for most of the samples, the observed magnetic fabric is  
422 dominated by the ferromagnetic component (Fig. 10) in most of the sites and a very good  
423 correspondence between the orientation of the principal axes of the ellipsoid at low-field and those  
424 of the ferromagnetic ellipsoid in high-field exists. This suggests that the magnetic fabric can be  
425 described in terms of the orientation of the ferromagnetic minerals. In samples where the HF-  
426 paramagnetic fraction is significant (>50%), there is a good correlation between low-field and high-  
427 field (ferromagnetic and paramagnetic) magnetic ellipsoids, whereas when the paramagnetic  
428 fraction is very low its orientation cannot be determined with the necessary accuracy (Fig. 10d).

429

## 430 **5. Discussion**

431 Magnetic fabric in intrusions can be purely magmatic (related to internal magma chamber  
432 processes, such as convection, magma surges, and dyke injection) or it can be the result of regional  
433 deformation (syn- to post-tectonic strain) or a combination of these two processes (Paterson et al.,  
434 1998). In the Predazzo and Monzoni bodies, thin section analyses show that the microstructures are  
435 purely magmatic (i.e., just after the complete crystallization of magma). The absence of evident  
436 solid-state deformation suggests that the magnetic fabric is not related to tectonic deformation after  
437 cooling, but it rather developed during magma emplacement and cooling (Büttner, 1999).  
438 Hydrothermal fluids can also modify the magnetic fabric orientation and parameters acquired

439 during magma emplacement and cooling, thus complicating the interpretation of magnetic fabric  
440 data (e.g. Just et al. 2004; Petronis et al. 2011; Nédélec et al. 2015; Tomek et al., 2017). Although  
441 some samples from the northern part of the Predazzo granite body (PA01, PA04, PA05, and PA17)  
442 showed evidence of hydrothermal alteration, in most of these sites magnetic foliations are generally  
443 tangent to the ring shape of the pluton. This suggests that hydrothermal alteration had no or minor  
444 effect on the magnetic fabric, with the exception of sample PA17, that is strongly hydrothermally  
445 altered and fractured and show a distinctive magnetic fabric. Therefore, site PA17 will be no longer  
446 considered in the discussion of the emplacement mode of the Predazzo pluton. Samples from site  
447 PA11, belonging to Monzontic Unit M3 of the Predazzo body, are highly altered and transformed as  
448 a result of hydrothermal solutions. However, the magnetic fabric orientation is concordant with NE-  
449 SW elongation shape of Monzontic Unit M3 and shows well-clustered magnetic fabric. The  
450 compatibility of the magnetic fabric with the elongation shape of this unit could be explained as the  
451 hydrothermal fluid was likely coeval with the emplacement as a single event (e.g. Nédélec et al.,  
452 2015). Moreover, the NE-SW orientation of the magnetic fabric and elongation of the Monzonitic  
453 Unit M3 suggests that the emplacement of this unit was controlled by NE-SW Middle Triassic  
454 (Ladinian) tectonic structures.

455 In the following, the Predazzo and Monzoni plutons will be discussed separately. However, Figure  
456 2 shows that these intrusive bodies may be parts of a single large and rather continuous body, as  
457 suggested by the outcrop of a small volume of intrusive rocks between the plutons and by the  
458 continuity of a metamorphic aureola from west of the Predazzo body to the Monzoni body. The  
459 emplacement of Ladinian intrusive bodies likely occurred along a fractured zone associated with  
460 previous strike-slip tectonics (Fig. 11a), as suggested by the parallelism between Ladinian  
461 intrusives and Middle Triassic faults (e.g., Stava-Trodona line, Fig. 2b).

462 The Predazzo and Monzoni plutonic rocks show distinct shapes, the first being roughly round  
463 shaped and characterized by ring type successive intrusions, the second being markedly NE-SW  
464 elongated, sub-parallel to the Middle Triassic Stava-Trodona line. Similarly, the AMS analyses

465 show markedly different results for the two intrusive bodies, suggesting different emplacement  
466 modes. Both the Predazzo and Monzoni bodies are the result of multiple intrusions, as indicated by  
467 the variety of lithologies described above (see also appendix A).

468

### 469 ***5.1 Emplacement mode of the Predazzo pluton***

470 In the Predazzo body, AMS has been measured in the different intrusive bodies that form the  
471 pluton, showing distinctive pattern of magnetic fabric. The Monzonitic Units M1 and M2, that  
472 represent the older portion of the pluton, are characterized by an annular ellipsoidal shape, gently  
473 elongated in a ENE-WSW direction. In this body, the magnetic foliation is generally oriented  
474 parallel to the borders of the intrusion (i.e., parallel to its perimeter). In sites that are located along  
475 the external rim, the foliations are predominantly steeply or shallowly radially dipping away from  
476 the pluton. On the contrary, in sites located along the internal rim of the annular intrusion the  
477 foliations radially dip towards the centre of the pluton. The magnetic lineation is generally gently  
478 dipping to sub-horizontal and parallel to the border of the intrusion. In the granite body the  
479 magnetic foliation is almost parallel to the rims of the pluton and dips away from the intrusion,  
480 whereas the magnetic lineation varies from sub-vertical to sub-horizontal. The rough ring shape of  
481 the Predazzo multistage intrusive complex and the presence of volcanic rocks at the centre of the  
482 ring (suggesting a caldera collapse of this area), led Castellarin et al. (1982b) to suggest a ring dyke  
483 emplacement mode. Ring dykes are cylindrical sheet intrusions occurring at subvolcanic level  
484 characterized by outward-dipping walls on all sides. They are due to magma ascent along steep  
485 outward-dipping ring fractures, induced by the collapse of the central block subsidence (e.g.,  
486 O'Driscoll et al., 2006). The development of caldera ring-faults and the related subsidence of a  
487 central block are the main structural processes that permit the intrusion of ring-dikes (Roche et al.,  
488 2000).

489 Our AMS data are consistent with the ring dyke emplacement mode. In particular magnetic  
490 foliation in the Monzonitic units is dominantly oblate and consistently parallel to the boundaries of

491 the intrusion and prevalently dips away from the intrusion. Only in places, where sites have been  
492 sampled close to the internal boundary of the Monzonitic units, the foliation is very steep and  
493 dipping toward the internal rim, describing a symmetrical pattern of the magnetic foliation respect  
494 to the dike rims. This geometry has been widely recognized in volcanic dykes, where it has been  
495 interpreted as related to imbrication of the magnetic foliation along the dyke margins, related to  
496 upward flow of the magma (Aubourg et al., 2002). In this mechanism, the horizontal magnetic  
497 lineation can be interpreted as an intersection lineation between differently oriented foliation planes  
498 , which is oriented orthogonal to the magma flow. In sites far from the pluton margins (e.g. PA11),  
499 the steep lineations associated with steeply dipping foliations are likely related to ascent paths of  
500 magma, in particular with laminar flow and wall friction during injection (Andersson et al., 2016).  
501 On the other hand, in sites far from the intrusive rims (e.g. PA02) the occurrence of sub-horizontal  
502 lineations (tangential to the shape of the pluton) could be related to lateral flow of magma induced  
503 by "roll-over" at propagating sheet tips (Emeleus et al., 2012; Andersson et al., 2016) or to semi-  
504 chaotic particle movement during ring fissure flow, as observed in analogue models (Kennedy et  
505 al., 2008). The occurrence in some samples of magmatic layering steeply dipping inward and  
506 magnetic lineations plunging toward the centre of the intrusion suggests that the shape of the walls  
507 was not as regular (i.e., constantly outward dipping) as assumed in ring dyke models (complex flow  
508 due to complex sheet geometry of Andersson et al., 2016). The steep attitude of inward dipping  
509 foliations is not consistent with a lopolithic geometry of the Predazzo intrusion.

510 The degree of anisotropy ( $P_j$ ) varies between 1.01 and 1.15 and is not controlled by lithology (i.e.,  
511 low and high values are found both in monzonites and granites). More remarkably, the values do  
512 not show a pattern (e.g., high values aligned along WSW-ENE directions, typical of Ladinian  
513 tectonics) but are rather randomly distributed. This confirms a primary (i.e., emplacement-related)  
514 nature of magnetic anisotropy. Moreover, the nonlinear relationship between  $K_m$  and  $P_j$  supports  
515 that the obtained low  $P_j$  values indicate the existence of low strain during the emplacement.

516 Finally, also the orientation of dykes (mainly trending NNW-SSE) crosscutting intrusive rocks is  
517 at odds with sinistral strike slip tectonics along WSW-ENE structures, that would be rather  
518 associated with NE-SW trending dilational (extensional) structure. NE-SW trending dykes are  
519 rather found in the host rocks of the pluton, suggesting that they utilized previous extensional  
520 structures associated with sinistral strike-slip faulting. Thus, their emplacement and the  
521 emplacement of the pluton were post-tectonics.

522 In summary, field petrographic and AMS data are consistent with a multistage ring dyke  
523 emplacement mode, similar to the piston floor subsidence mechanism (Tomek et al., 2014), likely  
524 post-tectonics. The Predazzo sheets were emplaced via prevalent updip magma flow associated with  
525 local along-strike lateral magma transport (Fig. 11b).

526

### 527 ***5.1 Emplacement mode of the Monzoni pluton***

528 The shape of the Monzoni pluton was clearly controlled by Middle Triassic tectonics, being it  
529 elongated WSW-ENE, parallel to the Stava-Trodene strike-slip fault. It remains to be discussed  
530 whether this control was direct (syn-tectonic emplacement of the pluton) or indirect (emplacement  
531 along pre-existing tectonic structures). The host rocks of the Monzoni pluton are affected on all  
532 sides by contact metamorphism. This suggests that the host rock-pluton contacts are primary, thus  
533 no or very poorly affected by post-emplacement tectonics.

534 Comparing magnetic and deformation fabrics in the pluton with strain markers in the country  
535 rocks one can determine whether the magnetic fabric in pluton is primary or reflects regional  
536 tectonic strain (Benn et al., 1998, 2001; Talbot et al., 2005; Raposo et al., 2012). Three different  
537 areas, with distinct magnetic fabric can be recognized in the Monzoni body. In the NW side, the  
538 magnetic foliation is well defined, sub-vertical, and parallel to the E-W oriented boundaries of the  
539 igneous body in this area, with a very steep magnetic lineation. Along the NE side of the intrusive  
540 body the magnetic foliation and magnetic lineation vary from very gently dipping to sub-horizontal.  
541 Along the SE side the magnetic foliation is almost parallel to the boundary of the intrusive and

542 gently to strongly dipping toward the internal part of the pluton, whereas the magnetic lineation is  
543 prevalently gently plunging.

544 Our AMS results suggest that the magnetic fabric in Monzoni pluton was not directly controlled  
545 by Middle Triassic or post-tectonic deformation. This conclusion is supported by the absence of  
546 solid state deformation, by the general steeply magnetic fabric on the two sides of the pluton with  
547 absence of the NE-SW horizontal magnetic lineation and by the low degree of anisotropy ( $P_j$ ),  
548 suggesting that magnetic fabric developed during magma emplacement and cooling and was likely  
549 controlled by the shape of the magma chamber.

550 The magnetic fabric can be read in terms of direction of flow and can help to infer the location and  
551 geometry of the feeding or root zones for magmatic bodies (e.g., Marre, 1986; Djouadi et al., 1997;  
552 Callot et al., 2001; Petronis et al., 2005; O'Driscoll et al., 2006; Maes et al., 2007). Magma  
553 originating from a planar dyke generates a parallel flow pattern with lineations pointing to  
554 opposing, but consistent directions, on either side of the dyke (Knight and Walker, 1988; Ernst and  
555 Baragar, 1992; Maes et al., 2007). Generally, the magnetic lineation, which represents the magma  
556 flow, plunges toward the magma source (Knight and Walker, 1988; Ernst and Baragar, 1992; Maes  
557 et al., 2007). In case of magma fed from a sub-vertical conduit, radial magma flow pattern is  
558 expected. Multiple feeders can produce more complex patterns of magma flow (Maes et al., 2007).  
559 In the Monzoni pluton, the magnetic lineations converge towards the north-eastern part of the  
560 pluton (PA15, PA16, PA18, PA22, PA23, and PA24), suggesting that the root zone was not located  
561 at the centre of the pluton but rather towards NE. This interpretation is also consistent with the  
562 magmatic evolution of the pluton. Indeed, the most evolved rocks are located at the south-western  
563 edge of the pluton, while the less evolved rocks are located at the north-eastern part of the pluton.

564 In the Monzoni pluton, steep to moderate foliations and lineations at the western and eastern  
565 borders of the pluton leave space to shallowly dipping fabric in its intermediate parts. This fabric  
566 may have been induced by shear of magma along the host-rocks at the top of the pluton. This  
567 inference is in agreement with field host-rocks above the pluton, in agreement with geological



568 observations that allow to infer that the top boundary of the pluton was located just above the  
569 mountain peaks in the central part of the pluton (Castellarin et al., 1982b).

570 In summary, field, petrographic and AMS data and the ENE-WSW elongated shape indicate that  
571 the site and shape of the Monzoni pluton was controlled by strike-slip faults associated with  
572 Ladinian-tectonics. However, the absence of deformation at the field- and micro- scale is consistent  
573 with a post Ladinian-tectonics timing of emplacement, as for the Predazzo body.

574

## 575 **6. Conclusions**

576 Petrographic and AMS data, coupled with field geological data allowed us to investigate the  
577 emplacement modes of the Predazzo and Monzoni bodies. Although these plutons are considered in  
578 the literature as separated bodies, the outcrop of a small volume of intrusive rocks between the  
579 bodies and the continuity of metamorphic aureola from west of the Predazzo body to east of the  
580 Monzoni body suggest that they are parts of a ~20 km long SW-NE oriented continuous pluton,  
581 sub-parallel to Ladinian strike-slip faults. However, our results suggest a variable control of  
582 Ladinian tectonic structures on the emplacement modes of the two bodies.

583 AMS and petrographic data from the Predazzo body are consistent with a multistage ring dyke  
584 emplacement mode, with areas of upward flow of the magma located in the NE and SW part of the  
585 intrusion, whereas in the southern part of the pluton our data suggest prevalently horizontal flows.  
586 Generally, the Predazzo sheets were emplaced via either updip magma flow or along-strike lateral  
587 magma transport, and the round shape suggests no influence of Ladinian tectonic structures.

588 On the contrary, the ENE-WSW elongated shape of the Monzoni body was controlled by the  
589 occurrence of strike-slip faults associated with Ladinian-tectonics, the feeder being likely located at  
590 the NE edge of the body. However, the absence of deformation at the field- and micro- scale is  
591 consistent with a post Ladinian-tectonics timing of emplacement, as for the Predazzo pluton.

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## Appendix A

### *Petrographic description*

#### *Predazzo pluton*

##### *Clinopyroxenite (PA12, PR11a, b, c)*

Clinopyroxenites show a typical hypidiomorphic inequigranular medium- to coarse grained cumulitic texture. Cumulitic phase (clinopyroxene) accounts for more than ~65% of the rock with usually subhedral, fresh and rarely twinned crystals. Clinopyroxene is mainly medium grained (~3 mm) but a few reach larger dimensions, up to ~6 mm. The intercumulus phases consist of subhedral fine- to medium-grained opaques (~0.3-1.3 mm; ~15%), sometimes included in larger biotite crystals, anhedral to subhedral biotite (~13%) with an average size of ~4 mm and anhedral to subhedral small (~1 mm) plagioclase (~7%). In few cases biotites are partly chloritized, while plagioclases are usually partially sericitized. Fine-grained opaques, biotite and plagioclase are also found included in the clinopyroxene oikocrysts (poikilitic). Apatite and zircon are the common accessory minerals usually found as tiny grains included in clinopyroxene and biotite.

##### *Cumulitic gabbro (PA 10)*

The cumulitic gabbro is medium-grained with hypidiomorphic inequigranular texture. The cumulitic phases are plagioclase (~50%), clinopyroxene (~36%) and opaques (~10%). Subhedral to euhedral medium-grained (~3 mm) plagioclase is highly altered to sericite with cores more altered than rims. Clinopyroxene is subhedral medium grained (~2 mm), highly fractured, slightly altered and usually twinned. Opaques occurs as subhedral to anhedral fine grained (<1 mm) and usually found in clusters with clinopyroxene or included in clinopyroxene and biotite. The intercumulus

631 phases (~4%) consist of anhedral to subhedral fine grained (<1 mm) biotite and plagioclase. Biotite  
632 and plagioclase also occur as anhedral small grains included in the clinopyroxenes. Apatite is a  
633 common accessory mineral occurring as minute inclusion in clinopyroxene and biotite.

634

635 *Diorite (PA06)*

636 The diorite is characterized by hypidiomorphic inequigranular with medium- to fine-grained  
637 texture. The rock is composed of plagioclase (~60%), amphibole (~15%), biotite (~10%),  
638 clinopyroxene (~10%), plus smaller amounts of K-feldspar, opaques, quartz and accessory  
639 minerals. Plagioclase occurs as slightly sericitized tabular to equant subhedral crystals with an  
640 average size of ~1.5 mm. Anhedral to subhedral amphibole, biotite and clinopyroxene occur as  
641 small (~1 mm) interstitial clusters, together with subhedral fine-grained opaques, usually found as  
642 inclusion in these minerals. Clinopyroxene is generally replaced to different degrees to amphibole.  
643 Most of the biotite crystals are slightly to moderately altered to chlorite. K-feldspar and quartz (<1  
644 mm) occur as anhedral intergranular crystals in between plagioclase laths. Apatite and rare zircon  
645 are present as small inclusions mainly within plagioclase and clinopyroxene.

646

647 *Monzonites (PA02, PA10), monzodiorites (PA08, PR14c, PA09) and monzogabbro (PR12)*

648 These three types of rocks generally share the same petrographic features, being different only for  
649 the relative K-feldspar/plagioclase ratio. The amount of mafic minerals increases from monzonites  
650 to monzodiorites and monzogabbros. This rock group shows hypidiomorphic inequigranular  
651 texture. Monzonite and monzogabbros are medium-grained, while monzodiorites are medium- to  
652 fine-grained. The rocks are poikilitic, with big anhedral K-feldspars including other minerals.

653 The rocks are generally composed, in order of abundance, of plagioclase, K-feldspar,  
654 clinopyroxene, amphibole, biotite, quartz, opaques, orthopyroxene and accessory minerals.  
655 Plagioclase is usually euhedral with variable grain size (~0.5-3 mm) and sometimes zoned, with  
656 cores always more altered than the rims (i.e. sericitized and saussuritized). Few crystals show

657 combined pericline and albite twining. Alkali feldspar (~1-4 mm) occurs as anhedral irregular  
658 grains characterized by perthitic exsolution. Clinopyroxene is subhedral with medium size (~1-2  
659 mm), sometimes twined and in most cases found in clusters. The clinopyroxene crystals are  
660 partially to completely altered to amphibole (uralitization). Amphibole is anhedral to subhedral  
661 (~0.5-1.5 mm) and mostly found along the margin of clinopyroxene. Biotite occurs as subhedral to  
662 anhedral crystals with different grain size (~2-0.5mm) and often found in clusters. In some cases,  
663 large biotite crystals are poikilitic for the presence of opaque mineral inclusions. The biotite state  
664 generally is good but, in some cases, it is partly altered into chlorite. Anhedral quartz is fine- to  
665 medium-grained (~1.5-0.3 mm) and occurs as interstitial phase. Orthopyroxene is subhedral to  
666 anhedral and are usually found in few percent and recorded not in all the thin sections. Also,  
667 orthopyroxenes show alteration to amphibole with various degrees. Opaques are small subhedral  
668 grains usually included in the other mafic minerals or occupying interstitial areas. The accessory  
669 minerals are apatite, zircon and sphene, observed as inclusions or along mineral boundaries.

670

671 *Granite group (PA01, PA03, PA04, PA05, PA07, PA13, PA17)*

672 The samples exhibit hypidiomorphic inequigranular texture. In a few cases, granophyric texture is  
673 also recorded. The granite rocks are classified into two main groups: albitized granite (affected by  
674 hydrothermal alteration) and biotite granite.

675 In the first group biotite is completely transformed mainly to sericite and minor chlorite (PA01,  
676 PA04, PA05, PA17), while in the second group biotite is generally found in a good state of  
677 preservation (PA07, PA03, PA13). The biotite granite group is characterized by the presence of  
678 microgranular quartz usually forming aggregates around feldspar crystals.

679 The rocks are made up, in order of abundance, of K-feldspar, quartz and plagioclase with minor  
680 biotite, muscovite, chlorite and rare amphibole.

681 K-feldspar occurs as subhedral medium grained (~2-4 mm) crystals characterized by perthitic  
682 exsolution lamellae. Carlsbad twining is common and the crystals usually shows minor alteration.

683 Quartz mainly occurs in anhedral grains (~1-3 mm) but is also sometimes found in the interstitial  
684 areas (<0.5 mm) or forming aggregates around feldspar crystals. Quartz crystal shows no or  
685 incipient undulatory extinction. Plagioclase is subhedral medium grained (~1-3 mm), sometimes  
686 zoned and usually show albite twinning. In biotite granite, most of the plagioclase crystals are  
687 slightly to moderately altered (sericitized and saussuritized), with the cores more altered than the  
688 rims. On the other hand, in albitized granite plagioclase is completely transformed having lost  
689 completely its anorthite component. Biotite is present as subhedral platy crystals (~0.5-2 mm) and  
690 usually forms clusters of numerous crystals. Biotite is partially to completely altered to chlorite and  
691 sericite. Sericite occurs as anhedral to subhedral (~1-2 mm) pseudomorphs after biotite and is  
692 commonly associated with chlorite. Chlorite is subhedral to anhedral (~0.5-2 mm) pseudomorphs  
693 after biotite. Rare amphibole crystals have been recorded in the second group. Accessory minerals  
694 are zircon, apatite, fluorite, iron oxide and monazite.

695

696 *Monzonite to Syenite? (PA11)*

697 This sample is strongly affected by hydrothermal alteration and a precise classification cannot be  
698 conducted.

699

700 ***Monzoni pluton***

701 The samples from Monzoni pluton have been classified into two main groups: Gabbroic Rock  
702 (olivine-gabbros, gabbros, monzogabbros), mainly located at the northeastern part of Monzoni  
703 pluton, and monzogabbros (PA21).

704 These rocks are medium- to coarse-grained with hypidiomorphic inequigranular texture. The  
705 rocks are composed, in order of abundance, of plagioclase, clinopyroxene, K-feldspar, opaques,  
706 olivine, biotite and accessory minerals.

707 Plagioclase is the most abundant phase. It is euhedral to subhedral medium-grained (~1-4 mm),  
708 always twinned, rarely zoned and mostly unaltered. Clinopyroxene is represented by subhedral

709 medium- to coarse-grained (~1-5 mm) unaltered crystals. K-feldspar is anhedral to subhedral  
710 medium- to fine-grained (~0.5-4 mm), unaltered, untwined, usually occupying the interstitial areas  
711 and in some cases as oikocryst, including the other minerals (poikilitic texture). Opaques are  
712 subhedral fine- to medium-grained (~0.2-1.3 mm), mainly included within other minerals (biotite,  
713 clinopyroxene and olivine) or occupying interstitial areas. Olivine is subhedral medium-grained  
714 (~1-5 mm), usually unaltered and fractured. Biotite is anhedral to subhedral fine- to medium-  
715 grained and unaltered, occupying the interstitial areas between the early crystallized minerals.

716 Gabbro (non-cumulitic) PA 16. This rock exhibits coarse-grained with hypidiomorphic  
717 inequigranular texture. It is made up with plagioclase, clinopyroxene, opaque, biotite and accessory  
718 minerals (in order of occurrence). Plagioclase is euhedral medium- to coarse-grained (~2-5 mm),  
719 usually found in good state or showing slight alteration to sericite and is usually twinned.  
720 Clinopyroxene is subhedral medium- to coarse-grained (~2-6 mm), unaltered, rarely twinned, with  
721 ophitic and subophitic texture (plagioclase partially or completely enclosed by clinopyroxene).  
722 Opaques are subhedral fine- to medium-grained (~0.3-1.3 mm), occupying the interstitial areas or  
723 included within the biotite and clinopyroxene. Biotite is anhedral to subhedral, fine- to medium-  
724 grained (~0.5-2.5 mm), unaltered, and interstitial.

725 Gabbro (cumulitic) PA15. This rock is coarse-grained with cumulitic texture. Cumulus phases are  
726 mainly clinopyroxene with minor olivine. Intercumulus phases are primarily plagioclase and biotite  
727 with minor opaque oxides. Clinopyroxene is euhedral to subhedral coarse- to medium-grained (~2-8  
728 mm), rarely twinned and sometimes slightly zoned. Olivine is subhedral medium-grained (~1-3  
729 mm) and usually found in good state with fracture. It is slightly altered to iddingsite particularly  
730 along the fractures. Plagioclase is euhedral to subhedral medium-grained (~1-2 mm), slightly  
731 altered to sericite and always twinned. Biotite is subhedral to anhedral medium- to fine-grained  
732 (~0.5-2 mm) and in a few cases is slightly chloritized. Opaques are subhedral fine- to medium-  
733 grained (~0.1-1.5 mm). They occur both as interstitial phases or included within clinopyroxene and  
734 biotite.

735 Olivine gabbro (PA20, PA18). These rocks are medium- to coarse-grained. Cumulus phases are  
736 represented by clinopyroxene, plagioclase, and olivine. Clinopyroxenes occurs as subhedral  
737 medium- to coarse-grained (~ 2-6 mm), unaltered and usually untwined. Clinopyroxene oikocrysts  
738 usually include small crystals from opaques, plagioclase, olivine and biotite. Olivine crystals are  
739 subhedral medium-grained (~ 1-2.5 mm). Olivine in sample PA20 is fresh and fractured, whereas in  
740 sample PA18, it is completely altered to secondary minerals (iddingsite, bowlingite and celadonite).  
741 Plagioclase is euhedral to subhedral medium-grained (~ 1-2.5 mm), rarely zoned, and always  
742 showing twinning. Plagioclase is fresh in sample PA20 and slightly altered in PA18. Intercumulus  
743 phases are composed of plagioclase, biotite, opaques, and K-feldspar. Plagioclase occurs as fresh  
744 subhedral fine-grained (~ 1 mm). Biotite is fresh medium-grained (~ 1-3 mm), subhedral or  
745 sometimes anhedral, when occupying interstitial positions. Opaques occur as subhedral fine- to  
746 medium-grained (~ 0.5-1.3 mm), and commonly are interstitial phases or are included in  
747 clinopyroxene, biotite and olivine. K-feldspar is clear anhedral fine- to medium-grained (~ 0.5-1.5  
748 mm) and is usually found as interstitial crystals between the early crystallized minerals.

749 Monzonite (PA22, 22A, 23, 24). These rocks are mainly located in the south-western sector of  
750 Monzoni pluton and represent the most widespread rock type. These rocks are medium- to fine-  
751 grained and exhibit hypidiomorphic inequigranular texture. The rocks are composed, in order of  
752 abundance, of plagioclase, K-feldspar, biotite, clinopyroxene, amphibole, opaques, quartz and  
753 accessory minerals.

754 Plagioclase represents the most abundant phase with euhedral to subhedral tabular laths with  
755 variable grain size (up to 4 mm), usually twinned. Plagioclase crystals generally show slight to  
756 moderate degrees of alteration (sericitization). K-feldspar occurs as anhedral to subhedral, rarely  
757 perthitic, untwined with variable size (up to 5 mm) and is usually found in a good state or in some  
758 cases slightly sericitized. K-feldspar oikocrysts usually include other minerals in a poikilitic  
759 relation. Clinopyroxene is subhedral to anhedral fine- to medium-grained (up to 2 mm), usually  
760 showing different degrees of alteration to amphibole (uralitization). Biotite is subhedral to anhedral



761 fine- to medium-grained (up to 3 mm), generally found in good state or sometimes showing slight  
762 to moderate alteration to chlorite. Quartz occurs as fine interstitial grains between the early  
763 crystallized minerals. Opaques are subhedral to anhedral fine-grained (~0.2-1 mm), and occupy the  
764 irregular interstices in between the other minerals or are included within K-feldspar. Orthopyroxene  
765 is rarely found with anhedral to subhedral medium-grained. Sample PA24 is highly altered  
766 compared to the other Monzonite samples.

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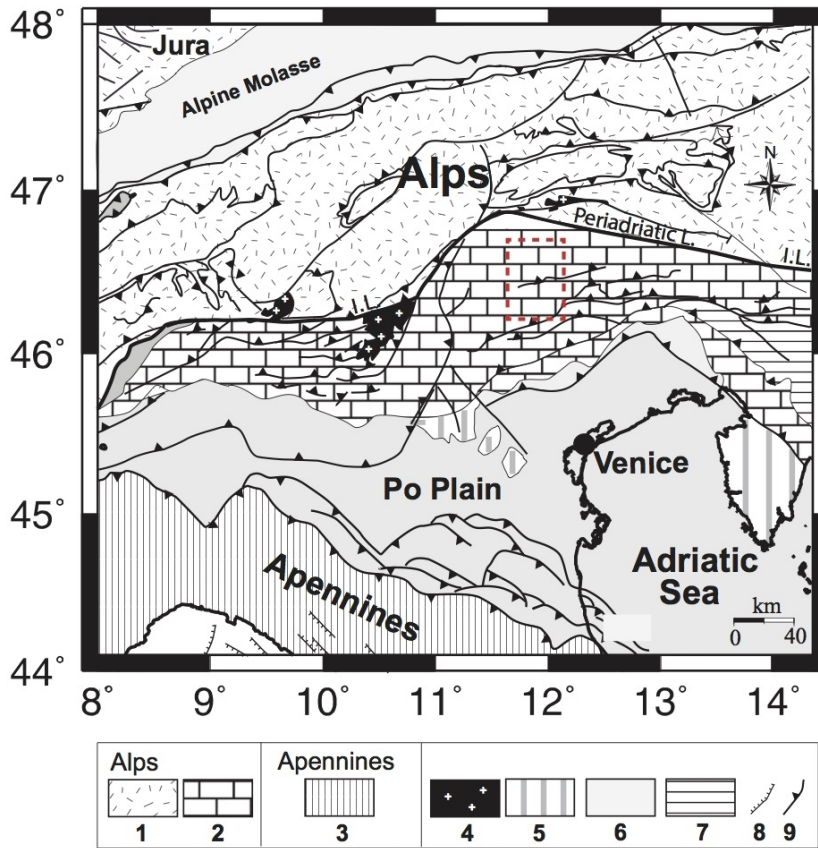
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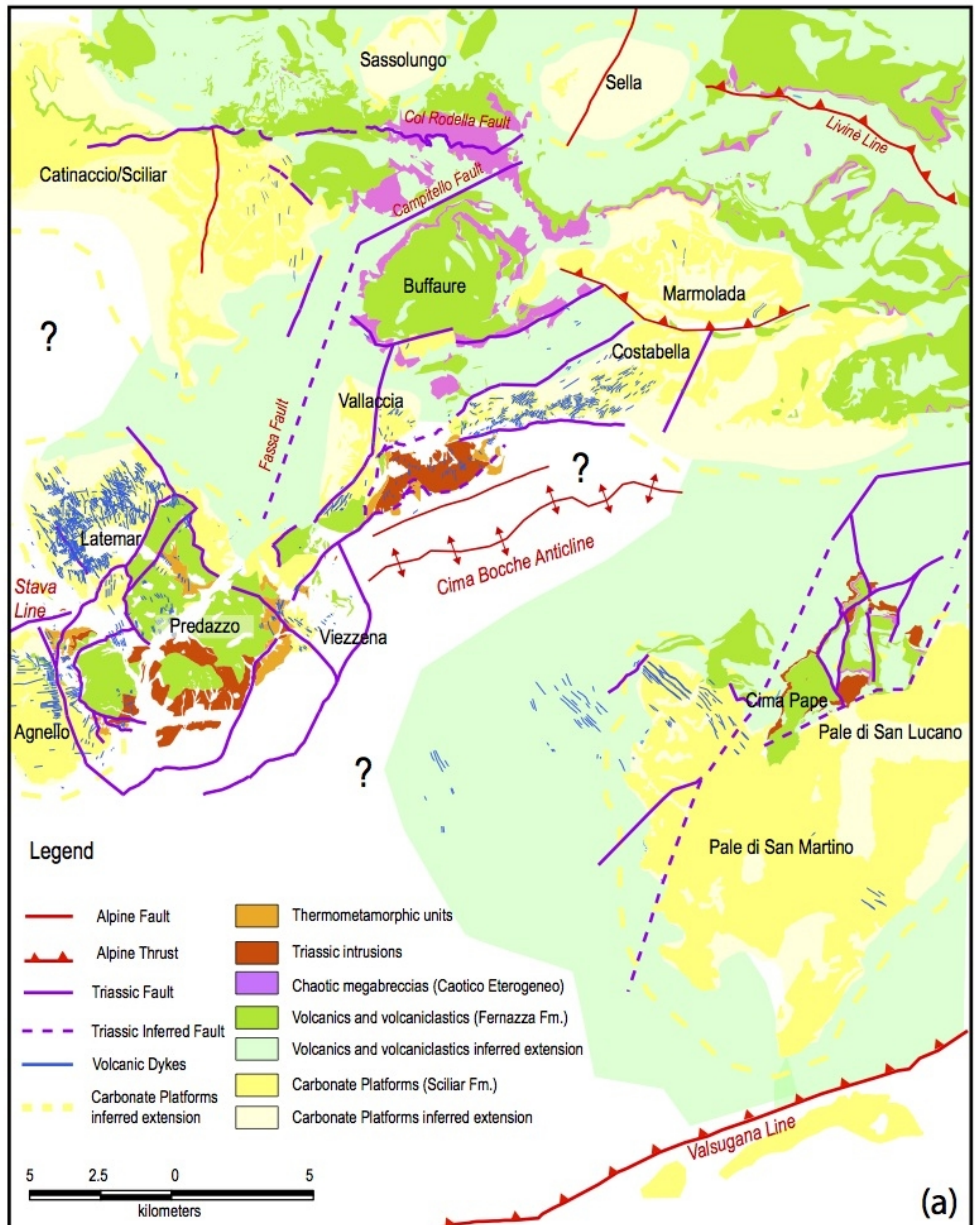
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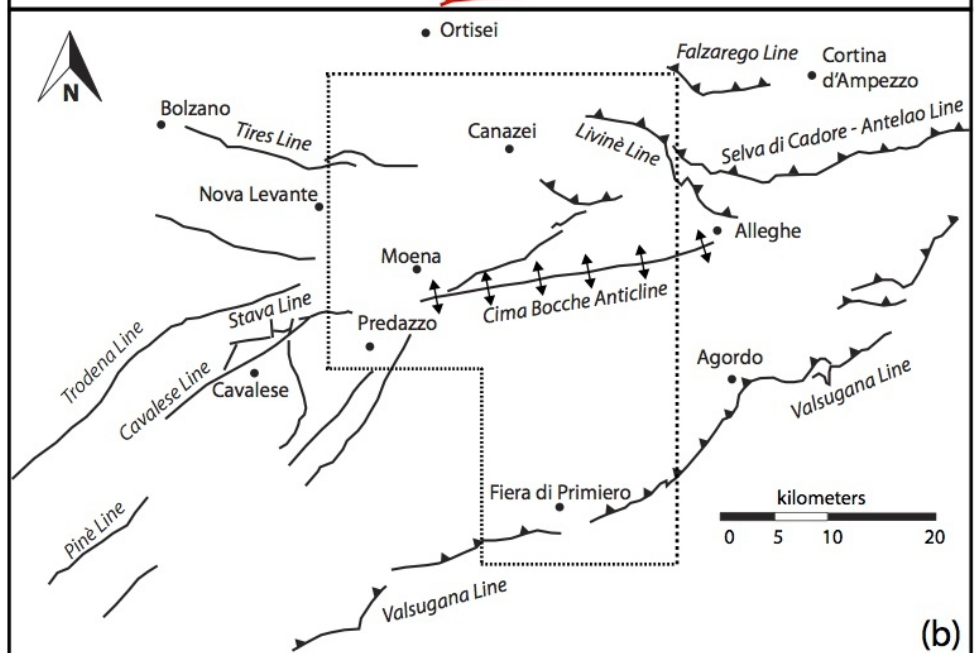


1119 Figure 1: Simplified geological map of the Southern Alps. Alps: 1) Australpine, Penninic and  
 1120 Helvetic units; 2) Southern Alps units. Apennines: 3) Apenninic units; 4) Cenozoic volcanic and  
 1121 plutonic bodies; 5) foreland units; 6) foreland basin units; 7) Dinaric units; 8) normal faults; 9)  
 1122 thrust faults. Redrawn and simplified from Bigi et al. (1990). The dashed rectangle shows the  
 1123 location of the map of Figure 2. I.L.: Insubric line.





(a)

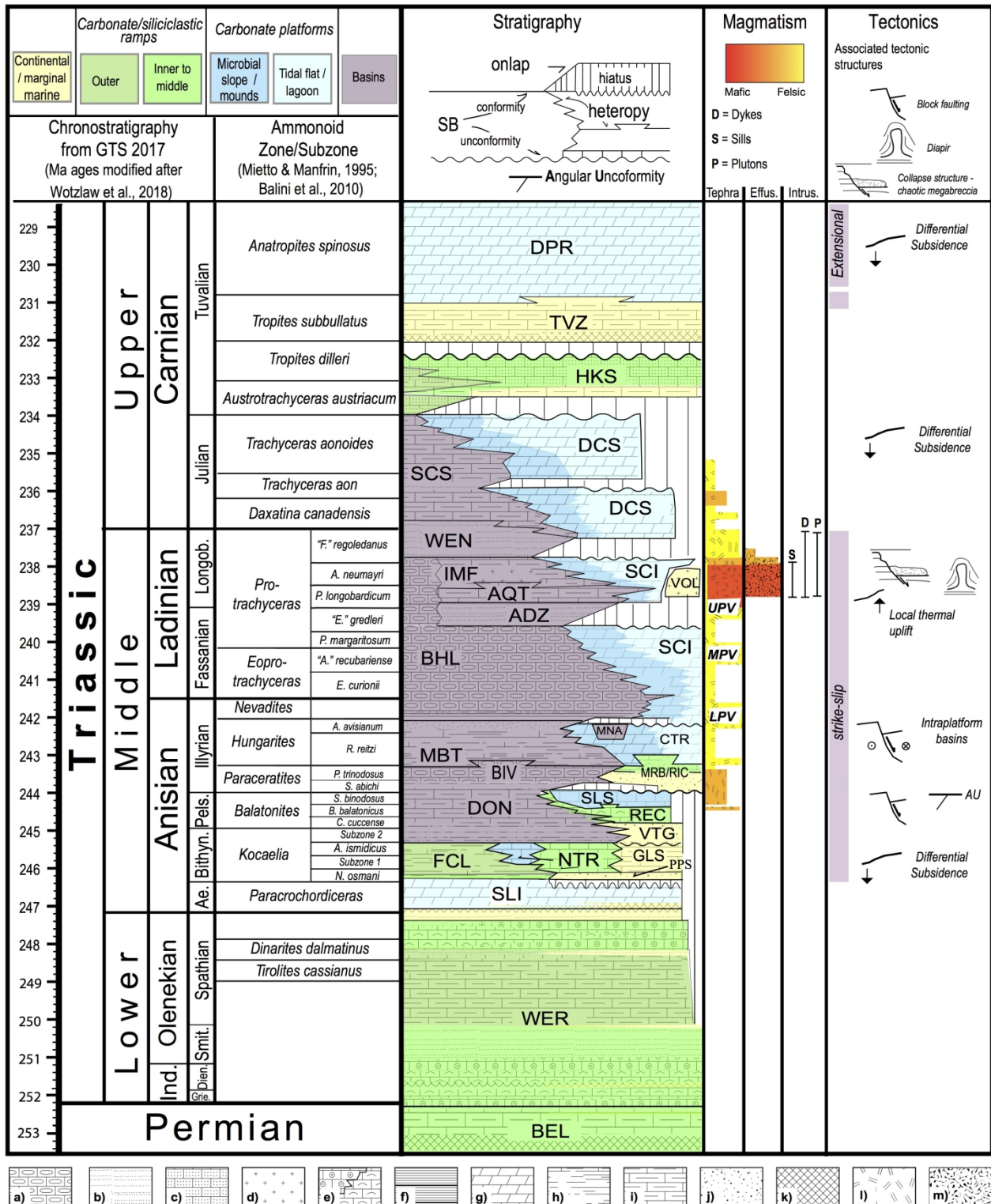


(b)

1126

1127 Figure 2: a) Unrestored paleogeographic map at Ladinian times of the central-western region of the  
1128 Dolomites. Notice the regional extent of volcanics and the continuity of plutonic bodies and  
1129 associated thermo-metamorphic rocks for more than 20 km in a SW-NE direction, i.e., parallel to  
1130 major Triassic faults. Cenozoic faults and structures are shown for reference. The location of the  
1131 map is shown in Fig. 1. b) Simplified tectonic map of the Dolomites, showing only major faults,  
1132 not differentiated by their age. The dashed area represents the location of panel a.

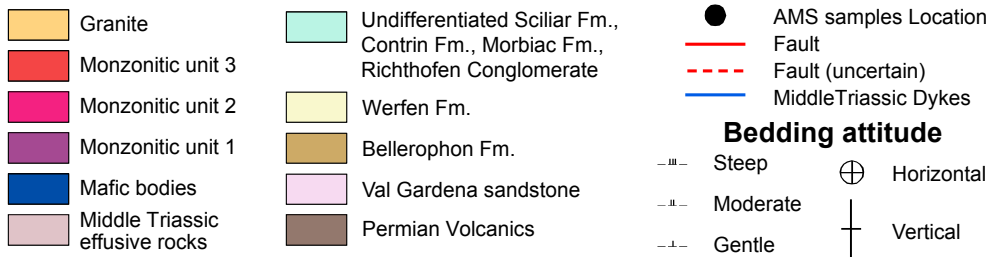
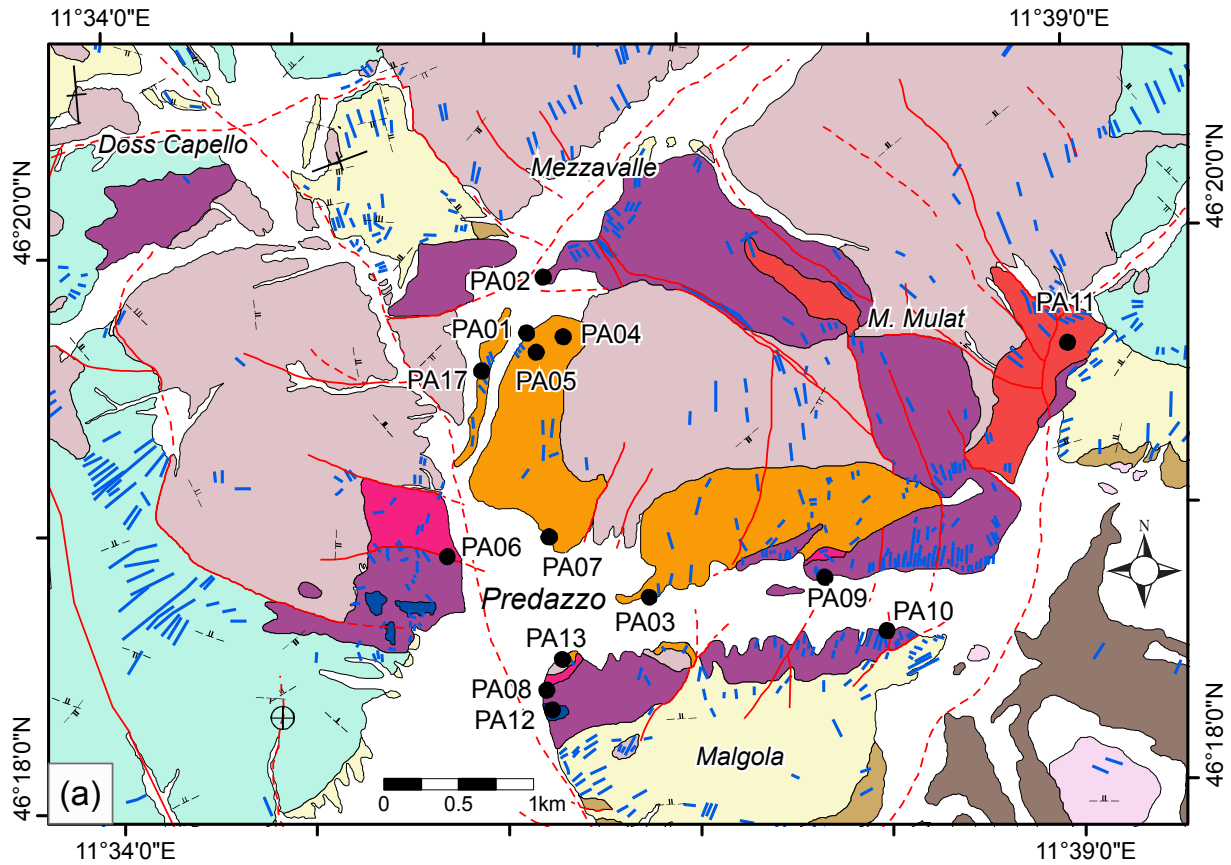
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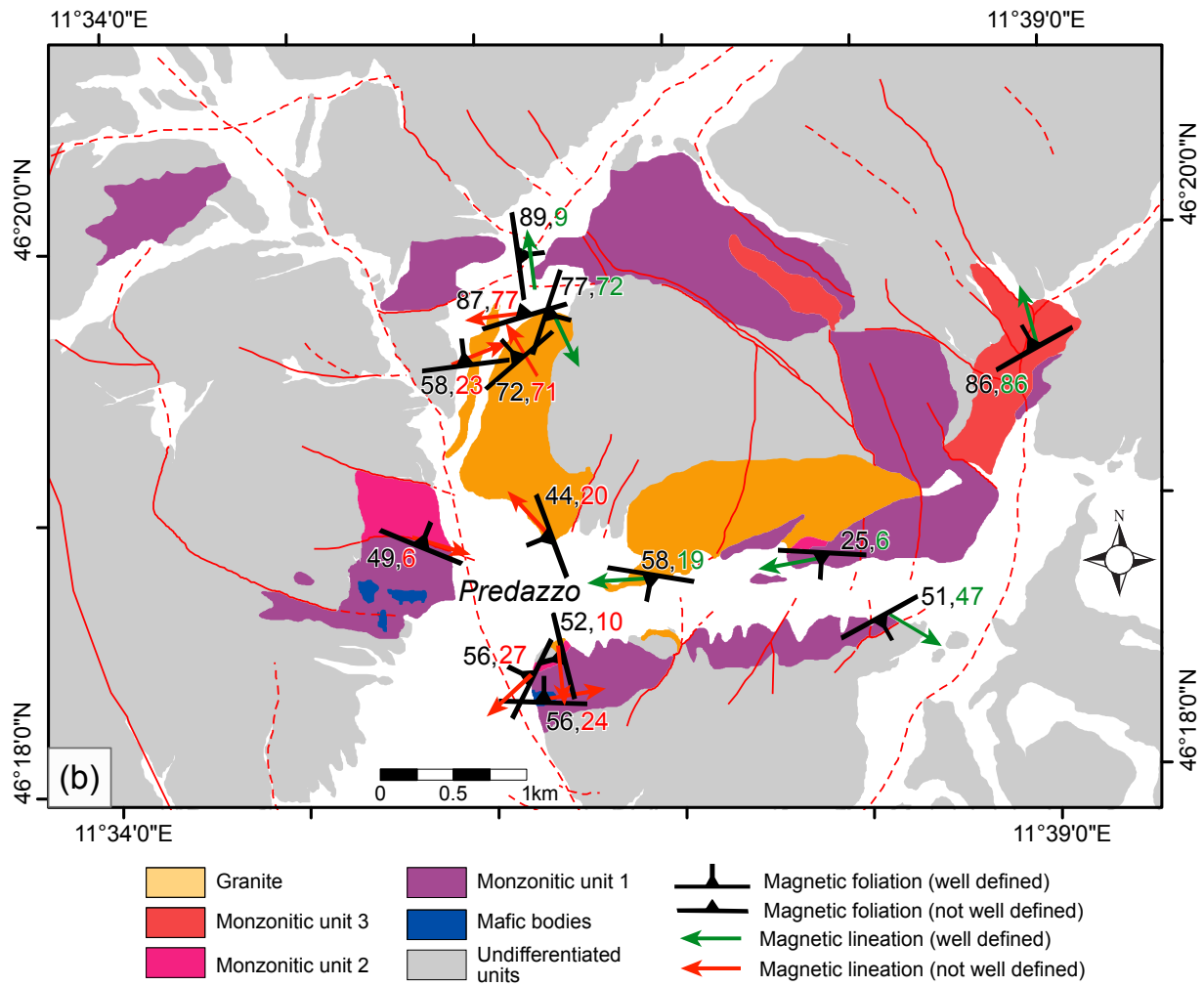
1135 Figure 3: Schematic bio-chrono-stratigraphic scheme of the Middle-Upper Triassic succession of  
 1136 the Dolomites with the most important magmatic pulse recorded as ash falls, tephtras or effusives.  
 1137 The position of the known possible source volcanic areas from the Southern Alps is indicated. In  
 1138 the subsurface of Venetian Plain, a significant number of volcanic products (mainly effusve and

1139 intrusive) is known (e.g., Brusca et al., 1981) Lithostratigraphic abbreviations: BEL:  
1140 Bellerophon Formation; WER: Werfen Formation; SLI: Lower Serla Dolomite; PPS: Piz da  
1141 Peres Conglomerate; FCL: Coll'Alto dark Limestones; NTR: Monte Rite Formation; GLS:  
1142 Gracilis Formation; VTG: Voltago Conglomerate; DON: Dont Formation; REC: Recoaro  
1143 Limestone; SLS Upper Serla Dolomite/Formation; MRB/RIC: Richthofen Conglomerate and  
1144 Morbiac dark Limestone; BIV: Bivera Formation; MBT: Ambata Formation; MNA: Moena  
1145 Formation; CTR: Contrin Formation; BHL: Livinallongo Formation; SCI: Sciliar Formation;  
1146 ADZ: Zoppè Sandstone; AQT: Aquatona Formation; IMF: Fernazza Volcanic Complex  
1147 (Fernazza Formation); WEN: Wengen Formation; SCS: San Cassiano Formation; DCS: Cassian  
1148 Dolomite; HKS: Heiligkreuz Formation; TVZ: Travenanzes Formation; DPR: Dolomia  
1149 Principale. Lithologies: a) cherty limestone; b) sandstone; c) sandy limestone; d) volcanics and  
1150 volcanoclastics; e) oolitic-bioclastic limestone; f) black platy limestone or dolostone, black shale;  
1151 g) dolostone; h) marlstone, claystone and shale; i) marly limestone; j) conglomerate; k)  
1152 evaporates; l) tuffs, pyroclastics; m) lava, pillow-lava-pillow breccia; m) volcanos with mainly  
1153 effusive eruptions. LPV, MPV, UPV= Lower -Middle - Upper Pietra Verde.



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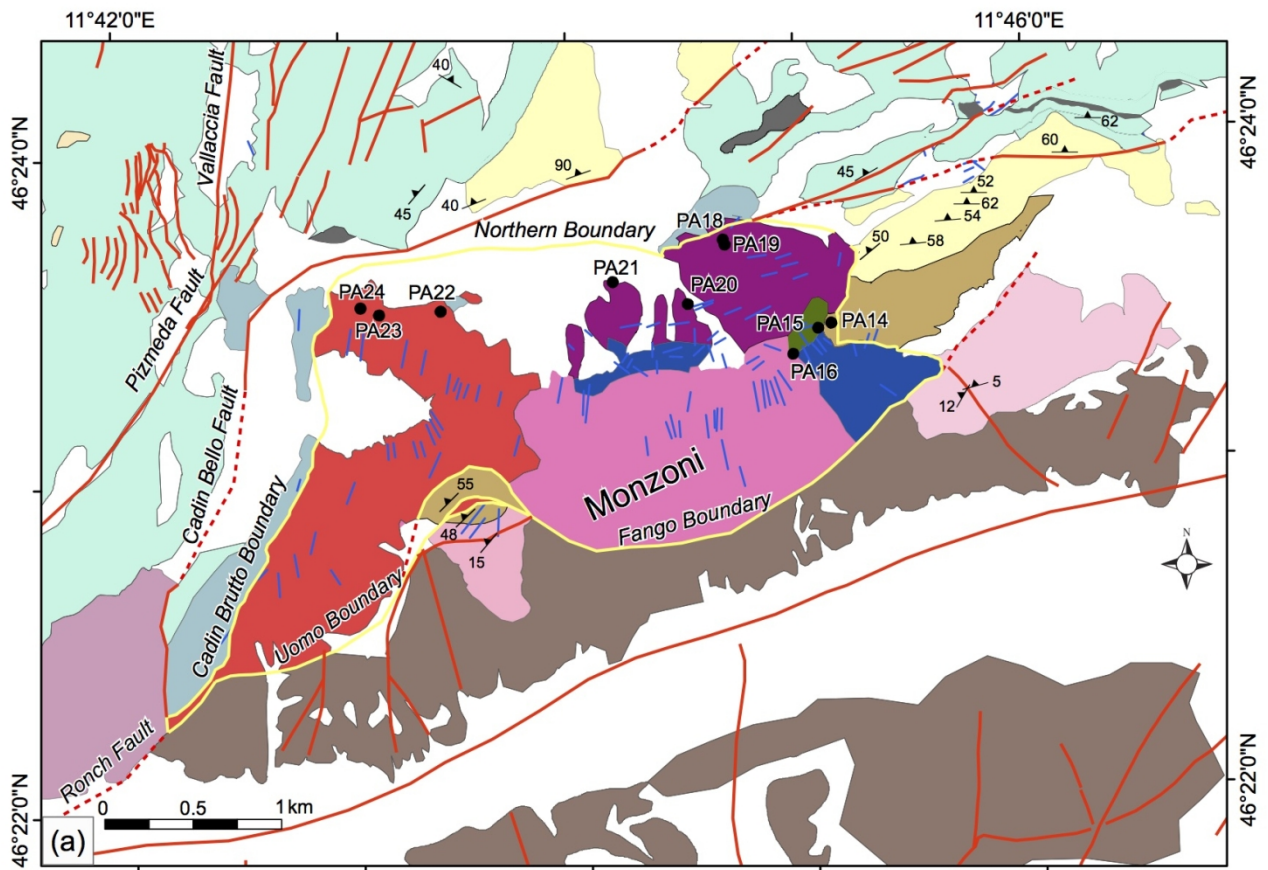
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1157 Figure 4: Geological map of the pre-Quaternary units of the Predazzo area (from Visonà, 1997),  
 1158 showing the location of the sampling sites (a) and measured magnetic foliations and lineations (b).

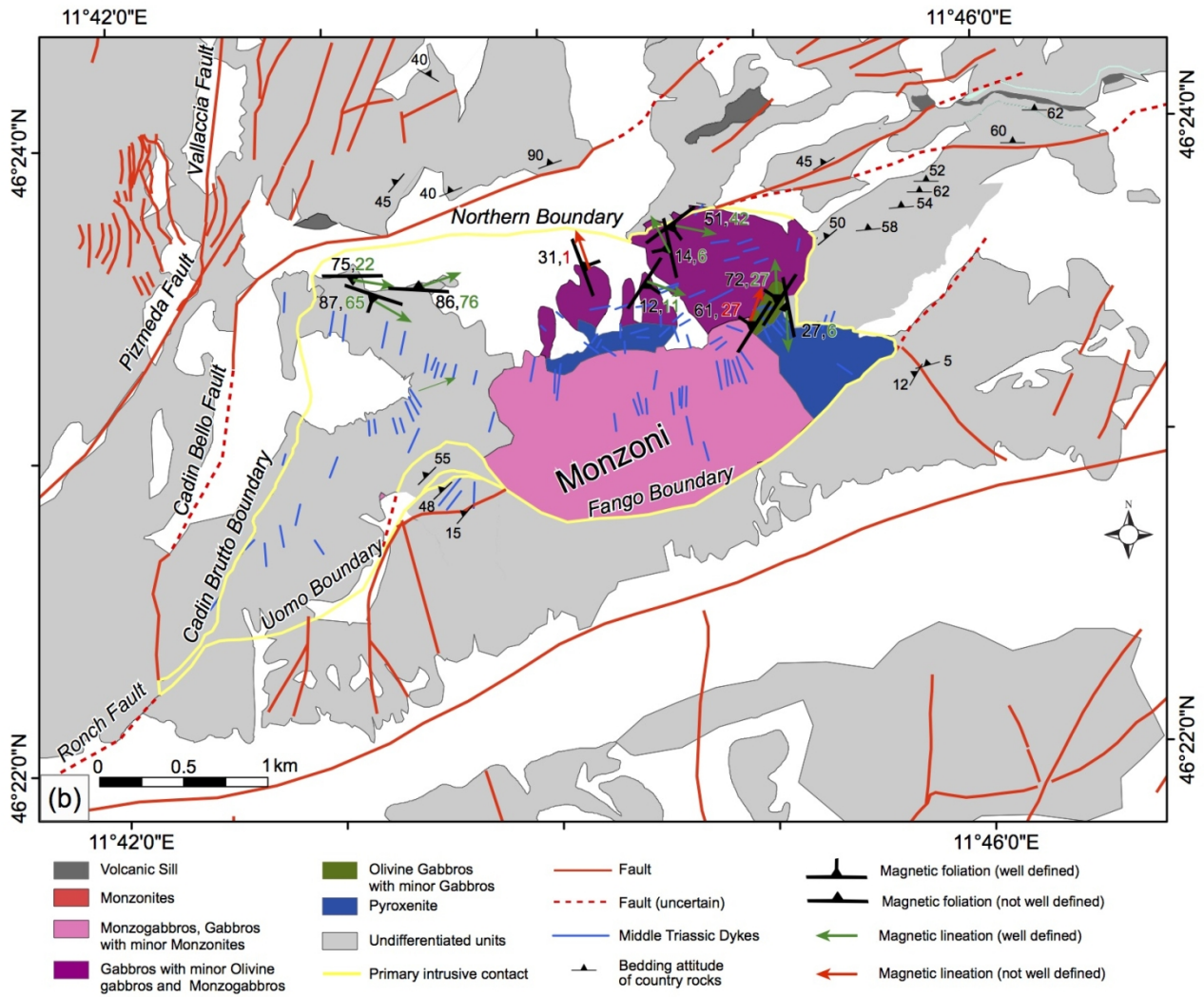
1159 The two numbers besides each site indicate the magnetic foliation and lineation dips, respectively.



11°42'0"E

11°46'0"E

- |  |   |  |
|--|---|--|
| <ul style="list-style-type: none"> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: black; margin-right: 5px;"></span> Volcanic Sill</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: red; margin-right: 5px;"></span> Monzonites</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: pink; margin-right: 5px;"></span> Monzogabbros, Gabbros with minor Monzonites</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: purple; margin-right: 5px;"></span> Gabbros with minor Olivine gabbros and Monzogabbros</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: green; margin-right: 5px;"></span> Olivine Gabbros with minor Gabbros</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: blue; margin-right: 5px;"></span> Pyroxenite</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: lightgrey; margin-right: 5px;"></span> Middle Triassic effusive rocks</li> </ul> | <ul style="list-style-type: none"> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: lightblue; margin-right: 5px;"></span> Sciliar Fm (metamorphosed)</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: cyan; margin-right: 5px;"></span> Undifferentiated Sciliar Fm., Livinallongo Fm., Contrin Fm., Moena Fm., Richthofen Conglomerate</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: yellow; margin-right: 5px;"></span> Werfen Fm</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: tan; margin-right: 5px;"></span> Bellerophon Fm</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: lightpink; margin-right: 5px;"></span> Val Gardena Sandstones (metamorphosed)</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: lightpurple; margin-right: 5px;"></span> Val Gardena Sandstones</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: brown; margin-right: 5px;"></span> Permian Volcanics</li> </ul> | <ul style="list-style-type: none"> <li><span style="display: inline-block; width: 10px; height: 10px; background-color: black; border-radius: 50%; margin-right: 5px;"></span> AMS samples location</li> <li><span style="display: inline-block; width: 15px; border-bottom: 2px solid yellow; margin-right: 5px;"></span> Primary intrusive contact</li> <li><span style="display: inline-block; width: 15px; border-bottom: 2px solid red; margin-right: 5px;"></span> Fault</li> <li><span style="display: inline-block; width: 15px; border-bottom: 2px dashed red; margin-right: 5px;"></span> Fault (uncertain)</li> <li><span style="display: inline-block; width: 15px; border-bottom: 2px solid blue; margin-right: 5px;"></span> Middle Triassic Dykes</li> <li><span style="display: inline-block; width: 0; height: 0; border-left: 5px solid transparent; border-right: 5px solid transparent; border-bottom: 8px solid black; margin-right: 5px;"></span> Bedding attitude of country rocks</li> </ul> |
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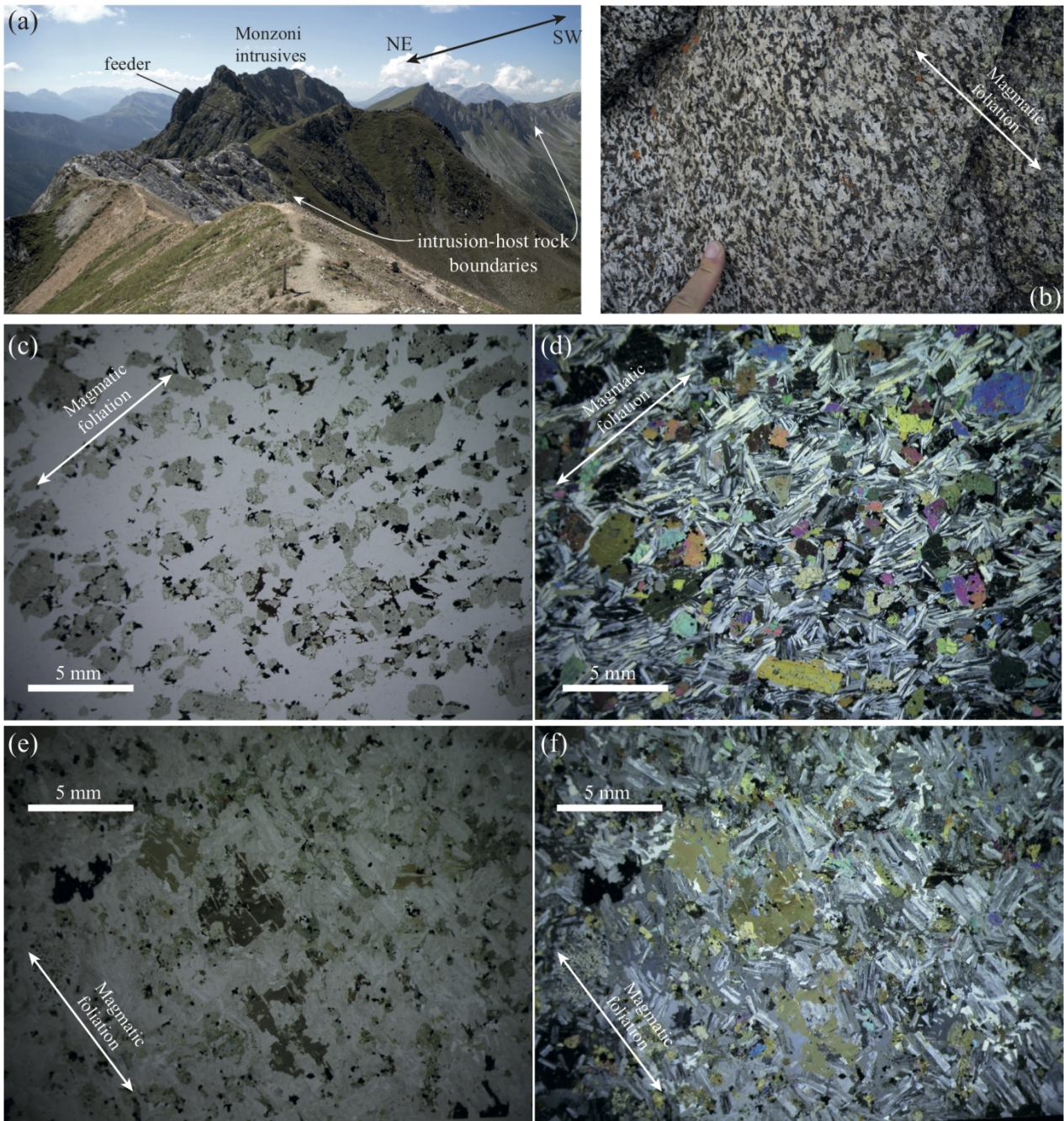


1161

1162 Figure 5: Geological map of the pre-Quaternary units of the Monzoni area, showing the location of  
 1163 the sampling sites (a) and measured magnetic foliations and lineations (b). The two numbers at each  
 1164 site indicate the magnetic foliation and lineation dips, respectively.

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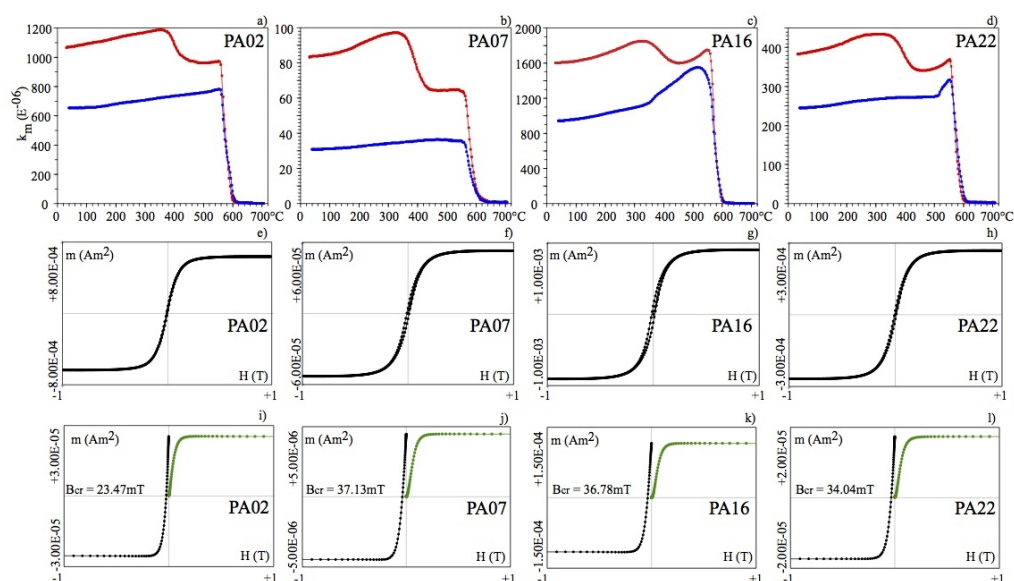




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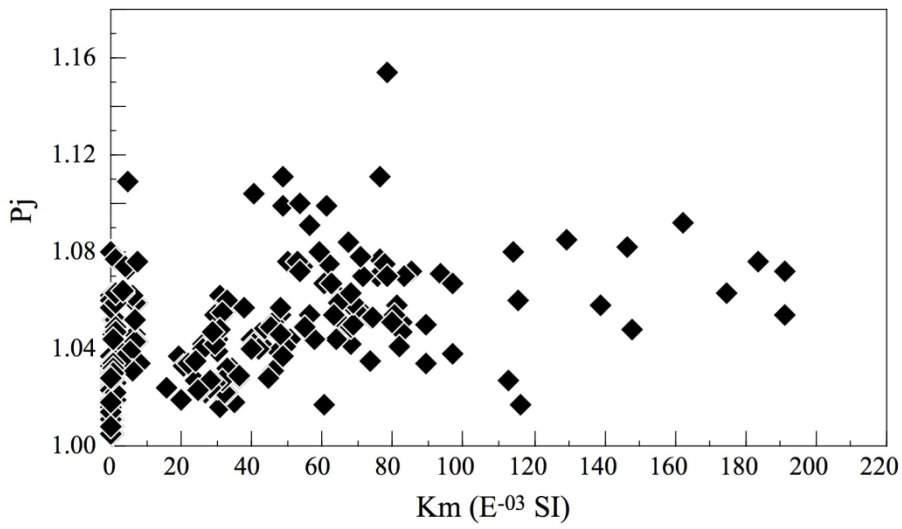
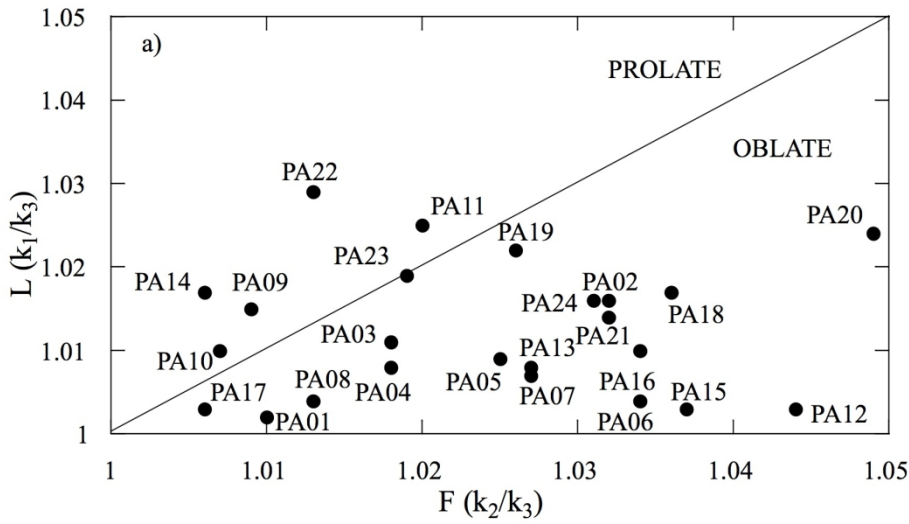
1167 Figure 6: a) Monte Monzoni crest, showing the contacts between intrusive and host rocks. The  
 1168 location of the feeder area is also shown. b) Granite from the Predazzo body showing a well defined  
 1169 magmatic foliation; c) Olivine gabbro showing preferred orientation of plagioclase and pyroxene  
 1170 crystals (sample PA20); c) Monzonite showing preferred orientation of plagioclase and biotite  
 1171 crystals (sample PA22A, same location of sample 22).

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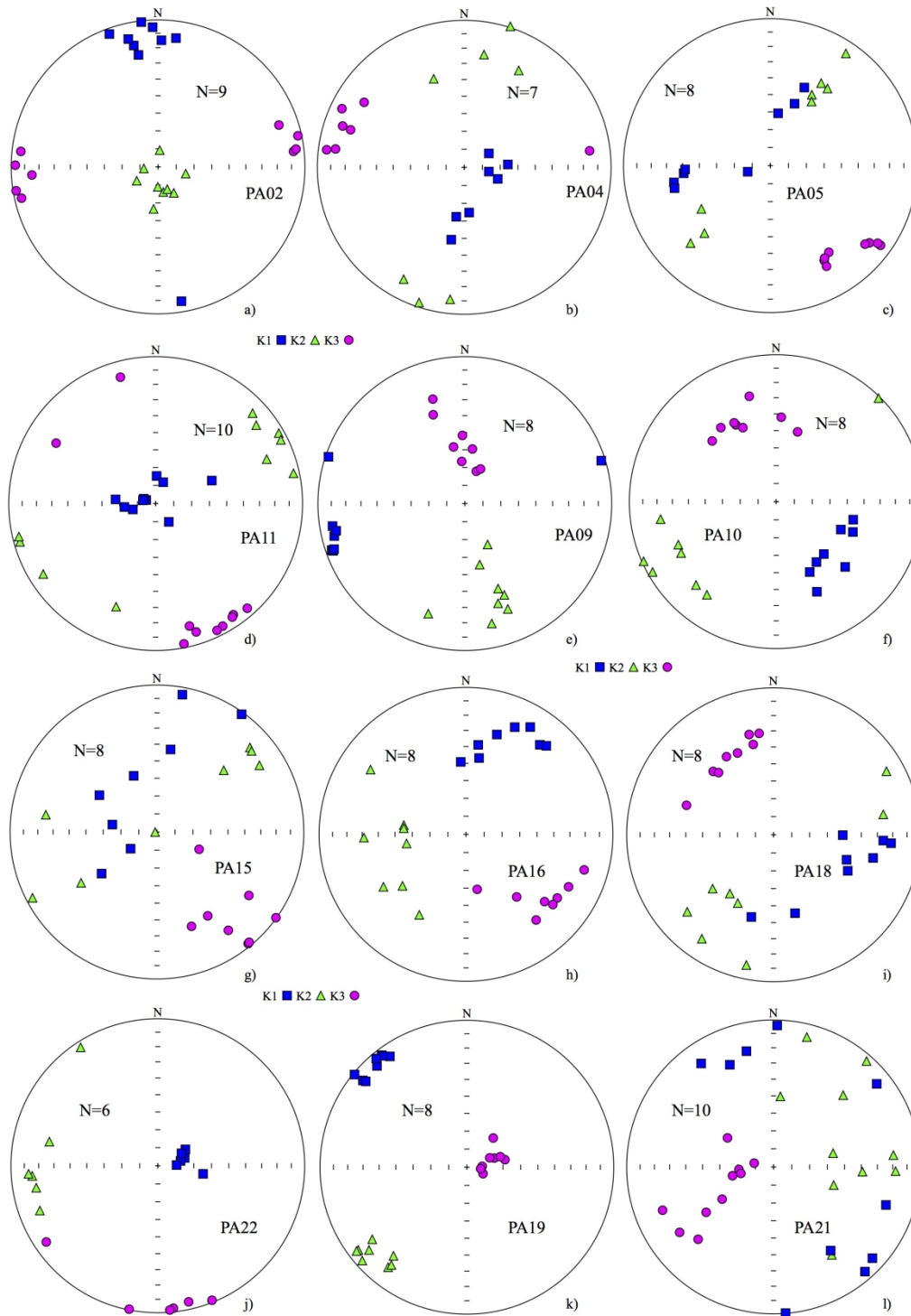


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1174 Figure 7: Magnetic mineralogy results for selected samples from Predazzo and Monzoni plutons. a-  
 1175 d) Thermomagnetic curves; red and blue lines represent the heating  $\square$ -cooling cycle respectively. e-  
 1176 h) Hysteresis loops, corrected for the paramagnetic linear trend. i-l) IRM acquisition curves (green  
 1177 lines) and backfield applications (black lines).



1178  
 1179 Figure 8: Shape parameters for the analysed sites: a) F-L diagram; b) K-Pj diagram.



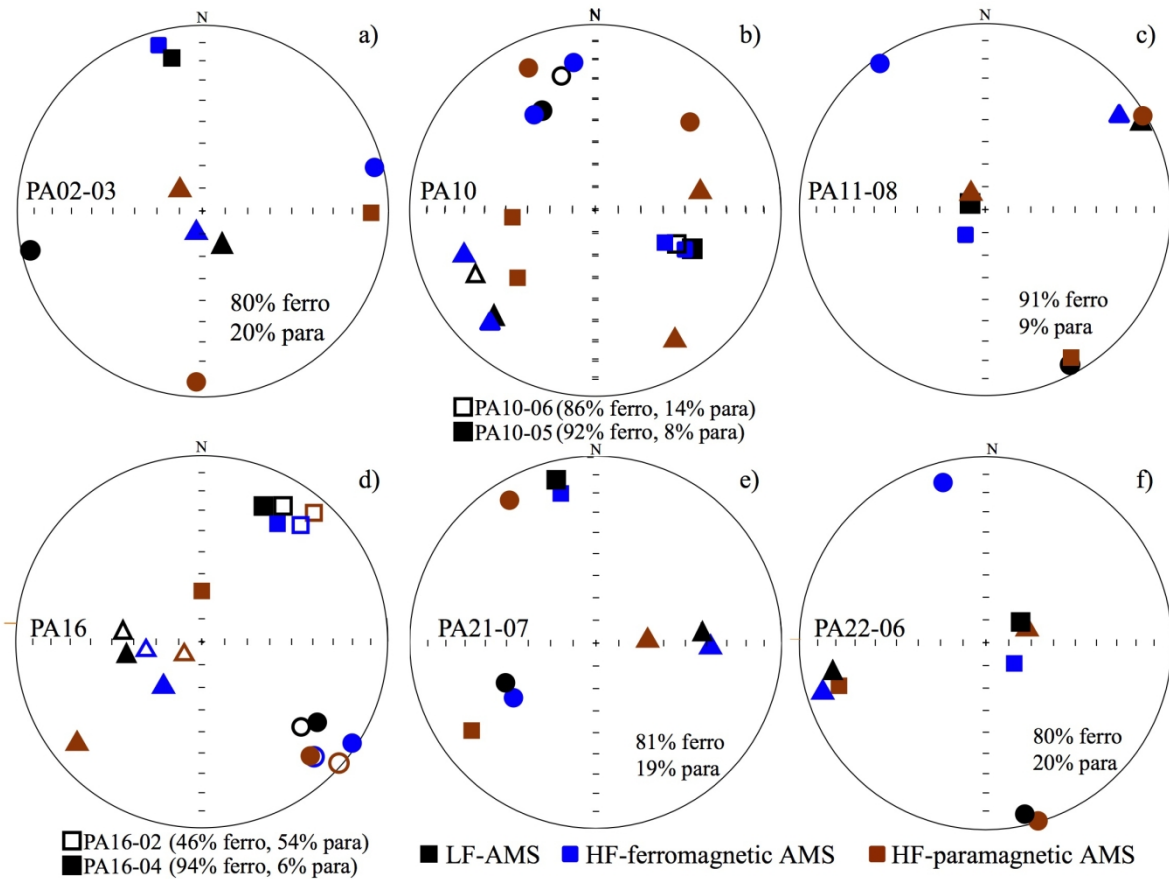
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1181 Figure 9: Low-field AMS plots for representative sites in the Predazzo (a-f) and Monzoni (g-l)

1182 intrusive bodies. Data are plotted on lower hemisphere, equal area projections. Squares, triangles

1183 and circles represent maximum, intermediate and minimum axes, respectively, plotted relative to

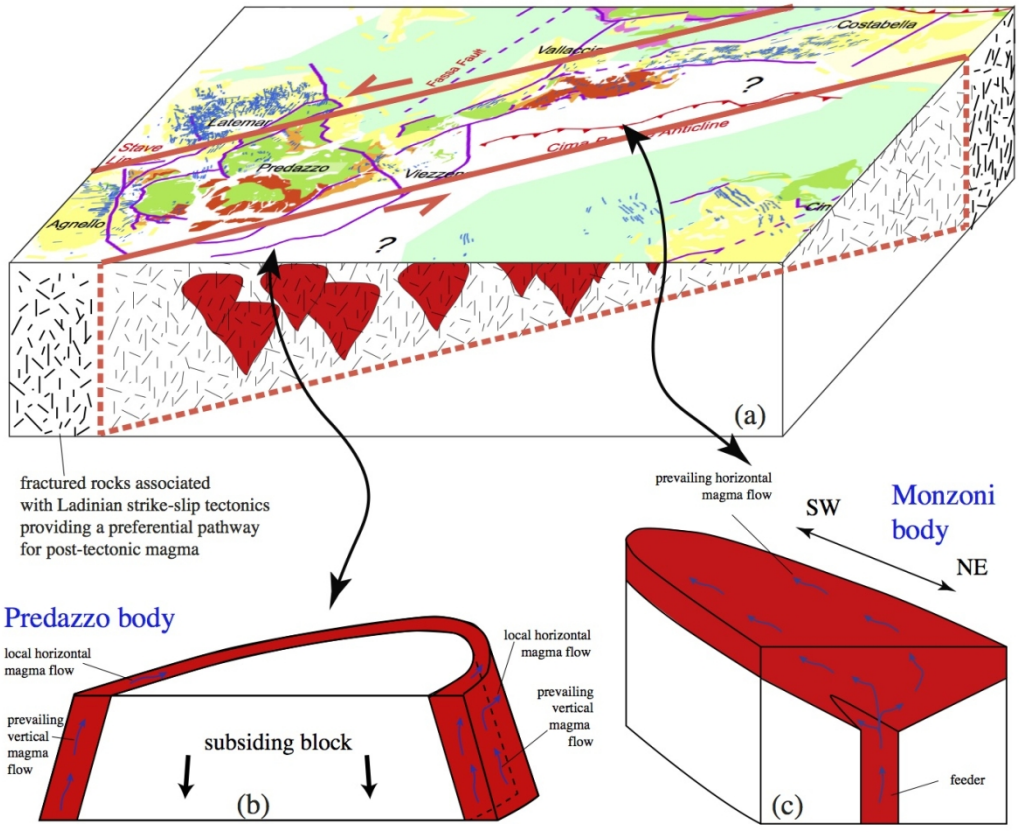
1184 paleo-geographic coordinates.



1185

1186 Figure 10: Lower hemisphere equal area projections of the principal axes of the low-field/room  
 1187 temperature (black symbols), high-field paramagnetic (red symbols) and high-field ferromagnetic  
 1188 (blu symbols) susceptibility ellipsoids. Percentages of the relative contribution of ferromagnetic and  
 1189 paramagnetic susceptibility to the magnetic fabric is also reported for each specimen.

1190



1191

1192 Figure 11: a) Sketch showing the emplacement of Ladinian intrusive bodies along a wide fractured  
 1193 zone associated with previous strike-slip tectonics. b) Sketch of the emplacement mode for the  
 1194 Predazzo body; c) Sketch of the emplacement mode for the Monzoni body.

## 1195 TABLES

Site	Lithology	Lat	Long	N	Km	std	L	std	F	std	Pj	std	T	std	D,I (k <sub>1</sub> )	E <sub>2-3</sub>	D,I (k <sub>3</sub> )	E <sub>1-2</sub>
PA01	Albitized granite	46°19'41"N	11°36'09"E	10	4.04E <sup>-04</sup>	3.75 E <sup>-04</sup>	1.002	0.01	1.010	0.011	1.013	0.018	0.667	0.461	263,77	74.7/36.4	162,3	40.9/21.3
PA02	Monzonites	46°19'53"N	11°36'15"E	8	6.90E <sup>-02</sup>	2.70E <sup>-03</sup>	1.016	0.006	1.032	0.006	1.049	0.006	0.318	0.217	353,9	11.3/7.8	262,1	9.4/5.4
PA03	Biotite granite	46°18'42"N	11°36'45"E	8	4.48E <sup>-03</sup>	3.3E <sup>-03</sup>	1.011	0.009	1.018	0.013	1.030	0.01	0.256	0.443	266,19	23.7/20.5	9,32	24.1/18.5
PA04	Albitized granite	46°19'39"N	11°36'21"E	6	1.03E <sup>-04</sup>	1.01 E <sup>-05</sup>	1.008	0.002	1.018	0.005	1.026	0.006	0.394	0.188	154,72	23.5/3.6	288,13	11.2/5.6
PA05	Albitized granite	46°19'36"N	11°36'13"E	7	8.43E <sup>-05</sup>	3.88 E <sup>-05</sup>	1.009	0.01	1.025	0.015	1.035	0.02	0.483	0.329	329,71	35.9/8.2	139,18	18.1/5.9
PA06	Diorite	46°18'52"N	11°35'44"E	9	4.41E <sup>-02</sup>	8.80 E <sup>-03</sup>	1.004	0.006	1.034	0.008	1.042	0.008	0.809	0.284	107,6	37.2/4.7	202,41	6.3/4.1
PA07	Biotite granite	46°18'56"N	11°36'14"E	5	6.37E <sup>-03</sup>	3.99 E <sup>-04</sup>	1.007	0.008	1.027	0.006	1.036	0.012	0.577	0.184	317,20	45.8/13.3	70,46	16.1/9.3
PA08	Monzodiorite	46°18'23"N	11°36'09"E	8	3.72E <sup>-02</sup>	3.13 E <sup>-03</sup>	1.004	0.003	1.013	0.006	1.018	0.006	0.496	0.286	227,27	39.4/7.7	116,34	10.2/8.1
PA09	Monzodiorite	46°18'46"N	11°37'40"E	8	3.11E <sup>-02</sup>	1.47 E <sup>-03</sup>	1.015	0.003	1.009	0.004	1.024	0.003	-0.244	0.283	260,6	12.6/4.1	3,65	12.3/3.7
PA10	Monzonites	46°18'38"N	11°37'59"E	8	7.39E <sup>-03</sup>	9.51 E <sup>-03</sup>	1.01	0.007	1.007	0.005	1.017	0.012	-0.204	0.262	121,47	13.1/4	331,39	9.2/5.2
PA11	Monzonites to Syenite	46°18'52"N	11°39'26"E	9	2.91E <sup>-02</sup>	2.00 E <sup>-02</sup>	1.025	0.01	1.02	0.09	1.046	0.012	-0.099	0.265	344,86	18.9/7.4	151,4	16.6/7.1
PA12	Clinopyroxenite	46°18'16"N	11°36'11"E	8	1.63E <sup>-01</sup>	2.33 E <sup>-02</sup>	1.003	0.01	1.044	0.015	1.052	0.015	0.858	0.318	79,24	68.5/18.3	182,26	18.4/12.6
PA13	Biotite granite	46°18'29"N	11°36'17"E	4	1.63E <sup>-03</sup>	7.49 E <sup>-04</sup>	1.008	0.007	1.027	0.017	1.037	0.015	0.542	0.423	174,10	37.2/11.8	76,38	17.6/9.4
PA14	Monzodiorite	46°19'33"N	11°35'54"E	9	2.57E <sup>-02</sup>	3.13 E <sup>-03</sup>	1.017	0.004	1.006	0.009	1.024	0.006	-0.495	0.409	177,6	13.9/6.9	75,63	40.1/9.6
PA15	Gabbros	46°23'25"N	11°45'07"E	9	7.34E <sup>-02</sup>	2.53 E <sup>-02</sup>	1.003	0.013	1.037	0.039	1.045	0.046	0.850	0.55	357,67	70.6/14.9	137,18	24.5/15.0
PA16	Gabbros (cumulate)	46°23'25"N	11°45'04"E	9	1.63E <sup>-03</sup>	1.64 E <sup>-03</sup>	1.01	0.012	1.034	0.025	1.047	0.028	0.532	0.36	26,27	25.4/6.5	132,29	12.0/4.8
PA17	Albitized granite	46°23'20"N	11°44'57"E	9	1.02E <sup>-04</sup>	1.32 E <sup>-05</sup>	1.003	0.004	1.006	0.004	1.010	0.007	0.334	0.413	68,23	35.2/15.9	173,32	24.7/17.8
PA18	Olivine gabbros	46°23'41"N	11°44'39"E	8	7.68E <sup>-02</sup>	1.12 E <sup>-02</sup>	1.017	0.009	1.036	0.01	1.055	0.011	0.351	0.272	107,42	18.4/6.3	331,39	16.4/3.8
PA19	Olivine gabbros	46°23'40"N	11°44'40"E	8	3.07E <sup>-02</sup>	1.30 E <sup>-03</sup>	1.022	0.005	1.026	0.003	1.049	0.006	0.084	0.12	317,6	7.3/3.2	73,76	6.4/3.8
PA20	Olivine gabbros	46°23'30"N	11°44'30"E	9	5.26E <sup>-02</sup>	6.07 E <sup>-03</sup>	1.024	0.01	1.049	0.017	1.075	0.015	0.344	0.239	108,11	17.8/11.0	310,78	18.6/7.6
PA21	Monzogabbros	46°23'34"N	11°44'10"E	9	6.22E <sup>-02</sup>	2.19 E <sup>-02</sup>	1.014	0.014	1.032	0.018	1.048	0.01	0.383	0.481	336,1	19.1/11.9	244,59	25.0/10.1

Site	Lithology	Lat	Long	N	Km	std	L	std	F	std	Pj	std	T	std	D,I (k <sub>1</sub> )	E <sub>2-3</sub>	D,I (k <sub>3</sub> )	E <sub>1-2</sub>
PA22	Monzonites	46°23'30"N	11°43'24"E	6	3.73E <sup>-02</sup>	1.54 E <sup>-02</sup>	1.029	0.007	1.013	0.011	1.043	0.016	-0.364	0.185	76,76	5.7/4.4	184,4	37.6/2.8
PA23	Monzonites	46°23'30"N	11°43'08"E	8	7.36E <sup>-02</sup>	2.79 E <sup>-02</sup>	1.019	0.007	1.019	0.015	1.038	0.013	-0.02	0.47	121,65	10.8/7.1	25,3	14.8/7.8
PA24	Monzonites	46°23'31"N	11°43'03"E	9	8.14E <sup>-02</sup>	2.10 E <sup>-02</sup>	1.016	0.007	1.031	0.014	1.049	0.021	0.325	0.149	97,22	22.4/11.7	0,15	17.3/11.0

1196

1197 Table I: Location of sampling sites in the Predazzo and Monzoni plutons and measured magnetic parameters. N = number of specimens;  $K_m = (k_{max} + k_{int} +$

1198  $k_{min}) / 3$  (mean susceptibility, in SI units);  $L = k_1 / k_2$ ;  $F = k_3 / k_1$   $P_j = \exp \{2[(\eta_1 - \eta)^2 + (\eta_2 - \eta)^2 + (\eta_3 - \eta)^2]\}^{1/2}$  (corrected anisotropy degree; Jelinek, 1981);  $T = 2(\eta_2$

1199  $- \eta_3) / (\eta_1 - \eta_3) - 1$  (shape factor; Jelinek, 1981);  $\eta_1 = \ln k_1$ ;  $\eta_2 = \ln k_2$ ;  $\eta_3 = \ln k_3$ ;  $\eta = (\eta_1 + \eta_2 + \eta_3) / 3$ ; D, I (k<sub>1</sub>) = declination and inclination of the maximum

1200 susceptibility axis (paleo-geographic coordinates); D, I (k<sub>3</sub>) = declination and inclination of the minimum susceptibility axis (paleo-geographic coordinates);  $\alpha_{95}$ :

1201 confidence angles; std: standard deviation.

1202



1 **Emplacement modes of the Ladinian plutonic rocks of the Dolomites: insights**  
2 **from Anisotropy of Magnetic Susceptibility**

3

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26 **Abstract**

27

28 In the Dolomites (Eastern Southern Alps, Italy), a diffuse Middle Triassic igneous activity is now  
29 present mostly as lava flow and pyroclastic successions, with rare shallow-depth intrusive bodies  
30 cropping out at Predazzo, Monzoni and Cima Pape areas. In this work, the emplacement modes of  
31 the Predazzo and Monzoni bodies were investigated by means of petrographic and anisotropy of  
32 magnetic susceptibility (AMS) data coupled with a field geological study. The presence of  
33 intrusive rocks in between these two bodies and the continuity of the metamorphic aureola from  
34 west of the Predazzo to east of the Monzoni body suggest that they are parts of a ~20 km wide SW-  
35 NE oriented continuous pluton, sub-parallel to Ladinian strike-slip faults.

36 AMS and petrographic data from the Predazzo body are consistent with a multistage ring-dyke  
37 emplacement mode, with areas of upward flow of the magma located in the NE and SW part of the  
38 intrusion, whereas in the southern sector of the pluton our data suggest prevalently horizontal flows.  
39 In general, the Predazzo sheets indicate either ~~updip~~ (upward?) magma flow or along-strike lateral  
40 magma transport, and the round shape suggests no influence of Ladinian tectonic structures.

41 On the contrary, the ENE-WSW elongated shape of the Monzoni body was controlled by the  
42 occurrence of strike-slip faults associated with Ladinian-tectonics, the feeder being likely located at  
43 the NE edge of the body. However, the absence of deformation at the field- and micro-scale is  
44 consistent with a post Ladinian-tectonics timing of emplacement, as for the Predazzo pluton.

45

46 **Keywords:** Dolomites, anisotropy of magnetic susceptibility, pluton, Predazzo, Monzoni, mode of  
47 emplacement

48

## 50 1. Introduction

51 The Middle Triassic igneous activity in the Dolomites (eastern Southern Alps, Italy; Figs. 1 and 2)  
52 is well known from nearly two centuries (e.g., von Richthofen, 1860; Hansel, 1878). The Dolomites  
53 represent a worldwide reference area for the relationships between magmatism, sedimentation and  
54 tectonics (e.g., Ogilvie-Gordon, 1902, 1903; Hörnes, 1912; Penck, 1911; Vardabasso, 1929, 1930;  
55 Leonardi, 1967; Castellarin et al., 1982, 1982b; Visonà, 1997). The igneous activity of the  
56 Dolomites is a part of a more widespread magmatism developed during Middle and early Late  
57 Triassic in the western Tethys comprising the Southern Alps (~~Adriatic foreland; Brescian Alps;~~  
58 ~~Vicentinian Alps, Carnia and Julian Alps~~), Dinarids, Transdanubian Range and Austroalpine  
59 (Lucchini et al., 1982). In the Dolomites area, Middle Triassic igneous rocks are mostly pyroclastic,  
60 but abundant submarine and subaerial lava and dyke swarms also occur, with magma chambers  
61 eroded to shallow-depth intrusive body levels, cropping out ~~only~~ at Predazzo, Monzoni and Cima  
62 Pape (Fig. 2).

63 Several contrasting geodynamic/tectonic models were proposed to explain Middle Triassic  
64 igneous activity in the Southern Alps: 1) An aborted continental rifting, based on the association of  
65 extensional structures and volcanism (Bechstädt et al., 1977); 2) Northward subduction and  
66 delamination of lower continental crust in the upper mantle, based on the calcalkaline and  
67 shoshonitic magmatic association and on local compressional structures of Middle Triassic age  
68 (Castellarin et al., 1980, 1988; Casetta et al., 2017); 3) Sinistral strike-slip tectonics associated with  
69 local compressional and extensional structures (“rhomb-horsts” and “pull-apart basins”) generating  
70 magma extrusion and a subsidence as result of the collapse of magma chamber roofs (Blendinger,  
71 1985; Doglioni, 1987, 1988); 4) Marginal back-arc basin associated with the post-Variscan  
72 evolution of the Alpine sector (Marinelli et al. 1980; Viel, 1982); 5) Partial melting of a mantle  
73 source modified during the preceding Variscan orogeny and contaminated by the incorporation of  
74 large portions of crustal material (Crisci et al., 1984; Sloman, 1989; Bonadiman et al., 1994); 6)  
75 Intra-Pangea dextral megashear system with lithosphere-scale extension enabling hybridization

76 between mantle melts and lower crust lithologies (Brandner and Keim, 2011); 7) Rifting related  
77 with the opening of the Neotethys (Beltran-Trivinõ et al., 2016; Brandner et al., 2016); 8) Active  
78 upwelling of hot asthenospheric mantle due to the insulating thermal effect of the huge Pangea  
79 landmass (Stahle et al., 2001); 9) Subduction of a small Permian back-arc oceanic (Garzanti 1985;  
80 Zanetti et al. 2013). The models involving subduction (2,4,9) are not coherent with the geological  
81 context of the Southern Alps that shows no evidence of volcanic arcs or oceanic subduction. The  
82 other models are consistent with geodynamic scenarios involving extensional tectonics, either  
83 controlled by rifting or strike-slip tectonics. The recognition of Middle Triassic NE-SW strike-slip  
84 faults in the Dolomites (e.g., Doglioni 1984a) testifies for the importance of wrench tectonics in this  
85 period.

86 The Predazzo, Monzoni and Cima Pape Middle Triassic intrusive bodies in the Dolomites crop out  
87 close to ~~the~~ Middle Triassic NE-SW strike-slip faults (e.g. Stava line; Fig. 2), suggesting a potential  
88 role for strike-slip tectonics in the emplacement of these plutons. The generation, ascent and  
89 emplacement of magma through the crust and its relation to strike-slip faulting ~~is~~are still matter of  
90 debate (Castro 1987; Tikoff and Teyssier 1992; Paterson and Fowler 1993; Romáan-Berdiel et al.  
91 1997; Rosenberg 2004). The emplacement of intrusive bodies can be considered either as controlled  
92 by regional tectonics (syntectonic) if the magmatic fabric is consistent with the regional strain field,  
93 or caused by the internal dynamics of the magma chamber if the magmatic fabric patterns are  
94 independent from the regional tectonic structures (Hutton, 1988; Paterson et al., 1998; Rosenberg,  
95 2004).

96 In the past years, several structural studies on intrusive bodies have been carried out using the  
97 anisotropy of magnetic susceptibility (AMS) technique (e.g., Van der Voo and Klootwijk 1972;  
98 Bouchez et al. 1990; Raposo and Gastal 2009, Cifelli et al., 2012). The magnetic fabric in a pluton  
99 is affected by several factors, such as the flow of the magma, the changes in its effective viscosity  
100 and the finite deformation it undergoes before complete crystallization. Assuming a direct  
101 relationship between mineral and magnetic fabrics (e.g., Graham 1954), the analysis of the AMS in

102 igneous bodies can be used to define the relationship between magma emplacement and tectonics.  
103 This is particularly crucial for rocks that often appear isotropic and where magmatic foliation and  
104 lineation are difficult to observe and measure at the outcrop scale, such as granites (e.g., Knight and  
105 Walker, 1988, Tarling and Hrouda 1993).

106 In this study, we investigate the space and time relationship between the Ladinian Predazzo and  
107 Monzoni plutons and Middle Triassic strike-slip faulting in the Dolomites using AMS techniques,  
108 coupled with petrographic and field studies. In addition to this regional significance, our work can  
109 contribute to the understanding of magma migration and emplacement in the upper crust. A few  
110 exposed subvolcanic and caldera-related plutons have been reported and magma-plumbing systems  
111 of active volcanic areas cannot be directly studied. Therefore, developing and testing models for the  
112 emplacement mechanisms of the ancient exposed sheet intrusions can contribute to the assessment  
113 of volcanic hazard and risk in active volcanic areas (Sparks, 2003; Tibaldi and Pasquarè, 2008;  
114 Cashman and Sparks, 2013).

115

## 116 **2. Geological setting**

117 The Dolomites (Figs. 1 and 2) are located in the central-eastern portion of the Southern Alps, a  
118 south-verging fold-and-thrust belt that belongs to the much larger Alpine Orogeny (Carminati et al.,  
119 2010b; Handy et al., 2010). The Southern Alps (Fig. 1) are located south of the dextral Neogene  
120 Periadriatic Line (also known as Insubric Line) and represent the retro-wedge of the double-vergent  
121 Alpine Chain (Doglioni, 1987; Castellarin et al., 1998; Castellarin and Cantelli, 2000; Bosellini et  
122 al., 2003; Doglioni and Carminati, 2008). The Southern Alps consist of a well-preserved Mesozoic  
123 passive continental margin inverted during the Alpine orogeny (Doglioni, 1987, 2007; Handy et al.,  
124 2010).

125 The area of the Dolomites testify several tectonic and magmatic events recorded in the  
126 stratigraphic succession (Fig. 3), including: 1) Permian extensional tectonics and massive acid  
127 magmatism (Barth et al., 1993; Schaltegger and Brack, 2007; Visonà et al., 2007; Brandner et al.,

128 2016) that induced a lithospheric anisotropy that significantly influenced the Triassic and Alpine  
129 evolution; 2) Middle Triassic tectonics, associated with differential subsidence and uplift and  
130 diffuse magmatic events during the late Ladinian (Fig. 3); 3) A magmatic rifting, started in the Late  
131 Triassic (Fig. 3), evolved into the western Tethys spreading during Early Jurassic times (Carminati  
132 et al., 2010); 4) Several superimposed phases of compressional Alpine deformation including the  
133 Eo-Alpine, Mesoalpine and Neoalpine phases (Castellarin et al., 2004, 2006).

134 The dolomitic area was a wide shallow sea during Late Permian and Early Triassic times, but  
135 started to differentiate at the beginning of early-middle Anisian (Bosellini et al., 2003), probably as  
136 consequence of strike-slip tectonics development (Fig. 3; Brandner, 1984; Doglioni, 1984a, 1987;  
137 Masetti and Trombetta, 1998; Bosellini et al., 2003). Later, a sudden increase in subsidence  
138 combined with a strong sea level rise (Gianolla et al., 1998) drove to a general deepening,  
139 associated with the formation of high-relief carbonate buildups and retreat of the siliciclastic  
140 shoreline (De Zanche et al., 1993; Brack et al., 2007; Stefani et al., 2010; Marangon et al., 2011).  
141 Subsidence rates reached a climax during late Anisian, when the paleogeography of the Dolomites  
142 featured numerous small isolated microbial carbonate platforms (Sciliar Formation) surrounded by  
143 a deep basin (Buchenstein Formation). During Middle Triassic (Ladinian) the Dolomites witnessed  
144 a short-lived massive magmatic event, associated with a strong and localized tectonic activity  
145 (Assereto et al., 1977; Viel, 1979; Bosellini et al., 1982; Castellarin et al. 1988). Magmatic edifices  
146 such as Predazzo, Monzoni and Cima Pape (Fig. 2; Castellarin et al., 1982b; Sarti and Ardizzoni,  
147 1984), now eroded to subvolcanic to epi-pluton levels, developed during significant tectonic  
148 displacement and huge accumulation of megabreccia and chaotic mass-flow deposits (Caotico  
149 Eterogeneo, Fernazza Formation). The volcanic sequence (both submarine pillow lava and pillow  
150 breccias and subaerial lava flows) is composed of alkali olivine basalt to latite association  
151 (Castellarin et al., 1982b; Visona, 1997) and huge volumes of tuffs and volcanoclastics (Fernazza  
152 Formation). The rare quartz syenitic and the much more common shoshonitic dyke swarms cut the  
153 sedimentary cover and intrude the magmatic edifices (Vardabasso, 1930; Castellarin et al., 1982b;

154 Doglioni, 1983). Volcanic activity is also associated with the formation of evaporitic diapirs  
155 (sourced in the Upper Permian evaporitic Bellerophon Formation) that deform sedimentary covers  
156 in areas adjacent to volcanic centers. The syn-volcanic age of these structures is documented by the  
157 fact that they are often cut by the magmatic dykes (Castellarin et al., 1998b). The volcanic activity  
158 ceased in upper Ladinian time and large volumes of volcanic material were dismantled and  
159 deposited as delta and turbiditic sequences in the surrounding basins (Wengen Formation). From  
160 late Ladinian to early Carnian, the subsidence rate decreased, resulting in the progradation of the  
161 southern shoreline and a general shallowing of the basins. This regressive trend culminated in the  
162 late Carnian, with a strong north-eastward shift of the coastline and complete flattening of the  
163 palaeotopography restoring a relative homogeneity in sedimentary palaeoenvironments, as  
164 documented by the Heiligkreuz and Travenanzes Formations (Gianolla-Stefani et al., 2010). A new  
165 transgression in the latest Carnian allowed the deposition of the thick peritidal succession of the  
166 Dolomia Principale (Gianolla-Stefani et al., 2010), which records a huge regional platform that  
167 extended for hundreds of kilometres from north to south and east to west. Widespread carbonate  
168 platforms then characterised the Southern Alps for several million years, from the late Carnian to  
169 (at least) the late Norian.

170

### 171 ***2.1 Age and duration of the Ladinian magmatic event.***

172 The age of the igneous activity is well constrained by biostratigraphy and geochronology. The first  
173 tephra horizon (Fig. 3) with a mafic mineral association (clinopyroxene, plagioclase and olivine) is  
174 recorded in the Acquatona Fm. (~~Longobardicum-longobardicum Subzone~~ ammonoid subzone; Viel.,  
175 1979; De Zanche and Gianolla, 1995; Gianolla et al., 1998 Fig. 3) and in the coeval Buchenstein  
176 Fm. (sensu Brack and Rieber, 1993) Viel., 1979; De Zanche and Gianolla, 1995). The main phase  
177 of volcanic activity is recorded by the Fernazza Fm. (Neumayri-neumayri and early Regoledanus  
178 regoledanus Subzone ammonoid subzones) while the often unconformably overlaid post volcanic  
179 unit (Wengen Fm.) is assigned to the Regoledanus-regoledanus Zone-ammonoid zone (Stefani et

180 al., 2010; Mietto et al., 2012). Absolute ages from ash layers of the Seceda section (Brack et al.,  
181 1996, 1997; Brack and Muttoni, 2000; Wotzlaw et al., 2018) suggest that the first evidence of mafic  
182 activity (tuffs, lava flows or submarine debris flow with lava blocks) is younger than  $239.04 \pm 0.04$   
183 Ma (U-Pb geochronology, Wotzlaw et al., 2018) and possibly coeval with the Upper Pietra Verde  
184 volcanics, where an ash layer (close to the *Lombardicum/Neumayri* subzones boundary)  
185 showed an age of  $238.0 \pm 0.05$  Ma (Mundil et al. 1996). The age of the ~~upper limit, or the~~  
186 termination of the paroxysmal effusive phase, is given by a tuff from the area of Alpe di Siusi  
187 (Mietto et al., 2012), where an ash layer, few meters above the top of the pillow-lava, gives an age  
188 of  $237.77 \pm 0.05$  Ma (U-Pb geochronology).

189 These ages confine the duration of the paroxysmal phase of Ladinian volcanism in the Dolomites  
190 to a time interval no more than 0.7 ~~Ma-Myrs long~~ (considering all analytical errors) and are in  
191 agreement with the absolute age from the Predazzo intrusion, where zircons from the granitic phase  
192 were dated to  $237.3 \pm 1.0$  Ma (Mundil, 1996; Brack et al., 1997) and thus confirming a short-lived  
193 Upper Ladinian magmatic Event.

194

## 195 **2.2 Ladinian tectonics in the Dolomites**

196 During Middle Triassic time, the Dolomites were affected by N 70°-90°E trending strike-slip  
197 faulting (along the Stava, Trodena and Cavalase Lines), which locally was associated with  
198 transtensional and transpressional structures. These faults cut basement and sedimentary succession  
199 up to lower-middle Ladinian rocks (Doglioni, 1984b; Doglioni, 1987; Doglioni and Carminati,  
200 2008). These structures are concentrated along the alignment of the Stava Line – northern limb of  
201 the Cima Bocche Anticline – where flower structures suggest a sinistral kinematics.

202 Middle Triassic compressional structures were locally documented in the Dolomites and consist of  
203 folds and reverse faults (Bechstadt et al., 1977, Pisa et al., 1980, Bosellini et al., 1982; Castellarin et  
204 al., 1982; Doglioni 1982, 1984a, 1984b, 1985, 1987; Doglioni and Carminati, 2008). In addition,  
205 diapiric structures (originating from the Upper Permian evaporitic Bellerophon Fm.) elongated



206 along N70E axis and dated to the Middle Triassic crop out in the central Dolomites (Doglioni,  
207 1984a). These Middle Triassic compressional structures were interpreted as related to N70E  
208 sinistral transpressional tectonics (Doglioni 1984a, 1984b, 1987, 2007), resulting from the sinistral  
209 relative movement between Africa and Europe (Doglioni 1984b). According to Doglioni (1983)  
210 Ladinian mafic volcanic dykes in Dolomites show a radial pattern, which was interpreted as related  
211 to a domal uplift induced by coeval magmatism, possibly inheriting previous structures ~~(Doglioni,~~  
212 ~~1983).~~  
213

### 214 ***2.3 The Predazzo intrusive complex***

215 The Predazzo intrusive complex (Fig. 4) is ring-shaped, ~4 km in diameter and covers an area of  
216 ~13 km<sup>2</sup>. It has been subdivided into four intrusive units on the basis of magma chemistry,  
217 geometry and relative geochronology (Menegazzo et al. 1995; Visonà 1997). Monzonitic unit M1  
218 represents the first intruded unit and forms the outer part of the ring with mainly monzonitic  
219 composition associated with ultramafic rock types (pyroxenites). These ultramafic bodies are  
220 generally small, tabular and vertical with sinuous sharp contacts. Monzonitic unit M2 is intruded  
221 into the Middle Triassic volcanic rockss and into the Mmonzonitic unit M1 and cut them with short  
222 dykes. This unit crops out in the western part of the igneous complex and is mainly composed of  
223 quartz monzonite with subordinate leuco-quartz monzonite and quartz monzodiorite. In more recent  
224 studies, M1 and M2 units were merged into a single shoshonitic silica-saturated (SS) series (Casetta  
225 et al., 2017). Monzonitic unit M3 is mainly located in the eastern part of the pluton and intrudes  
226 both volcanic rockss and Mmonzonitic unit M1. It consists of monzodiorite to syenite, both quartz-  
227 or foid-bearing. The granite unit is located in the central part of the pluton and cuts both volcanic  
228 rockss and Monzonitic units M1 and M2. It consists of two separate lithotypes: a) biotite granite,  
229 b) tourmaline leuco-granite (Visonà, 1997). In Fig. 4 we observe vVariably (mainly NNW-  
230 SSradially) oriented systems of basaltic to trachytic composition-dykes that cut the entire intrusive

231 complex together with the surrounding volcanic products, ~~that~~which in total cover an area of ~25  
232 km<sup>2</sup> (Casetta et al., 2017).

233

234

#### 235 **2.4 The Monzoni intrusive complex**

236 The Monzoni intrusive complex (Fig. [5](#) and [6](#)), located 8 km to the NE of the Predazzo complex  
237 ([2](#)) is a NE-SW elongated pluton with a length of <5 km covering an area of ~8 km<sup>2</sup>. The Monzoni  
238 pluton played a central role not only for the study of the Middle Triassic magmatism but also in the  
239 development of petrography, being the type locality for monzonitic rocks (Brogger, 1895). The  
240 intrusion comprises a series of basic to intermediate plutonic rocks, which consist of gabbroic rocks  
241 (gabbro, olivine gabbro, monzogabbro), cropping out in the north-eastern part of the complex  
242 together with clinopyroxenite, while monzonites and monzodiorites constitute the western part of  
243 the intrusion (Del Monte et al., 1967; Bonadiman et al., 1994; Gallien et al., 2007) ([Fig. 5](#)). The  
244 Monzoni complex and its thermo-metamorphosed Permian to Triassic host-rocks are cut by quartz  
245 syenitic and shoshonitic dyke swarms (Bonadiman et al., 1994).

246

#### 247 **2.5 Intrusions' host rocks**

248 The country rocks of the Ladinian plutons include ([Castellarin et al., 1982](#) ~~[b](#)~~ [Gianolla et al., 2010](#))  
249 lower Permian acidic volcanic rocks of the Athesian Volcanic Group (mostly rhyolites; Marocchi et  
250 al., 2008), a ~~widespread~~ succession of volcanites up to >2 km thick, the Upper Permian fluvial red  
251 beds of Val Gardena Sandstones (~100 m thick; [Figs. 4, 5](#)), the Upper Permian ~~dolomitic~~  
252 ~~limestones~~ ~~marls and evaporites~~ of the Bellerophon Fm. (~300 m; [Fig. 4](#)), the Lower Triassic clastic-  
253 carbonate Werfen Fm. (~280-500 m; [Figs. 3, 4](#)), the middle Anisian ~~low-relief unit~~ ~~mixed carbonate-~~  
254 ~~siliciclastics units~~ (from Richthofen to Contrin Fm.; ~150-200 m; [Figs. 3, 5](#)), the ~~high-relief~~ Sciliar  
255 carbonate platform (~800 m) and the ~~basinal deposits~~ ~~mainly cherty limestones~~ of Buchenstein Fm  
256 (max 80 m).

257 The sedimentary cover is overprinted by ~~the local effects of~~ contact metamorphism around the  
258 plutons (Vardabasso, 1929,1930; Ferry, et al., 2002, Gallien, et al., 2007), and exhibit strong  
259 evidence of regional tectonic deformation. The area around the intrusions is characterized also by  
260 significant collapses of the sedimentary cover (Vardabasso, 1930; Castellarin et al., 1982b) with  
261 vertical displacements of several hundred meters (e.g., Monte Agnello area) and platform-block  
262 tilting (e.g., Vallaccia area).

263

### 264 **3. Sampling and Methods**

#### 265 **3.1 Sampling**

266 ~~In this study,~~ Sampling for petrographic and AMS analyses was carried out both in the Predazzo  
267 and Monzoni plutons (Table 1). In the Predazzo intrusive body, 14 sites were sampled and 107  
268 cylindrical cores were collected for AMS analysis (Fig. 4a). In the Monzoni intrusive body, 10 sites  
269 were sampled for a total of 84 cylindrical cores (Fig. 5a). At each site, cores were drilled using an  
270 ASC 280E petrol-powered portable drill and oriented *in situ* by a magnetic compass, corrected to  
271 account for a local  $\sim 2^\circ$  magnetic declination according to the NOAA National Geophysical data  
272 center. The geographic distribution of the sampling was influenced by the difficulty to find  
273 accessible outcrops in many areas, preventing the possibility to make a homogeneously distributed  
274 sampling throughout the two intrusive bodies.

275

#### 276 **3.2 Petrographic analysis**

277 The collected samples were cut with a diamond-disc saw to obtain 29 thin sections for  
278 petrographic study and the reminder parts were grounded in a steel mill to about mm-scale  
279 fragments. ~~Then, the fragments were washed with distilled water and then dried in an oven at 110~~  
280 ~~°C for 10 hours and eventually pulverized in a low blank agate mortar.~~ The petrographic  
281 description of the thin sections was accomplished using an optical polarizing microscope.

282

### 283 **3.3 Magnetic mineralogy**

284 The AMS technique provides a quick and accurate determination of igneous rock fabric. The  
285 magnetic fabric (lineation and foliation) data obtained from AMS measurement can record the  
286 primary magma flow in magmatic sheet intrusions (Polteau et al., 2008; Petronis et al., 2013,  
287 Andersson et al., 2016; Magee et al., 2016), although magnetic fabric data are sometimes complex  
288 and in some cases subject of controversy.

289 The precise knowledge of the magnetic mineralogy is an important aspect to use AMS for tectonic  
290 purposes because the preferred orientation of different magnetic minerals reflects the deformation  
291 history of the rock (e.g., Rochette et al. 1992; Hrouda et al. 1997). Magnetic mineralogy analyses  
292 were carried out in order to characterize which are the main magnetic minerals in the sampled sites.  
293 The variation of magnetic susceptibility with temperature was measured on powders from 24  
294 representative samples, one for each site, by means of the same Agico KLY-3 Kappabridge used for  
295 LF-AMS measurements, equipped with a CS-2 furnace, at the paleomagnetic laboratory of the  
296 Department of Sciences of Roma Tre University. Samples were heated up to 700 °C and cooled  
297 back to 40 °C to estimate the Curie/Néel range of temperatures, according to the inverse  
298 susceptibility method proposed by Petrovský and Kapička (2006), and to examine any possible  
299 mineralogical changes associated to the heating process in air. Moreover, the hysteresis properties  
300 of powders from 21 representative samples were measured on a Princeton Measurements  
301 Corporation 3900 vibrating sample magnetometer (VSM), in field up to 1 T. The powders have  
302 been placed in pharmaceutical gel caps suitable for vibrating in the VSM, in order to determine,  
303 after subtracting the high field linear trend, the coercive force ( $B_c$ ), the saturation remanent  
304 magnetization ( $M_{rs}$ ), as well as the saturation magnetization ( $M_s$ ). The coercivity of remanence  
305 ( $B_{cr}$ ) values have been extrapolated from backfield remagnetization curves up to -1 T, following  
306 forward magnetization in a +1 T field. These measurements were carried out in the Istituto  
307 Nazionale di Geofisica e Vulcanologia (INGV, Rome).

308

### 309 **3.4 Anisotropy of low-field magnetic susceptibility (LF-AMS)**

310 AMS is defined by a second rank tensor and represented geometrically by an ellipsoid in which  
311 the greatest intensity of magnetization is induced along the long axis  $k_1$  and the weakest intensity  
312 along the short axis  $k_3$  (with the principal axes  $k_1 > k_2 > k_3$ ). Since the pioneering work of Graham  
313 (1954), a close correlation between the directions of the main axes of AMS ellipsoid ( $k_1, k_2, k_3$ ) and  
314 the petrofabric strain axes ( $\lambda_1, \lambda_2, \lambda_3$ ) has been widely demonstrated. Several parameters have been  
315 defined both for the quantification of the magnitude of anisotropy and for defining the shape of the  
316 ellipsoid (Table; Jelinek, 1981; Hrouda, 1982). The mean susceptibility values  $k_m$  have been  
317 computed as  $k_m = (k_1 + k_2 + k_3)/3$ . The magnetic lineation is computed by  $L$  ( $k_1/k_3$ ) and has an  
318 orientation defined by the orientation of  $k_1$ , while the magnetic foliation is computed by  $F$  ( $k_2/k_3$ )  
319 and it is defined as the plane perpendicular to  $k_3$ .  $T$  is the shape parameter and range from -1  
320 (perfectly prolate ellipsoid with  $L \gg F$ ) to +1 (perfectly oblate ellipsoid with  $F \gg L$ ) with zero  
321 values corresponding to a triaxial shape ( $F \sim L$ ). The anisotropy degree is computed by the  
322 parameter  $P_j$  (Jelinek, 1981), which is obtained considering all the three principal susceptibility  
323 values.

324 Measurement of the anisotropy of low-field magnetic susceptibility (LF-AMS) represents a rapid  
325 and non-destructive technique for the characterisation of the mineral fabric in rocks (Hrouda, 1982).  
326 In this study, the LF-AMS was measured on about 200 specimens, with an Agico KLY-3S  
327 susceptibility bridge (Jelínek and Pokorný, 1997) in the paleomagnetic laboratory of the  
328 Department of Sciences of Roma Tre University. The anisotropy measurements at both the  
329 specimen and the site scale were evaluated using Jelínek's statistics (Jelinek, 1977).

330

### 331 **3.5 Anisotropy of high-field magnetic susceptibility (HF-AMS)**

332 As the LF-AMS is the sum of the contribution from all minerals, which include ferromagnetic,  
333 paramagnetic and diamagnetic phases (Rochette et al., 1983), we measured high-field AMS (HF-  
334 AMS) on 13 selected samples in order to discriminate the relative contribution of ferromagnetic and

335 paramagnetic minerals to the magnetic anisotropy (e.g., Martin Hernandez and Hirt, 2001). HF-  
336 AMS measurements were carried out, using magnetic fields up to 1500 mT. These fields are strong  
337 enough to saturate all ferromagnetic minerals except hematite (not present in the analyzed samples),  
338 and allow the separation of paramagnetic and ferromagnetic contribution to the magnetic anisotropy  
339 (e.g., Hrouda and Jelínek, 1990). Measurements were made with a high-field torque magnetometer  
340 (Bergmüller et al., 1994) in the Laboratory of Natural Magnetism of the Institute of Geophysics  
341 ETH in Zürich.

342

## 343 **4. Results**

### 344 *4.1. Petrographic description*

345 A complete petrographic description of the samples (Table 1) is provided in Appendix A. Here a  
346 summary is presented.

347 In the Predazzo pluton, lithologies vary from cumulitic clinopyroxenite (samples PA12, PA11a, b,  
348 c) to cumulitic gabbro (PA10), diorites (PA06), monzonite (PA02, PA10), monzodiorite (PA08,  
349 PA14c, PA09), monzogabbro (PA12) albitized granite (PA01, PA04, PA05, PA17) and biotite  
350 granite (PA07, PA03, PA13). We found evidence of hydrothermal alteration in samples from the  
351 northern part of granite body of the Predazzo pluton (PA01, PA04, PA05, and PA17).

352 The samples from Monzoni pluton are classified into two main groups: gabbroic rocks and  
353 monzonites. Gabbroic rocks are mainly located in the north-eastern sector of the pluton and consist  
354 of monzogabbros (PA21), non-cumulitic gabbros (PA16) cumulitic gabbros (PA15) and olivine  
355 gabbros (PA20, PA18). Monzonites (PA22, PA22a, PA23, PA24) are mainly located in the south-  
356 western sector of the pluton and represent the most widespread rock type.

357 As widely accurately described in the appendix, The samples from both plutons show purely  
358 magmatic structures (for most of lithologies hypidiomorphic inequigranular medium- to coarse-  
359 grained textures with anhedral, to euhedral crystals) with undeformed feldspar, clinopyroxene, and

360 amphibole ~~devoid of any deformation~~. In few cases, kinked biotite occurs. Quartz does not show  
361 any or very limited undulatory extinction, and no or rare sub-grains.

362

#### 363 *4.2 Magnetic fabric results*

364 The magnetic susceptibility and main anisotropy parameters of the analyzed sites are listed in  
365 Table 1. The orientation of the magnetic foliation and magnetic lineation has been reported in pre-  
366 tilting coordinates, on the base of the regional structural evolution and geological mapping, which  
367 show a 10° of tilting toward NE in the Predazzo area and 15° toward N in the Monzoni area. In the  
368 Predazzo pluton, a bimodal distribution of  $k_m$  values is observed, which reflects the lithological  
369 differences of the analyzed samples (Table 1). Samples taken from granites show low values, in  
370 the range of  $E^{-03}$ - $E^{-05}$  SI, whereas samples from clinopyroxenites, gabbros and diorites show higher  
371 values (up to  $1.63 E^{-01}$  SI), qualitatively suggesting a major contribution of ferromagnetic minerals  
372 to the magnetic susceptibility in these latter lithologies. These data are consistent with the  
373 occurrence of magmatic foliation (Fig. 6b) both at meso- and micro-scale. In the Monzoni pluton,  
374 monzonites and gabbroic rocks show similar values of  $k_m$ , in the range of  $E^{-02}$  SI, suggesting a  
375 strong contribution of ferromagnetic minerals (Table 1) consistent with preferred orientation of  
376 minerals observed in thin sections (Fig. 6c,d,e,f).—The susceptibility vs. temperature heating-  
377 cooling curves indicate that low-Ti content titanomagnetite and magnetite are the main  
378 ferromagnetic minerals both in the Pradazzo and Monzoni intrusive bodies. A slight to moderate  
379 step around 350 °C is attributed to the presence of a small amount of maghemite which converted to  
380 hematite as confirmed by the slightly lower susceptibilities recorded along the cooling curves (Fig.  
381 76 a-d). Also, a well-defined Hopkinson peak has been recorded in few samples, before a sudden  
382 drop in susceptibility which might correspond to a partially oxidized titanomagnetite (Fig. 76-c and  
383 d). Hysteresis loops (Fig. 76 e-h), isothermal remanent magnetization (IRM) acquisition curves and  
384 backfield applications are well defined, due to the relatively high values of the concentration

385 dependent magnetic parameters. The results are mainly consistent with a prevailing low-coercivity  
386 component, as evidenced by Bcr values, which ~~is~~ are lower than 40 mT (Fig. ~~76~~ i-l).

387 In most of the sites, the magnetic foliation is well developed and its values (F) are greater than  
388 those of the magnetic lineation (L; ~~Table Tab-1~~ and Fig. ~~87~~). Magnetic shape factors (T) in most of  
389 the samples show a dominant oblate shape, and for few samples, it shows prolate and triaxial shape  
390 (~~Table. 1 and Fig. 7~~). The degree of anisotropy (Pj) values do not show significant difference  
391 between monzonite and granites and vary between 1.01 and 1.15 (Fig. 8b Table 1).

392 In the Predazzo intrusives, the Monzonitic Unit M1 has been sampled in different sites along the  
393 southern (PA08, PA09, PA10), the south-western (PA06) and north-western (PA02) borders of the  
394 plutonic body (Fig. 4a). In all these sites AMS shows a well-defined magnetic foliation, which  
395 ranges from moderately dipping (~~235~~<sup>23</sup>°) to vertical (~~898~~<sup>89</sup>°) and strikes almost parallel to the intrusive  
396 borders. In particular the magnetic foliation is oriented WSW-ENE at sites PA08, PA09, and PA10,  
397 ~~WNW-ESEENE-WSW~~ at site PA06, and N-S at site PA02 (Figs. 4b and 98a, e, f). Furthermore, we  
398 sampled a site (PA12) in one of the mafic bodies that outcrop along the western part of the  
399 intrusive. The magnetic foliation dips outward the intrusive body at sites PA02, PA09 and PA10  
400 and toward the boundary within Monzonitic Unit M2 at sites PA06, PA08 and in the mafic body  
401 site PA12. The magnetic lineation shows gentle to sub-horizontal dipping, and is variably oriented  
402 respect to the intrusive body, ranging from sub parallel to the boundary (PA02, PA06, PA08, PA09)  
403 to orthogonal to it (PA10) to disperse around a great circle (PA12). The Monzonitic Unit M3 has  
404 been sampled at one site (PA11), located in the eastern part of the intrusive. In this site, magnetic  
405 foliation is very well defined and is sub-vertical with a WSW-ENE direction, parallel to the  
406 elongation of this unit. Magnetic lineation is also well defined and sub-vertical (Figs. 4b and 98d).

407 The granite intrusion has been sampled in 7 sites, located in the north-western (PA01, PA04,  
408 PA05 and PA17), in the south and south-western (PA03, PA07 and PA08) boundaries of the body  
409 (Fig. 4a). The magnetic foliation is well defined in all the sites, but in site PA01 where it shows a  
410 significant dispersion around an E-W direction. In the north-western part of the intrusion magnetic



411 foliation is oriented NNE-SSW at sites PA04 and PA05, where it is sub-vertical and dips toward the  
412 internal and the external border of the intrusive body, respectively (Figs. 4b and 98b, c), whereas at  
413 site PA17 the magnetic foliation is E-W oriented and dips toward the north. In the south-western  
414 part of the granitic body, the magnetic foliation is also parallel to the border of the intrusion, being  
415 W-E oriented at site PA03 and NW-SE at site PA07. In both sites, the foliation is dipping toward  
416 the external part of the intrusion. The magnetic lineation is very poorly defined at sites PA01 and  
417 PA07, whereas is sub-vertical at sites PA04 and PA05<sup>7</sup>. At sites PA03 and PA17 the magnetic  
418 lineation is poorly grouped with a sub-horizontal E-W orientation (Figs. 4 and 98a-f).

419 In the Monzoni pluton we sampled mafic rocks in the eastern part of the intrusive, and monzonite  
420 units in the western part of the body (Fig. 5a). In the monzonite sites (PA22, PA23, and PA24), the  
421 magnetic foliation is well defined, with a W-E orientation and a sub-vertical attitude. In these sites,  
422 the magnetic lineation is well defined and mostly shows sub-vertical dip (Figs. 5b and 98j). In the  
423 mafic units, the magnetic foliation is well defined and varies from gently dipping toward the SE  
424 (PA18) to a sub-horizontal attitude (PA19, PA20, PA21). In all these sites, the magnetic lineation is  
425 well defined with a WNW-ESE orientation (Figs. 5b and 98i, k, l). At sites located in the eastern  
426 part of the pluton, the magnetic foliation is well defined at sites PA15 and PA16, where it shows a  
427 NE-SW orientation and a step dipping to NW. At site PA14 the magnetic foliation is poorly  
428 defined, being dispersed in a E-W direction. Magnetic lineation is well defined at sites PA14 and  
429 PA16, where it is sub-horizontal and N-S oriented respectively, whereas it is poorly defined at site  
430 PA15. (Figs. 5b and 98g-h).

431 HF-AMS measurements indicate that, for most of the samples, the observed magnetic fabric is  
432 dominated by the ferromagnetic component (Fig. 109) in most of the sites and a very good  
433 correspondence between the orientation of the principal axes of the ellipsoid at low-field and those  
434 of the ferromagnetic ellipsoid in high-field exists. This suggests that the magnetic fabric can be  
435 described in terms of the orientation of the ferromagnetic minerals. In samples where the HF-  
436 paramagnetic fraction is significant (>50%), there is a good correlation between low-field and high-

437 field (ferromagnetic and paramagnetic) magnetic ellipsoids, whereas when the paramagnetic  
438 fraction is very low its orientation cannot be determined with the necessary accuracy (Fig. 109d).

439

## 440 5. Discussion

441 ~~The AMS technique provides a quick and accurate determination of igneous rock fabric. The~~  
442 ~~magnetic fabric (lineation and foliation) data obtained from AMS measurement can record the~~  
443 ~~primary magma flow in magmatic sheet intrusions (Polteau et al., 2008; Petronis et al., 2013;~~  
444 ~~Andersson et al., 2016; Magee et al., 2016), although magnetic fabric data are sometimes complex~~  
445 ~~and in some cases subject of controversy. In particular, Mmagnetic fabric in intrusions can be~~  
446 purely magmatic (related to internal magma chamber processes, such as convection, magma surges,  
447 and dyke injection) or it can be the result of regional deformation (syn- to post-tectonic strain) or a  
448 combination of these two processes (Paterson et al., 1998). In the Predazzo and Monzoni  
449 samplesbodies, thin section analyses show that the microstructures are purely magmatic (i.e., just  
450 after the complete crystallization of magma). The absence of evident solid-state deformation  
451 suggests that the magnetic fabric is not related to tectonic deformation after cooling, but it rather  
452 developed during magma emplacement and cooling (Büttner, 1999). Hydrothermal fluids can also  
453 modify the magnetic fabric orientation and parameters acquired during magma emplacement and  
454 cooling, thus complicating the interpretation of magnetic fabric data (e.g. Just et al. 2004; Petronis  
455 et al. 2011; Nédélec et al. 2015; Tomek et al., 2017). Although some samples from the northern part  
456 of the Predazzo granite body (PA01, PA04, PA05, and PA17) showed evidence of hydrothermal  
457 alteration, We found evidences of hydrothermal alteration in sites from the northern part of granite  
458 body of the Predazzo pluton (PA01, PA04, PA05, and PA17). However, in most of these sites  
459 magnetic foliations are generally tangent to the ring shape of the pluton. This suggests that  
460 hydrothermal alteration had no or minor effect on the magnetic fabric, with the exception of sample  
461 PA17, that is strongly hydrothermally altered and fractured and show a distinctive magnetic fabric.  
462 Therefore, site PA17 will be no longer considered in the discussion of the emplacement mode of the

463 Predazzo pluton. ~~Concerning the Monzoni pluton, samples from site~~ PA11, belonging to  
464 Monzontic Unit M3 of the Predazzo body, is-are highly altered and transformed as a result of  
465 hydrothermal solutions. However, the magnetic fabric orientation is concordant with NE-SW  
466 elongation shape of Monzontic Unit M3 and shows well-clustered magnetic fabric. The  
467 compatibility of the magnetic fabric with the elongation shape of this unit could be explained as the  
468 hydrothermal fluid was likely coeval with the emplacement as a single event (e.g. Nédélec et al.,  
469 2015). Moreover, the NE-SW orientation of the magnetic fabric and elongation of the Monzontic  
470 Unit M3 suggests that the emplacement of this unit was controlled by NE-SW Middle Triassic  
471 (Ladinian) tectonic structures.

472 In the following, the Predazzo and Monzoni plutons will be discussed separately. However, Figure  
473 2 shows that these intrusive bodies may be parts of a single large and rather continuous body, as  
474 suggested by the outcrop of a small volume of intrusive rocks between the plutons and by the  
475 continuity of a metamorphic aureola from west of the Predazzo body to the Monzoni body. The  
476 emplacement of Ladinian intrusive bodies likely occurred along a fractured zone associated with  
477 previous strike-slip tectonics (Fig. 11a), as suggested by the parallelism between Ladinian  
478 intrusives and Middle Triassic faults (e.g., Stava-Trodona line, Fig. 2b).

479 The Predazzo and Monzoni plutonic rocks show distinct shapes, the first being roughly round  
480 shaped and characterized by ring type successive intrusions, the second being markedly NE-SW  
481 elongated, sub-parallel to the Middle Triassic Stava-Trodona line. Similarly, the AMS analyses  
482 show markedly different results for the two intrusive bodies, suggesting different emplacement  
483 modes. Both the Predazzo and Monzoni bodies are the result of multiple intrusions, as indicated by  
484 the variety of lithologies described above (see also appendix A).

485

486

487

488 ***5.1 Emplacement mode of the Predazzo pluton***

489 In the Predazzo body, AMS has been measured in the different intrusive bodies that form the  
490 pluton, showing distinctive pattern of magnetic fabric. The Monzonitic Units M1 and M2~~The~~  
491 ~~Monzonite intrusion (M1+M2)~~, that represents the older portion of the pluton, is-are characterized  
492 by an annular ellipsoidal shape, gently elongated in a ENE-WSW direction. In this body, the  
493 magnetic foliation is generally oriented parallel to the borders of the intrusion (i.e., parallel to its  
494 perimeter). In sites that are located along the external rim, the foliations are predominantly steeply  
495 or shallowly radially dipping away from the pluton. On the contrary, in sites located along the  
496 internal rim of the annular intrusion the foliations radially dip towards the centere of the pluton. The  
497 magnetic lineation is generally gently dipping to sub-horizontal and parallel to the border of the  
498 intrusion. In the granite body the magnetic foliation is almost parallel to the rims of the pluton and  
499 dips away from the intrusion, whereas the magnetic lineation varies from sub-vertical to sub-  
500 horizontal. The rough ring shape of the Predazzo multistage intrusive complex and the presence of  
501 volcanic rocks at the centre of the ring (suggesting a caldera collapse of this area), led Castellarin et  
502 al. (1982b) to suggest a ring dyke emplacement mode. Ring dykes are cylindrical sheet intrusions  
503 occurring at subvolcanic level characterized by outward-dipping walls on all sides. They are due to  
504 magma ascent along steep outward-dipping ring fractures, induced by the collapse of the central  
505 block subsidence (e.g., O'Driscoll et al., 2006). The development of caldera ring-faults and the  
506 related subsidence of a central block are the main structural processes that permit the intrusion of  
507 ring-dikes (Roche et al., 2000).

508 Our AMS data are consistent with the ring dyke emplacement mode. In particular magnetic  
509 foliation in the Monzonitic units is dominantly oblate and consistently parallel to the boundaries of  
510 the intrusion and prevalently dips away from the intrusion. Only in places, where sites have been  
511 sampled close to the internal boundary of the Monzonitic units, the foliation is very steep and  
512 dipping toward the internal rim, describing a symmetrical pattern of the magnetic foliation respect  
513 to the dike rims. This geometry has been widely recognized in volcanic dykes, where it has been  
514 interpreted as related to imbrication of the magnetic foliation along the dyke margins, related to

515 upward flow of the magma (Aubourg et al., 2002). In this mechanism, the horizontal magnetic  
516 lineation can be interpreted as an intersection lineation [between differently oriented foliation planes](#)  
517 , which is oriented orthogonal to the magma flow. In sites far from the pluton margins (e.g. PA11),  
518 the steep lineations associated with steeply dipping foliations are likely related to ascent paths of  
519 magma, in particular with laminar flow and wall friction during injection (Andersson et al., 2016).  
520 On the other hand, in sites far from the intrusive rims (e.g. PA02) the occurrence of sub-horizontal  
521 lineations (tangential to the shape of the pluton) could be related to lateral flow of magma induced  
522 by "roll-over" at propagating sheet tips (Emeleus et al., 2012; Andersson et al., 2016) or to semi-  
523 chaotic particle movement during ring fissure flow, [as](#) observed in analogue models (Kennedy et  
524 al., 2008). The occurrence in some samples of magmatic layering steeply dipping inward and  
525 magnetic lineations plunging toward the centre of the intrusion suggests that the shape of the walls  
526 was not as regular (i.e., constantly outward dipping) as assumed in ring dyke models (complex flow  
527 due to complex sheet geometry of Andersson et al., 2016). The steep attitude of inward dipping  
528 foliations is not consistent with a lopolithic geometry of the Predazzo intrusion.

529 The degree of anisotropy ( $P_j$ ) varies between 1.01 and 1.1507 and is not controlled by lithology  
530 (i.e., low and high values are found both in monzonites and granites). More remarkably, the values  
531 do not show a pattern (e.g., high values aligned along WSW-ENE directions, typical of Ladinian  
532 tectonics) but are rather randomly distributed. This confirms a primary (i.e., emplacement-related)  
533 nature of magnetic anisotropy. Moreover, the nonlinear relationship between  $K_m$  and  $P_j$   
534 [s](#)-supports that the obtained low  $P_j$  values indicate the existence of low strain during the  
535 emplacement.

536 Finally, also the orientation of dykes (mainly trending NNW-SSE) crosscutting intrusive rocks is  
537 at odds with sinistral strike slip tectonics along WSW-ENE structures, that would be rather  
538 associated with NE-SW trending dilational (extensional) structure. NE-SW trending dykes are  
539 rather found in the host rocks of the pluton, suggesting that they utilized previous extensional

540 structures associated with sinistral strike-slip faulting. Thus, their emplacement and the  
541 emplacement of the pluton were post-tectonics.

542 In summary, field petrographic and AMS data are consistent with a multistage ring dyke  
543 emplacement mode, similar to the piston floor subsidence mechanism (Tomek et al., 2014), likely  
544 post-tectonics. ~~In particular, AMS data suggest that areas of upward flow of the magma are located~~  
545 ~~in the NE and SW part of the Monzonitic intrusion, whereas in the southern part of the pluton data~~  
546 ~~suggests prevalently horizontal flows.~~ Generally, the Predazzo sheets were emplaced via either  
547 prevalent updip magma flow ~~or associated with local~~ along-strike lateral magma transport (Fig.  
548 11b).

549 ~~NON SI CAPISCE TOGLIEREI~~

550

### 551 ***5.1 Emplacement mode of the Monzoni pluton***

552 The shape of the Monzoni pluton was clearly controlled by Middle Triassic tectonics, being it  
553 elongated WSW-ENE, parallel to the Stava-Trodona strike-slip fault. It remains to be discussed  
554 whether this control was direct (syn-tectonic emplacement of the pluton) or indirect (emplacement  
555 along pre-existing tectonic structures). The host rocks of the Monzoni pluton are affected on all  
556 sides by contact metamorphism. This suggests that the host rock-pluton contacts are primary, thus  
557 no or very poorly affected by post-emplacement tectonics.

558 Comparing magnetic and deformation fabrics in the pluton with strain markers in the country  
559 rocks one can determine whether the magnetic fabric in pluton is primary or reflects regional  
560 tectonic strain (Benn et al., 1998, 2001; Talbot et al., 2005; Raposo et al., 2012). Three different  
561 areas, with distinct magnetic fabric can be recognized in the Monzoni body. In the NW side, the  
562 magnetic foliation is well defined, sub-vertical, and parallel to the E-W oriented boundaries of the  
563 igneous body in this area, with a very steep magnetic lineation. Along the NE side of the intrusive  
564 body the magnetic foliation and magnetic lineation vary from very gently dipping to sub-horizontal.  
565 Along the SE side the magnetic foliation is almost parallel to the boundary of the intrusive and

566 gently to strongly dipping toward the internal part of the pluton, whereas the magnetic lineation is  
567 prevalently ~~gently plungingsub-horizontal~~.

568 Our AMS results suggest that the magnetic fabric in Monzoni pluton was not directly controlled  
569 by Middle Triassic or post-tectonic deformation. This conclusion is supported by the absence of  
570 solid state deformation, by the general steeply magnetic fabric on the two sides of the pluton with  
571 absence of the NE-SW horizontal magnetic lineation and by the low degree of anisotropy ( $P_1$ ),  
572 suggesting that magnetic fabric developed during magma emplacement and cooling and was likely  
573 controlled by the shape of the magma chamber.

574 The magnetic fabric can be read in terms of direction of flow and can help to infer the location and  
575 geometry of the feeding or root zones for magmatic bodies (e.g., Marre, 1986; Djouadi et al., 1997;  
576 Callot et al., 2001; Petronis et al., 2005; O'Driscoll et al., 2006; Maes et al., 2007). Magma  
577 originating from a planar dyke generates a parallel flow pattern with lineations pointing to  
578 opposing, but consistent directions, on either side of the dyke (Knight and Walker, 1988; Ernst and  
579 Baragar, 1992; Maes et al., 2007). Generally, the magnetic lineation, which represents the magma  
580 flow, plunges toward the magma source (Knight and Walker, 1988; Ernst and Baragar, 1992; Maes  
581 et al., 2007). In case of magma fed from a sub-vertical conduit, radial magma flow pattern is  
582 expected. Multiple feeders can produce more complex patterns of magma flow (Maes et al., 2007).  
583 In the Monzoni pluton, the magnetic lineations ~~on the two sides of pluton trajectories~~ converge  
584 towards the north-eastern part of the pluton (PA15, PA16, PA18, PA22, PA23, and PA24),  
585 suggesting that the root zone was not located at the centere of the pluton but rather towards NE.  
586 This interpretation is also consistent with the magmatic evolution of the pluton. Indeed, the most  
587 evolved rocks are located at the south-western edge of the pluton, while the less evolved rocks are  
588 located at the north-eastern part of the pluton.

589 In the Monzoni pluton, steep to moderate foliations and lineations at the western and eastern  
590 borders of the pluton leave space to shallowly dipping fabric in its intermediate parts. This fabric  
591 may have been induced by shear of magma along the host-rocks at the top of the pluton. This

592 inference is in agreement with field host-rocks above the pluton, in agreement with geological  
593 observations that allow to infer that the top boundary of the pluton was located just above the  
594 mountain peaks in the central part of the pluton (Castellarin et al., 1982b).

595 In summary, field, petrographic and AMS data and the ENE-WSW elongated shape indicate that  
596 the site and shape of the Monzoni pluton was controlled by strike-slip faults associated with  
597 Ladinian-tectonics. However, the absence of deformation at the field- and micro- scale is consistent  
598 with a post Ladinian-tectonics timing of emplacement, as for the Predazzo body.

599

## 600 **6. Conclusions**

601 Petrographic and AMS data, coupled with field geological data allowed us to investigate the  
602 emplacement modes of the Predazzo and Monzoni bodies. Although these plutons are considered in  
603 the literature as separated bodies, the outcrop of a small volume of intrusive rocks between the  
604 bodies and the continuity of metamorphic aureola from west of the Predazzo body to east of the  
605 Monzoni body suggest that they are parts of a ~20 km long SW-NE oriented continuous pluton,  
606 sub-parallel to Ladinian strike-slip faults. However, our results suggest a variable control of  
607 Ladinian tectonic structures on the emplacement modes of the two bodies.

608 AMS and petrographic data from the Predazzo body are consistent with a multistage ring dyke  
609 emplacement mode, with areas of upward flow of the magma located in the NE and SW part of the  
610 intrusion, whereas in the southern part of the pluton our data suggest prevalently horizontal flows.  
611 Generally, the Predazzo sheets were emplaced via either updip magma flow or along-strike lateral  
612 magma transport, and the round shape suggests no influence of Ladinian tectonic structures.

613 On the contrary, the ENE-WSW elongated shape of the Monzoni body was controlled by the  
614 occurrence of strike-slip faults associated with Ladinian-tectonics, the feeder being likely located at  
615 the NE edge of the body. However, the absence of deformation at the field- and micro- scale is  
616 consistent with a post Ladinian-tectonics timing of emplacement, as for the Predazzo pluton.

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618

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## Appendix A

### *Petrographic description*

#### *Predazzo pluton*

##### *Clinopyroxenite (PA12, PR11a, b, c)*

Clinopyroxenites show a typical hypidiomorphic inequigranular medium- to coarse grained cumulitic texture. Cumulitic phase (clinopyroxene) accounts for more than ~65% of the rock with usually subhedral, fresh and rarely twinned crystals. Clinopyroxene is mainly medium grained (~3 mm) but a few reach larger dimensions, up to ~6 mm. The intercumulus phases consist of subhedral fine- to medium-grained opaques (~0.3-1.3 mm; ~15%), sometimes included in larger biotite crystals, anhedral to subhedral biotite (~13%) with an average size of ~4 mm and anhedral to subhedral small (~1 mm) plagioclase (~7%). In few cases biotites are partly chloritized, while plagioclases are usually partially sericitized. Fine-grained opaques, biotite and plagioclase are also found included in the clinopyroxene oikocrysts (poikilitic). Apatite and zircon are the common accessory minerals usually found as tiny grains included in clinopyroxene and biotite.

##### *Cumulitic gabbro (PAR 10)*

The cumulitic gabbro is medium-grained with hypidiomorphic inequigranular texture. The cumulitic phases are plagioclase (~50%), clinopyroxene (~36%) and opaques (~10%). Subhedral to euhedral medium-grained (~3 mm) plagioclase is highly altered to sericite with cores more altered than rims. Clinopyroxene is subhedral medium grained (~2 mm), highly fractured, slightly altered and usually twinned. Opaques occurs as subhedral to anhedral fine grained (<1 mm) and usually found in clusters with clinopyroxene or included in clinopyroxene and biotite. The intercumulus

656 phases (~4%) consist of anhedral to subhedral fine grained (<1 mm) biotite and plagioclase. Biotite  
657 and plagioclase also occur as anhedral small grains included in the clinopyroxenes. Apatite is a  
658 common accessory mineral occurring as minute inclusion in clinopyroxene and biotite.

659

660 *Diorite (PA06)*

661 The diorite is characterized by hypidiomorphic inequigranular with medium- to fine-grained  
662 texture. The rock is composed of plagioclase (~60%), amphibole (~15%), biotite (~10%),  
663 clinopyroxene (~10%), plus smaller amounts of K-feldspar, opaques, quartz and accessory  
664 minerals. Plagioclase occurs as slightly sericitized tabular to equant subhedral crystals with an  
665 average size of ~1.5 mm. Anhedral to subhedral amphibole, biotite and clinopyroxene occur as  
666 small (~1 mm) interstitial clusters, together with subhedral fine-grained opaques, usually found as  
667 inclusion in these minerals. Clinopyroxene is generally replaced to different degrees to amphibole.  
668 Most of the biotite crystals are slightly to moderately altered to chlorite. K-feldspar and quartz (<1  
669 mm) occur as anhedral intergranular crystals in between plagioclase laths. Apatite and rare zircon  
670 are present as small inclusions mainly within plagioclase and clinopyroxene.

671

672 *Monzonites (PA02, PA10), monzodiorites (PA08, PR14c, PA09) and monzogabbro (PR12)*

673 These three types of rocks generally share the same petrographic features, being different only for  
674 the relative K-feldspar/plagioclase ratio. The amount of mafic minerals increases from monzonites  
675 to monzodiorites and monzogabbros. This rock group shows hypidiomorphic inequigranular  
676 texture. Monzonite and monzogabbros are medium-grained, while monzodiorites are medium- to  
677 fine-grained. The rocks are poikilitic, with big anhedral K-feldspars including other minerals.

678 The rocks are generally composed, in order of abundance, of plagioclase, K-feldspar,  
679 clinopyroxene, amphibole, biotite, quartz, opaques, orthopyroxene and accessory minerals.  
680 Plagioclase is usually euhedral with variable grain size (~0.5-3 mm) and sometimes zoned, with  
681 cores always more altered than the rims (i.e. sericitized and saussuritized). Few crystals show

682 combined pericline and albite twining. Alkali feldspar (~1-4 mm) occurs as anhedral irregular  
683 grains characterized by perthitic exsolution. Clinopyroxene is subhedral with medium size (~1-2  
684 mm), sometimes twined and in most cases found in clusters. The clinopyroxene crystals are  
685 partially to completely altered to amphibole (uralitization). Amphibole is anhedral to subhedral  
686 (~0.5-1.5 mm) and mostly found along the margin of clinopyroxene. Biotite occurs as subhedral to  
687 anhedral crystals with different grain size (~2-0.5mm) and often found in clusters. In some cases  
688 large biotite crystals are poikilitic for the presence of opaque mineral inclusions. The biotite state  
689 generally is good, but in some case it is partly altered into chlorite. Anhedral quartz is fine- to  
690 medium-grained (~1.5-0.3 mm) and occurs as interstitial phase. Orthopyroxene is subhedral to  
691 anhedral and are usually found in few percent and recorded not in all the thin sections. Also  
692 orthopyroxenes show alteration to amphibole with various degrees. Opaques are small subhedral  
693 grains usually included in the other mafic minerals or occupying interstitial areas. The accessory  
694 minerals are apatite, zircon and sphene, observed as inclusions or along mineral boundaries.

695

696 *Granite group (PA01, PA03, PA04, PA05, PA07, PA13, PA17)*

697 The samples exhibit hypidiomorphic inequigranular texture. In a few cases, granophyric texture is  
698 also recorded. The granite rocks are classified into two main groups: albitized granite (affected by  
699 hydrothermal alteration) and biotite granite.

700 In the first group biotite is completely transformed mainly to sericite and minor chlorite (PA01,  
701 PA04, PA05, PA17), while in the second group biotite is generally found in a good state of  
702 preservation (PA07, PA03, PA13). The biotite granite group is characterized by the presence of  
703 microgranular quartz usually forming aggregates around feldspar crystals.

704 The rocks are made up, in order of abundance, of K-feldspar, quartz and plagioclase with minor  
705 biotite, muscovite, chlorite and rare amphibole.

706 K-feldspar occurs as subhedral medium grained (~2-4 mm) crystals characterized by perthitic  
707 exsolution lamellae. Carlsbad twining is common and the crystals usually shows minor alteration.

708 Quartz mainly occurs in anhedral grains (~1-3 mm) but is also sometimes found in the interstitial  
709 areas (<0.5 mm) or forming aggregates around feldspar crystals. Quartz crystal shows no or  
710 incipient undulatory extinction. Plagioclase is subhedral medium grained (~1-3 mm), sometimes  
711 zoned and usually show albite twinning. In biotite granite, Most of the plagioclase crystals are  
712 slightly to moderately altered (sericitized and saussuritized), with the cores more altered than the  
713 rims. On the other hand, in albitized granite plagioclase is completely transformed having lost  
714 completely its anorthite component. Biotite is present as subhedral platy crystals (~0.5-2 mm) and  
715 usually forms clusters of numerous crystals. Biotite is partially to completely altered to chlorite and  
716 sericite. Sericite occurs as anhedral to subhedral (~1-2 mm) pseudomorphs after biotite and is  
717 commonly associated with chlorite. Chlorite is subhedral to anhedral (~0.5-2 mm) pseudomorphs  
718 after biotite. Rare amphibole crystals have been recorded in the second group. Accessory minerals  
719 are zircon, apatite, fluorite, iron oxide and monazite.

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721 *Monzonite to Syenite? (PA11)*

722 This sample is strongly affected by hydrothermal alteration and a precise classification cannot be  
723 conducted.

724

725 ***Monzoni pluton***

726 The samples from Monzoni pluton have been classified into two main groups: Gabbroic Rock  
727 (olivine-gabbros, gabbros, monzogabbros), mainly located at the northeastern part of Monzoni  
728 pluton, and monzogabbros (PA21).

729 These rocks are medium- to coarse-grained with hypidiomorphic inequigranular texture. The  
730 rocks are composed, in order of abundance, of plagioclase, clinopyroxene, K-feldspar, opaques,  
731 olivine, biotite and accessory minerals.

732 Plagioclase is the most abundant phase. It is euhedral to subhedral medium-grained (~1-4 mm),  
733 always twinned, rarely zoned and mostly unaltered. Clinopyroxene is represented by subhedral

734 medium- to coarse-grained (~1-5 mm) unaltered crystals. K-feldspar is anhedral to subhedral  
735 medium- to fine-grained (~0.5-4 mm), unaltered, untwined, usually occupying the interstitial areas  
736 and in some cases as oikocryst, including the other minerals (poikilitic texture). Opaques are  
737 subhedral fine- to medium-grained (~0.2-1.3 mm), mainly included within other minerals (biotite,  
738 clinopyroxene and olivine) or occupying interstitial areas. Olivine is subhedral medium-grained  
739 (~1-5 mm), usually unaltered and fractured. Biotite is anhedral to subhedral fine- to medium-  
740 grained and unaltered, occupying the interstitial areas between the early crystallized minerals.

741 Gabbro (non-cumulitic) PA 16. This rock exhibits coarse-grained with hypidiomorphic  
742 inequigranular texture. It is made up with plagioclase, clinopyroxene, opaque, biotite and accessory  
743 minerals (in order of occurrence). Plagioclase is euhedral medium- to coarse-grained (~2-5 mm),  
744 usually found in good state or showing slight alteration to sericite and is usually twinned.  
745 Clinopyroxene is subhedral medium- to coarse-grained (~2-6 mm), unaltered, rarely twinned, with  
746 ophitic and subophitic texture (plagioclase partially or completely enclosed by clinopyroxene).  
747 Opaques are subhedral fine- to medium-grained (~0.3-1.3 mm), occupying the interstitial areas or  
748 included within the biotite and clinopyroxene. Biotite is anhedral to subhedral, fine- to medium-  
749 grained (~0.5-2.5 mm), unaltered, and interstitial.

750 Gabbro (cumulitic) PA15. This rock is coarse-grained with cumulitic texture. Cumulus phases are  
751 mainly clinopyroxene with minor olivine. Intercumulus phases are primarily plagioclase and biotite  
752 with minor opaque oxides. Clinopyroxene is euhedral to subhedral coarse- to medium-grained (~2-8  
753 mm), rarely twinned and sometimes slightly zoned. Olivine is subhedral medium-grained (~1-3  
754 mm) and usually found in good state with fracture. It is slightly altered to iddingsite particularly  
755 along the fractures. Plagioclase is euhedral to subhedral medium-grained (~1-2 mm), slightly  
756 altered to sericite and always twinned. Biotite is subhedral to anhedral medium- to fine-grained  
757 (~0.5-2 mm) and in a few cases is slightly chloritized. Opaques are subhedral fine- to medium-  
758 grained (~0.1-1.5 mm). They occur both as interstitial phases or included within clinopyroxene and  
759 biotite.

760 Olivine gabbro (PA20, PA18). These rocks are medium- to coarse-grained. Cumulus phases are  
761 represented by clinopyroxene, plagioclase, and olivine. Clinopyroxenes occurs as subhedral  
762 medium- to coarse-grained (~ 2-6 mm), unaltered and usually untwined. Clinopyroxene oikocrysts  
763 usually include small crystals from opaques, plagioclase, olivine and biotite. Olivine crystals are  
764 subhedral medium-grained (~ 1-2.5 mm). Olivine in sample PA20 is fresh and fractured, whereas in  
765 sample PA18, it is completely altered to secondary minerals (iddingsite, bowlingite and celadonite).  
766 Plagioclase is euhedral to subhedral medium-grained (~ 1-2.5 mm), rarely zoned, and always  
767 showing twining. Plagioclase is fresh in sample PA20 and slightly altered in PA18. Intercumulus  
768 phases are composed of plagioclase, biotite, opaques, and K-feldspar. Plagioclase occurs as fresh  
769 subhedral fine-grained (~ 1 mm). Biotite is fresh medium-grained (~ 1-3 mm), subhedral or  
770 sometimes anhedral, when occupying interstitial positions. Opaques occur as subhedral fine- to  
771 medium-grained (~ 0.5-1.3 mm), and commonly are interstitial phases or are included in  
772 clinopyroxene, biotite and olivine. K-feldspar is clear anhedral fine- to medium-grained (~ 0.5-1.5  
773 mm) and is usually found as interstitial crystals between the early crystallized minerals.

774 Monzonite (PA22, 22A, 23, 24). These rocks are mainly located in the south-western sector of  
775 Monzoni pluton and represent the most widespread rock type. These rocks are medium- to fine-  
776 grained and exhibit hypidiomorphic inequigranular texture. The rocks are composed, in order of  
777 abundance, of plagioclase, K-feldspar, biotite, clinopyroxene, amphibole, opaques, quartz and  
778 accessory minerals.

779 Plagioclase represents the most abundant phase, with euhedral to subhedral tabular laths with  
780 variable grain size (up to 4 mm), usually twinned. Plagioclase crystals generally show slight to  
781 moderate degrees of alteration (sericitization). K-feldspar occurs as anhedral to subhedral, rarely  
782 perthitic, untwined with variable size (up to 5 mm) and is usually found in a good state or in some  
783 cases slightly sericitized. K-feldspar oikocrysts usually include other minerals in a poikilitic  
784 relation. Clinopyroxene is subhedral to anhedral fine- to medium-grained (up to 2 mm), usually  
785 showing different degrees of alteration to amphibole (uralitization). Biotite is subhedral to anhedral

786 fine- to medium-grained (up to 3 mm), generally found in good state or sometimes showing slight  
787 to moderate alteration to chlorite. Quartz occurs as fine interstitial grains between the early  
788 crystallized minerals. Opaques are subhedral to anhedral fine-grained (~0.2-1 mm), and occupy the  
789 irregular interstices in between the other minerals or are included within K-feldspar. Orthopyroxene  
790 is rarely found with anhedral to subhedral medium-grained. Sample PA24 is highly altered  
791 compared to the other Monzonite samples.

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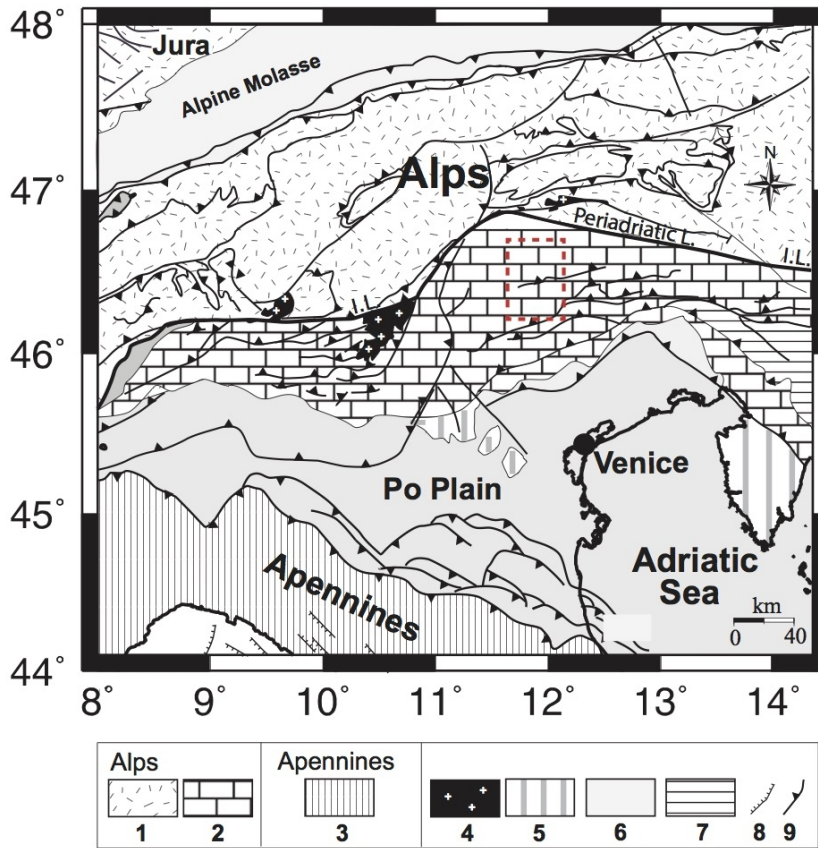
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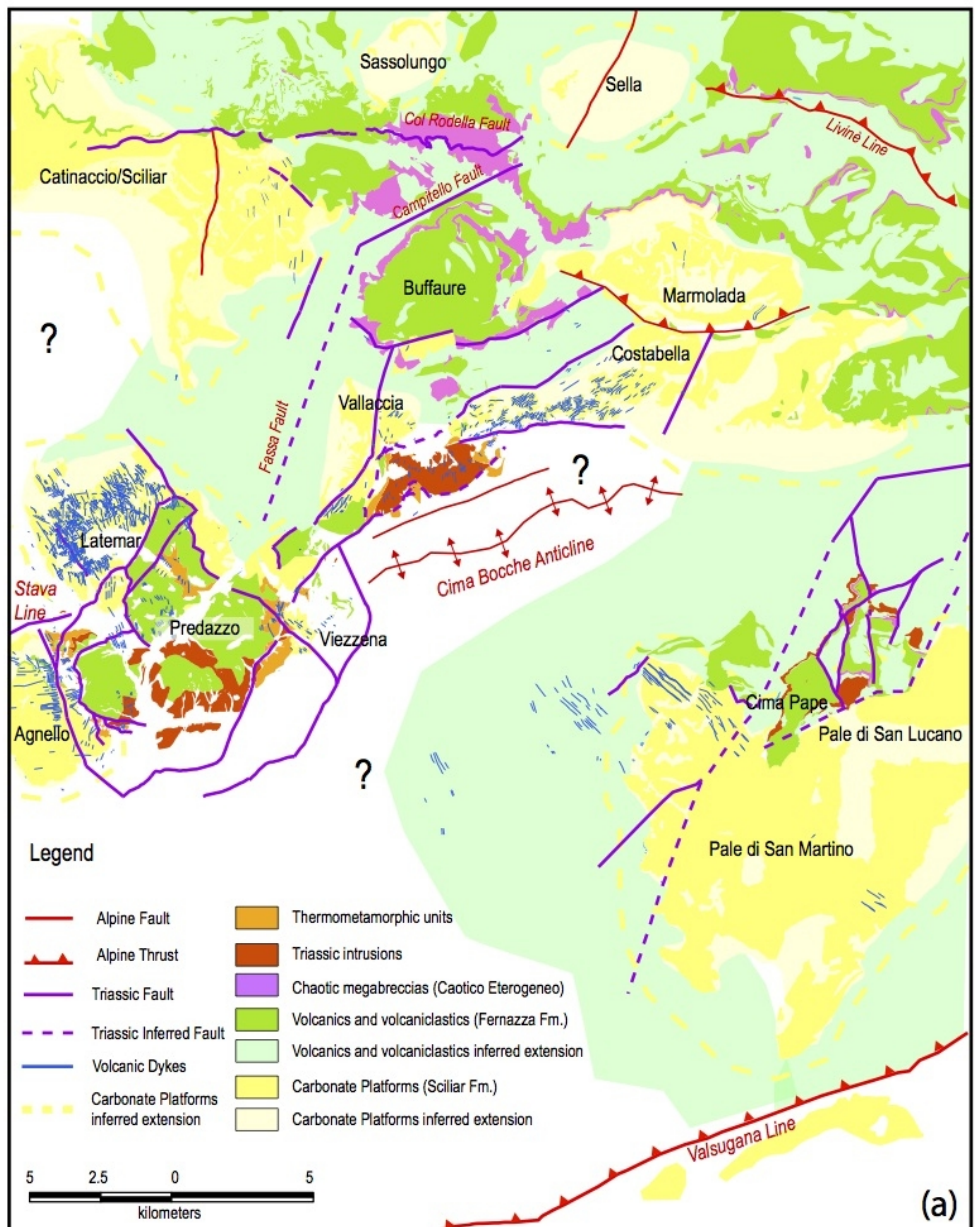
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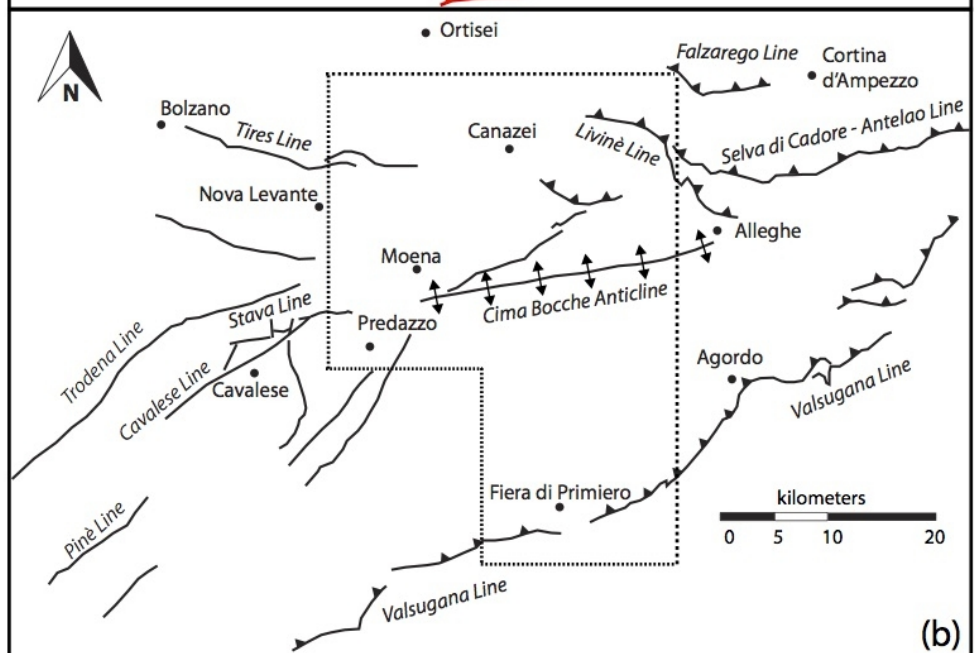
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- 1138
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1144 Figure 1: Simplified geological map of the Southern Alps. Alps: 1) Australpine, Penninic and  
 1145 Helvetic units; 2) Southern Alps units. Apennines: 3) Apenninic units; 4) ~~Tertiary and~~  
 1146 ~~Quaternary Cenozoic~~ volcanic and plutonic bodies; 5) foreland units; 6) foreland basin units; 7)  
 1147 Dinaric units; 8) normal faults; 9) thrust faults. Redrawn and simplified from Bigi et al. (1990).  
 1148 The dashed rectangle shows the location of the map of Figure 2. I.L.: Insubric line.



(a)



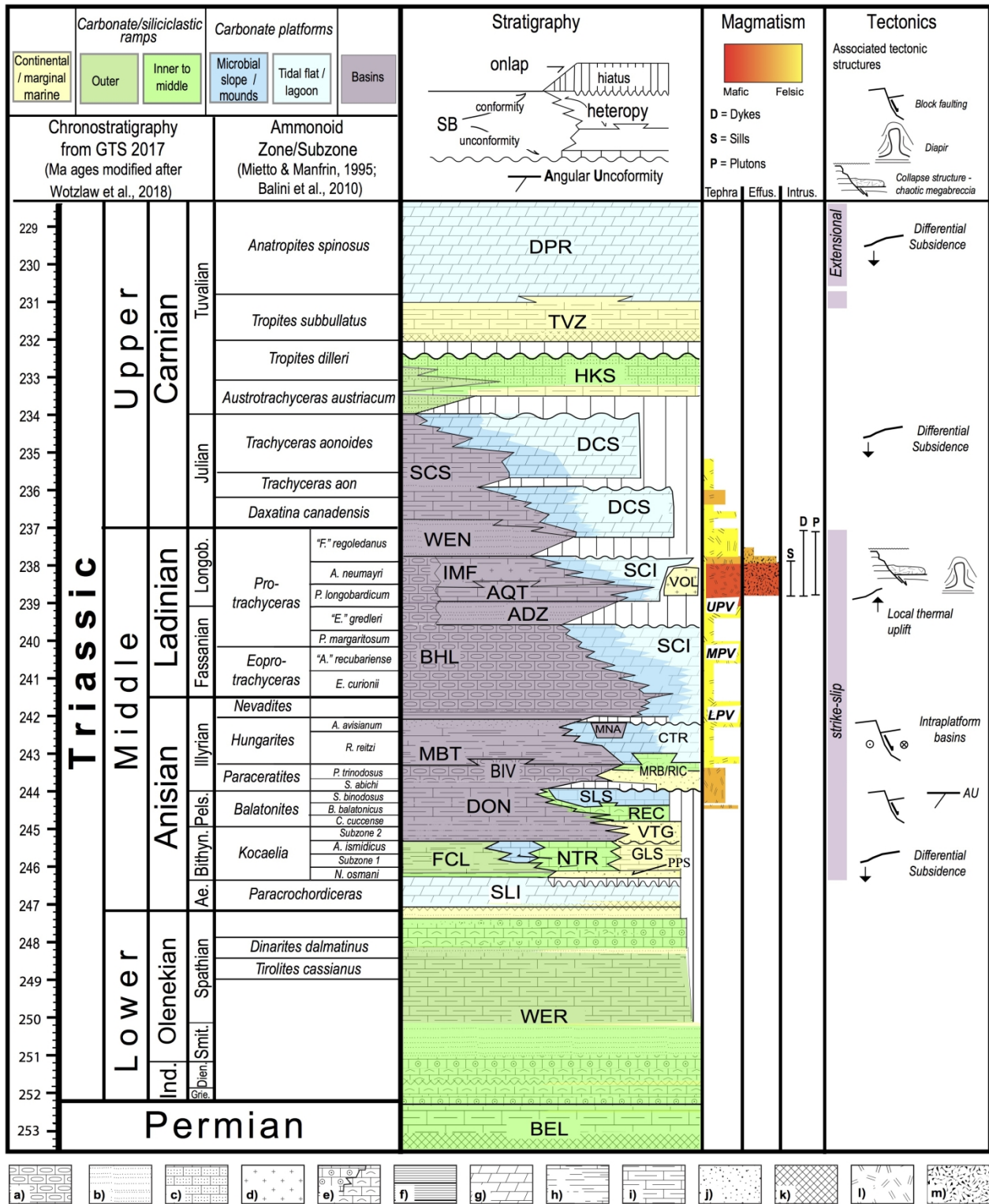
(b)



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1152 Figure 2: a) Unrestored paleogeographic map at Ladinian times of the central-western region of the  
1153 Dolomites. Notice the regional extent of volcanics and the continuity of plutonic bodies and  
1154 associated thermometamorphic rocks for more than 20 km in a SW-NE direction, i.e., parallel to  
1155 major Triassic faults. Cenozoic faults and structures are shown for reference. The location of the  
1156 map is shown in Fig. 1. b) Simplified tectonic map of the Dolomites, showing only major faults,  
1157 not differentiated by their age. The dashed area represents the location of panel a.

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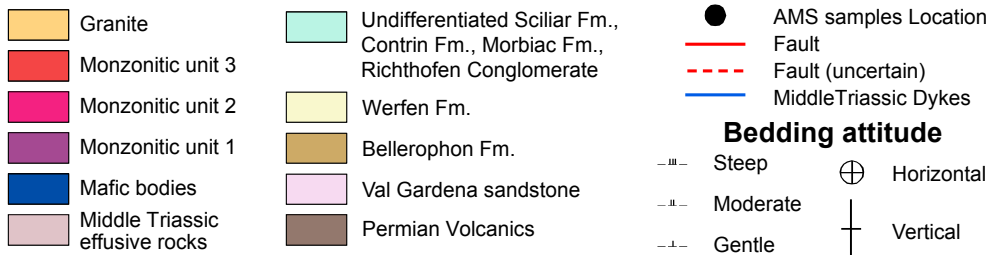
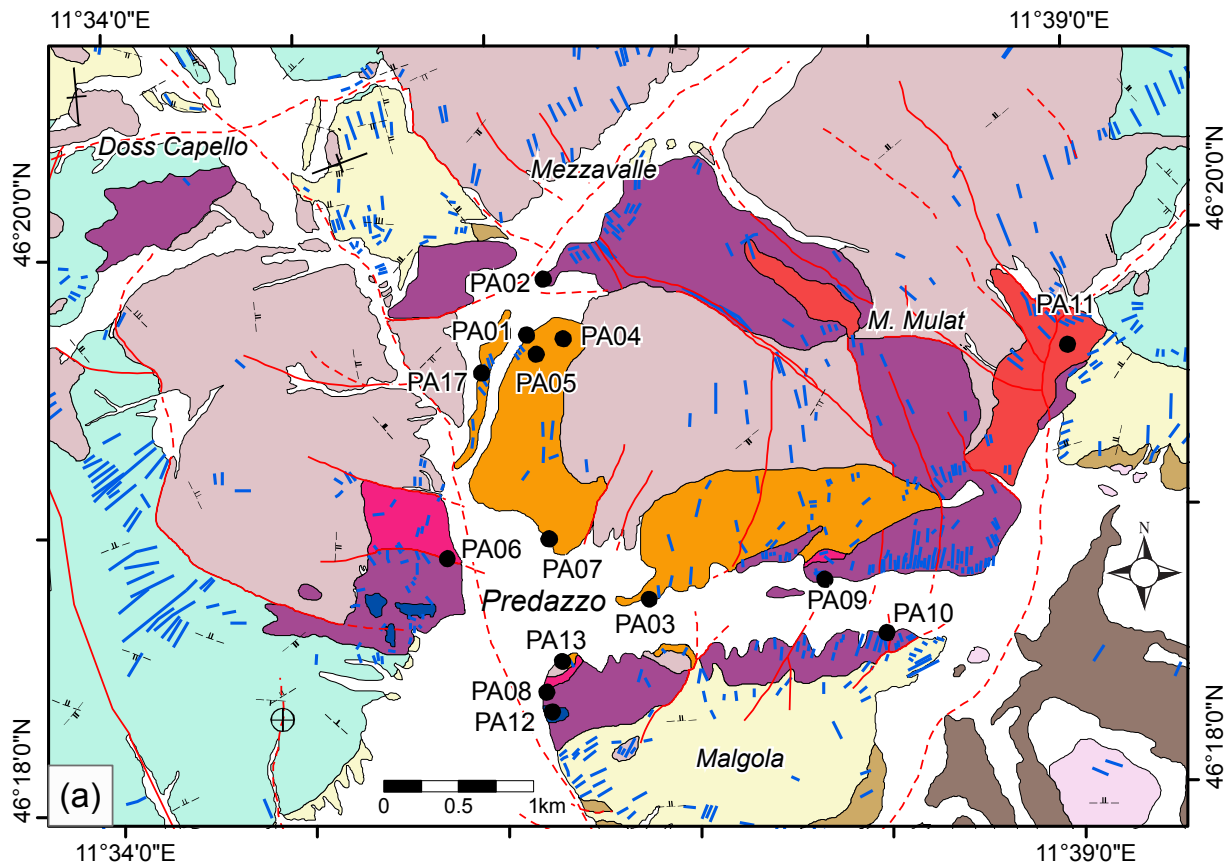
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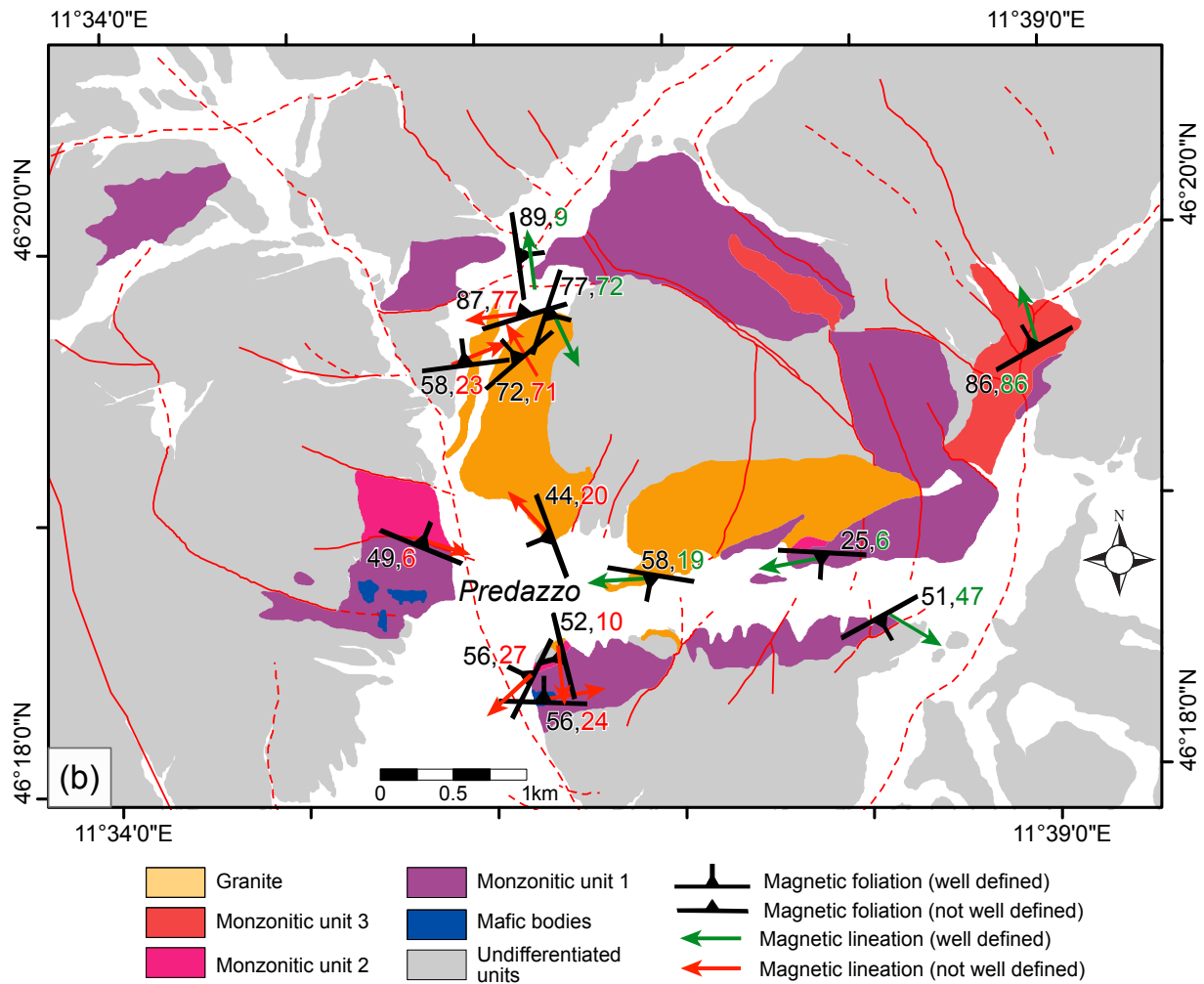
Figure 3: Schematic bio-chrono-stratigraphic scheme of the Middle-Upper Triassic succession of the Dolomites with the most important magmatic pulse recorded as ash falls, tephtras or effusives. The position of the known possible source volcanic areas from the Southern Alps is indicated. In the subsurface of Venetian Plain, a significant number of volcanic products (mainly effusive and

intrusive) is known (e.g., Brusca et al., 1981) Lithostratigraphic abbreviations: BEL:  
Bellerophon Formation; WER: Werfen Formation; SLI: Lower Serla Dolomite; PPS: Piz da  
Peres Conglomerate; FCL: Coll'Alto dark Limestones~~Collalto Formation;~~ NTR: Monte Rite  
Formation; GLS: Gracilis Formation; VTG: Voltago Conglomerate; DON: Dont Formation;  
REC: Recoaro Limestone; SLS Upper Serla Dolomite/Formation; MRB/RIC: Richthofen  
Conglomerate and Morbiac dark Limestone; BIV: Bivera Formation; MBT: Ambata Formation;  
MNA: Moena Formation; CTR: Contrin Formation; BHL: Livinallongo Formation; SCI: Sciliar  
Formation; ADZ: Zoppè Sandstone; AQT: Aquatona Formation; IMF: Fernazza Volcanic  
Complex (Fernazza Formation); WEN: Wengen Formation; SCS: San Cassiano Formation;  
DCS: Cassian Dolomite; HKS: Heiligkreuz Formation; TVZ: Travenanzes Formation; DPR:  
Dolomia Principale. Lithologies: a) cherty limestone; b) sandstone; c) sandy limestone; d)  
volcanics and volcanoclastics; e) oolitic-bioclastic limestone; f) black platy limestone or  
dolostone, black shale; g) dolostone; h) marlstone, claystone and shale; i) marly limestone; j)  
conglomerate; k) evaporates; l) tuffs, pyroclastics; m) lava, pillow-lava-pillow breccia; ~~m)~~  
~~volcanos with mainly explosive eruptions;~~ m) volcanos with mainly effusive eruptions. LPV,  
MPV, UPV= Lower -Middle - Upper Pietra Verde. ~~Ages from GTS 2012 modified after~~  
~~Wotzlaw et al. (2018).~~



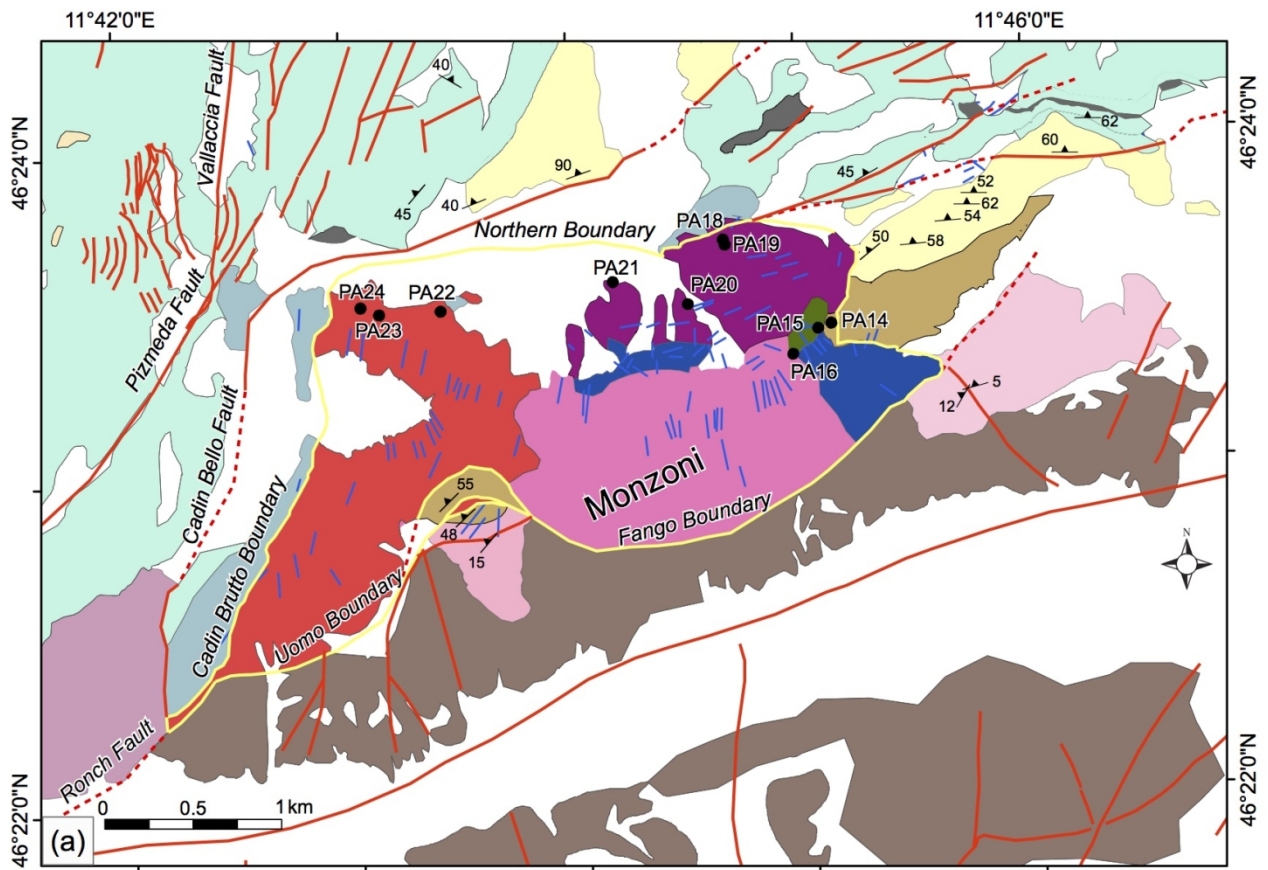
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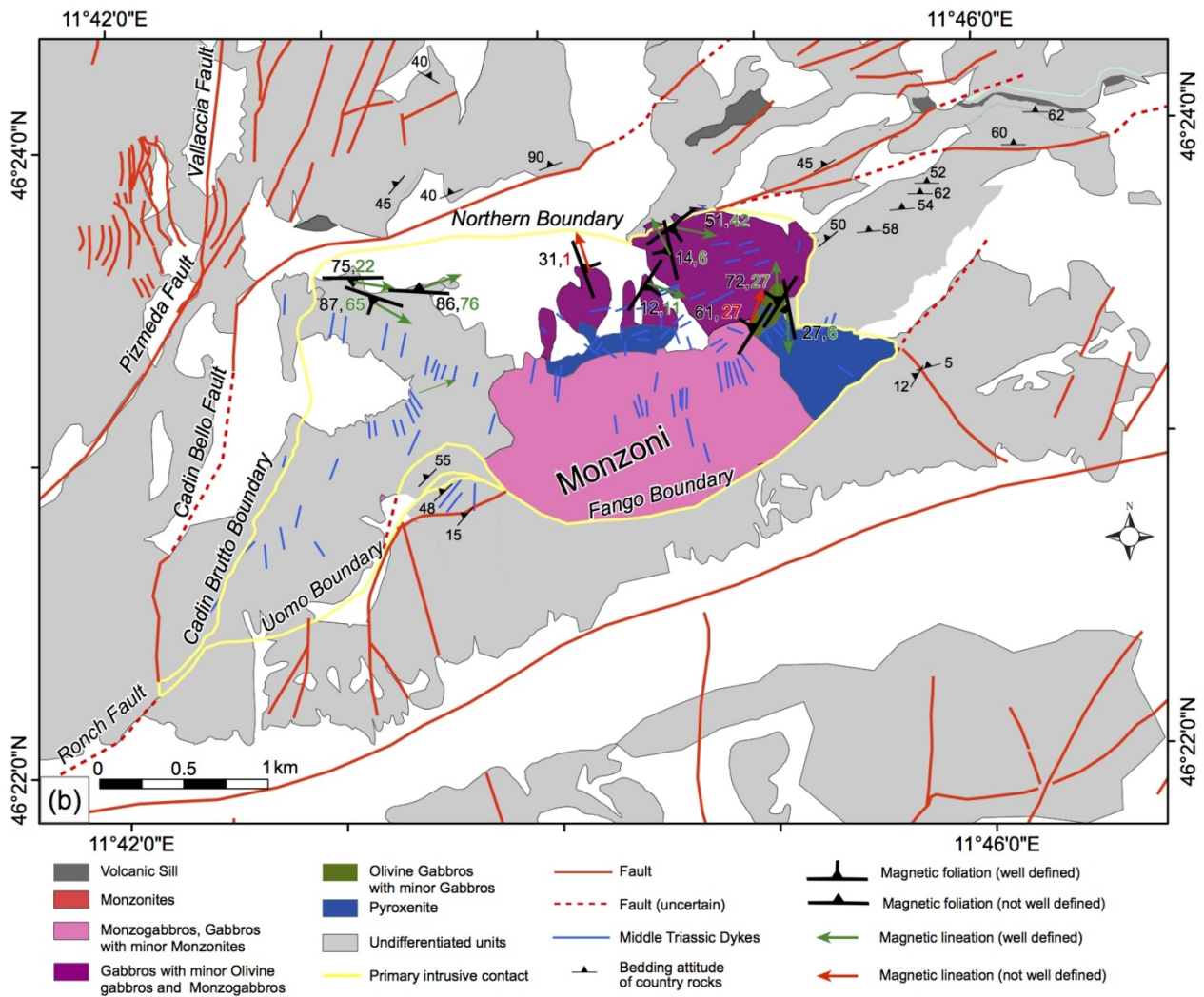
1184 Figure 4: Geological map of the [pre-Quaternary units of the](#) Predazzo area (from Visonà, 1997),  
 1185 showing the location of the samplig sites (a) and ~~relative~~ measured magnetic foliations and  
 1186 lineations (b). [The two numbers besides each site indicate the magnetic foliation and lineation dips,](#)  
 1187 [respectively.](#)



11°42'0"E

11°46'0"E

- |  |   |  |
|--|---|--|
| <ul style="list-style-type: none"> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: black; margin-right: 5px;"></span> Volcanic Sill</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: red; margin-right: 5px;"></span> Monzonites</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: pink; margin-right: 5px;"></span> Monzogabbros, Gabbros with minor Monzonites</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: purple; margin-right: 5px;"></span> Gabbros with minor Olivine gabbros and Monzogabbros</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: green; margin-right: 5px;"></span> Olivine Gabbros with minor Gabbros</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: blue; margin-right: 5px;"></span> Pyroxenite</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: lightgrey; margin-right: 5px;"></span> Middle Triassic effusive rocks</li> </ul> | <ul style="list-style-type: none"> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: lightblue; margin-right: 5px;"></span> Sciliar Fm (metamorphosed)</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: cyan; margin-right: 5px;"></span> Undifferentiated Sciliar Fm., Livinallongo Fm., Contrin Fm., Moena Fm., Richthofen Conglomerate</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: yellow; margin-right: 5px;"></span> Werfen Fm</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: tan; margin-right: 5px;"></span> Bellerophon Fm</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: lightpink; margin-right: 5px;"></span> Val Gardena Sandstones (metamorphosed)</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: lightpurple; margin-right: 5px;"></span> Val Gardena Sandstones</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: brown; margin-right: 5px;"></span> Permian Volcanics</li> </ul> | <ul style="list-style-type: none"> <li><span style="display: inline-block; width: 10px; height: 10px; background-color: black; border-radius: 50%; margin-right: 5px;"></span> AMS samples location</li> <li><span style="display: inline-block; width: 15px; border-bottom: 2px solid yellow; margin-right: 5px;"></span> Primary intrusive contact</li> <li><span style="display: inline-block; width: 15px; border-bottom: 2px solid red; margin-right: 5px;"></span> Fault</li> <li><span style="display: inline-block; width: 15px; border-bottom: 2px dashed red; margin-right: 5px;"></span> Fault (uncertain)</li> <li><span style="display: inline-block; width: 15px; border-bottom: 2px solid blue; margin-right: 5px;"></span> Middle Triassic Dykes</li> <li><span style="display: inline-block; width: 10px; height: 10px; border-left: 1px solid black; border-right: 1px solid black; margin-right: 5px;"></span> Bedding attitude of country rocks</li> </ul> |
|--|---|--|



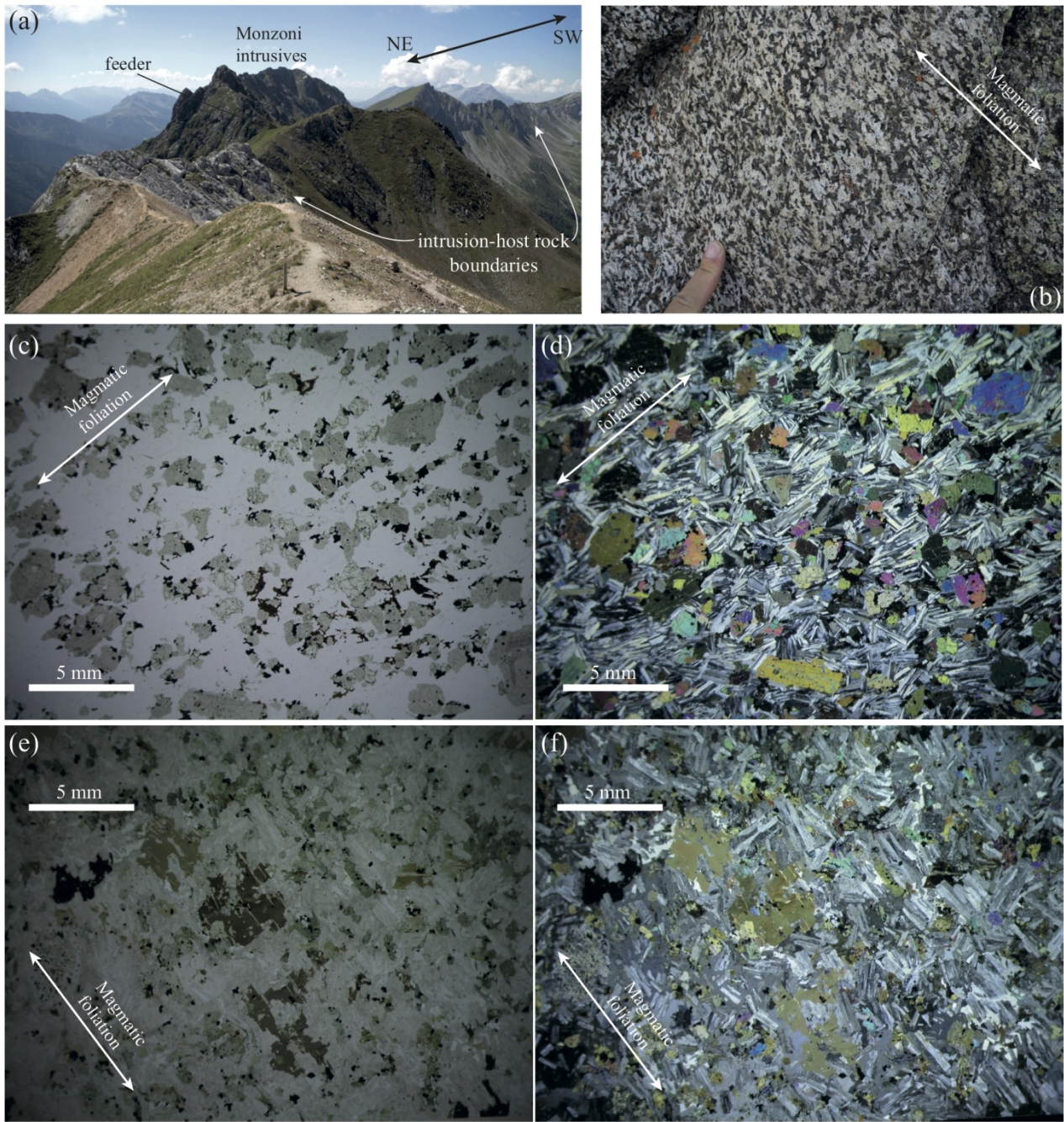
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1190

1191

1192 Figure 5: Geological map of the [pre-Quaternary units of the Monzoni area](#), showing the location of  
 1193 the sampling sites [\(a\)](#) and [relative-measured magnetic foliations and lineations \(b\)](#). [The two](#)  
 1194 [numbers besides at each site indicate the magnetic foliation and lineation dips, respectively.](#)

1195

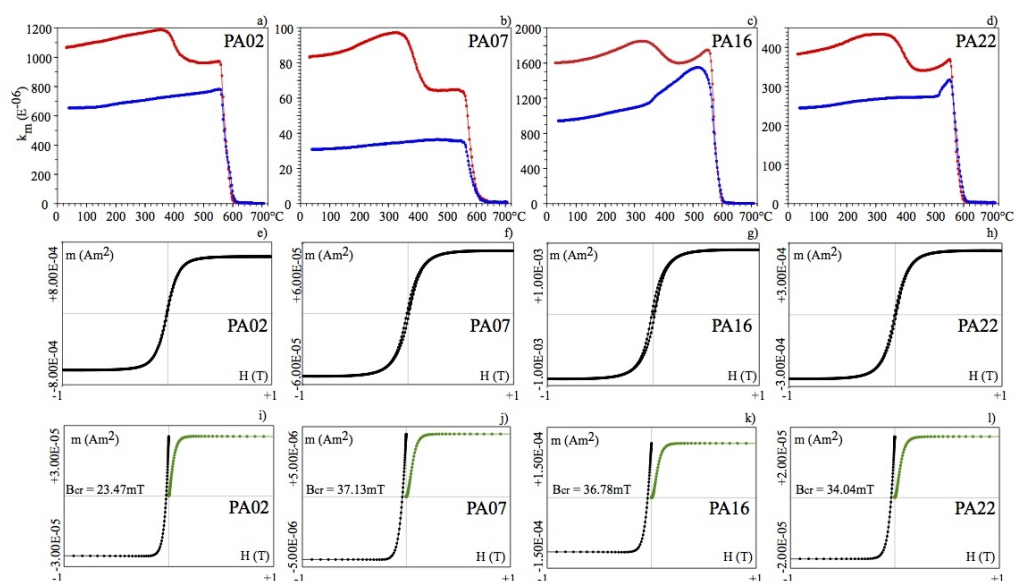


1196

1197 Figure 6: a) Monte Monzoni crest, showing the contacts between intrusive and host rocks. The  
 1198 location of the feeder area is also shown. b) Granite from the Predazzo body showing a well defined  
 1199 magmatic foliation; c) Olivine gabbro showing preferred orientation of plagioclase and pyroxene  
 1200 crystals (sample PA20); c) Monzonite showing preferred orientation of plagioclase and biotite  
 1201 crystals (sample PA22A, same location of sample 22).

1202





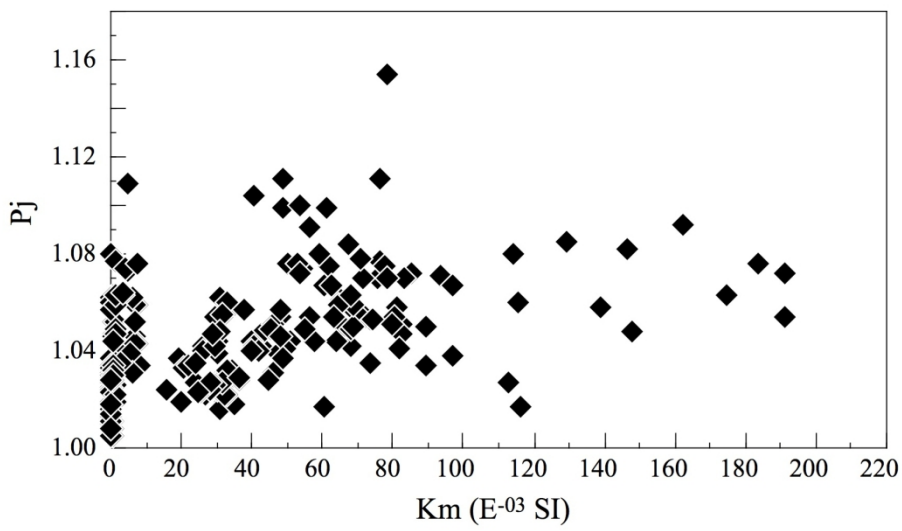
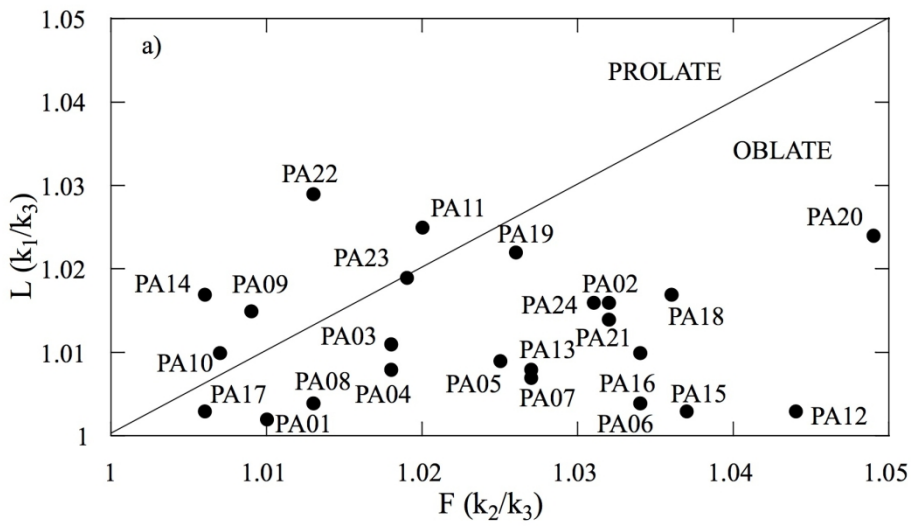
1203

1204 Figure 76: Magnetic mineralogy results for selected samples from Predazzo and Monzoni plutons.

1205 a-d) Thermomagnetic curves; red and blue lines represent the heating □-cooling cycle respectively.

1206 e-h) Hysteresis loops, corrected for the paramagnetic linear trend. i-l) IRM acquisition curves

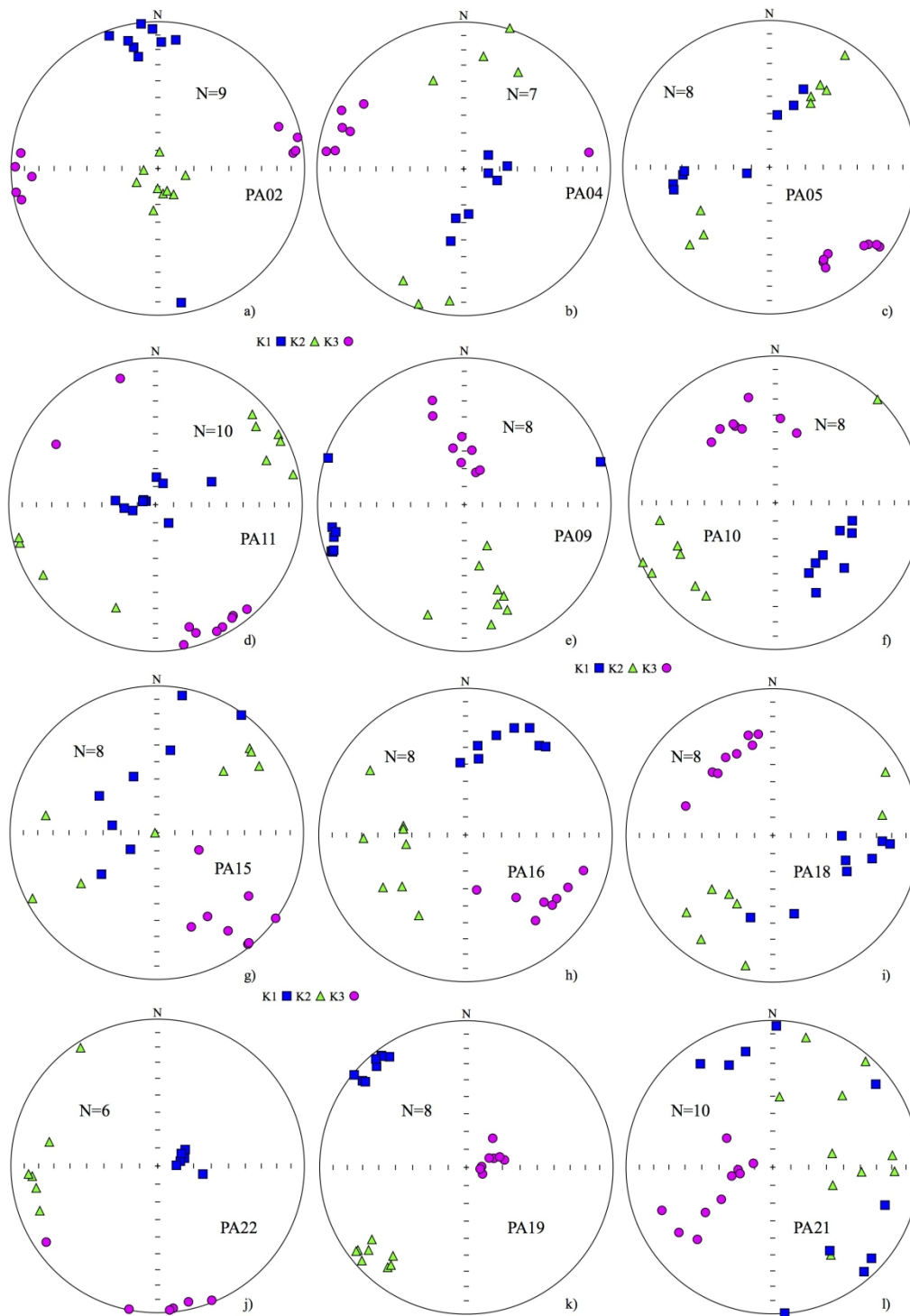
1207 (green lines) and backfield applications (black lines).



1208

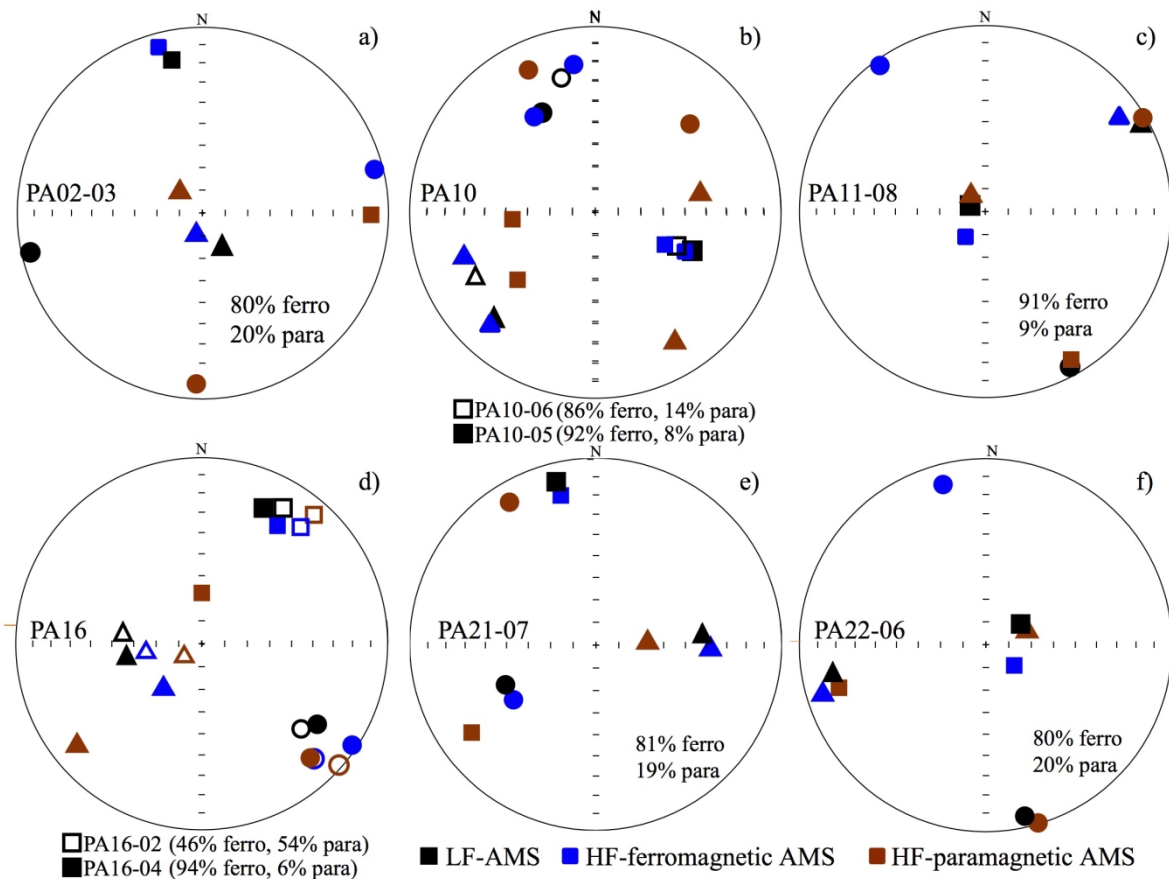
1209

Figure 87: Shape parameters for the analyzed sites: a) F-L diagram; b)  $K-P_j$  diagram.



1210

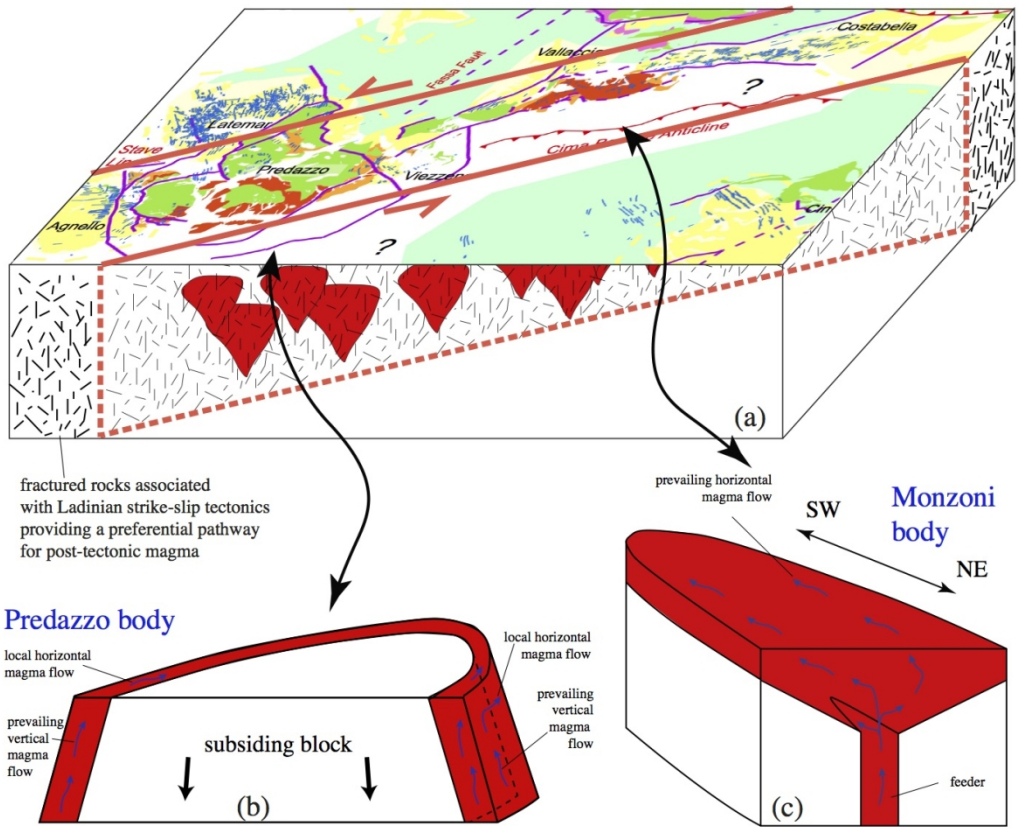
1211 Figure 98: Low-field AMS plots for representative sites in the Predazzo (a-f) and Monzoni (g-l)  
 1212 intrusive bodies. Data are plotted on lower hemisphere, equal area projections. Squares, triangles  
 1213 and circles represent maximum, intermediate and minimum axes, respectively, plotted relative to  
 1214 paleo-geographic coordinates.



1215

1216 Figure 109: Lower hemisphere equal area projections of the principal axes of the low-field/room  
 1217 temperature (black symbols), high-field paramagnetic (red symbols) and high-field ferromagnetic  
 1218 (blue symbols) susceptibility ellipsoids. Percentages of the relative contribution of ferromagnetic and  
 1219 paramagnetic susceptibility to the magnetic fabric is also reported for each specimen.

1220



1221

1222 Figure 11: a) Sketch showing the emplacement of Ladinian intrusive bodies along a wide fractured

1223 zone associated with previous strike-slip tectonics. b) Sketch of the emplacement mode for the

1224 Predazzo body; c) Sketch of the emplacement mode for the Monzoni body.

1225

1226

## 1227 TABLES

Site	Lithology	Lat	Long	N	Km	std	L	std	F	std	Pj	std	T	std	D,I (k <sub>1</sub> )	E <sub>2-3</sub>	D,I (k <sub>3</sub> )	E <sub>1-2</sub>
PA01	Albitized granite	46°19'41"N	11°36'09"E	10	4.04E <sup>-04</sup>	3.75 E <sup>-04</sup>	1.002	0.01	1.010	0.011	1.013	0.018	0.667	0.461	263,77	74.7/36.4	162,3	40.9/21.3
PA02	Monzonites	46°19'53"N	11°36'15"E	8	6.90E <sup>-02</sup>	2.70E <sup>-03</sup>	1.016	0.006	1.032	0.006	1.049	0.006	0.318	0.217	353,9	11.3/7.8	262,1	9.4/5.4
PA03	Biotite granite	46°18'42"N	11°36'45"E	8	4.48E <sup>-03</sup>	3.3E <sup>-03</sup>	1.011	0.009	1.018	0.013	1.030	0.01	0.256	0.443	266,19	23.7/20.5	9,32	24.1/18.5
PA04	Albitized granite	46°19'39"N	11°36'21"E	6	1.03E <sup>-04</sup>	1.01 E <sup>-05</sup>	1.008	0.002	1.018	0.005	1.026	0.006	0.394	0.188	154,72	23.5/3.6	288,13	11.2/5.6
PA05	Albitized granite	46°19'36"N	11°36'13"E	7	8.43E <sup>-05</sup>	3.88 E <sup>-05</sup>	1.009	0.01	1.025	0.015	1.035	0.02	0.483	0.329	329,71	35.9/8.2	139,18	18.1/5.9
PA06	Diorite	46°18'52"N	11°35'44"E	9	4.41E <sup>-02</sup>	8.80 E <sup>-03</sup>	1.004	0.006	1.034	0.008	1.042	0.008	0.809	0.284	107,6	37.2/4.7	202,41	6.3/4.1
PA07	Biotite granite	46°18'56"N	11°36'14"E	5	6.37E <sup>-03</sup>	3.99 E <sup>-04</sup>	1.007	0.008	1.027	0.006	1.036	0.012	0.577	0.184	317,20	45.8/13.3	70,46	16.1/9.3
PA08	Monzodiorite	46°18'23"N	11°36'09"E	8	3.72E <sup>-02</sup>	3.13 E <sup>-03</sup>	1.004	0.003	1.013	0.006	1.018	0.006	0.496	0.286	227,27	39.4/7.7	116,34	10.2/8.1
PA09	Monzodiorite	46°18'46"N	11°37'40"E	8	3.11E <sup>-02</sup>	1.47 E <sup>-03</sup>	1.015	0.003	1.009	0.004	1.024	0.003	-0.244	0.283	260,6	12.6/4.1	3,65	12.3/3.7
PA10	Monzonites	46°18'38"N	11°37'59"E	8	7.39E <sup>-03</sup>	9.51 E <sup>-03</sup>	1.01	0.007	1.007	0.005	1.017	0.012	-0.204	0.262	121,47	13.1/4	331,39	9.2/5.2
PA11	Monzonites to Syenite	46°18'52"N	11°39'26"E	9	2.91E <sup>-02</sup>	2.00 E <sup>-02</sup>	1.025	0.01	1.02	0.09	1.046	0.012	-0.099	0.265	344,86	18.9/7.4	151,4	16.6/7.1
PA12	Clinopyroxenite	46°18'16"N	11°36'11"E	8	1.63E <sup>-01</sup>	2.33 E <sup>-02</sup>	1.003	0.01	1.044	0.015	1.052	0.015	0.858	0.318	79,24	68.5/18.3	182,26	18.4/12.6
PA13	Biotite granite	46°18'29"N	11°36'17"E	4	1.63E <sup>-03</sup>	7.49 E <sup>-04</sup>	1.008	0.007	1.027	0.017	1.037	0.015	0.542	0.423	174,10	37.2/11.8	76,38	17.6/9.4
PA14	Monzodiorite	46°19'33"N	11°35'54"E	9	2.57E <sup>-02</sup>	3.13 E <sup>-03</sup>	1.017	0.004	1.006	0.009	1.024	0.006	-0.495	0.409	177,6	13.9/6.9	75,63	40.1/9.6
PA15	Gabbros	46°23'25"N	11°45'07"E	9	7.34E <sup>-02</sup>	2.53 E <sup>-02</sup>	1.003	0.013	1.037	0.039	1.045	0.046	0.850	0.55	357,67	70.6/14.9	137,18	24.5/15.0
PA16	Gabbros (cumulate)	46°23'25"N	11°45'04"E	9	1.63E <sup>-03</sup>	1.64 E <sup>-03</sup>	1.01	0.012	1.034	0.025	1.047	0.028	0.532	0.36	26,27	25.4/6.5	132,29	12.0/4.8
PA17	Albitized granite	46°23'20"N	11°44'57"E	9	1.02E <sup>-04</sup>	1.32 E <sup>-05</sup>	1.003	0.004	1.006	0.004	1.010	0.007	0.334	0.413	68,23	35.2/15.9	173,32	24.7/17.8
PA18	Olivine gabbros	46°23'41"N	11°44'39"E	8	7.68E <sup>-02</sup>	1.12 E <sup>-02</sup>	1.017	0.009	1.036	0.01	1.055	0.011	0.351	0.272	107,42	18.4/6.3	331,39	16.4/3.8
PA19	Olivine gabbros	46°23'40"N	11°44'40"E	8	3.07E <sup>-02</sup>	1.30 E <sup>-03</sup>	1.022	0.005	1.026	0.003	1.049	0.006	0.084	0.12	317,6	7.3/3.2	73,76	6.4/3.8
PA20	Olivine gabbros	46°23'30"N	11°44'30"E	9	5.26E <sup>-02</sup>	6.07 E <sup>-03</sup>	1.024	0.01	1.049	0.017	1.075	0.015	0.344	0.239	108,11	17.8/11.0	310,78	18.6/7.6
PA21	Monzogabbros	46°23'34"N	11°44'10"E	9	6.22E <sup>-02</sup>	2.19 E <sup>-02</sup>	1.014	0.014	1.032	0.018	1.048	0.01	0.383	0.481	336,1	19.1/11.9	244,59	25.0/10.1

Site	Lithology	Lat	Long	N	Km	std	L	std	F	std	Pj	std	T	std	D,I (k <sub>1</sub> )	E <sub>2-3</sub>	D,I (k <sub>3</sub> )	E <sub>1-2</sub>
PA22	Monzonites	46°23'30"N	11°43'24"E	6	3.73E <sup>-02</sup>	1.54 E <sup>-02</sup>	1.029	0.007	1.013	0.011	1.043	0.016	-0.364	0.185	76,76	5.7/4.4	184,4	37.6/2.8
PA23	Monzonites	46°23'30"N	11°43'08"E	8	7.36E <sup>-02</sup>	2.79 E <sup>-02</sup>	1.019	0.007	1.019	0.015	1.038	0.013	-0.02	0.47	121,65	10.8/7.1	25,3	14.8/7.8
PA24	Monzonites	46°23'31"N	11°43'03"E	9	8.14E <sup>-02</sup>	2.10 E <sup>-02</sup>	1.016	0.007	1.031	0.014	1.049	0.021	0.325	0.149	97,22	22.4/11.7	0,15	17.3/11.0

1228

1229 Table I: Location of sampling sites in the Predazzo and Monzoni plutons and measured magnetic parameters. N = number of specimens; K<sub>m</sub> = (k<sub>max</sub> + k<sub>int</sub> +

1230 k<sub>min</sub>) / 3 (mean susceptibility, in SI units); L=k<sub>1</sub> /k<sub>2</sub>; F=k<sub>3</sub> /k<sub>1</sub> Pj = exp {2[(η<sub>1</sub> - η)<sup>2</sup> + (η<sub>2</sub> - η)<sup>2</sup> + (η<sub>3</sub> - η)<sup>2</sup>]}<sup>1/2</sup> (corrected anisotropy degree; Jelinek<sub>s</sub>, 1981); T =

1231 2(η<sub>2</sub> - η<sub>3</sub>) / (η<sub>1</sub> - η<sub>3</sub>) - 1 (shape factor; Jelinek<sub>s</sub>, 1981); η<sub>1</sub> = lnk<sub>1</sub>; η<sub>2</sub> = lnk<sub>2</sub>; η<sub>3</sub> = lnk<sub>3</sub>; η = (η<sub>1</sub> + η<sub>2</sub> + η<sub>3</sub>) / 3; D, I (k<sub>1</sub>) = declination and inclination of the maximum

1232 susceptibility axis ([paleo-geographic coordinates](#)); D,I (k<sub>3</sub>) = declination and inclination of the minimum susceptibility axis ([paleo-geographic coordinates](#)); α<sub>95</sub>:

1233 confidence angles; std: standard deviation.

1234