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Internal structure of basalt flows: insights from magnetic and crystallographic fabrics of the *La Palisse* volcanics, French Massif Central

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Abstract:

We present a new interpretation of anisotropy of magnetic susceptibility (AMS) fabrics in basaltic lava flows based on the detailed study of magnetic mineralogy and silicate crystallographic fabric of a Quaternary lava flow from the French Massif Central (La Palisse). We consider the model of AMS fabric imbrication between magnetic foliation and flow surface, as initially proposed for dikes. At the two sampling sites, the concordance between the flow direction deduced from the AMS foliation and that deduced from field observations indicates that the imbrication model could apply to the lava flows. However, the flow senses inferred from AMS are systematically opposed between the two sampling sites suggesting permutations between K_1 and K_3 AMS axes, a configuration referred to as inverse fabric. Electron backscatter diffraction (EBSD) measurements show strong lattice-preferred orientations (LPO) for plagioclase, especially the (010)-plagioclase plane, which tends to be parallel to the flow. Clinopyroxene LPO remains less marked than plagioclase LPO, whereas titanomagnetite does not display a significant LPO. Comparison between magnetic and crystallographic fabrics suggests that the AMS fabric of the lava flow results from the distribution of titanomagnetite grains, which is in turn controlled by the fabric of the silicate framework. Magnetic hysteresis parameters and anisotropy of remanent magnetization (ARM) measurements exclude a significant contribution from single-domain grains, often called upon to explain inverse magnetic fabrics. The origin of the observed inverse magnetic fabric may relate to the dip of the paleosurface, which is the only remarkable difference between the two sampling sites. AMS appears as a good tool to determine the direction of

40 basaltic lava flows and coupling with local crystallographic fabric data provides a valuable
41 control of relationships between magnetic fabrics and flow and thus contributes to better
42 constrain the AMS signature of lava flows.

43

44 **1. Introduction**

45 The internal structure of basaltic lava flows may provide key information on flow
46 mechanisms and on lava rheology (e.g., Ventura et al., 1996; Smith, 2002). In general,
47 macroscopic markers such as vesicles (e.g., Aubele et al., 1988) and measurement of lattice-
48 preferred orientation (LPO) allow to investigate the internal structure of a flow (e.g., Long
49 and Wood, 1986; Smith, 2002). However, the scarcity of markers in these rocks which are
50 weakly anisotropic and the time-intensive nature of LPO measurements are significant
51 hindrances to systematic studies of a flow from bottom to top.

52 The main goal of this study is to investigate if the anisotropy of magnetic susceptibility
53 (AMS) technique can provide reliable information on internal structures and flow direction.
54 The AMS technique has already been successfully used elsewhere to track both magmatic and
55 deformation fabrics on a wide variety of rocks (e.g., Tarling and Hrouda, 1993; Borradaile
56 and Henry, 1997; Bouchez et al., 2000; Ferré et al., 2003; Borradaile and Jackson, 2004),
57 including volcanic rocks (e.g., Knight and Walker, 1988; Cañón-Tapia et al., 2004; Plenier et
58 al., 2005; Loock et al., 2008; Petronis and Geissman, 2008). The significance of magnetic
59 fabrics in volcanic rocks has been questioned because these rocks tend to show a weak
60 magnetic anisotropy, near the detection limit of the AMS technique (Tarling and Hrouda,
61 1993).

62 Despite the weak anisotropy of the volcanic rocks, AMS measurements show relationships
63 between magnetic fabric and flow: maximum susceptibility axis K_1 tend to be parallel to the
64 flow direction and minimum susceptibility axis K_3 tend to be perpendicular to the flow plane
65 (Cañón-Tapia et al., 1996; Cañón-Tapia et al., 1997; Herrero-Bervera et al., 2001; Zhu et al.,
66 2003; Cañón-Tapia et al., 2004; Raposo and Berquo, 2008). However complications have
67 arisen regarding the significance of AMS fabrics and their relationship to magma flow
68 directions (e.g., Rochette et al., 1999; Henry et al., 2003; Plenier et al., 2005).

69 In dike the imbrication model proposed by Knight and Walker (1988) considers that K_1 and
70 K_3 should be oblique and symmetrical with respect to the flow direction and flow plane. In
71 this case, the obliquity further indicates the flow sense. This model often uses K_1 -angle to

72 determine the flow direction (Staudigel et al., 1992; Herrero-Bervera et al., 2001). When the
73 magnitudes of K_1 and K_2 axes are too close (oblate magnetic fabrics), a switch occurs between
74 these two axes. The flow direction can be determined using the distribution of K_3 axes (Callot
75 et al., 2001; Geoffroy et al., 2002). Callot and Guichet (2003) also proposed an analytical
76 model in dikes and concluded that the determination of the flow direction with the maximum
77 susceptibility axis is a misuse, and recommend generalizing the magnetic foliation use.

78 Complications could also occur when single-domain (SD) magnetite grains are significant
79 contributors to AMS (Potter and Stephenson, 1988). Indeed, in contrast to MD grains, K_1 is
80 parallel to the short axis and K_3 is parallel to the long axis of SD grains. This generates an
81 “inverse” magnetic fabric (Rochette et al., 1999; Ferré, 2002). Other difficulties to interpret
82 the AMS signature could also appear due to magnetic interactions when the ferromagnetic
83 (s.l.) grains are at close distance from each other (Grégoire et al., 1995; Fanjat et al., 2012),
84 the effects of multiple mineral-preferred orientations (Hrouda, 1992), viscous strain variations
85 in magma (Dragoni et al., 1997), post-flow alteration (Park et al., 1988) or thermal contraction
86 (Gil-Imaz et al., 2006).

87 In basaltic lava flows, AMS is also used to infer the flow direction (e.g., Cañón-Tapia et al.,
88 1996, 1997; Bascou et al., 2005; Looock et al., 2008). The imbrication model is used to
89 determine the flow direction with either K_1 or K_3 . In lava flows, inverse fabrics are also
90 observed (Rochette et al., 1999). Other parameters as chemical composition related to
91 viscosity or paleosurface topography could influence the AMS fabrics (Cañón-Tapia et al.,
92 1995; Merle 1998; Henry et al., 2003). In addition, the identification of relationships between
93 AMS and the flow direction may depend on height in the flow. In their AMS study from
94 basaltic lava flow, Bascou et al. (2005) observe a stronger correlation between AMS and
95 flow-related plagioclase preferred orientation in the lower part of the lava flow than at other
96 levels. Thus, the relationships between AMS and flow direction in a flow that could present
97 variations from the base to the top in magnetic mineralogy, crystallographic and magnetic
98 fabrics is still unclear.

99 In this study, AMS measurements were carried out on a Quaternary lava flow from the French
100 Massif Central (La Palisse basaltic flow), which is exposed at different levels. A detailed
101 study of the magnetic mineralogy has been carried out and relationships between AMS and
102 the flow related silicate framework were investigated through 3-D crystallographic fabrics

103 characterization of main minerals (plagioclase, clinopyroxene and titanomagnetite) using
104 electron backscatter diffraction (EBSD).

105

106 **2. Geological settings and petrology**

107 The La Palisse basaltic lava flow is located in the Bas-Vivarais volcanic province, in the East
108 part of the French Massif Central (Fig.1a). The volcanic activity of the Bas-Vivarais province
109 is characterized by alternated phreatomagmatic eruptions and strombolian activity and is
110 spread over a large time interval, from 166 ± 15 ka to 45.4 ± 3.2 ka (Guérin and Gillot 2007).
111 The La Palisse lava flow belongs to an eruptive episode occurring around 78.8 ± 5.3 ka
112 (Guérin and Gillot 2007). Its emission source is at the Suc de Bauzon scoria cone, from which
113 the flow went NW into the Loire paleo-valley which was incised in the granitic substratum
114 (Fig. 1b). The thickness of the flow is ≈ 40 meters at the sampling sites.

115 Two sampling sites were selected to address distinct structural levels of the flow. In sampling
116 site 1, the colonnade and the entablature are clearly observed. The apparent thickness of the
117 colonnade ranges from less than 1 m to about 3 m. Columns are vertical, oriented
118 perpendicularly to the horizontal substratum surface and have a mean width of 0.4 m. In the
119 entablature level, in which thickness ranges from 6 m to 12 m, columns are randomly oriented
120 and only a few centimeters in width. In sampling site 2, three zones can be distinguished from
121 base to top of (Fig. 2): the colonnade (from 1 to 3 m thick), an intermediate zone presenting
122 planar layering and hereafter referred to as layered zone (from 1 to 2 m thick) and the pseudo-
123 colonnade (From 2 to 4 m thick). The intermediate zone differs from the entablature level of
124 site 1 by its planar structure. The strike of volcanic layers is NE-SW with a 50° dip to NW
125 (Fig. 2). Because the La Palisse basalt flow is channeled by a paleo-valley, the underlying
126 paleosurface, currently not outcropping, is assumed sub-horizontal at site 1 and parallel to the
127 layered zone at site 2.

128 Regardless of the structural level, the lava flow samples contain phenocrysts and xenocrysts
129 of olivine, phenocrysts of clinopyroxene, microphenocrysts (50 to 500 μm in size) of
130 plagioclase and a groundmass mainly composed of microlites of plagioclase, clinopyroxene
131 and iron oxides within partially devitrified glass. The fluidal texture displayed by plagioclase
132 microphenocrysts is observed in the different levels of the two sampling sites, whereas the
133 pseudo-colonnade level exhibits a more vesicular texture.

134 The La Palisse lava is basanite (from TAS diagram, *Lebas et al.*, 1986), The mean
 135 composition of phenocrysts are An50 for plagioclase, Fo78 for olivine and diopside for
 136 clinopyroxene (*Boiron*, 2011). The oxide grains are mainly Ti-rich titanomagnetite ($\text{Fe}_{3-x}\text{Ti}_x\text{O}_4$
 137 with x mean value of 0.6; *Boiron*, 2011).

138

139 3. Methods

140 3.1. Magnetic methods

141 The anisotropy of magnetic susceptibility (AMS) was measured with a KLY-3 instrument at
 142 the University of Montpellier (France). Thermomagnetic experiments were mainly conducted
 143 under argon atmosphere, with a CS4 furnace coupled to a MFK1 Kappabridge instrument at
 144 the University of Saint Étienne (France). AMS in low magnetic field ($< 1\text{mT}$) is
 145 mathematically described as a symmetric second rank tensor, which can be geometrically
 146 expressed as an ellipsoid with three principal susceptibility axes (K_1 , K_2 and K_3 with $K_1 \geq K_2 \geq$
 147 K_3). For magnetite, AMS is controlled by the shape-preferred orientation (SPO) of individual
 148 grains or aggregates (*Rochette et al.*, 1992). Many parameters are usually employed to
 149 describe the AMS fabric of rocks. In this paper, we used the bulk magnetic susceptibility
 150 $K_m = (K_1 + K_2 + K_3)/3$, the corrected degree of anisotropy (*Jelinek* 1981)

151 $P' = \exp\sqrt{\{2[(\eta_1 - \eta_m)^2 + (\eta_2 - \eta_m)^2 + (\eta_3 - \eta_m)^2]\}}$ where $\eta_1 = \ln K_1$, $\eta_2 = \ln K_2$,
 152 $\eta_3 = \ln K_3$ and $\eta_m = \sqrt[3]{(\eta_1 \cdot \eta_2 \cdot \eta_3)}$, and the shape parameter (*Jelinek* 1981) defined as
 153 $T = (2\eta_2 - \eta_1 - \eta_3)/(\eta_1 - \eta_3)$. The P' parameter is used to quantify the degree of magnetic
 154 anisotropy and T characterizes the AMS ellipsoid shape. T ranges from -1 (prolate shape) to
 155 +1 (oblate shape). Magnetic hysteresis and first order reversal curve (FORC) were measured
 156 on a Vibrating Sample Magnetometer Princeton Measurements 3900-04 at the University of
 157 South Illinois, Carbondale (USA). The anisotropy of anhysteretic remanent magnetization (A-
 158 ARM) measurements were carried out by three steps using a 2G cryogenic SQUID
 159 magnetometer with an alternating field (AF) demagnetizer at the University of Montpellier
 160 (France). The sample was first AF demagnetized along three perpendicular axes with a
 161 maximum magnetic field of 170 mT. In a second time, an ARM is acquired along a direction
 162 perpendicular to the last demagnetized axis with a bias direct field of 30 μT and AF of 120
 163 mT. In the third step, the induced ARM was measured. These three steps are repeated for 6
 164 positions following the sequence, +X, +Y, +Z, -X, -Y, and -Z.

165 ***3.2. Lattice-preferred orientation (LPO) and shape-preferred orientation (SPO)*** 166 ***methods***

167 The LPO of plagioclase, clinopyroxene and titanomagnetite was measured by indexation of
168 electron-backscattered diffraction patterns (EBSD) with a Zeiss Supra 55 VP SEM at the
169 École nationale supérieure des mines of Saint-Étienne (France). EBSD patterns are generated
170 by interaction of a vertical incident electron beam with a carefully polished thin section tilted
171 at 70°. The diffraction patterns are processed and indexed in terms of crystal orientation using
172 the CHANNEL5 software from HKL, Oxford Instruments. Crystallographic orientations were
173 measured grain-per-grain using an accelerating voltage of 20 kV, a working distance of 15
174 mm, a current intensity of 26 μA and a pressure of 15 Pa. The diffraction images indexation
175 was based on crystallographic data of respectively: Wechsler et al. (1984) for titanomagnetite,
176 Wenk et al. (1980) for plagioclase and Bertolo et al. (1994) for clinopyroxene.

177 Image analysis was performed from sets of 6 digital photos on thin sections in polarized light
178 with different angles (from 0° to 150°) using a binocular microscope equipped with color
179 CCD in order to obtain images displaying a relatively wide surface of analysis. The sets of
180 digitized images were then processed and the SPO was calculated using the Intercept software
181 developed by Launeau and Robin (1996). The 2-D SPO is represented by an ellipse
182 characterized by the shape ratio (SR = ratio of the ellipse long/short axes) and the angle (α)
183 between the ellipse long axis and the reference sample direction (X). The 3-D SPO
184 corresponds to the best ellipsoid calculated from the combination of ellipses taken on three
185 perpendicular sections following the procedure of Launeau and Robin (2005) modified by
186 Launeau et al. (2010); see also <http://www.sciences.univ-nantes.fr/lpgnantes/SPO>.

187

188 **4. Magnetic mineralogy**

189 The mode of titanomagnetite grains, determined by image analysis and reflected-light
190 microscopy, is about 3% in volume for each level in the flow (Fig. 3). Grains are subhedral in
191 shape and exhibit a mean size around 15 μm . The grains, observed through optical
192 microscopy and SEM, appear free of exsolutions.

193 Thermomagnetic curves were performed on basaltic powder coming from sampling at
194 different levels of the flow (Fig. 4). Curves are generally reversible and show a Curie
195 temperature (T_C) ranging from 100°C to 140°C. These low T_C attest of the high titanium

196 content of titanomagnetite, with an average composition of $\text{Fe}_{2.4}\text{Ti}_{0.6}\text{O}_4$ (Dunlop and Özdemir
197 1997; Lattard et al., 2006). This composition is in agreement with microprobe data.
198 Thermomagnetic analyses further suggest that the titanomagnetite grains are rather
199 homogeneous in composition

200 The hysteresis parameters were measured on 26 samples of the different levels from sites 1
201 and 2. Hysteresis curves clearly indicate the dominance of ferromagnetic (s.l.) minerals. The
202 hysteresis curves are simple, no wasp-waisted shape being observed (Fig. 5a). The data in a
203 plot of (M_{rs}/M_s) versus (H_{cr}/H_c) lies in the PSD domain in agreement to data from other
204 natural basaltic lava of similar composition with Ti-rich titanomagnetite (Fig. 5b; Hartstra
205 1982; O'Donovan et al., 1986). According to Dunlop (2002), the PSD grain size range is
206 narrower for Ti-rich titanomagnetite than for magnetite and could extend from approximately
207 2 to 25 μm . The observed hysteresis properties are ambiguous and could result from either an
208 intermediate and homogeneous grain size between SD and MD grains, or from a mixture of
209 various SD and MD grain sizes. In order to precise the potential contribution of single-domain
210 grains, First Order Reveal Curves (FORC) diagrams were carried out on samples from site 1
211 and 2. FORCs are expressed by contour plots of a two-dimensional distribution function and
212 they provide an accurate mean to reveal information on the different components in a mixed
213 magnetic mineral assemblage (Pike et al., 1999; Roberts et al., 2000). FORC diagrams
214 obtained from 4 samples from the colonnade (08tb12 and 08tb18, site 1) and from the layered
215 zone (08tb59 and 08tb68, site 2) are provided on Fig. 6. The outer contours diverge from the
216 $H_u = 0$ axis and intersect the $H_c = 0$ axis whereas the inner contours are less divergent. The
217 absence of any central peak in the four FORC diagrams confirms a very small contribution of
218 SD particles (Roberts et al., 2000) and suggests a dominating PSD + MD mixing in the
219 samples.

220

221 **5. Anisotropy of Magnetic Susceptibility (AMS)**

222 *5.1. AMS scalar parameters*

223 For site 1, the anisotropy degree P' is higher in the entablature level (P' mainly ranges from
224 1.03 to 1.11) than in the colonnade level (P' mainly ranges from 1.01 to 1.08) whereas the
225 mean susceptibility K_m is lower in the entablature (K_m mainly ranges from $4.1 \cdot 10^{-2}$ SI to $5.3 \cdot$
226 10^{-2} SI) than in the colonnade (K_m mainly ranges from $4.9 \cdot 10^{-2}$ SI to $5.8 \cdot 10^{-2}$ SI; Fig. 7a). In
227 the entablature level, the distribution of the shape parameter ranges around a value of $T = 0$

228 (triaxial shape). On the other hand, the shape parameter is more scattered in the colonnade
 229 (Fig. 7b). For site 2, the range of P' values of the pseudo-colonnade is narrower (around 1.03)
 230 than for colonnade and layered zone, from 1.02 to 1.06 and from 1.01 and 1.08, respectively.
 231 The mean susceptibility K_m is similar for the colonnade and the layered zone ($5.0 \cdot 10^{-2} \text{ SI} <$
 232 $K_m < 6.1 \cdot 10^{-2} \text{ SI}$) whereas it is lower in the pseudo-colonnade ($4.3 \cdot 10^{-2} \text{ SI} < K_m < 5.0 \cdot 10^{-2}$
 233 SI ; Fig. 7c). The shape parameter T for the layered zone and the colonnade is scattered in
 234 oblate and prolate domains with a larger number of data for the oblate shape. Pseudo-
 235 colonnade mainly spans the oblate domain ($0.2 < T < 0.7$; Fig.7d).

236

237 **5.2. AMS fabrics**

238 AMS fabrics measured in the different flow levels of sites 1 and 2 are presented on
 239 stereograms in the geographic referential (Fig. 8). In all stereograms, the AMS eigenvectors
 240 ($K_1 \geq K_2 \geq K_3$) are well grouped with narrow confidence ellipse and therefore the mean of
 241 principal susceptibility axes is statistically significant. The K_3 axes for site 1 are particularly
 242 well grouped and the mean K_3 displays close strike and dip. Maximum and intermediate axes
 243 are also well grouped but seem to be inverted between the colonnade and the entablature. For
 244 site 2, the minimum susceptibility axes remain the most grouped for all levels. The orientation
 245 of the mean principal susceptibility axes (K_1, K_2, K_3) is similar in the colonnade and the
 246 layered zone but different for the pseudo-colonnade.

247 The determination of flow direction and flow sense from AMS fabrics is obtained by means
 248 of the imbrication of the magnetic foliation with a sub-horizontal paleosurface for site 1. For
 249 site 2, the paleosurface is assumed to be parallel to the layered zone (NE-SW striking and
 250 50° NW dipping; Fig. 8). The flow direction is given by the pole of the paleosurface plane and
 251 the pole of magnetic foliation (i.e., the minimum principal axis K_3). The angle between K_3 and
 252 the paleosurface defines the imbrication angle that allows determining the flow sense
 253 (Geoffroy et al., 2002). For site 1, flow direction and flow sense deduced from AMS are
 254 consistent with field observations, both for the colonnade and the entablature. Similarly, for
 255 site 2 a good correlation between flow direction deduced from AMS for the colonnade and the
 256 layered zone and from field observations is obtained. For the pseudo-colonnade, the K_3
 257 direction at high angle ($> 50^\circ$) perpendicularly to the layered plane, in comparison to the
 258 lower levels suggests an opposite imbrication located on the top of the flow. However, the
 259 magnetic foliation for pseudo-colonnade is strongly tilted and the imbrication angle is less

260 clear for this level. In addition, it must be noted that the flow sense deduced from AMS for
261 the colonnade and the layered zone is opposed to field observations. The expected AMS
262 diagram for site 2 with respect to the field geological evidences and the coherent AMS
263 measurements for site 1, suggest an inversion between the maximum and the minimum axis
264 for the colonnade and the layered zone of site 2.

265

266 6. Magnetic and crystallographic fabrics

267 6.1. Lattice preferred orientation

268 The LPO of plagioclase, clinopyroxene and titanomagnetite are presented on equal area and
269 lower hemisphere projections in the specimen reference framework for the colonnade and the
270 entablature of site 1 (Fig. 9a) and for the colonnade, the layered zone and the pseudo-
271 colonnade of site 2 (Fig. 9b, c). Density contours are expressed in multiple uniform
272 distribution (MUD) using the software PFch5 developed by David Mainprice
273 (ftp://www.gm.univmontp2.fr/mainprice//CareWare_Unicef_Programs/, University of
274 Montpellier, France). The fabric strength is expressed by the texture index J (Bunge 1982),
275 which ranges from 1 in the case of random orientation to ∞ in the case of an ideal single
276 crystal.

277 Plagioclase presents the highest fabric strength ($4.5 < J < 5.8$). The plagioclase (010)-plane
278 systematically shows the strongest maximum of density. For site 1, (010)-maximum of
279 density values of plagioclase from the colonnade and the entablature are 4.40 and 5.37,
280 respectively. Lower maximum of density values are observed for (100)-plagioclase (3.68 and
281 4.38) and (001)-plagioclase (2.24 and 2.81). For site 2, maximum of density values of (010)-
282 plagioclase for the colonnade, the layered zone and the pseudo-colonnade are 4.91, 5.23 and
283 4.81, respectively, while lowest value are observed for the (100) and (001)-plagioclase. The
284 highest (010)-plagioclase maximum of density values are reached for the entablature of site 1
285 and for the layered zone of site 2. The highest values of the plagioclase fabric strength J are
286 also reached in these zones (5.5 in the site 1 entablature and 5.8 in the site 2 layered zone).
287 However, the site 2 colonnade and pseudo-colonnade present high fabric strengths as well (J
288 > 5).

289 Clinopyroxene LPO is not as strong as plagioclase LPO with a fabric strength J that ranges
290 from 3.35 to 3.70. Maximum of density values are generally lower than 3 except for the

291 entablature and the layered zone for which the (001) plane is higher (3.73 and 3.63,
292 respectively).

293 Close relationships are observed between crystallographic planes of plagioclase and
294 clinopyroxene: (100)-plagioclase tends to be parallel to (001)-clinopyroxene and (010)-
295 plagioclase tends to be parallel to (100)-clinopyroxene for the two sites and at all levels.

296 Finally, no clear preferred orientation can be deduced from the LPO of titanomagnetite, even
297 considering maximum of density values higher than 2. However, it can be noticed that [100]-
298 titanomagnetite has the highest maximum of density compared to [111] and [110]-
299 titanomagnetite, especially for the colonnade at both site 1 and 2 (maximum of density values
300 of 2.30 and 2.49 respectively).

301

302 ***6.2. Comparison between magnetic and crystallographic fabrics***

303 In order to precise the relationships between the plagioclase crystallographic preferred
304 orientations and the AMS, we compared the orientation of K_1 , K_2 and K_3 axes with the
305 plagioclase crystallographic fabrics on samples representative of the different flow levels. The
306 principal susceptibility axes, as well as the best axes (eigenvectors) and the maximum of
307 density of (100), (010) and (001)-plagioclase were projected on lower hemisphere
308 stereograms in the specimen referential (Fig. 10). For site 1, in both colonnade and entablature
309 levels, a clear correlation appears between the maximum susceptibility K_1 and the “Best Axis”
310 of (100)-plagioclase, between the minimum susceptibility K_3 and the “Best Axis” of (010)-
311 plagioclase and between the intermediate susceptibility K_2 and the “Best Axis” of (001)-
312 plagioclase. For site 2, relationships are less obvious: (100)-plagioclase is related to K_3 in the
313 pseudo-colonnade, but related to K_2 in the layered zone and (001)-plagioclase presents a clear
314 correlation with K_2 in the pseudo-colonnade and also with K_3 (DM Pl) in the colonnade. The
315 (010)-plagioclase “Best Axis” shows high orientation correlations with K_1 in the three flow
316 levels.

317

318 **7. Discussion**

319 ***7.1. Relation between AMS and flow***

320 The results of the present study show that the use of AMS to determine the flow direction,
321 which is largely employed in dikes (e.g., Knight and Walker, 1988, Geoffroy et al., 2002;
322 Hastie et al., 2011), is also efficient in lava flows. We can notice that neither the maximum of
323 magnetic susceptibility axis itself nor the imbrication of the magnetic lineation allow to find a
324 flow direction that fit with the flow direction deduced from field evidences. In accord with
325 previous AMS studies of lava flows (Saint-Thibéry; Bascou et al., 2005), the magnetic
326 foliation imbrication appears as the best mean to obtain an accurate flow direction. .
327 Concerning the flow sense, our results are contrasted. For site 1, the flow sense deduced from
328 AMS coincides with the field observations, whereas for site 2, they are systematically
329 opposed. The flow sense deduced from AMS for site 2 appears to coincide with a permutation
330 between the minimum and the maximum axes compared to site 1. The origin of the inversion
331 of AMS axes is discussed in a following part.

332

333 *7.2. Origin of AMS*

334 Magnetic anisotropy of volcanic rocks can result from different intrinsic properties of
335 minerals such as: magnetocrystalline anisotropy, shape anisotropy and a non-intrinsic
336 property as the distribution anisotropy that could result from clustering of small and equant
337 ferromagnetic grains (Hargraves et al., 1991). Petrographical observations indicate that the
338 titanomagnetite grains, which are the main carrier of the AMS in the La Palisse basalt flow,
339 are subhedral. As a consequence, shape anisotropy of individual grains can be neglected. In
340 addition, titanomagnetite LPO is randomly oriented that excludes a magnetocrystalline
341 anisotropy, in particular a preferred orientation of [100]-titanomagnetite that corresponds to
342 the best magnetization axis (Dunlop and Özdemir 1997). For lava flow, experimental studies
343 of Hargraves et al. (1991) indicate that AMS can be produced from an anisotropy distribution
344 of ferromagnetic particles constrained by a silicate “template”.

345 Image analysis based on 2-D and 3-D images was performed in order to precise the
346 relationships between crystallographic and magnetic fabrics. The shape ellipse from image
347 analysis is shown for site 1 (colonnade) where AMS signature is coherent with field flow
348 direction and sense and for site 2 (pseudo-colonnade) where an inversion between K_1 and K_3
349 is observed relative to their plagioclase relationship in site 1 (Fig. 11).

350 For site 1, magnetic fabric, SPO and LPO of plagioclase show close relationships. The
351 “magnetic lineation” (K_1) is parallel to plagioclase-(100) “Best Axis” and also parallel to the
352 lath of plagioclase alignment. The “magnetic foliation” (plane perpendicular to K_3) is parallel
353 to plagioclase-(010) and corresponds to the flow plane (Fig.11a). These relationships between
354 magnetic and the related flow crystallographic preferred orientation of plagioclase are totally
355 coherent with the crystal habitus ‘in lath’ of plagioclase. The tight relationships between the
356 crystallographic (LPO and SPO) and magnetic fabrics strongly suggest that plagioclase laths
357 mainly control the spatial distribution of titanomagnetite grains, carrier of the AMS. In
358 addition, EBSD analyses show that clinopyroxene and plagioclase LPO are coaxial and
359 therefore, both flow related. Plagioclase and clinopyroxene could constitute a silicate
360 framework that constrains the spatial distribution of titanomagnetite grains. These results are
361 in accordance with the experimental studies of Hargraves et al. (1991) and observations in
362 natural flow by Bascou et al. (2005).

363 For site 2, magnetic and crystallographic fabrics are also coaxial. However, contrary to site 1,
364 relationships between AMS and crystallographic axes differ between the different levels,
365 except for K_1 that systematically coincide to the (010)-plagioclase “Best Axis” (Fig.10). In the
366 pseudo-colonnade (site 2), the relationship between crystallographic and magnetic fabric
367 shows a permutation of K_1 with K_3 compared to those observed for site 1. The (100)-
368 plagioclase “Best Axis” tends to be parallel to K_3 and to the long axis of the shape fabric
369 (SPO) and the (010)-plagioclase “Best Axis” tends to be parallel to K_1 and the short axis of
370 the shape fabric (Fig. 11b).

371

372 ***7.3. Inverse AMS fabrics of La Palisse flow***

373 Distinctive AMS fabrics from those measured for site 1, which are considered normal because
374 of their agreement with field observations and relationships with plagioclase (and
375 clinopyroxene) crystallographic fabrics, are observed in the different levels of site 2. For the
376 colonnade and the layered zone of site 2, a systematic permutation of K_1 and K_3 axes could
377 allow to define a flow sense conform to the field evidences. Such inversion between K_1 and
378 K_3 is defined as an inverse magnetic fabric. Such fabric has already been described in other
379 contexts and several explanations have been proposed for their occurrence. For example,
380 Rochette et al. (1999), Potter and Stephenson (1988) and Borradaile and Puumala (1989) have
381 proposed that inverse fabrics result from the presence of Single Domain titanomagnetite

382 grains within the rocks. Crystallization of secondary magnetic oxides in residual magma or as
383 a result of hydrothermal alteration has also been evoked to be at the origin of ferromagnetic
384 SD grain crystallization and therefore of inverse fabrics (Archanjo et al., 2002).

385 In the La Palisse basalt flow, the absence of Single Domain grains is highlighted by hysteresis
386 parameters and FORC diagrams, both indicating a large and homogenous grain size of
387 ferromagnetic grains in the two sites and in all levels of the flow. Thus, the inverse magnetic
388 fabrics cannot be explained by the presence of small SD magnetic grains. The great
389 homogeneity in size and shape of the titanomagnetite grains also excludes crystallization of
390 secondary oxides during hydrothermal alteration processes. In addition, electron microprobe
391 and thermomagnetic curves indicate that Ti-rich titanomagnetite grains, which are the main
392 carrier of AMS, are relatively homogeneous in composition in the whole lava flow. The
393 magnetic mineralogy study of the La Palisse basaltic lavas tends to exclude the presence of
394 SD ferromagnetic grains as the cause of the inverse fabric. However, as underlined by
395 Chadima et al. (2009), several studies have shown obvious inverse fabric in dikes whereas the
396 magnetic grain size study from hysteresis measurements did not reveal SD grains evidences
397 (e.g., Callot et al., 2001; DeFrates et al., 2006). Chadima et al. (2009) proposed to measure the
398 anisotropy of remanent magnetization (ARM) when the presence of SD grains is supposed. In
399 case of inverse AMS fabric, ARM shows a permutation of AMS maximum and minimum
400 directions. In order to check the presence of these SD grains in the La Palisse samples, ARM
401 measurements were performed (Fig. 12). ARM fabrics of the studied samples are
402 characterized by K_3 parallel to A_3 (minimum axis of ARM) and therefore indicate no
403 permutation between ARM and AMS fabrics. These results confirm that inverse AMS fabric
404 is not a consequence of SD grain occurrence.

405 Petrological and chemical study of the La Palisse basaltic lava flow (Boiron, 2011) don't
406 show significant difference in composition between samples of sites 1 and 2. Thermomagnetic
407 data confirm that the samples are very fresh, unaffected by post-emplacement alteration
408 processes. Magnetic susceptibility is high but relatively similar for both sites, in particular for
409 the colonnade ($4.9 \cdot 10^{-2} \text{ SI} < K_m < 6.1 \cdot 10^{-2} \text{ SI}$). This point is important because a higher
410 value of susceptibility to one of the sites could be associated with an increase of magnetic
411 interactions due to a higher clustering of ferromagnetic grains, which could generate abnormal
412 magnetic fabric (Fanjat et al., 2012). Various numerical and analogical modeling (Merle,
413 1998; Cañón-Tapia and Pinkerton 2000; Cañón-Tapia, E. and Chávez-Álvarez, M., 2004)
414 show that the shear intensity could impact on magnetic fabrics. When the shear is important,

415 the foliation development promotes an orientation of the minimum axis K_3 perpendicular to
416 the shear plane. On the contrary, in the case of weaker shear intensity, the magnetic fabric is
417 preferentially lineated and the maximum axis K_1 tends to be perpendicular to the shear plane.
418 Elongation ration of the particles could also affect the orientations. It is particularly difficult
419 to quantify in natural lava. However, images analysis from digital photos on thin sections
420 does not show significant differences in grain size of minerals coming from similar areas
421 (e.g., the top of the colonnade). In addition, neither the crystallographic fabric strength (J_{index})
422 of plagioclase, nor the magnetic anisotropy values (P') do not show strong variations between
423 the both sites that suggests relatively comparable amount of shearing strain during the latest
424 stages of the lava flow evolution.

425 A synthesis of data characterizing the studied sites of the La Palisse lava flow is presented in
426 Figure 13. It clearly appears that the main difference between the both sites concerns the
427 paleosurface slope, very gently for site 1 and high (50°) slope for site 2. Canon-Tapia et al.
428 (1995, 1996, 1997) indicate that the morphology of a lava flow is strongly controlled by the
429 rheology and the slope of the pre-existing terrain. The maximum of susceptibility axes are
430 more scattered and sometimes even perpendicular to the flow direction when the slope of
431 paleosurface is very weak whereas less scattered maximum axes are observed with a stronger
432 slope. Numerical modeling of Merle (1998) shows that flowing over an inclined base
433 produces complex stretch and flattening plane trajectories in the vertical plane and thus,
434 generate significant gap between the stretching direction and the flow direction (and the
435 associated fabric development).

436 Finally, the viscosity of the lava during emplacement can also have a great influence on the
437 degree of anisotropy as shown by Hrouda et al. (2005). Such geological causes could explain
438 the colonnade and the layered zone inverse fabrics of site 2.

439

440 **8. Conclusions**

441 In this AMS study, we show that the determination of the flow direction and the sense can be
442 achieved through the use of the magnetic foliation imbrication, in particular at the base of the
443 flow. Contrary to others studies that base the AMS analysis on the K_1 directions (with or
444 without imbrication), the measurements on the La Palisse lava flow highlight the poor

445 reliability of magnetic lineation. This can easily induce inversion between K_1 and K_2 during
446 the flow.

447 EBSD data show clear correlations between plagioclase and clinopyroxene LPO: (100)-
448 plagioclase tends to be parallel to (001)-clinopyroxene and (010)-plagioclase tends to be
449 parallel to (100)-clinopyroxene. In addition, LPO orientations, and also shape preferred
450 orientations of plagioclase show tight relationship with principal AMS directions. For site 1,
451 (010)-plagioclase is parallel to the magnetic foliation (K_1 , K_2) and coincides to the flow plane,
452 and the pole of (100)-plagioclase is parallel to K_1 and coincide the flow direction indicated by
453 the preferred alignment of plagioclase laths. These close relationships between
454 crystallographic and magnetic fabrics suggest a control of the silicate framework (plagioclase
455 and clinopyroxene) on AMS carried by the titanomagnetite grains.

456 For both sampling sites (sites 1 and 2), the flow direction deduced from AMS is consistent
457 with field evidences. However, only AMS in site 1 allows determining the geological flow
458 sense. For site 2, the flow sense is systematically opposed to the geological flow sense.
459 Relations between AMS and LPO are systematically different of those of site 1; for site 2, the
460 pole of (010)-plagioclase is always parallel to K_1 for the three levels, the pole of (100)-
461 plagioclase is parallel to K_3 for pseudo-colonnade, (001)-plagioclase tends to be parallel to the
462 magnetic foliation (K_1 , K_2) for colonnade whereas the layered zone do not indicate other clear
463 relations.

464 Petrographic observation, thermomagnetic curves as well as hysteresis parameters indicate
465 that magnetic minerals are mainly subhedral Ti-rich titanomagnetite grains belonging to Multi
466 Domain and Pseudo-Single Domain. FORC diagrams exclude a grain size population
467 dominated by single domain grain in the samples. Therefore, the permutation between K_1 and
468 K_3 axes cannot be related to the presence of SD grains that is confirming by ARM data.

469 Magnetic susceptibility parameters (P' and K_m) are relatively similar for the two sites, except
470 in the entablature of site 1 where the anisotropy degree (P') is higher than in the other levels.
471 We also observe that the layered zone (site 2) is not the equivalent of the entablature (site 1),
472 although both are located in the middle part of the flow. The crystallographic fabric strength
473 (J_{index}) of plagioclase (and clinopyroxene) is also relatively similar in the two sites.

474 The main difference between site 1 and site 2 concerns the paleosurface slope, very gently for
475 site 1 and high (50°) slope for site 2 as indicated by the layered zone inclination and the tilt of

476 the columns. Inverse fabrics of site 2 may be then due to other factors than magnetic grain
477 size such as viscosity or the paleosurface slope during the emplacement of the flow. However,
478 additional analyses are needed to determine precisely which of these factors exerted the main
479 control on the permutation of AMS axes.

480 If AMS appears as an efficient tool to reveal the structure of basalt flows and to deduce the
481 flow direction, our study supports that inverse magnetic fabrics can occur even in the absence
482 of Single Domain grains. Recently, Chadima et al. (2009) proposed to use preferably ARM
483 rather than AMS fabric to determine flow direction and tectonic interpretations of magnetic
484 fabric in dikes. However, this technique remains less usual than the measurement of AMS,
485 which has become a common tool in rock magnetism. In lava flows, AMS measurements
486 coupled with local analyses such as LPO obtained through EBSD technique or SPO deduced
487 from image analysis could allow preventing misinterpretations based on AMS fabrics alone.

488

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495

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- 697

698 **Figure Captions:**

699 **Figure 1:** Location of the La Palisse basalt flow. (a) Location of the Bas-Vivarais volcanic region.
 700 Black area refers to the volcanic provinces of the French Massif Central, (b) Geological map of the
 701 studied area. Black arrows indicate the flow direction. The location of studied sites is also indicated.
 702 GPS data: Site 1: N 44°47.38', E 4°05.33', Site 2: N 44°46.88', E 4°06.32'.

703 **Figure 2:** Photo of the La Palisse village outcrop (site 2) showing the colonnade, the layered zone and
 704 the pseudo-colonnade levels within the lava flow.

705 **Figure 3:** Reflected light photomicrograph of representative thin section from the colonnade of the La
 706 Palisse basalt flow (08tb14b sample; site 1). The white spots are mainly constituted of titanomagnetite
 707 grains (Ti-Mt). Pl = plagioclase, Px = pyroxene, Ol = olivine.

708 **Figure 4:** Magnetic susceptibility (K/K_0) versus temperature for representative samples from the
 709 different levels of the La Palisse basalt for site 1 and 2. The thermomagnetic curves are commonly
 710 reversible and the rapid change in susceptibility indicates a Curie temperature (T_c) of about 110°C
 711 associated to the Ti-rich titanomagnetite grains. Thermomagnetic curves determination under argon
 712 atmosphere at heating rate of 11°C min⁻¹.

713 **Figure 5:** a) Representative hysteresis curves (magnetic moment, m versus applied field, H) indicating
 714 the presence of ferromagnetic (s.l.) grains. b) Mrs/Ms ratio versus Hcr/Hc ratio diagrams of samples
 715 from the different levels of site 1 (LP site 1) and site 2 (LP site 2). Mrs: saturation remanence; Ms:
 716 saturation magnetization; Hcr: remanent coercive force; Hc: ordinary coercive force. The limits of the
 717 pseudo-single domain of titanomagnetite (TM60) are defined from Dunlop (2002). Titanomagnetite
 718 experimental data are reported from Day et al. (1977). Titanomagnetite grains belong to the pseudo-
 719 single domain (PSD) are consistent with data, also reported, from natural Ti-rich titanomagnetites
 720 (O'Donovan et al., 1986; Hartstra et al., 1982). Numbers indicate the grain size in micrometers, C
 721 (coarse grain) and F (fine grain) for experimental data.

722 **Figure 6:** FORCs diagrams from site 1 colonnade (samples 08tb12 and 08tb18) and from site 2
 723 layered zone (samples 08tb59 and 08tb68). These diagrams are characteristic of Pseudo-Single
 724 Domain + Multi Domain grains mixing.

725 **Figure 7:** Diagrams representing the anisotropy parameter P' versus the bulk magnetic susceptibility
 726 (K_m) for the different levels of site 1 (a) and site 2 (c). Diagrams of P' versus the shape parameter T
 727 are shown in (b) and (d) for site 1 and site 2, respectively.

728 **Figure 8:** Equal area projection in the lower hemisphere and geographical referential of the principal
 729 magnetic susceptibilities axes (K_1 , K_2 , K_3) measured in specimens from the different levels of the La
 730 Palisse flow for sites 1 and 2. The flow direction inferred from field observations is shown by the
 731 black arrow and the flow direction determined from AMS study is shown by the white arrow. The
 732 confidence ellipses are computed from Jelinek's statistics (Jelinek, 1978). N = number of
 733 measurements. For site 2, the layered flow plane is also presented in full line for layered zone and in
 734 dashed line for colonnade and pseudo-colonnade.

735 **Figure 9:** Lattice Preferred Orientation (LPO) of plagioclase, clinopyroxene and titanomagnetite of
 736 samples from the different levels of the La Palisse flow: (a) from the colonnade and the entablature of
 737 site 1, (b) from the colonnade and the layered zone of site 2 and (c) from the pseudo-colonnade of site
 738 2. Equal area, lower hemisphere projection in the specimen coordinates system with the field

739 measured sample angles X (azimuth) and Z (dip). Contours are in Multiples of Uniform Distribution
740 (MUD). DM is the maximum of density, (black square in pole figures); white triangle represents the
741 "Best Axis"; J is the texture index; N is the number of measurements. (d) Representative habitus of
742 plagioclase, clinopyroxene and titanomagnetite single crystals.

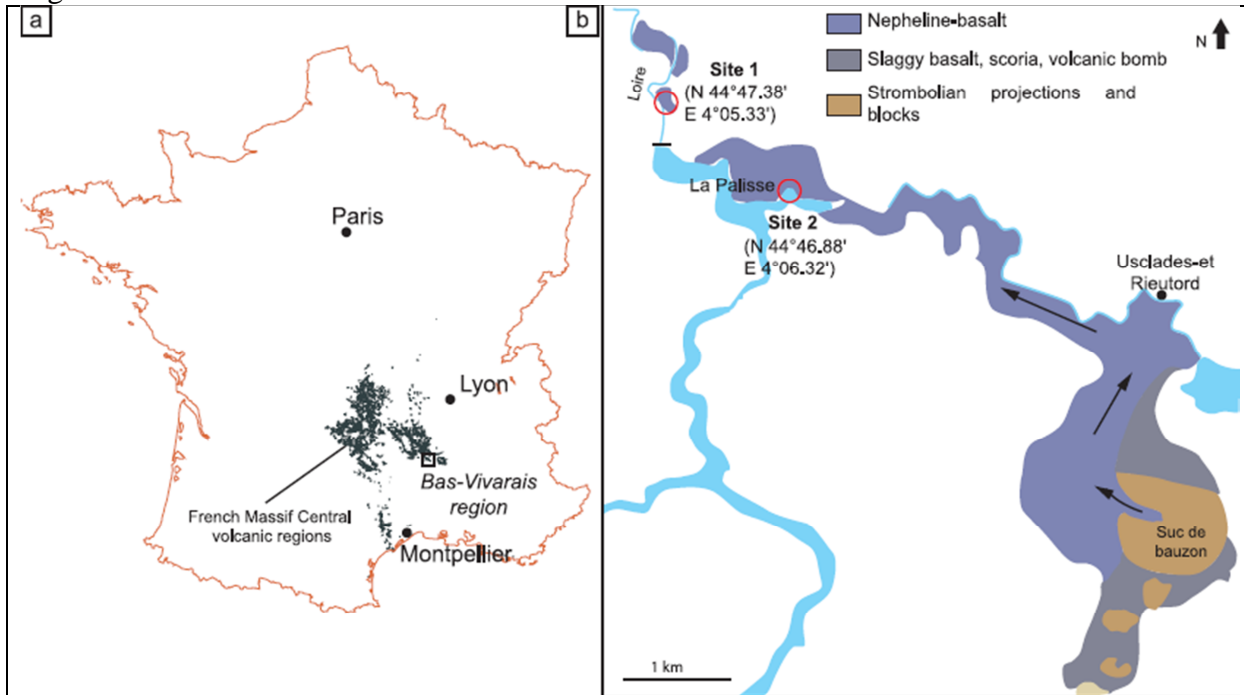
743 **Figure 10:** Projection in the specimen referential (as Fig. 9) of maximum of density (DM-Pl) and
744 "Best Axis" (eigenvector) of plagioclase LPO for samples from the different flow levels. Maximum of
745 density of titanomagnetite [111]-axes and mean eigenvectors K_1 , K_2 and K_3 are plotted.

746 **Figure 11:** (a) Projection of plagioclase LPO (maximum of density (DM-Pl) and "Best Axis") and
747 AMS fabrics in lower hemisphere and specimen referential of 08tb14b sample from the colonnade site
748 1, compared to the Shape Preferred Orientation (SPO) of plagioclase deduced from 2-D image
749 analysis (rose of mean length intercepts); $SR = 1.468$, $\alpha = 76^\circ$. (b) Projection of plagioclase LPO, AMS
750 and 3-D plagioclase SPO of 08tb70b sample from the pseudo-colonnade site 2.

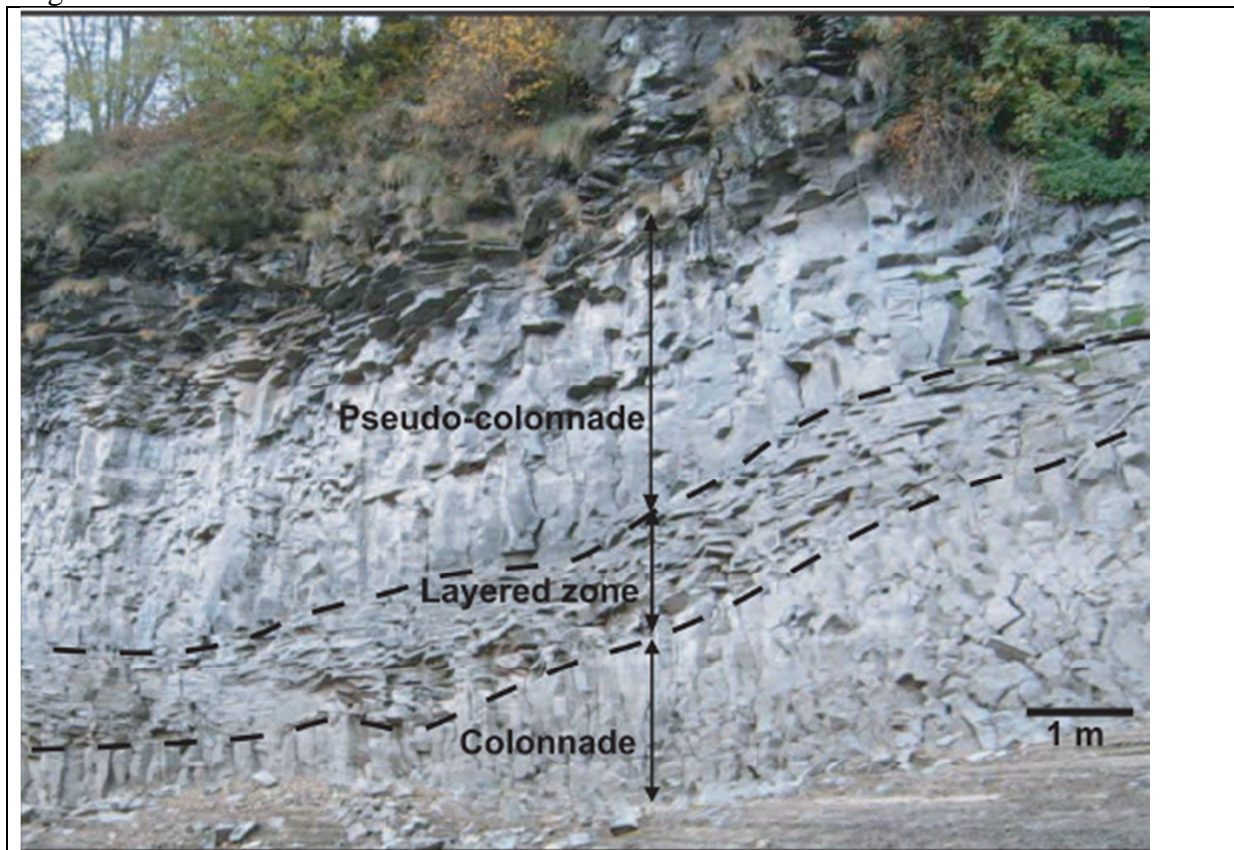
751 **Figure 12:** Principal directions of the AMS and ARM fabrics for samples from colonnade, layered
752 zone and pseudo-colonnade, site 2 in the equal-area, lower-hemisphere projections in specimen
753 coordinate system. The black and white symbols are AMS and ARM principal directions, respectively.

754 **Figure 13:** Summarize of site 1 and 2 characteristics (paleosurface slope, columns shape, AMS
755 direction, magnetic properties, lattice preferred orientation of plagioclase and the relationship between
756 magnetic and crystallographic fabric). For plagioclase SPO, S.A. indicates the Short Axis and L.A. is
757 the Long Axis.
758

759 Figure 1

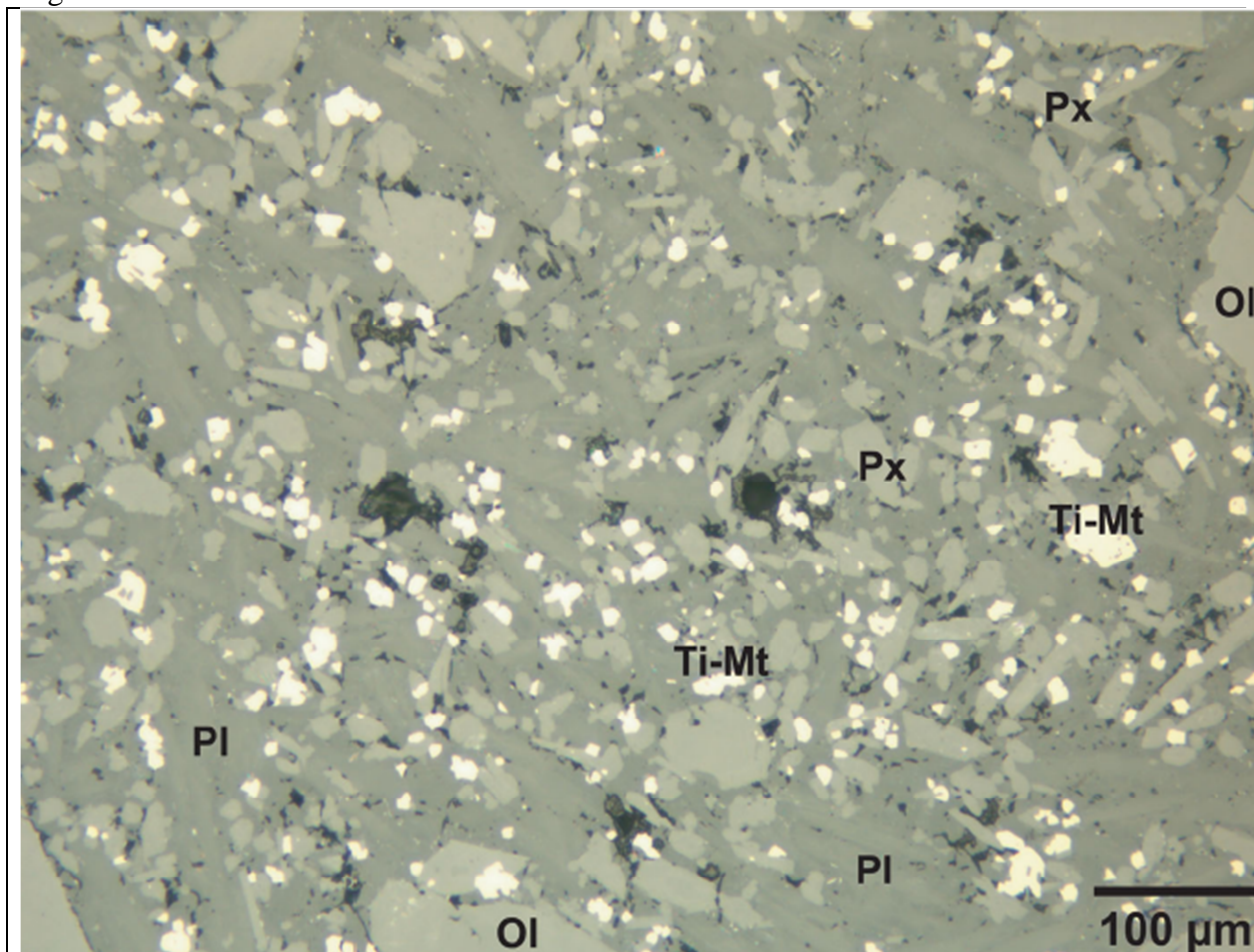


760 Figure 2



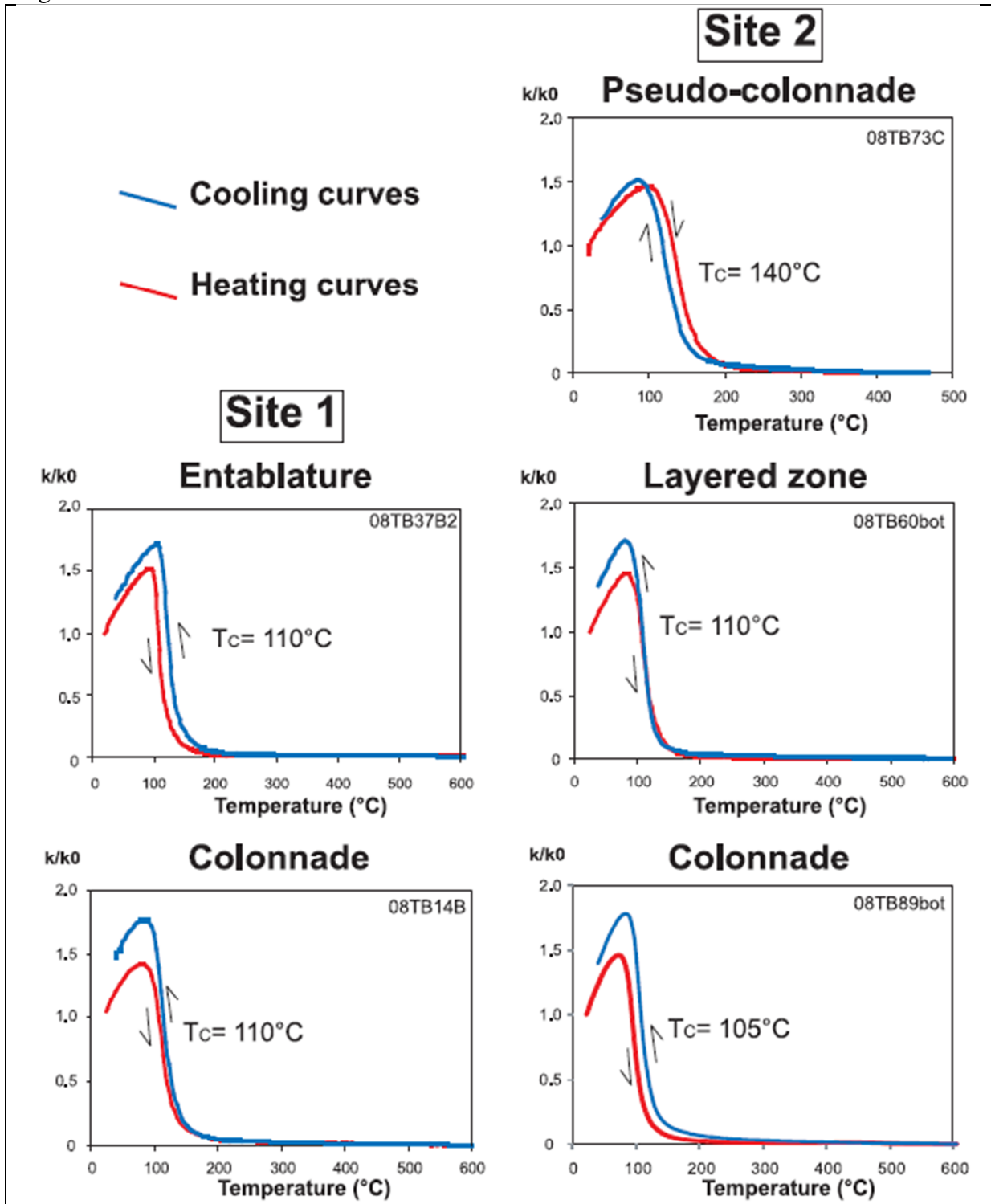
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762 Figure 3



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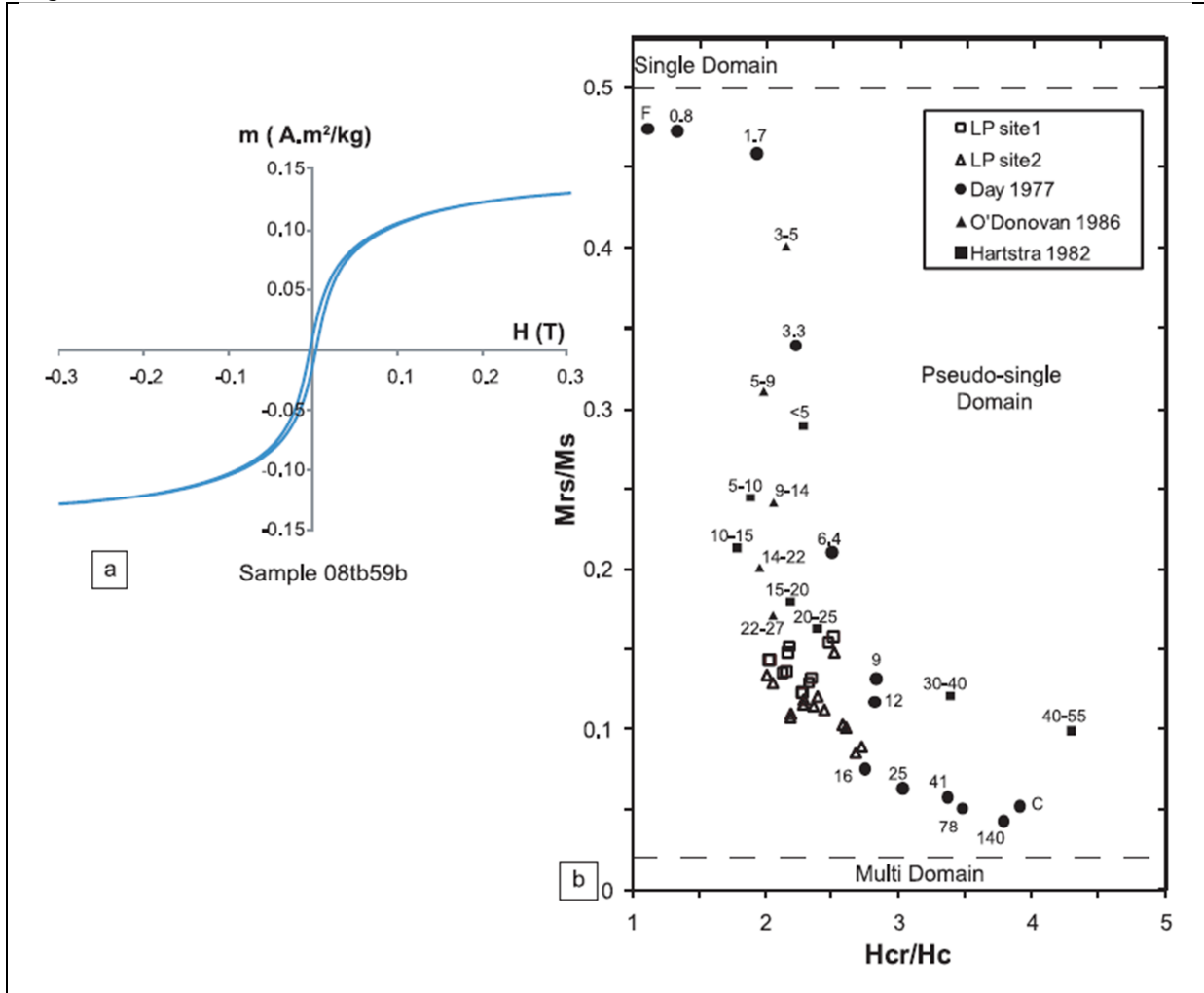
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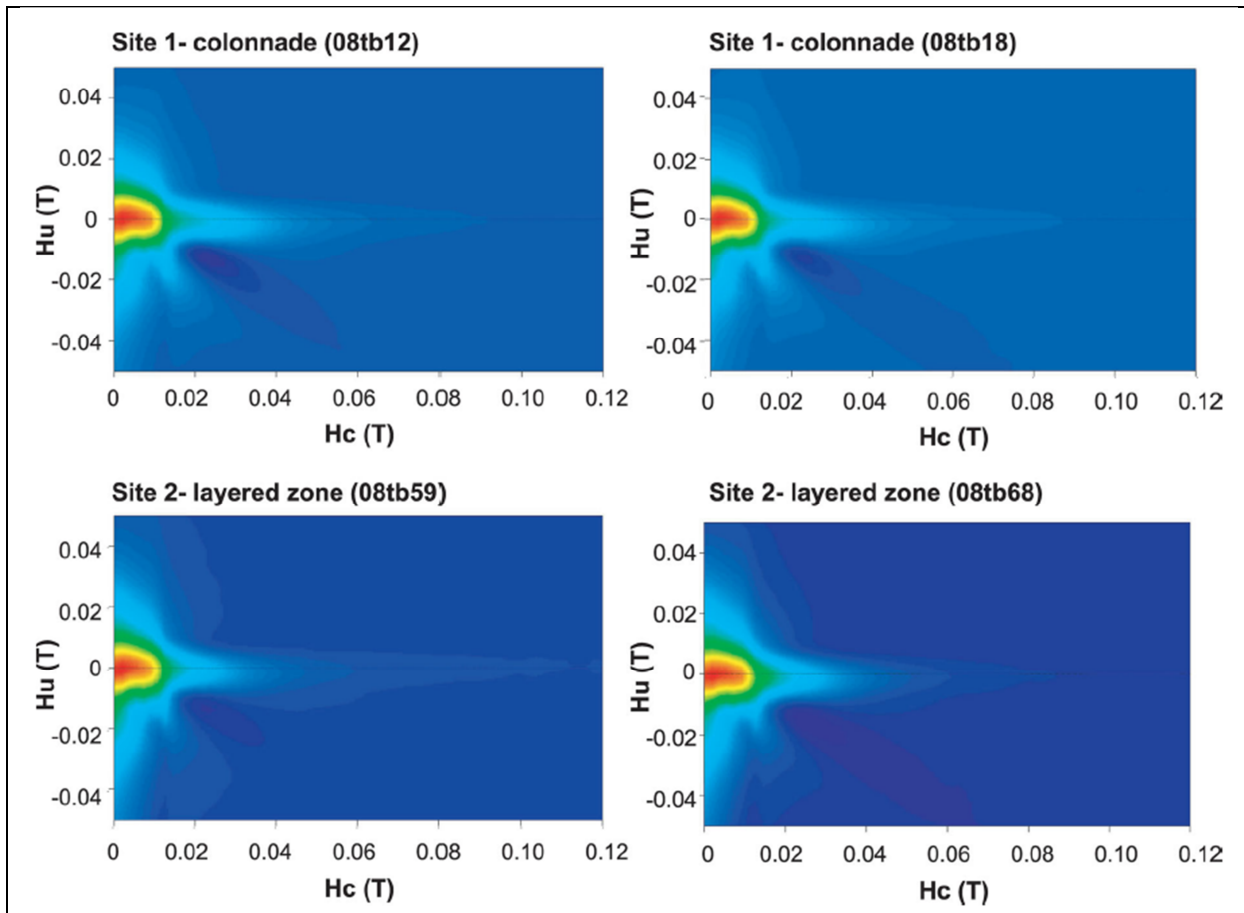
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768 Figure 5



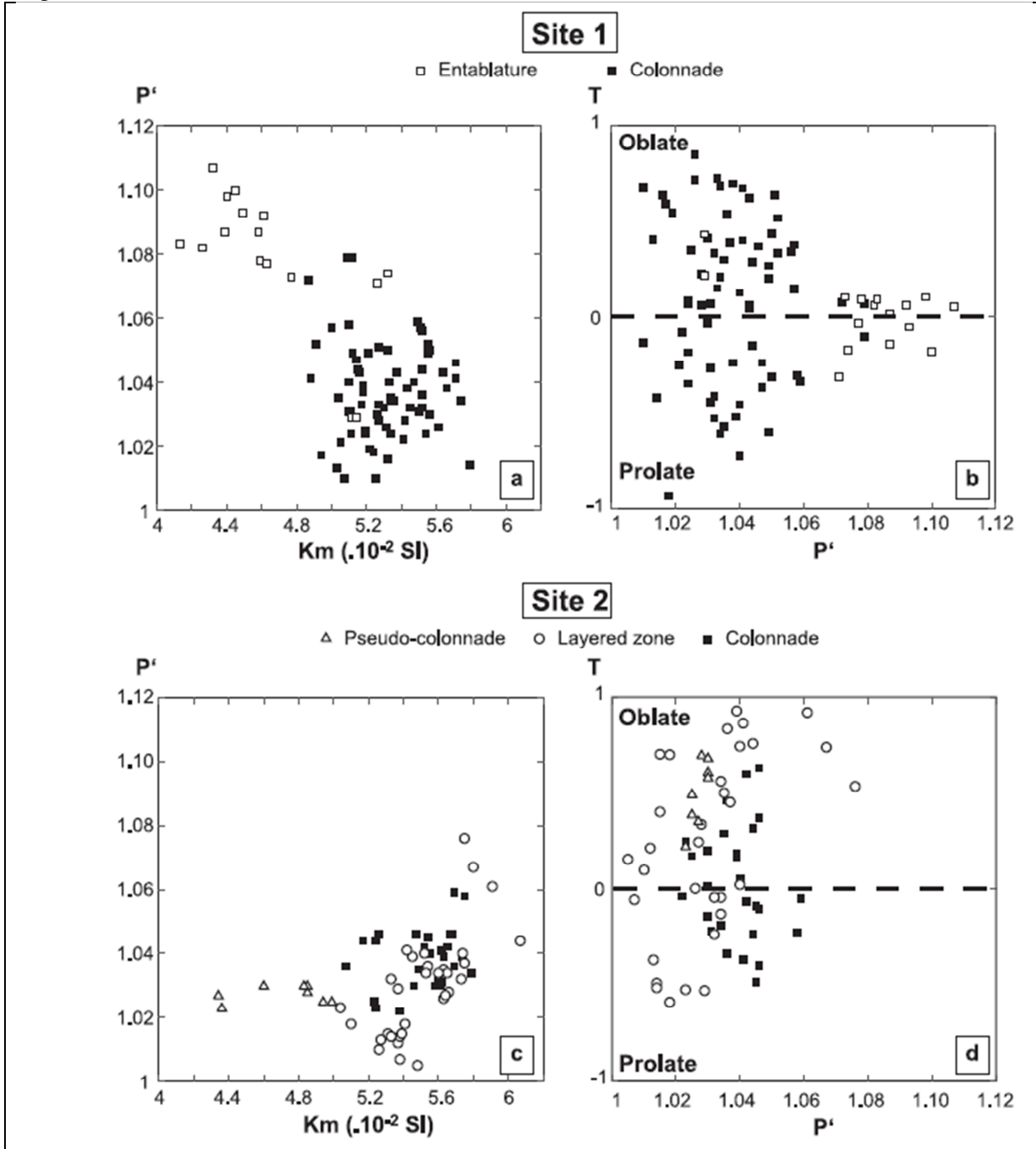
769 Figure 6



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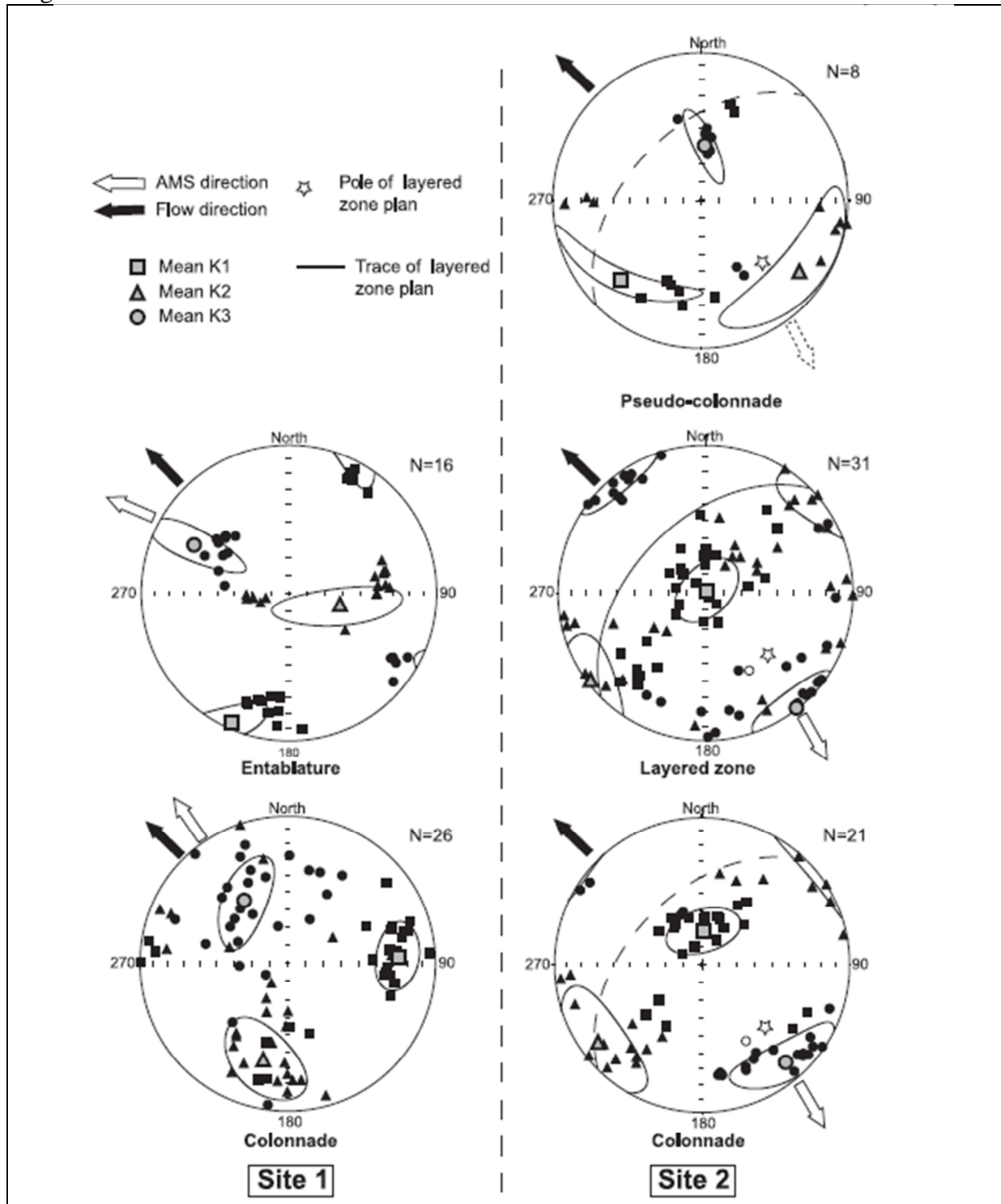
772 Figure 7



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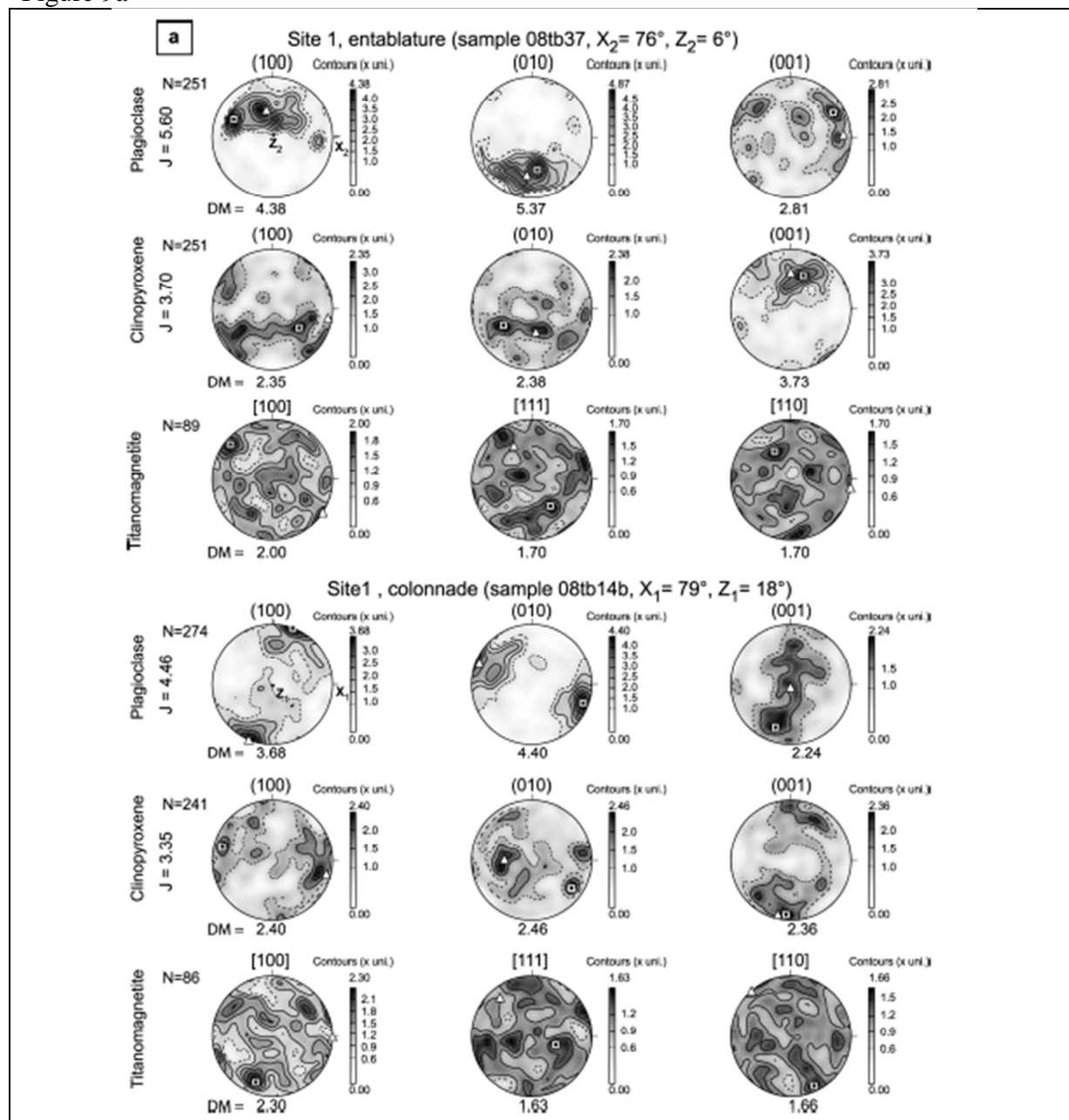
775 Figure 8



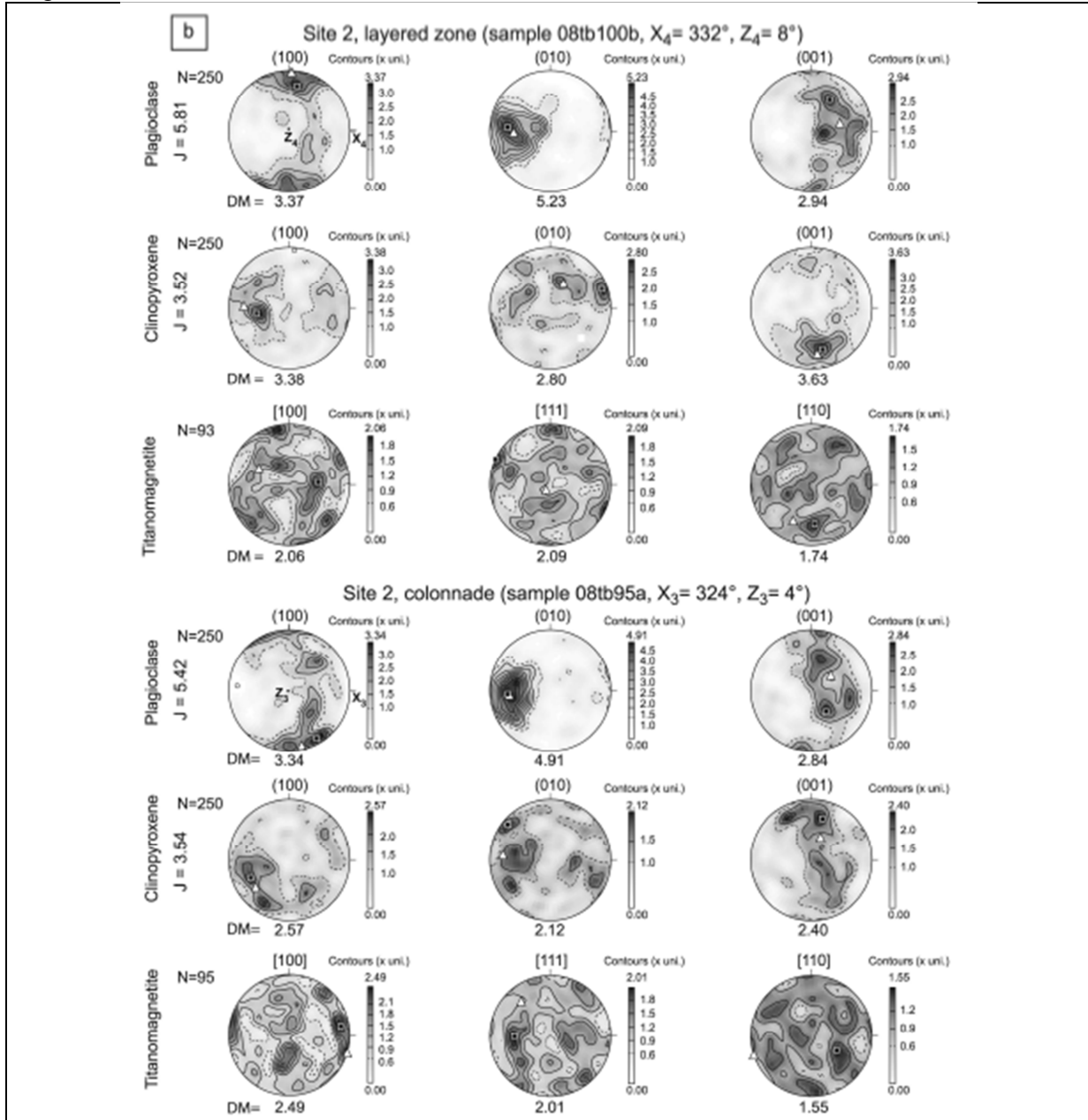
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778 Figure 9a



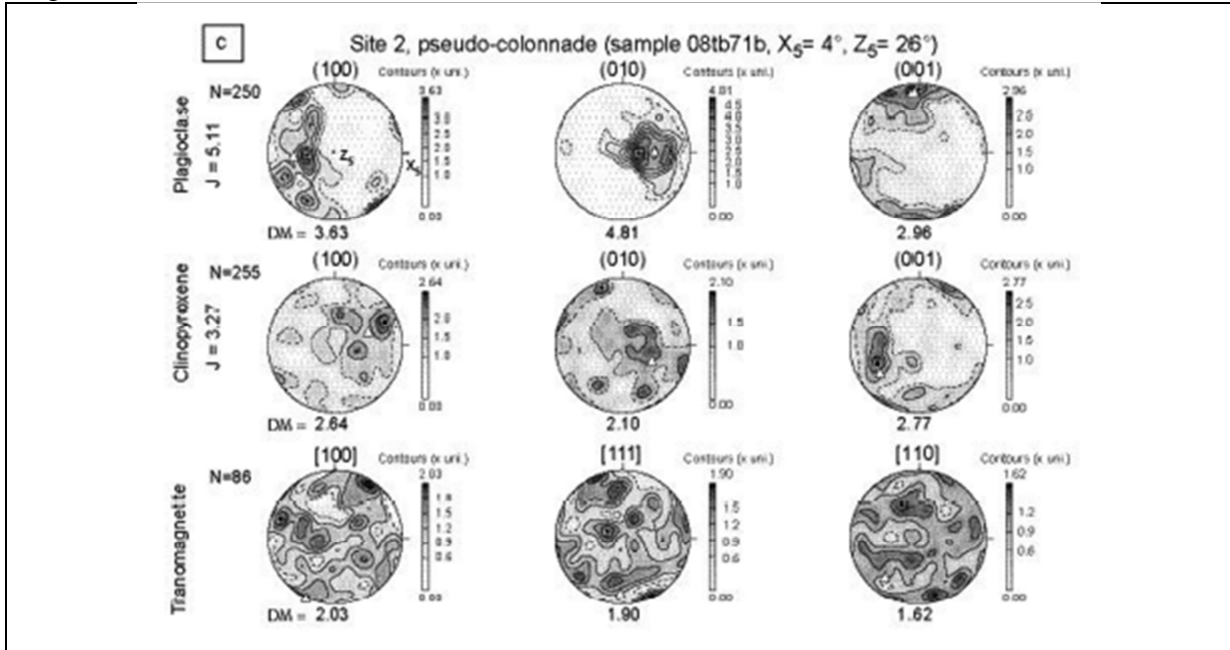
780 Figure 9b



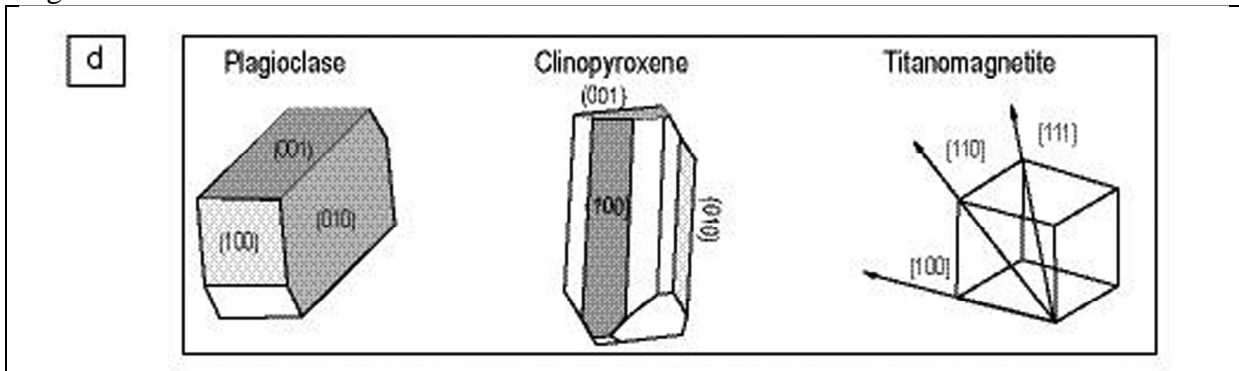
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783 Figure 9c



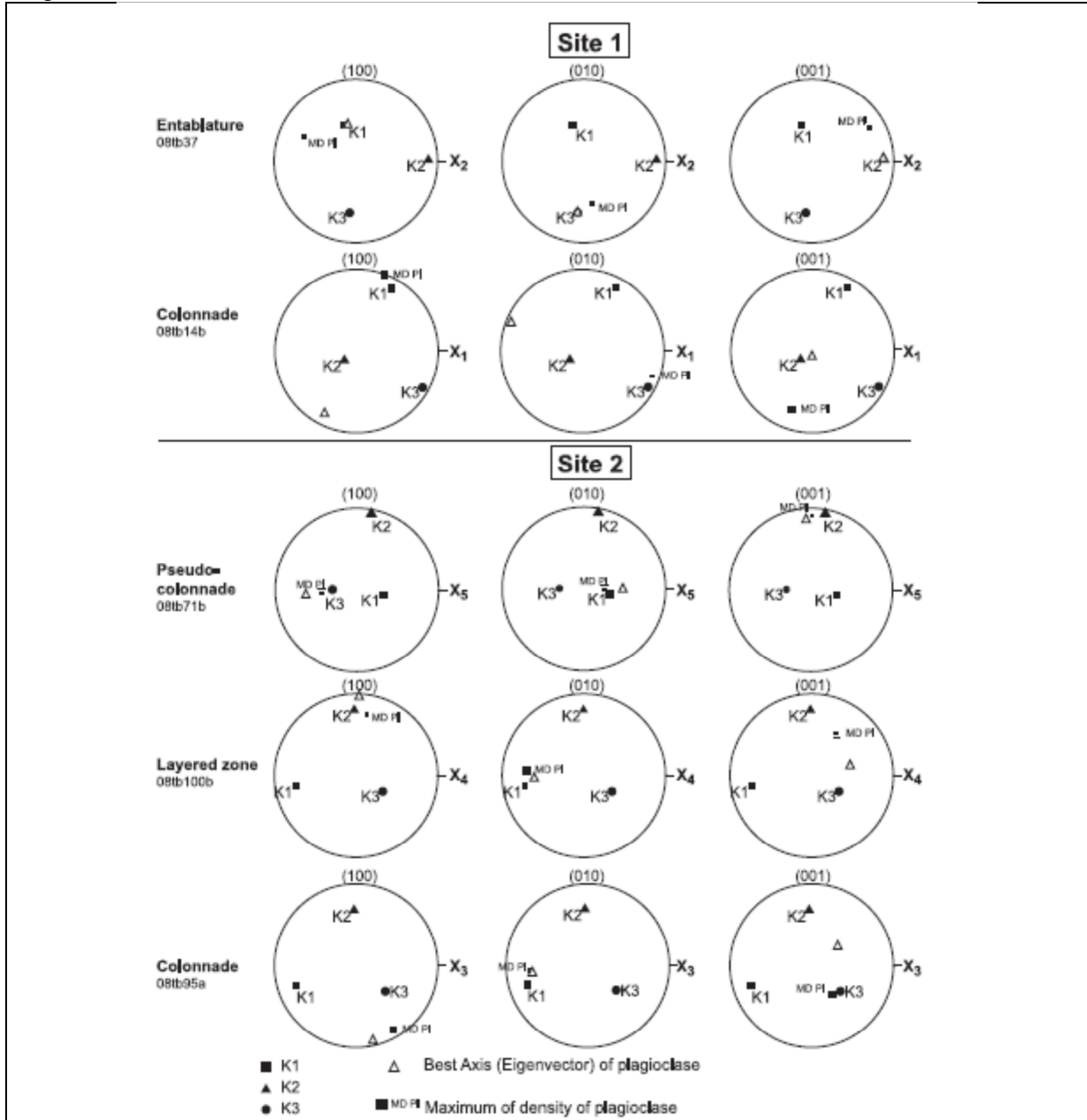
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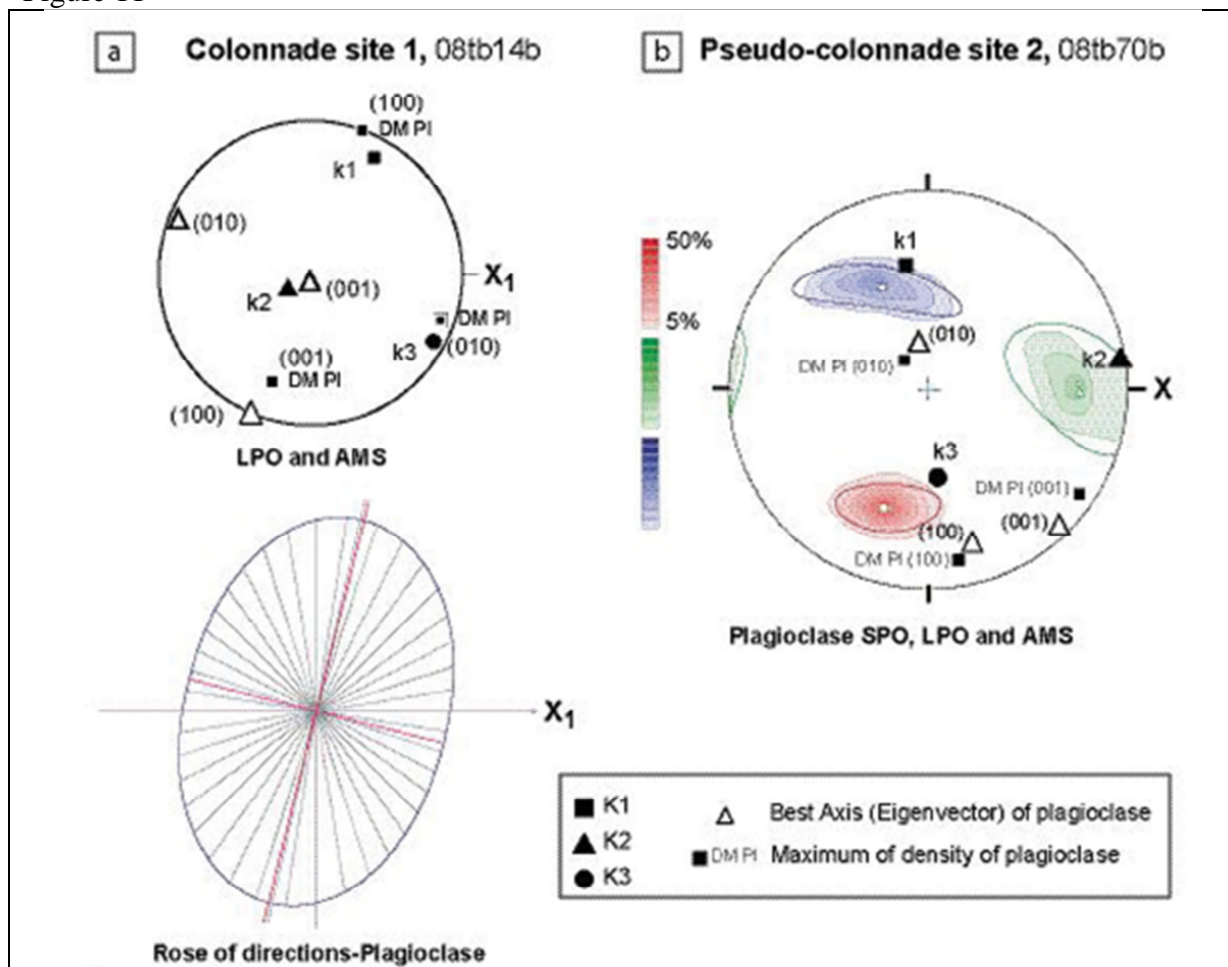
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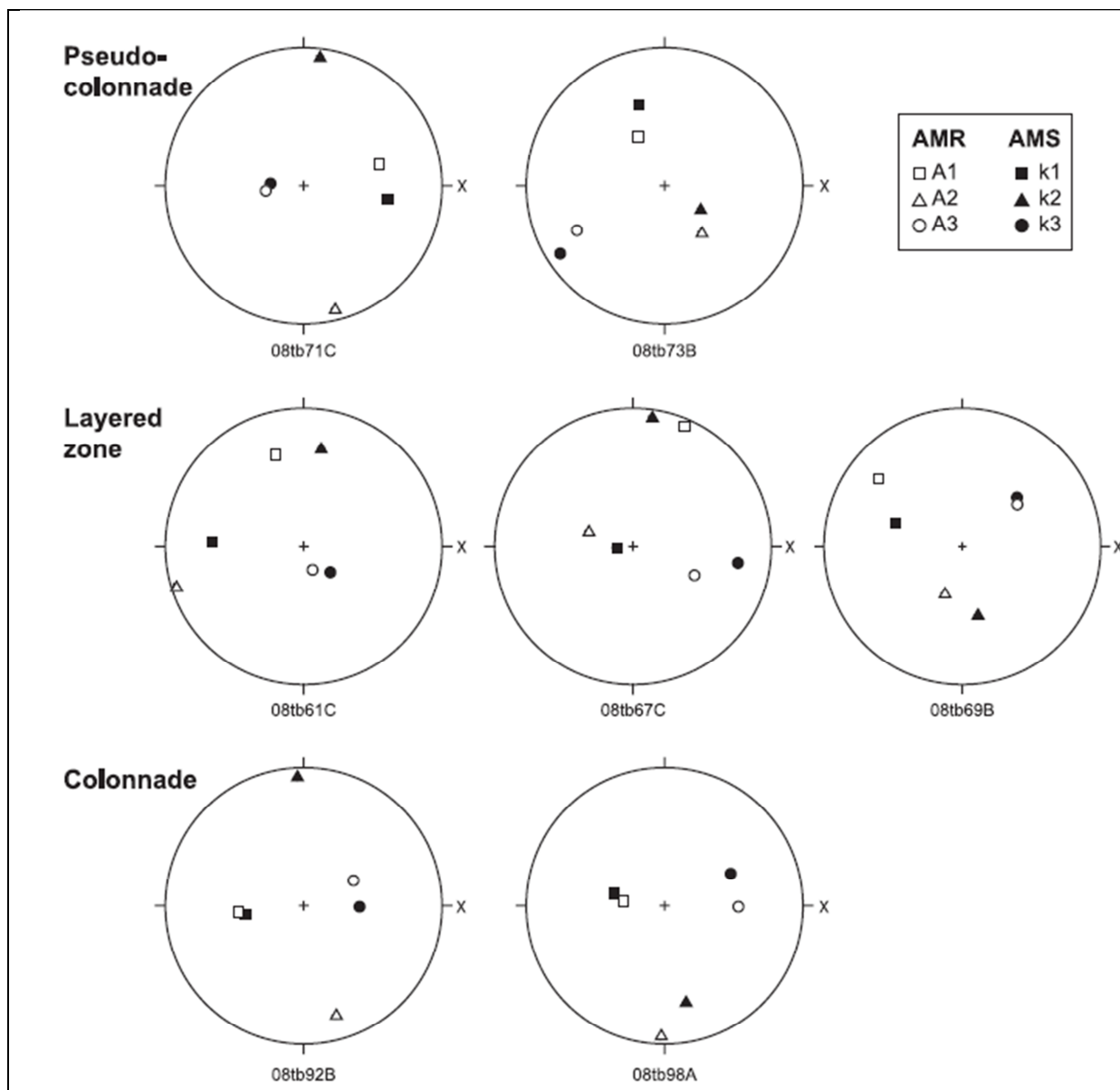
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790 Figure 11



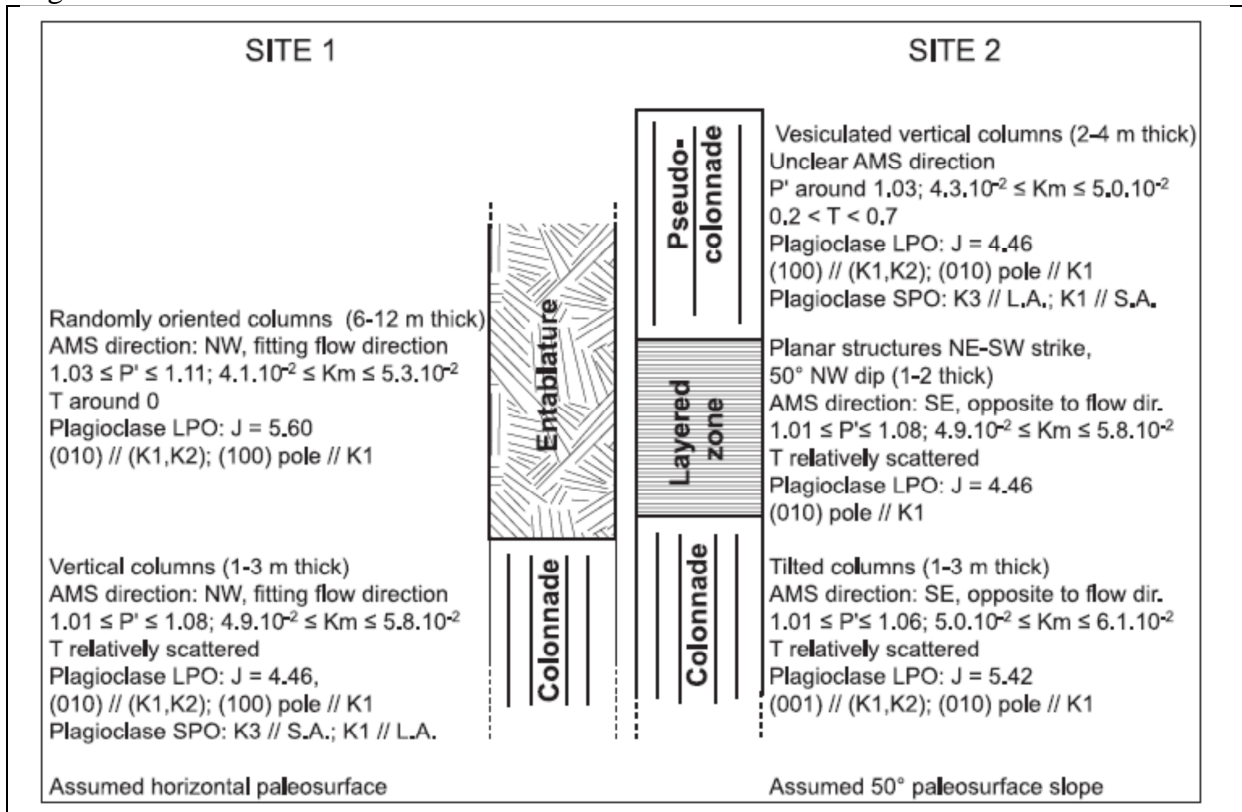
791 Figure 12



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793

794 Figure 13



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