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3 **Composite detrital and thermal remanent magnetization in tuffs from Aeolian Islands**
4 **(southern Tyrrhenian Sea) revealed by magnetic anisotropy**
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16 **Abstract**

17 This paper reports on the complex relation between rock emplacement and remanence
18 acquisition in tuffs deposited by pyroclastic density currents (PDCs), disclosed by systematic
19 measurements of the anisotropy of magnetic susceptibility (AMS) and natural remanent
20 magnetization (NRM). Thermal demagnetization shows that the NRM consists of two components
21 with different blocking-temperature spectra. The direction of the low-temperature component is
22 consistent with the geocentric axial dipole value, whereas the high-temperature component has
23 dispersed directions. The magnetic fabric is oblate, the magnetic foliation is close to the bedding
24 and the lineations are generally dispersed along a girdle within the foliation plane. The directions of
25 the magnetic lineation and the high-temperature remanence component of individual specimens are
26 close to each other. This correspondence suggests that the high blocking-temperature grains
27 acquired a remanence aligned to their long dimension before deposition, while cooling within the
28 explosive cloud and the moving pyroclastic current. Thereafter, during deposition the traction
29 processes at the base of the current oriented the grains along the flow direction and affected both
30 fabric and high-temperature remanence. This NRM component results from mechanical orientation
31 of previously magnetized grains and is thus detrital in origin. A second, thermal component was
32 then acquired during the cooling of the low blocking-temperature grains after deposition. These
33 results show that NRM in fine-grained pyroclastic rocks is affected by the Earth's magnetic field as

34 well as the emplacement processes and that magnetic fabric data are essential to unravel its complex
35 nature.

36
37 Key words: magnetic fabric, remanent magnetization, pyroclastic rocks

38
39 **Introduction**

40 The primary remanent magnetization of volcanic rocks is typically thermal (TRM) in origin. It
41 is acquired as the rock cools through the Curie point (T_c) of its ferromagnetic minerals and passes
42 through the blocking temperature T_b spectrum of its ferromagnetic grains. This simple model fully
43 applies to lavas. The temperature of the molten magma is much higher than the Curie point of Ti-
44 magnetite ($T_c \leq 575$ °C), by far the most widespread primary ferromagnetic mineral in volcanic
45 rocks. A lava flow thus acquires a magnetic remanence when cooling after movement has stopped
46 and the two processes are distinct in time. Emplacement of pyroclastic rocks occurs at temperatures
47 that may be as high as for lavas (e.g. fall-out scoriae) and as low as ambient temperature (e.g.
48 lahars), and, in many cases, a substantial cooling occurs while particles are still moving, as in the
49 case of pyroclastic density currents (PDCs) (Cioni et al., 2004; Zanella et al., 2007). Calling
50 deposition temperature (T_{dep}) the temperature at the very moment the pyroclastic material stops
51 moving, two fractions of ferromagnetic grains in principle occur in the rock: those characterized by
52 $T_b > T_{dep}$, which already carry a remanent magnetization as they deposit, and those with $T_b < T_{dep}$,
53 which acquire a TRM as they cool after deposition. The rock's natural remanent magnetization
54 (NRM) consists therefore of a high-temperature component, acquired during the emplacement, and
55 a low-temperature component, acquired during cooling after deposition. The time interval between
56 the acquisition of the two components is so small with respect to the secular variation of the Earth's
57 magnetic field that they are expected to have the same direction and be therefore hardly
58 distinguishable. The composite nature of the NRM in pyroclastic rocks has therefore been
59 overlooked in most paleomagnetic studies.

60 This paper reports on the case history of Brown Tuffs, a series of tuffs cropping out in the
61 Aeolian Islands (southern Tyrrhenian Sea, Italy), where combination of anisotropy of magnetic
62 susceptibility (AMS) and NRM measurements provides essential information on the timing of
63 remanence acquisition.

64
65 **Geological setting and sampling**

66 The Brown Tuffs are a sequence of ash-deposits emplaced in the seven islands of the Aeolian
67 archipelago by distinct eruptions that occurred in the last 80 kyr. On the basis of two widespread

68 tephra layers, they have been divided into three successions, known as Lower (emplaced between
69 80 and 56 ka), Intermediate (between 56 and 20-22 ka) and Upper (between 20-22 and 4-5 ka)
70 Brown Tuffs (Lucchi et al., 2008). Their lithological, sedimentological and compositional features
71 are similar, irrespective of the age and the geographical distribution of the deposits (De Astis et al.
72 1997; Lucchi et al. 2008). The Brown Tuffs consist of massive, brown to red, no stratified fine-
73 grained ash, with local discontinuous bedding surfaces and internal banding. The grains mainly
74 consist of juvenile glassy and crystal fragments with minor ($\approx 5\%$) lithic content, and their size is
75 from fine (<0.064 mm) to coarse ash (0.064-2 mm). The crystals are represented by clinopyroxene,
76 plagioclase and minor amounts of olivine and Fe-Ti oxides. Distinct depositional units within the
77 sequence, a few decimeters up to 2-3 m thick, may be identified on the basis of interbedded tephra
78 layers, volcanoclastic deposits and paleosols (De Astis et al. 1997; Lucchi et al. 2008). The Brown
79 Tuffs were emplaced by PDCs: the ash particles were transported by turbulent suspension and
80 deposited at the very base of the current, under the effect of the traction processes exerted by the
81 overlying flow.

82 A paleomagnetic, rock-magnetic and volcanological investigation has been done to contribute
83 to the between-islands stratigraphical correlation and chronology of the Brown Tuffs units, the
84 results of which are reported in a comprehensive paper (Cicchino et al. in preparation). Here we
85 present the results from selected sites on Lipari and Vulcano islands (Fig. 1) that are useful to
86 understand the effects that the magnetic anisotropy exerts on NRM. At each site, eight to fifteen
87 cores were drilled and oriented with both magnetic and solar compass, collected and then cut to
88 standard ($\Phi = 24.5$ mm, $h = 23$ mm) cylindrical specimens in the laboratory.

89

90 **Measurements and results**

91 All measurements were made at the ALP Laboratory (Peveragno, Italy) using a KLY-3
92 Kappabridge and a JR-6 spinner magnetometer. A Schoenstedt furnace and a Molspin demagnetizer
93 were used for thermal and AF demagnetization, and a PUM pulse magnet for isothermal remanence
94 (IRM) acquisition. Paleomac (Cogné 2003) and Anisoft 4.2 (Chadima and Jelinek 2008) programs
95 were used for data elaboration.

96 AMS measurements (Table 1) show that the bulk susceptibility value is rather high ($K_m =$
97 $14,000 \pm 5,000$ μSI) and the anisotropy degree low ($P < 1.030$). The geometry of the fabric,
98 however, is well defined and typically oblate. The magnetic foliation is well developed (Fig. 2),
99 whereas lineations are either grouped or dispersed along a girdle within the foliation plane. The
100 main ferromagnetic (*s.l.*) mineral in the Brown Tuffs is Ti-magnetite (Losito 1989; Zanella et al.
101 1999; Cicchino 2007) and no evidence for other minerals was found in the present investigation.

102 Interpretation of the AMS fabric of a Ti-magnetite bearing rock requires further information
103 on the magnetic state of the grains, as the AMS maximum axis (K_1) of an unequant grain is parallel
104 to its longest or shortest dimension depending upon whether the grain is multi- or single-domain
105 respectively. This problem was investigated by measuring anisotropy of remanence, since the
106 maximum axis of remanence is always parallel to the longest dimension of a grain. Anisotropy of
107 isothermal remanent magnetization (AIRM) was therefore measured in some specimens. They were
108 first tumbling demagnetized at 60 mT, then given a steady field of 20 mT and the acquired IRM
109 was measured. These steps were repeated in twelve different sample orientations according to the
110 procedure suggested by Jelinek (1996), in order to cancel out any possible NRM component with
111 coercivity higher than 60 mT, which could bias the IRM measurement. The results show that the
112 three principal IRM and susceptibility axes fall close to each other (Fig. 3). The consistency
113 between AMS and AIRM measurements shows that both maximum axes (K_1 and I_1) match the
114 longest dimension of grains and the magnetic fabric of a specimen can therefore be interpreted as
115 the result of preferential orientation of the longest direction of individual grains. Occurrence of a
116 well developed magnetic foliation shows that the deposition process was highly effective in
117 orienting the longest dimensions of the grains parallel to the bedding plane, yet only in few cases
118 enough to fully align them to a single direction. At most sites, the magnetic lineations are randomly
119 distributed within the foliation plane (Fig. 2b), and we shall see below that this dispersion is
120 relevant to the magnetic remanence of the deposits.

121 A series of selected specimens was stepwise demagnetized by either thermal or AF methods.
122 A negligible magnetization component of probable viscous origin (VRM) was erased in the first
123 steps. Thermal demagnetization reveals a large (80-90 % of initial NRM) low-temperature (low-T)
124 and a small high-temperature (high-T) component, clearly shown in the Zijdeveld (1967) diagram
125 and equal-area projection (Fig. 4a, b, c). As demagnetization proceeds, the measured direction
126 moves along a great circle and points to an overlap of the T_b spectra of the low- and high-T
127 components. AF demagnetization usually fails to pick out the two components (Fig. 4d). Thermal
128 demagnetization was therefore systematically applied to all specimens, heating at 30-40 °C steps.
129 Bulk susceptibility checked after each step showed that no major changes occurred due to heating.
130 Analysis of the results at the site level shows that the attitude of the great circle varies from one
131 specimen to another (Fig. 5) and the great circles intersection yields a statistically significant mean
132 direction ($D = 4.4^\circ$, $I = 53.9^\circ$, Fisher (1954) precision $k = 145$, $\alpha_{95} = 3.8^\circ$). This means that in each
133 individual specimen a high-T component with variable direction occurs together with a low-T
134 component whose direction is the same in all specimens. This interpretation is further substantiated
135 by the results from site VBT15, where the two components could be separated (Fig. 6) in six

136 specimens. The high-T directions are dispersed, yet they fall along a great circle that crosses the
137 95% ellipse of confidence of the site mean value ($D = 343.4^\circ$, $I = 57.2^\circ$, $k = 147$, $\alpha_{95} = 5.5^\circ$) of the
138 well-grouped low-T directions. This direction, as well as the low-T directions from the other sites
139 (Table 1), is close to the geocentric axial dipole (GAD) value for the Aeolian Islands ($D = 0^\circ$, $I =$
140 59°) and fully consistent with the paleosecular variation changes around it (Zanella, 1995; Lanza
141 and Zanella, 2003).

142 Joint examination of the AMS and TRM results shows that the maximum anisotropy axis, K_1 ,
143 of a specimen falls on, or close to, its remagnetization great circle and the remanence direction
144 measured after each step moves toward K_1 as heating proceeds (Fig. 7). We conclude that the K_1
145 axis of the magnetic fabric biases the direction of the high-T remanence component. This is also
146 clear at the site level. Here, the intersection of the specimens' great circles yields a well defined
147 common direction whereas their dispersion mimics that of the K_1 axes (Fig. 5).

148 Finally, in the few cases lithic clasts large enough to be measured are embedded in the Brown
149 Tuffs deposits, as at site VBT15 (Fig. 1), the T_{dep} value has been estimated according to the
150 procedure by Cioni et al. (2004). Comparison of thermal demagnetization diagrams (Fig. 8) shows
151 that the reheating ranges of the lithic clasts carried by the PDC and the derived T_{dep} value are
152 consistent with the temperature threshold between the high-T and low-T components of fine-
153 grained tuff. That means that, at the moment of deposition, the decreasing temperature of the
154 cooling ash and the increasing temperature of the warming lithic clasts were similar and
155 corresponded to the deposition temperature. The T_{dep} value falls in the range 320-360 °C at site
156 VBT15, and varies from 280 °C to 360 °C at the other sites.

157

158 **Discussion and conclusions**

159 The NRM of the Brown Tuffs deposits is carried by primary Ti-magnetite grains and can be
160 regarded as primary in origin because there is no evidence for secondary chemical or thermal
161 processes in the rock. This remanence, however, consists of two components with different
162 directions. The difference cannot result from mechanical deformation due to the load of the
163 overlying deposits because it would have affected the grains carrying both components. Moreover,
164 the thickness of individual Brown Tuffs levels is small (up to a few meters maximum) and the two
165 components occur irrespective of the deposits age, both in the young Upper Brown Tuffs (< 20-22
166 ka) with little or no overburden as well as in the older Intermediate Brown Tuffs (> 20-22 ka),
167 which in some sections are overlain by the thick pyroclastic deposits of the Monte Guardia
168 sequence.

169 We are thus confronted with the problem of two magnetizations acquired at the same
170 (geological) time along two distinct directions. Thermal demagnetization shows that the T_b spectra
171 of the two magnetizations are different, even if overlapping, and the direction of the high-T
172 magnetization is deflected toward the AMS maximum axis, K_1 . All these results concur to model
173 the NRM acquisition process. The hot grains started to cool down within the explosive cloud and
174 the moving pyroclastic current and, in the absence of external constraints, the high- T_b grains
175 acquired a remanence along the easy magnetization long axis. This process continued until the
176 suspended ash in the flow deposited and the shear exerted by the overlying part aligned the long
177 axes of the grains to the flow direction. The coherent orientation of the grains resulted in the
178 preferential direction of both the rock's fabric and high- T_b remanence. During the eventual cooling
179 below the deposition temperature T_{dep} , the low- T_b grains acquired a remanence along the direction
180 of the Earth's magnetic field. Rock's NRM consists of two components with different origin. An
181 independent evidence of the T_{dep} value is given by the reheating temperatures of the embedded
182 lithic clasts, when available.

183 According to the model, the high- T_b magnetization component ($T_b > T_{dep}$) of the Brown Tuffs
184 ash deposits is mainly controlled by the depositional dynamics and thus detrital (DRM) in origin,
185 whereas the low- T_b component ($T_b < T_{dep}$) is thermal (TRM), as usual in cooling deposits. The
186 importance of deposition temperature in the magnetic remanence acquisition of pyroclastic rocks
187 was first stressed by Aramaki and Akimoto (1957). Their simple model was based on the
188 consistency of the remanence directions of lithic fragments contained in the deposit: deposition has
189 occurred beyond the Curie point if the directions are uniform, below if they are random. The present
190 model takes into account the T_b spectrum of the fine-grained matrix and thus allows a closer
191 definition of the relation between rock emplacement and remanence acquisition.

192 Two main conclusions come from the Brown Tuffs test case:

- 193 1) paleomagnetic investigation of fine-grained pyroclastic rocks should always be preceded by
194 AMS measurements, in order to assess the possible effects the magnetic fabric has exerted on the
195 NRM;
- 196 2) the usual standard to regard the more stable NRM component as the ChRM, i.e. as the
197 characteristic magnetization carrying the direction of the paleofield, could fail when the deposition
198 temperature T_{dep} falls within the T_b spectrum of the rock. In this case, the paleomagnetic
199 information is carried by the component acquired below T_{dep} , whereas the component acquired at
200 higher temperature is related to the emplacement processes.

201

202 **Acknowledgements**

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207

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247

248 **Figure captions**

249

250 **Fig. 1** Geological sketch map of Lipari and Vulcano, Aeolian Islands (courtesy F. Lucchi).

251 Acronyms: UBT / IBT / LBT = Upper / Intermediate / Lower Brown Tuffs. Symbols: square = fine-
252 grained tuff sampling site; dot = fine grained tuff + lithic clasts sampling site.

253

254 **Fig. 2** Magnetic fabric of the Brown Tuffs: equal-area projection of the principal susceptibility axes.

255 Symbols: square = maximum axis, K_1 ; triangle = intermediate axis, K_2 ; dot = minimum axis, K_3 ;
256 large symbol: site mean value (Jelinek 1977) with 95% ellipse of confidence; great circle =
257 magnetic foliation.

258

259 **Fig. 3** Equal-area projection of principal susceptibility (a) and isothermal remanence (b) axes at site

260 LBT5. Symbols: square = maximum axis (K_1, I_1); triangle = intermediate axis (K_2, I_2); dot =
261 minimum axis (K_3, I_3); large symbol: site mean value with 95% ellipse of confidence.

262

263 **Fig. 4** Stepwise thermal (a, b, c) and AF (d) demagnetization. Left: normalized intensity decay

264 curve. Middle: Zijderveld diagram; symbols: full/open dot = declination/apparent inclination. Right:
265 equal-area projection; symbols: full/open dot = positive/negative inclination.

266

267 **Fig. 5** Equal-area projection of thermal demagnetization results and magnetic lineation at site

268 LBT5. Symbols: great circle = remagnetization circle (Halls 1978); star = site mean value with 95%
269 ellipse confidence; square = magnetic lineation. Figures refer to individual specimens.

270

271 **Fig. 6** Equal-area projection of thermal demagnetization results at site VBT15.

272 Symbols: dots + great circle = high-T directions + best fitting plane (McFadden and McElhinny
273 1988); square = site mean low-T direction with 95% ellipse of confidence.

274

275 **Fig. 7** Equal-area projection of remanence direction during stepwise thermal demagnetization and

276 magnetic lineation. Symbols: dot = remanence direction; square = magnetic lineation, k_1 ; full/open
277 symbol = positive/negative inclination. The arrow points towards increasing temperature values.

278

279 **Fig. 8** Deposition temperature of Brown Tuffs deposits at site VBT15. Thermal demagnetization of
280 a fine-grained tuff (a) and an embedded lithic clast (b); symbols as in Fig. 4. Determination of T_{dep} :

281 horizontal bar = reheating range; stippled area = overlapping of ranges of individual clasts (see
282 Cioni et al., 2004, for further explanation).

283

284 **Table caption**

285

286 **Table 1** Site mean susceptibility and remanence data. Columns: n = number of specimens; K_m =
287 bulk susceptibility; P = degree of anisotropy; K_1 , K_3 = maximum, minimum susceptibility axes: D =
288 declination, I = inclination, E_{1-2} , E_{1-3} = K_1 95% confidence angles, E_{3-2} , E_{3-1} = K_3 95% confidence
289 angles; J_r = NRM intensity; Low-T component: D = declination, I = inclination, k = Fisher's (1954)
290 precision, α_{95} = 95% semi-angle of confidence.

291

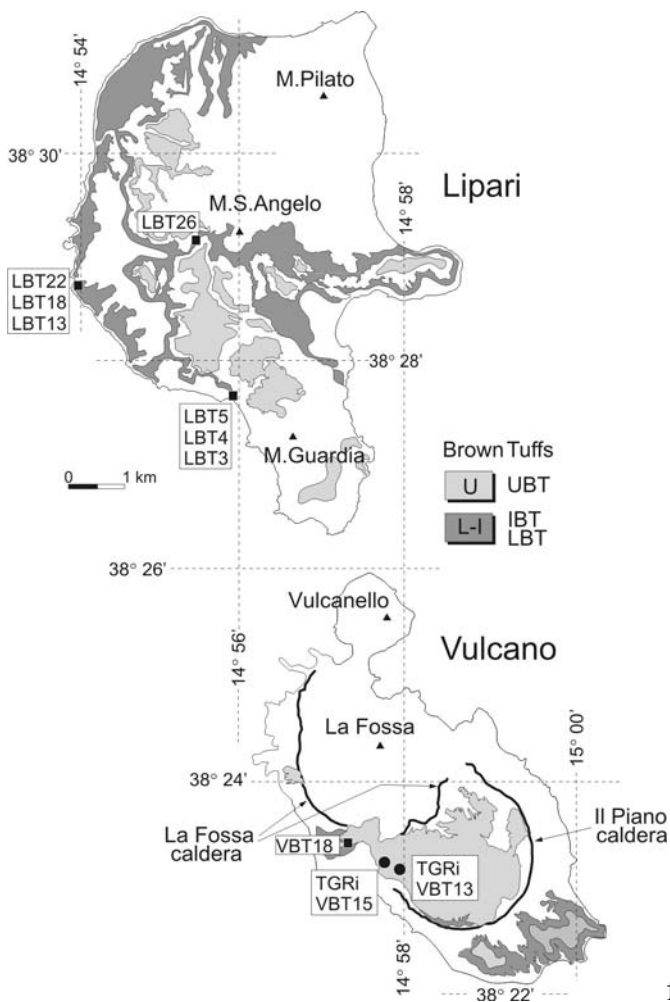
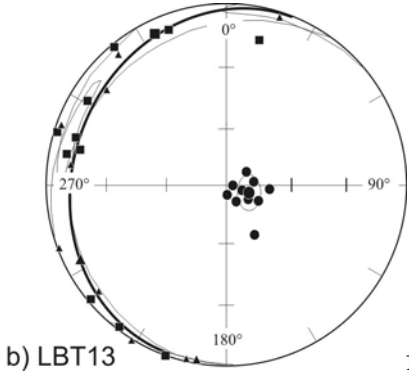
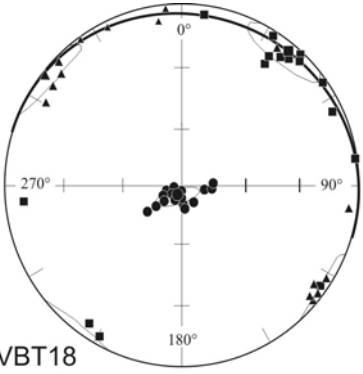


fig.1

292

293

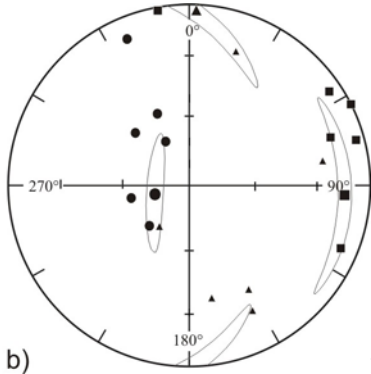
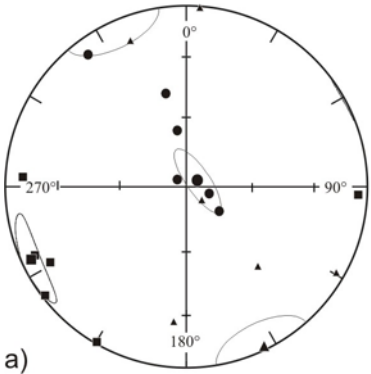


294
295

a) VBT18

b) LBT13

fig.2



296
297

a)

b)

fig.3

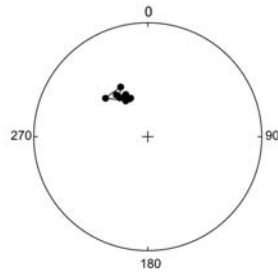
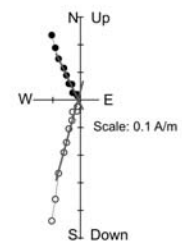
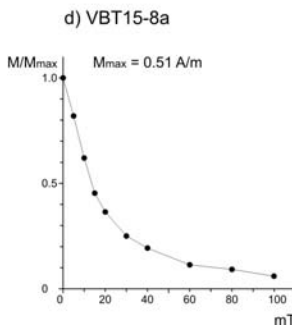
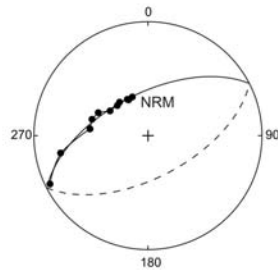
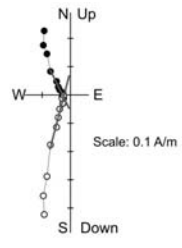
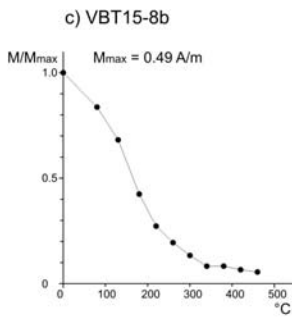
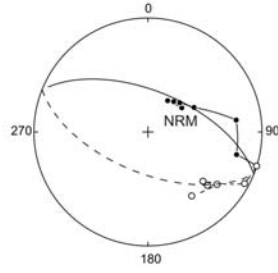
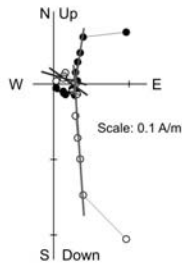
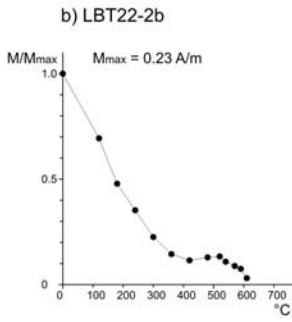
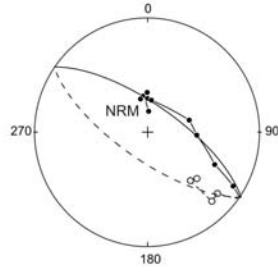
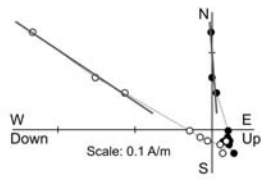
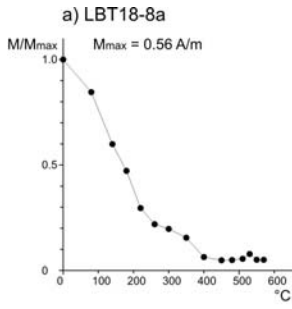
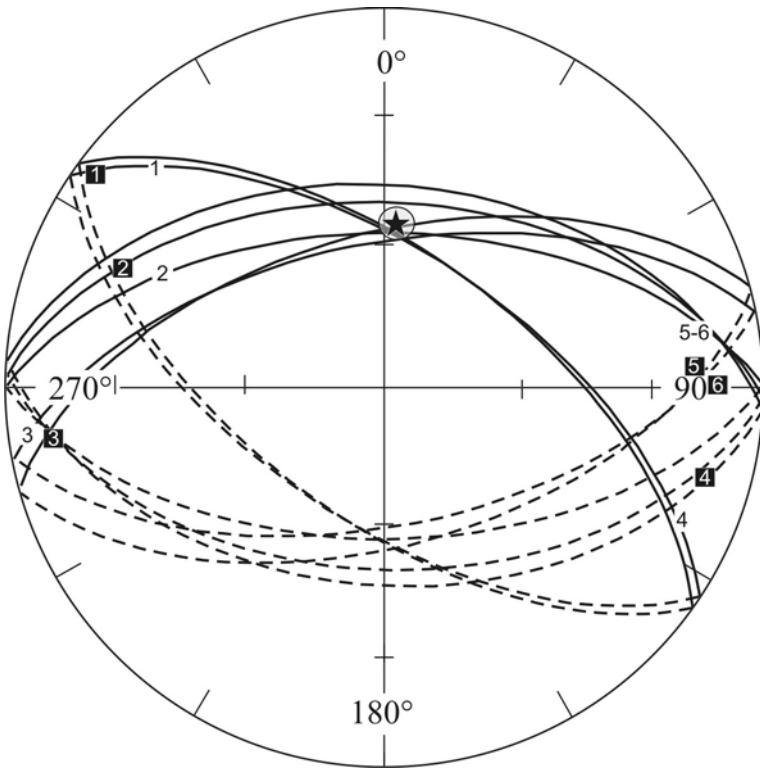


fig.4

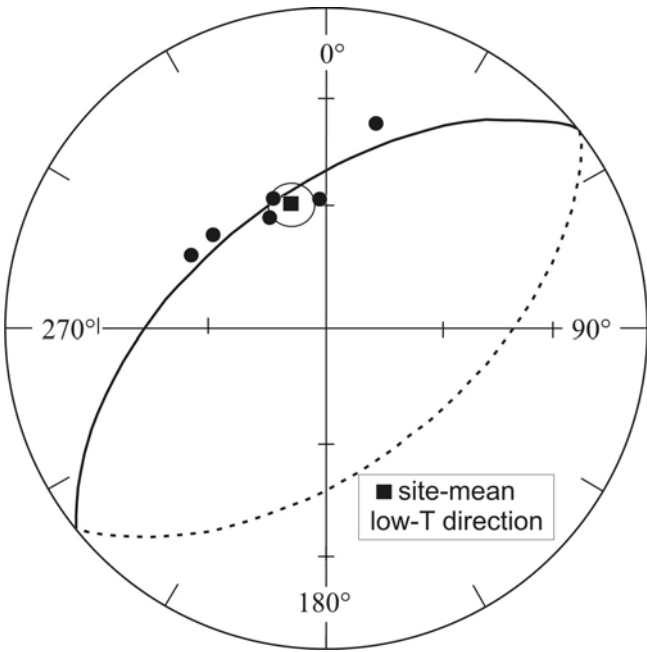
298

299



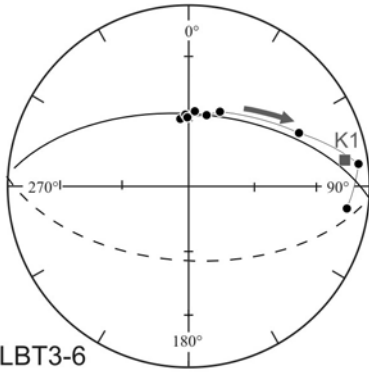
300
301

fig.5

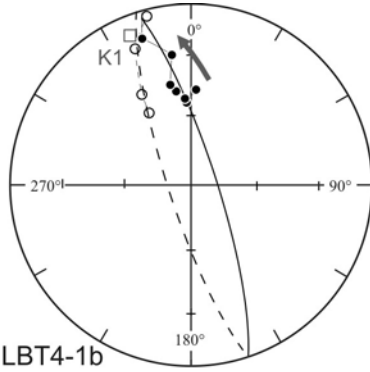


302
303

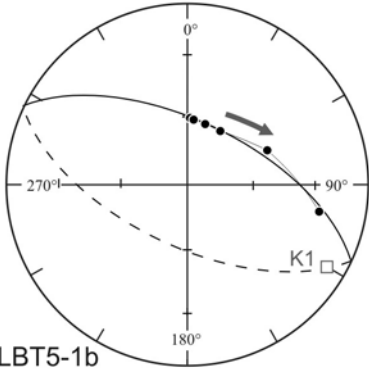
fig.6



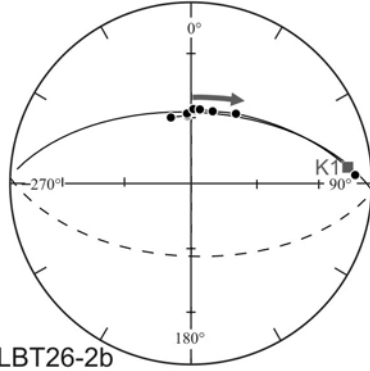
a) LBT3-6



b) LBT4-1b



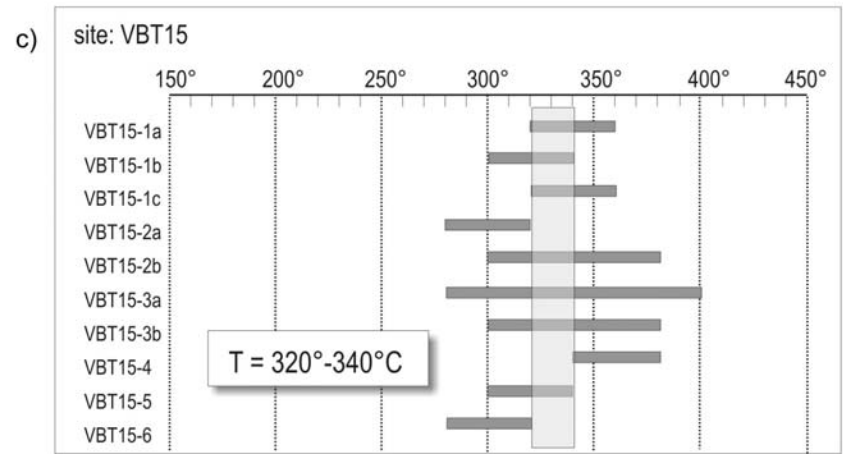
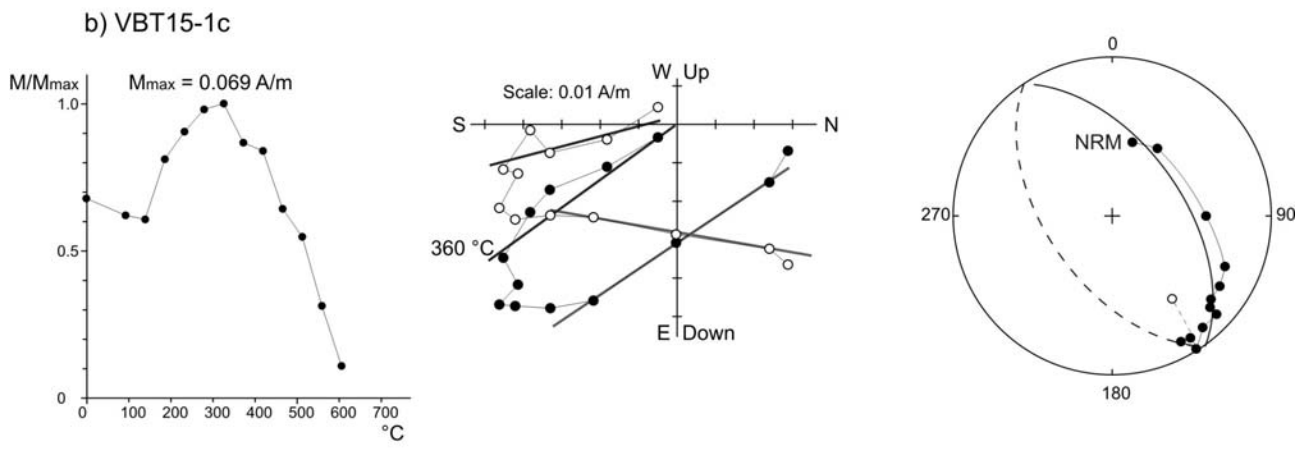
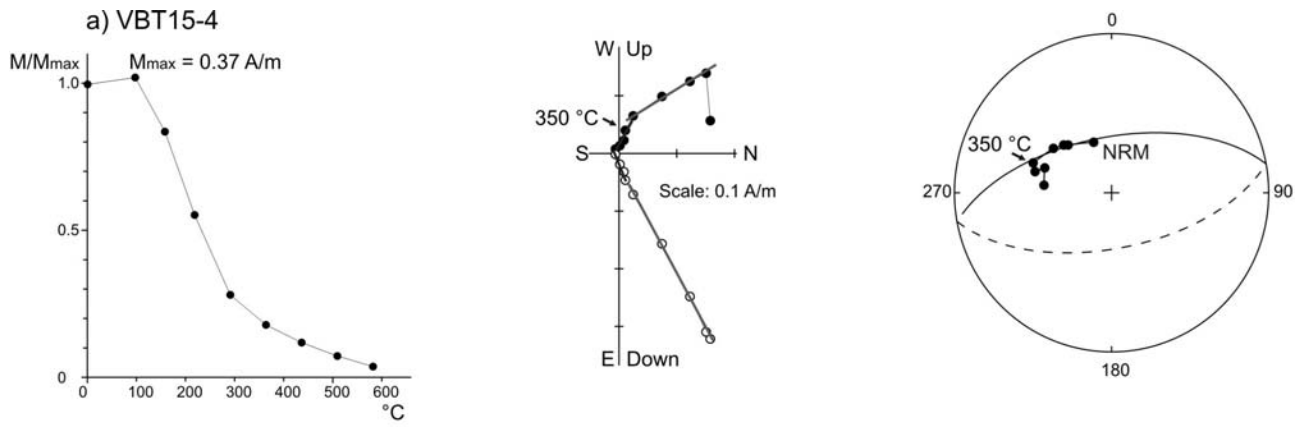
c) LBT5-1b



d) LBT26-2b

fig.7

304
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306
 307 Fig.8
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Level	n	K _m (μ SI)	P	K ₁				K ₃				n	Jr A/m	Low-T component			
				D	I	E ₁₋₂	E ₁₋₃	D	I	E ₃₋₂	E ₃₋₁			D	I	k	α_{95}
LBT3	11	15180	1.010	227	53	15.5	13.9	119	13	54.6	15.0	11	0.73	6.8	52.6	162	3.8
LBT4	11	17100	1.011	89	12	11.0	5.2	230	74	7.0	5.2	14	0.81	353.8	48.3	59	5.3
LBT5	10	16620	1.013	112	1	27.7	16.1	335	89	24.5	12.5	12	0.98	4.4	53.9	145	3.8
LBT13	10	13550	1.003	334	7	66.3	7.0	109	80	7.6	5.4	8	0.52	14.1	36.0	68	7.2
LBT18	13	19240	1.002	144	16	40.9	31.1	313	74	60.5	30.4	13	0.66	3.2	51.3	134	3.7
LBT22	9	15050	1.007	350	10	53.0	10.2	125	76	18.1	4.1	9	0.66	11.3	57.6	168	4.1
LBT26	20	18270	1.018	115	8	36.0	6.4	328	81	22.6	6.9	19	0.49	357.0	56.8	288	2.0
VBT13	9	13240	1.020	246	29	44.7	28.4	94	58	33.9	58.4	7	0.18	346.2	69.0	105	6.9
VBT15	16	12720	1.003	136	23	53.0	19.6	287	64	22.1	19.8	10	0.36	333.3	56.4	140	4.1
VBT18	16	11720	1.043	38	5	15.2	8.9	197	85	10.4	2.9	7	0.14	328.7	64.4	238	4.1

315 Table1