

1 Anisotropic magnetite growth in remagnetized limestones:  
2 Tectonic constraints and implications for basin history

3 **Pablo Calvín<sup>1</sup>, Juan J. Villalaín<sup>1</sup>, and Antonio M. Casas-Sainz<sup>2</sup>**

4 <sup>1</sup>*Laboratorio de Paleomagnetismo, Universidad de Burgos, Av/ Cantabria s/n, 9006*  
5 *Burgos, Spain*

6 <sup>2</sup>*Geotransfer Research Group (IUCA), Universidad de Zaragoza, C/ Pedro Cerbuna 12,*  
7 *50009 Zaragoza, Spain*

8 **ABSTRACT**

9 Magnetic properties of sedimentary rocks have been commonly exploited to  
10 determine the tectonic and chemical evolution of sedimentary basins. We here propose  
11 the use of the anisotropy of the anhysteretic remanent magnetization (ARM) to infer the  
12 orientation of magnetite grains formed during remagnetization stages, and hence to obtain  
13 the tectonic regime during the magnetization period, whose age can also be constrained  
14 by paleomagnetic methods. The anisotropy of ARM technique is here applied to  
15 remagnetized Jurassic limestones from the Central High Atlas (North Africa). These  
16 rocks were remagnetized during the Cretaceous Normal Superchron (121–83 Ma) in an  
17 extensional tectonic setting. The magnetic fabric carried by authigenic magnetite (which  
18 is also the carrier of the remagnetization) shows a consistent orientation after a partial  
19 bedding correction, which precisely corresponds with the attitude of strata at the time of  
20 remagnetization. The anisotropy of the ARM tensor shows a well-defined horizontal  
21 lineation parallel to the Mesozoic regional extension, and a horizontal magnetic foliation  
22 perpendicular to the lithostatic maximum stress axis. Therefore, our results demonstrate

23 that (1) the magnetite grain growth was consistent with the stress conditions and did not  
24 follow any preexisting fabric of the rock, and (2) these grains did not rotate during the  
25 subsequent compressional events.

## 26 INTRODUCTION

27 Magnetic methods commonly applied in basin analysis include the analysis of the  
28 anisotropy of magnetic susceptibility (AMS) that results from the contribution of ferro-,  
29 para-, and dia-magnetic minerals (see García-Lasanta et al., 2014, and references therein)  
30 and more specific methods (Hirt and Almqvist, 2012; see below) that are able to isolate  
31 the ferromagnetic contribution to the magnetic fabric of the sedimentary rock.

32 Particularly, analysis of the anisotropy of remanent magnetization is a tool to infer the  
33 orientation of ferromagnetic (*sensu lato*, s.l.) grains. Previous studies (McCabe et al.,  
34 1985; Jackson et al., 1989; Jackson, 1990) have used the anisotropy of the anhysteretic  
35 remanent magnetization (ARM) to understand the behavior of neoformed magnetite  
36 under compressional tectonic regimes; specifically, its applicability for estimating strain  
37 in weakly deformed rocks. **Because** remagnetization processes can be linked to magnetite  
38 neoformation, whose age and relationship with geometrical features within sedimentary  
39 basins can be controlled (pre-, syn- or post-folding), the fabric defined by these crystals  
40 can provide information about basin history. However, in the described example (the  
41 Appalachian Mountains **of the United States**; e.g., Jackson, 1990), remagnetization and  
42 compression occurred simultaneously, and therefore it remains unclear whether the  
43 compressional magnetic fabric carried by magnetite is due to (1) growth of the magnetic  
44 grains according to the tectonic strain field or, alternatively, (2) compressional  
45 modification of an initially isotropic fabric (Sun et al., 1993).

46 The Central High Atlas chain (North Africa; Fig. 1) shows a distinct and well-  
47 defined temporal relationship between remagnetization and tectonics, which can help to  
48 clarify the tectonic significance of anisotropy of the ARM. Its regional geological history  
49 is summarized as follows. During the Triassic and the Jurassic, a thick sedimentary  
50 sequence was deposited under a northwest-southeast extensional tectonic regime (e.g.,  
51 Ait-Brahim et al., 2002). Jurassic sedimentation produced a thick sedimentary pile (>5  
52 km in the depocenters) composed almost entirely of carbonates, which was subsequently  
53 deformed by extensional and halokinetic processes during the Jurassic (e.g., Ettaki et al.,  
54 2007). During the Cretaceous, these rocks were affected by a widespread interfolding  
55 remagnetization carried by magnetite, dated to ca. 100 Ma by comparison with the global  
56 apparent polar wander path (Torres-López et al., 2014). Using this remagnetization, it is  
57 possible to restore the attitude of the beds (for each paleomagnetic site) at the moment of  
58 remagnetization (e.g., Calvín et al., 2017); in other words, we can determine the paleodip  
59 of the bedding during the precompressional stage (Fig. 2). Note that the interfolding  
60 behavior of this remagnetization means that it is temporally bracketed between two  
61 different folding stages (Jurassic extension and Cenozoic compression). After the  
62 extensional stage and remagnetization event, the basin was inverted during the Cenozoic  
63 (Mattauer et al., 1977). Compression was accompanied by the development of an ESE-  
64 WNW-trending pressure-solution cleavage associated both with layer-parallel shortening  
65 and flattening derived from folding (Calvín et al., 2017). In this setting, we analyze the  
66 magnetic fabric of the magnetite that carries the ca. 100 Ma remagnetization by means of  
67 the ARM anisotropy. By comparing the ARM magnetic ellipsoid before bedding  
68 correction, after partial bedding correction (i.e., restoring to the paleodip at the

69 remagnetization time), and after total bedding correction, we infer the controls on the  
70 growth of magnetite grains and the effects of the subsequent cleavage development on  
71 their magnetic fabrics.

## 72 **METHODS**

73 The anisotropy of the ARM was measured in 62 standard paleomagnetic  
74 specimens of Jurassic limestones from 13 different sites **in the Atlas Mountains of**  
75 **Morocco** (4–5 specimens per site) **(see Table DR1 in the GSA Data Repository<sup>1</sup>)**. The  
76 measurement procedure of the ARM tensor was performed according to **the method of**  
77 **McCabe et al. (1985)**, using a direct field of 0.05 mT coupled with a coaxial alternating  
78 field with a peak of 90 mT. After each ARM step, the specimens were demagnetized in a  
79 peak alternating field of 100 mT, and this measurement was used as a baseline for each  
80 position to remove the contribution of grains with coercivities over 100 mT. This process  
81 was performed at the University of Burgos **(Spain)** using a 2G 755 cryogenic  
82 magnetometer with integrated direct- and alternating-field coils. The symmetric second-  
83 rank tensor that defines the ARM ellipsoid was calculated with the least squares method  
84 from the nine measured positions, according to Girdler's (1961) procedure.

85 Twin specimens from the 13 analyzed sites were previously demagnetized and  
86 paleomagnetically analyzed (Calvín et al., 2017). Using the Small Circle methods (Fig.  
87 DR1 in the Data Repository), **we** calculated the remagnetization direction (**declination,**  
88 **D: 330.9°; inclination, I: 35.1°**) and the paleodips of the beds at the remagnetization time.  
89 Present-day dips and paleodips vary between 14°–64° and 5°–49°, respectively (Table  
90 DR1). These data were used to restore the ARM principal axes. After both restorations of  
91 the ARM tensor (i.e., according to the dip and the paleodip of the bedding), we obtained a

92 fresh view of the principal axes (1) in their present-day position, (2) after total bedding  
93 correction, i.e., in stratigraphic coordinates, and (3) after partial bedding correction,  
94 which represents the orientation of the ARM ellipsoid after restoring bedding geometry to  
95 the remagnetization time (Fig. 3).

## 96 **RESULTS**

97 Rock magnetic experiments (Figs. DR2 and DR3) point to stable single-domain  
98 (SSD) magnetite as the carrier of the remagnetization, which covers the coercivity spectra  
99 (0–90 mT) used in the ARM acquisition (Fig. DR3b). Negligible differences between the  
100 magnetization applied along both the  $z$  and  $-z$  axis directions (Fig. DR3f; Mitra et al.,  
101 2011) are indicative of uniaxial particles.

102 The directional data of the ARM tensor (Fig. 3) show different degrees of  
103 clustering in the different coordinate systems, with significantly better clustering after  
104 applying the partial bedding correction. The maximum ellipsoid axes tend to be  
105 horizontal with a NNW-SSE trend, and the minimum axes are nearly vertical and  
106 contained within an ENE-WSW vertical plane. Dispersion of both the minimum and the  
107 maximum axes before and after total bedding correction occurs within a NNW-SSE  
108 vertical plane, perpendicular to the average bedding strike. Directional data show a well-  
109 defined cluster of maximum axes and a girdle between the minimum and intermediate  
110 axes. However, it is possible to statistically define a horizontal magnetic foliation (with a  
111 vertical minimum axis). At specimen level, the shape parameter  $T$  (Table DR2) shows a  
112 dominance of negatives values (mean:  $-0.17$ ). The anisotropy degree defined by the  $P_j$   
113 parameter [[Define this parameter]] presents low values, i.e., between 1.02 and 1.07 for

114 most samples (mean:  $1.04 \pm 0.02$ ), very similar to other remagnetized limestones (e.g.,  
115 McCabe et al., 1985; Jackson, 1990; Lu and McCabe, 1993).

## 116 **DISCUSSION**

117 The rock magnetic and paleomagnetic analyses indicate that the ARM is carried  
118 by uni-axial SSD magnetite grains, also responsible for the remagnetization. The  
119 directional data from the ARM ellipsoid show the best clustering after applying the  
120 partial bedding corrections. Therefore, a clear link exists between the structure at the  
121 remagnetization time and the magnetic fabric defined by the carriers of the  
122 remagnetization. In addition, the ferromagnetic fabric can be interpreted to have formed  
123 under an extensional tectonic regime because a well-defined cluster of the maximum axes  
124 is in a horizontal position aligned with the NW-SE to NNW-SSE extension dominant  
125 during the Mesozoic (e.g., Ait-Brahim et al., 2002), and the horizontal magnetic foliation  
126 is perpendicular to the lithostatic stress (the maximum stress axis in an extensional  
127 regime).

128 Three main conclusions can be inferred from these results. (1) The growth of  
129 magnetite grains was not conditioned by preexisting sedimentary or mineralogical  
130 structures, such as laminations. (2) Additionally, these grains did not grow **accordingly an**  
131 **[[missing word here?]]** isotropic fabric. Conversely, the magnetite grains grew  
132 following the extensional tectonic constraints present in the Atlas Mountains, producing a  
133 weak but well-defined magnetic fabric (Fig. 4A). (3) The post-remagnetization  
134 compression, which involved the development of pressure-solution cleavage, was not  
135 capable of modifying the orientation of the magnetite grains since no evidence of the

136 influence of north-south compression is present in the ARM ellipsoid (an east-west  
137 magnetic lineation, parallel to the intersection lineation, could be expected).

138         These points seem to be interrelated with the growth mechanism of the magnetite  
139 grains. Clay transformations and pyrite oxidation are the main possible remagnetization  
140 mechanisms in carbonates (see Elmore et al., 2012). If magnetite is related to clay  
141 transformations, authigenic grains are expected to follow preexisting structures defined  
142 by clays. Furthermore, magnetite grains should have been affected by compression since  
143 phyllosilicates are rotated according to cleavage formation (Calvín et al., 2017).  
144 However, pyrite oxidation imposes a completely different scenario. Pyrite crystals are  
145 isotropic and the grains themselves are not affected by preexisting sedimentary fabrics.  
146 Then, nanometric magnetite grains can grow within an isotropic space (inside the pyrite  
147 grains) being conditioned only by the infinitesimal strain (equivalent to the stress  
148 conditions) during their growth. Finally, during compression, pyrite grains are competent  
149 enough to deflect cleavage surfaces, and shield magnetite grains from the effects of  
150 compression.

151         These results are applicable to ARM anisotropy studies performed in the  
152 Appalachian Mountains of the United States, where remagnetization is related to  
153 compression (e.g., Jackson, 1990). Similar to this work, several studies on magnetic  
154 fabrics (McCabe et al., 1985, and references therein; Jackson et al., 1989; Sun et al.,  
155 1993) documented a ferromagnetic fabric whose maximum principal axis tends to be  
156 horizontal and perpendicular to the compression, and the minimum and intermediate axes  
157 are distributed in a girdle within the vertical plane that contains the compression  
158 direction. Sun et al. (1993) suggested that this ARM ellipsoid reflects either (1)

159 neoformation or growth of SSD magnetite during remagnetization according to layer-  
160 parallel compression, or (2) reorientation during compression of a previous isotropic  
161 fabric defined by SSD grains. In light of the results shown in this work, the growth of  
162 magnetic grains is more likely to directly mimic the compression (Fig. 4B),  
163 corresponding to the first hypothesis. Thus, the ARM magnetic ellipsoid can be  
164 considered a primary fabric because it is fixed during the growth of the grains.

165 In summary, the ARM anisotropy is capable of recording the stress conditions in  
166 limestones (even under weak deformation) during the growth of the remagnetization  
167 carriers (Fig. 4). When remagnetization occurs in an extensional setting (Fig. 4A), the  
168 maximum principal axis of the ARM tensor tends to be parallel to the minimum  
169 (horizontal) stress, whereas the minimum principal axis tends to parallelize the maximum  
170 (vertical) stress. On the other hand, when remagnetization occurs under compression, the  
171 maximum horizontal axis is horizontal and perpendicular to the compression direction  
172 (i.e., parallel to the intersection lineation), and minimum and intermediate axes lie in a  
173 vertical plane parallel to compression (Fig. 4B).

174 This arrangement results from the interaction between the lithostatic pressure and  
175 the horizontal compression. **[[Move this sentence to the end of the previous  
176 paragraph?]]**

177 This novel approach for working with magnetic fabrics can be extended to other  
178 sedimentary basins. Classically, the (para-)magnetic fabric carried by phyllosilicates is  
179 used to infer the tectonic evolution of sedimentary basins (e.g., Cifelli et al., 2004;  
180 García-Lasanta et al., 2014, and references therein) because the phyllosilicates are  
181 aligned with the stretching direction during early diagenesis. Several of these basins are

182 affected by widespread remagnetizations (e.g., García-Lasanta et al., 2014), and therefore  
183 the evolutionary knowledge of the basins can be complemented with the application of  
184 the anisotropy of the ARM and its restoration to the remagnetization time.

## 185 CONCLUSIONS

186 Rock magnetism experiments carried out in chemically remagnetized limestones  
187 of the Central High Atlas (North Africa) show that the remanence is mainly carried by  
188 uni-axial SSD magnetite grains. The anisotropy of the ARM can be interpreted as an  
189 extensional fabric, and the best clustering of the magnetic axes is observed after partial  
190 restoration of bedding (to its position at the remagnetization acquisition time). Therefore,  
191 the magnetic fabric was developed during growth of the magnetite grains without  
192 following a preexisting fabric, and was not modified during subsequent compression and  
193 cleavage development. The anisotropy degree is low, but a defined fabric reflects the  
194 stress conditions during growth of magnetic grains. When a remagnetization occurs in an  
195 extensional tectonic context, the maximum magnetic axis is horizontal and parallel to the  
196 stretching direction, whereas the minimum axis is vertical and controlled by lithostatic  
197 pressure. The fact that the magnetic fabric does not follow preexisting fabrics and is not  
198 affected by subsequent compression can be explained if magnetite grains grew inside  
199 bigger, undeformed pyrite grains: magnetite grew in an isotropic framework, and besides  
200 magnetite grains were protected from compression by the pyrite grains. A comparison of  
201 our results with those of studies on limestones that were remagnetized in compressional  
202 settings seems to indicate that, in this context, the growth of the authigenic grains is also  
203 constrained by tectonics: the maximum axis of the magnetic ellipsoid is parallel to the

204 bedding-cleavage intersection lineation, and the minimum axis is contained within a  
205 vertical plane with a strike that is parallel to the compression direction.

## 206 **ACKNOWLEDGMENTS**

207 ARM tensors were calculated with an MSEXcel spreadsheet developed by Mike  
208 Jackson ([Institute for Rock Magnetism, University of Minnesota, USA](#)). This study was  
209 supported by the MINECO (Spanish Ministry of Economy and Competitiveness),  
210 together with ERDF funding ([European Regional Development Fund](#), European Union)  
211 (research projects CGL2012–38481 and CGL2016–77560). Calvin also acknowledges  
212 the MINECO (F.P.I. research grant BES-2013–062988) and the Institute for Rock  
213 Magnetism (University of Minnesota, USA) for the use of the IRM laboratory. Mike  
214 Jackson, Bjarne Almqvist, and an anonymous reviewer are thanked for their constructive  
215 comments that help to improve the manuscript.

## 216 **REFERENCES CITED**

- 217 Ait-Brahim, L., et al., 2002, Paleostress evolution in the Moroccan African margin from  
218 Triassic to Present: Tectonophysics, v. 357, p. 187–205,  
219 [https://doi.org/10.1016/S0040-1951\(02\)00368-2](https://doi.org/10.1016/S0040-1951(02)00368-2).
- 220 Calvín, P., Casas-Sainz, A.M., Villalaín, J.J., and Moussaid, B., 2017, Diachronous  
221 folding and cleavage in an intraplate setting (Central High Atlas, Morocco)  
222 determined through the study of remagnetizations: Journal of Structural Geology,  
223 v. 97, p. 144–160, <https://doi.org/10.1016/j.jsg.2017.02.009>.
- 224 Cifelli, F., Mattei, M., Hirt, A.M., and Günther, A., 2004, The origin of tectonic fabrics in  
225 “undeformed” clays: The early stages of deformation in extensional sedimentary

- 226 basins: *Geophysical Research Letters*, v. 31, L09604,  
227 <https://doi.org/10.1029/2004GL019609>.
- 228 Elmore, R.D., Muxworthy, A.R., and Aldana, M., 2012, Remagnetization and chemical  
229 alteration of sedimentary rocks, *in* Elmore, R.D., et al., eds., *Remagnetization and*  
230 *Chemical Alteration of Sedimentary Rocks: Geological Society of London Special*  
231 *Publications*, v. 371, p. 1–21, <https://doi.org/10.1144/SP371.15>.
- 232 Ettaki, M., Ibouh, H., Chellaï, E.H., and Milhi, A., 2007, Les structures “diapiriques”  
233 liasiques du Haut-Atlas central, Maroc: Exemple de la ride d’Ikerzi: *Africa*  
234 *Geoscience Review*, v. 14, p. 79–93.
- 235 García-Lasanta, C., Oliva-Urcia, B., Román-Berdiel, T., Casas, A.M., and Hirt, A.M.,  
236 2014, Understanding the Mesozoic kinematic evolution in the Cameros basin  
237 (Iberian Range, NE Spain) from magnetic subfabrics and mesostructures: *Journal of*  
238 *Structural Geology*, v. 66, p. 84–101, <https://doi.org/10.1016/j.jsg.2014.05.013>.
- 239 Girdler, R.W., 1961, The measurement and computation of anisotropy of magnetic  
240 susceptibility of rocks: *Geophysical Journal International*, v. 5, p. 34–44,  
241 <https://doi.org/10.1111/j.1365-246X.1961.tb02927.x>.
- 242 Hext, G.R., 1963, The estimation of second-order tensors, with related tests and designs:  
243 *Biometrika*, v. 50, p. 353–373, <https://doi.org/10.1093/biomet/50.3-4.353>.
- 244 Hirt, A.M., and Almqvist, B.S.G., 2012, Unraveling magnetic fabrics: *International*  
245 *Journal of Earth Sciences*, v. 101, p. 613–624, [https://doi.org/10.1007/s00531-011-](https://doi.org/10.1007/s00531-011-0664-0)  
246 [0664-0](https://doi.org/10.1007/s00531-011-0664-0).
- 247 Jackson, M., 1990, Magnetic anisotropy of the Trenton limestone revisited: *Geophysical*  
248 *Research Letters*, v. 17, p. 1121–1124, <https://doi.org/10.1029/GL017i008p01121>.

- 249 Jackson, M., Craddock, J.P., Ballard, M., Van Der Voo, R., and McCabe, C., 1989,  
250 Anhyseretic remanent magnetic anisotropy and calcite strains in Devonian  
251 carbonates from the Appalachian Plateau, New York: Tectonophysics, v. 161, p. 43–  
252 53, [https://doi.org/10.1016/0040-1951\(89\)90300-4](https://doi.org/10.1016/0040-1951(89)90300-4).
- 253 Lu, G., and McCabe, C., 1993, Magnetic fabric determined from ARM and IRM  
254 anisotropies in Paleozoic carbonates, Southern Appalachian Basin: Geophysical  
255 Research Letters, v. 20, p. 1099–1102, <https://doi.org/10.1029/93GL00986>.
- 256 Mattauer, M., Tapponnier, P., and Proust, F., 1977, Sur les mecanismes de formation des  
257 chaines intracontinentales; l'Exemple des chaines atlasiques du Maroc: Bulletin de la  
258 Societe Geologique de France, v. S7, XIX, p. 521–526, doi:10.2113/gssgfbull.S7-  
259 XIX.3.521.
- 260 McCabe, C., Jackson, M., and Ellwood, B.B., 1985, Magnetic anisotropy in the Trenton  
261 Limestone: Results of a new technique, anisotropy of anhysteretic susceptibility:  
262 Geophysical Research Letters, v. 12, p. 333–336,  
263 <https://doi.org/10.1029/GL012i006p00333>.
- 264 Mitra, R., Tauxe, L., and Gee, J.S., 2011, Detecting uniaxial single domain grains with a  
265 modified IRM technique: Geophysical Journal International, v. 187, p. 1250–1258,  
266 <https://doi.org/10.1111/j.1365-246X.2011.05224.x>.
- 267 Sun, W., Jackson, M., and Craddock, J.P., 1993, Relationship between remagnetization,  
268 magnetic fabric and deformation in Paleozoic carbonates: Tectonophysics, v. 221,  
269 p. 361–366, [https://doi.org/10.1016/0040-1951\(93\)90167-I](https://doi.org/10.1016/0040-1951(93)90167-I).

270 Tauxe, L., and Watson, G.S., 1994, The fold test: An Eigen analysis approach: Earth and  
271 Planetary Science Letters, v. 122, p. 331–341, [https://doi.org/10.1016/0012-](https://doi.org/10.1016/0012-821X(94)90006-X)  
272 821X(94)90006-X.

273 Torres-López, S., Villalaín, J.J., Casas, A.M., El Ouardi, H., Moussaid, B., and Ruiz-  
274 Martínez, V.C., 2014, Widespread Cretaceous secondary magnetization in the High  
275 Atlas (Morocco): A common origin for the Cretaceous remagnetizations in the  
276 western Tethys?: Journal of the Geological Society, v. 171, p. 673–687,  
277 <https://doi.org/10.1144/jgs2013-107>.

## 278 **FIGURE CAPTIONS**

279 Figure 1. A: Location of the Central High Atlas in North Africa. B: Geological sketch  
280 showing the study area (highlighted by the box in A). C: Remagnetization in the context  
281 of the main tectonic events. **[[In figure, change “b” label of box in A to uppercase B]]**

282

283 Figure 2. A: Mean paleomagnetic directions of the 13 **study sites (from the Atlas**  
284 **Mountains of Morocco)** represented in an equal area projection (lower hemisphere), with  
285 different bedding corrections. B: Bootstrap fold-test (Tauxe and Watson, 1994) showing  
286 the synfolding behavior of the remagnetization. **[[Define  $\tau$ ]]**

287

288 Figure 3. A: Orientation of the principal axis of **anhysteretic remanent magnetization**  
289 (ARM) and Hext (1963) ellipses. B: Contour plots (interval 4% per 1% area) of the  
290 maximum and minimum axes. The results from 62 specimens (13 paleomagnetic sites **in**  
291 **the Atlas Mountains, Morocco)** are represented. The contour interval is 3%. The raw data

292 are shown in Table DR2 (see footnote 1). ATBC—after total bedding correction;  
293 APBC—after partial bedding correction; BBC—before bedding correction.

294

295 Figure 4. Model for the growth of magnetite in limestones during remagnetization events  
296 under (A) extensional and (B) compressional settings. Note that, independently of the  
297 bedding attitude, magnetite grains define a prolate ellipsoid with a horizontal maximum  
298 anisotropy axis ( $k_{\max}$ ) that is parallel to extension or perpendicular to compression in the  
299 different settings, and a girdle between the minimum ( $\min$ ) and intermediate ( $\text{int}$ ) axes.

300 **Atlasic—Atlas Mountains, Morocco; Appalachian—Appalachian Mountains, eastern**  
301 **USA.**

302

303 <sup>1</sup>GSA Data Repository item 2018xxx, **the Small Circle method and bedding restorations,**  
304 **rock magnetism of the remagnetized limestones,** and Tables DR1 and DR2 and Figures  
305 DR1–DR3, is available online at <http://www.geosociety.org/datarepository/2018/> or on  
306 request from [editing@geosociety.org](mailto:editing@geosociety.org).