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1 Rapid fore-arc extension and detachment-mode spreading

2 following subduction initiation

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- 16
- 17 ABSTRACT
- 18
- 19 Most ophiolites have geochemical signatures that indicate formation by
- 20 suprasubduction seafloor spreading above newly initiated subduction zones, and
- 21 hence they record fore-arc processes operating following subduction initiation. They
- 22 are frequently underlain by a metamorphic sole formed at the top of the downgoing
- 23 plate and accreted below the overlying suprasubduction zone lithosphere

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24 immediately following ophiolite formation. Paleomagnetic analyses of ophiolites can 25 provide important insights into the enigmatic geodynamic processes operating in this setting via identification of tectonic rotations related to upper plate extension. Here 26 27 we present net tectonic rotation results from the Late Cretaceous Mersin ophiolite of southern Turkey that document rapid and progressive rotation of ophiolitic rocks and 28 29 their associated metamorphic sole. Specifically, we demonstrate that lower crustal 30 cumulate rocks and early dykes intruded into the underlying mantle section have 31 undergone extreme rotation around ridge-parallel, shallowly-plunging axes, consistent with oceanic detachment faulting during spreading. Importantly, later 32 33 dykes cutting the metamorphic sole experienced rotation around the same axis but 34 with a lower magnitude. We show that these rotations occurred via a common 35 mechanism in a pre-obduction, fore-arc setting, and are best explained by combining 36 (hyper)extension resulting from detachment-mode, amagmatic suprasubduction zone 37 spreading in a fore-arc environment with a recently proposed mechanism for 38 exhumation of metamorphic soles driven by upper plate extension. Available age 39 constraints demonstrate that extreme rotation of these units was accommodated 40 rapidly by these processes over a time period of < -3 Myr, comparable with rates of 41 rotation seen in oceanic core complexes in the modern oceans.

42

Keywords: ophiolite; paleomagnetism; subduction initiation; suprasubduction zone;
fore-arc extension; metamorphic sole

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49 **1. Introduction**

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51 Ophiolites provide insights into fundamental oceanic tectonic processes associated 52 with their formation at spreading axes and subsequent intraoceanic- and emplacement-related deformation. The majority of the world's ophiolites have a 53 54 geochemical signature interpreted as indicating formation above newly initiated 55 intraoceanic subduction zones, in so-called suprasubduction zone environments (e.g. 56 Pearce and Robinson, 2010). This setting can also account for the observation that ophiolite accretion is often closely followed by subduction-related emplacement onto 57 58 continental margins (Robertson 2002). In contrast to true mid-ocean ridge systems, 59 suprasubduction zone ophiolite formation and subsequent evolution is the result of a 60 complex process controlled by both the subducting plate and tectonic processes in 61 the fore-arc region. This is clearly demonstrated by the occurrence of so-called 62 metamorphic soles below many suprasubduction zone ophiolites. Metamorphic soles 63 are thin (< 500 m) layers of granulite to greenschist facies rocks, which experienced 64 high temperature and pressure metamorphism (850-900°C, 10-15 kbar) above a subducting lithosphere, prior to their accretion to the overriding plate (for a review 65 66 see van Hinsbergen et al., 2015). In several well-preserved ophiolites like that of 67 Oman, the metamorphic sole is spread over a broad area below the ophiolite, up to c. 100 km away from the paleo-trench, suggesting original accretion as a large semi-68 69 continuous metamorphic layer. The accretion of metamorphic soles below ophiolites 70 necessarily requires some sort of fore-arc thinning to exhume the sole from peak 71 metamorphic depths, either tectonically via extension of the overriding plate (e.g. 72 Hacker and Gnos, 1997), or magmatically via partial melting and resulting volume 73 decrease of the forearc mantle wedge below the newly formed suprasubduction zone

crust (van Hinsbergen *et al.*, 2015). The similarity of ages of ophiolitic crust and peak
metamorphism of associated metamorphic soles observed in nearly all ophiolites
indicates that spreading and metamorphic sole exhumation are almost simultaneous
processes, and both occur during or shortly after subduction initiation.

78

79 Obtaining geological evidence that constrains the kinematics and timing of tectonic 80 processes affecting fore-arc systems during subduction initiation in the modern 81 oceans is difficult as incipient subduction zones are rare (Gurnis et al., 2004). Hence, well-exposed ophiolites provide important records of fore-arc processes operating 82 83 during and following subduction initiation that are otherwise difficult to investigate 84 (Stern and Bloomer, 1992; Robertson 2002). Numerous studies have highlighted how 85 paleomagnetic analyses of ophiolites can help to unravel the tectonic evolution of 86 these systems. A focus has been the Tethyan ophiolites of the eastern 87 Mediterreanean/Middle East region, where magnetic techniques have been used to 88 constrain the structure and orientation of suprasubduction spreading axes (e.g. 89 Allerton and Vine, 1987; Hurst et al., 1992; Morris and Maffione, 2016; Maffione et 90 al., 2017), patterns of magmatic flow during crustal accretion (e.g. Staudigel et al., 91 1992; Granot et al., 2011), the kinematics of transform fault systems (e.g. Morris et 92 al., 1990; MacLeod et al., 1990; Morris and Maffione, 2016), and the response of the 93 upper plate to impingement of continental margins with subduction zones (Clube et 94 al., 1985; Inwood et al., 2009; Morris et al., 2002).

95

Renewed interest in ophiolites has followed the discovery of the importance of
oceanic detachment faulting and the formation of oceanic core complexes (OCCs) in
slow-ultraslow spreading lithosphere in the Atlantic and Indian Oceans (e.g. Smith *et*

99 al., 2008; MacLeod et al., 2017) and the definition of a new amagmatic "detachment-100 mode" of seafloor spreading (Escartín and Canales 2011). This is fundamentally 101 different from classic magmatic spreading and involves plate divergence being taken 102 up by slip on lithospheric-scale faults that rotate during displacement, resulting in 103 exhumation of their footwall sections and exposure of lower crustal and mantle rocks 104 on the seafloor. Studies of samples recovered by scientific ocean drilling have shown 105 45-65° rolling-hinge rotations of OCC footwalls in the Atlantic Ocean around ridge-106 parallel, sub-horizontal axes (Garcés and Gee, 2007; Morris et al., 2009; MacLeod et 107 al., 2011). This characteristic has allowed Maffione et al. (2013) to extend the record 108 of detachment-mode spreading back to the Jurassic by demonstrating the existence 109 of a fossil OCC preserved within the Mirdita ophiolite of Albania. More recently, 110 Maffione et al. (2015) showed that oceanic detachment faulting was responsible for 111 large tectonic rotations and extensional thinning of fore-arc lithosphere preserved in 112 the Cretaceous ophiolites of southern Tibet. This led them to propose a new concept 113 of "fore-arc hyperextension", demonstrating how the exchange of ideas between 114 studies in the modern oceans and in ophiolites can lead to advances in our 115 understanding of lithospheric processes.

116

Here we present the first paleomagnetic data from the Late Cretaceous Mersin
ophiolite of southern Turkey. Like many Tauride ophiolites (Dilek *et al.*, 1999), Mersin
consists predominantly of tectonized mantle rocks and ultramafic/mafic cumulates,
with no sheeted dyke complex and only limited exposures of extrusive rocks, and is
underlain by a metamorphic sole that has ⁴⁰Ar-³⁹Ar cooling ages that are similar to
the age of the ophiolitic magmatic rocks (Parlak *et al.*, 2013; van Hinsbergen *et al.*,
2016). Our data constrain the axes, magnitudes and timing of tectonic rotations in

these units, and provide evidence for rapid fore-arc (hyper)extension via detachmentmode seafloor spreading (Escartin and Canales, 2011). We show that this style of
Neotethyan suprasubduction zone spreading provides a viable mechanism to explain
the exhumation of metamorphic soles, their structural disruption following welding to
the base of the lithosphere, and the lack of upper crustal sequences in many Tauride
ophiolites.

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131 **2. The Mersin ophiolite**

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The Mersin ophiolite complex outcrops over a 60 km long, 25 km wide area in
southern Turkey (Fig. 1a). It consists of an Upper Cretaceous ophiolite sequence,
underlain by metamorphic sole rocks and then by the Mersin Mélange (Fig. 1b;
Parlak and Delaloye, 1996, 1999; Parlak *et al.*, 2013). These units form the highest
structural unit of the uppermost Cretaceous-Eocene Tauride fold-thrust belt
dominated by Paleozoic-Mesozoic platform carbonates (Robertson, 2002).

139

140 The ophiolite has a suprasubduction zone geochemical signature (Parlak et al., 141 1996a) and consists of tectonized peridotites (harzburgites and dunites), ultramafic 142 and mafic cumulates, isotropic gabbro, minor plagiogranites, and rare basalts 143 associated with deep marine sediments (Parlak et al., 1996a). The cumulate rocks 144 are best exposed along the Sorgun valley (between the villages of Sorgun and 145 Arsalanlı; Fig. 1a), where ~800 m of ultramafic cumulates at the base pass upwards 146 into ~2500 m of modally layered gabbroic rocks consisting of gabbro, olivine gabbro 147 and anorthosite (Parlak et al., 1996a). Way-up criteria (mineralogical grading; 148 evidence of scouring at the base of some layers; Fig. 2) indicate that steeply-dipping modal compositional layering in the gabbros is in places overturned. The cumulate
layers are occasionally intruded at a high angle by thin, fine-grained basaltic dykes.

152 Lower levels of the ophiolite are best exposed in the Findikpinari valley area (Fig. 153 1a), nearly 20 km to the NE of the Sorgun valley, providing sections through both the 154 mantle sequence and the metamorphic sole. The latter has a thickness of about 50-155 70 m and consists predominantly of amphibolites, amphibolitic schists, epidote-156 amphibolite schists, guartz-mica schists, calcschists and marble, with a typical inverted metamorphic zonation from upper amphibolite at the top to greenschist 157 158 facies at the bottom (Parlak et al., 1996b). The sole rocks are intensely deformed, 159 with development of a pronounced foliation, a NW-SE-trending mineral stretching 160 lineation and intrafolial folds (Parlak et al., 1996b). Kinematic indicators all indicate a 161 top to the NW shear sense during formation of the sole (Parlak et al., 1996b).

162

163 Both the tectonized harzburgite and sole are cut by undeformed, discrete doleritic 164 dykes composed of plagioclase, clinopyroxene and amphibole, with subophitic and 165 microgranular textures and variable degrees of hydrothermal alteration. They have 166 geochemical signatures similar to evolved island-arc tholeiites and were derived from 167 a mantle wedge that underwent previous melt extraction and subsequent 168 metasomatism by LILE- and light REE-enriched fluids (Dilek et al., 1999). Dykes 169 hosted by tectonized harzburgite are up to 5 m thick and dip at ~30° to the ~ESE, 170 whereas those hosted by the metamorphic sole are characteristically thinner (< 1 m), 171 clearly post-metamorphic and post-shearing, and dip at ~55° to the ~NW. 172

Available high precision ⁴⁰Ar–³⁹Ar and U-Pb age constraints for the Mersin ophiolite 173 174 and its metamorphic sole are summarized in Table 1. Only one U-Pb zircon date is 175 available from the Mersin gabbros (Parlak et al., 2013), yielding an age of 82.8±4.0 176 Ma. This Is deemed unreliable, however, due to evidence for hydrothermal alteration 177 of the dated zircons, and the age of crystallization of the suprasubduction zone crust 178 regionally is considered by Parlak et al. (2013) to be ~89 Ma. The remaining data 179 indicate that intrusion of dykes into the mantle sequence, formation of the 180 metamorphic sole (cooling through amphibolite facies conditions) and intrusion of dykes through the sole were broadly synchronous events. This has important 181 182 implications for the rapidity of the rotations determined from the paleomagnetic data 183 presented here.

184

185 **3. Sampling and methods**

186

187 To quantify tectonic rotations that have affected the Mersin ophiolite, we sampled the 188 lower crustal sequence (ultramafic and gabbroic cumulates) exposed continuously 189 along the Sorgun valley section (Fig. 1a), together with dolerite dykes cutting 190 tectonized harzburgites of the mantle sequence, and dolerite dykes cutting the 191 metamorphic sole of the ophiolite (both exposed near the village of Findikpinari; Fig 192 1a). An average of eight samples per site were drilled in situ using standard 193 paleomagnetic procedures, yielding up to 13 specimens per site for analysis. 194 Sampling was restricted to exposures that showed either consistent planar layering in 195 cumulate rocks or dykes with parallel planar margins. Structural orientations were 196 measured in the field to an accuracy of $\pm 5^{\circ}$.

198 Natural remanences were measured in the University of Plymouth palaeomagnetic laboratory using either Molspin or AGICO JR-6A fluxgate spinner magnetometers 199 (with respective noise levels of 0.05×10^{-3} and 0.01×10^{-3} A/m). Specimens were 200 201 subjected to either alternating field (AF) demagnetization using an AGICO LDA-3A 202 demagnetizer in 13 incremental steps from 5 to 100 mT or thermal demagnetization 203 using a Magnetic Measurements MMTD80A demagnetizer with 19 temperature 204 increments from 100 to 580°C (or until complete demagnetization). Demagnetization 205 data were displayed on orthogonal vector plots and remanence components isolated 206 via principal component analysis using MacPaleomag software (written by Jeff Gee, 207 Scripps Institution of Oceanography). Site mean directions were evaluated using 208 Fisherian statistics on virtual geomagnetic poles (VGPs) corresponding to the 209 isolated characteristic remanent magnetizations (ChRMs). Paleomagnetic guality 210 criteria proposed by Deenen et al. (2011) were adopted to estimate the reliability of 211 the ChRM/VGP distribution at the site level. In particular, the VGP scatter (i.e., A_{95}) 212 obtained at each site was compared to the expected scatter induced by paleosecular 213 variation (PSV) of the geomagnetic field (i.e., A_{95min} - A_{95max}) to assess whether PSV 214 was sufficiently represented in our datasets (Deenen *et al.*, 2011). For values of A_{95} < 215 A_{95min} PSV is not adequately represented, indicating insufficient time averaging of the 216 geomagnetic field (i.e. resulting from rapid cooling), slow cooling and protracted 217 acquisition of remanence (such that PSV is largely averaged at the specimen level) 218 or remagnetization. Conversely, values of $A_{95} > A_{95max}$ may indicate additional 219 (tectonic) processes responsible for an enhanced scatter of paleomagnetic 220 directions. Site mean magnetization directions were interpreted using a net tectonic 221 rotation approach (Allerton and Vine, 1987; Morris et al., 1998) to determine rotation

axes and magnitudes and recover the initial strikes of dykes. This technique isdiscussed more fully below.

224

225 Rock magnetic experiments were performed to characterize remanence-carrying 226 minerals in sampled lithologies. The high-temperature (20-700°C) variation of 227 magnetic susceptibility, k, of representative samples was measured in an argon 228 atmosphere using an AGICO Kappabridge KLY-3S coupled with a CS-3 furnace. 229 Curie temperatures were determined from these experiments by the Petrovsky & 230 Kapička (2006) method on 1/k data using the AGICO program Cureval v. 8.0.2. 231 Isothermal remanent magnetization (IRM) acquisition experiments were conducted 232 on representative samples to determine coercivity spectra (using a Molspin pulse 233 magnetizer to apply peak fields up to 800 mT, with resulting IRMs measured using an 234 AGICO JR-6A spinner magnetometer), followed by backfield IRM experiments to 235 determine coercivities of remanence. Ferromagnetic phases were further 236 characterized in thin section by optical microscopy and by EDX spectral analyses 237 performed on a JEOL7001 FEG-SEM and analyzed using Oxford Instruments Aztec 238 software.

239

240 **4. Results and analysis**

241

242 4.1 Magnetic mineralogy and palaeomagnetic results from the ophiolite

243

High-temperature variation of magnetic susceptibility experiments revealed

consistent maximum Curie temperatures of ~580°C (Figure 3a), indicating that the

246 ferromagnetic fraction in both cumulate rocks and dykes includes near-stoichiometric

247 magnetite. Some specimens exhibit increased susceptibility upon cooling, suggesting 248 production of new magnetite during heating. A limited number of specimens (e.g. 249 specimen MC1804 in Fig. 3a) show a hump in the heating curve between 150-400°C. 250 The increasing temperature limbs of these humps are reversible until 300°C, but 251 become irreversible after further heating, suggesting the presence of 252 titanomagnetite/titanomaghemite in addition to magnetite. IRM acquisition 253 experiments show that saturation is reached at applied fields of 200-300 mT (Figure 254 3b) indicating presence of low coercivity minerals in these rocks. Backfield IRM 255 experiments yield coercivity of remanence values of 24-53 mT suggesting presence 256 of fine-grained single domain or pseudo-single domain magnetite. These rock 257 magnetic observations are consistent with petrographic and SEM analyses that show 258 that magnetite and minor titanomagnetite are the dominant oxides present in both 259 cumulate rocks and dykes. In the ultramafic cumulates (sites MC01-03), secondary 260 magnetite is present in serpentinized olivine grains, whereas primary magnetite (plus 261 titanomagnetite) with little alteration is observed in the cumulate gabbros and diabase 262 dykes. Ferromagnetic pyrrhotite is also occasionally seen in the dykes, but 263 demonstrably carries the same magnetization direction as the dominant magnetite 264 phase. Overall, these results are entirely compatible with those obtained in other Late 265 Cretaceous Neotethyan ophiolites in this region (e.g. Troodos, Hatay, Baër-Bassit, 266 Alihoca, Göksun, Divriği; Morris et al., 1998, 2002; Inwood et al., 2009; Morris and 267 Maffione, 2016; Maffione et al., 2017), where magnetic remanences have been 268 shown to be of primary, pre-deformational origin, acquired during or shortly after 269 seafloor spreading.

271 Intensities of natural remanences in these rocks vary by lithology, with highest 272 average intensities in the layered gabbros (1.12 A/m) and lower values of 132 mA/m 273 and 80 mA/m in the ultramafic cumulates and dykes, respectively. Stable 274 components of magnetization were isolated at all sites, following removal of 275 occasional minor secondary components during initial demagnetization. Typical 276 examples of demagnetization behaviour are shown in Fig. 4. Most samples are 277 dominated by univectorial, single component decay to the origin. Both AF and 278 thermal demagnetization experiments yielded identical remanence directions (Fig. 4). 279 Stable components of magnetization were identified from individual specimens and 280 subsequently combined to give a mean ChRM for each site. These *in situ* magnetic 281 remanences are given in Table 2 and shown with corresponding specimen directions 282 and VGPs in the stereographic equal area projections of Supplemental Fig. 1. With 283 the exception of one specimen (at site MD11), all VGPs fell within the 45° cut-off at 284 each site recommended by Johnson et al. (2008). Directions are unrelated to the 285 present-day geocentric axial dipole field in the Mersin region ($D = 000^\circ$, $I = 56^\circ$), 286 excluding recent remagnetization. Cumulate rocks (ultramafic cumulates and layered 287 gabbros) have NE-directed in situ ChRMs with negative inclinations, indicating 288 substantial tectonic rotation since magnetization acquisition. Dykes hosted in the 289 mantle sequence also have in situ negative inclinations, whereas those cutting the 290 metamorphic sole have shallow positive inclinations, with both sets having generally 291 northerly declinations.

292

VGP scatter at 11 out of 28 sites (Table 2) is within the limits of that expected from
PSV (Deenen *et al.*, 2011), consistent with a primary origin of the remanence.
Underrepresentation of PSV at remaining sites is interpreted to reflect significant

averaging of secular variation at the sample level during slow cooling of the cumulate
rocks (as seen in samples of lower crustal gabbros recovered by scientific ocean
drilling; Gee and Kent, 2007) and of dykes intruded into the mantle sequence and
metamorphic sole.

300

301 4.2 Reference direction

302

303 Remanence directions must be compared to an appropriate reference direction to 304 determine the extent of tectonic rotation affecting the ophiolite. In our analysis, the 305 reference direction has a declination = 000°, assuming an original normal magnetic 306 polarity as the ophiolite formed during the Cretaceous Normal Superchron (C34N). 307 This implies that calculated net rotations arise from a combination of plate motion 308 and intra-plate deformation. The inclination of the reference direction was determined 309 from paleolatitude estimates based on kinematic reconstructions (van Hinsbergen et 310 al., 2016) placed in the paleomagnetic reference frame of Torsvik et al. (2012). 311 Uncertainties in the reference inclination relate to the reconstructed width of the 312 Neotethys Ocean and the A_{95} error of the reference global apparent polar wander 313 path. Reconstructions for the Late Cretaceous at 100-90 Ma constrain the 314 Neotethyan spreading axis to lie between the southern margin of Eurasia at 33±3°N 315 and the northern margin of Gondwana at 16±3°N. We have no other paleolatitudinal 316 control on the position of the future Mersin ophiolite within these limits, and therefore 317 used a paleolatitude of 24.5±11.5°N to encompass this range. Assuming a geocentric 318 axial dipole field, this corresponds to a reference inclination of 40.2±15.4°.

319

320 4.3 Determination of net tectonic rotations

321

322 Standard paleomagnetic structural corrections involve untilting inferred 323 paleohorizontal/vertical surfaces around strike-parallel axes. Corrected declinations 324 are then compared to the reference direction to determine vertical axis rotations. This 325 approach therefore arbitrarily decomposes the total deformation at a site into 326 rotations around two orthogonal axes (vertical and horizontal). Interpretations then 327 frequently focus entirely on the vertical axis rotations, ignoring the tilting component 328 of the deformation. In complexly deformed terrains, where fold axes are seldom 329 horizontal and where multiple phases of deformation may occur, this procedure can 330 introduce serious declination errors (MacDonald, 1980). It is more appropriate, 331 therefore, to describe the deformation at a site in terms of a single rotation about an 332 inclined axis, which restores both the paleosurface to its initial orientation and the site 333 mean magnetization vector to the reference direction. This single rotation may then 334 be decomposed into any number of component rotations on the basis of additional 335 structural data. Importantly, in the case of dykes, this approach can resolve rotations 336 around margin-normal axes that are impossible to observe in the field and that act as 337 a source of error when standard tilt corrections are employed (Morris and Anderson, 338 2002). This approach also facilitates back-stripping of later rotations from the total 339 deformation to recover earlier rotations.

340

Here we use the net tectonic rotation method of Allerton and Vine (1987), which has
been employed effectively in numerous previous studies in ophiolites (e.g., Morris *et al.*, 1990, 1998, 2002; Hurst *et al.*, 1992; Inwood *et al.*, 2009; Maffione et al, 2015,
2017; Morris and Maffione, 2016, van Hinsbergen *et al.*, 2016). This technique
(Supplemental Fig. 2) can be applied to either paleovertical or paleohorizontal cases,

346 with the key assumption that no internal deformation of a sampled unit has occurred. 347 In this case, the angle β between the site magnetization vector (SMV) and the 348 present day pole to the paleosurface (PDP) remains constant during deformation 349 (Allerton and Vine, 1987). A circle of radius β centred on the reference magnetization 350 vector (RMV) therefore defines the locus of potential positions of the initial pole to the 351 paleosurface. In the case of a dyke, the intersections of this circle with the horizontal 352 represent the poles to two possible vertical initial dyke orientations (Supplemental 353 Fig. 2), and additional constraints are required to select a preferred solution. If a 354 vertical solution cannot be found then the dyke initial strike is invariable and fixed by 355 the reference direction and we exclude the result from the analysis of restored dyke 356 trends. In the case of cumulate rocks, an initial pole for the paleosurface is selected 357 at the steepest point on the circle of radius β centred on the RMV in order to restore 358 the structure to a minimum possible dip (Supplemental Fig. 2). In all cases, the SMV is then restored to the RMV and the PDP to its initial orientation by rotating around an 359 360 axis at the intersection of the planes (great circles) bisecting the pairs of vectors 361 (Supplemental Fig. 2). The net tectonic rotation is described by the azimuth and 362 plunge of this rotation axis and the angle and sense of rotation.

363

In a modification of this method used here (Morris *et al.*, 1998; Koymans *et al.*, 2016),
the effects of uncertainties on the input vectors are modelled by applying the Allerton
and Vine (1987) algorithm to all combinations of three estimates of the reference
inclination (mean plus two values at the edge of its error bar), and five estimates
each of the SMV and present day pole to paleosurface (see Supplemental Fig. 2).
This yields 75 estimates of the rotation parameters at each site, defining a noncircular distribution of acceptable rotation axes. The mean rotation axis can be

determined using Bingham statistics (orientation of maximum eigenvector), and the
distribution of rotation angles plotted as histograms (Supplemental Fig. 2) and
described by the mean value and standard deviation. Restored dyke trends can be
represented on rose diagrams, with the mean strike determined from the
intermediate eigenvector of the corresponding distribution of initial dyke poles. When
distributions of rotation parameters at multiple sites overlap, these may be
amalgamated to determine the most robust overall solution.

378

379 4.4 Net tectonic rotation solutions

380

381 Out of 28 sampled sites, 25 gave net tectonic rotation solutions that are considered 382 reliable. The three rejected sites are: (i) two dyke sites (MD01 and MD10) that gave 383 scattered rotation axes and too few vertical solutions to be considered reliable; and 384 (ii) a thin basaltic dyke (site MC10) intruding the layered gabbros of site MC09, that 385 has a direction of magnetization statistically indistinguishable from its host rocks and 386 that is not considered separately in the analysis of rotations. Mean net tectonic 387 rotation parameters at the remaining sites are given in Table 3. In the case of the 388 dyke sites (Table 3), our preferred solutions are those with NE-SW-directed rotation 389 axes as these: (i) are consistent with results from the cumulate section; (ii) yield more 390 consistent rotation angles between sites than the alternative solutions; and (iii) 391 produce initial NE-SW dyke strikes that are in agreement with a regional-scale 392 dataset of restored Neotethyan paleo-spreading directions recently reported by 393 Maffione et al. (2017).

Fig. 5 illustrates the distributions of rotation parameters amalgamated by
lithostratigraphic level in the ophiolite, whereas results at individual sites are shown in
Supplemental Fig. 3 (for dyke sites) and Supplemental Fig. 4 (for cumulate sites).
The analyses demonstrate that all levels of the Mersin ophiolite have experienced
significant tectonic rotation around shallowly-plunging, NE-SW-directed axes. The
overall mean rotation parameters (Tables 3 and 4; Fig. 5) for the three sampled
lithostratigraphic levels are:

402

403 Cumulate section: $120.0^{\circ}\pm 27.4^{\circ}$ clockwise rotation, axis = $058^{\circ}/23^{\circ}$, N = 1200

404 Mantle-hosted dykes: 125.0°±8.4° clockwise rotation, axis = 047°/-04°, N = 257

405 Metamorphic sole-hosted dykes: $45.0^{\circ} \pm 11.8^{\circ}$ clockwise rotation, axis = $040^{\circ}/31^{\circ}$, N =

406 290

407

408 where errors on rotation angles are ± 1 standard deviation.

409

410 This indicates that, despite a present day geographic separation of c. 20 km, the mantle and crustal sections of the ophiolite display structural integrity and 411 412 experienced a common rotation history since acquiring their magnetizations. The 413 metamorphic sole has also experienced rotation around a similar NE-SW-directed 414 axis but with a much lower magnitude. This is considered to represent the latest 415 phase of rotation to affect the ophiolite and potentially reflects a combination of 416 intraoceanic and emplacement-related deformation. We assume that this net rotation 417 also affected the overlying mantle and crustal sites. This assumption is supported by 418 similar initial strikes for the mantle- and metamorphic sole-hosted dykes (Fig. 5), that 419 suggests intrusion of these units occurred in a common stress field associated with

upper plate extension during formation of the ophiolite in a suprasubduction zone
setting. The earlier phase of rotation affecting the mantle and crustal sections can
then be determined by back-stripping the effect of the later rotation of the
metamorphic sole prior to calculation of revised net tectonic rotation parameters for
these units (Tables 3 and 4). This yields the following mean rotation parameters:

425

426	Cumulate section	$79.9^{\circ}\pm 25.7^{\circ}$ clockwise rotation, axis = $060^{\circ}/12^{\circ}$, N = 1200
427	Mantle-hosted dykes:	92.4° \pm 8.2° clockwise rotation, axis = 032°/-15°, N = 252
428	Combined:	82.1°±24.1° clockwise rotation, axis 056°/08°, N = 1452

429

430 The combined result represents the best estimate for early tilting of the sampled 431 parts of the future ophiolite prior to emplacement of dykes into its metamorphic sole. 432 and confirms that all phases of deformation involved rotation around similar, shallow 433 NE-directed axes. Moreover, given the close timing of crustal accretion, cooling of 434 the metamorphic sole and dyke intrusion (Parlak and Delaloye, 1996, 1999; Dillek et 435 al., 1999; Parlak et al., 2013), these data indicate that rotations accumulated 436 progressively within the ophiolite over a very short time interval of < -3 Myr, requiring 437 a tectonic environment capable of generating rapid and large rotations.

438

439 **5. Discussion**

440

5.1 Tectonic environment for extreme and rapid early rotation of the Mersin ophiolite

The early phase of rotation documented above is demonstrably of intraoceanic originand associated with suprasubduction zone spreading of the Mersin ophiolite as it

occurs between two phases of dyke emplacement. In addition, rotation axes are
broadly aligned with the restored trends of dykes in both the mantle sequence and
metamorphic sole. Assuming that these are intruded perpendicular to the
suprasubduction zone extension direction, this indicates rotation dominated by tilting
around ridge-parallel axes.

450

451 In seafloor spreading systems, large rotations around shallowly plunging axes may 452 be accommodated by normal faulting during plate divergence. For example, net tectonic rotation analyses in Troodos have highlighted rotations of dykes and lavas in 453 454 the hanging wall of listric normal faults (Allerton and Vine, 1987; Hurst et al., 1992) 455 during the development of axial and off-axis graben structures by upper crustal 456 extension. These faults dip symmetrically towards graben axes and are inferred to 457 flatten at depth to sole out into detachments at the base of the upper crust (at the 458 dyke-gabbro transition; Varga and Moores, 1985), without affecting deeper levels of 459 the ophiolite. Large listric faults that dip towards the spreading axis have also been 460 observed by seismic imaging in the slow-spreading Atlantic Ocean (e.g. Salisbury and Keen, 1993), but these sole out near the base of the crust. To accommodate the 461 462 rotations observed in the Mersin ophiolite by listric faulting during spreading would, 463 however, require faults that sole out at the base of the lithosphere (within the upper 464 mantle). In addition, even if lithospheric-scale listric faults were capable of 465 accommodating rotation of the Mersin crust and upper mantle, they would be 466 incapable of capturing rocks of the metamorphic sole at depth (i.e. near their 467 detachment level) and rotating these as well.

469 In contrast to downwards-convex listric faulting, displacement on upwards-convex 470 oceanic detachment faults (Escartín and Canales, 2011) provides a viable potential 471 mechanism for rotation of upper mantle, crustal and metamorphic sole rocks. 472 Investigations of oceanic core complexes in the modern oceans (Garcés and Gee, 473 2007; Morris et al., 2009; MacLeod et al., 2011) have shown that rolling hinge 474 rotation of detachment fault footwalls around sub-horizontal, ridge-parallel axes is a 475 characteristic signature of these lithospheric-scale structures. Within ophiolites, 476 Maffione et al. (2013) showed that such fault systems may be recognised paleomagnetically using this characteristic rotation style. Most recently, Maffione et 477 478 al. (2015) used a net tectonic rotation approach to document rotations around sub-479 horizontal axes of mantle-hosted intrusions in the lower Cretaceous suprasubduction 480 zone ophiolites of south Tibet. Maffione et al. (2015) suggested that these rotations 481 result from upper plate extension accommodated by widespread detachment faulting. 482 They termed this process "forearc hyperextension" and inferred that structural 483 dismemberment occurred shortly after magmatic accretion.

484

485 We propose that the early rotation documented in the Mersin ophiolite likewise is 486 related to fore-arc (hyper)extension taken up by detachment-mode suprasubduction 487 zone spreading. This is supported by four lines of argument: (i) rolling hinge rotations 488 of the footwalls of oceanic detachment faults are characterized by ridge-parallel, sub-489 horizontal rotation axes (Garcés and Gee, 2007; Morris et al., 2009; MacLeod et al., 490 2011), directly comparable to the style of rotation seen in Mersin (Fig. 6); (ii) rotation 491 during the development of oceanic core complexes occurs very rapidly, as required 492 by the full Mersin dataset based upon available age constraints. For example, along 493 the Mid Atlantic Ridge, 46° of rotation of the Atlantis Massif footwall occurred in < 1.2 494 Myr (Morris et al., 2009), whereas 64° of rotation of the 15°45'N oceanic complex 495 was achieved within a very narrow inferred period of activity spanning a time interval 496 between ~2.5 to 2.1 Ma (MacLeod et al., 2011); (iii) oceanic detachment faults are 497 lithospheric-scale structures that in the modern oceans have demonstrably exhumed 498 mantle rocks onto the seafloor (Cannat et al., 2006), and are therefore capable of 499 rotating both crustal and mantle sections of the Mersin ophiolite around the same 500 axis, in contrast to "standard" oceanic normal faults that only affect the brittle upper 501 crust; and (iv) displacement on oceanic detachment faults tectonically juxtaposes 502 rotated lower crustal and upper mantle rocks in their footwalls with unrotated upper 503 crustal lavas in hanging wall blocks (MacLeod et al., 2009), providing a plausible 504 explanation for similar geological relationships in the Mersin and other Tauride 505 ophiolites (where limited exposures of extrusive rocks are in close proximity to lower 506 crustal/upper mantle rocks without an intervening sheeted dyke complex).

507

508 We note that the c. 82° early rotation seen in the Mersin ophiolite exceeds the range 509 of footwall rotations observed in single oceanic detachment fault systems such as 510 those sampled in the Atlantic Ocean (Fig. 6). However, numerical modeling of 511 detachment faulting at slow-spreading ridges (Tucholke et al., 2008) suggests that 512 the active root zone of a weak, asymmetric fault should migrate with its hanging wall 513 across the axis of rifting if magmatic accretion in the hanging wall takes up <<50% of 514 the plate separation (Tucholke et al., 2008; MacLeod et al., 2009; Supplemental Fig. 515 5). Reston and McDermott (2011) suggested that such migration would result in fault 516 abandonment as a new fault cuts up from the rift axis through the preceding footwall 517 (Supplemental Fig. 5), and invoked this mechanism to explain unroofing of broad 518 expanses of mantle seen in the magma-poor rifted margins between Iberia and

Newfoundland. Capture of a portion of a previously rotated footwall section by a
second, successor fault in this way can increase the net rotation experienced by the
initial footwall, providing a mechanism capable of easily accommodating the
magnitude of early rotation seen in the Mersin ophiolite.

523

524 5.2 Mode of formation and rotation of the metamorphic sole

525

The later, post-magmatic net rotation affecting the metamorphic sole of the Mersin ophiolite may have occurred: (i) in an intraoceanic, pre-obduction setting; (ii) during emplacement onto the Tauride margin; or (iii) have a composite origin. However, the consistency of rotation axes throughout the ophiolite is most simply explained by a common tectonic process related to spreading.

531

532 Dykes cutting the sole have geochemical signatures indicating derivation from partial 533 melting of a depleted mantle wedge (Dilek et al., 1999). Hence the metamorphic sole 534 must have been above this melt source during dyke intrusion, requiring a mechanism 535 for exhuming sole rocks from peak metamorphic depths to near the top of the mantle 536 wedge. Models for the formation of metamorphic soles involving intraoceanic 537 thrusting of young, hot oceanic lithosphere (e.g. Celik, 2008) require dykes to intrude 538 through the complete footwall of the under-thrust lithosphere in order to be emplaced into the metamorphic sole along the footwall-hanging wall contact. However, an 539 540 alternative model involving formation of metamorphic soles along the upper interface 541 of a down-going plate following subduction initiation and subsequent exhumation and 542 welding of the sole rocks to the base of overriding plate has recently been proposed 543 by van Hinsbergen et al. (2015). This model provides a mechanism for rapid

544 exhumation a newly-formed metamorphic sole to a position at the top of the mantle 545 wedge, allowing post-metamorphic dyke intrusion through the sole very shortly after 546 its formation. This is required in the case of the Tauride ophiolites, where ages of 547 dykes and metamorphic sole rocks typically differ in age by < 3 Myr (Table 1; Parlak 548 and Delaloye, 1996, 1999; Dilek et al., 1999). The van Hinsbergen et al. (2015) 549 model involves slab flattening in response to formation and extension of the 550 suprasubduction zone crust, bringing sole rocks upwards to the base of the 551 overriding lithosphere, followed by slab steepening in response to negative buoyancy 552 resulting from eclogitization of the slab, leading to decoupling from the sole and influx 553 of asthenosphere below the sole from which the intruding dykes derive.

554

555 This model provides a critical link between early rotation of the Mersin cumulates and 556 mantle sequence dykes via fore-arc (hyper)extension involving oceanic detachment 557 faulting and later rotation of dykes cutting the Mersin metamorphic sole. Welding of 558 the metamorphic sole to the base of the mantle section via slab flattening would allow 559 these rocks to be captured in the base of detachment fault footwall sections. This 560 would allow rotation of the sole rocks around similar ridge-parallel, shallowly-plunging 561 axes to those documented in the overlying ophiolite. As well as accounting for the 562 similarity of rotation axes through the sampled units, this mechanism can also 563 account for the rapid sequence of rotations required by our data, with all phases of 564 rotation occurring over a restricted time interval of <~3 Myr during which crustal 565 accretion, formation of the sole and dyke emplacement occurred.

566

567 5.3 A conceptual model for rotation of an ophiolite and its metamorphic sole in a fore-568 arc environment

569

Linking the upper plate process of fore-arc hyperextension (Maffione *et al.*, 2015) with the lower plate process of metamorphic sole formation and exhumation (van Hinsbergen *et al.*, 2015) leads to a combined conceptual model (Fig. 7) that can elegantly explain rapid, near-synchronous rotation of crust, mantle and sole around consistent ridge-parallel axes. This involves the following sequence of events:

575

a) initiation of an intraoceanic subduction zone, resulting concurrently in the early
stages of formation of the future metamorphic sole (along the upper interface
of the down-going plate) and suprasubduction zone spreading in the fore-arc
region above the mantle wedge. This initial phase of magmatic spreading
generates cumulate gabbros in the new suprasubduction zone lower crust and
emplacement of dykes in the lithospheric mantle below (Fig. 7a);

582

b) amagmatic detachment-mode suprasubduction spreading, resulting in rotation
of cumulate gabbros and mantle-hosted dykes in the footwall of an oceanic
detachment fault (D1; Fig. 7b);

586

c) lack of melt supply leads to migration of the D1 detachment towards the locus
of rifting (Tucholke et al., 2008; Reston and McDermott, 2011; MacLeod *et al.*,
2009), followed by initiation of a successor detachment (D2; Fig. 7c) that
captures part of the rotated D1 footwall. Displacement on D2 then increases
the rotation experienced by the cumulates and mantle-hosted dykes. At the
same time, the down-going plate experiences slab flattening in response to
suprasubduction zone spreading, mantle wedge volume decrease and upper

plate extension, leading to shallowing of the future metamorphic sole and
development of its inverted pressure-temperature gradient (van Hinsbergen *et al.*, 2015);

597

598	d) at the plate contact, the metamorphic rocks at the top of the lower plate are	
599	welded to the base of the upper plate to form the metamorphic sole.	
600	Eclogitization of the lower plate then results in negative buoyancy and the	
601	initiation of slab pull, resulting in decoupling from the sole and steepening of	
602	the slab. Influx of asthenospheric mantle into the wedge generates melt and	
603	leads to intrusion of dykes into the emplaced metamorphic sole (Fig. 7d); and	
604		
605	e) further displacement on the D2 detachment results in additional rotation of the	
606	cumulate gabbros and mantle-hosted dykes and in disruption of the	
607	metamorphic sole, part of which rotates in the D2 footwall (Fig. 7e).	
608		
609	6. Conclusions	
610		
611	Net tectonic rotation analysis of paleomagnetic data from the suprasubduction Mersin	
612	ophiolite reveals large rotations around shallowly-plunging rotation axes that are	
613	consistently oriented NE-SW, parallel to the inferred orientation of the Neotethyan	
614	spreading axis. The data are best explained by combining recent concepts of	
615	detachment-mode spreading (leading to fore-arc hyperextension; Maffione et al.,	
616	2015) and the formation and exhumation of metamorphic soles (van Hinsbergen et	
617	al., 2015). Rotation of both the ophiolite and its metamorphic sole are inferred to be	

618 linked to rolling hinge rotation of detachment footwalls, as seen in oceanic core

619 complexes in modern (ultra-)slow spread lithosphere. This mode of spreading can 620 also explain the absence of sheeted dyke complexes in several Upper Cretaceous 621 Tauride ophiolites, as detachment-mode spreading characteristically results in 622 tectonic juxtaposition of lower crustal and upper mantle rocks in detachment footwalls 623 with upper crustal lavas in their hanging walls. Our results suggest that metamorphic 624 sole rocks exhumed from peak metamorphic depths to the base of the 625 suprasubduction zone lithosphere are then rotated as part of the upper plate. In 626 addition, similar ages of crust and of dykes hosted in both the mantle and 627 metamorphic sole require suprasubduction zone spreading, metamorphic sole 628 exhumation, dyke emplacement and tectonic rotation to be essentially synchronous 629 processes in a dynamic, intraoceanic fore-arc environment.

630

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- 801
- 802 Figure captions

803

804	Fig. 1. Summary of the geology of the Mersin ophiolite of southern Turkey. (a)
805	Simplified geological map (after Tekin et al., 2016); (b) tectonostratigraphic column
806	(after Parlak et al., 1996b). In this study we have sampled dykes cutting the
807	metamorphic sole of the ophiolite, dykes cutting the mantle sequence, and ultramafic
808	and gabbroic cumulates of the lower crust for paleomagnetic analysis.
809	(a color version of this figure is available with the web version of the article).
810	
811	Fig. 2. (a) Modal compositional layering in cumulate gabbros exposed along the
812	Sorgun valley in the Mersin ophiolite (site MC09; compass-clinometer for scale). (b)
813	Close-up of modal layering (coin for scale). In this example, compositional grading
814	from olivine-rich bases to plagioclase-rich tops (X) combined with scour structures
815	(dashed lines) provide way-up indicators that indicate overturning of the section.
816	Darker area (Y) is a remnant of a thin (< 3 cm thick) basaltic dyke cutting the gabbros
817	(sampled as site MC10).
818	
819	Fig. 3. (a) High-temperature variations of low-field magnetic susceptibility (k) showing
820	maximum Curie temperatures of ~580°C. Inset diagrams show the variation of $1/k$,
821	allowing accurate determination of Curie temperatures using the Petrovsky and
822	Kapička (2006) method. (b) Isothermal remanent magnetization (IRM) acquisition
823	curves showing presence of low coercivity magnetite.
824	
825	Fig. 4. Typical examples of orthogonal demagnetization diagrams, showing well-
	

826 defined, characteristic remanence directions isolated by both alternating field (AF)

and thermal (Th) treatment in all lithologies. Solid circles = horizontal plane; open
symbols = vertical N-S or E-W plane.

829

830 Fig.5. Net tectonic rotation results from the Mersin ophiolite, combining site-level 831 preferred solutions from each lithostratigraphic unit. (a) histograms of rotation angles; 832 (b) contoured equal area stereographic projections of rotation axes; and (c) rose 833 diagrams of restored initial dyke strikes. Note that rotation axes are consistently NE-834 SE-directed and parallel to initial dyke strikes. Inset diagrams show the results for 835 early rotation of the dykes cutting the mantle section and for lower crustal cumulates 836 found by back-stripping the mean net tectonic rotation determined from dykes in the 837 metamorphic sole (representing the latest component of rotation in the Mersin 838 ophiolite).

839 (a color version of this figure is available with the web version of the article).

840

841 Fig. 6. Equal area stereographic projections comparing (a) the style of the early 842 rotation of the cumulate and mantle-hosted dykes of the Mersin ophiolite with footwall 843 rotations documented in (b) the Atlantis Massif (Morris et al., 2009) and (c) 15°45'N 844 (MacLeod et al., 2011) OCCs on the Mid Atlantic Ridge (MAR) and in (d) a fossil 845 OCC preserved in the Mirdita ophiolite of Albania (Maffione et al., 2013). The results 846 for the Mersin ophiolite shown here represents an average amalgamating all net 847 tectonic rotations solutions after back-stripping the effects of the later rotation of the 848 metamorphic sole. Note that in all cases, rotation axes are shallowly-plunging and 849 parallel to the observed or inferred orientation of the associated spreading axis. 850

852	Fig. 7. Conceptual model for rapid and extreme tectonic rotation of a
853	suprasubduction zone ophiolite and its metamorphic sole in a fore-arc environment
854	(see text for details). Note that detachment-mode spreading in the upper plate may
855	involve development of multiple oceanic detachment faults, but the model shows only
856	the minimum number of structures required to explain the Mersin paleomagnetic
857	data.
858	(a color version of this figure is available with the web version of the article).
859	
860	Table 1. Summary of geochronological constraints from the Mersin ophiolite.
861	
862	Table 2. Paleomagnetic results from the Mersin ophiolite. Orientation of
863	paleosurfaces (dyke margins; cumulate layering) are expressed as dip direction/dip.
864	O/T = overturned. D, I, declination and inclination of <i>in situ</i> site mean remanence.
865	$\Delta D,$ $\Delta I,$ declination and inclination error, respectively. k, $\alpha_{95},$ precision parameter and
866	95% cone of confidence around the site mean characteristic remanent
867	magnetizations (ChRMs). K, A_{95} , precision parameter and 95% cone of confidence
868	around the site mean virtual geomagnetic pole (VGP). A_{95min} , A_{95max} , minimum and
869	maximum value of A_{95} expected from paleosecular variation of the geomagnetic field,
870	according to Deenen et al. (2011). N, number of total samples used for the statistics.
871	
872	Table 3. Net tectonic rotation parameters for dykes and cumulate rocks of the Mersin
873	ophiolite
874	
875	Supplemental Fig. 1. Equal area stereographic projections summarizing

876 paleomagnetic results obtained from sites in the Mersin ophiolite. Blue circles =

877 specimen characteristic remanent magnetizations (ChRMs, top projections, with 878 closed/open symbols indicating directions on the lower/upper hemispheres 879 respectively) or corresponding virtual geomagnetic poles (VGPs, with mean rotated 880 to vertical, bottom projections); green diamond = present day field direction 881 (inclination = 56°); orange square = Late Cretaceous reference direction (inclination = 882 40.2°); black circles = site mean magnetization directions; red circles = α_{95}/A_{95} cones 883 of confidence on site mean magnetizations/VGP distributions, respectively; dashed 884 line = 45° cut-off on VGP distributions (following Johnson *et al.*, 2008). See Table 1 885 for details of site locations and lithologies.

886

887 Supplemental Fig. 2. Illustration of the net tectonic rotation algorithm employed in this 888 study, based on the Allerton and Vine (1987) method for (a) the paleovertical (dyke) 889 case and (b) the paleohorizontal (layered gabbro) case. SMV = site magnetization 890 vector (*in situ* remanence); RMV = reference magnetization vector; PDP = present 891 day pole to paleosurface; IP = initial pole to paleosurface; RP = axis of net tectonic 892 rotation; dotted line indicates circle of radius β (= angle between SMV and PDP) 893 centred on RMV; dashed lines indicate great circles that bisect the pairs of vectors; 894 subscripts 1 and 2 refer to alternative solutions in the dyke case, whereas the 895 paleohorizontal case gives only one solution. Multiple application of this method for 896 (c) the paleovertical and (d) paleohorizontal cases using all combinations of five 897 estimates of SMV and PDP and three estimates of RMV. This yields 75 estimates of 898 the rotation axis for each site, from which a mean estimate can be derived using 899 Bingham statistics. Inset histograms illustrate the associated distributions of net 900 tectonic rotation angles.

Supplemental Fig. 3. Net tectonic rotation results from individual dyke sites within the
Mersin ophiolite. Results at each site are presented as a histogram of potential
rotation angles, a contoured equal area stereographic projection of potential rotation
axes and a rose diagram of restored initial dyke strikes.

906

Supplemental Fig. 4. Net tectonic rotation results from individual lower crustal
cumulate sites within the Mersin ophiolite. Results at each site are presented as a
histogram of potential rotation angles and a contoured equal area stereographic
projection of potential rotation axes.

911

912 Supplemental Fig. 5. Accommodation of extreme rotation through displacement on 913 successive oceanic detachment faults, based on the model of Reston and 914 McDermott (2011). (a) Amagmatic extension is taken up on an oceanic detachment 915 fault D1 rooted at the rift axis (grey arrow); (b) as the D1 footwall experiences rolling 916 hinge rotation and is pulled out from beneath the hanging wall, the active fault root 917 moves (white arrow) with the hanging wall over the rift axis; (c) the D1 detachment 918 then becomes inactive and a new fault (D2) cuts up from the rift axis, capturing part 919 of the rotated D1 footwall; (d) rolling hinge rotation of the D2 footwall increases the 920 net rotation of the captured portion of the D1 footwall.







Figure 4 low-res Click here to download Figure: Fig4_Z-plots.pdf







Figure 7 colour low-res

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