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1 **Comment on “Interplay of deformation and magmatism in the Pangong Transpressional Zone,**
2 **Eastern Ladakh, India: Implications for remobilization of the trans-Himalayan magmatic arc**
3 **and initiation of the Karakoram Fault” by K. Sen, B.K. Mukherjee and A.S. Collins, Journal**
4 **of Structural Geology 62 (2014) 13-24**

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11 **leucogranite, magmatism, deformation**

12 **1. Introduction**

13 Sen et al. (2014) address the issue of the age of the Karakoram Fault Zone (KFZ), western Tibet, and
14 suggest that the fault has accommodated significant eastward extrusion of the Tibetan plateau since
15 initiating prior to c. 23 Ma. Anisotropy of magnetic susceptibility (AMS) data provided by Sen et al.
16 potentially provide a new approach to investigating the relationship between the KFZ and the c. 22-
17 16 Ma Tangtse-Darbuk leucogranite (TDL) (Phillips et al., 2004). However, we show that
18 misinterpretation of key microstructures has led Sen et al. to reach conclusions starkly at odds with
19 the evidence that they present. Furthermore, we demonstrate that the study lacks the cautionary
20 procedures and considerations that are crucial to the valid interpretation of AMS data. We show that
21 the findings of Sen et al. are entirely consistent with pre-kinematic rather than syn-kinematic
22 emplacement of the TDL. We conclude that the KFZ initiated after cooling of the TDL to ambient

23 lower amphibolite grade conditions after 15.55 ± 0.74 Ma (Phillips et al., 2004) and is a relatively
24 recent structure of the India-Asia collision zone.

25 **2. Re-interpretation of field and microstructural observations**

26 Sen et al. recognise that the main bulk of the TDL is relatively undeformed and that strain increases
27 dramatically towards the Tangtse fault strand. This structural relationship is consistent with the
28 findings of previous studies of the TDL (Phillips and Searle, 2007; Wallis et al., 2013) and is widely
29 recognised as indicative of pre-kinematic intrusion of granitic bodies (Lamouroux et al., 1980;
30 Paterson and Tobisch, 1988). Sen et al. provide AMS data for fifteen KFZ samples and suggest that
31 ten show magnetic fabrics consistent with the known kinematics of the Pangong Transpressional
32 Zone (PTZ). Notably, two samples (7/4B and 7/5A) from the TDL interior show AMS fabrics
33 discordant to the KFZ deformation, which Sen et al. suggest result from magma chamber convection.
34 These discordant fabrics, preserved outside the marginal KFZ shear zones, fulfil another important
35 criterion for identification of pre-kinematic granites (Miller and Paterson, 1995; Paterson et al.,
36 1998).

37 The syn-kinematic interpretation of the TDL put forward by Sen et al. relies on their statement that
38 samples “MST 7/3A and MST 7/3B, which are relatively undeformed, show a magnetic fabric that is
39 emplacement related and not tectonized”, presumably meaning that the magnetic fabric formed after
40 emplacement but before full crystallisation. The evidence that they put forward as showing that these
41 samples are not ‘tectonized’ are their figures 4a-c. Figures 4a and 4b show only a large garnet in
42 MST 7/3B and are insufficient to determine whether or not the sample is tectonized as the matrix is
43 not shown. The quartz microstructure in the sample is shown however in Figure 4c, where the
44 authors describe it as “devoid of dynamic recrystallization features and lacking any preferred
45 orientation, showing regular grain boundaries and undulatory extinction.” This description is
46 inconsistent with the microstructure shown in their Figure 4c. The highly irregular, amoeboid and

47 embayed quartz grain boundaries are indicative of deformation by grain boundary migration dynamic
48 recrystallization. Sub-grain walls are also present within larger grains, suggesting a component of
49 sub-grain rotation. These combined deformation mechanisms indicate deformation at c.500°C at
50 typical geological shear zone strain rates of c. 10^{-12} s⁻¹ (Stipp et al., 2002) and are consistent with
51 previous microstructural observations and deformation temperature estimates within the Tangtse
52 fault strand (Wallis et al., 2013). Higher temperature quartz deformation microstructures such as
53 “chess board” extinction, which form at near-solidus temperatures (Blumenfeld et al., 1986), are
54 absent from the images provided. An alternative explanation for the quartz deformation
55 microstructures could be that they formed by deformation during, and resulting from, ascent and
56 emplacement of partially crystallised granitic magma, as proposed by Sen and Collins (2013) for the
57 Ladakh batholith. However, such an interpretation should be supported by evidence of
58 ascent/emplacement related deformation microstructures (e.g. crystal tiling, magmatic growth in
59 pressure shadows). Similarly, the interpretation by Sen et al. that the TDL magma chamber
60 underwent significant convection supports emplacement of mobile fluid magma rather than a crystal
61 mush undergoing dynamic recrystallization. Sen et al. note that the centre of the TDL preserves
62 magmatic or high temperature microstructures such as fluid/melt inclusions in garnet and “melt”
63 filled cleavage and fractures in feldspar. These microstructures alone are insufficient to support syn-
64 ascent/emplacement deformation of the quartz or a syn-KFZ interpretation of the TDL as they may
65 (most likely given the aforementioned evidence) result from normal magmatic processes including
66 deformation during magmatic convection, as suggested by Sen et al. for the magnetic fabrics of the
67 TDL interior. The concordance between the magnetic fabrics in samples MST 7/3A and MST 7/3B
68 and the wider macroscopic, microstructural and magnetic deformation fabrics of the KFZ is therefore
69 best explained by deformation of these samples at c.500°C in the margin of the Tangtse fault strand,
70 not by deformation during ascent/emplacement or sub-solidus cooling. The evidence put forward by
71 Sen et al. is therefore entirely consistent with a pre-KFZ interpretation of the TDL and lends no

72 support to the syn-KFZ interpretation. The KFZ must therefore have initiated after final solidification
73 of the TDL at 15.55 ± 0.74 Ma (Phillips et al., 2004). The syn-kinematic migmatite structures formed
74 at c.17.4 Ma (Phillips et al., 2013) therefore do not record anatexis and melt migration within the
75 KFZ shear zone but provide valuable information on magma migration through the regionally
76 deforming crust of the Karakoram terrane prior to KFZ initiation.

77 **3. Critique of AMS analysis**

78 AMS can serve as a proxy for deformation when (1) all magnetic carriers are identified, that (2) all
79 possible controls on AMS are carefully taken into account and (3) a genetic relationship between the
80 origin of AMS and deformation fabrics is confirmed (Borradaile & Jackson, 2004, 2010). Modern
81 AMS investigations (Borradaile et al., 2011; Kontny et al., 2011; Kruckenberg et al., 2010) include a
82 variety of corroborative data (other than AMS data) to identify the magnetic carriers, and determine
83 the grain size and extent of magnetostatic interactions of any ferromagnetic phases. These additional
84 procedures include magnetic hysteresis measurements (Tauxe et al., 2002), Isothermal Remanent
85 Magnetisation (IRM) acquisition curve analysis (Robertson & France, 1994), FORC analysis
86 (Roberts et al., 2000) and thermomagnetic experiments (Ferré et al., 2003). In some cases it is also
87 necessary to determine the petrological relationship between the magnetic carriers and surrounding
88 crystal fabric with microscopy and/or SPO or CPO measurements (Kruckenberg et al., 2010). By
89 failing to conduct most of these additional analyses, Sen et al. are unable to correctly identify the
90 magnetic carriers and cannot rigorously evaluate the controls that may influence their AMS results.

91 Sen et al. present AMS data from 15 samples identified as leucogranite, dioritic gneiss, pink
92 mylonitised granite and migmatite. Sen et al. first use bulk susceptibility (K_m) and corrected degree
93 of anisotropy (P') (Jelínek, 1981) to split their sample suite into paramagnetic and ferromagnetic
94 samples (Figure 5a, Sen et al.). Sen et al. correctly note that many of the dioritic gneisses have high
95 values of $K_m (>10^{-3}$ SI) which are typical values for ferromagnetic materials. Sen et al. use a single

96 thermal magnetisation experiment on sample 7/3AX (Figure 5b, Sen et al.) to infer the presence of
97 magnetite in all sample lithologies other than leucogranite. Whilst most of the values of K_m are high
98 for these samples ($>10^{-3}$ SI), the variability in K_m and P' suggests that magnetite may not be the
99 magnetic carrier in all of these samples and at least two of these samples (7/7, 26/8/4, 27/8/2A) are
100 most likely to be paramagnetic. This variability in K_m and P' highlights the inappropriateness of
101 using a single thermomagnetic result to determine the magnetic carriers of multiple samples with a
102 variety of lithologies. Valid identification of the magnetic carriers requires further investigation,
103 either via additional thermal magnetisation experiments or more suitably via magnetic hysteresis
104 analysis (Tauxe et al., 2002) and IRM acquisition curve analysis (Robertson & France, 1994). Where
105 ferromagnetic phases are identified, the grain sizes and magnetostatic interactions between these
106 grains, which also control AMS, should also be evaluated through magnetic hysteresis and FORC
107 analysis (Roberts et al., 2000; Dunlop, 2002).

108 There are other unexplained errors presented in the K_m , P' and T plots in Figures 5a and 5d. Figure
109 5a (K_m vs. P') displays seven leucogranite data points (white circles) and eight dioritic gneiss data
110 points (black squares), whilst Figure 5d (T vs. P') displays eight leucogranite data points and seven
111 dioritic gneiss data points. Figure 5a displays an anomalous data point ($K_m = 17500$: $P' = 1.7$) that is
112 not presented in Table 2. Only three leucogranite data points with $P' > 1.2$ are displayed in Figure 5a,
113 whereas four leucogranite samples have $P' > 1.2$ in Table 2. Sample 27/8/2A (migmatite) is
114 represented by a white circle (i.e. leucogranite) in Figure 5a and a black square (diorite gneiss) in
115 Figure 5d. We highlight this last error because if sample 27/8/2A had been displayed as a black
116 square amongst the white circled leucogranite data cluster then Figure 5a would actually disagree
117 with Sen *et al.*'s assumption that magnetite controls the AMS of all samples except leucogranite. The
118 values of K_m displayed in Table 2 and Figure 5a should also be presented as an order of $\times 10^{-6}$
119 (Tarling & Hrouda, 1993).

120 Sen et al. state that the AMS fabrics of the diorite gneisses, migmatites and pink mylonitic granites
121 are concordant with the local strike of the KFZ and must be representative of lateral shearing along
122 the KFZ. However, the magnetic foliation of half of these samples is misaligned with the strike and
123 dip of the local structural foliation by 15-90° and 9-38° respectively. Sen et al. claim that the
124 discordances between the orientations of the structural and magnetic fabrics “can be attributed to
125 scattered crystallization of very fine grained magnetite having no significant preferred orientation,”
126 however, there is no clear evidence that magnetite controls the AMS of all of these samples and
127 without knowing the nature of all magnetic carriers and their relation to the surrounding deformation
128 fabric, it is not possible to justify a correlation between magnetic and deformation fabrics.
129 Furthermore, Sen et al.’s explanation is actually incorrect. A scattering of magnetite grains with no
130 significant preferred orientation would produce a very scattered AMS fabric with wide confidence
131 ellipses surrounding the mean AMS axis orientations. Most of the AMS fabrics presented in Figure 6
132 are actually very well defined, with tight clusters and small confidence ellipses around the mean
133 AMS axes.

134 Sen et al. present good evidence to suggest that biotite is the magnetic carrier in the leucogranite
135 samples and that their random orientations within the Durbuk Pluton are likely to represent a
136 magmatic fabric. However, the authors’ interpretation that the AMS fabrics of leucogranite samples
137 7/3A and 7/3B represent syn-kinematic magmatic fabrics is less convincing. Such interpretations
138 require evidence of a KFZ aligned magmatic fabric in the absence of solid-state deformation. We
139 have demonstrated that the microstructural evidence from sample 7/3B is actually typical of dynamic
140 recrystallisation textures formed during solid-state deformation. It should also be noted that the
141 accompanying AMS fabric from this sample is actually misaligned with the strike and dip of the
142 KFZ by 28-43° and 27-42° respectively. We find the AMS orientation of 7/3B to be statistically
143 indistinguishable from the random AMS orientations of the rest of the leucogranite samples and
144 cannot justify a correlation between the AMS of this sample and KFZ-related deformation. Without

145 evidence for a lack of solid state deformation from 7/3A, it is not possible to suggest that this AMS
146 fabric was formed during syn-kinematic magmatic flow. It is just as likely that the strong AMS
147 fabric in 7/3A is due to localised shearing at the margin of the pluton after crystallisation.

148 **4. Concluding Remarks**

149 Mis-interpretation of critical microstructures has led Sen et al. to a syn-kinematic emplacement
150 interpretation of the TDL. Instead, the field and microstructural evidence that they observe is entirely
151 consistent with a pre-KFZ interpretation of the TDL, and precludes syn-KFZ emplacement.
152 Furthermore, the AMS results reported by Sen et al. lack the supporting magnetic data needed to
153 determine and evaluate the AMS controls. Without these constraints, a valid correlation between
154 AMS and deformation fabrics cannot be made. We conclude that KFZ deformation in this region
155 commenced after solidification of the TDL at 15.55 ± 0.74 Ma (sample P1, Phillips et al., 2004) and
156 cooling to ambient lower amphibolite grade conditions (Wallis et al., 2013).

157 **References**

- 158 Blumenfeld, P., Mainprice, D., Bouchez, J.L., 1986. C-slip in quartz from subsolidus deformed
159 granite. *Tectonophysics* 127, 97-115.
- 160 Lamouroux, C., Soula, J.C., Deramond, J., Debut, P., 1980. Shear zones in the granodioritic massifs
161 of the central Pyrenees and the behaviour of these massifs during Alpine orogenesis. *J. Struct. Geol.*
162 2, 49-53.
- 163 Borradaile, G.J., Almqvist, B.S.G., Geneviciene, I., 2011. Anisotropy of magnetic susceptibility
164 (AMS) and diamagnetic fabrics in the Durness Limestone, NW Scotland. *J. Struc. Geol.* 34, 54-60.
- 165 Borradaile, G.J., Jackson, M., 2004. Anisotropy of magnetic susceptibility (AMS): magnetic
166 petrofabrics of deformed rocks. *Geol. Soc., Lond., Spec. Pub.* 238, 299-360.
- 167 Borradaile, G.J., Jackson, M., 2010. Structural geology, petrofabrics and magnetic fabrics (AMS,
168 AARM, AIRM). *J. Struc. Geol.* 32, 1519-1551.

169 Dunlop, D.J., 2002. Theory and application of the Day plot (Mrs/Ms versus Hcr/Hc) 1. Theoretical
170 curves and tests using titanomagnetite data. *J. Geophys. Res.: S. Earth* 107, EPM 4-1-EPM 4-22.

171 Ferré, E.C., Teyssier, C., Jackson, M., Thill, J.W., Rainey, E.S.G., 2003. Magnetic susceptibility
172 anisotropy: A new petrofabric tool in migmatites. *J. Geophys. Res.: S. Earth* 108, 2086.

173 Jelínek, V., 1981. Characterization of the magnetic fabric of rocks. *Tectonophys.* 79, T63-T67.

174 Kontny, A., Engelmann, R., Grimmer, J., Greiling, R., Hirt, A., 2011. Magnetic fabric development
175 in a highly anisotropic magnetite-bearing ductile shear zone (Seve Nappe Complex, Scandinavian
176 Caledonides). *Int. J. Earth Sci.*, 10.1007/s00531-011-0713-8, 1-22.

177 Kruckenberg, S.C., Ferré, E.C., Teyssier, C., Vanderhaeghe, O., Whitney, D.L., Seaton, N.C.A.,
178 Skord, J.A., 2010. Viscoplastic flow in migmatites deduced from fabric anisotropy: An example
179 from the Naxos dome, Greece. *J. Geophys. Res.*, 115, B09401.

180 Miller, R.B., Paterson, S.R., 1995. Construction of mid-crustal magma chambers during regional
181 contraction, North Cascades, Washington. In: Brown, M., Piccoli, P.M. (Eds.), *The Origin of*
182 *Granites and Related Rocks*. U.S. Geol. Surv. Circ. 1129, 97-98.

183 Paterson, S.R., Fowler, T.K., Schmidt, K.L., Yoshinobu, A.Y., Yuan, E.S., Miller, R.B., 1998.
184 Interpreting magmatic fabric patterns in plutons. *Lithos* 44, 53-82.

185 Paterson, S.R., Tobisch, O.T., 1988. Using pluton ages to date regional deformations: Problems with
186 commonly used criteria. *Geology* 16, 1108-1111.

187 Phillips, R.J., Parrish, R.R., Searle, M.P., 2004. Age constraints on ductile deformation and long-
188 term slip rates along the Karakoram fault zone, Ladakh. *E. Plan. Sci. Lett.* 226, 305-319.

189 Phillips, R.J., Searle, M.P., 2007. Macrostructural and microstructural architecture of the Karakoram
190 fault: relationship between magmatism and strike-slip faulting. *Tectonics* 26, TC3017.

191 Phillips, R.J., Searle, M.P., Parrish, R.R., 2013. The geochemical and temporal evolution of the
192 continental lithosphere and its relationship to continental-scale faulting: The Karakoram Fault,
193 eastern Karakoram, NW Himalayas. *Geochem., Geophys., Geosys.* 14, 583-603.

194 Robertson, D.J., France, D.E., 1994. Discrimination of remanence-carrying minerals in mixtures,
195 using isothermal remanent magnetisation acquisition curves. *Phys. Earth Plan. Int.* 82, 223-234.

196 Roberts, A.P., Pike, C.R., Verosub, K.L., 2000. First-order reversal curve diagrams: A new tool for
197 characterizing the magnetic properties of natural samples. *J. Geophys. Res.: S. Earth* 105, 28461-
198 28475.

199 Sen, K., Collins, A.S., 2013. Reply to comment on “Dextral transpression and late-Eocene
200 magmatism in the trans-Himalayan Ladakh Batholith (North India): implications for tectono-
201 magmatic evolution of the Indo-Eurasian collisional arc. *Int. J. Earth Sci.* 102, 973-975.

202 Sen, K., Mukherjee, B.K., Collins, A.S., 2014. Interplay of deformation and magmatism in the
203 Pangong Transpressional Zone, Eastern Ladakh, India: Implications for remobilization of the trans-
204 Himalayan magmatic arc and initiation of the Karakoram Fault. *J. Struct. Geol.* 62, 13-24.

205 Stipp, M., Stünitz, H., Heilbronner, R., Schmid, S.M., 2002. Dynamic recrystallization of quartz:
206 correlation between natural and experimental conditions. In: De Meer, S., Drury, M.R., De Bresser,
207 J.H.P., Pennock, G.M. (Eds.), *Deformation Mechanisms, Rheology and Tectonics: Current Status*
208 *and Future Perspectives*. Geol. Soc., Lond., Spec. Pub. 200, 171-190.

209 Tarling, D.H., Hrouda, F., 1993. *The magnetic anisotropy of rocks*, 1st ed., 217 pp, Chapman and
210 Hall, London.

211 Tauxe, L., Bertram, H.N., Seberino, C., 2002. Physical interpretation of hysteresis loops:
212 Micromagnetic modeling of fine particle magnetite. *Geochem. Geophys. Geosys.* 3, 1055.

213 Wallis, D., Phillips, R.J., Lloyd, G.E., 2013. Fault weakening across the frictional-viscous transition
214 zone, Karakoram Fault Zone, NW Himalaya. *Tectonics* 32, 1227-1246.