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

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1. Introduction

Sen et al. (2014) address the issue of the age of the Karakoram Fault Zone (KFZ), western Tibet, and suggest that the fault has accommodated significant eastward extrusion of the Tibetan plateau since initiating prior to c. 23 Ma. Anisotropy of magnetic susceptibility (AMS) data provided by Sen et al. potentially provide a new approach to investigating the relationship between the KFZ and the c. 22-16 Ma Tangtse-Darbuk leucogranite (TDL) (Phillips et al., 2004). However, we show that misinterpretation of key microstructures has led Sen et al. to reach conclusions starkly at odds with the evidence that they present. Furthermore, we demonstrate that the study lacks the cautionary procedures and considerations that are crucial to the valid interpretation of AMS data. We show that the findings of Sen et al. are entirely consistent with pre-kinematic rather than syn-kinematic emplacement of the TDL. We conclude that the KFZ initiated after cooling of the TDL to ambient lower amphibolite grade conditions after 15.55±0.74 Ma (Phillips et al., 2004) and is a relatively recent structure of the India-Asia collision zone.

2. Re-interpretation of field and microstructural observations

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

The syn-kinematic interpretation of the TDL put forward by Sen et al. relies on their statement that samples “MST 7/3A and MST 7/3B, which are relatively undeformed, show a magnetic fabric that is emplacement related and not tectonized”, presumably meaning that the magnetic fabric formed after emplacement but before full crystallisation. The evidence that they put forward as showing that these samples are not ‘tectonized’ are their figures 4a-c. Figures 4a and 4b show only a large garnet in MST 7/3B and are insufficient to determine whether or not the sample is tectonized as the matrix is not shown. The quartz microstructure in the sample is shown however in Figure 4c, where the authors describe it as “devoid of dynamic recrystallization features and lacking any preferred orientation, showing regular grain boundaries and undulatory extinction.” This description is inconsistent with the microstructure shown in their Figure 4c. The highly irregular, amoeboid and embayed quartz grain boundaries are indicative of deformation by grain boundary migration dynamic recrystallization. Sub-grain walls are also present within larger grains, suggesting a component of sub-grain rotation. These combined deformation mechanisms indicate deformation at c.500°C at typical geological shear zone strain rates of c.10^{-12} s^{-1} (Stipp et al., 2002) and are consistent with previous microstructural observations and deformation temperature estimates within the Tangtse fault strand (Wallis et al., 2013). Higher temperature quartz deformation microstructures such as "chess board" extinction, which form at near-solidus temperatures (Blumenfeld et al., 1986), are absent from the images provided. An alternative explanation for the quartz deformation microstructures could be that they formed by deformation during, and resulting from, ascent and emplacement of partially crystallised granitic magma, as proposed by Sen and Collins (2013) for the Ladakh batholith. However, such an interpretation should be supported by evidence of ascent/emplacement related deformation microstructures (e.g. crystal tiling, magmatic growth in pressure shadows). Similarly, the interpretation by Sen et al. that the TDL magma chamber underwent significant convection supports emplacement of mobile fluid magma rather than a crystal mush undergoing dynamic recrystallization. Sen et al. note that the centre of the TDL preserves magmatic or high temperature microstructures such as fluid/melt inclusions in garnet and "melt" filled cleavage and fractures in feldspar. These microstructures alone are insufficient to support syn-ascent/emplacement deformation of the quartz or a syn-KFZ interpretation of the TDL as they may (most likely given the aforementioned evidence) result from normal magmatic processes including deformation during magmatic convection, as suggested by Sen et al. for the magnetic fabrics of the TDL interior. The concordance between the magnetic fabrics in samples MST 7/3A and MST 7/3B and the wider macroscopic, microstructural and magnetic deformation fabrics of the KFZ is therefore best explained by deformation of these samples at c.500°C in the margin of the Tangtse fault strand, not by deformation during ascent/emplacement or sub-solidus cooling. The evidence put forward by Sen et al. is therefore entirely consistent with a pre-KFZ interpretation of the TDL and lends no support to the syn-KFZ interpretation. The KFZ must therefore have initiated after final solidification of the TDL at 15.55±0.74 Ma (Phillips et al., 2004). The syn-kinematic migmatite structures formed at c.17.4 Ma (Phillips et al., 2013) therefore do not record anatexis and melt migration within the KFZ shear zone but provide valuable information on magma migration through the regionally deforming crust of the Karakoram terrane prior to KFZ initiation.

3. Critique of AMS analysis

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

Sen et al. present AMS data from 15 samples identified as leucogranite, dioritic gneiss, pink mylonitised granite and migmatite. Sen et al. first use bulk susceptibility (K_m) and corrected degree of anisotropy (*P'*) (Jelínek, 1981) to split their sample suite into paramagnetic and ferromagnetic samples (Figure 5a, Sen et al.). Sen et al. correctly note that many of the dioritic gneisses have high values of K_m ($>10^{-3}$ SI) which are typical values for ferromagnetic materials. Sen et al. use a single thermal magnetisation experiment on sample 7/3AX (Figure 5b, Sen et al.) to infer the presence of magnetite in all sample lithologies other than leucogranite. Whilst most of the values of K_m are high for these samples (>10^{-3} SI), the variability in K_m and *P'* suggests that magnetite may not be the magnetic carrier in all of these samples and at least two of these samples (7/7, 26/8/4, 27/8/2A) are most likely to be paramagnetic. This variability in K_m and *P'* highlights the inappropriateness of using a single thermomagnetic result to determine the magnetic carriers of multiple samples with a variety of lithologies. Valid identification of the magnetic carriers requires further investigation, either via additional thermal magnetisation experiments or more suitably via magnetic hysteresis analysis (Tauxe et al., 2002) and IRM acquisition curve analysis (Robertson & France, 1994). Where ferromagnetic phases are identified, the grain sizes and magnetostatic interactions between these grains, which also control AMS, should also be evaluated through magnetic hysteresis and FORC analysis (Roberts et al., 2000; Dunlop, 2002).

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

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

Sen et al. present good evidence to suggest that biotite is the magnetic carrier in the leucogranite samples and that their random orientations within the Durbuk Pluton are likely to represent a magmatic fabric. However, the authors' interpretation that the AMS fabrics of leucogranite samples 7/3A and 7/3B represent syn-kinematic magmatic fabrics is less convincing. Such interpretations require evidence of a KFZ aligned magmatic fabric in the absence of solid-state deformation. We have demonstrated that the microstructural evidence from sample 7/3B is actually typical of dynamic recrystallisation textures formed during solid-state deformation. It should also be noted that the accompanying AMS fabric from this sample is actually misaligned with the strike and dip of the KFZ by 28-43° and 27-42° respectively. We find the AMS orientation of 7/3B to be statistically indistinguishable from the random AMS orientations of the rest of the leucogranite samples and cannot justify a correlation between the AMS of this sample and KFZ-related deformation. Without evidence for a lack of solid state deformation from 7/3A, it is not possible to suggest that this AMS fabric was formed during syn-kinematic magmatic flow. It is just as likely that the strong AMS fabric in 7/3A is due to localised shearing at the margin of the pluton after crystallisation.

4. Concluding Remarks

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

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