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Discussion

Reply to Comment on "Large-scale geometry, offset and kinematic evolution of the Karakorum fault, Tibet"

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Searle and Phillips' comment provides us with a welcome opportunity to discuss further a fundamental problem in continental collision zones, namely whether deformation is better approximated by fluid flow or block tectonics. The central issue being whether strain is localized or not on faults and shear zones, estimates of geological offsets, slip-rates, and ages of shear are the most crucial data. Searle and Phillips question the new results we present, claiming instead that: (1) Cosmogenic dating indicates slow late-Quaternary slip-rates on Asian faults (a few mm/year or less), including the Karakorum, in conflict with early inferences [1–3]; (2) The leucogranites we dated near Zhaxigang, and those that Searle et al. [4] studied near Tangtse are not syntectonic but predate the onset of dextral ductile shear, implying that the KFZ is a relatively recent structure (<15 Ma); and (3) The correlations of Mesozoic markers across the fault we find most convincing, hence the geological offsets we deduce (≈300 km) from them, are incorrect, implying that Tertiary movement has been smaller than we suggest, by a factor of ≈2.

Although several of the points raised by Searle and Phillips, which are not new, had been addressed in our paper [5], we clarify below our conclusions while drawing attention to biases and flaws in their approach. As illustrated by several ongoing studies, determining finite offsets and slip rates on large faults is no trivial task. We emphasize the three main points that are key to the debate on the Karakorum fault.

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1. Ages of geomorphic markers and Quaternary slip-rates

When Liu Qing [2] and Avouac and Tapponnier [3] proposed a rate of 32±8 mm/year on the Karakorum fault, direct dating of fluvial and glacial features offset by faults in Tibet had barely begun. The assumptions that large lateral moraines with fresh morphology were last modified during the LGM (18–21 ka), and that most low-level terraces bounded by steep risers emplaced during the following warmer period (after 14 ka) were thus used to infer the ages of their offsets. At the time, the rare, youngest cosmogenic He ages on moraines [2], and the climatic record derived from the Sumxi lake-bed core [6] were consistent with this inference. Near the Gar bridge along the Karakorum fault, in particular, one moraine boulder had yielded a ^{3}He–^{21}Ne exposure age of 8234±668 years (Staudacher et al. in [2]).

This dearth of chronological constraints has been corrected in the course of the last ten years. Many recent studies have now produced a large database of radiocarbon and cosmogenic exposure ages of geomorphic features (e.g., [7–19]). Contrary to the view of Searle and Phillips who base their opinion on only two such studies [10,11], the bulk of the data in Tibet [7–9,12,15,19] indicates that the youngest fluvial terraces postdate 16 ka, and that major LGM (20 ka) glacial advances are ubiquitous, thus generally vindicating the above assumptions. The corresponding horizontal slip-rates now constrained by scores of cosmogenic and radiocarbon ages on the Haiyuan, Kunlun, and Altyn Tagh faults are all on order of 1–2 cm/year, or greater. Far from being "meaningless", given the abundance of accurate dates now available for geomorphic features of different ages at many distinct sites, such slip-rates are not in doubt. Terraces older than the LGM evidently exist, but those dated by Hetzel et al. [11] are not offset by a strike-slip fault.

Comparable studies in less-accessible parts of western Tibet are less advanced but point towards similar results. At variance with the inference by Brown et al.'s [10] that the most recent major glacial advance in Ladakh might be as old as 90 ka (oldest ^{10}Be ages of only 2 out of a total of 4 boulders of the 3900-m high Ganglas moraine near Leh), the youngest ^{10}Be exposure ages obtained on dozens more morainic boulders in the western Himalayas [13,14,16], western Kunlun [19], and Karakorum and Kailas [20], generally at elevations ≥4500 m, demonstrate that the last two major glacial advances occurred circa 40±5 and 20±5 ka, with the former being often the most prominent. Using dextrally offset moraines on the west side of the Gar basin provides a minimum post-150 ka slip-rate of 1 cm/year on one branch of the Karakorum fault [20]. The upper bound on this rate remains to be determined, but ~1 cm/year is consistent with the results of one GPS study involving one station north of the fault [21], and with the 23–34 Ma average geological rate we propose.

2. Synkinematic granites

As pointed out by Searle and Phillips in their comment, the field relationships in the deformed Tangtse granites are strikingly similar to those observed at Zhaxikang. In the Zhaxigang area, the evidence for leucogranite synkinematic emplacement is quite clear, as acknowledged by one of the referees of our paper (J.P. Brun). Several generations of more or less deformed melt veins are observed on the same outcrop. They range from strongly sheared veins, now parallel to foliation, that were intruded early, to slightly deformed ones oblique to the main mylonitic gneiss fabric. The relationships between these veins and the surrounding gneisses, as well as their deformation pattern, are identical to those found in the Ailao Shan Red River shear zone, where their synkinematic nature is beyond doubt [22–25]. Another widely used indicator of synkinematic emplacement (e.g., [26]) is the pervasive C/S fabric in the leucogranites at Zhaxikang and Tangtse. Such fabric is the telltale sign that the granites are cooling below the solidus during shear. The evidence for deformation and recrystallisation of K-feldspars and micas in the Zhaxikang gneisses, together with the $^{40}Ar/^{39}Ar$ cooling ages, provides further evidence of a high temperature ductile shear regime before 19 Ma. The claim by Searle and Phillips that the Tangtse and Zhaxikang granites predate dextral shear is thus not tenable in our view. It should be recalled that, prior to our study, one of the authors of the comment (M. Searle) hinted that the 18–15 Ma Tangtse granite and associated veins might have been intruded coevally with strike-slip motion (p.905 in [27], p.887 in [28]).

By the same token, the existence of undeformed granites away from the shear zone can hardly be used as proof of their pretectonic character. Rather, it is merely proof of the localization of deformation in the shear zone. In our paper, we suggested that the KFZ leucogranites we studied might result from shear-induced melting, as observed in the Ailao Shan–Red River shear zone. Of course, other intrusives found along and away from the KFZ might be due to other melting processes. We did not claim that the entire Baltoro pluton was a result of strike-slip shear, although its markedly asymmetric emplacement might suggest it is. More work would be needed to prove or disprove such a claim. However, whatever the origin of melting, the implications of synkinematic granite emplacement are inescapable. Our conclusion that the onset of dextral motion along the KFZ occurred prior to 23 Ma is therefore robust.

3. Offset markers and eastward extent of the KFZ

As briefly summarized in our paper, Searle's estimates of the total geological offset of the Karakorum fault zone have fluctuated with time. This is understandable because, as correctly pointed out by Searle and Phillip, detailed mapping is essential to firmly establish convincing offset values. We have added some such mapping in the Kailas–Gurla Mandhata and Zhaxikang–Gar regions, where our paper now provides more accurate, integrated maps of active faulting and basement deformation than hitherto available (figures 2 and 6 in [5]).

Searle and Phillips claim that the 120- to 150-km offsets previously discussed by Searle et al. [4] represent upper bounds. Unfortunately, none of the three main observations they bring forth to support this claim provide such constraint. Two of them in fact provide lower bounds. First, the Tangtse granitic complex forms a sliver between two branches of the KFZ (Figs. 2, 3, and 4 in [4]). Consequently, it cannot be used to define a piercing point NE of the northeastern branch of the fault. Correlating the Tangtse sliver with the tail of the Baltoro granite, ~150 km northwestwards [4], therefore provides a minimum rather than an upper bound on the finite offset. The likely synkinematic nature of the Tangtse granite strengthens this conclusion. Second, Searle and Phillips continue to use the antecedence of the Indus river course, which is offset 120 km by the Karakorum fault—two facts first pointed out by Gaudemer et al. [29] and Liu Qing [2]—to define another upper bound on the total geological offset. But the existence of uplifted Eocene–Oligocene conglomerates in the Kailas [31] and of younger (likely Neogene), perched conglomerates on the flank and top of the Karakorum range NW of Baer (Baer located on Fig. 1 in [5]) implies that the drainage pattern 30–20 Ma ago was far different from that observed today, making it particularly improbable that the river, unlike most other great Tibetan rivers, would not have changed course since collision began. When in fact did the Indus River start to incise and become captive of the surrounding relief? The rapid cooling of the KFZ mylonites at 12–8 Ma near Zhaxikang (fig. 5B in [5] and ~8 Ma near Tangtse [27,28] yields the best evidence to date for differential uplift along the Karakorum range, suggesting that it was at that time that the Indus entrenched its course across the range and the fault. Thus, as is the case for most rivers crossing strike-slip faults (e.g., [29]), the 120-km Indus offset (a cumulative geomorphic offset) also provides a minimum rather than an upper bound on the geological offset. That the dextral slip-rate derived by pairing that offset with the entrenchment age is consistent both with the minimum Late Pleistocene rate [20] and the 23–34 Ma average geological rate we find is unlikely to be coincidental.

Third, Searle et al. ([4,30], this comment) maintain their match of the closest sutures (Shyok and Bangong) on either side of the KFZ, hence evidently minimizing the offset. Let us reiterate here that we fully agree with Searle and Phillips' remark that more mapping is needed to nail down the exact correspondence of Mesozoic sutures across the fault. However, given the >1000 km length of the fault and the small number of detailed studies in the remote mountains along it, we, like them, must rely on maps and evidence collected by others. In particular, the data gathered by Matte et al. [32], Kapp et al. [33], and Russian scientists in regions that have not been visited by Searle et al. must be taken into account. In view of such data, a correlation between the Shyok and Shiquanhe sutures is in much better accordance with the lithologies observed and the age of closure of both (e.g., [5,32,34]). Although the Rushan–Pshart suture zone in the Pamir has not yet been a target of modern studies, the extant data rules out a Late Paleozoic closure. It clearly corresponds to a Permo-Triassic to Jurassic oceanic basin that closed in the Late Jurassic-Early Cretaceous [35–39]. Correlating the Rushan–Pshart suture with the Tibetan Bangong–Nujiang suture [37, 40] is therefore the most credible solution. This yields a 250–300 km minimum offset rather than the 150-km maximum value postulated by Searle et al. Given the Zhaxikang ages, an average rate of 1±0.3 cm/year along the northern branch of the Karakorum fault ensues. The amount of dextral motion on the southern branch of the fault (Fig. 8 in [5]) will be more difficult to constrain. At this stage, we proposed the 400-km deflection of the Indus suture between the Amlang La klippe and the Deosai plateau as a working hypothesis. That at least a few hundred kilometers of dextral motion took place east of Kailas, in accordance with the hitherto overlooked evidence of Tertiary and active oblique dextral shear along the southern Kailas zone and piedmont (Fig. 7 in [5]), however, is inescapable, even if one accepts the inference of a few tens of kilometres of low-angle normal faulting on the west flank of Gurla Mandatha [41].

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