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Discussion

Comment on: “Does the Karakoram fault interrupt mid-crustal channel flow in the western Himalaya?” by Mary L. Leech, Earth and Planetary Science Letters 276 (2008) 314–322

M.P. Searle [a,*], R.J. Phillips [b]

[a] Dept. Earth Sciences, Oxford University, Parks Road, Oxford OX1 3PR, UK
[b] School of Geosciences, University of Edinburgh, Drummond Street, Edinburgh, EH8 9XP, UK

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ABSTRACT

Leech [Leech, M.L., 2008, Does the Karakoram fault interrupt mid-crustal channel flow in the western Himalaya? Earth Planet. Sci. Lett., 276, 314–322.] proposed that (1) Himalayan granites are significantly more abundant east of the Karakoram fault termination (around Mount Kailas, in SW Tibet) than west of it in the Zanskar–Kumaon region, that (2) the fault may have created a barrier to southward flow of mid-crustal channel flow, and that (3) the fault acted as a vertical conduit for these melts. These inferences are based upon new U–Pb SHRIMP data from the Leo Pargil dome, NW India, and the analysis of published U–Pb ages from additional Himalayan domes. Here we point out the flaws in all these hypotheses and suggest a much closer comparison of granites along the Karakoram shear zone to the widespread Miocene crustal melt granites of the Baltoro Karakoram range in North Pakistan. Field relationships combined with U–(Th)–Pb dating of granites and metamorphic rocks clearly shows that the leucogranites exhumed along the Karakoram fault are related to regional metamorphic and melting events along the Baltoro Karakoram range of the Asian plate and not to Indian plate Himalayan leucogranites at all. We discuss individually the points raised.

1. Change in volume and age of leucogranites from west to east along the Himalaya

Leech (2008) states “East of the Karakoram fault termination leucogranites are abundant and are as young as 7 Ma; west of the termination, channel granites are less abundant and no younger than 18 Ma”. This presumption is not correct. Although impossible to accurately quantify, the volume of partial melting in the Zanskar Himalaya does not appear greatly different from the regions east of the Karakoram fault termination (Garhwal, Nepal, Bhutan). If volume of migmatite is taken as a proxy for the amount of partial melting then the Zanskar region probably contains more than is exposed in the Garhwal, Nepal and Bhutan regions. This inference is derived from the mapping experience of one of us (MPS) who has undertaken 5 traverses of the Zanskar Himalaya and has mapped profiles across the Greater Himalaya in Garhwal, Nepal (Annapurna, Manaslu, Langtang, Everest), Sikkim and Bhutan. Although the large granite bodies such as Manaslu, Shisha Pangma, Makalu, Kangchenjunga and those in Bhutan are missing in Zanskar, the migmatite complex is considerably larger than many profiles in the central and eastern Himalaya. Structural cross-sections across the Zanskar–Kishtwar region indicate about 20 km structural thickness of the mid-crust partial melt (migmatite) channel (Searle et al., 2007). This is a greater thickness and volume of melt than similar profiles across Garhwal (Searle et al., 1993) or the Annapurna region for example (Godin et al., 2001). Contrary to Leech's assertion that “in the western Himalaya leucogranites are restricted to the Early Miocene” young leucogranites (Late Miocene–Pliocene) are also well known from the Nanga Parbat region in the western Himalaya (e.g.: Zeitler et al., 1993, 2001).

Leech (2008) also states that “It is reasonable to use the number of dated granite bodies as a proxy for actual abundance…” a statement that is incomprehensible. Whereas some large (5–7 km thick) granite bodies (e.g.: Shisha Pangma; Searle et al., 1997) have 2 U–(Th)–Pb ages, a series of thin (1–2 m) leucogranite sills and cross-cutting dykes in the Everest region for example have numerous U–(Th)–Pb ages (e.g.: Murphy and Harrison, 1999; Searle et al., 2003, 2006). The number of U–(Th)–Pb ages has absolutely nothing to do with the quantity or size of melts.

2. Relationship of leucogranites to the Karakoram shear zone

Leech (2008) states that the “presence of leucogranites in the Karakoram fault zone may be explained by synchronous deformation, metamorphism and plutonism” and that “Slip initiation on the Karakoram fault is dated from syn-kinematic granites in the shear

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[*] Corresponding author.
E-mail address: mike.searle@earth.ox.ac.uk (M.P. Searle).

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zone in the Shiquanhe region at c. 25–21 Ma (Valli et al., 2007)". Both of these statements are considered incorrect. In Ladakh, the Karakoram fault along the Nubra valley and the two strands of the fault (Tangste and Pangong faults) in the Pangong region clearly abruptly cut all leucogranites (Searle et al., 1998; Phillips et al., 2004; Rutter et al., 2007; Phillips and Searle, 2007; Phillips, 2008) and must therefore post-date magmatism. Thus U–Pb ages from leucogranites that date initial crystallization of the granite must be pre-brittle faulting along the Karakoram fault. Only a few leucogranites could be synchronous with earliest ductile motion in the shear zone, but all the dated samples are clearly pre-kinematic with relationship to the right-lateral shearing, including the Tangtse granite (Searle et al., 1998; Phillips et al., 2004). As discussed in Phillips and Searle (2007), fault zone rocks within the Ladakhi segment of the fault are variably deformed and display high- to low-temperature solid-state fabrics. Mylonites within the shear zone indicate subsolidus noncoaxial deformation at temperatures that have not exceeded greenschist–lower amphibolite facies with no evidence for submagmatic deformation. In addition, there are no textural or structural indicators that suggest syn-kinematic magmatism. Thus, deformation fabrics within granites along the fault in Ladakh and, by correlation, Shiquanhe, must be formed after crystallization of the granite (Searle et al., 1998; Phillips et al., 2004; Searle and Phillips, 2007) and not during (Lacassin et al., 2004; Valli et al., 2007, 2008). In the Ladakhi fault segment, brittle motion along the Karakoram fault must be younger than 13.73 ± 0.28 Ma, the U–Pb age of the youngest leucogranite dated (Phillips et al., 2004). Likewise in the SW Tibet sector, using the U–Pb ages of Valli et al. (2007, 2008), initiation of shearing along the fault must be younger than 22 Ma at that locality.

3. Karakoram fault acted as a barrier to the southward flow of granites

The model that the Karakoram fault acted as some sort of barrier to the southward flow of mid-crustal melts (Leech, 2008) is also hard to comprehend. The implication one presumes is that Himalayan mid-crustal melts originated from north of the Karakoram fault which somehow prevented their lateral flow southwards to the Himalaya. The granitoids exposed along the Karakoram fault in northern Ladakh consist of a suite of Mid Cretaceous diorites with low $^{143}Nd/^{144}Nd$ ratios of −7.5 to −8.9 and initial $^{87}Sr/^{86}Sr$ in the range of 0.710317–0.714870, a Late Cretaceous granitoid suite with highly radiogenic $^{143}Nd/^{144}Nd$ ratios corresponding to ENd values between +1.5 and +3.0 and low initial $^{87}Sr/^{86}Sr$ (0.704816–0.709269), and a Miocene leucogranite suite with low $^{143}Nd/^{144}Nd$ ratios of −3.1 to −6.8 and moderate initial $^{87}Sr/^{86}Sr$ (0.708238–0.711905) typical of crust-derived granites (Phillips, 2004; Phillips and Searle, 2007). Consequently, these granites are all undoubtedly of Asian plate (Karakoram crust) origin, similar to those in the Baltoro batholith in Pakistan (Searle et al., 1989, 1992; Fraser et al., 2001). It is therefore evident that these partial melts are not related to Indian plate Himalayan leucogranites, which are all located within the Greater Himalayan Sequence structurally beneath the South Tibetan Detachment (Zanskar shear zone) ~100 km to the SW of the Karakoram fault. The continuity of leucogranites exposed along the Karakoram fault with the leucogranites exposed in the Baltoro batholith is clear (Searle, 1991, 1996; Searle and Phillips, 2007; Jain and Singh, 2008).

4. Karakoram fault acted as a conduit for magmas

As well as apparently acting as a barrier for granite magma flow, the Karakoram fault acted as a vertical conduit for these same melts (Leech, 2008). This follows the incorrect presumption that because leucogranites were exhumed along these faults, in situ melting was synchronous with dextral shearing and strike-slip faulting (Lacassin et al., 2004; Valli et al., 2007; Weinberg et al., 2009). Within the Karakoram shear zone exhumed in between the two dextral strike-slip faults exposed in the Tangtse–Pangong region of Ladakh, numerous generations of migmatisation, granite melting, and dyking can be deciphered from outcrop mapping (Searle et al., 1998; Phillips, 2004, 2008; Phillips and Searle, 2007). Vertical right-lateral strike-slip fabrics are later than the earlier fabrics formed during regional metamorphism and crustal melting. All these leucogranites are truncated and cut by the brittle strike-slip faults that must be later than the melting events.

5. Discussion and conclusions

We see no sense in correlating the leucogranites exhumed along the Karakoram fault zone with Himalayan leucogranites exposed along the entire length of the Indian plate >50 km to the south. Regional mapping in both northern Pakistan (Searle, 1991; Fraser et al., 2001) and northern Ladakh (Phillips, 2008) shows that the leucogranites exhumed along the Karakoram fault are equivalent to the Baltoro leucogranites to the west (Searle et al., 1992). Direct continuity between the Nubra–Siachen leucogranites with the granites west of the Siachen glacier across the Karakoram fault has recently been confirmed (Jain and Singh, 2008). We also question the timing constraints of Leech (2008), which are based on the structural interpretations of Lacassin et al. (2004) and Valli et al. (2007, 2008) in Tibet. Their interpretation of syn-kinematic intrusion of the Tangtse and Zhaxigang granites is incorrect because the strike-slip fabrics were imposed after crystallization of the granite in a subsolidus ductile state; thus the U–Pb ages do not date shearing along the fault but must be prior to initiation of shearing along the fault (Searle et al., 1998; Phillips et al., 2004, Searle and Phillips, 2004).

We also dispute the model of Leech (2008) whereby the Karakoram fault acted as a vertical conduit for the melts, following the model of Weinberg et al. (2009). Although magma segregation and melt flow pathways are beautifully exposed along the Tangtse and Darbuk gorge sections in Ladakh these fabrics and granites are invariably superimposed and cut by the later, vertical strike-slip fabrics related to right-lateral motion along both strands of the Karakoram fault. Both the staurolite–sillimanite grade metamorphism and the granite melting events exhumed along the Karakoram fault are related to earlier regional metamorphism and melting across the entire Karakoram ranges, and are certainly not restricted to the strike-slip fault. The fault has merely acted as the final transpressional exhumation mechanism to bring these deep level rocks up to the surface. The continuity of the Baltoro–Siachen leucogranites away from the fault zone, across the Eastern and Western Karakoram, and the obvious decrease in strain gradient away from the fault clearly indicates that the granites were pre-kinematic to strike-slip shear, and that melting was a widespread regional event, unrelated to strike-slip shearing.

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Discussion

Comment on: "Does the Karakoram fault interrupt mid-crustal channel flow in the western Himalaya?" by Mary L. Leech, Earth and Planetary Science Letters 276 (2008) 314–322

Randall R. Parrish

Department of Geology, University of Leicester, UK
Natural Environment Research Council Isotope Geosciences Laboratory, British Geological Survey, Keyworth, Nottinghamshire NG12 5GG, UK

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ABSTRACT

Leech (Mary L. Leech, Earth and Planetary Science Letters 276 (2008) 314–322) presents new U–Pb Ion Microprobe zircon ages from the Leo Pargil dome in NW India in an attempt to delineate the potential tectonic relationships between initiation of the Karakoram Fault and the timing of mid-crustal flow in the Himalayan orogen. Unfortunately, as presented, the data are incapable of answering the question posed because: 1) no field, petrographic or other contextual information is presented for the dated samples making their relevance to the problem uncertain and 2) the U–Pb data themselves are limited by inadequate discussion of complexities including apparent analytical issues (non-linearity of secondary electron multiplier) and, in my view unjustified rejection of ca. 88% of the dataset. The combination of these two factors undermines the usefulness of the data to the relationship of the Karakoram Fault to mid-crustal 'channel flow' in the western Himalaya.

1. Introduction

Leech (2008) addresses the very interesting problem of the potential relationship between the Karakoram Fault (KF) and extrusion and flow of deep crustal material southward from within the Himalaya. The paper contributes new U–Pb measurements from granitic rocks within the Leo Pargil dome, NW India near the site of southeast termination of the KF and potentially has something to contribute to this issue. The relationship between North Himalayan domes and the KF has been the subject of much debate (e.g., Murphy et al., 2002; Lacassin et al., 2004; Phillips et al., 2004; Thiede et al., 2006; Godin et al., 2006) and delineating their role in the evolution of the Himalayan–Tibet orogen is clearly a major issue. Leech attempts to further define the role of large-scale structures in mid-crustal melting by presenting new U–Pb zircon ages from the Leo Pargil dome obtained by Sensitive High Resolution Ion Microprobe (SHRIMP), data that could be of value to this problem. Using this and other published data Leech argued that the 25–21 Ma initiation of the Karakoram fault potentially stopped southward extrusion of Greater Himalayan mid-crustal material (i.e. a type of channel flow) from beneath the Tibetan plateau.

In this note I highlight problems with the U–Pb data interpretation and criticize the geochronological ethos of the paper which neglects essential contextual field, petrographic, structural and chemical data that are needed to validate the age interpretations and tectonic inferences made. In the paper, the interpreted ages of granitic rocks range from 27 to 19 Ma, and are used in conjunction with pre-existing data from other regions of the Himalaya to the east and west to infer that at 25–21 Ma initiation of the KF potentially stopped southward extrusion of Greater Himalayan mid-crustal material from beneath the Tibetan Plateau. The first problem is that because there is so little information presented on the context of the samples, the reader is unable to assess either the significance of the U–Pb data or the relevance of these ages to the tectonic question posed. The age range of the granites overlaps that from most of the metamorphic core of the Himalaya and the North Himalayan domes, the only difference being the apparent absence of any dated samples in Leo Pargil Dome younger than ~15 Ma, an observation that could be biased by inadequate sampling to capture younger intrusions, for example. The second major problem concerns the geochronology: the data are limited by inadequate discussion of complexities within the dataset and apparent analytical issues (non-linearity of secondary electron multiplier), and justification for rejection of ca. 88% of the dataset. Importantly, these criticisms are not a reflection on the analytical technique itself; U–Pb dating of these types of materials by Ion Microprobe is feasible as demonstrated by the published literature. For example, Lee and Whitehouse (2007), working in the Mabja North Himalayan gneiss dome, used an Ion Microprobe to

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E-mail address: rrp@nigl.nerc.ac.uk.

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successfully date zircons of similar age and U concentration to those from Leo Pargil dome.

2. Whence the samples?

It is surprising that this paper lacks description of sample locations, descriptions of mineralogy, field relations, macro- and/or microscopic texture, chemistry, or petrography. The age determinations presented are thus without geological context and the question arises as to whether this contextual information is relevant to the tectonic problem addressed in the paper. Leech (2008, p.320) agree this information can be useful because she uses the deformational state of dated granitic rocks intruding the Karakoram Fault zone and their field relationships (i.e. synkinematic, post-kinematic) to interpret the duration of Karakoram Fault movement. While we do not necessarily agree that the Karakoram Fault has a movement history extending into the Pliocene as is stated, we agree that this information is highly relevant to making deformational history interpretations. It is thus puzzling why this information is absent.

To illustrate why this information may well be relevant, consider the following hypothetical situation: granites that intrude synkinematically or discordantly the upper detachment of a North Himalayan Dome would place powerful constraints on the age of extension and mid-crustal flow, but this constraint could only be applied if their field relationships to the structure were clear. Alternatively, a granite intruding the core of such a dome (whether older or younger than the shear zone above it), but which was unaffected by that shear zone (due to the depth beneath it) could not be used to draw any conclusion about the age of that shearing. A wide range of ages might be obtained from samples described above, but only with the contextual information could the age of shearing be constrained. Without knowing the field relationships of dated granitic samples in this 'example' it would be impossible to assess the relationship of the granitic rocks to 'channel flow,' other than to infer that some form of crustal melting took place over a period of time. The channel flow model can only be temporally tested by dating movement on relevant shear zones bounding flowing rocks; the mere presence of granites does not constitute a test of the channel flow model in of itself. If field and contextual data exist for the dated samples, it would be very useful to provide this information to better place the magmatism within Leo Pargil dome in a more robust tectonic context.

3. The U–Pb data and interpretation of ages of zircons

Leech presents 93 U–Pb analyses of separated zircons from 8 samples from the Leo Pargil dome. Of these, 80 analyses were rejected because 1) "their U concentration is >4000 ppm" and/or 2) "they contain >2% common lead." These rejection criteria were established in order to counter the effects related to non-linearity of secondary electron multiplier at high count rates and uncertainty in correction for common lead given uncertainties in its composition, respectively. A further two analyses that do not fit either criteria are also not plotted, and presumably rejected, from their Fig. 2b. First, the impression needs to be corrected that zircons with these characteristics are un-datable and un-usable — this is simply not true. The author appeals to a linear correlation of "age vs. U concentration" (their inset to Fig. 2A) in an attempt to cast doubt on the analytical reliability of all analyses with >4000 ppm U; however, it is noted that the correlation coefficient (r^2) of the linear regression is 0.0756, a value so low as to have no statistical significance (following the definition of Rodgers and Nicewander, 1988). Furthermore, this plot comprises data from samples with a possible spread in ages and/or inaccuracies due to high Pb_c content, and it is therefore unsurprising that no correlation is observed. Undoubtedly the very high U content has caused instrumental challenges; unfortunately the author has failed to adapt the methodology to overcome these issues by (1) developing a high-U zircon standard, (2) modifying the primary incident ion beam current or spot size to reduce the production of U and avoid multiplier saturation, (3) obtaining multiple analyses on individual growth zones within high-common Pb zircons to define a coherent chord on the Tera–Wasserburg plot to arrive at a sensible age for a given zircon crystal, and/or (4) characterising and correcting for non-linear response of the multiplier (Richter et al., 2001).

The data on zircons from any given sample show considerable spread in apparent common-Pb corrected ages, an observation that could have many causes ranging from (1) instrumental issues and standardisation; (2) inaccurate common Pb correction; (3) an actual age spread of crystallisation during residence in the middle crust; and/or (4) a spread of ages reflecting both magmatic crystallisation and incorporation of inherited xenocrysts. All are possible and have been observed in many other studies.

Eleven analyses from 7 samples used in the 'age interpretation' were considered usable, and they have a spread of apparent dates from 27 to 19 Ma about a mean of ~22 Ma. Unfortunately nowhere in the paper are the data discussed on a sample-by-sample basis, and no attempt has been made to offer a coherent explanation of the data complexity. These ages were inferred to "likely reflect multiple intrusive events." Unfortunately no statistical logic supports any analysis of this dataset; it is equally plausible on the basis of the information provided that granitic samples range from >35 Ma to ≤16 Ma, a conclusion that in of itself would undermine Leech's assertion that the KF represents a major boundary separating mid-crust of contrasting magmatic histories.

Four analyses yield $^{206}Pb/^{238}U$ ages >35 Ma. These analyses had U concentrations/common lead levels of 39,152 ppm/2.9% (spot 1-2-6B); 1144 ppm/0.7% (spot 8-17-6); 1084 ppm/6.9% (spot 28-50-13); 6890 ppm/3.4% (spot 26-45-19). Two of these analyses have high U concentrations and there is no way to assess the resultant effect due to SEM non-linearity except that it would result in an apparent increase in ages. Three of the analyses also have moderate levels of common lead. Correction for the composition of any initial common lead is problematic for such samples with low radiogenic to common lead ratios. Assuming appropriate uncertainties are assigned to the initial common lead composition the increase in common lead content should result in corresponding increased age uncertainties (see below). Importantly one analysis does meet Leech's 'selection' criteria of <4000 ppm U and <2% common lead. This sample also yields another older $^{206}Pb/^{238}U$ age at 33.1 ± 0.5 with U concentration and common lead levels below the thresholds set for rejection, yet were not included in the final culled dataset or considered during the tectonic synthesis. This is especially disappointing given that these 'older' ages potentially reveal important information on the Eocene–Oligocene history of the Leo Pargil dome, a finding which in of itself deserves due attention, and which increases the similarity to some of the North Himalayan Domes exposed farther east (Zhang et al., 2004).

The two youngest analyses reported (50-21 and 50-26) (Leech, 2008 Table 2) have common lead corrected $^{206}Pb/^{238}U$ ages of 16.1 ± 0.5 Ma and 15.6 ± 0.5 Ma, significantly younger than the main group of 27–19 Ma ages. These analyses are dismissed outright. Looking in detail at the former analysis, the U concentration is 6319 ppm which, according to Leech, indicates that the measured age is older than its actual age (because of the proposed non-linearity effect leading to "older apparent ages"). In other words the actual age should, in reality, be <16.1 Ma. The amount of common lead assigned to this analysis (Leech assigns 3.7%), could in theory result in an inaccurate age determination. However, to have a noticeable effect the inaccuracy in the correction would have to be significant (e.g. hypothetically if 10% of the total ^{206}Pb is common then the $^{206}Pb/^{238}U$ age would increase by only ~1.7 Ma). Likewise, a 10% change in the common lead composition used results in only a ~0.05 Ma shift in the age. In any event, the possibility that there are ages as young as 16 Ma within the Leo Pargil dome suggests a high degree of commonality with the remainder of the Himalayan orogen and undermines her conclusion that the Leo Pargil Dome is dissimilar to domes east of the southern termination of the Karakoram Fault. I suggest that these data are perhaps some of the most interesting of the entire dataset and as such warrant detailed consideration rather than arbitrary rejection. In my view, uncertainties arising from non-linearity effects and/or lead loss and/or variable common lead could easily be tested by completing multiple replicate analyses on these and other crystals from the same sample in order to define the amount of common lead present, the scale and magnitude of lead loss (if present) and the effect of variable U concentration.

4. Summary

The lack of contextual information about the dated samples makes it very difficult to assess the relevance of these granitic rocks to the tectonic history of Leo Pargil Dome or to test the channel flow model in the western Himalaya. An alternative analysis of the data suggests that the actual age range of granitic rocks from Leo Pargil Dome could in fact span the range from >30 Ma to <16 Ma, undermining the interpretation that the Leo Pargil dome granites are dissimilar to other North Himalayan domes farther east.

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Discussion

Reply to comment by M.P. Searle and R.J. Phillips (2009) and R.R. Parrish (2009) on: "Does the Karakoram fault interrupt mid-crustal channel flow in the western Himalaya?" by Mary L. Leech, Earth and Planetary Science Letters 276 (2008) 314–322

Mary L. Leech*

Department of Geosciences, San Francisco State University, San Francisco, CA 94132, United States

My paper "Does the Karakoram fault interrupt mid-crustal channel flow in the western Himalaya?" proposes, as the title indicates, a model based on geological and geophysical evidence to explain differences between the Himalaya west of and east of the eastern termination of the Karakoram fault. Granites in the western Himalaya are substantially older than the youngest granites exposed in the east; the youngest granites in the west are found in the Karakoram shear zone and have ages that coincide with or post-date the onset of motion on the Karakoram fault. Magnetotelluric data show that mid-crustal melts extend from beneath the Himalaya to well north of the Indus–Yarlung suture zone but the volume of melt in the west is significantly less than in the east. The crustal-scale Karakoram fault may have tapped mid-crustal melts and prevented southward flow of channel granites since the Early Miocene.

Searle and Phillips (2009) and Parrish (2009) put forward five main points regarding my model in their Comments, claiming 1) that there is no change in the volume and age of leucogranites from west to east along the Himalaya, 2) that leucogranites in the Karakoram shear zone are pre-tectonic, 3) that leucogranites in the Karakoram shear zone are entirely of Asian crustal affinity, 4) that leucogranites in the Leo Pargil gneiss dome may have no relationship to the channel flow process, and 5) that I have haphazardly rejected U–Pb SHRIMP data for Leo Pargil granites and misinterpreted the age data. I welcome the opportunity to clarify key aspects of my work and I will cover each main point raised by Searle and Phillips (2009) and Parrish (2009) and discuss how each point is baseless.

1. On the change in volume and age of leucogranites from west to east along the Himalaya

Searle and Phillips (2009) suggest that despite large granite bodies in the eastern Himalaya, there is little difference between the volume of granite exposed in the eastern vs. the western Himalaya because migmatite is found in the Zanskar region, and that there is equally no difference in the age of granites from east to west because very young leucogranites are found in the western syntaxis at Nanga Parbat. The volume of granites exposed in the western Himalaya is subsidiary to the argument in Leech (2008); large volumes of latest Oligocene and Early Miocene granite could be present in the western Himalaya and my model would still be valid — it is the age of the granites that is key to the model. By referring to the very young granites the western syntaxis at Nanga Parbat, Searle and Phillips (2009) create a red herring in an attempt to disprove the Leech (2008) model. The tectonic aneurysms that occur in the Himalayan syntaxes result from enhanced, localized erosion that creates a high-temperature anomaly causing partial melting in a process that is substantially different from those in the main Himalaya.

In Leech (2008), I point to geophysical evidence that shows melt in the middle crust extends north beneath the Lhasa block in the eastern Himalaya and at least as far north as the Karakoram fault in the west. There is evidence that the Karakoram fault is crustal-scale and should therefore intersect partial melts in the middle crust: a change in the nature of the receiver functions across the fault suggests a significant difference in the crustal structure across the fault down to the Moho (as Searle himself noted in Rai et al., 2006), and elevated ^{3}He/^{4}He ratios from hot springs in Panamik and Changlung in the Nubra valley (S.L. Klemperer, pers. comm.) suggest a mantle contribution and hence continuity of the Karakoram fault to the Moho. When slip began on the Karakoram fault in the Early Miocene, it would have acted as a magma trap (Weinberg et al., 2009) and ascent pathway to southward flowing partial melts in the mid-crust beneath the Tibetan plateau and thus reduced the total volume of mid-crustal melt delivered to the western Himalaya over the lifetime of active channel flow.

2. On the relationship of leucogranites to the Karakoram shear zone

Many of the arguments made here by Searle and Phillips (2009) about the relationship of Miocene granites in the Karakoram shear zone to the timing of slip on the fault are simply restatements of the points made in their earlier Comment (Searle and Phillips, 2004) on Lacassin et al. (2004a). Lacassin et al. (2004b) adequately dismissed those comments in this same journal and there is no need to duplicate their rebuttal.

Searle and Phillips (2009) state that the intrusions must be pre-kinematic, yet Searle himself leaves open the possibility of syn-kinematic intrusion: From Weinberg and Searle (1998), p. 887: "It is most likely that the early foliation into which granites intruded and late

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* Tel.: +1 415 338 1144; fax: +1 415 338 7705.
E-mail address: leech@sfsu.edu.

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foliation development were part of a continuous deformation process. Based on regional observations, Searle et al. (1998) argued that movement along the Karakoram fault began after granite emplacement. However, their considerations do not exclude the possibility of granite having intruded during the early stages of movement on the fault. In this case, granite intrusion would have been contemporaneous with the development of early foliations". On p. 890 of the same paper: "In Tangtse, syn-magmatic structures have been obscured by postmagmatic deformation. The structural complexity exhibited by the intrusions is believed to result from the interaction between magmatic and tectonic stresses superimposed on rock-strength anisotropies". From Dunlap et al. (1998), p. 905: "The Karakoram rocks of the Tangtse shear zone comprise interlayered marble, calcsilicate, granitic pegmatites and boudins of amphibolite gneisses, as well as kilometre-scale pods of strongly sheared leucogranite, all of which exhibit evidence for right lateral shear under greenschist facies conditions (in particular the Tangtse Gompa locality). The pegmatites intruded the carbonate host rocks before or during deformation related to the Karakoram fault zone, and they are interpreted to be part of the regional leucogranite suite."

In support of the syntectonic nature of magmatism, Weinberg et al. (2009), p. 283, describe features that suggest "dextral brittle faulting formed during shearing on the Tangtse strand and was exploited by a synkinematic leucogranite dike. Once solidified, the dike was overprinted by continued shearing." "There are examples of folded dikes with apparently undeformed pegmatites coexisting in the same dike with strongly foliated medium-grained leucogranites. All the evidence in this outcrop is strongly suggestive of continued magma intrusion during shearing." Searle and Phillips (2007) point to discordant leucogranite dikes in the Tangste area dated at 13.73 ± 0.28 Ma (see their Fig. 3) to constrain the latest ductile shearing along the Karakoram fault; locally, this dike does cross-cut the foliation but elsewhere the same dike is ductilely-deformed and is therefore syn-kinematic. Searle and Phillips (2007) and Phillips et al. (2004) use dates of 15.7 ± 0.5 Ma for mylonitic leucogranites interpreted as pre-kinematic and 13.7 ± 0.3 Ma for those cross-cutting leucogranite dikes to constrain the onset of slip on the Karakoram fault, implying two distinct magmatic intrusions separated by a mere 2 Ma rather than being part of the same continuing magmatic event. Searle and Phillips (2007) also point out that "All the granites are cut by the later brittle strike-slip fault" to demonstrate that magmatism pre-dates brittle faulting and are therefore pre-kinematic, oddly equating brittle faulting in the upper crust to the entire faulting history. The fault zone was active through at least the Pleistocene (140 to 20 ka) based on cosmogenic nuclide dating of offset moraines (Chevalier et al., 2005) and into the Holocene (2 to 1 ka) based on offset debris flows (Brown et al., 2002). While it is absolutely correct that temperatures during melt migration are too high for brittle deformation, this does not prove the magmatism is pre-kinematic. Magmatism is contemporaneous with high-temperature, ductile deformation that preceded brittle overprinting after the rocks were exhumed and the system cooled during continued transpression.

There is abundant evidence that melt was present during deformation: Valli et al. (2007, 2008) describe coexisting leucocratic dikes that are deformed and transposed parallel to the foliation within the fault zone and mildly deformed to undeformed dikes that crosscut the foliation and the deformed dikes that are part of the same continuous magmatic event, indicating the dikes are synkinematic to right-lateral deformation (see Fig. 3 in Valli et al., 2008). Weinberg et al. (2009) explains the variable deformation seen in the granitic dikes (from mylonitic to weakly-deformed to undeformed) is a result of varying grain size (e.g., coarse-grained granites and pegmatites), modal composition (mica-rich vs. mica-poor granites), and the time of intrusion. Further, the S–C fabrics described in these rocks are typical of shear during intermediate- to high-temperature conditions and typical of syn-tectonic granites (e.g., Gapais and Barbarin, 1986; Gapais, 1989); these same fabrics are noted on p. 310 in Phillips et al. (2004) who then inexplicably state "There is no evidence for high-temperature deformation and there are no textural or structural indicators that suggest that the granite was emplaced coeval with fault initiation or evolution". Valli et al. (2007, 2008) report abundant geo/thermochronology and microstructural data to show that the timing of high-temperature, ductile deformation of synkinematic granites occurred prior to 21 Ma and that ductile deformation continued as the rocks cooled through 300 °C between 15 and 10 Ma, followed by brittle deformation in the Karakoram fault zone. It is clear that Searle and Phillips (2009) are choosing to ignore the overwhelming data supporting syn-kinematic intrusion of leucogranites in the Karakoram fault zone in favor of a model-driven interpretation that supports their prejudice but finds no support in basic geological data.

3. On the Asian origin of Karakoram leucogranites and their relationship to the Baltoro pluton

Searle and Phillips (2009) state that εNd and $^{87}Sr/^{86}Sr$ values for granitoids in the Karakoram fault zone are unquestionably Asian in origin. These data are presented as a challenge to my suggestion that melts from a mid-crustal channel could have been tapped by the Karakoram fault and if so, leucogranites in the Karakoram shear zone should have an Indian plate origin. Fig. 1 plots the Nd and $^{87}Sr/^{86}Sr$ range of values for granitoids in the Karakoram fault zone from the Searle and Phillips (2009) Comment and values summarized for Baltoro granitoids from Mahéo et al. (2009) against a field representing Asian crust (from King et al., 2007). From the data presented by Searle and Phillips, Miocene leucogranites from the Karakoram fault zone appear distinct from Baltoro granites and also fall partially outside the Asian crust field, so that an unbiased observer might not conclude they are "undoubtedly of Asian plate origin". Allègre and Ben Othman (1980) calculated εNd and εSr values for mixing between mantle and continental crust (including the Greater Himalayan leucogranites, Fig. 1); the spread in Karakoram Miocene leucogranite values correspond to mixing within the Allègre and Ben Othman (1980) field suggesting the mixing could be attributable to a contribution of Himalayan melt from the underlying subducting Indian crust. Further, isotopic data summarized in France-Lanord et al. (1993) suggest considerable overlap in εNd and $^{87}Sr/^{86}Sr$ values of Karakoram leucogranite data with values for Greater Himalaya

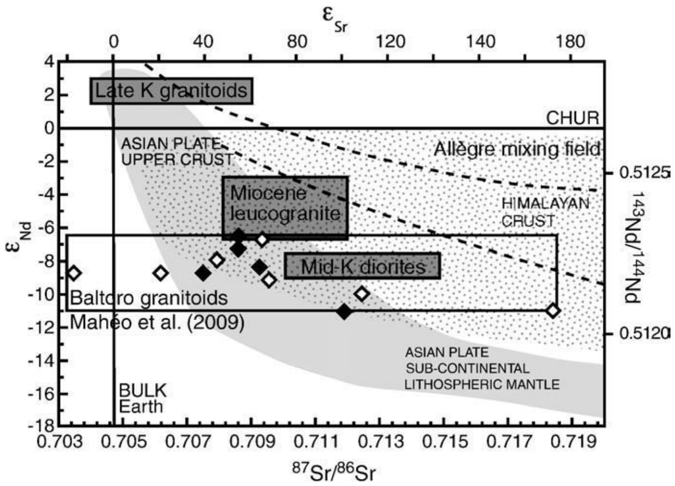

Fig. 1. εNd vs. $^{87}Sr/^{86}Sr$ diagram showing the range of values for granitoids in the Karakoram fault zone (dark gray boxes) from Searle and Phillips (2009), and values for the Baltoro granite (unfilled box includes data from Schärer et al., 1990, and Searle et al., 1992 [white diamonds]; and Mahéo et al., 2009 [black diamonds]. The gray region indicates mixing between Asian upper crust and Asian plate subcontinental lithospheric mantle (SCLM, from King et al., 2007). Dashed lines outline a plausible mixing zone between Indian plate SCLM and the Greater Himalayan Sequence (from Zhang et al., 2004). The stippled area shows a mixing field between mantle values and continental crust from Allègre and Ben Othman (1980). CHUR—chondrite uniform reservoir. Modified from King et al. (2007).

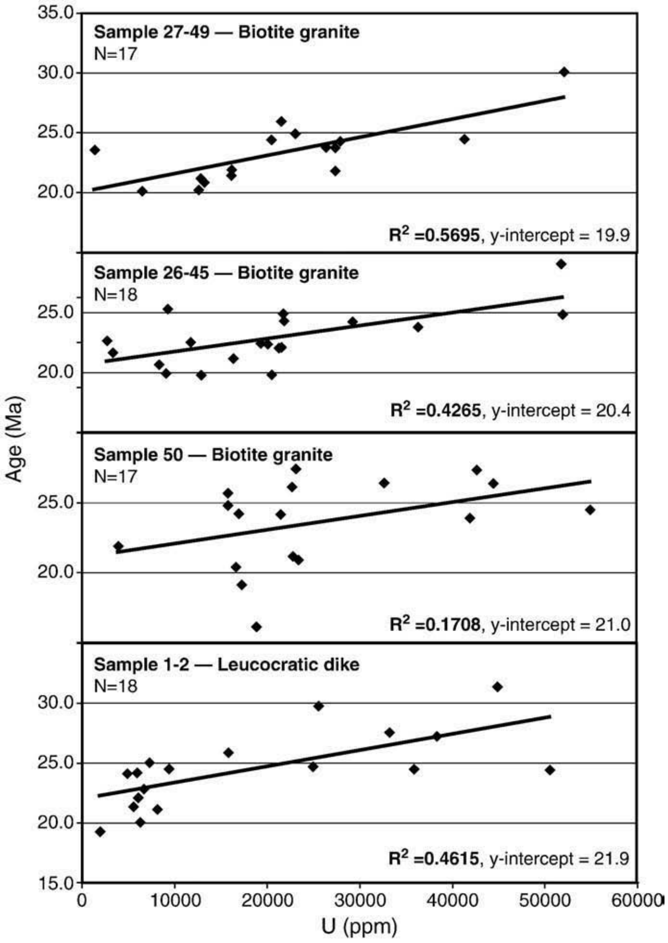

Fig. 2. Age vs. U concentration plots for the four granitic samples (27–49, 26–45, 50, 1–2) from the Leo Pargil gneiss dome showing the regression line fitted to those data and their corresponding coefficients of determination, R^2. Tertiary data for each sample is plotted except for very discordant data (analyses with common Pb > 10,000 ppm).

gneisses and leucogranites and Tethyan Himalaya Sequence rocks. Thus it seems that there is sufficient doubt as to whether Miocene leucogranites have a Himalayan signature that additional isotopic tests are warranted.

4. On the role of granites in the evolution of the Leo Pargil gneiss dome

Certainly, not much has been published on the Leo Pargil gneiss dome, thus contributing to Parrish's confusion about the relevance of ages for Leo Pargil granites to the geology of Himalayan gneiss domes and the role granitic intrusions have played in their evolution. Nonetheless, Thiede et al. (2006) summarized the geology and late-stage exhumation of the Leo Pargil dome from the mid-crust. Thiede et al. (2006) report ^{40}Ar/^{39}Ar white mica ages of 16–14 Ma interpreted to be minimum estimates for the onset of dome exhumation, and apatite fission-track ages between 10 and 8 Ma indicating the end of ductile shearing. Rapid exhumation of the high-grade core of the Leo Pargil dome and concomitant granitoids cooled these rocks to below 450–300 °C between 16 and 14 Ma (Thiede et al., 2006), corresponding to two c. 16 Ma U–Pb zircon SHRIMP ages reported in Leech (2008). Those two analyses (outliers from a total of 93 analyses) likely reflect zircon recrystallization during exhumation of the Leo Pargil gneiss dome and do not date the crystallization age of the mid-crustal melts that would have crystallized earlier (27–19 Ma in Leech, 2008) at much higher temperatures.

5. On the U–Pb data and interpretation of zircon ages

Parrish (2009) brings up several points regarding my U–Pb SHRIMP analyses of high-U zircon, my methods for rejecting data, and my interpretation of the data. In Leech (2008), I included a plot of U–Pb age vs. U concentration for eight granitic samples, all with similar age populations, and showed a best-fit line for all Tertiary analyses only to visually demonstrate that apparent older ages correspond to high U concentrations (a result of the instrumentation undercounting U). Parrish (2009) points to an R^2 value of 0.0756 for that regression line to suggest there is no statistical significance to a linear correlation between age and U concentration. By combining results from eight different samples and including very discordant data to calculate R^2, Parrish virtually ensures a low R^2 value. Fig. 2 plots age vs. U concentration for the four granite samples for which I have more than three Tertiary data points and, in common with standard practice, excludes analyses with high common Pb (>10%, very discordant data). Three samples have calculated R^2 values from 0.4615 to 0.5695, that is, 46–57% of the total variation in age can be explained by the linear relationship between age and U concentration. There is a stronger correlation (i.e., R^2) if the remaining discordant analyses (due to high common Pb) are excluded, thus suggesting common Pb accounts for part of the age scatter, and that a lower threshold for acceptable analyses with high common Pb is appropriate. One sample (#50) has an R^2 value of only 0.1708 because it includes one of the 16 Ma analyses (see discussion above) from a sample that likely underwent some recrystallization during exhumational shearing and also includes older, discordant analyses that are mixed ages. Parrish (2009) points to older ages (>30 Ma) that are not included in the final discussion of the data; these discordant data have no geological significance and were excluded because the older ages correspond to higher common Pb ($R^2 = 0.6852$), and because they appear to fall on mixing lines between the Tertiary and inherited zircon cores (data that was not presented in Leech, 2008). Working with the existing dataset, I have simply derived the most accurate age for crystallization of Leo Pargil granites. There has been no unjustified rejection of data: every Tertiary analysis is included in Leech (2008), and I stand by my appropriate treatment of those analyses.

In summary, none of the points raised by Searle and Phillips (2009) or by Parrish (2009) represent substantive arguments against the proposed model of Leech (2008).

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