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Response to Comment on "Slip-Rate Measurements on the Karakorum Fault May Imply Secular Variations in Fault Motion"

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TECHNICAL COMMENT

Response to Comment on "Slip-Rate Measurements on the Karakorum Fault May Imply Secular Variations in Fault Motion"

Brown *et al.* (*1*) argue that the dispersion in the exposure ages we obtained from the Manikala glacier moraines (*2*) is influenced by postdepositional processes and that only the oldest boulder age on each moraine group can be used to assess its abandonment age. Determining the appropriate age of a geomorphic offset from a dispersed age population does indeed present a considerable challenge, especially where dates from surface samples are not supported by subsurface sampling, radiocarbon dating, or climatic correlation. In general, predepositional exposure will yield ages that are too old, and postdepositional processes will yield ages that are too young.

The slip rates determined by Chevalier *et al.* (*2*) were based on the surface exposure ages of two composite moraine groups that were displaced from their source by right-lateral motion on the Karakorum Fault. The younger moraine deposits yielded surface exposure ages ranging from 21 to 45 thousand years (ky), and the older moraine yielded ages from 103 to 325 ky. On either moraine, the frequency of ages displayed distinct modes that correspond to the coldest epochs of the last two glacial cycles—which, contrary to the assertion of Brown *et al.* (*1*), is unlikely to be coincidental. We argued (*2*) that the offset moraine edges only became passive offset markers when the glaciers had retreated, and inferred the age of the offsets to be those of the younger peaks in the distribution, which correlate with global and regional climate records (*3*–*6*): The ~1500-m offset thus accumulated since the end of Marine Isotope Stage 6 (MIS 6, ~140 ky) and the ~220-m offset since the last glacial maximum (LGM, ~20 ky). The resulting slip rate is ~10 mm/year—greater than the geomorphic rate (~4 mm/year) determined by Brown *et al.* (*7*), the interferometric synthetic aperture radar (InSAR)–derived rate (~0 mm/year) of Wright *et al.* (*8*), and the recent Global Positioning System (GPS) results (3.4 ± 5 mm/year) of Jade *et al.* (*9*) but in agreement with the GPS results (11 ± 4 mm/year) of Banerjee and Bürgmann (*10*) (Fig. 1A). The disparity among the rates may indicate secular variation in the slip rate.

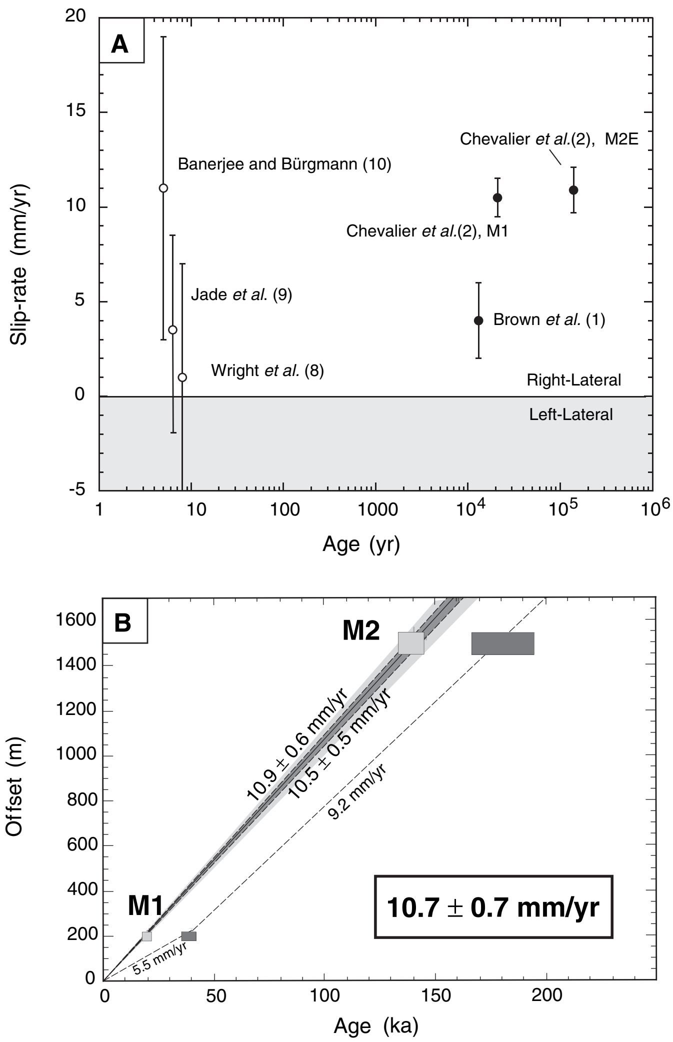

Fig. 1. (**A**) Comparison of slip-rate determinations with observation interval from geodetic methods (open symbols) and geomorphic methods (filled symbols). (**B**) Rates obtained from the offset age relations for the Manikala moraine complex. An average rate of 10.7 ± 0.7 mm/year is obtained from linking the 1520 ± 50 m and 220 ± 10 m offsets, with the end of MIS 6 (~140 ka) and MIS 2 (~20 ka), respectively. This association yields a constant slip rate over the entire observation interval. A slip rate of 5.5 mm/year is implied if the 220 ± 10 m is linked with the 40 ± 3 ky age of the older subgroup on M1. This low slip rate over the past ~40 ky requires a rate of 9.2 mm/year between ~40 ka and ~180 ka to reconcile the rate obtained if the 1520 ± 50 m offset is linked with the 181 ± 14 ky age cluster on M2E.

Brown *et al.* (*1*) argue that the slip-rate disparity is not real and that we have systematically underestimated the ages of the offsets. They contend that the younger moraine was emplaced during MIS 3, which, based on glacial chronologies in the Himalayas, as opposed to Tibet proper, would have been the period of greatest glacial expansion during the last glacial cycle (*11*, *12*). However, LGM advances of large Tibetan glaciers like the Manikala, although restricted, have been documented (*13*). Moreover, the history of glaciation on the plateau is variable. Owen *et al.* (*14*) have dated LGM and post-LGM moraines in the western Nyainqentanglha Shan at Karola Pass (three glacial advances younger than 20 ky) and in the Gongar Shan (four advances younger than 10 ky).

At Manikala, two LGM-age samples—with ages that are statistically distinct from all others found on M1—support the contention that glacial expansion during the LGM was sufficient to allow the glacier to cross the fault. The age of the offset may thus be approximated by the youngest ages, yielding the higher rate. The distribution of 18 ages from the older moraine has peaks at ~140 and ~180 ky, consistent with cold periods during and at the end of MIS 6. Two of the 18 samples yielded ages of ~315 and ~325 ky, forming another small, statistically distinct cluster that is only slightly younger than the age of the glacial maximum just prior to MIS 9.3 (~340 ky). The small number of ~325 ky ages relative to those between 140 and 180 ky and the similarity of these ages to a previous glacial maximum suggest that they represent deposits of a previous glaciation that were carried across the fault during subsequent glacial advances. They would thus represent an inherited component, such as that documented in most of the cases where enough individual boulders are dated to characterize the surface age distribution [usually up to 10 or more, e.g. (*15*, *16*)]. As for the younger moraine, the age of glacial retreat, 140 thousand years ago (ka), determines the age of the offset.

The extent to which surface reworking influences the apparent surface exposure ages of glacial moraines is not solidly established. Using surface exposure and radiocarbon dating of alluvial terraces and moraines along the Altyn Tagh fault in northwest Tibet, Mériaux *et al*. (*17*) demonstrated a constant slip rate (linear offset versus age) for the last ~120 ky. Erosion, surface reworking, or both will preferentially "young" the exposure ages of the oldest samples, resulting in a nonlinear relation between offset and age in which apparent slip rate increases with time. That this is not observed suggests that the most important process in degrading glacial surfaces may be headward stream erosion and fluvial incision of the original glacial surface, which is easily identified in the field and on satellite images and which was absent where we sampled at Manikala.

Our study (*2*) considered the possibility that the younger moraine was abandoned at ~36 ka and the older moraine at ~180 ka (the older peak in the age distribution). This offset-age assignment results in a rate of 5.5 mm/year between 36 ka and the present and a rate of 9.2 mm/year between 180 ka and 36 ka (Fig. 1B), well in excess of the InSAR rate over much of the observation interval. This scenario, however, requires a major change in the long-term slip rate without plausible tectonic justification. Extrapolating a lower rate of 4 to 5 mm/year back in time would yield an age of >350 ky for the ~1500-m offset recorded in the older moraines. If that were the case, one would have to explain the highly unlikely scenario in which the prominent cold periods during MIS 6 produced no discernible glacial record, whereas other cold maxima did. Arguing that the ages of ~140 and ~180 ky from the older moraine represent this record is, in essence, the interpretation of Chevalier *et al*. (*2*). Given the inconsistencies inherent in alternative models, we believe that the glaciotectonic history and derived slip rates we present (*2*) provide the simplest interpretation of the overall distribution of ages. Whether there is disparity between millennial and decadal rates will depend as much upon future geodetic measurements as it does upon our confidence in the geomorphic determinations.

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