Slip rates of the Karakorum fault, Ladakh, India, determined using cosmic ray exposure dating of debris flows and moraines

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[1] We measure an average slip rate of 4 ± 1 mm yr^{-1} along the Karakorum fault, heretofore considered one of Earth's greatest strike-slip faults and thought by many to play a key role in Asian deformation kinematics. Levees of a debris flow, and contours of the fan on which it was deposited, have been displaced 40 ± 5 m. Concentrations of ^{10}Be in boulders from the debris flow yield ages of $11-14$ ka, implying a slip rate of 4 ± 1 mm yr^{-1} during that period. A fresher debris flow has been offset $2-2.5$ m since $1-2$ ka, implying the occurrence of an earthquake with $M \sim 7$ since that time. Concentrations of ^{10}Be in boulders on the crest of the most extensive moraine near Leh imply that the most recent major glacial advance occurred at 90 ± 15 ka. This is consistent with the inference of others that alpine glaciers in this region have not necessarily expanded in concert with Northern Hemisphere continental ice sheets. If features, including lateral moraines, that Liu inferred to have been offset $300-350$ m by the Karakorum fault date from the same period, they too imply a slip rate of $3-4$ mm yr^{-1}. This slip rate is comparable to rates of extension across grabens within Tibet. With recent evidence that slip along the Altyn Tagh fault occurs at ~ 10 mm yr^{-1}, our rate suggests that slip along the boundaries of Tibet is not significantly more rapid than extension within the plateau. Hence, plate tectonics, in the strictest sense, ought not be applied to Tibet, because Tibet does not behave as a rigid plate. *INDEX TERMS:* 1824 Hydrology: Geomorphology (1625); 1035 Geochemistry: Geochronology; 9320 Information Related to Geographic Region: Asia; 8107 Tectonophysics: Continental neotectonics; *KEYWORDS:* Karakorum Fault, slip rate, cosmic ray exposure age, beryllium 10

1. Introduction

1.1. Tectonics and Climate Change of Central Asia

[2] Two extreme views of continental tectonics can be contrasted by the significance that they attribute to major faults in the crust. One view treats such faults as major lithospheric discontinuities that separate nearly rigid blocks, such that resistance to regional deformation depends on resistance to slip along the faults. The other view treats the upper crust as weak, compared to a stronger, but nevertheless viscous, substratum. In this view, the strength of the con-tinuously deforming upper mantle, and perhaps lower crust, determines the distribution of regional deformation and the strain of the upper crust, manifested by faulting and folding, provides a roughened image of that deeper deformation.

[3] The difference in these views developed in part from studies of Asian tectonics. Proponents of the first view have worked to quantify rates and amounts of slip along major faults (Figure 1) [*Armijo et al.*, 1986, 1989; *Liu*, 1993; *Peltzer et al.*, 1989], and have used elements of plate tectonics to describe the kinematics of deformation [*Avouac and Tapponnier*, 1993]. Others [*England and McKenzie*, 1982; *England and Houseman*, 1986] have utilized numerical experiments on a thin viscous sheet that deforms continuously, and implicitly treated the upper crust as merely a collection of passive markers floating on a stronger, deforming, viscous substratum. Although the average kinematic descriptions resulting from the two approaches differ little when smoothed (compare *Avouac and Tapponnier* [1993] and *Peltzer and Saucier* [1996] with *England and Molnar* [1990], *Holt and Haines* [1993] or any of *Holt et al.* [2000, 1995, 1991]), the mechanical underpinnings differ profoundly in one respect. The first view suggests that much of India's collision with Eurasia is

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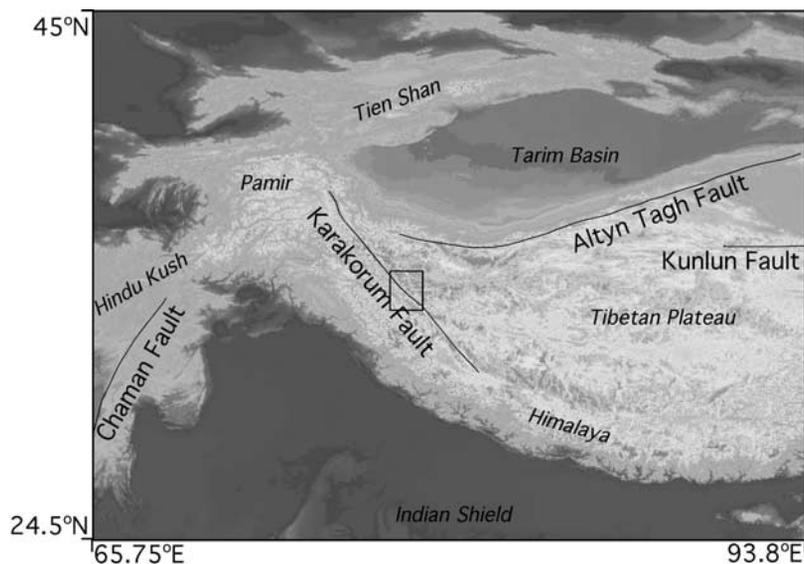
Figure 1. Topographic map of central Asia, based on satellite digital elevation data, showing topographic expression of tectonic features, including major active faults. The region of our study, shown in more detail in Figure 2, is outlined. See color version of this figure at back of this issue.

absorbed by lateral transfer along strike-slip faults penetrating into the upper mantle and carrying material eastward out of India's northward path; the second view considers most of India's penetration into Eurasia to be absorbed by crustal thickening with minor lateral transfer.

[4] These contrasting points of view have their origins in differing estimates of the slip rates along the major strike-slip faults in Asia. Assuming postglacial ages (i.e., 10 ± 2 ka, or more recently, 13.5 ± 2 ka) for displaced landforms, some have argued that slip along several of the major faults is rapid: ~30 mm yr^{-1} on the Altyn Tagh and Karakorum faults [*Avouac and Tapponnier*, 1993; *Liu*, 1993; *Peltzer et al.*, 1989] and 10–20 mm yr^{-1} on right-lateral faults across the middle of Tibet [*Armijo et al.*, 1989] (Figure 1). Others suggest significantly lower rates for right-lateral faults within Tibet [*Molnar*, 1992]. On the basis of analyses of slip vectors of earthquakes along the Himalayas, *Molnar and Lyon-Caen* [1989] argued that slip along the Karakorum fault could not exceed ~10 mm yr^{-1}. *England and Molnar* [1997], exploiting a method similar to that of *Haines and Holt* [1993], found that it is not possible to generate a consistent velocity field (i.e., one obeying compatibility of strain) for Asia with a slip rate greater than ~10 mm yr^{-1} on the Karakorum fault or greater than ~15 mm yr^{-1} for the Altyn Tagh fault.

[5] Although there is no historical record of a significant earthquake on the Karakorum fault, its importance was noted by *Burtman et al.* [1963] and *Peive et al.* [1964], who estimated, on the basis of observed offset units, that 250 km of right-lateral slip had occurred. As Landsat and SPOT imagery became available, the Karakorum fault was recognized as one of Asia's major active faults [*Liu*, 1993; *Molnar and Tapponnier*, 1975, 1978]. Right-lateral slip along this fault accommodates part of India's penetration into Eurasia, as the western syntaxis of the Himalaya advances toward stable parts of Eurasia. In the region of the Karakorum fault, India's motion toward Eurasia is nearly due north [e.g., *DeMets et al.*, 1990], but

slip vectors of earthquakes show northeastward underthrusting of India beneath the Himalayas in this region [e.g., *Molnar and Lyon-Caen*, 1989]. Right-lateral slip along the Karakorum fault, thus, absorbs part of the east-west component of movement, so that the oblique slip at the Himalaya is partitioned into pure thrust slip at the Himalaya and pure strike slip farther northeast. *Armijo et al.* [1989] suggested that the Karakorum fault is the westernmost of a series of en echelon right-lateral faults along which much of Tibet is transferred east with respect to both stable Eurasia and India. Additional studies have produced estimates of total slip along the Karakorum fault ranging from as little as 85–120 km [*Searle*, 1996] to perhaps as much as 1000 km [*Peltzer and Tapponnier*, 1988], implying average slip rates that differ by nearly an order of magnitude.

[6] In the most extensive geologic study of slip rates carried out along the Karakorum fault, *Liu* [1993] and *Liu et al.* [1992] exploited satellite (SPOT) imagery as well as field investigations on the Tibetan side that allowed direct examination of offset features along parts of the fault. *Liu* [1993] studied 24 sites in the southern Karakorum with clear offsets (ranging from ~50 to ~350 m) along the fault, suggesting sustained and present-day activity. One third of these sites show offsets of 250–350 m; assuming that the offset landforms date from approximately 10 ± 2 ka, *Avouac and Tapponnier* [1993] and *Liu* [1993] inferred slip rates of 30–35 mm yr^{-1}.

[7] A critical component of the rapid inferred rate is the assumption that the history of expansion and retreat of glaciers in this region corresponds directly to global paleoclimatic variations. If dates of formation of offset geomorphological features were older than the postglacial ages assigned by *Avouac and Tapponnier* [1993] and *Liu* [1993], the corresponding slip rates would be proportionally lower. The assumed chronology for formation of major geomorphological features is supported by correlations with lacustrine sedimentary records from western Tibet [*Gasse et al.*,

1991, 1996; *Van Campo and Gasse*, 1993]. These, as well as sedimentary records from lakes in the central and eastern Tibetan Plateau [*Lister et al.*, 1991] and in northern Xinjiang [*Rhodes et al.*, 1996], provide generally consistent evidence of a humid period during the latest Pleistocene and early Holocene. However, the sediment cores on which these records are based provide little information on climatic variability earlier than 15–20 ka.

[8] The history of glaciation in much of high Asia remains poorly known, and there are few direct dates on the formation of glacial features. Nevertheless, there is evidence that central Asian glaciation was characterized by relatively small valley glaciers and not a regional ice sheet. In some areas, particularly in the northern and eastern areas of the Tibetan plateau, these valley glaciers reached their maximum positions during the Last Glacial Maximum (∼20 ka), but in areas to the southwest of the Tibetan Plateau maximum expansions of valley glaciers occurred earlier (see reviews by *Benn and Owen* [1998], *Derbyshire et al.* [1991], *Lehmkuhl and Haselein* [2000], and *Shroder et al.* [1993]). In any case, there is a clear need for additional direct dating of geomorphic features and a better knowledge of timing of glacial expansion in this part of the world.

[9] Because the Karakorum fault has been assigned one of the highest slip rates, it provides an ideal laboratory to examine the suggestions (1) that major glacial and alluvial landforms in central Asia date from the last glacial period, (2) that rates of slip along major strike-slip faults in Asia can be estimated reliably by assuming that landforms formed during the last deglaciation, (3) that rates of slip along such faults are high, and thus (4) that eastward extrusion of Tibetan crust is rapid and plays a key role in the kinematics of Asian deformation.

1.2. Cosmic Ray Exposure Techniques

[10] Cosmic ray exposure dating utilizes the accumulation of rare nuclides in rock exposed at the earth's surface. These nuclides are produced through nuclear reactions induced by high-energy cosmic radiation. This method has been applied to a range of problems in climate history and geomorphology (see reviews by *Bierman*, [1994], *Cerling and Craig* [1994], or *Lal* [1991]) including applications to dating of depositional features [*Anderson et al.*, 1996; *Brown et al.*, 1998]. The approach provides a means of determining slip rates along faults by dating offset depositional features (alluvial fans, moraines, debris flows). Here we use in situ-produced [10]Be ($t_{1/2}$ = 1.5 Myr), to date debris flows deposited over active faults, and subsequently displaced by movement on those faults.

[11] In general, the accumulation of these nuclides in a rock exposed at the earth's surface and undergoing erosion at a constant rate (ε; g cm^{-2} yr^{-1}) may be described by

$$N(t) = \frac{P}{(\varepsilon/L + \lambda)} \left[1 - e^{-t(\varepsilon/L+\lambda)} \right] + N(0)e^{-t\lambda},$$

where $N(t)$ is the concentration of a cosmogenic nuclide at time t, P represents the production rate at the rock's surface (atom g^{-1} yr^{-1}); L is the characteristic attenuation length (g cm^{-2}) for cosmic secondary particles (mostly neutrons) producing cosmogenic nuclides, and λ is the decay constant for radioactive cosmogenic nuclides (yr^{-1}). Because the

half-lives of the cosmogenic radionuclides commonly used for cosmic ray exposure dating ([10]Be, [26]Al, [36]Cl) are long relative to the ages of most landforms in a tectonically active region, little additional information is gained by measurement of multiple nuclides in the same sample. Any date obtained through this method can thus either overestimate (due to exposure prior to the episode of interest such that $N(0)$ is significant) or underestimate (because of decreased accumulation of the cosmogenic nuclide resulting from postdepositional processes such as burial, shielding, or erosion) the time of the deposition or the formation of a feature. These biases may be evaluated by judicious sampling and field observations. The working hypothesis we adopted for sampling was that rocks in our study area had minimal near-surface exposure before deposition, so that their cosmogenic nuclide content would reflect surface exposure in their present positions. Any scatter in the values would be the result of postdepositional processes, all of which decrease the accumulation of cosmogenic nuclides. Under these conditions, the sample with the highest cosmogenic nuclide concentration would be the one least affected by postdepositional processes and would thus yield the most accurate age, ignoring potential errors due to uncertainties in cosmogenic nuclide production rates [*Brown et al.*, 1998]. These assumptions may be reasonable in many high-energy depositional environments and may be evaluated through examination of "geological blanks": samples of rocks whose exposure histories in source regions and during transport were similar to those of the materials to be dated, but that have been exposed only briefly in their present positions [*Brown et al.*, 1998].

2. Field Work, Sampling and Laboratory Methods

2.1. Field Observations and Site Descriptions

[12] This study focuses on three sites in the Karakorum Range in Ladakh, India: the Nubra Valley and the Tangtse Valley, which contain the mapped trace of the Karakorum fault, and a large moraine at the village of Ganglas, near the city of Leh (Figure 2). We collected datable material at all three sites (charcoal for radiocarbon dating at Nubra and quartz-rich rocks for cosmic ray exposure dating at Tangtse and Ganglas) and mapped the two valley sites.

2.1.1. Nubra Valley

[13] We visited the southern end of the Nubra Valley, a NW trending valley, which the Karakorum fault appears to follow [*Searle*, 1996; *Searle et al.*, 1998]. Although highly deformed rock, including mylonite, crops out along the margins of the valley, clear evidence of recent tectonic activity is sparse. Despite two visits that included walking along nearly the entire segment of the fault zone (25 km) for which we could obtain permits to visit, we found only one site where recent surface deformation is distinct from the ongoing regional erosion and mass wasting. Southwest of the village of Panamik (at 34°45.27′N, 77°33.57′E, 3100 m) a prominent west facing scarp, 2 m (±0.2 m) high and striking N145°E, crosses an alluvial fan on the east side of the valley (Figure 3). At this locality, deformation is spread over a zone some 20 m wide, with other nearly parallel scarps and tension cracks forming a small graben west of the high scarp. These features appear to be the result of
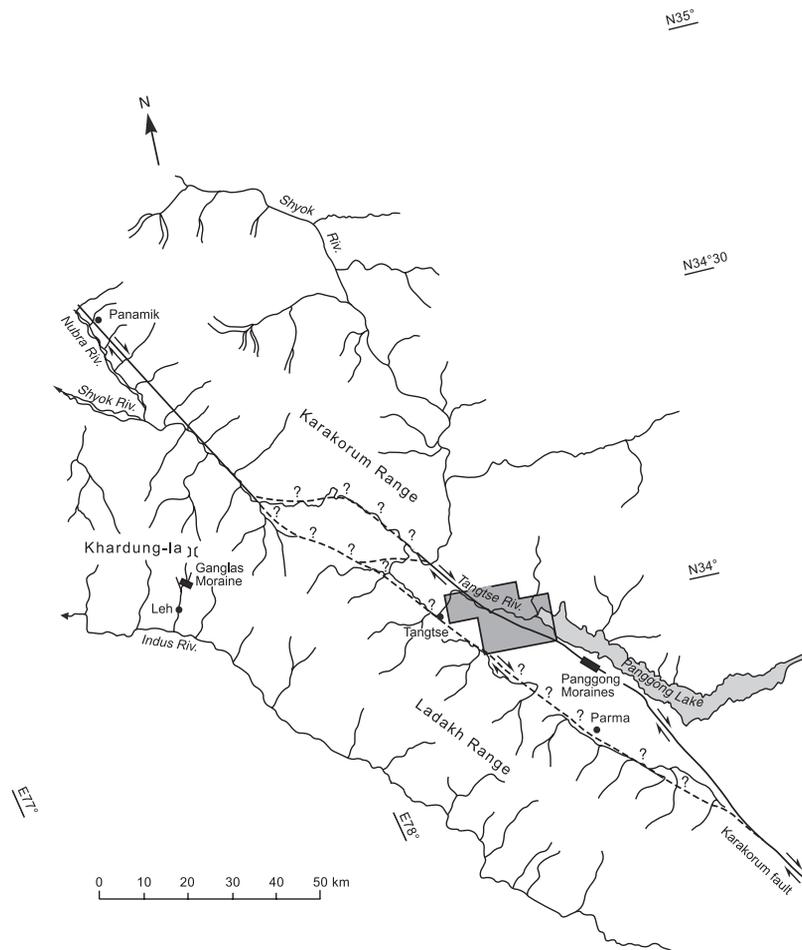
Figure 2. Map of the Karakorum fault in Ladakh, India, modified after *Searle et al.* [1998]. The locations of our study areas (Tangtse Valley, Nubra Valley, and the moraine near Ganglas), as well as those of geographic features and towns noted in the text, are shown. The Tangtse Valley site, presented in more detail in Figure 4, is outlined.

extension perpendicular to the valley; there is no clear evidence of a strike-slip component at this site. We traced surface deformation across a series of fans for a distance of ~0.5 km to both the northwest and southeast. Most of this deformation consists of tension cracks, which we found to be most prominent on steep parts of fans and whose alignment varies from almost N-S to E-W. The lack of a consistent relation with the orientation of the northwest tending Karakorum fault suggests that this deformation is superficial, and not directly related to any simple pattern of faulting at depth.

2.1.2. Tangtse Valley

[14] A number of the features that *Liu* [1993] interpreted from satellite imagery to be moraines with 300–350 m offsets are on the western shore of Lake Panggong (Banggong Tso), which presently occupies a closed basin (Figure 2). Because we were unable to obtain permission for fieldwork in those areas we focused our research efforts in the Tangtse Valley near the northwestern end of the lake (Figure 4). During highstands the lake flowed out through the Tangtse Valley to the Shyok River and ultimately to the Indus. Studies of lake sediments deposited over the past 12 kyr indicate that climatic conditions were sufficiently wet for significant outflow to occur between 8 and 10 [14]C

ka [*Gasse et al.*, 1996]. These ages, however, may be subject to systematic uncertainties associated with the large (6700 year) reservoir effect assumed for this lake [*Fontes et al.*, 1996]. In any case, they indicate the significance of late Pleistocene and Holocene climatic changes in this area. A series of terraces perched up to 40 m above the present valley floor, appear to be remnants of active outflow through the Tangtse Valley. In this valley a number of landforms, including tributary stream valleys, debris flow, and alluvial fans, and individual debris flows, also show evidence of right-lateral offset by active faulting (Figure 4).

[15] Although most of the offset landforms were too eroded either to be good candidates for cosmic ray exposure dating or to allow unequivocal mapping of offsets, at one site we found deposits from two debris flows deposited nearly perpendicular to the strike of the fault and offset ~2 m and ~40 m by right-lateral movement on the fault (Figures 5a, 5b, and 5c). These features lie at elevations above those of the perched river terraces and therefore could have not been directly affected by Lake Panggong outflow. Moreover, the offset of the older debris flow matches that of edge of the entire fan.

[16] Levees marking the older of the debris flows can be seen on the fan, particularly in the part below a stone wall
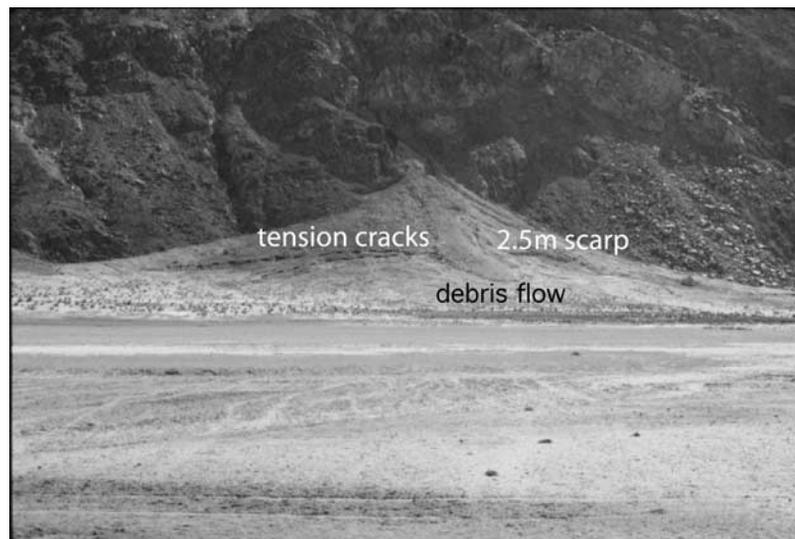
Figure 3. Photograph of a small scarp crossing an alluvial fan on the eastern side of the Nubra Valley viewed from the west. This is the only clear example of surface deformation we found in the southern Nubra Valley. A shoreline of an ancient lake abuts against the fans, particularly to the south of the area where the scarps are clearest. Below the shoreline, horizontal, laminated fine-grained sediments imply prolonged lacustrine conditions. Our limited observations do not permit assessment of whether these sediments were deposited in a lake created by damming of the valley, or simply in ponded water adjacent to the river. The laminated sediments contained enough charcoal to permit radiocarbon dating. The ages we obtained (1180 ± 40 (Beta-112102), 1580 ± 40 (WHOI AMS OS-17067), and 1920 ± 217 ^{14}C years (WHOI AMS OS-17648) for layers that were 1.2 ± 0.2, 3.2 ± 1.0, and 8.7 ± 0.5 m below the ancient shoreline, respectively) are internally consistent with the oldest at the bottom and youngest at the top. They indicate that over the past 2000 years, tectonic activity has not brought about major offsets (i.e., greater than tens of meters) or tilting at this site, but only the tension cracking and surface rupturing described above. This is consistent with only a modest level of tectonic activity along the fault segment. Surface ruptures do not cut the shorelines anywhere that we saw. Clearly, the fan had formed when these sediments were deposited. Thus the shorelines lap onto the fan, but fan debris covers the shoreline in places. See color version of this figure at back of this issue.

that has been built nearly parallel to the fault trace and 10–20 m below it (Figure 5b). Over most of the fan, boulders with dimensions of 1–3 m are sparse, but two lines of them mark levees of what appears to have been the last debris flow to deposit boulders on the surface, before the fan was incised by the stream to the northwest. The source of the debris flow lies at the mouth of the canyon above the fan. These levees are less distinct above the fault scarp. Boulders were moved to make a stone wall, presumably for defensive purposes, and we suppose that the builders took advantage of gravity to roll boulders down from the levees of the debris above the fault, rather than carrying those below it up to the wall. Levees ~6 m apart and with a channel 1–2 m deeper between them mark the more recent debris flow, which is sharply displaced by the fault (Figure 5c).

[17] We created a topographic map of the debris fan containing offset debris flows using kinematic GPS data (Figure 6). These data were collected at a 10 s sampling interval while the antenna was moved across the fan, providing sampling at a spacing of ~21 m along lines spaced ~5 m apart. They were then processed relative to a fixed base station at the bottom of the fan, whose position was measured continuously for 3 days. The map of the fan surface corroborates the evidence of right-lateral offset of the debris flow and allows quantification of the offset of the southeast edge of the fan, seen in the photos (Figures 4

and 5). Contours of the fan curve abruptly at its southeast side, and matching of profiles made parallel to the fault shows a horizontal separation of 45 ± 5 m. As the edge of the fan is oriented obliquely, not perpendicular to the fault trace, the magnitude of this separation depends on the distance of the profiles from the fault, and because of the finite width of the fault zone, we cannot construct profiles at it. To correct for an overestimated measure of the offset, we must subtract an amount, $d \cos \phi = 5$ m, where d ($= 20$ m) is the distance between the profiles and ϕ ($= 75°$) is the angle between the trend of the edge of the fan and the strike of the fault. Thus, we estimate an offset of 40 ± 5 m, which is consistent with that of 45 ± 10 m we measured in the field for the offset of the debris flow and suggests that fan abandonment occurred near the time of deposition of this debris flow. With a measurement of the offset, the date of deposition of this debris flow should permit estimation of the average late Quaternary rate of slip. That of the younger debris flow should constrain the average recurrence interval of major earthquakes on the fault.

[18] The presence of surface features with 2-m and 40-m offsets in close proximity implies that a recent large earthquake activated a section of the fault that has been repeatedly active in the past. The 2-m offset almost surely occurred in a single earthquake with a magnitude of ~7, although we cannot preclude the possibility that it repre-
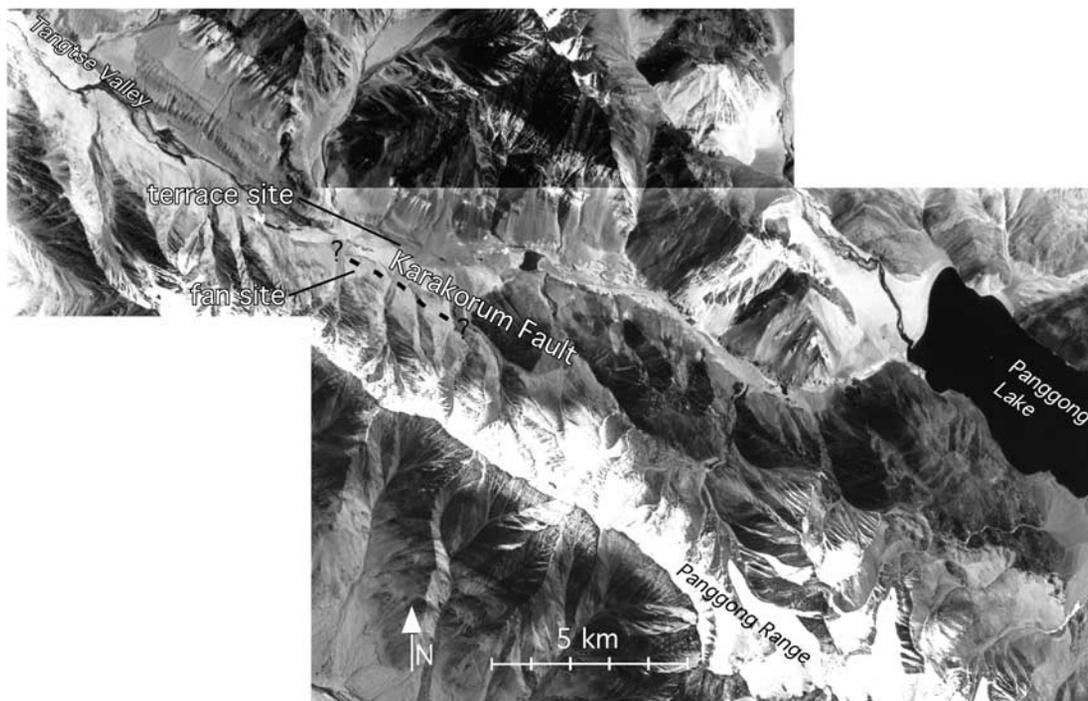
Figure 4. CORONA satellite photographs of the Tangtse Valley study site (available from the U.S. Geological Survey, http://edcwww.cr.usgs.gov/glis/hyper/guide/disp). This valley was the outflow of Lake Panggong during highstands and is within ∼20 km of a site of geomorphological surfaces described by *Liu* [1993] and *Liu et al.* [1992] as having been offset 300–350 m by slip along the fault. The trace of the Karakorum fault, with clear evidence of right-lateral movement, crosses the debris flow fan that we mapped and studied in detail.

sents the cumulative offset of multiple smaller earthquakes. The absence of any historic record [*Gutenberg and Richter*, 1954] implies that such an event occurred before 1900. The form of the debris flow, with clear levees and lower area between them shows well how mass wasting occurs, and how the fan to its northwest was built.

[19] In addition, we examined the valley to the southwest of the Tangtse Valley searching for traces of active faulting
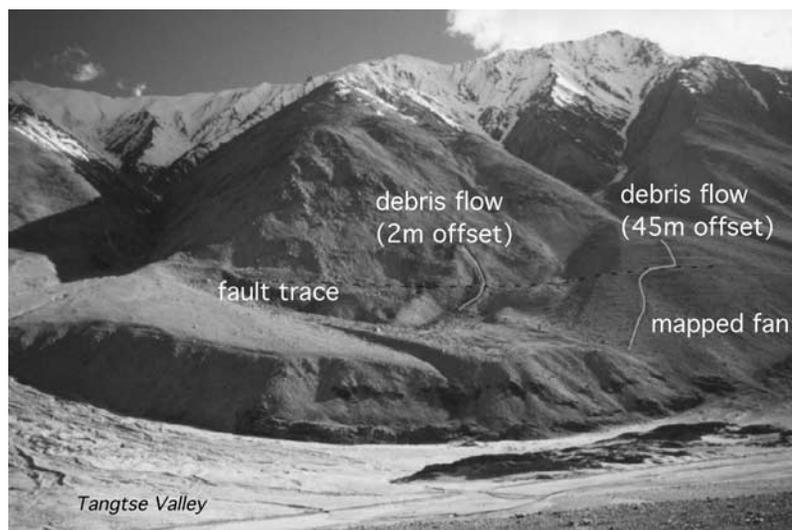

Figure 5a. Wide-angle view, looking southwest, of the Karakorum fault trace in the Tangtse Valley. This photograph was taken from the highest of the fluvial terraces on the northeast side of the valley (see Figure 4). The fault trace can be seen crossing a debris flow fan on the right, offsetting both an old debris flow on the fan and a younger debris flow to its left, and then disrupting topography farther to the left across another fan. Figures 5b and 5c show closer views from the same angle of the two debris flows and their offsets. See color version of this figure at back of this issue.

Figure 5b. Closer view, with the same orientation, of the abandoned debris flow fan in the Tangtse Valley that shows clear evidence of right-lateral strike-slip movement. Levees of the debris flow, defined by parallel lines of boulders, can be discerned below the fault, but above it, they are much less distinct. The trace of the fault, somewhat obscured by construction of a stone wall approximately parallel to it, crosses the middle of the fan and offsets both contours of the fan and the debris flow by ~40 m. See color version of this figure at back of this issue.

(see Figure 2). This would be a possible site of activity along the Karakorum fault if the faulting we studied in the Tangtse Valley represented a minor splay of the fault. Although our observations were not as carefully made or detailed as those in the Nubra or Tangtse Valleys, we saw no clear evidence of faulting in the segment (~30 km) to the southwest, between the villages of Tangtse and Parma. Examination of satellite images also shows little evidence for active faulting.

2.1.3. Moraine at Ganglas

[20] We also sampled a large moraine near the village of Ganglas, ~10 km northeast of the city of Leh (Figure 2), for the purpose of determining when glaciers last expanded to their maximum positions in the Karakorum range. Cosmic ray exposure dates of boulders on the moraine should provide direct chronological control for the last major glacial expansion. This moraine, deposited in a broad valley with a span of ~1 km between its distinct lobes, is the largest and reaches the lowest elevation among moraines in the valleys west of and below the pass, Kardung-La. In fact, this moraine is the only distinct terminal moraine that we saw in the valley, though till abounds at higher elevations. Its size and position suggest that it was deposited during the last major glacial expansion in the region. The morphology of this feature (distinct ridge-like lobes (lateral moraines) and an apparently partially breached terminal moraine (Figure 7)) indicates that it is not likely to be the result of a massive rock avalanche [*Hewitt*, 2000]. We suspect that it may correlate with many of

Figure 5c. Closer view of the smaller debris flow in the Tangtse Valley, offset 2 m right-laterally. Note the levees ~6 m apart that have a trough between them and are sharply offset. See color version of this figure at back of this issue.
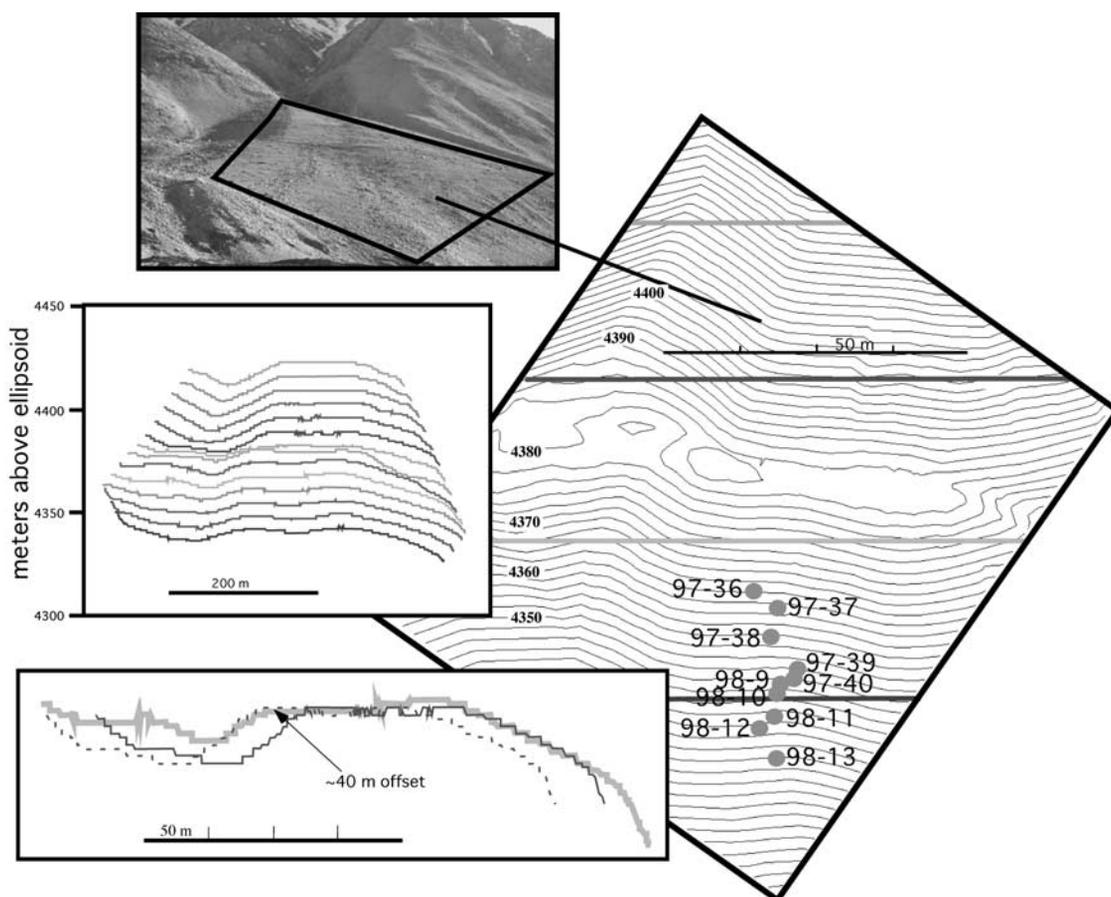
Figure 6.   Topographic map of the Tangtse Valley debris flow fan based on a kinematic GSP survey. The debris flow that we sampled for cosmic ray exposure dating is cut by right-lateral slip along the fault and shows ∼45 m of offset (compare with photographs in Figure 5c). Interpolated profiles parallel to the fault, corresponding to the color-coded lines on the topographic map, are shown at the left. Like the debris flow, these profiles have features, notably changes in slope across the face of the fan, with ∼40-m right-lateral offsets as shown at the bottom left. Sampling locations are noted on the topographic map. There is no obvious relationship between the [10]Be content of a boulder and its position within a given debris flow (compare data in Table 1 with sample positions). See color version of this figure at back of this issue.

the features that *Liu* [1993] and *Liu et al.* [1992] inferred (using satellite imagery) to be offset 300–350 m. The moraine at Ganglas is at significantly lower elevation (3800–3900 m) than those studied by *Liu* [1993] near Lake Panggong (4300–4400 m), but this may be a manifestation of the more humid climate at Ganglas and should not preclude correlation of features in the two areas.

2.2.   Sampling and Analyses

[21]   To determine the timing of formation of these features, we sampled quartz-bearing granidiorite boulders (1–3 m diameter) in the levees of the two Tangtse Valley debris flows and incorporated in the surface of the Ganglas moraine. We collected material from boulders with well-developed desert varnish and avoided boulders that showed evidence of recent disturbance (rolling) or loss of material through spalling. To evaluate exposure prior to deposition in the features to be dated, we collected "geological blanks" from the active stream in the valley immediately to the north of Tangtse Valley debris flow fan (Figure 5b) and also from a boulder exposed by a road-cut at a switchback on the Ganglas Moraine at a subsurface depth of ∼4 m. Material

from the debris flow offset ∼2 m might also be considered to be a geological blank for the debris flow offset by ∼40 m.

[22]   Quartz was purified from samples of granite and granidiorite by preferential acid attack (HCl, H_2SiF_6, HF) of other minerals. To eliminate any possibility of contamination by [10]Be produced in the atmosphere, this purified quartz was cleaned by a series of HF-cleaning steps before the final cleaned quartz (5–20 g) was dissolved in HF. After addition of a 300 mg [9]Be carrier, targets for analysis by accelerator mass spectrometry were prepared by solvent extraction and precipitation [*Brown et al.*, 1991]. Analyses, with calibration against NIST Standard Reference Material 4325, were undertaken at the Tandétron Accelerator Mass Spectrometer at Gif-sur-Yvette, France [*Raisbeck et al.*, 1994, 1987]. Analytical uncertainties are based on counting statistics and conservative assumptions of a 5% uncertainty in machine calibration and a 50% uncertainty in the chemical and analytical blank correction. These blank corrections were <1% for samples from surfaces to be dated and <10% for the geological blanks.

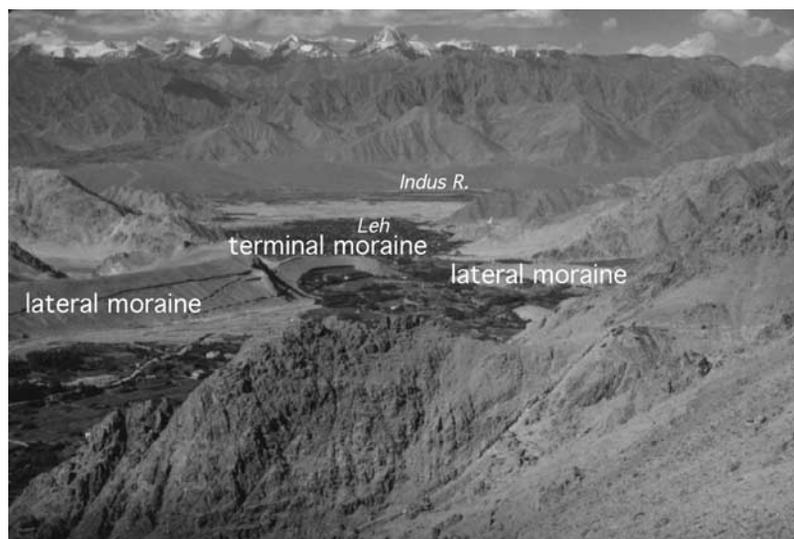[23]   At the Earth's surface, production rates of cosmogenic nuclides vary with time, altitude, and location. Appa-

Figure 7. Moraine near the village of Ganglas photographed from the northeast. This site is ∼7 km northeast of the city of Leh, which is visible as a vegetated region. This is the lowest elevation and the largest (∼1 km between lobes) moraine in the valleys west of and below the pass, Kardung-La. The ridges of the lateral moraines and the breached terminal moraine are clearly visible. We suspect that formation of this moraine correlates with deposition of the features inferred (using satellite imagery) to be offset by 300–350 m [*Liu*, 1993; *Liu et al.*, 1992]. See color version of this figure at back of this issue.

rent exposure ages were calculated using production rates calculated for the altitude and geomagnetic inclination of our site following the calculations of *Dunai* [2000] but neglecting production by muons, which produce only ∼1% of [10]Be at sea level [*Braucher et al.*, 1998; *Brown et al.*, 1995] and contribute an even smaller amount at mountain altitudes. At our sites, production rates calculated using the commonly used polynomials of *Lal* [1991] are ∼15% lower than those we adopt and would yield correspondingly greater exposure ages. This difference is primarily due to the lower attenuation length in air inherent in the calculations of *Dunai* [2000], which is also consistent with recent experimental results [*Brown et al.*, 2000]. Because the average location of the geomagnetic North Pole over the past 10,000 years is very close to the geographic North Pole [*Ohno and Hamano*, 1992], we utilize production rates calculated with inclinations relative to the geographic pole. Production rates at individual sampling sites were corrected for shielding by local topography by integrating field measurements of skylines with the $\sin^{2/3}\theta$ dependence of the cosmic ray flux on angle θ above horizontal [*Conversi and Rothwell*, 1954]. This correction was always less than 10%. For comparison of exposure ages within a given landform or region, we report ages in terms of "[10]Be years" propagating experimental uncertainties, but ignoring any uncertainty in production rate [*Brown et al.*, 1998; *Gosse et al.*, 1995]. In contrast, for comparison of our ages with those determined by other methods, we assume a 15% uncertainty in the value of production rates and report ages in "years."

3. Results

3.1. Tangtse Valley Site

[24] The distributions of [10]Be concentrations of boulders incorporated in the two debris flows cluster tightly enough to suggest that they date the flows. In both cases, 7 or 8 of the 10 measured concentrations cluster within a fairly narrow range and 2 or 3 outlying samples have much higher concentrations (Table 1). This suggests that there are two distinct populations of boulders within each debris flow: Most were exhumed from depth when the debris flow occurred, and a few previously exposed on the fan surface were entrained in the debris flow as it passed over the fan. *Van der Woerd et al.* [1998] took a similar approach in evaluating [10]Be results from alluvial terraces along the Kunlun fault. There is no obvious relationship between [10]Be concentrations and sample positions within the debris flows (Figure 6 and Table 1). Disregarding these high outliers, the [10]Be concentrations correspond to ages ranging from 0.9 to 3.7 [10]Be ka and 10.9 to 13.7 [10]Be ka for the debris flows with 2-m and 40-m offsets, respectively (Figure 8). Exposure ages of 0.4 ± 0.1 and 1.6 ± 0.4 [10]Be ka for boulders in the active fan are consistent with only modest levels of prior exposure for material within the debris flows. Using the average cosmic ray exposure ages of boulders in the 2-m offset debris flow and the adjacent active fan as a geological blank, we adopt an age of 10 ± 2 [10]Be ka for deposition of the 40 ± 5 m offset debris flow.

3.2. Moraine at Ganglas

[25] The four samples from the moraine at Ganglas yielded ages ranging from 67 to 93 [10]Be ka (Table 1). The low [10]Be content of the geological blank corresponds to less than 1000 [10]Be years of exposure. Limited prior exposure is not unexpected; virtually all of the material incorporated in a moraine of this size would have been excavated from substantial subsurface depth. This implies that the scatter observed in the dates is the result of postdepositional processes (burial, erosion from boulder surfaces, spalling of boulder tops, rolling of boulders) all of which decrease the quantity of [10]Be accumulated in a given time [*Brown et al.*, 1998; *Hallet and Putkonen*, 1994].

Table 1. Cosmic Ray Exposure Dates of Landforms

Sample	Mass Quartz, g	[10]Be, 10^3 atom g^{-1}	[10]Be Error, 10^3 atom g^{-1}	Age, [10]Be ka	Age Error, [10]Be ka	Calendar ka
Tangste Valley Debris Flow, 40-m Offset						
KK97-36	7.84	1968	132	21.3	1.4	3.5
KK97-37	8.67	2307	198	25.0	2.1	4.3
KK97-38	7.87	1016	111	11.0	1.2	2.0
KK97-39	16.79	1214	90	13.1	1.0	2.2
KK97-40	14.46	1264	100	13.7	1.1	2.3
KK98-9	9.23	1068	74	11.5	0.8	1.9
KK98-10	11.09	1040	162	11.2	1.8	2.4
KK98-11	17.03	1008	111	10.9	1.2	2.0
KK98-12	15.79	1141	85	12.3	0.9	2.1
KK98-13	11.13	2814	170	30.5	1.8	4.9
Tangste Valley Debris Flow, 2-m Offset						
KK98-1	21.83	143	38	1.5	0.4	0.5
KK98-3	19.95	207	32	2.2	0.3	0.5
KK98-4	15.92	442	51	4.8	0.5	0.9
KK98-5	16.20	111	15	1.2	0.2	0.2
KK98-6	7.90	345	44	3.7	0.5	0.7
KK98-7	8.09	300	59	3.2	0.6	0.8
KK98-8	17.56	789	59	8.5	0.6	1.4
KK98-14	12.67	107	14	1.2	0.2	0.2
KK98-15	8.45	80	14	0.9	0.2	0.2
Tangste Valley, Active Stream						
KK97-41	14.86	42	10	0.4	0.1	0.1
KK97-41.5	8.39	147	35	1.6	0.4	0.4
Moraine at Ganglas						
KK97-43	23.02	5021	293	69.5	4.0	11.2
KK97-44	27.88	6701	388	93.2	5.4	15.0
KK97-48	12.26	6192	408	86.0	5.7	14.1
KK97-49	15.99	4812	501	66.5	6.9	12.1
Moraine at Ganglas, Road Cut						
KK97-46	25.75	39	39	0.5	0.5	0.5

This implies that the ages are lower limits and that the oldest probably most closely approach the actual age of the moraine. Given the analytical uncertainties, the two oldest are statistically indistinguishable. The mean age, 90 ± 15 ka (with the assumption of a 15% uncertainty in [10]Be production rates; see Methods) suggests that this moraine was deposited during a cold period with enhanced precipitation at least 75 ka, perhaps early in marine isotope stage 4. Given that cosmic ray exposure dates represent lower limits for ages of landforms, assuming a single episode of exposure, our ages are not inconsistent with moraine deposition at an earlier time. In any case, our direct date of the last major glacial advance in the region requires that it be far earlier than the Last Glacial Maximum.

4. Discussion and Conclusions

4.1. Implications for Asian Climate History

[26] The relationship of the timing of glacial expansion in central Asia with regional records of monsoon circulation and with variations in orbital parameters remains difficult to resolve. This is due to both the paucity of dates for deposition of glacial landforms and the complexity of the regional climate system. Glacial expansion is generally a response to lower temperatures, but at high altitudes it may be more sensitive to changes in moisture transport. Precipitation patterns in the Karakorum and western Tibet are strongly dependant on the Indian Summer Monsoon. A number of sedimentary records from the Arabian Sea suggest that intensity of the Indian Monsoon was generally greater during interglacial rather than glacial periods [*Clemens et al.*, 1991; *Emeis et al.*, 1995; *Rostek et al.*, 1997]. These records include: mean grain size, reflecting wind intensity; UK37 paleothermometry of sea surface temperature, with cooler temperatures reflecting lower insulation or more intense upwelling associated with increased wind stress; and barium and silicate fluxes to sediments, indicating enhanced productivity in response to greater upwelling. Enhancement of precipitation resulting from stronger summer monsoonal circulation during interglacial periods could lead to alpine glaciation that was either synchronous or asynchronous with Northern Hemisphere glaciation, depending on whether a given locality was more sensitive to changes in temperature or in precipitation, respectively.

[27] Some general relationships between the histories of Himalayan glaciation and of regional climate are emerging. In some areas, particularly in the northern and eastern areas of the Tibetan Plateau, glaciers appear to have reached their maximum positions during the Last Glacial Maximum, whereas in areas to the southwest of the Tibetan Plateau, glacial expansion occurred earlier and may not have coincided with Northern Hemisphere glaciation (see review by *Benn and Owen* [1998]). Our results, suggesting maximum glacial expansion in Ladakh at 90 ± 15 ka, support this view, as do other recent studies that date glacial deposits. Qualitative studies of moraine advances in the northern
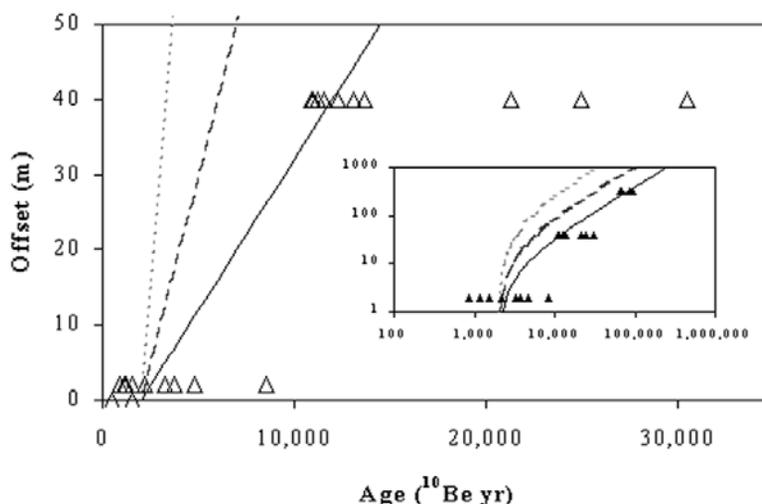
Figure 8. Offset as a function of [10]Be age for the debris flows in the Tangtse Valley. Boulders within the two debris flows have similar distributions of exposure ages, with a tight cluster of ages and a few older outliers. This suggests that a few of the boulders in the debris flow levees had been previously exposed on the fan surface and entrained into the debris flow. The "geological blank" measurements for boulders in the active stream adjacent the abandoned fan containing the 40-m offset are assumed to have no offset. The solid line, fit to the centers of the data clusters, has a slope that corresponds to a slip rate of 4 mm yr^{-1}. Lines with slopes corresponding to slip rates of 30 mm yr^{-1} (short dashes) and 10 mm yr^{-1} (long dashes), clearly inconsistent with the data, are included for comparison. Coupled with our measured 2-m offset for the most recent earthquake, this slip rate implies a recurrence interval of 500 years. The inset includes (on a logarithmic scale) our dates for deposition of the moraine at Ganglas coupled with *Liu*'s [1993] inferred offsets for moraines near Lake Panggong. These results are also consistent with a slip rate of ~4 mm yr^{-1} (the lines in the inset is the same as those in the main part of the figure) and suggest that this relatively low rate of slip may be representative of fault activity on a 10^5 year timescale.

Pamir, some 1000 km to the north of our study site, indicate that moraines from the most recent glacial advance are at much higher elevations than the more prominent moraines deposited by an earlier glacial expansion [*Arrowsmith and Strecker*, 1999]. Examination of glaciation at Nanga Parbat (northern Pakistan; ~700 km northwest of our study site) using dates based on [10]Be and infrared stimulated luminescence indicated significant glacial expansion during the early to middle Holocene (5.5–9 ka) but provided no evidence of glacial expansion during the Last Glacial Maximum [*Phillips et al.*, 2000]. An optically stimulated luminescence date of 78 ± 12 ka for extensive valley glaciation in the Zanskar Range at a site within 50–100 km of our study areas [*Taylor and Mitchell*, 2000] is consistent with our date for formation of the moraine at Ganglas and could be consistent with glacial expansion during marine isotope stage 4.

4.2. Slip Rates and Implications for Dynamics of Continental Tectonics

[28] The ages for deposition (10 ± 2 ka) and measured offset (40 ± 5 m) of the larger debris flow in the Tangtse Valley indicate an average slip rate of 4 ± 1 mm yr^{-1} along this segment of the fault (Figure 8). Assuming that the 2-m offset observed for the smaller debris flow represents a single seismic event, this rate corresponds to a recurrence interval of ~500 years for such earthquakes at this site, or proportionally shorter intervals for smaller events. If the moraine inferred by Liu to have been offset 300–350 m were associated with stage 4 glaciation like the Ganglas

moraine, it would also suggest a slip rate of 3–4 mm yr^{-1}, consistent with the rates we obtain for the debris flow in the Tangtse Valley (Figure 8). These rates are roughly an order of magnitude lower than those reported by *Liu* [1993] and utilized by *Avouac and Tapponnier* [1993] to describe the kinematics of active deformation in central Asia. They are also somewhat lower than rates of 10 mm yr^{-1} estimated for offsets occurring over the past 18 Myr [*Searle et al.*, 1998], a much greater temporal scale than that of our study. In addition, our rate is nearly the same as that inferred by *Murphy et al.* [2000] for the southeast end of the Karakorum fault. *Murphy et al.* [2000] matched a thrust fault active over the past 11 Myr and offset 66 ± 6 km, corresponding to an average rate of ~6 mm yr^{-1}. From the difference in the offset they measured and that inferred by *Searle et al.* [1998], they deduced that the fault has propagated to the southeast.

[29] The large overestimate of the rate of the Karakorum fault in the earlier works raises the question of how such an error was made. Until GPS measurements were made [*Bendick et al.*, 2000; *Chen et al.*, 2000; *Shen et al.*, 2001] the rate of slip along only one fault within Tibet (the Kunlun fault) had been based on quantitative estimates of both offsets and ages of offset features [*Kidd and Molnar*, 1988; *Van der Woerd et al.*, 1998]. For rates along all other faults, offset features were assumed to have formed since the last glacial maximum as defined by the marine record: Altyn Tagh fault [*Meyer et al.*, 1996; *Peltzer et al.*, 1989], Kunlun Pass fault [*Kidd and Molnar*, 1988], the Karakorum-Jiali fault zone across the middle of Tibet [*Armijo et*

al., 1989], and the normal faults in grabens in southern Tibet [Armijo et al., 1986]. Despite enhanced humidity in Tibet during the period following last glacial termination [Gasse et al., 1991, 1996; Lister et al., 1991; Rhodes et al., 1996], no direct evidence links the formation of these offset features to specific climatic events. None of the assumed chronologies are based on radiometric dates or magneto-stratigraphy. Although, these relatively young assumed ages might seem consistent with the well-preserved surfaces typical of these landforms, the effects of erosional processes are attenuated under the cold dry conditions prevailing in these sites. Thus a surface of a given age is likely to appear much fresher than a surface of the same age exposed to more temperate conditions [Gillespie and Molnar, 1995; Ritz et al., 1995].

[30] The slip rate of 4 ± 1 mm yr^{-1} suggests that the Karakorum fault does not play a major role in accommodating present-day convergence between India and the rest of Eurasia. To appreciate the significance of this relatively low rate, one must reconsider the implications of previous studies that suggested far higher rates. The rates of $30-35$ mm yr^{-1} inferred by Liu [1993] and Liu et al. [1992] buttressed the view that rapid strike-slip occurs both on a series of faults across the middle of the Tibetan Plateau (the Karakorum-Jiali fault zone of Armijo et al. [1989] and on the Altyn Tagh fault across the northern margin of the plateau [Peltzer et al., 1989]. Because these assumed rates are much higher than those on normal faults within Tibet, a number of studies [Avouac and Tapponnier, 1993; Peltzer and Tapponnier, 1988; Tapponnier et al., 1986] have inferred that Tibet hardly deforms at all except on its margins, where rapid strike-slip faulting occurs, and hence that much of the Tibetan Plateau can be treated as rigid body. Thus they suggest that the rule of plate tectonics can be applied to the Tibetan Plateau [Avouac and Tapponnier, 1993] and therefore to continental tectonics in general.

[31] Clearly, the much lower slip rate of 4 ± 1 mm yr^{-1} that we deduce does not render the Karakorum fault insignificant, but it does deny this fault precedence over the numerous normal faults that bound grabens in Tibet [Armijo et al., 1986; Mercier et al., 1987]. Moreover, with the GPS evidence for a slip rate of only ~10 mm yr^{-1} on the Altyn Tagh fault [Bendick et al., 2000; Chen et al., 2000; Wang et al. 2001; Shen et al., 2001] the internal deformation of Tibet does not seem especially mild compared to that on its margins. Treating Tibet as a rigid plate, similar to oceanic plates, is a poor approximation.

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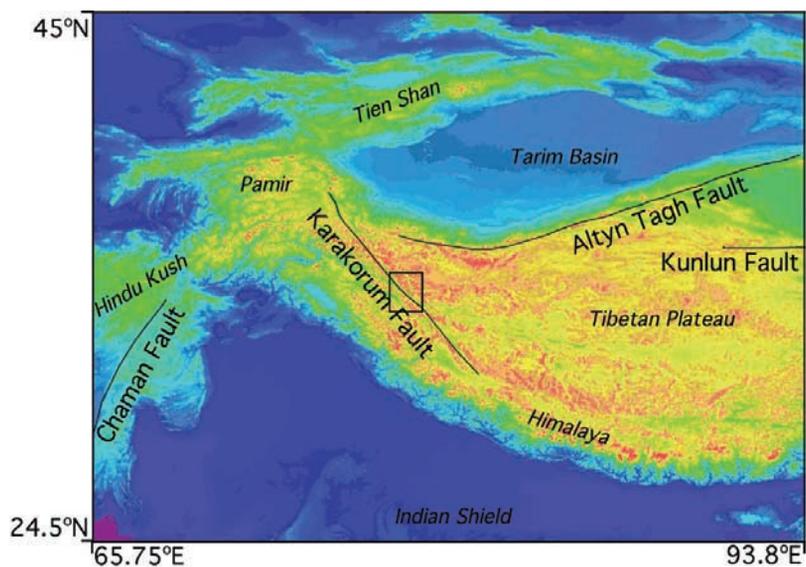
Figure 1. Topographic map of central Asia, based on satellite digital elevation data, showing topographic expression of tectonic features, including major active faults. The region of our study, shown in more detail in Figure 2, is outlined.

Figure 3. Photograph of a small scarp crossing an alluvial fan on the eastern side of the Nubra Valley viewed from the west. This is the only clear example of surface deformation we found in the southern Nubra Valley. A shoreline of an ancient lake abuts against the fans, particularly to the south of the area where the scarps are clearest. Below the shoreline, horizontal, laminated fine-grained sediments imply prolonged lacustrine conditions. Our limited observations do not permit assessment of whether these sediments were deposited in a lake created by damming of the valley, or simply in ponded water adjacent to the river. The laminated sediments contained enough charcoal to permit radiocarbon dating. The ages we obtained (1180 ± 40 (Beta-112102), 1580 ± 40 (WHOI AMS OS-17067), and 1920 ± 217 ^{14}C years (WHOI AMS OS-17648) for layers that were 1.2 ± 0.2, 3.2 ± 1.0, and 8.7 ± 0.5 m below the ancient shoreline, respectively) are internally consistent with the oldest at the bottom and youngest at the top. They indicate that over the past 2000 years, tectonic activity has not brought about major offsets (i.e., greater than tens of meters) or tilting at this site, but only the tension cracking and surface rupturing described above. This is consistent with only a modest level of tectonic activity along the fault segment. Surface ruptures do not cut the shorelines anywhere that we saw. Clearly, the fan had formed when these sediments were deposited. Thus the shorelines lap onto the fan, but fan debris covers the shoreline in places.
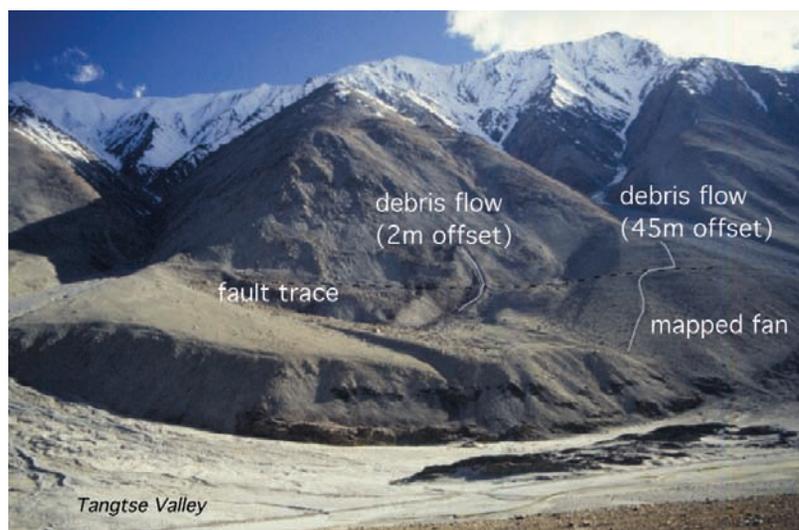
Figure 5a. Wide-angle view, looking southwest, of the Karakorum fault trace in the Tangtse Valley. This photograph was taken from the highest of the fluvial terraces on the northeast side of the valley (see Figure 4). The fault trace can be seen crossing a debris flow fan on the right, offsetting both an old debris flow on the fan and a younger debris flow to its left, and then disrupting topography farther to the left across another fan. Figures 5b and 5c show closer views from the same angle of the two debris flows and their offsets.

Figure 5b. Closer view, with the same orientation, of the abandoned debris flow fan in the Tangtse Valley that shows clear evidence of right-lateral strike-slip movement. Levees of the debris flow, defined by parallel lines of boulders, can be discerned below the fault, but above it, they are much less distinct. The trace of the fault, somewhat obscured by construction of a stone wall approximately parallel to it, crosses the middle of the fan and offsets both contours of the fan and the debris flow by ~40 m.

Figure 5c. Closer view of the smaller debris flow in the Tangtse Valley, offset 2 m right-laterally. Note the levees ~6 m apart that have a trough between them and are sharply offset.
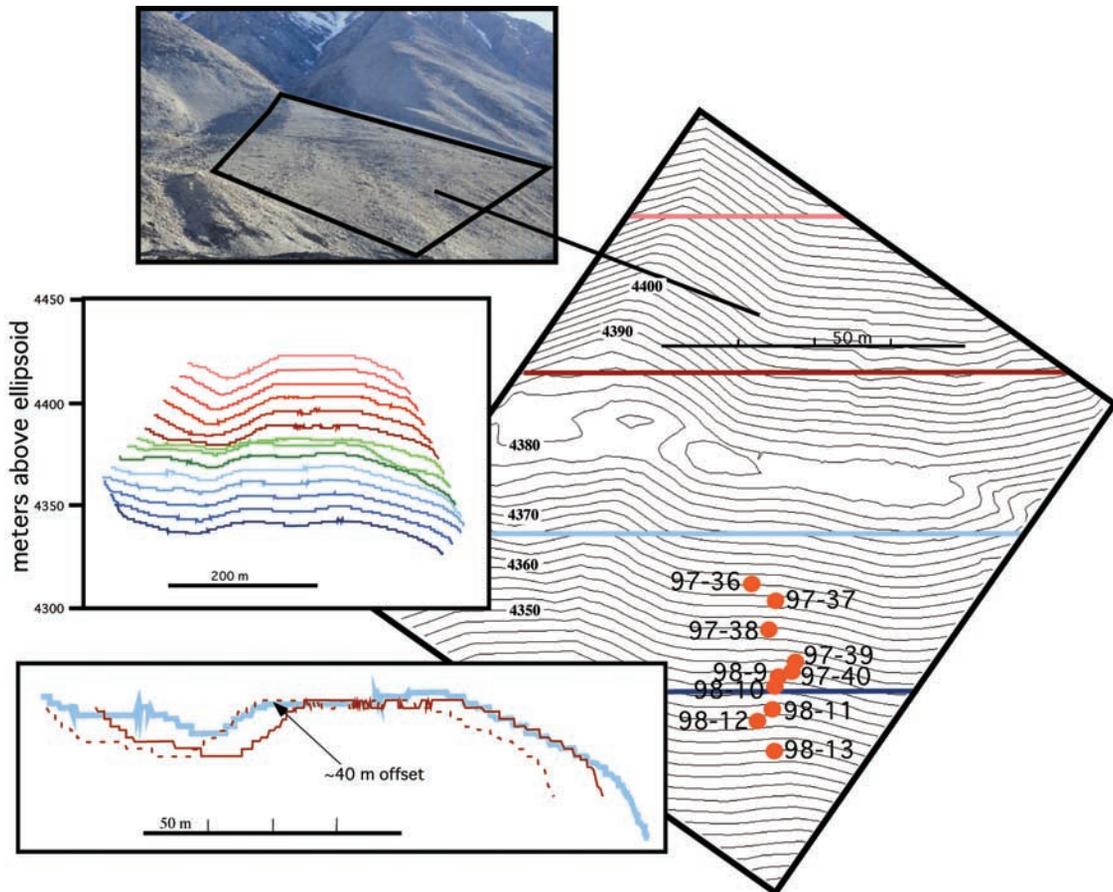
Figure 6. Topographic map of the Tangtse Valley debris flow fan based on a kinematic GSP survey. The debris flow that we sampled for cosmic ray exposure dating is cut by right-lateral slip along the fault and shows ~45 m of offset (compare with photographs in Figure 5c). Interpolated profiles parallel to the fault, corresponding to the color-coded lines on the topographic map, are shown at the left. Like the debris flow, these profiles have features, notably changes in slope across the face of the fan, with ~40-m right-lateral offsets as shown at the bottom left. Sampling locations are noted on the topographic map. There is no obvious relationship between the [10]Be content of a boulder and its position within a given debris flow (compare data in Table 1 with sample positions).
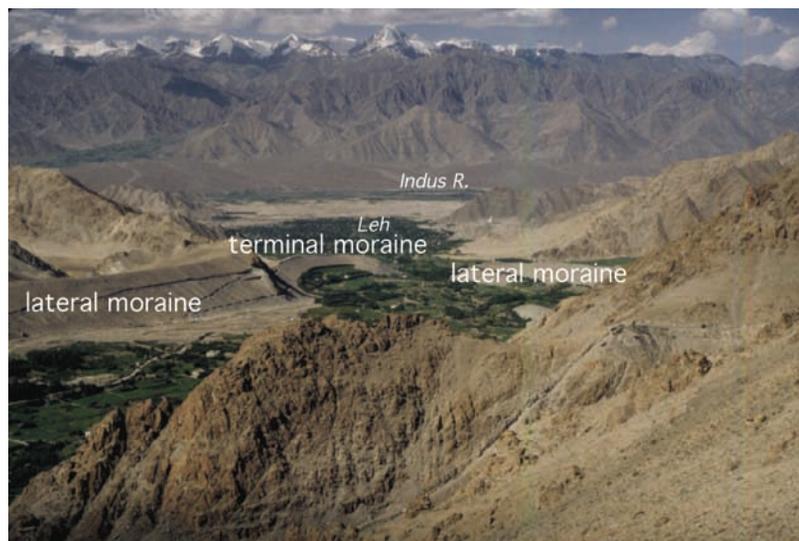
Figure 7. Moraine near the village of Ganglas photographed from the northeast. This site is ~7 km northeast of the city of Leh, which is visible as a vegetated region. This is the lowest elevation and the largest (~1 km between lobes) moraine in the valleys west of and below the pass, Kardung-La. The ridges of the lateral moraines and the breached terminal moraine are clearly visible. We suspect that formation of this moraine correlates with deposition of the features inferred (using satellite imagery) to be offset by 300–350 m [*Liu*, 1993; *Liu et al.*, 1992].