Slip rates along active faults estimated with cosmic-ray–exposure dates: Application to the Bogd fault, Gobi-Altaï, Mongolia

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ABSTRACT

Dating morphological features displaced along active faults presents a major difficulty in evaluation of slip rates. We used in-situ–produced ^{10}Be to calculate minimum ages for alluvial surfaces misaligned by movement along a major active fault in the Gobi-Altaï (western Mongolia). The maximum slip rate of ~1.2 mm/yr suggested by this method contrasts strongly with rates of ~20 mm/yr that we estimated by correlation of alluvial deposition with warm humid periods associated with the last glacial termination estimated to have occurred about 12 ka in western Tibet. The ^{10}Be-based slip rate indicates that strong earthquakes can occur along faults with low slip rates and demonstrates the contribution of cosmic-ray–exposure dating in Quaternary tectonic analyses.

INTRODUCTION

Studies of intracontinental seismotectonics show that present-day deformations (i.e., during the past ~100 yr) are commonly unrepresentative of late Quaternary tectonics. For instance, no major earthquakes occurred along the Altyn Tagh fault during the past century (Fig. 1A) although it is considered the largest active fault in central Asia (e.g., Avouac and Tapponnier, 1992). Estimation of long-term deformation rates generally involves examination of surface features that accumulate deformation over geologically significant time scales.

Even if morphological markers (river networks, alluvial fans, moraines, or terraces) displaying accumulated displacement can be identified (Sengör, 1979; Allen et al., 1984; Gaudemer et al., 1989), determining their ages remains problematic. The absence of organic material or periglacial fine-grained deposits (loess) in many Central Asian sites precludes radiocarbon or thermoluminescence dating, so ages of morphological markers are typically estimated by correlation with global and regional climatic variations. In central Asia, markers are often considered to be associated with regional climatic pulses that occurred contemporaneously with late Quaternary global climate changes. Armijo et al. (1986) and Armijo and Tapponnier (1989) in southern Tibet, Peltzer et al. (1988) along the Altyn Tagh fault, and Avouac et al. (1993) in the northern Tien Shan have assumed that the most recent major regional climatic event was the Würm deglaciation (~12 ka). This assumption is supported by recent paleoclimatic studies of western Tibet that indicate warm and humid climatic pulses at 12.5 and 10 ka (Gasse et al., 1991; Gasse and Van Campo, 1994) and by thermoluminescence dates of 11.5 ± 1.5 and 9.4 ± 0.1 ka for deformed alluvial terraces along the Ta Quen Kou strike-slip fault in northeastern Tibet (Meyer, 1991). Under this assumption, Peltzer et al. (1989) determined a slip rate of 20 mm/yr in the Karakax valley along the western part of the Altyn Tagh fault.

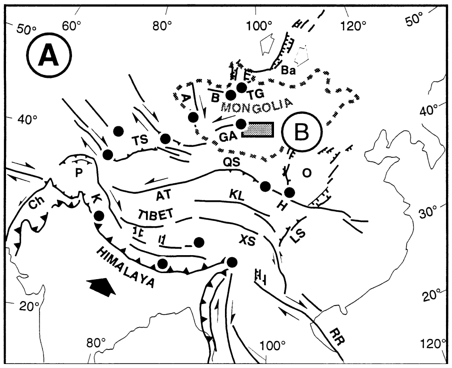
A recent study of the four M ≥ 8 intracontinental earthquakes of this century in western Mongolia and adjacent parts of China (Tsetserleg, July 9, 1905, M = 8.4; Bulnay, July 23, 1905, M = 8.7; Fu-Yun, August 10, 1931, M = 8.0; and Gobi-Altaï, December 4, 1957, M = 8.3) (Fig. 1A) yielded a 90 year average seismic deformation rate consisting of 49 ± 15 mm/yr of northeast-southwest shortening and 40 ± 12 mm/yr of northwest-southeast extension (Baljinnyam et al., 1993). Considering the 50 mm/yr of northeast-southwest convergence between India and Asia (DeMets et al., 1990), these strain rates appear to be abnormally high (Baljinnyam et al., 1993) and would imply very short earthquake recurrence intervals in western Mongolia (~100 yr).

Our study examines whether these strain rates are representative of tectonic activity on longer time scales. Because of its well-preserved surface breaks and clearly evident cumulative displacements, we focused on the Bogd fault in the Gobi-Altaï (Fig. 1B). The 1957 earthquake that occurred on this fault resulted in more than 250 km of seismic ruptures (Florensov and Solonenko, 1963) with an average horizontal left-lateral strike-slip offset of 5 ± 2 m (Figs. 1B, 1C).

MORPHOLOGICAL EVIDENCE

We made a preliminary estimation of the slip rate along the Bogd fault on the basis of a detailed field study and analysis of Russian aerial photographs taken a few months after the 1957 event. At Noyan Uul, to the west of the Ike Bogdo massif (location in Fig 1B), there are morphological features clearly displaying cumulative horizontal displacements (Fig. 2A). The east-southeast–trending fault scarp delimits two morphological domains: (1) to the south a mountainous area incised by deep ravines and (2) an alluvial plain that dips gently (5°–10°) northward. The drainage network clearly shows small-scale left-lateral strike-slip movement; along the fault a 6.6 ± 0.3 m offset is visible, and numerous small streams show left-lateral displacements.

At a larger scale, various markers allow identification of cumulative displacements. North of the fault scarp there are several generations of incised alluvial fans. The younger fans are cone



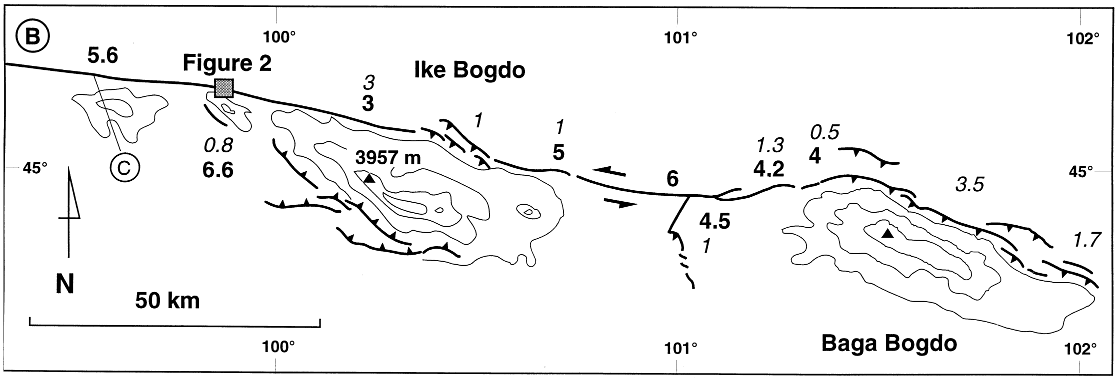


Figure 1. A: Simplified structural sketch map of active faults in central Asia and their associated M ≥ 8 earthquakes (solid dots) recorded during past century (modified after Molnar and Deng, 1984). Bal—Baïkal, TG—Tsetserleg fault, B—Bulnay fault, A—Altaï, GA—Gobi-Altaï, TS—Tien Shan, P—Pamir, Ch—Chaman fault, K—Karakorum fault, AT—Altyn Tagh fault, QS—Qilian Shan, O—Ordos, H—Haiyuan fault, KL—Kunlun fault, XS—Xian Shui fault, LS—Lungmen Shan, RR—Red River fault. B: Surface breaks associated with 1957 Gobi-Altaï earthquake. Bold and italic numbers indicate horizontal and vertical displacements in metres, respectively (data from Florensov and Solonenko [1963], Baljinnyam et al. [1993], and this work). C: Example of pure sinistral offset associated with 1957 earthquake; view toward north; black arrows indicate fault, and black triangles show displacement (people stand on ridges that are left-laterally displaced by 5.6 m).

shaped in plan view. During deposition, they truncated parts of the older fans. In our study area, some fans (S1, S2) do not at present correspond to any upslope stream (Fig. 2A), implying that the alluvial plain has been sinistrally displaced relative to the mountainous domain. This left-lateral strike-slip offset is also manifested by the misalignment of the two largest stream incisions in the alluvial fans (D1, D2) relative to streams upslope of the fault. Simultaneous alignment of flood-plain features (S2, D1, and D2) with upslope streams (U0, U1, and U2, respectively) requires compensation for a 223 ± 13 m horizontal offset (Fig. 2C).

Assuming a major regional climate change contemporaneous with the Würm deglaciation, the incision of valleys U1-D1 and U2-D2 can be interpreted as the result of enhanced stream power associated with glacial meltwater. On the lower ground to the east, enhanced sediment transport at that time could have resulted in deposition of material (S2) at the outflow of stream U0. In this scenario, fan S1 (offset 110 m relative to stream U0) would have been deposited during a later episode of enhanced sediment transport (Fig. 2B), and fan S0 would be active at the present time. We have observed suites of analogously displaced fans for several kilometres in both directions along the fault. The foregoing observations indicate a slip rate of 22 mm/yr along the Bogd fault, close to the abnormally high rate of 25 mm/yr calculated from twentieth-century seismic data. This rate would imply that the Bogd fault is as active as the Altyn Tagh fault has been reported to be (Peltzer et al., 1989). Such rapid movement appears unlikely in western Mongolia and challenges the hypothesis that the selected markers are of Holocene age.

COSMOGENIC NUCLIDE EVIDENCE

To examine the question quantitatively, we determined in-situ–produced cosmogenic ^{10}Be concentrations in quartz from gneiss boulders exposed on alluvial-fan surfaces S1 and S2 and at the ridge (R1) to the east of stream D1. In-situ–produced cosmogenic nuclides result from nuclear interactions between cosmic rays and the constituents of surficial rocks. Such nuclides are produced only within the upper 2 m of material at the earth surface. When they are efficiently retained within the matrices of the minerals in which they were produced, in-situ–produced cosmogenic nuclides accumulate with time until their concentrations reach a steady-state balance between production and loss by erosion and radioactive decay (Brown et al., 1991; Lal, 1991). In specific cases, cosmogenic nuclide concentrations may be used to date events that have brought material to the surface from significant depths. The assumption of negligible erosional loss results in a calculated lower limit for the exposure age of a surface, but only if exposure to cosmic rays prior to the present episode was minimal. This technique has permitted determination of exposure ages for previously undatable geologic markers such as glacial moraines, lava flows, meteor craters, and alluvial deposits (as recently reviewed by Bierman, 1994; Cerling and Craig, 1994).

Our working assumptions for slip-rate determinations are (1) that transport, burial, and reworking of material was sufficiently rapid in active fans for little cosmogenic nuclide accumulation to occur and (2) that little loss of cosmogenic nuclides due to erosion occurred subsequent to fan abandonment. Under these conditions, the concentration of an in-situ–produced cosmogenic nuclide is directly related to the time since abandonment of a surface and hence to the initiation of its offset from its upslope sediment source. The surfaces S1 and S2 are relatively flat (except where incised by small gulleys), have thin grassy cover, and are dotted with embedded and partially embedded boulders up to 1 m in diameter (Fig. 3). Surface R1 (Fig. 2A), a flat-topped ridge with steep slopes on both sides, appears to be a relict of an older alluvial fan. Sample collection

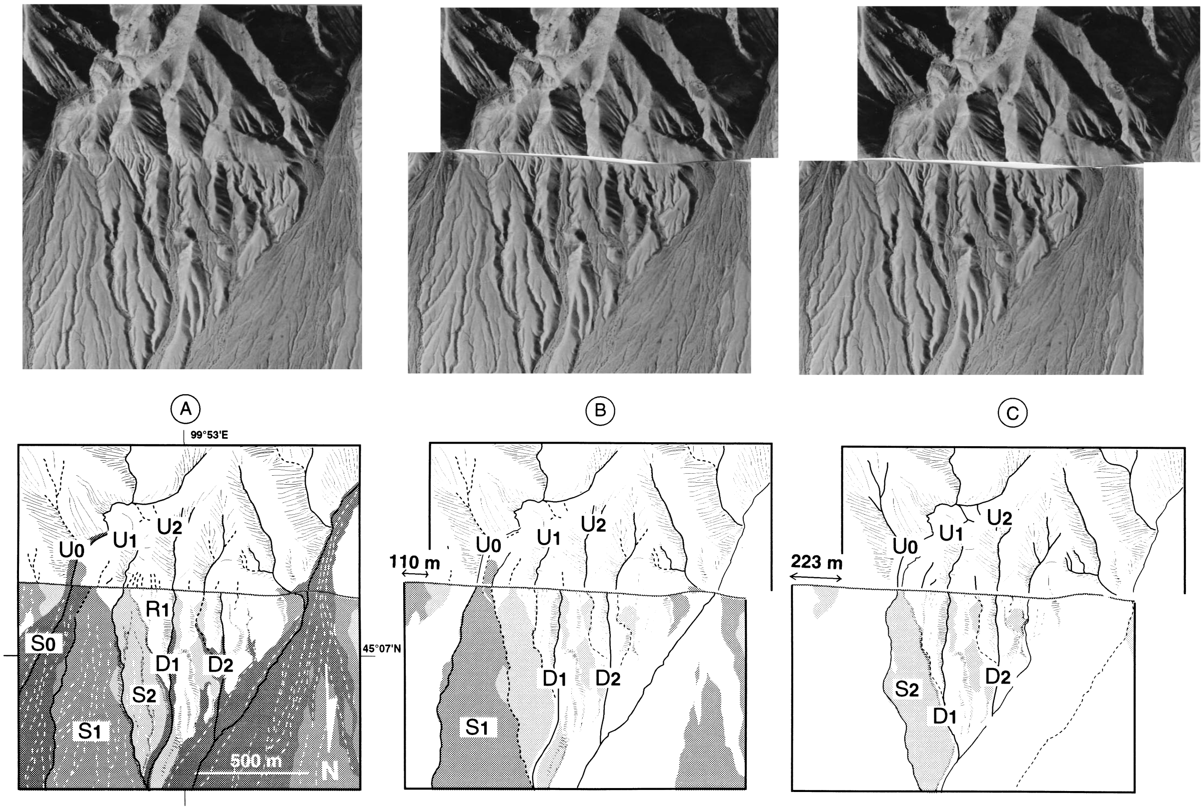


Figure 2. Reconstruction of history of alluvial-fan deposition and erosion along Bogd fault at Noyan Uul based on aerial photographs taken during Russian expedition a few months after 1957 earthquake (scaling factor between sketches and photos is 90%). A: Present day. B: Compensation for 110 m horizontal offset. C: Offset compensation of 223 m. Solid lines labeled U0, U1, and U2 designate major stream axes upstream of fault; D1 and D2 are major axes below fault. Dotted lines indicate smaller river valleys. Shading represents relative age of depositional surfaces (S2, S1, and S0); lightest tones corresponding to oldest surfaces. Only present-day relicts of alluvial fans S1 and S2 are represented in B and C.

strategies attempted to minimize the effects of exposure prior to deposition and of postdepositional erosion. We sampled the tops of gneiss and quartzite boulders (0.5 to 1 m in diameter) embedded in flat areas atop the three surfaces. The dark patinas developed on the boulders provide evidence for a low rate of erosional loss.

The samples were crushed and sieved to yield 0.25 to 1.0 mm fragments, which were then cleaned in HCl to eliminate potential surface contamination by ^{10}Be produced in the atmosphere (Brown et al., 1991). Quartz, the mineral of choice for studies of in-situ–produced ^{10}Be, was purified from the cleaned material by selective dissolution of feldspars with H_2SiF_6. After quantitative dissolution of this purified quartz in HF, the samples were spiked with ^{9}Be carrier for analyses of ^{10}Be. After target preparation, the ^{10}Be analyses were performed by accelerator mass spectrometry at the Tandétron AMS facility, Gif-sur-Yvette, France (Raisbeck et al., 1987, 1994).

The ^{10}Be concentrations of samples range from 1.0 to 1.8 × 10^6 atoms per gram; there are no major differences among the surfaces (Table 1). Interpretation of these results requires integration of field evidence on the relative ages of the surfaces. The offset of surface S2 relative to stream U0 is twice that of surface S1; assuming constant rates of offset (on the 10^4 yr scale), its age should be double that of the younger surface. The ridge (R1) is an eroded relict of an even older alluvial depositional surface. The minor variations of

Figure 3. Photograph of abandoned alluvial-fan surface S1 with some of the exposed gneiss boulders from which samples were collected; squatting people provide scale. View toward south; Noyan Uul foothills are in background (see Fig. 2A).

TABLE 1. ^{10}Be CONCENTRATIONS AND CALCULATED MINIMUM EXPOSURE AGES

Sample	Surface	^{10}Be (10^6 atoms/g)	Uncertainty (10^6 atoms/g)	Min. age (ka)	Uncertainty (ka)
D IV 1	R1	1.30	0.09	74.6	4.9
D IV 2	R1	1.13	0.08	64.7	4.4
D IV 3	R1	1.22	0.10	69.5	5.5
D IV 4	R1	0.97	0.09	55.3	5.4
D VI 1	S1	1.42	0.11	81.4	6.5
D VI 3	S1	1.30	0.17	74.2	9.7
D VI 4	S1	1.04	0.11	59.4	6.5
D VI 5	S1	1.37	0.14	78.5	8.3
D VII 1	S2	1.10	0.14	62.5	8.0
D VII 2	S2	1.56	0.17	89.5	10.0
D VII 3	S2	1.83	0.12	105.5	7.0
D VII 4	S2	1.65	0.14	94.7	8.0
D VII 5	S2	1.55	0.12	89.1	6.6

^{10}Be concentrations among samples from surfaces that should have large differences in exposure ages imply either that their exposure ages are short and most of the ^{10}Be accumulated while the boulders were being eroded in and then transported from their source regions or that the surfaces are all old enough to have concentrations approaching steady-state values. Although our data cannot exclude either of these scenarios, we favor the latter for the following reasons: (1) The presence of boulders (up to 1 m diameter) within the alluvial fans implies strong and rapid erosion in and transport from the source regions, and thus little time for accumulation of cosmogenic nuclides prior to deposition. (2) Minimal exposure prior to deposition has also been suggested by an observed trend of increasing ^{10}Be content with increased anticlinal folding found in rocks incorporated in uplifted river terraces in the northern Tien Shan, under similar climatic conditions and at similar altitude as the present site (Molnar et al., 1994).

If the three surfaces are approaching steady state, the apparent age calculated for the youngest surface is the closest to the true age, because that surface will have been the least affected by erosional losses. Adopting a production rate of 18 atoms per gram per year (calculated following Lal [1991] for lat 45°07′29″N and an altitude of 1760 m) for our site, samples from surface S1 yield minimum ages of 60 to 80 ka. The assumption of minimal prior exposure implies that the highest of these values approaches the true age. A minimum age of 80 ka for deposition of this surface that has been displaced 100 m yields a maximum horizontal slip rate of $\sim$1.2 mm/yr along the Bogd fault.

CONCLUSIONS

The minimum age of 80 ka obtained for paleo-alluvial surface S1 suggests that the event that formed this surface may have been deglaciation at the beginning of the Riss-Würm interglacial (120 ± 20 ka). If this is the case, the relative positions of surfaces S1 and S2 would imply that the surface S2 was deposited during the previous deglaciation at $\sim$240 ka. This line of reasoning further suggests that surface S0 was deposited at the Würm deglaciation and, because of the relatively slow movement on the fault, is still active because it has not been sufficiently displaced to be abandoned. The contrast between these conclusions and those based on assumed correlation with Holocene climatic events demonstrates the importance of quantitative surface dating for Quaternary tectonic analyses.

Our calculated rate is consistent with the range of 1 to 10 mm/yr proposed by Baljinnyam et al. (1993). It implies an average recurrence interval of $\sim$5 ka for strong earthquakes along the Bogd fault in the Gobi-Altaï and is compatible with the general geodynamic model of the Indo-Asiatic collision (e.g., Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979). Furthermore, this result suggests that along faults with low slip rates in western Mongolia, strong earthquakes can occur in clusters separated by long quiescent periods.

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