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Palaeogeography, Palaeoclimatology, Palaeoecology 199 (2003) 141–151

PALAEO

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Early Holocene climate recorded in geomorphological features in Western Tibet

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Received 31 May 2002; accepted 4 June 2003

Abstract

Cosmic ray exposure ages for formation of perched alluvial terraces and for abandonment of an alluvial/debris-flow fan on opposite sides of the Tangtse Valley (the outflow at the northwest end of Lake Panggong, which is in the Karakorum Range of Western Tibet) provide evidence of a humid period at ~11.5 to ~7 ka. This is consistent with other regional records and supports a controversial chronology for the sedimentary record from Lake Panggong. Fan abandonment appears to have occurred at ~11.5 ka as the climate presumably became more humid in response to initiation of enhanced monsoonal circulation, consistent with previously reported onset of humid conditions in a sedimentary record from the easternmost basin of the lake. In contrast, the terraces did not form until about 7 ka with downcutting of the transverse valley by overflow from Lake Panggong. This lag can be explained in light of the bathymetry of Lake Panggong; the modern lake consists of five basins separated by shallow sills, and outflow through the Tangtse Valley could not occur until the water level was substantially above its present level. The easternmost basin receives the inflow of the major rivers feeding the lake, making its chemistry highly sensitive to changes in precipitation. However, sustained wet conditions are required to fill the basins to the west to the sill depth necessary for overflow through the Tangtse Valley and resultant downcutting and terrace formation.

Keywords: cosmogenic nuclides; dating; paleoclimate; Karakorum; debris flow; fluvial features

1. Introduction

Records of changing climate conditions in Central Asia reflect the interaction of global, regional, and local processes. The relative positions of the Siberian High and the monsoonal circulation cells determine regional moisture transport patterns. The Tibetan Plateau exerts a strong influence on the interaction of these weather systems; summer heating of the plateau enhances the continental low-pressure system that drives the Indian Summer Monsoon. Variability in these systems

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doi:10.1016/S0031-0182(03)00501-7

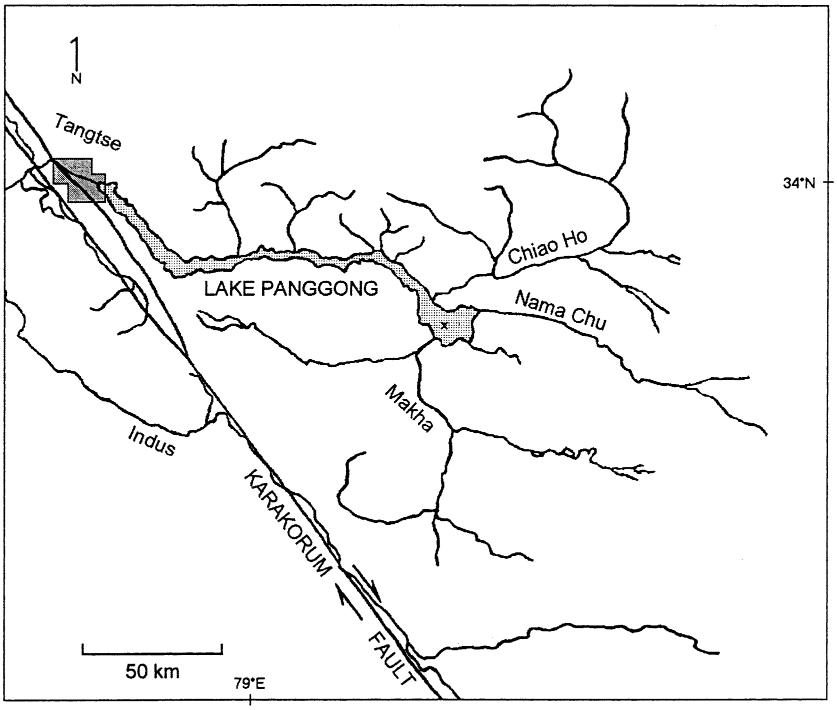

Fig. 1. Map of the Lake Panggong region in Ladakh, India and China, modified after Fontes et al. (1996). The Tangtse Valley site, presented in more detail in Fig. 2, is outlined and shaded. The approximate location of the eastern Lake Panggong coring site of Fontes et al. (1996), Gasse et al. (1996), Van Campo et al. (1996) and Hui et al. (1996) is also marked.

is superimposed on global climate shifts on Milankovitch timescales. Local factors, such as changes in meltwater discharge from mountain glaciers or tectonic and geomorphological events also can affect climate conditions at a given site. Unraveling records of past climate change in Asia thus have the potential to provide information on a broad range of processes. Quantitative study of the formation of geomorphological features is beginning to constrain the timing of climatic events (e.g. Phillips et al., 2000; Richards et al., 2000; Taylor and Mitchell, 2000). Here we study the timing of formation of a group of alluvial and debris-flow deposits adjacent to Lake Panggong (or Banggong Co) in the Karakorum Range of Ladakh (northeastern India) with the goal of understanding the linkages between the processes that formed them and regional climate forcing.

Lake Panggong is a closed basin lake situated in a ~200-km-long submerged valley (Fig. 1). Its outflow channel, the Tangtse Valley, may be controlled by a vertical component of slip on the Karakorum strike-slip fault (Searle, 1996; Searle et al., 1998). The lake presently consists of three basins up to ~40 m deep that are separated by shallow (1–2 m at present) sills. These separations, and the diversity of terrain drained by rivers flowing into the systems, mean that the present lake has significant heterogeneity in chemical composition, with the westernmost basin approximately 10 times more saline than the easternmost (Ou, 1981).

The lake has changed dramatically in the past; a series of ancient shorelines ring the basin (Fontes et al., 1996). During high stands the lake flowed out through the Tangtse Valley to the Shyok River and ultimately to the Indus. In the Tangtse Valley three alluvial terraces are perched along the northeast side of the valley at elevations up to 40 m above the present valley floor. In addition, there are a number of abandoned alluvial/debris-flow fans throughout valley.

Fig. 2. CORONA satellite photographs of the Tangtse Valley study site (available from the US Geological Survey, http://edcwww.cr.usgs.gov/glis/hyper/guide/disp). This valley was the outflow of Lake Panggong during high stands. The fluvial terraces and abandoned debris-flow fan on the north and south sides of the valley, respectively, are highlighted. The trace of the Karakorum Fault, with clear evidence of right lateral movement, appears to cross from the southwest to the northeast side of the valley a few km downstream of the terraces and fans we studied.

A record of changing climate conditions is preserved in Lake Panggong sediments as well. A series of papers report a continuous paleoclimate record from sediments of the easternmost basin. Several lines of evidence – $\delta^{18}O$ in authigenic inorganic carbonates (Fontes et al., 1996), terrestrial plant pollen (Van Campo et al., 1996), and changing lacustrine biota (Hui et al., 1996) – indicate that generally humid conditions prevailed in the Panggong basin from 9.5 to 6.2 ^{14}C ka. This humid period was interrupted by an episode of drier conditions between 8.6 and 7.7 ^{14}C ka and was then followed by a general trend of increasing aridity after $\sim$6.2 ^{14}C ka, with a particularly dry period occurring at 3.9–3.2 ^{14}C ka, that ultimately led to closed basin conditions after $\sim$1.2 ^{14}C ka.

These conclusions have been utilized in studies of Central Asian paleoclimate (e.g. Denniston et al., 2000; Phadtare, 2000; Phillips et al., 2000; Ricketts et al., 1999; Yan et al., 1999) and neotectonics (e.g. Lasserre et al., 1999); such applications require a robust chronology. Development of the radiocarbon chronology for this core required significant normalizations for reservoir effects due to the presence of carbonate rocks, and additional sources of dead carbon, in the drainage basin. These ages thus may be subject to systematic uncertainties associated with the large (6670 year) reservoir effect determined for this lake (Fontes et al., 1996). Because of the magnitude of these corrections, the chronology of Fontes et al. (1996) remains somewhat controversial (Lehmkuhl and Haselein, 2000).

2. Materials and methods

2.1. Fieldwork

To obtain additional information on the history of Holocene climate in this region, we collected

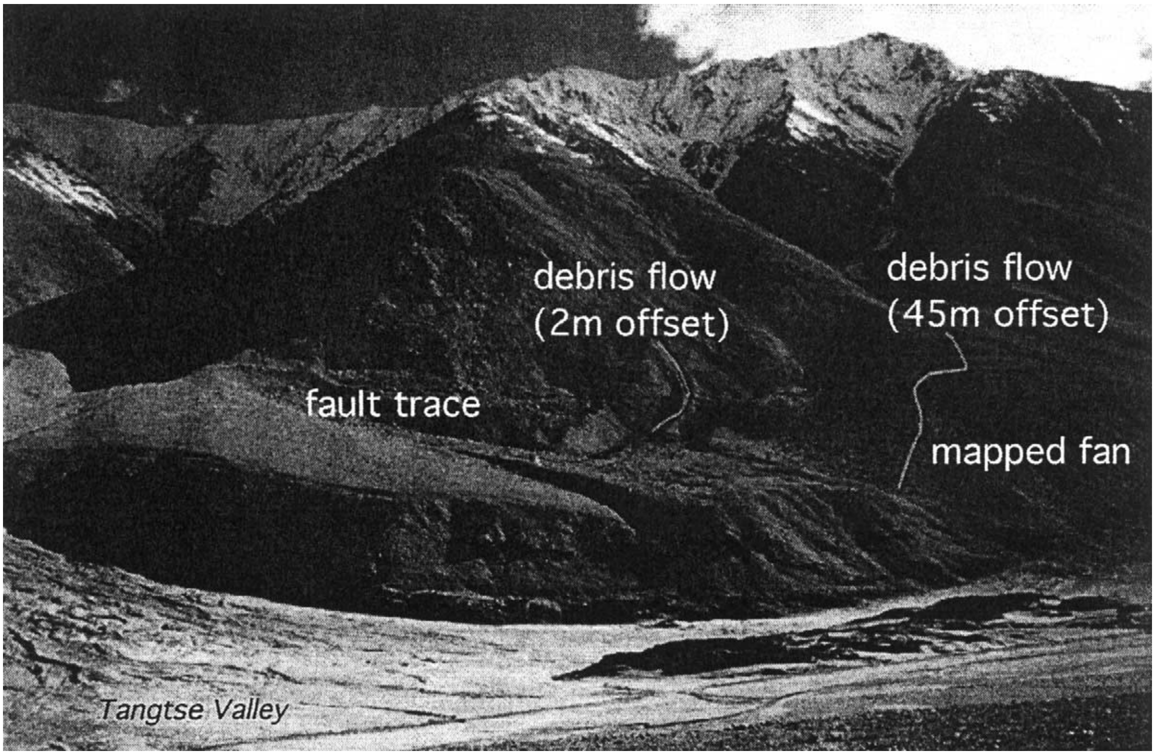

Fig. 3. Photograph of the abandoned fans, showing locations of debris flows offset by 2 and 40 m, as well as a scarp along the trace of the Karakorum Fault. This photo was taken from the highest of the perched terraces, looking southwest across the valley.

samples for cosmic ray exposure dating from geomorphological features likely to have been formed at the time of the humid episode recorded in Panggong sediments. These dates may provide independent evidence for the timing of this humid period, and provide information on the interplay of Holocene climate history with landform evolution.

In the Tangtse Valley, the outflow channel at the northwest end of Lake Panggong, we found a series of three perched terraces at elevations approximately 40 m, 14 m and 7 m above the presently active stream (Figs. 2 and 3). The uppermost of these terraces has a spatial extent of approximately 500×100 m while the lower two are considerably smaller: 200×50 m and 100×15 m, respectively. Determining the timing of the river incision that formed these terraces will provide insights into interplay between tectonic and climatic events that affect landform evolution.

There are numerous debris-flow fans, both active and abandoned throughout the Tangtse Valley. In an earlier study (Brown et al., 2002), we examined the history of abandonment of alluvial/debris-flow fans on the southwest side of the Tangtse Valley that had been deposited over the Karakorum Fault, and subsequently displaced by movement on the fault. Nearly directly across the valley from the perched terraces, one of these abandoned fans contains material from two debris flows that were deposited nearly perpendicular to the strike of the fault and subsequently offset by right lateral movement on the fault by ∼2 m and ∼45 m (Brown et al., 2002). The debris flow with the greater offset is larger, with a distance of ∼10 m between the boulders forming its levees. It appears to have been the last debris flow to deposit boulders on the surface, before the stream debouching onto the fan from the mountains to the southwest incised the fan.

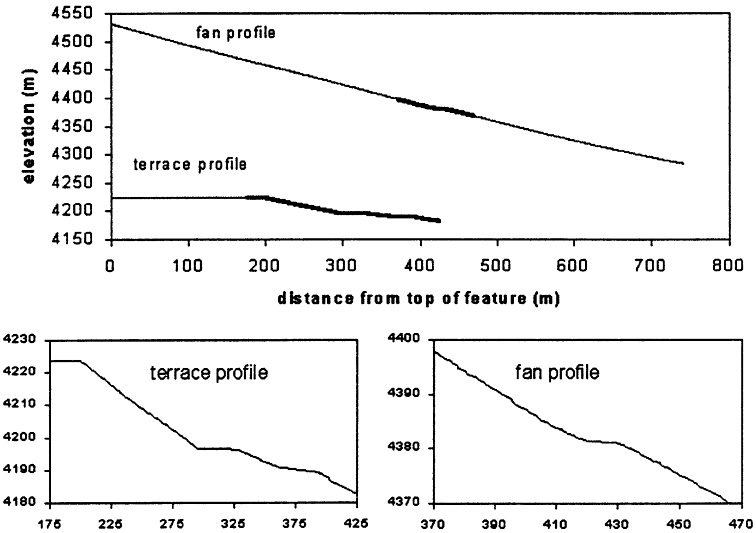

Fig. 4. Profiles across the fan and the terraces. Small insets show details of the three fluvial terraces and of the fault with its 5 m of reverse faulting. These correspond to the heavy lines in the larger plot.

The source of the debris flow lies at the mouth of the canyon above the fan. In contrast, the ridge that forms the western boundary of the abandoned fan supplied material to the smaller debris flow ($\sim$5 m between levees). This debris flow was deposited recently, 1000s of years after abandonment of the fan (Brown et al., 2002).

Using a topographic map of the area based on kinematic GPS data (Brown et al., 2002, in press) we created a profile across the valley, including the debris fan and the perched terraces (Fig. 4). The data were collected at a 10-s sampling interval while the antenna was moved across the fan, providing sampling at a spacing of about 10 m. GPS data were then processed relative to a fixed base station at the floor of the valley, where the position was measured continuously for 3 days. Our mapping quantified the right lateral offset of the debris flows (2 m and 45 ± 10 m) and of the morphology of the fan in general (40 ± 5) (Brown et al., 2002). The consistency of these latter offsets suggests that fan abandonment occurred shortly after deposition of the 45-m offset debris flow.

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 debris flows and incorporated them in the surfaces of the three alluvial terraces. We collected material from boulders embedded in the surfaces and with well-developed desert varnish, avoiding boulders that showed obvious evidence of recent disturbance (rolling) or loss of material through spalling. To evaluate exposure prior to deposition in the alluvial terraces, we collected 'geological blanks' (Brown et al., 1998) from the active stream in the valley immediately to the west of Tangtse Valley debris-flow fan (Figs. 2 and 3). In addition, material from the debris flow offset by $\sim$2 m might be considered to be a geological blank for the debris flow offset by $\sim$45 m.

2.2. Analytical methods

Following methods described elsewhere (Brown et al., 1991, 2002), quartz was purified from samples of granite and granidiorite and targets were prepared for analyses of ^{10}Be. These analyses were undertaken at the Tandétron Accelerator Mass Spectrometer at Gif-sur-Yvette, France (Raisbeck et al., 1994). Analytical uncertainties (reported as 1σ) 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'. Ratios of $^{10}Be/^{9}Be$ were measured relative to the NIST standard (SRM 4325), which has a certified value of 2.68×10^{-11} atom/atom.

Production rates of cosmogenic nuclides at the Earth's surface vary with time, altitude, and location. Apparent 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 $\sim1\%$ of ^{10}Be at sea level (Braucher et al., 1998; Brown et al., 1995) and contribute an even smaller amount at higher altitudes. At our study area, production rates calculated using the commonly used polynomials of Lal (1991) are $\sim15\%$ lower than those of Dunai (2000) and would yield correspondingly older exposure ages. This difference is linked to a lower attenuation length in air implicit in the work of Dunai (2000) that is consistent with recent experimental results (Brown et al., 2000). 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), so we utilize production rates calculated for magnetic inclinations relative to the geographic pole. Production rates at the individual sampling sites were normalized to eliminate the effects of 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%. Because these production rates are based on measurements calibrated against standards consistent with a value of 3.06×10^{-11} for the NIST standard (see discussions in Brown et al., 2000; Middleton et al., 1993), they were decreased by a factor of 0.875 for use with our measurements, which were calibrated against the NIST certified value (2.68×10^{-11}). For comparison of exposure ages within a given landform or region, we report ages in terms of '^{10}Be years' propagating experimental uncertainties for individual samples, but disregarding systematic uncertainties in production rates (Brown et al., 1998; Gosse et al., 1995). Comparison of these ages with absolute age requires propagation of an additional 15% uncertainty for the production rates.

3. Results

The data from the perched terraces suggest rapid downcutting and abandonment of the three terraces at approximately 8 ka (Table 1). There is considerable scatter in the dates for the oldest terrace, with exposure ages ranging from 8.6 to 47.5 ^{10}Be ka. We suppose that the two high values may result from exposure of material during a long low stand of the lake during the Late Pleistocene glacial period when there was minimal river outflow. In contrast, ages from the lower two terraces are more tightly grouped (7.5–10.5 ^{10}Be ka) with values close to the two youngest ages for the highest terrace (8.6 and 10.4 ^{10}Be ka). This suggests that disection of the upper terrace and formation of the lower two terraces may have occurred during a brief period of valley incision. Low levels of ^{10}Be for the boulders in the active streambed, and for the debris flow with a 2-m offset, suggest modest levels of prior exposure for material on the alluvial terraces. Using a mean age of 2.0 ± 1.2 ^{10}Be ka as a geological blank for the seven tightly grouped samples suggests that downcutting occurred at about 7.2 ± 1.7 ^{10}Be ka BP.

In an earlier study, which had the primary goal of determining slip rates on the Karakorum Fault, we estimated the timing of abandonment of the debris-flow fan on the southwest side of the valley, facing the perched terraces (Brown et al., 2002). The distributions of ^{10}Be concentrations of boulders incorporated in the two debris flows cluster tightly enough to suggest that they can be used to date the flows. In both cases, seven or eight of the 10 measured concentrations cluster within a fairly narrow range and two or three outlying samples have much higher concentrations. This suggests that there are two distinct populations of boulders within each debris flow: most boulders were exhumed from depth when the debris flows occurred, and a few previously exposed on the fan surface were entrained in the debris flows as they 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. Disregarding the outliers, the ^{10}Be concentrations (using the production rates described above) correspond to ages ranging from 1.0 to 4.2 ^{10}Be ka and 12.4 to 15.6 ^{10}Be ka for the debris flows with 2-m and 40-m offsets, respectively. Using the average cosmic ray exposure ages of boulders in the 2-m offset debris flow and the active stream (2.0 ± 1.2) as a geological blank, we adopt an age of 11.6 ± 1.8 ^{10}Be ka for deposition of the large debris flow and also for abandonment of the debris-flow fan. These results imply that slip along the Karakorum Fault consists of right lateral movement at a rate of 4 mm/

Table 1
Analytical results and exposure ages

Sample ID	^{10}Be (10^3 atoms/g)	^{10}Be error (10^3 atoms/g)	'Age' (^{10}Be ka)	'Age' error (^{10}Be ka)	'Age' error (calendar ka)
Debris flow – 2-m offset[a]					
KK98-1	143	38	1.8	0.5	0.5
KK98-3	207	32	2.5	0.4	0.6
KK98-4[b]	442	51	5.5	0.6	1.0
KK98-5	111	15	1.4	0.2	0.3
KK98-6	345	44	4.2	0.5	0.8
KK98-7	300	59	3.7	0.7	0.9
KK98-8[b]	789	59	9.7	0.7	1.6
KK98-14	107	14	1.3	0.2	0.3
KK98-15	80	14	1.0	0.2	0.2
Active stream[a]					
KK97-41	42	10	0.5	0.1	0.1
KK97-41.5	147	35	1.8	0.4	0.5
mean for 'geological blanks'					
Debris flow – 40-m offset[a]					
KK97-36[b]	1968	132	24.4	1.6	4.0
KK97-37[b]	2307	198	28.6	2.5	4.9
KK97-38	1016	111	12.5	1.4	2.3
KK97-39	1214	90	15.0	1.1	2.5
KK97-40	1264	100	15.6	1.2	2.7
KK98-9	1068	74	13.2	0.9	2.2
KK98-10	1040	162	12.8	2.0	2.8
KK98-11	1008	111	12.4	1.4	2.3
KK98-12	1141	85	14.1	1.0	2.4
KK98-13[b]	2814	170	34.9	2.1	5.6
mean					
Upper terrace					
KK97-24	850	74	10.4	0.9	1.8
KK97-26[b]	1303	129	16.0	1.6	2.9
KK97-27[b]	3831	302	47.5	3.7	8.0
KK97-28	702	78	8.6	1.0	1.6
Middle terrace					
KK97-29	750	101	9.2	1.2	1.9
KK97-30	697	75	8.6	0.9	1.6
Lower terrace					
KK97-33	850	91	10.5	1.1	1.9
KK97-34	607	51	7.5	0.6	1.3
KK97-35	814	70	10.0	0.9	1.7
mean of terraces					

[a] Values previously published in Brown et al. (2002).
[b] Outlying samples not included in means.

yr (for timescales of 10^4 yr) accompanied by a small amount of reverse thrusting, raising the valley floor at a rate of ~0.5 mm/yr (Brown et al., 2002). For comparison with the timing of terrace downcutting we do not propagate systematic uncertainties in the geological blank for the system, yielding ages of 7.2±1.1 ^{10}Be ka and 11.6±1.3 ^{10}Be ka, for terrace and debris-flow fan abandonment, respectively.

4. Discussion

Enhanced precipitation and river flow can lead to abandonment of fans by two mechanisms: incision of the fan due to increased streampower on the fan, or downcutting at the fan toe by enhanced flow in a transverse stream leading to formation of a knick point that propagates upward on the fan (Bull, 1991; Harvey, 2002a,b; Leeder and Mack, 2001). Fan abandonment through the first mechanism could be decoupled from valley incision, whereas abandonment by the latter mechanism would be coeval with valley downcutting. Our results indicate that the abandonment of the alluvial fans on the southwest side of the valley preceded, by ~4 kyr, the river incision that led to formation of the terraces perched on the northeast side of the valley (Fig. 5).

The difference between the time of abandonment of the debris-flow fan (11.6±1.3 ^{10}Be ka) and the valley incision (7.2±1.1^{10}Be ka) may be associated with the lag between initiation of humid conditions and commencement of outflow from Panggong through the Tangste Valley. The threshold for rainfall required to initiate fan abandonment by incision from the head is likely to be lower than the threshold for overflow of the lake and incision by the trunk stream. The trunk drainage (Tangtse) did not respond strongly to the enhanced precipitation until Lake Panggong began to overflow its sill. At that time, there was rapid downcutting in the valley, leaving the three perched terraces.

This scenario is consistent with earlier results on changes in the chemistry and biota of Lake Panggong (Fontes et al., 1996; Gasse et al., 1996; Hui et al., 1996; Van Campo et al., 1996),

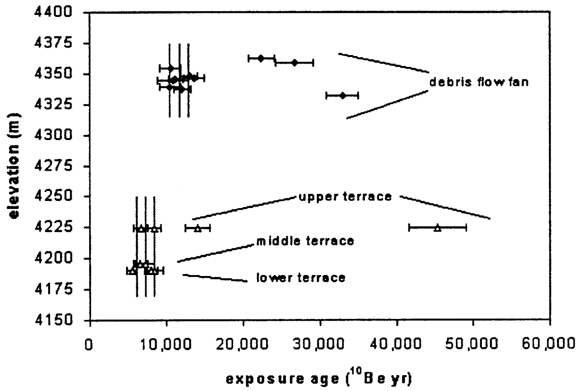

Fig. 5. Plot of age versus elevation above valley floor. Vertical lines show means and standard deviations (disregarding the high outliers, see text) of the ages for fan abandonment and valley incision. The results indicate that abandonment of the fan occurred at 11.6±1.3 ^{10}Be ka, whereas valley incision was later, at 7.2±1.1 ^{10}Be ka. Because this plot compares ages within a single study site, the uncertainties are based on counting statistics only, and do not include uncertainties in the 'geological blank' for the system or in cosmogenic nuclide production rates.

particularly when interpreted in light of the lake's bathymetry. That work indicated initiation of a humid period at 9.5 ^{14}C ka (10.9 ka BP), with a quite rapid response in lake chemistry. This may correspond to the timing of incision of the debris flow/alluvial fan in response to enhanced precipitation. The core examined in that work was from the easternmost of the Panggong basins, which receives the bulk of riverine runoff to the lake (Fontes et al., 1996) (Fig. 1). At the initiation of a humid period, the chemistry of the easternmost basin should respond quickly; once it filled beyond the sill depth (presently 1–2 m below lake level) it would become an open basin lake, overflowing to the other basins to the west and north. After an extended humid period, the lake would reach the levels recorded by the high strandlines and begin overflow at its western end, ultimately incising the Tangste Valley.

It may be possible to obtain information on the frequency of these downcutting events by examining the terrace elevations in light of the rate of the vertical component of slip rate on the Karakorum Fault, which intersects the Tangtse River a few km downstream of the terraces. At this site high-frequency tectonic events (the estimated recurrence interval for movement on the Karakorum Fault is ∼500 years (Brown et al., 2002)) are punctuated by lower frequency climatic pulses in which overflowing lake waters downcut the valley. Suppose that the valley floor northeast of the fault is raised above the baselevel southwest of the fault during dry intervals primarily through tectonic movement rather than accumulation of sediment, and that downcutting events return the riverbed to baselevel. Then the height of the terraces above the valley floor should correspond to the amount of vertical movement on the fault that occurred since the previous climatic pulse. The ratio of the elevation of the highest terrace above the valley floor (40 m) to the vertical component of slip on this segment of the Karakorum Fault of ∼0.5 mm/yr would imply that the penultimate major downcutting event occurred at ∼80 ka. The suggestion that alluvial landforms are produced by low-frequency climate events is consistent with other studies hypothesizing landform evolution punctuated by Milankovitch-scale climate cycles (Benedetti et al., 2000; Molnar et al., 1994; Ritz et al., 1995; Winter et al., 1993). At our study site, this could be linked to a regional increase in precipitation due to greater Indian Summer Monsoon strength during the warm periods immediately following glacial maxima (Clemens et al., 1991, 1996; Colin et al., 1998; Marcantonio et al., 2001; Reichart et al., 1997).

5. Summary and conclusions

1. Our results indicate that fluvial incision and downcutting events occurred at ∼11.5 and ∼7 ^{10}Be ka BP, suggesting enhanced precipitation during that time. This is consistent with a growing body of literature suggesting that the period from 10 to 6 ka BP was humid in Central Asia, most notably the Lake Panggong sedimentary record (Fontes et al., 1996; Gasse et al., 1996) that indicates that wet conditions prevailed from 9.5 to 6.2 ^{14}C ka (10.9–7.1 ka BP). Furthermore, this consistency indicates that the ∼6.7-kyr reservoir effect inferred for radiocarbon dates from Lake Panggong sediments by Fontes et al. (1996) is reasonable.

2. The alluvial terraces appear to have been formed approximately 4 kyr after abandonment of the alluvial/debris-flow fans on the opposite side of the valley. This is consistent with a two-step process in response to continued humid conditions in the basin. In this scenario, fan abandonment would have occurred at ca. 11.5 ^{10}Be ka as the climate became more humid presumably in response to enhanced monsoonal circulation, but the terraces would not have been formed until about 7 ^{10}Be ka with downcutting of the valley at the base of the fan in response to initiation of overflow from Lake Panggong. This proposed lag between the onset of humid conditions (also recorded in sediments of the eastern basin) and initiation of outflow is consistent with a several thousand year process of filling the lake's multiple basins before overflow could occur.

Acknowledgements

Funding for this project was provided by the National Science Foundation, Division of Earth Sciences (Grants EAR-9705841 and EAR-9706502 to E.T.B. and P.M., respectively). Discussions with Françoise Gasse, Doug Ricketts, Hugh Sinclair, and John Swenson and thoughtful reviews by Devendra Lal and Adrian Harvey improved this study considerably. We thank Jacques Lestringuez and Dominique Deboffle for their expertise in AMS measurements and Jason Agnich for skilled assistance in sample preparation. Tandétron operation is supported by CNRS, IN2P3, and CEA.

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