Z. Geomorph. N.F.	Suppl.-Vol. 130	263–276	Berlin · Stuttgart	March 2003

The timing and style of Late Quaternary glaciation in the La Ji Mountains, NE Tibet: evidence for restricted glaciation during the latter part of the Last Glacial

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with 3 photos, 4 figures and 1 table

Summary. Moraine successions along the northern margins of the La Ji Mountains at the northeastern edge of the Tibetan plateau were mapped and dated using cosmogenic radionuclides (CRN). The glacial geologic evidence and the CRN dating show that glaciers existed in this marginal region of Tibet during the latter part of the global Last Glacial Maximum and during the Lateglacial. These data suggest that temperatures were low enough and/or monsoon precipitation was sufficiently high to support one or more limited glacial advances between ~20 and 10 ka. Nevertheless glaciation was limited to glaciers of < 10 km in length and the estimated ELA depression was ~800 m. These results confirm studies throughout other regions of Tibet and the Himalaya that show that glaciation was restricted during the latter part of the Last Glacial.

Resume. Les successions de Moraines le long des marges nord des montagnes de La Ji, au niveau de la limite Nord-Est du plateau Tibetain, ont ete cartographiees et datees en utilisant les radionucleides cosmogeniques (CRN). Les temoins geologiques glaciaires et les datations par CRN montrent que les glaciers existaient dans cette zone de marge tibetaine durant la partie superieure du dernier maximum glaciere ainsi que durant la derniere periode glaciere superieure. Ces donnees suggerent que les temperatures etaient assez basses et/ou les precipitations dues au mousson etaient suffisament elevees pour favoriser une ou plusieurs avances glaciaires restreintes, entre environ 20 et 10 ka. Neanmoins, la glaciation etait reduite a des glaciers d'une longueur inferieur a 10 km et la depression ELA estimee a environ 800 metres. Ces resultats confirment les etudes a travers les autres regions du Tibet et de l'Himalaya qui montrent que la glaciation etait restreinte durant la derniere partie de la periode glaciere superieure.

Zusammenfassung. Moränensequenzen an der Nordabdachung des La Ji Shan im Nordosten des Tibetischen Plateaus wurden kartiert und mit Hilfe kosmogener Radionuklide (CRN) datiert. Die glazialgeologischen Befunde und die CRM-Daten zeigen für diese Randregion Tibets Gletschervorstöße in der Schlussphase des globalen letztglazialen Maximums (Last Glacial Maximum) und während des Spätglazials. Diese Daten suggerieren, dass die Temperaturen niedrig genug und/oder die monsunalen Niederschläge hoch genug waren, um

0044-2798/03/0130-0263 $ 3.50

einen oder mehrere begrenzte Gletschervorstöße zwischen ~ 20 und 10 ka zu ermöglichen. Die Gletscher hatten jedoch nur eine Ausdehnung von <10 km und die Schneegrenzdepression betrug ~ 800 m. Diese Ergebnisse bestätigen Untersuchungen in anderen Regionen Tibets und des Himalayas, die zeigen, dass die Vergletscherung in ihrer Ausdehnung während der letzten Phase der Letzten Kaltzeit eingeschränkt war.

Introduction

The Tibetan Plateau constitutes a formative influence upon the Asian monsoons (FLOHN 1960, 1968, REITER & DING 1980) and variations in snow and ice cover in this region have a major influence on the regional climate and hydrology (HAHN & SUHUKLA 1976, DEY &

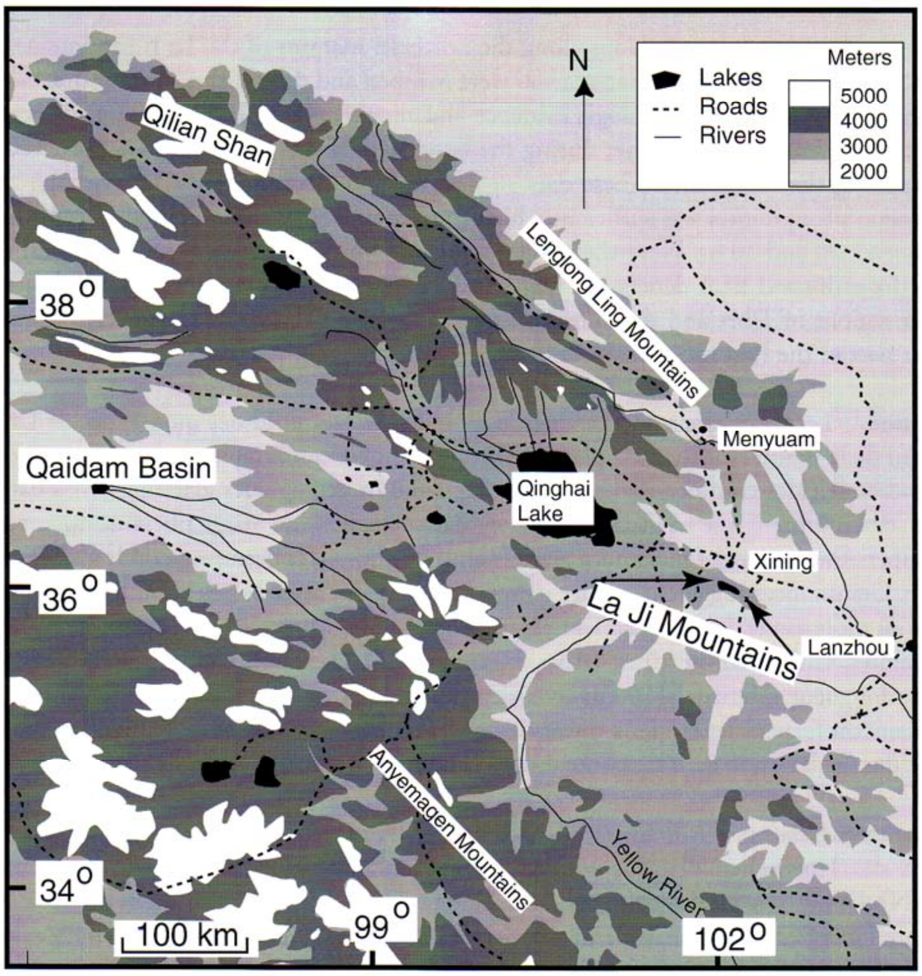

Fig. 1. Location of study area.

BHANU KHUMAR 1982, DICKSON 1984, BUSH 2000). Throughout the Quaternary the extent of snow and ice cover would have varied considerably, possibly influencing both regional and global climate (BENN & OWEN 1998). Despite the importance of glaciation in Tibet on the climatic and hydrological systems of Central Asia, there is still much controversy over the extent of former glaciers throughout the Late Quaternary. This is partially because of the inaccessibility of the region, but also because of the misinterpretation of glacial and non-glacial landforms and sediments, and the lack of numerical dating to define the ages of landforms and to make regional correlations (LEHMKUHL et al. 1998). In this study, we provide evidence for ice extent and define the timing of glaciation in a region of northeastern Tibet, the La Ji Mountains (Fig. 1). These mark the topographic and climatic limits of Late Quaternary glaciation and contribute to the regional reconstruction of ice extent and paleoenvironmental conditions.

Methods

Glacial landforms were mapped in the field in three valleys at the northwestern end of the La Ji Mountains using standard field mapping and morphostratigraphic techniques; Landsat images (Figs. 2 and 3) placed the field sites in a larger context and aided in interpreting the field data. Several stratigraphically distinct sets of moraines were observed within each valley. Samples (500–700 grams each) were collected from the surfaces of quartz rich boulders (> 1 m in diameter) along moraine crests. Care was taken to sample from locations where there was no apparent evidence of exhumation or slope instability. Furthermore, the boulders that were chosen for sampling had a substantial relief above the substrate (¼ to ¾ the length of the b-axis) yet were substantially buried within the substrate. This reduces the likelihood that they were significantly buried and later exhumed, but ensures that they were buried enough to reduce the possibly of toppling any significant time after their deposition. Where possible, several boulders were dated from each moraine ridge to provide a check on the reproducibility of the CRN dating and to assess the inheritance of CRNs. Photographs and full notes were taken to record the degree of weathering and the site conditions for each boulder. The inclination from the boulder site to the top of the surrounding mountain ridges and peaks was measured to determine the topographic shielding.

The samples were crushed and sieved and quartz in the size range of 250–500 μm was isolated using the method of KOHL & NISHIIZUMI (1992). After addition of Be and, where necessary, Al carrier, the Be and Al were separated and purified by ion exchange chromatography and precipitation at pH > 7. The hydroxides were oxidized by ignition in quartz crucibles. BeO was then mixed with Nb metal and Al_2O_3 with Ag metal prior to determination of the $^{10}Be/Be$ and $^{26}Al/Al$ ratios by accelerator mass spectrometry at the LLNL Center for Accelerator Mass Spectrometry. Isotope ratios were standardized against ICN ^{10}Be and National Institute of Science and Technology ^{26}Al standards prepared by K. NISHIIZUMI (priv. comm.). Stable aluminum concentrations were determined by ICP-ES or atomic absorption spectrometry on aliquots of the dissolved quartz. The measured isotope ratios were converted to nuclide concentrations in quartz using the total beryllium and aluminum in the samples and the sample weights. Nuclide concentrations were then converted to zeroerosion exposure ages using a sea level high latitude (SLHL) ^{10}Be production rate of 5.2 at/g-quartz/y and a $^{26}Al/^{10}Be$ production ratio of 6.0 (NISHIIZUMMI et al. 1989). In most instances, both ^{10}Be and ^{26}Al were measured. For each sample, the dates obtained using the different cosmogenic radionuclides are consistent, however, the ^{26}Al ages are systematically slightly younger for reasons that are unexplained. The beryllium production rate used is based on a number of independent measurements of production rate as discussed by OWEN et al. (2001 and 2002a). Production rates were scaled to the latitude and elevation of the La Ji sampling sites using the star scaling factors of LAL (1991) and an assumed 3% SLHL muon contribution to production rates, and were further corrected for changes in the geomagnetic field over time. Details of the calculation are given in OWEN et al. (2001 and 2002a).

Geomorphic setting and glacial geologic evidence

The La Ji Mountains are situated on the northeastern edge of the Tibetan Plateau and rise to an elevation of 4898 m asl with a relative relief of ~1500 m (Figs. 1 and 2). The region is moderately influenced by the southeast Asian summer monsoon and has an annual pre-

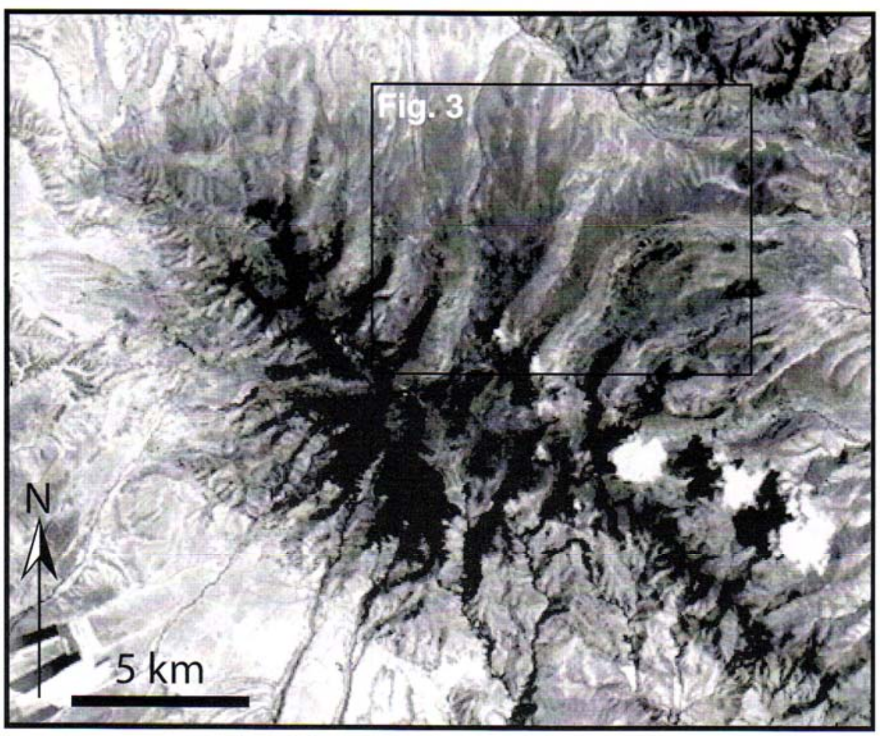

Fig. 2. Satellite image illustrating the geomorphic setting of the La Ji Mountains, the distinctive U-shaped valleys and extensive pediment surface beyond the glaciated valleys.

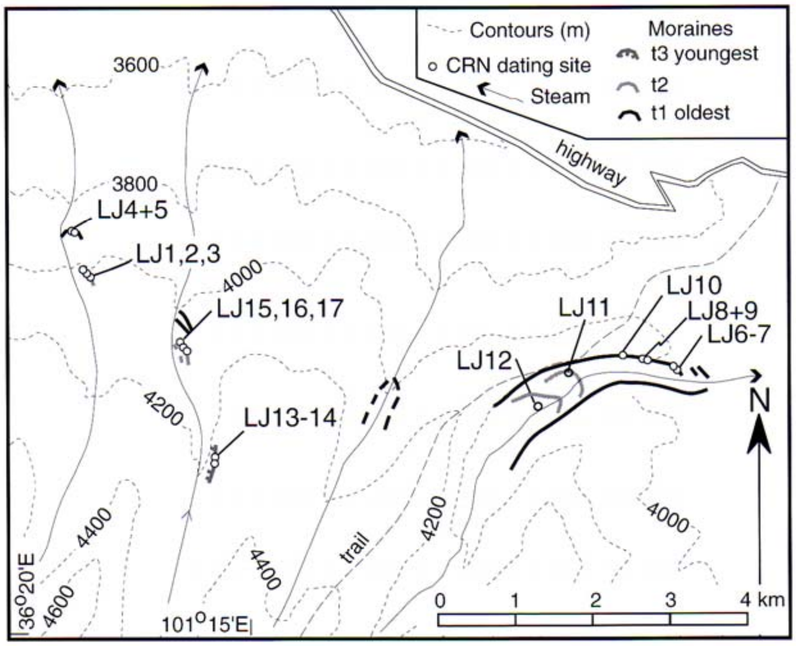

Fig. 3. Location of the moraines at the eastern end of the La Ji Mountains showing the sampling sites for CRN dating. See Fig. 2 for the location of the map.

cipitation of between 200–400 mm falling mainly during the summer months (DRONIA 1987). No glaciers exist in the region today, but during exceptional years small snow patches persist throughout the summer at the highest elevations. The valleys along the northern edge of the La Ji Mountains are U-shaped in their lower reaches with steep bare rock walls at their heads. Granitic and gneissic lithologies dominate the core of the mountains and the lithologies within the moraine, pediment and fluvial sediments. Hummocky and latero-frontal moraines are present within and beyond the mouths of the north-easternmost valleys (Photos 1 and 2) down to an elevation of 3900 m asl. Three sets of moraines can be differentiated on the basis of morphostratigraphy, although the weathering characteristics of each set of moraines are similar. The moraine ridges are subdued and their surfaces are covered with a cm- to dm-thick layer of solum and turf. The boulders on the crests of the moraines are usually half buried and their surfaces are pitted to a depth of ~ 5–10 mm exhibiting moderate exfoliation. The best-preserved moraines are present in the north-easternmost valley (Fig. 3 and Photo 1). An extensive latero-frontal moraine exists here, behind which an impressive suite of hummocky moraines and kettle holes are preserved. The southern margin of the hummocky moraines is marked by a steep scarp and associated debris aprons that mark a former ice margin. An extensive pediment surface exists beyond the glacial limits and is comprised of well-rounded boulders and cobbles covered by a thick organic-rich solum (Photo 3).

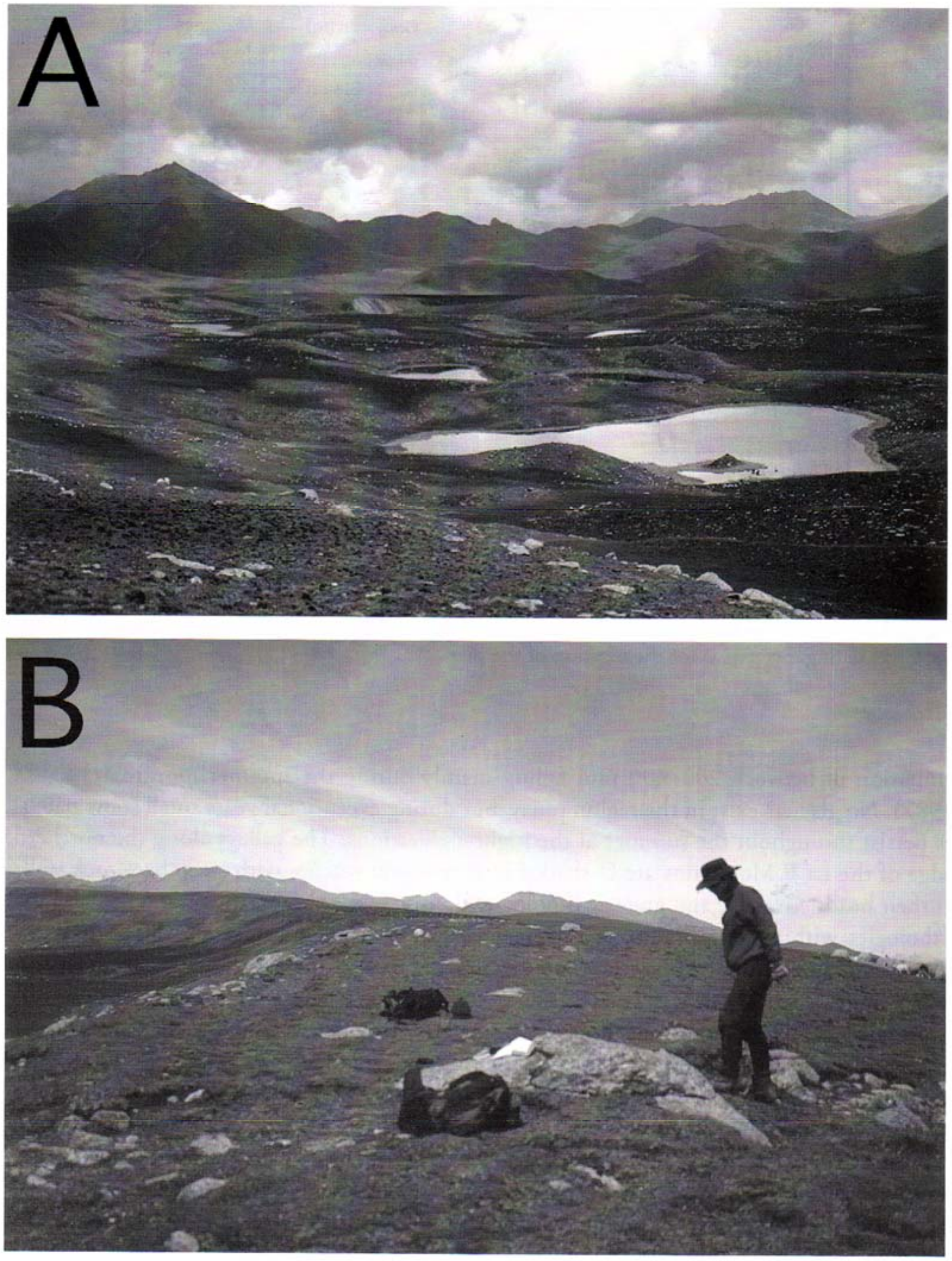

Photo 1. View of hummocky moraines (A) and latero-frontal moraine (B) in the easternmost valley of the La Ji Mountains.

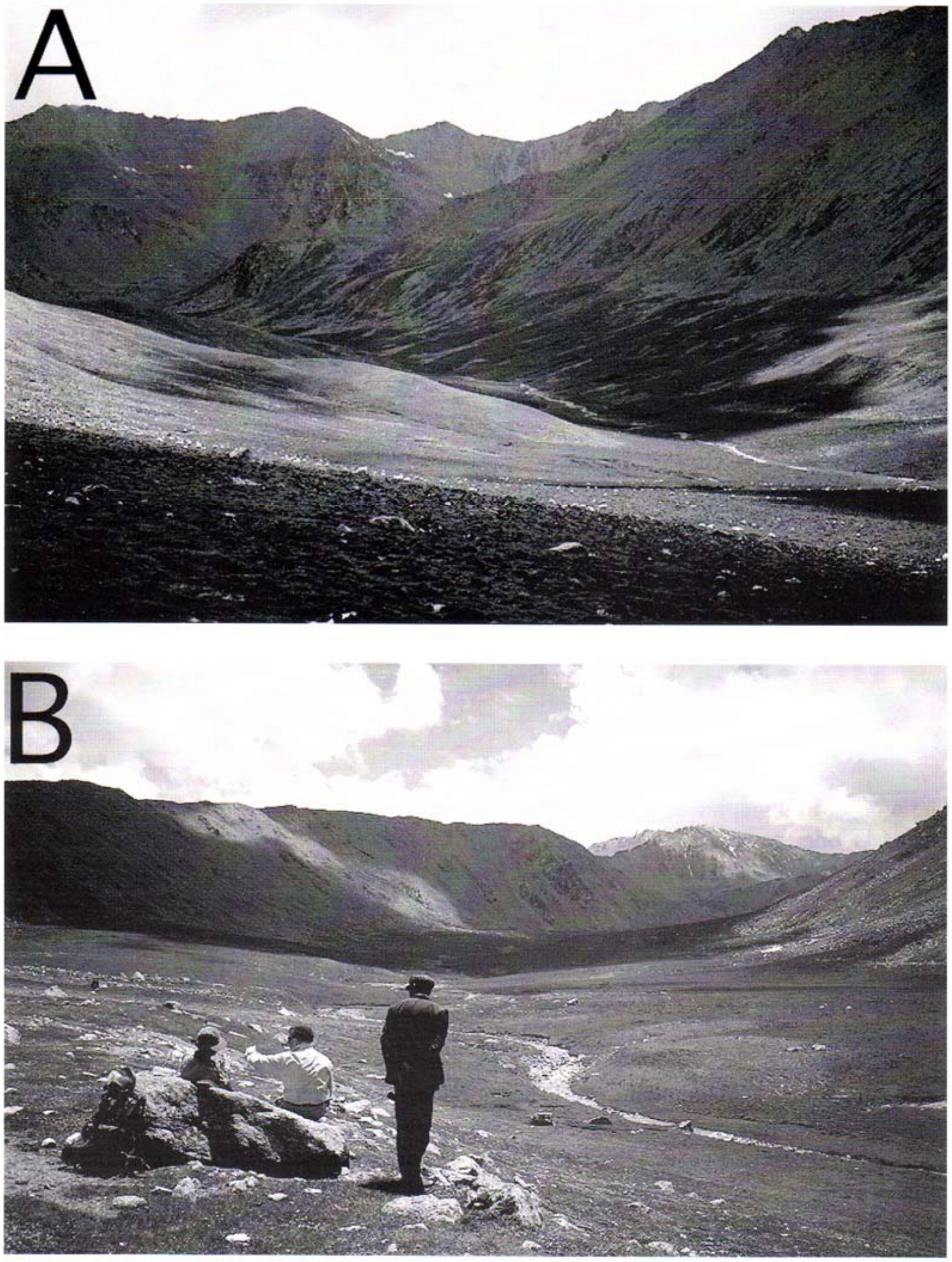

Photo 2. Views of typical moraine morphologies within the La Ji Mountains. (A) Subdued latero-frontal moraine within a typical U-shaped valley; and (B) Latero-frontal moraine showing a typical site chosen for CRN sampling and dating.

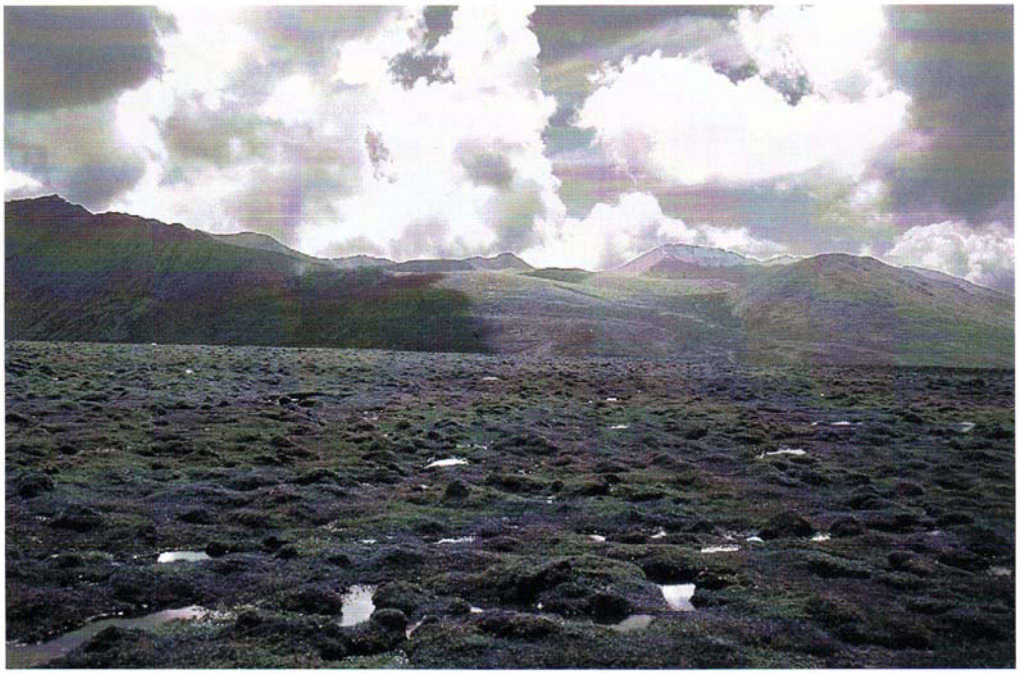

Photo 3. View looking west across the pedimont surface beyond the limit of the Last Glacial Maximum.

Results

The morphostratigraphic and geomorphic analyses show that one or more glacial advances occurred along the northern margin of the La Ji Mountains. The succession of landforms in the north-easternmost valley may represent a single advance with the latero-frontal moraines marking the glacial maximum, while the hummocky moraines represent a recessional stage or standstill. Alternatively the hummocky moraines, which are defined by a distinct scarp marking a former ice margin at the southernmost end, might represent a later advance. In the other valleys distinct sets of lateral moraines suggest that more than one, and possibly three advances occurred.

Unfortunately, CRN techniques do not have the resolution to allow the age differentiation of individual moraine ridges within an individual moraine complex. A specific problem affecting the resolution and accuracy of CRN exposure ages is inheritance of CRNs from a prior exposure. In particular, complex exposure histories can occur in outcrop, prior to the boulder being incorporated in the flowing ice stream, or during an intermediate stage while the boulder was part of an older moraine. Boulders can also contain inherited CRNs if they have been reworked from older deposits since, with each successive glaciation, the advancing glaciers may override previous glacial deposits. Some of the older glacial debris may therefore be reworked and deposited within the younger moraines. If younger moraines are inset into older moraines, colluvial processes may transport older material onto the younger surface. In both cases there is, therefore, the possibility that the exposure age of a boulder is greater than that of the moraine from which it was collected. Concordance between ages for several boulders from the same moraine increases the confidence with which the measured CRN content can be interpreted as the exposure age of the moraine and helps identify outliers that may have had complex exposure histories. An additional complicating factor in CRN dating is the possibility that an individual boulder has toppled and/or is intensely weathered, thereby exposing fresh surfaces. In this circumstance the CRN ages underestimate the true age of the moraine. Again, concordance in exposure age among several samples decreases the likelihood that these processes will significantly alter the accuracy of the exposure ages.

The CRN dates provide ages that range between 9 to 21 ka, with two boulders providing significantly older ages of ~33 and 63 ka (Table 1 and Fig. 4). The CRN ages on individual moraines are not tightly clustered, but they do show that the moraines formed some time between the latter part of the Last Glacial Maximum (LGM) and/or during the Lateglacial or possibly the early part of the Holocene. Furthermore, the data set shows no systematic difference between dated moraines that are morphostratigraphically older or younger than each other. Consequently, we are not in a position to assign moraines to different specific climatostratigraphic periods. Nevertheless, it can be seen that the CRN ages cluster, as a group, between 8 to 21 ka. This suggests that the moraines along the northern edge of the La Ji Mountains represent one or more glacial advances that occurred during the latter part of the global LGM and the Lateglacial or possibly the early part of the Holocene. The two oldest ages (LJ3 and LJ9) probably represent boulders that have inherited CRNs from prior exposure. The youngest ages of ~8 – 10 ka (LJ4, 11, 15 and 16) appear to be stratigraphically inconsistent with their location on moraines that should be stratigraphically older than those

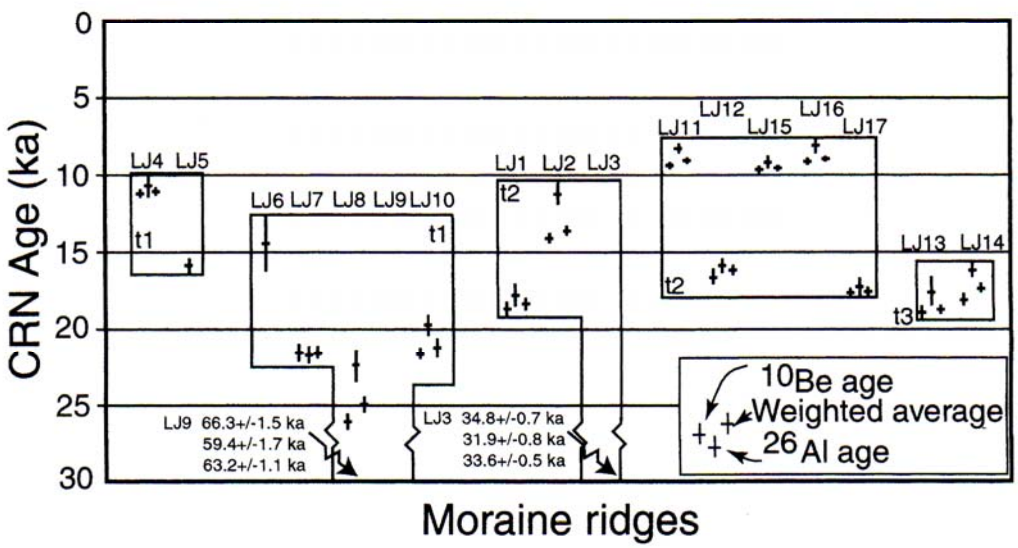

Fig. 4. CRN dates plotted by moraine ridge and relative ages. The boxes enclose individual moraines.

Table 1. Locations of samples that collected for CRN dating, the CRN data and the CRN ages.

Sample #	Latitude (° ± 0.01°N)	Longitude (° ± 0.01°E)	Altitude (m)	Shielding factor*	^{10}Be§ (10^6 atoms/g)	^{26}Al§ (10^6 atoms/g)	Exposure Age (ka)		Geomag Corr. † (ka)		Average+ (ka)
							^{10}Be§	^{26}Al§	^{10}Be§	^{26}Al§	
LJ1	36.37	101.21	4030	1	1.21±0.03	7.18±0.30	17.04±0.45	16.61±0.68	18.16±0.48	17.72±0.73	18.03±0.40
LJ2	36.37	101.21	4035	1	0.94±0.02	4.57±0.32	13.13±0.30	10.51±0.72	14.07±0.32	11.23±0.77	13.65±0.30
LJ3	36.37	101.21	4025	1	2.39±0.05	13.16±0.39	33.80±0.65	30.74±0.76	34.76±0.66	31.85±0.79	33.56±0.51
LJ4	36.38	101.22	3880	1	0.69±0.02	3.99±0.29	10.55±0.25	9.95±0.70	11.27±0.26	10.61±0.75	11.20±0.25
LJ5	36.38	101.22	3880	1	no data	5.91±0.26		14.77±0.64		15.81±0.69	
LJ6	36.37	101.31	3920	1	no data	5.61±0.70		13.73±1.71		14.72±1.83	
LJ7	36.37	101.31	3920	1	1.36±0.04	8.32±0.23	20.30±0.54	20.41±0.51	21.55±0.58	21.67±0.54	21.61±0.40
LJ8	36.37	101.31	3965	1	1.70±0.04	4.98±0.22	24.81±0.58	21.03±0.90	26.08±0.61	22.30±0.96	24.99±0.51
LJ9	36.37	101.30	3965	1	4.45±0.10	23.98±0.78	65.56±1.52	58.58±1.67	66.26±1.53	59.42±1.69	63.18±1.13
LJ10	36.37	101.30	3970	1	1.40±0.02	7.73±0.32	20.30±0.34	18.48±0.73	21.55±0.36	19.67±0.78	21.22±0.33
LJ11	36.37	101.30	3960	1	0.60±0.01	3.28±0.13	8.77±0.20	7.85±0.29	9.38±0.22	8.38±0.31	9.05±0.18
LJ12	36.36	101.30	3970	1	1.08±0.04	6.23±0.20	15.71±0.51	14.86±0.44	16.79±0.55	15.89±0.47	16.27±0.36
LJ13	36.35	101.24	4155	1	1.34±0.03	7.62±0.42	17.75±0.41	16.55±0.90	18.91±0.44	17.66±0.96	18.69±0.40
LJ14	36.35	101.24	4145	1	1.27±0.02	6.95±0.22	16.92±0.33	15.16±0.44	18.05±0.35	16.21±0.47	17.39±0.28
LJ15	36.37	101.25	4070	1	0.65±0.02	3.82±0.16	9.00±0.23	8.63±0.34	9.61±0.24	9.23±0.37	9.50±0.20
LJ16	36.37	101.24	4050	1	0.61±0.01	3.31±0.19	8.52±0.19	7.54±0.44	9.12±0.21	8.06±0.47	8.94±0.19
LJ17	36.37	101.24	4045	1	1.18±0.02	7.08±0.28	16.46±0.29	16.24±0.62	17.56±0.31	17.34±0.67	17.52±0.28

* The topographic shielding factor was determined using the methods of NISHIIZUMI et al. (1989).

§ Uncertainty includes only uncertainty in AMS measurement.

† Corrected for time varying geomagnetic field as described in text. The uncertainty is carried over from that in the average exposure age. No additional uncertainty was assigned arising from correction for geomagnetic field change.

\+ Weighted average of ^{10}Be and ^{26}Al corrected ages. The uncertainty is the propagated uncertainty of the two ages.

up valley. These may represent toppled boulders and/or boulders that were exhumed late in their history.

The extensive and detailed data from the Greenland ice cores show that climatic variability was often relatively rapid, on decadal to millennial timescales, during the latter part of the Last Glacial (e.g. DANSGAARD et al. 1993). Numerous workers have assumed that the construction of moraines occurs over a relatively short period and that CRN ages for boulders on moraine crests should provide reliable dates on the timing and duration of glaciation (GOSSE et al. 1995a, 1995b, PHILLIPS et al. 1990, 1996). Ice core collected in Northern Tibet and studied by THOMPSON et al. (1989 and 1997) also confirmed that rapid climatic instability occurred during the latter part of the Last Glacial. It is likely that the successions of moraines in the La Ji Mountains represent several glacial advances during the latter part of the Last Glacial spanning a period of approximately 8–20 ka. While our ages cannot be used to correlate specific glacial deposits with climate events, they show unequivocally that glaciers along the margins of Tibet, albeit restricted in extent (< 10 km long), did advance during the LGM and Lateglacial. Using the simple accumulation area ratios (AAR) for typical mountain glaciers of between 0.5 to 0.8 (BENN & GEMMELL 1997) we calculate that equilibrium line altitudes during this time were in the range ~ 4300–4400 m asl. LEHMKUHL et al. (1998) showed that the contemporary ELA in the glaciated mountains southwest of the Qaidam basin is ~ 5,500 m asl. Further to the east along the Kunlun Mountains, the modern ELA is lower, e.g., it is ~ 5,300–5,400 m asl south of Golmud (LEHMKUHL, pers. comm.). Using such observations, LEHMKUHL et al. (1998) showed that the ELA decreases in elevation by ~ 100 m for every degree of longitude to the east. Using this approach and the lack of contemporary glaciers in the La Ji Mountains, the present ELA for this region should lie at an altitude of ~ 5000 m, i.e., a little above the highest peak. This leads to the inference that ELA depression during the later part of the Last Glacial may have been as much as ~ 600 to 800 m. This supports the calculation by LEHMKUHL & ROST (1993) of an ELA depression of 800 m during the LGM for this region.

These data suggest that temperatures were low enough, and/or precipitation from the winter and/or summer monsoon was sufficiently high to support one or more limited glacial advances since ~ 19 ka. OWEN et al. (2002) suggested that glaciation throughout the Himalaya was also very limited in extent during the global LGM and that glaciers were more extensive during the early part of the Last Glacial. We found no evidence of an earlier glaciation in the La Ji Mountains other than the ones for which dates are presented here. This raises two possibilities; either all earlier glaciations may have been less extensive and thus the geological evidence of any such glaciations was destroyed by later and more extensive glaciations. Alternatively processes such as fluvial erosion could have either destroyed any evidence of more extensive older glaciations or this evidence could have been buried beneath valley fill sediment.

Few glacial successions in NE Tibet have been adequately dated by numerical techniques because of the scarcity of Pleistocene age organic material for radiocarbon dating. Where peat bogs exist they began to develop only during the Holocene, making them of very limited use in establishing glacial stratigraphy (LEHMKUHL 1997). However, on the basis of lacustrine sediments in the Qaidam Basin, HÖVERMANN & SÜSSENBERGER (1986) demonstrated the likelihood that a Lateglacial advance occurred south of the Qaidam Basin around 15 ka. Various workers have shown that climatic conditions in northeastern Tibet at the end of the Last Glacial (since ~ 13 ka) were characterized by dry and cold conditions (KELTS et al. 1989, LEHMKUHL 1997). Given the increased aridity after ~ 13 ka it is unlikely that there was sufficient precipitation to support the development of glaciers in the La Ji Mountains. This, and the Qaidam lacustrine record when combined with our CRN ages, lead us to favor a date of between 21–14 ka for the maximum advance in this region. The clustering of dates between 21–14 ka, and our preferred 21–14 ka age range, accords with a glacial maximum during MIS-2 in this region, post-dating the accepted age of the global LGM of around 21 ka (CLARK & MIX 2002). We speculate that local LGM in the La Ji Mountains may be approximately correlated with Heinrich Event 1 (H1) at 14.3 ^{14}C ka BP (~15.2 cal years BP). Recent work is increasingly indicating that glaciers and ice sheets in other regions of the world maintained their maximum extent until ~ H1, after which they underwent significant retreat (LICCIARDI et al. 2001, DYKE et al. 2002, CLAGUE & JAMES 2002). Furthermore, if the local last glacial maximum occurred during the Late Glacial Interstadial (~ 13–15 ka) it is likely that the monsoon during this time penetrated further northwestward into Tibet, increasing precipitation in the La Ji Mountains. This precipitation would have fallen as snow at high altitudes leading to positive glacier mass balances, thereby resulting in glacier advance. In addition, precipitation may have been supplied to this area during winter monsoon. The relative role of the winter versus the summer monsoon still has to be resolved. Despite the tentative nature of these correlations, our CRN data provide unequivocal evidence for a limited glacial advance in this marginal area of Tibet during the latter part of MIS-2. These data thus constitute the first numerical dates to define the timing of glaciation in Tibet.

Conclusions

Reconstruction of the extent of former glaciers, together with CRN dating, show that one or more glacial advances occurred during the latter part of the Last Glacial and the Lateglacial in the La Ji Mountains. Owing to effects arising from possible reworking, burial, and weathering or toppling of boulders, the CRN dates cannot resolve age differences between moraines. Nevertheless, the data confirm that glaciation along the northeastern margin of Tibet during the latter part of the Last Glacial was restricted in extent. Glaciers were < 10 km in length, and the ELA depression was of the order of 800 m. This is consistent with evidence drawn from other regions of Tibet and the Himalaya indicating that glaciation during the LGM was restricted in extent.

Acknowledgements

We should like to thank the National Geographic Society for funding our fieldwork. The cosmogenic radionuclide dating analysis was undertaken at the Lawrence Livermore National Laboratory (under DOE contract W-7405-ENG-48) as part of an IGPP/LLNL research grant. Thanks are also given to Drs. Douglas Benn and Kazuomi Hirakawa for their careful review of our paper and their constructive and useful comments. Furthermore, we should like to thank Frank Lehmkuhl for his helpful comments and for translating our abstract into German, and Paul Pinzuti for translating the abstract into French.

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