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Relative Dating of Quaternary Moraines, Rongbuk Valley, Mount Everest, Tibet: Implications for an Ice Sheet on the Tibetan Plateau

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Relative-dating studies applied to high-altitude moraines (5000–5500 m) in the Rongbuk valley on the northern flank of Mt. Everest reveal strong contrasts in the weathering characteristics of the boulders exposed along moraine crests. These differences serve to define three intervals of major Pleistocene glaciation that, on the basis of the degree of weathering, are interpreted to extend back to at least the penultimate glaciation and probably encompass at least one still older glaciation. Either interpretation indicates that some of these moraines are considerably older than their previously assigned ages. The magnitude of equilibrium-line lowering during Neoglacial and late Pleistocene times is calculated to be ca. 50–100 and 350–450 m, respectively. The data described here are incompatible with the recently proposed model (Kuhle, 1987) for large-scale ice-sheet development on the Tibetan Plateau. The reconstructed equilibrium-line lowering in the Everest region is only 30% of that cited in the ice-sheet model. Moreover, the flow patterns and geometry of the former Rongbuk glaciers are in opposition to those proposed by the model. Based on the data from the Everest region, it appears that valley glaciation, rather than ice-sheet growth, characterized the southern margin of the Tibetan Plateau during the middle and late Pleistocene glaciations.

INTRODUCTION

Because the High Himalaya and the Tibetan Plateau have a pronounced influence on global climatic patterns (Manabe and Hahn, 1977; Thompson and Warren, 1982; Barron and Washington, 1984; Ruddiman and Kutzbach, 1989), a reconstructed, well-dated history of glaciation there can provide important input (or cross-checks) to models of past and present climates on a global basis. Despite the numerous studies of the glaciated terrain in the High Himalaya that have been conducted since the pioneering research of Dainelli (1922) and de Terra and Paterson (1939), the chronology of Pleistocene glaciation remains poorly defined. In addition to the restricted access permitted to the Tibetan Plateau, its remoteness and large extent have forestalled extensive study of the glacial record. Along the moist, eastern rim of Tibet and the south flank of the Himalaya, limiting radiocarbon dates serve to constrain the timing of some of the latest Pleistocene and Holocene glacial advances (e.g., Fushimi, 1981; Röthlisberger, 1986). In the absence of similar dates in the more interior portions of the plateau, the potential implications of these ages for regional climatic changes remain uncertain. There is also a paucity of dates along the relatively dry, northern flank of the Himalaya. For example, despite numerous expeditions to the slopes of Mt. Everest since 1920 (e.g., Odell, 1925; Liu, 1962; Miller, 1970; Xu Dong, 1974; Zheng and Shi, 1975, 1976; Iwata, 1976; Williams, 1983; Kuhle, 1987; Zheng, 1988; Röthlisberger, 1986), a detailed chronology of pre-Holocene glaciation is still lacking in this region.

In many other regions where abundant datable material appears to be absent, relative-dating studies have provided a means of distinguishing between deposits belonging to different intervals of former glacia-

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tion (e.g., Sharp, 1969; Burke and Birkeland, 1979; Crook and Gillespie, 1986). If these same deposits can be chronologically dated (i.e., Colman, 1986), then, in addition to providing temporal constraints on these particular deposits, a basis is created for drawing chronological inferences from deposits in nearby localities that exhibit similar relative-weathering characteristics and experience the same climatic regime.

The results reported here from the northern flank of Mt. Everest (Fig. 1) represent the first step in this two-step process. We have used relative-dating techniques to de-

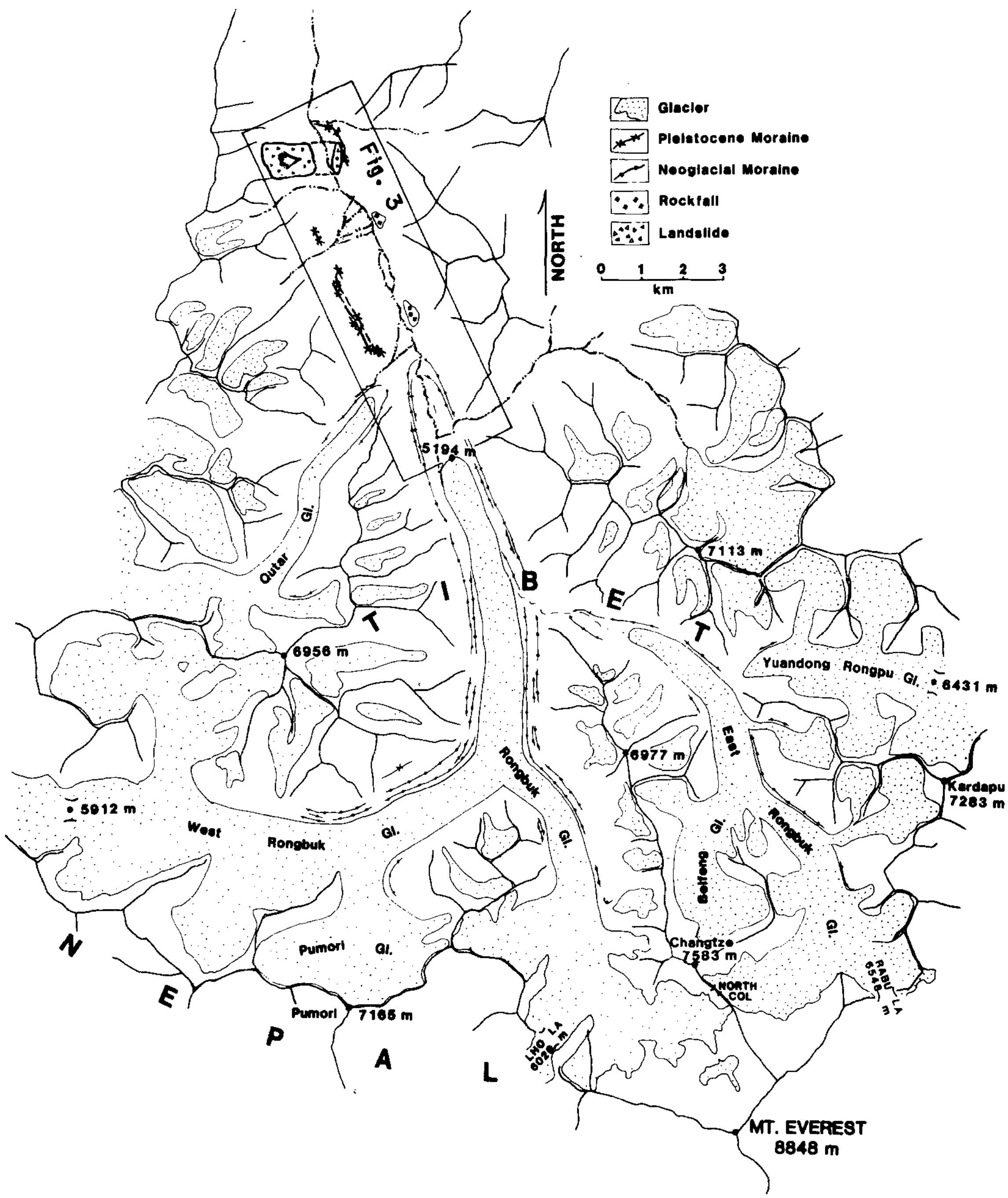

FIG. 1. Map showing location of study area, presently glaciated area, and Neoglacial and Pleistocene moraine crests. Based on 1:50,000 Mount Everest topographic map published by National Geographic Magazine and on 1:25,000 aerial photographs. Area enlarged in Figure 3 is outlined.

fine several different groupings of glacial deposits attributable to separate glaciations and to draw distinctions between moraines that were formerly grouped together. In addition, we have calculated the former and present equilibrium-line altitude (ELA) for the glacial advances preserved in the Rongbuk valley. These permit an assessment of the magnitude of climatic changes responsible for past intervals of glaciation and allow us to test recently proposed models (Kuhle, 1987) for ice-sheet glaciation in this region.

PREVIOUS RESEARCH

The first detailed map of the geomorphology of the northern flank of Mt. Everest (Mt. Qomolongma) was produced following the 1966–1968 Chinese scientific expeditions (Academica Sinica, 1973; Zheng and Shi, 1975, 1976; Zheng, 1988). A threefold, Pleistocene glacial succession was delineated within the Rongbuk valley (Fig. 2A). The oldest glaciation was represented by remnants of till, up to 2 km in length, located along bevelled ridge crests >10 km north of the present glacier terminus. The late Pleistocene glaciation, called the Qomolangma Glaciation, was subdivided into two stages (I and II). Lateral moraines from glacial advances attributed to this glaciation are well preserved at altitudes between 5300 and 5500 m along the west side of the Rongbuk River, ca. 3–4 km north of the present, debris-covered terminus of Rongbuk Glacier (Fig. 1). Farther downvalley there are landforms, including moraine segments, attributed to these glacial episodes, and numerous well-preserved Neoglacial moraines (Rongbude Neoglaciation and Little Ice Age; Zheng, 1988) are found flanking and fronting the modern terminus.

More recent studies (Zheng, 1988) concluded that only the two youngest Pleistocene glaciations (Qomolangma) are well represented in the Rongbuk valley.

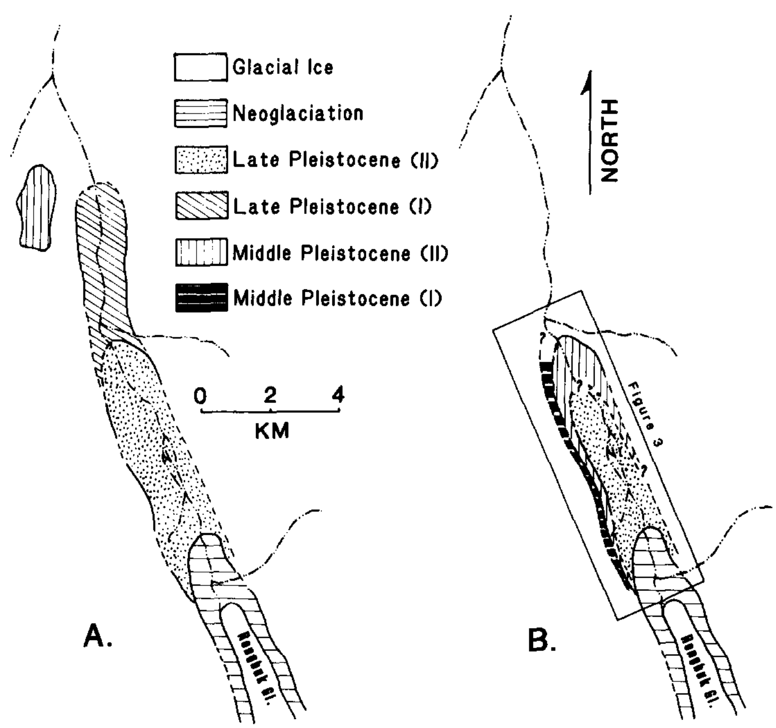

FIG. 2. (A) Simplified map of former glacier geometries in the Rongbuk valley as defined by previous Chinese investigations (after Zheng (1988) and Academica Sinica (1973)). (B) Simplified map of former glacier geometries in the Rongbuk valley based on relative-weathering studies of moraines (this study). Dashed lines or "?" mark uncertain or projected contacts. Box marks the location of Figure 3.

Whereas deposits of older glaciations (Xixibangma and Nyanyaxungla Glaciation; Zheng, 1988) are preserved on the east slope of Mt. Everest, only rare remnants of bouldery deposits attributed to pre-late Pleistocene glaciations were found on slopes high above the Rongbuk River. In this more recent classification, The Qomolongma II glaciation is represented by end moraines found near the Rongbuk monastery, 8 km north of the present terminus of Rongbuk Glacier, and by extensive lateral moraines on both sides of the valley (Fig. 2). These moraines are inferred (Zheng, 1988) to correlate with late Pleistocene advances dated at >11,000 yr in the Nanjibawa region of the Xizang Plateau (Zhang, 1984). The Qomolongma I glaciation (Zheng, 1988) is represented by a "broken end moraine" near the Jilong temple, about 13 km north of the modern glacier terminus, and by the highest preserved lateral moraines along the intervening valley (Fig. 2). This glaciation is thought to be early late Pleistocene in age (Zheng, 1988; Derbyshire, 1987). Multiple, late Holocene moraines (Rongbude Neoglaciation and Little Ice Age; Zheng, 1988) extend up to 3 km downvalley from the present glacier terminus.

Following the 1984 German–Chinese expedition to the Mt. Everest region, Kuhle (1987) interpreted the outermost Neoglacial moraines in the Rongbuk valley as belonging to the >4000-yr-old "Nauri Stadium V" that he had defined on the south flank of the Himalaya (Kuhle, 1986) and for which he had calculated an ELA depression of 500–700 m. Kuhle (1987) also proposed that the Rongbuk valley served as a conduit for an outlet glacier that drained part of an extensive ice sheet covering much of the Tibetan Plateau during the last glaciation, when the mean ELA was depressed >1000 m, according to him. In the Rongbuk valley, Kuhle defined a south-sloping, upper surface for the reconstructed "outlet glacier" that flowed over the Lho La (>6000 m; Fig. 1) before joining the Khumbu Glacier. Under this interpretation, the lateral and terminal moraines assigned to the Qomolongma I and II glaciations by Zheng (1988) would have to be relegated to recessional phases of the last glaciation and to Holocene glacial advances.

There is a clear contradiction between the results of previous Chinese research in the Rongbuk valley, as summarized by Zheng (1988), and those of Kuhle (1987). Zheng (1989) indicates that data gathered by Chinese scientists (Zheng and Shi, 1976; Zheng *et al.*, 1981; Zheng, 1986) in several portions of the Tibetan Plateau appear to be incompatible with parts of Kuhle's ice-sheet hypothesis. In the Mt. Everest area, if the Qomolongma I and II deposits do indeed represent late and early late Pleistocene advances, then no outlet glacier to the south could have existed in the valley at those times. If, on the other hand, there was a late Pleistocene ice sheet in southern Tibet with outlet glaciers such as those proposed by Kuhle, then all of the moraines in the Rongbuk valley must postdate this phenomenon. Whereas absolute dates would be most unequivocal in resolving these apparent contradictions, relative dating and subsequent age assignments on the basis of the degree of weathering can also serve to distinguish between these possibilities.

METHODOLOGY

This study focused primarily on the lateral moraines attributed to either late Pleistocene or Holocene advances by earlier Chinese studies. The present study was aided by new aerial photographs with nominal scales of ~1:25,000 and by new 1:10,000- and 1:50,000-scale topographic maps that had been generated from these photographs. The photographs and maps provided coverage of nearly the entire study area. The studied moraines lie at altitudes ranging from 5000 to 5450 m. On most moraines, two surficial sampling sites, separated by at least 100 m, were defined along those portions of the moraine crests displaying the highest apparent density of erratic boulders. The selected moraines were topographically elevated with respect to the adjacent terrain (i.e., they were not the edge of a geomorphic platform), and areas were avoided where periglacial debris lobes might have deposited clasts on a moraine following its deposition. Moraine crests with unusual vegetation were also avoided. All moraines studied, with the exception of site 9 located farther downvalley, lie on the western margin of the Rongbuk valley and represent left-lateral moraines.

At each selected site, boundaries measuring 10 × 30 m were delimited along the moraine crest, and the following measurements were made: pitted vs unpitted boulders; rough vs smooth boulders; mean pit depth; maximum pit depth; fresh-to-weathered ratio; surface boulder frequency; and boulder relief. The criteria for defining each of these categories are listed in Table 1. All measurements were made by the authors, except in the fresh-to-weathered category, where subjective acoustical judgments were made by other observers. Comparisons of data collected at two sites along the same moraine permitted the consistency of data gathered from a deposit of a single age to be examined, whereas comparisons between moraines were used to classify them as belonging to either the same or separate glacial episodes. The criterion of assigning moraines to different glaciations (Burke and Birkeland, 1979) was that averaged data along a moraine had to vary by ≥50% from that collected from a stratigraphically younger or older moraine. For Pleistocene glaciations, this arbitrary cutoff is likely to be a conservative figure because weathering generally proceeds at an exponential rate (e.g., Colman, 1986), such that a comparable magnitude of change requires more time to accumulate in increasingly older deposits. In addition, by comparing the observed magnitude of changes of various weathering criteria with age-calibrated rates of change determined from other regions (e.g., Colman, 1986), some limits could be placed on the probable ages of these moraines.

The modern equilibrium-line altitude (ELA) was estimated by several methods: (1) the highest altitude of medial and lateral moraines; (2) the altitude of the change in glacier surface contours from concave to

TABLE 1. RELATIVE-WEATHERING MEASUREMENTS

Measurement	Number of measurements	Criteria for classification
Pitted (vs unpitted)	≥100	Pits ≥5 mm depth covering more than 25% of the exposed surface of boulders ≥30 cm in diameter
Rough (vs smooth)	≥100	Small-scale surface relief ≥ single crystal dimensions covering more than 25% of the exposed surface of boulders ≥30 cm in diameter
Mean pit depth	10	Average of measurements to nearest 0.5 cm of the deepest pits found on boulders ≥30 cm in diameter; no more than two on any single boulder
Maximum pit depth	1	Maximum pit depth found at site
Fresh-to-weathered	≥100	Based on sound of repeated hammering of surfaces of boulders ≥30 cm in diameter; sharp "pings" defined as "fresh"; "thuds" defined as "weathered"
Surface boulder frequency	All boulders	Number of boulders ≥30 cm in intermediate diameter
Boulder relief	≥100	Boulders ≥30 cm in diameter classified according to height (H) above the ground surface versus intermediate diameter (ID) of widest cross-section. High relief: H > 0.75 ID; Intermediate relief: 0.75 ID ≥ H ≥ 0.25 ID; Low relief: H < 0.25 ID

convex (Andrews, 1975); and (3) the altitude below which lies 35% of the glacierized area (assumes an accumulation-area ratio (AAR) of 0.65). Former ELA's were estimated based on the AAR and, for Neoglacial moraines, on the upper altitude limit of preserved lateral moraines. It should be noted that this approach differs from that of Kuhle (1987) who halved the altitudinal difference between the headwall and the toe of the glacier. It is clear that the steep rock faces rising around the headward portion of the glaciers in the Everest region contribute considerable snow to them due to avalanching. Consequently, when applying AAR's to estimate former ELA's, nonglaciated faces that appear likely (on aerial photographs) to have contributed snow to a glacier were also included in its accumulation area. The inability, however, to define precisely former ice margins and contributory faces in the headward areas of glaciers introduces increased uncertainty into the ELA estimate.

The distribution of modern ELA's was used to calculate an ELA gradient across the crestal region of the Himalaya. The changes in ELA's between modern and past glaciations were determined with reference to this regional gradient. Uncertainties concerning past regional gradients, however, introduce additional potential errors into estimates of ELA changes in the past.

RESULTS

Relative Dating

In the primary study area along the western wall of the Rongbuk valley (Fig. 3), at least four Pleistocene moraine crests are clearly visible. These moraines are essentially straight-crested and nearly horizontal or sloping very gently to the north. In comparison to the adjacent surfaces, they are characterized by an abundance of well-rounded boulders and by the absence of significant veneers of fine-grained sediments. This moraine grouping had been previously classified (Academica Sinica, 1973; Zheng, 1988) as belonging to the late Pleistocene and was further subdivided into an early and late-glacial interval (Derbyshire, 1987; Zheng, 1988). The youngest and lowest of the moraines are represented by only a small remnant (not studied) that has not been modified by periglacial slope processes. The oldest, well-preserved moraine is a sharp-crested, elongate ridge at ca. 5450 m that lies slightly below slopes cov-

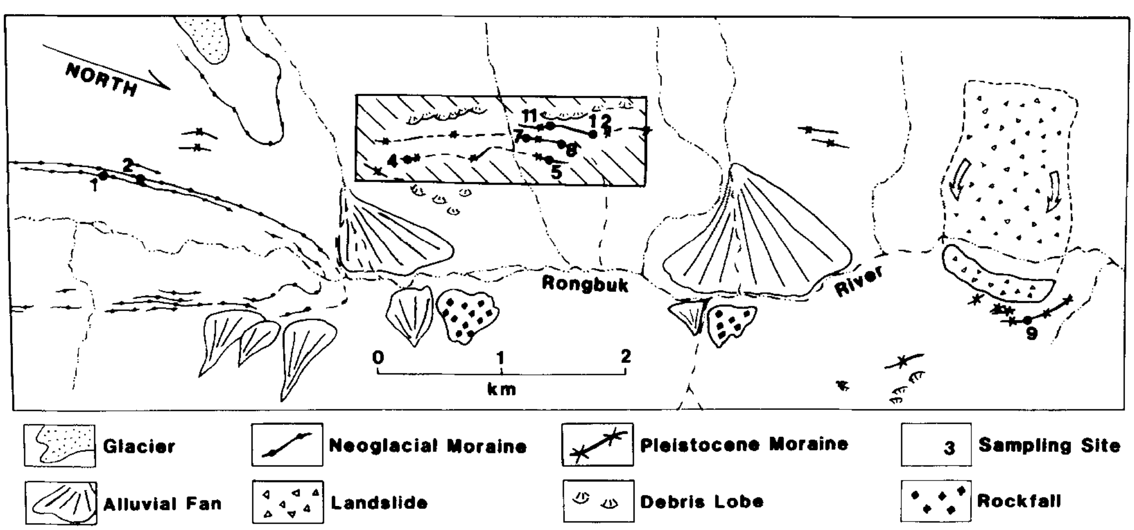

FIG. 3. Detailed map of the region studied (shown by boxes in Figs. 1 and 2). Sampling sites on moraine crests correspond with the site numbers described in the text, figures, and tables. Hachured box indicates the primary study area.

ered with major periglacial rock lobes. Possibly these lobes mantle, bury, and rework additional, still-older moraines, but none of them were studied here.

The results (Fig. 4 and Table 2) from the paired sites on each of the three remaining Pleistocene moraines in the primary study area (sites 4 and 5 on the youngest moraine; sites 7 and 8 on the intermediate moraine; and sites 11 and 12 on the oldest moraine: Fig. 3) indicate considerable differences in the weathering characteristics of these moraines. The most effective discriminators between them are the degree of pitting (Figs. 4A and 5), surface roughness (Fig. 4B), pit depths (Figs. 4C and 4D), and boulder relief (Figs. 4E and 6). Fresh-to-weathered ratios (Fig. 4F) were poorer discriminators, and surface boulder frequencies (Fig. 4G) were poor discriminators. Despite the lower boulder frequencies on the intermediate-aged moraine (Fig. 4G), measurements of boulder relief, pitting, roughness, pit depths, and to a lesser extent, fresh-to-weathered ratios (Fig. 7) yielded variations that were consistent with increasing and considerable age differences among the Pleistocene moraines.

Two Neoglacial moraine crests within 1 km of the present glacier terminus were also studied (sites 1 and 2; Figs. 3 and 4). Although these could generally be separated from the youngest Pleistocene moraines on the basis of pitting, pit depths, and, to a lesser extent, fresh-to-weathered ratios (Figs. 4A, C, D, and F), there was considerable overlap in the other categories.

Two deposits at ca. 5000 m altitude and ~8 km north of the glacier terminus were also examined (Fig. 3). Both had been previously mapped (Fig. 2) as moraines by Chinese geologists (Academica Sinica, 1973; Zheng, 1988). A massive, hummocky deposit measuring 900 × 200 m in the central portion of the valley (Fig. 3) appears to have resulted from mass movement, rather than glacial deposition. Its irregular surface is littered with angular metamorphic clasts of local derivation. Leucogranite boulders, such as those that abound elsewhere on the studied Rongbuk moraines, are nearly absent. On the western slope of the Rongbuk valley and directly opposite this deposit, an elongate region of hummocky terrain descends from high on the ridge and is the probable source area of this landslide. Where studied, the landslide debris in the valley bottom is at least 15 m thick, and the underlying deposits appear to be glaciofluvial gravels and boulders, rather than till, as previously suggested (Zheng, 1988).

The other deposit examined in this most northerly study area is clearly a moraine. Its rapidly descending crestline indicates

TABLE 2. RELATIVE-WEATHERING DATA FOR INDIVIDUAL SITES

Site no.	Surface boulder frequency	Relief: high (%)	Relief: intermediate (%)	Relief: low (%)	Fresh/ weathered	Smooth/ rough	Unpitted/ pitted	Mean pit depth (cm)	Max. pit depth (cm)	Inferred age
1	323	38	41	21	1.33	1.63	2.27	2.0	3.0	Neoglacial
2	187	26	47	26	1.13	1.07	2.26	2.6	5.0	Neoglacial
4	489	42	44	14	1.00	2.55	0.95	3.8	5.0	Late Pleistocene
5	250	27	38	35	0.82	1.03	0.96	3.4	5.0	Late Pleistocene
7	112	12	42	44	0.68	0.48	0.30	6.6	11.0	Middle Pleistocene (II)
8	114	0	39	61	0.98	0.58	0.18	7.0	8.0	Middle Pleistocene (II)
9	86	7	37	56	0.72	0.72	0.48	3.8	9.0	Middle Pleistocene (II)
11	351	5	36	59	0.62	0.18	0.07	9.0	11.0	Middle Pleistocene (I)
12	427	4	45	51	0.96	0.22	0.10	9.1	13.0	Middle Pleistocene (I)

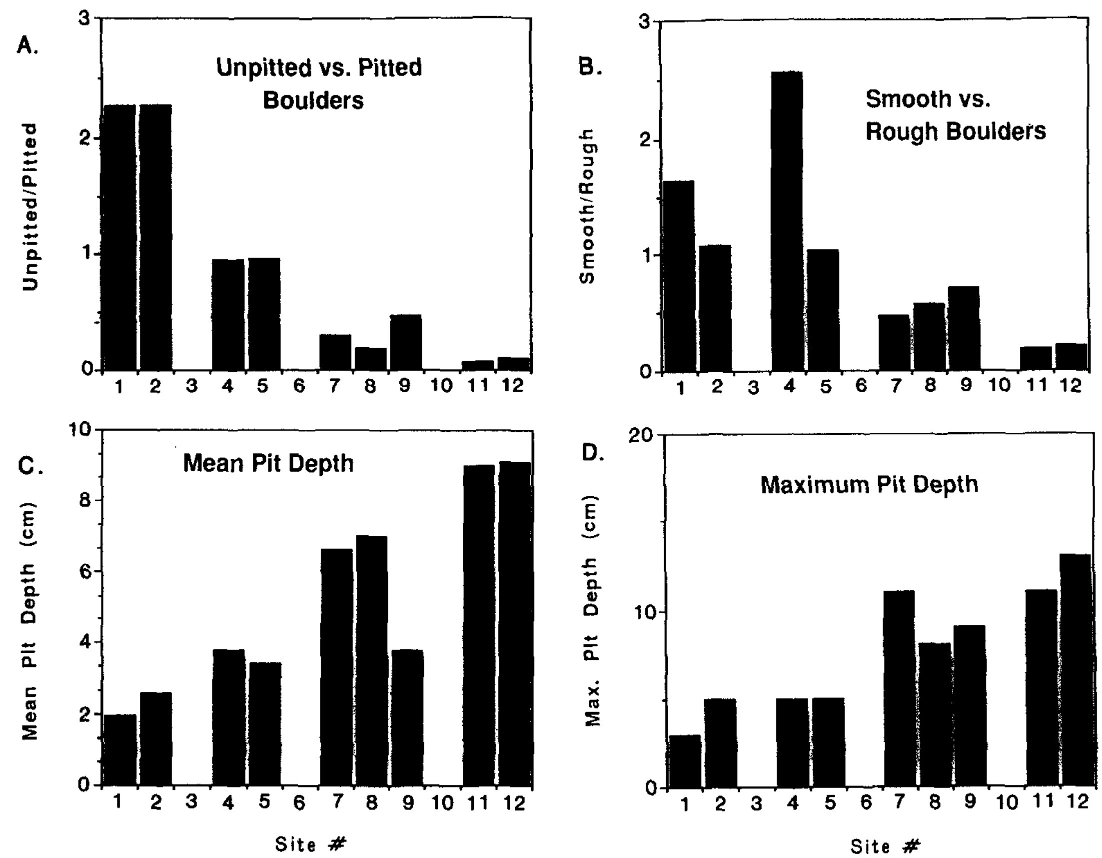

FIG. 4. Relative-weathering data for sampling sites. Site numbers are those depicted in Figure 3. For criteria for classification, see Table 1. (A) Unpitted versus pitted boulders. (B) Smooth versus rough boulders. (C) Mean pit depth. (D) Maximum pit depth. (E) Boulder relief. (F) Fresh versus weathered boulders. (G) Surface boulder frequencies.

that it was deposited adjacent to the former terminus of the glacier at 4980 m. Like the previously described moraines and in contrast to the adjacent mass movement deposit, it is covered with subrounded, leucogranitic boulders. Sampling site 9 (Fig. 3) was located on this moraine in order to determine with which lateral moraines farther up valley it would correlate, thus providing a basis for reconstructing the former glacial margins at one particular time. Several much smaller moraine remnants are inset within this moraine; these were not studied. The weathering data collected from this moraine (site 9; Fig. 4 and Table 2) are most similar to those of sites 7 and 8 on the "intermediate-aged" lateral moraine 4 km to the south.

Equilibrium-Line Altitudes

All of the methods converged toward comparable estimates of the modern ELA (±100 m) for each individual glacier to which they were applied, although AAR's tended to yield estimates that were 50–100 m lower than the other methods. This may reflect the fact that the lower 5–10 km of the largest glaciers are extensively mantled with debris which likely retards ablation while extending the area below the ELA.

The modern ELA's are lowest on the glaciers lying to the northwest of Mt. Everest (Rongbuk, Pumori, and West Rongbuk glaciers; Fig. 1), where the ELA's average between 5800 and 5900 m. Due north of Mt. Everest, the East Rongbuk and Changtze (Beifeng) glaciers have ELA's of ~6400 and 6200 m, respectively. The difference in ELA's between the northern and northwestern glaciers can be attributed to the low passes west of Mt. Everest (e.g., Lho La at 6026 m; Fig. 1) that permit monsoonal

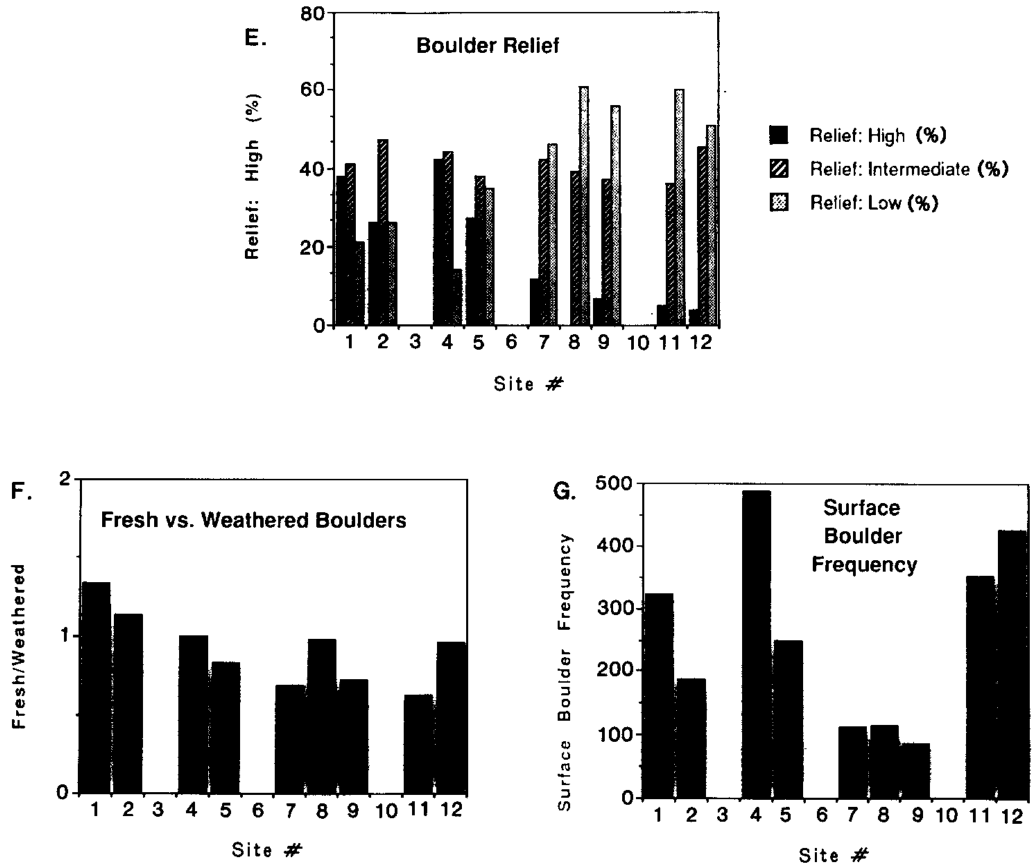

FIG. 4—*Continued*

moisture from the south to penetrate more effectively across the range crest. The Everest massif itself and a ridge averaging ≥7000 m in height and running east from Lhotse (a few km south of Mt. Everest) reduce the moisture transport to the north and east of the summit.

Despite such local variations, the regional distribution of modern ELA's within 20 km of the Himalayan crest yields a generally consistent, northward-rising gradient of 20–25 m/km (Fig. 8). This reflects a predictable orographic effect across the range crest, and, although somewhat greater in magnitude, this gradient accords well with other reconstructions of past and present ELA gradients in the Everest region (Williams, 1983).

Major changes in glacier thickness have occurred in the past. In the vicinity of the modern terminus, the Neoglacial ice was about 100–150 m thicker than the present-day glacier. Well-preserved moraines altitudinally above the modern terminus, as well as downvalley, indicate that the late Pleistocene glaciers were >300 m thicker than modern glaciers. Such variations in glacier thicknesses represent factors that should be incorporated into ELA reconstructions. Because the lower 10–20 km of these glaciers occupied gentle valley bottoms (often slopes of <40 m/km), such large increases in ice thickness permit relatively small decreases in the ELA altitude to lead to significant advances of the terminus. For example, if the regional ELA surface were to be maintained in its present orientation, but the glacier were permitted to thicken to its Pleistocene condition, the terminus of the Rongbuk glacier would advance downvalley more than 4 km; approximately half its reconstructed late Pleistocene extent.

Commonly, Neoglacial moraines are preserved high in the glacier catchment areas at altitudes 50–100 m below the present

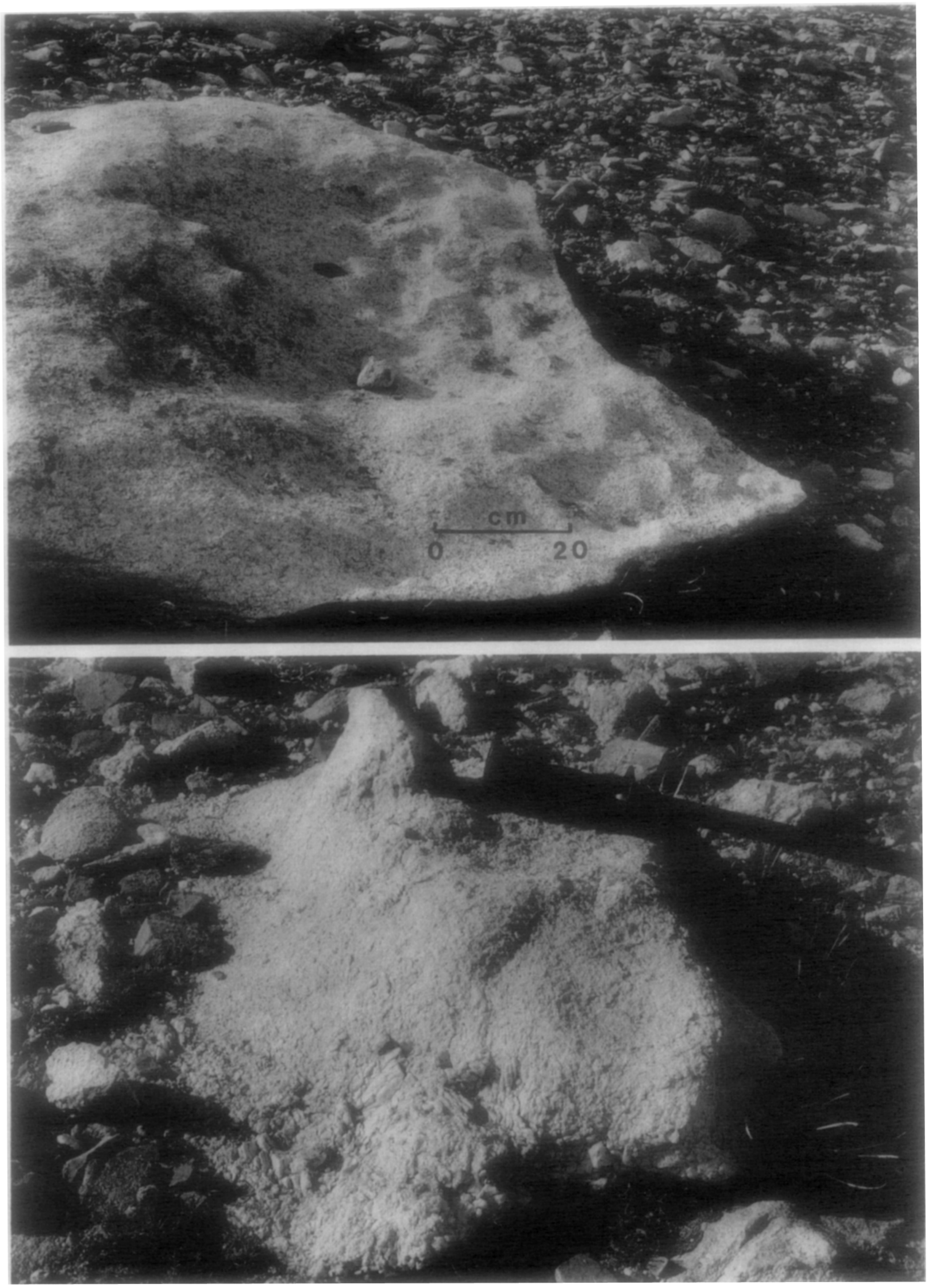

FIG. 5. Highly pitted and deeply weathered boulders on the outer studied moraine. These boulders display the low relief, multiple deep pits, and pervasively rough surfaces that typify the moraines interpreted to correlate with oxygen isotope stage 6 or older.

equilibrium line. Based both on Neoglacial moraine position and AAR's, the estimated maximum ELA lowering during Neoglaciation was ≤100 m. Late Pleistocene ELA's were estimated using AAR's in conjunction with the reconstructed geometry of the former glaciers. With respect to the modern ELA surface, the amount of ELA lowering

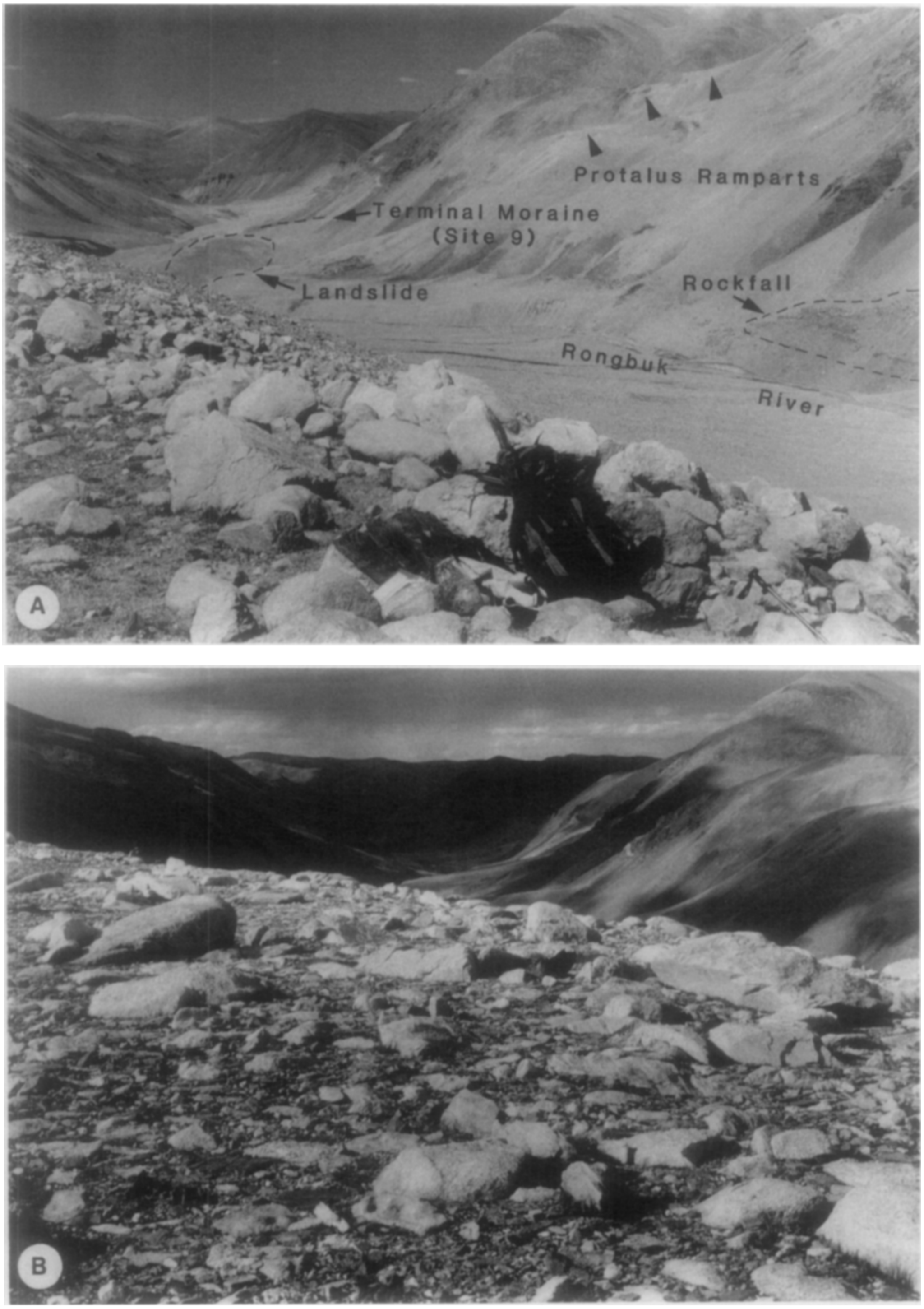

FIG. 6. Contrasting moraine crests and boulder relief on the youngest and the oldest Pleistocene moraines studied. (A) View NNW along the Late Pleistocene moraine crest where sites 4 and 5 are located. Numerous fresh, "high relief" boulders are preserved along the crest. In the background are visible a rockfall derived from the east wall of the valley; a large landslide deposit (formerly mapped as moraine) in the central valley; and the terminal moraine fragment (site 9) that correlates with the intermediate-aged lateral moraine (sites 7 and 8). (B) View NNW across crest of oldest moraine showing predominantly "low relief" boulders, characterized by extensive pitting and rough surfaces.

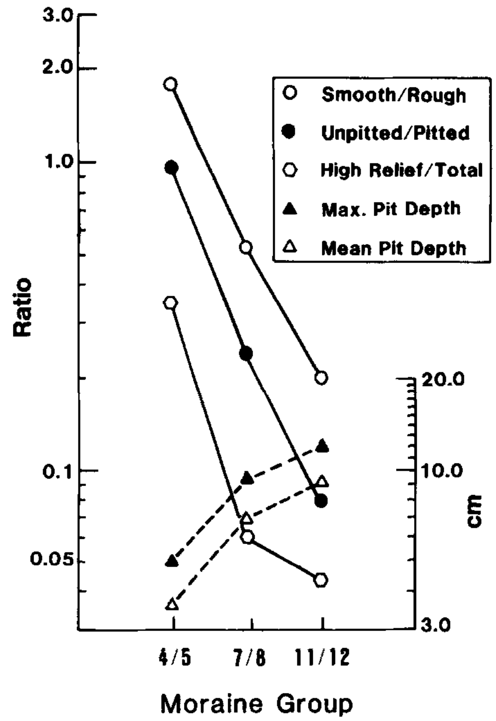

FIG. 7. Relative-weathering data averaged for sites along single moraines. For tabulated data, see Table 3.

during the late Pleistocene is estimated at ≤400 ± 100 m. The uncertainty in this result arises from the imprecise reconstruction of the upper portions of the Pleistocene glaciers and from potential changes in the past ELA regional gradient. Nevertheless, the limited ELA lowering is supportive of estimates for cold, dry conditions in this region during the late Pleistocene maximum (Gates, 1976).

DISCUSSION

Our geomorphological analysis based on field observations, the new 1:10,000-scale maps, and the new aerial photographs permits a more precise mapping of the north flank of Mt. Everest than previously undertaken. This analysis, however, has uncovered only two significant discrepancies with previous Chinese maps. First, evidence in the lowermost Rongbuk valley for lateral moraines related to the "broken end moraine" at Jilong temple is scarce, at best. Earlier maps (Academica Sinica, 1973) show nearly continuous moraines along steep valley walls where few, if any, appear to exist. The only evidence for a former end moraine at Jilong temple is a concentrated "lag" of outsized boulders sitting on a fluvial terrace (Zheng, 1988). It seems reasonable that these were winnowed from a larger end moraine, but the evidence is equivocal. Second, a large deposit formerly interpreted as an end moraine near the Rongbuk temple has been re-interpreted as a mass-movement deposit. However, the presence of an end moraine (site 9, Fig. 3) immediately adjacent to the mass movement deposit does not alter earlier interpretations of the basic geometry of the reconstructed glacier.

It is noteworthy that the younger, Neoglacial moraines do not consistently exhibit lesser degrees of weathering than the older moraines (Figs. 3 and 4). Whereas fresh-to-weathered ratios, pitting, and pit depths exhibit trends consistent with the stratigraphic order, other indicators are more ambiguous. Similar apparent reversals in weathering trends have been observed elsewhere for Holocene-aged moraines (Birman, 1964; Gillespie, 1982). The discrepancies at Mt. Everest likely result from incorporation of boulders that were derived from adjacent periglacial slopes and that have been little modified by glacial transport, so that inherited weathering traits are preserved in the younger moraines. In the study area, the Neoglacial moraines are perched along a steep valley wall. Although the Pleistocene moraines are fairly continuous farther downvalley, segments of older moraines preserved higher on the valley walls are very rare in this locality. This suggests that considerable slumping of both periglacial and morainal debris off the steep walls during the Neoglacial interval may have provided previously weathered boulders to the lateral moraines. Although similarly weathered boulders should also have been incorporated in the Pleistocene moraines, they would have been transported 2–4 km farther downvalley to the area where they are well preserved. Presum-

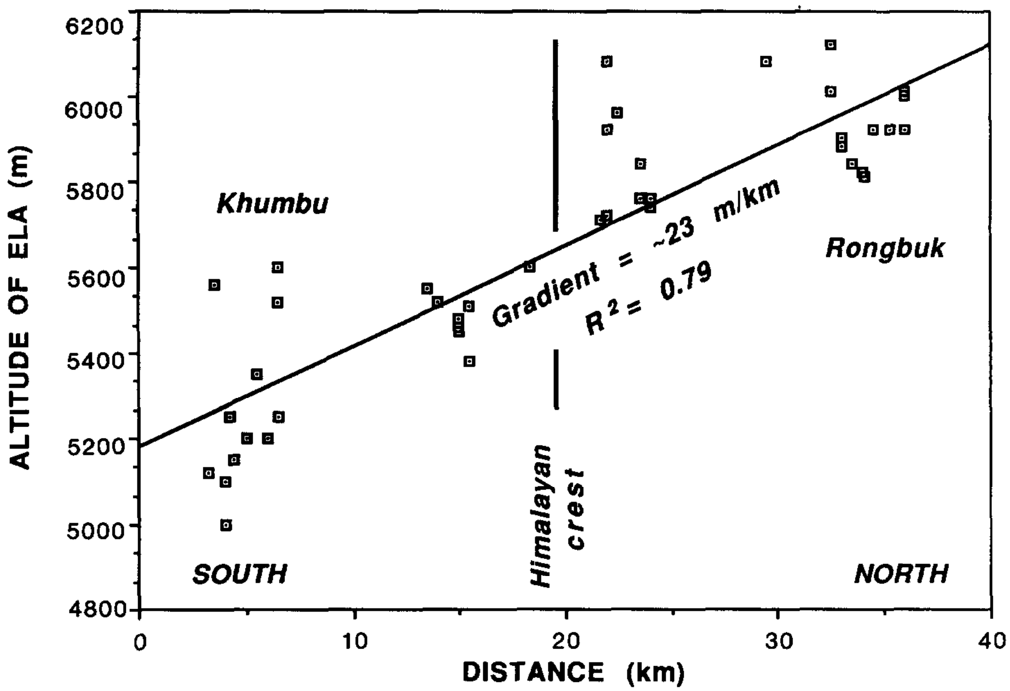

FIG. 8. North–south gradient of the modern ELA based on the regional snowline distribution. This surface serves as a reference frame for estimating changes in past ELA's.

ably, this distance of transport was sufficient to remove their inherited weathering traits. Furthermore, because the Neoglacial moraines are situated upvalley from a major glacier confluence (Fig. 1), possibly the boulders incorporated into them have somewhat different weathering characteristics than those found farther downvalley.

When the relative-dating data for the sites on each individual moraine are averaged (Fig. 7 and Table 3), clear distinctions can be drawn between these moraines that were all classified as late Pleistocene by previous investigators (Fig. 2; Zheng, 1988). For most of the parameters measured (especially pitting, boulder relief, and roughness), the variability between sites sampled on the same moraine was much less than that found between moraines. The mean relative-dating characteristics on a given moraine frequently varied by a factor of 2 to 5 from the mean on adjacent older or younger moraines. The most useful discriminators were the degree of pitting, pit depths, surface roughness, and boulder relief.

In the field, it was obvious that surface boulder frequencies would not effectively separate moraines of different ages. Even though the segment of the moraine crest with the most numerous boulders was selected for study in each case, following cur-

TABLE 3. RELATIVE-WEATHERING DATA BY MORAINE

Site no.	Surface boulder frequency	Relief: high (%)	Relief: intermediate (%)	Relief: low (%)	Fresh/ weathered	Smooth/ rough	Unpitted/ pitted	Mean pit depth (cm)	Max. pit depth (cm)	Inferred age
1–2	255	32.0	44.0	23.5	1.23	1.35	2.27	2.3	4.0	Neoglacial
4–5	370	35.0	41.0	25.0	0.90	1.79	0.96	3.6	5.0	Late Pleistocene
7–8	111	6.0	40.5	53.5	0.83	0.53	0.24	6.8	9.5	Middle Pleistocene (II)
11–12	389	4.5	40.5	55.0	0.79	0.20	0.08	9.1	12.0	Middle Pleistocene (I)

sory visual inspections, it was clear that the intermediate-aged moraine (Sites 7 and 8, Fig. 3) had far fewer surface boulders than the older moraine (sites 11 and 12, Fig. 3) adjacent to it. Because the lengths of the preserved moraine crests are often about 100–300 m, it was not possible to test whether there were significant differences along a single moraine beyond those illustrated by our measurements.

Although distinctions can be readily drawn among the sampled moraine crests on the basis of the relative-weathering data (Fig. 7), in the absence of absolute dates, their relationship to established chronologies of global glaciation (e.g., Shackleton and Opdyke, 1973; Sibrava *et al.*, 1986) is less obvious. We have used two different approaches to estimate the ages of the studied moraines on Mt. Everest.

In the first approach, we combine three assumptions to reach our conclusions. First, we assume that the glacial episodes in the Mt. Everest area are Pleistocene in age and are essentially "in phase" with global ice-volume changes, although their relative magnitudes may vary. Consequently, we refer the Rongbuk glacial succession to the glacial stages defined by marine oxygen isotopes (Shackleton and Opdyke, 1973). This assumption appears to be validated by the available dates (18,000–20,000 yr B.P.) for at least the latest Pleistocene glaciation in the Himalaya (e.g., Singh and Agrawal, 1976; Röthlisberger, 1986). Second, following the approach of Burke and Birkeland (1979), we assume that changes of a factor of 2 or more in weathering characteristics serve to differentiate moraines belonging to separate glaciations, rather than stades within a glaciation. Third, we assume that the actual degree of weathering we observe on a particular moraine in the Rongbuk valley can be approximately correlated with the degree of weathering found on better-dated moraines in other areas having similar climatic conditions, i.e., the rates of weathering are comparable within similar climatic regimes.

Given the above assumptions, we want to determine whether the moraines studied represent just one, or as many as three, glaciations. The magnitude of changes (>50%) in relative-weathering characteristics between the younger and intermediate-aged moraines (Fig. 7) suggests that they belong to separate glaciations. Although these could be assigned to isotope stages 2 and 4, and consequently would represent stades within the last glaciation, we think it is more likely that they represent isotope stages 2 and 6, because of the large observed differences in weathering between them. Similarly, the relative-weathering characteristics differ sufficiently between the intermediate and oldest moraines studied to suggest that the outermost moraine should predate isotope stage 6, rather than belonging to the late Pleistocene (Qomolongma 1), as previously inferred by several researchers (Academica Sinica, 1973; Zheng, 1988). This is a conclusion consistent with the pervasive weathering displayed by this moraine (sites 11 and 12, Figs. 4–6).

Unless weathering around Mt. Everest proceeds at a much more rapid pace than it does in similar arid to semi-arid (but lower-altitude) environments, such as the eastern Sierra Nevada of California, the outer moraine should belong to at least the penultimate glaciation (isotope stage 6), if not an earlier one. Given the considerably lower mean annual and seasonal temperatures in the Everest region, all temperature-dependent weathering should occur at a slower, rather than a faster, pace. Based on the arguments presented above, we suggest that the outermost moraine correlates to isotope stage 8 or older. Although more reliable age assignments must await radiometric dating of these moraines, this approach to the assessment of the relative-weathering data indicates the presence of moraines from at least two and probably three former glaciations, representing isotope stages 2, 6, and either 10 or possibly 8, the latter not having been a "large" glaciation (Shackleton and Opdyke, 1976). These age assignments contrast with the previous interpretation of these deposits as encompassing only two glaciations, both within the late Pleistocene (Zheng, 1988).

In the second approach to inferring ages for these moraines, we assume (1) that the youngest Pleistocene moraines studied correlate with the late Pleistocene maximum advances dated to about 18,000 to 20,000 yr B.P. in other parts of the Himalaya (Röthlisberger, 1986) and (2) that the effects of weathering, such as pitting, accumulate at an exponentially decreasing rate through time, in a manner similar to that documented for weathering rinds (e.g., Colman, 1986; Whitehouse *et al.,* 1986). Through utilization of a generalized equation for the development of weathering characteristics ($d = kt^{(1/n)}$; where d = weathering characteristic, k is a constant, t = time, and $1 \leq n \leq 2$; Colman, 1986), estimates can be made of the likely minimum and maximum ages of the deposits studied (Table 4). Assumption of a linear rate of weathering ($n = 1$) yields a minimum estimate of age, whereas $n = 2$ probably provides a reasonable upper limit for calculated ages.

Minimum estimates (Table 4) for the intermediate moraines range from 34,000 to 72,000 yr, and maximum estimates range from 64,000 to 285,000 yr. Age estimates for the oldest moraines range from a minimum of 43,000 to 202,000 yr to a maximum of 104,000 to 2,271,000 yr. Although the pit-depth measurements yield the lowest estimated ages, the observed pitting of virtually the entire surface of older boulders, suggests that these depths (and derived ages) are also minimum values, because the original surface of each boulder has been removed. Ratios, such as pitted/unpitted boulders, may not be entirely justified for usage in these equations which were derived from measured characteristics like rind thicknesses (Colman, 1986). Nevertheless, these calculations suggest that correlations of the intermediate-aged moraines with isotope stage 6 and of the oldest moraines with isotope stage 10 or older are reasonable.

Clearly, the calculated ages for the older moraines (Table 4) are strongly dependent on the assignment of a Pleistocene age to the younger moraine grouping. If these moraines were actually Neoglacial in age, then the estimated ages for the other moraines would be incorrect. Similarly, our earlier argument based on correlation with isotopic stages would also be compromised. We maintain, however, that a Neoglacial age is very unlikely. Kuhle (1987) has suggested that the outermost moraine adjacent to the modern terminus is early Neoglacial in age. We also assign this and other inset moraines (Figs. 2 and 3) a Neoglacial age. The moraines that we have assigned to the Pleistocene represent repeated, large-scale ice advances. They are massive, bulky moraines that appear to represent a long-term accumulation of till and that stand in contrast to the Neoglacial moraines that are

TABLE 4. ESTIMATED AGES BASED ON WEATHERING DATA OF MORAINE GROUPINGS

Moraine group	Model ages in thousands of years[a]											
	Mean pit depth			Max. pit depth			Pitted/unpitted			Rough/smooth		
	Char.[b]	Limits[c]		Char.	Limits		Char.	Limits		Char.	Limits	
Site numbers	cm	$n = 1$	$n = 2$	cm	$n = 1$	$n = 2$	Ratio	$n = 1$	$n = 2$	Ratio	$n = 1$	$n = 2$
4/5[d]	3.6	18 K[d]	18 K	5.0	18 K	18 K	1.05	18 K	18 K	0.56	18 K	18 K
7/8	6.8	34 K	64 K	9.5	34 K	65 K	4.2	72 K	285 K	1.87	60 K	202 K
11/12	9.05	45 K	114 K	12.0	43 K	104 K	11.8	202 K	2271 K	5.0	161 K	1445 K

[a] Based on $d_1/d_2 = (t_1^{(1/n)})/(t_2^{(1/n)})$; t = age in Kyr; d_1, d_2 = weathering characteristics.
[b] Char., measurement of weathering characteristic.
[c] Age limits based on exponent $n \geq 1$, $n \leq 2$.
[d] Age of moraine group 1 assumed 18 Kyr.

generally sharp-crested, thin veneers on the valley walls immediately adjacent to the present glacier. Whereas the Neoglacial moraines indicate former ice thicknesses up to 100–150 m above the modern glacier and an extension of the terminus of ca. 2 km, the Pleistocene moraines represent former ice thicknesses >400 m more than present and a downvalley advance of the terminus of 8 km or more. We know of no precedent for Neoglacial ice advances in semi-arid areas of this magnitude. Consequently, the Pleistocene age assignment of these moraines appears to be justified.

If our analyses of the relative-weathering data are correct, then the only well-defined Pleistocene terminal moraine in the Rongbuk valley (at Rongbuk temple) corresponds to an isotope stage 6 (or possibly stage 4) glaciation, i.e., site 9 correlates with sites 7 and 8 (Fig. 4). Although this site is 8 km downvalley from the present terminus of Rongbuk glacier, it is only about 200 m lower in altitude. The magnitude of ELA lowering required to produce the observed extension of the glacier terminus is only 350–450 m.

This finding has important implications for the recently proposed glaciation of the Tibetan Plateau (Kuhle, 1987), because it contradicts several aspects of the model. First, Kuhle (1987) has suggested a late Pleistocene snowline lowering of >1000 m for the Tibetan Plateau and the High Himalaya, including the Everest region. In the Rongbuk valley, an ELA depression of this amount would have placed the "stage 6" ELA at the same altitude as the observed "stage 6" terminus, a clear impossibility. Ironically, if Kuhle's (1987) method for calculating snowline depression were applied to the late Pleistocene deposits in the Rongbuk valley, they would yield an ELA lowering of only 100 m, less than 10% of that required by his model. Second, Kuhle suggests that the outermost Neoglacial moraines in the Rongbuk valley correspond to an early Neoglacial advance (Nauri Stadium V, Kuhle, 1987) that he has studied on the south flank of the Himalaya, including the Khumbu valley of Mt. Everest. There, a snowline lowering of 500–600 m was calculated. In the Rongbuk valley, a Neoglacial ELA lowering of this magnitude would have caused the terminus to advance more than 10 km, rather than the observed 2 km (Fig. 1). Our calculation of the Neoglacial snowline lowering along the Rongbuk glacier is ≤100 m. Third, Kuhle's reconstructed late Pleistocene glacier in the Rongbuk area flowed *south* and functioned as an outlet glacier to a portion of the "Tibetan ice sheet." The observable geometries for the late and middle Pleistocene glaciers in the Rongbuk valley are clearly incompatible with this model. Despite visits to some of the same localities used to illustrate a southward-sloping Pleistocene glacial surface by Kuhle (e.g., Fig. 20 in Kuhle, 1987), all moraines, trim lines, and erratic boulder trains observed during this study provide evidence for northward-flowing former valley glaciers. Moreover, the new maps show that south-sloping "surface" defined by Kuhle above the present Rongbuk glacier terminus is altitudinally below the pass through which the outlet glacier is hypothesized to have flowed to the south.

The only circumstance under which Kuhle's hypothesis could be correct is one in which the rates of weathering on the north side of Mt. Everest are so accelerated that there is no equivalency between observed amounts of weathering here and in other, better-dated areas. In this situation, all of the glacial features studied here would have to be essentially postglacial. Even this, however, would not be consistent with Kuhle's (1987) interpretation of the Neoglacial sequence in the Rongbuk valley. Consequently, these data from the Mount Everest region reinforce the interpretations offered by Zheng (1989) that there was no large ice sheet on the Tibetan Plateau during the middle and late Pleistocene.

CONCLUSIONS

Relative dating in the Rongbuk valley on the northern slope of Mt. Everest indicates that well-preserved Pleistocene moraines found there are likely to represent three major ice advances, widely separated in time. These advances are interpreted to correspond with oxygen isotope stages 2, 6, and 10 (or 8?), although both of the more recent glaciations could be younger than stage 5. In contrast to the results from earlier studies, the relative dating indicates that there are pre-late Pleistocene glaciations represented by the lateral moraines in the Rongbuk valley. Similar weathering characteristics enable terminal moraines to be correlated with specific lateral moraines, so that former glacier extents can be reliably reconstructed. Based on the former extent of Rongbuk glacier, ELA reconstructions suggest a Neoglacial snowline lowering of $\sim$100 m and a late Pleistocene snowline lowering of $\leq$450 m.

Because Kuhle's (1987) recently proposed model for ice-sheet growth across the Tibetan Plateau has important implications for climatic reconstructions and modeling, it is important to test the tenets of the model. His model is largely based on field observations and snowline reconstructions, and therefore, can be compared with the data described here. Although these data have been gathered from a single valley on the northern flank of the Himalaya, they strongly contradict several key aspects of Kuhle's model. In particular, the magnitude of late Pleistocene snowline lowering in this region has been greatly overestimated and the direction of flow of the Pleistocene glaciers (north) is opposite to that which he describes for this area. Because Kuhle's estimates of ELA lowering and glacial geometries are completely irreconcilable with the data from this area, we suggest that his model for Tibetan glaciation, although intriguing, is not viable.

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