For Don — to help his aim high. How about
joining us on our return to Base Camp in 1973!
or later -
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Glaciology of the Khumbu Glacier and Mount Everest

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Glaciology of the Khumbu Glacier and Mount Everest

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The American expedition to the inner Himalaya of Nepal and Mount Everest (fig. 1) in the winter and spring of 1963 provided a unique opportunity for glaciophysical investigations of the Mahalangur Himal, the world's highest mountain massif. The main glacier system there is the Khumbu, born at the crest of this range which separates northeastern Nepal from Tibet. This paper reviews the geophysical program of the expedition, emphasizing the glaciological and meteorological studies supported by the National Geographic Society.

Prior to the 1950's, expeditions to Mount Everest maintained daily observations on the climate of this region but primarily from the Tibetan side. Brief scientific observations were made in the Khumbu Valley on the south side of the mountain by the Swiss in 1952 and 1956, by the British in 1953, and by the Indians in 1960, 1962, and 1965. These give a more helpful sequence of data, but such comparisons are beyond the scope of this present review.

Our expedition, led by Norman Dyhrenfurth, was comprised of 18 American climbers and scientists. Assisting me in the glaciological program was Barry W. Prather of the Foundation for Glacier and Field Research, Seattle, Washington. To abet our meteorological records, a set of high-altitude radiation measurements was obtained with instruments brought by Barry Bishop of the National Geographic Society staff. The results of this research have been reported elsewhere (Bishop, Ångström, Drummond, and Roche, 1966).

In this region, any time before April, fierce winds and intense cold make it difficult to carry out high-altitude work. After the first of June monsoon storms further restrict the possibilities for activity. But in the several months available we were able to gather information on the landforms and glaciation and make measurements on the atmospheric processes affecting regime of the Khumbu Glacier.

Techniques and Instrumentation

The Khumbu Glacier averages less than a mile in width (fig. 2) but has one of the widest elevation ranges of any known glacier system. Avalanche snow and wind-drift nourish it from within 2,000 feet of the summits of Everest and Lhotse. From a height of 27,000 feet the glacier descends to 15,000 feet in a distance of only 12 miles. Our investigations were aimed at the fundamental factors controlling terminal fluctuations, as significant to the problem of regional climatic change. A lichenometric study of the marginal moraine pattern was hindered by injuries to the field party, but sufficient observations were made to suggest that the glacier's fluctuational history is typical of high valley glaciers in the eastern Himalaya. A reconnaissance assessment of the geology of the Khumbu Valley and Mount Everest was also made and has been reported on in other publications (Miller, 1964a and 1965).

The glaciological plans also involved working at elevations extending from 15,000 to 23,000 feet. We paid special attention to the accretion zone in the Western Cwm, using standard glaciological techniques. Basic geophysical measurements were also made, involving gravity and seismic profiles and surface-movement surveys on seven across-glacier transects (PI to VII, fig. 2). These data are the substance of another paper being prepared. For the ice-depth profiles, a Beard World-wide gravity meter and a Geospace portable seismic interval timer were used. For the surveys, Wild T-2 and T-12 theodolites with an Invar subtense bar were employed, together with a set of precision Wallace and Tiernan aneroids. For the radiation measurements an Eppley Hemispheric Radiometer was used with interchangeable filters for breakdown of the solar spectrum (fig. 3). Direct solar-radiation measurements were made with an Eppley pyranometer (and normal incidence radiometer). An inventory of the glaciological, meteorological, and glaciothermal instrumentation has been listed elsewhere (Miller, 1964b).

Regional Climatic Observations

Because of great differences in elevation and seasonal alternations from the dry to rainy months, extreme climatic contrasts were encountered. The Khumbu Glacier lies but 100 miles from the steaming tropical jungles of the Ganges plain, yet on Mount Everest polar glacial climatic conditions were found. In further contrast, 30 miles to the north lies the dusty, nonglacial desert of the Tibetan plateau.

In the Nepal Midlands the dry season begins in October and lasts through May. Our 16 February days on the 185 miles of trail from Kathmandu to Namche Bazar (fig. 1) were, therefore, dry and warm. Two late-winter cloudbursts were experienced on March 4-5 in the Dudh Kosi and on March 9-10 in the Imja Khola Valley. Fresh snow at the 13,000-foot level lay knee-deep at Thangboche (near the base of Everest), when we reached it in the second week of March. This was the only significant snowfall in the province of Solu Khumbu during the hydrological winter of 1962-63. In the higher Khumbu Valley, sporadic afternoon snow squalls fell daily in April. Drenching monsoon rains can strike as early as the middle of May and extend well into September, the result being treacherous avalanches high in the mountains. In 1963, not until the last days of May did early monsoon snows blanket the peaks. With the advent of the monsoon, our field observations were completed.

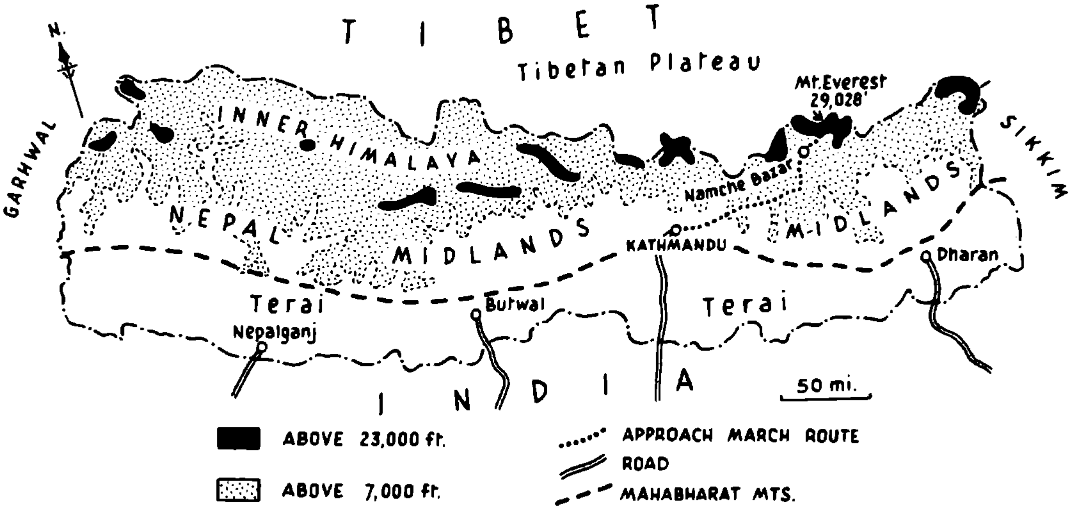

FIG. 1. Map of Nepal, showing location of Mount Everest.

The Glaciological Research Sites

Base Camp was established at 17,800 feet (fig. 2). Here a rimming line of massifs stretched along the Tibetan border and included Pumori (23,441 feet), Lingtren (20,735 feet), and Khumbutse (21,785 feet), extending the prodigious west shoulder of Everest. Above were the gale-whipped summits of the Chomolongma group (Everest, 29,028 feet; Lhotse, 27,890 feet; and Nuptse, 25,850 feet). From the two highest, banners of clouds perpetually trailed toward the east.

The Khumbu Glacier's terminus rests at the outlet of a hanging valley which drains southward into the broad till plain and valley train (outwash) comprising the yak pastures at Pheriche. The terminal moraine system boldly displays a dozen ice-cored fluctuational ridges, indicating a complex recent glacioclimatic history. The ice contact is at 16,000 feet; the base of the outer moraine rampart rests at 14,500 feet.

The debris-charged ice surface in the lower 8 miles of the glacier is characterized by sliding morainic blocks, hidden crevasses, treacherous ice ponds, and 60-foot-high radiation pinnacles (nieves penitentes). At the 16,175-foot camp (Lobuje, fig. 2) a weather shelter was set up on March 16. Here, also, a base line was established on a consolidated moraine ridge from which the surface movement surveys and geophysical depth measurements were initiated. At Gorak Shep (17,000 feet) another thermograph was placed in a windscreen. By March 25 instruments were also installed at the 17,800-foot level. Continuous daily records and geophysical observations were made for the following two months, including englacial temperatures on a thermistor cable in a 25-foot bore-hole near the glacier's center.

The pyrheliometer and radiation recorders were also in operation during April and May. We hoped to carry the actinograph to the South Col, but Prather suffered high-altitude pulmonary edema at 24,800 feet, shortly after I had sustained a crushed foot in a rock avalanche while engaged in a gravity survey of the tributary glacier west of Base Camp. To compound difficulties our Sherpa assistants in the geophysical program became ill with altitude effects. We had to be content with total radiation and spectral measurements at 18,000 feet. But a meteorological field station was set up early in April at Camp I (20,200 feet) at the top of the Khumbu Icefall. Here weather records were maintained until the end of May. At Camp II (21,350 feet) a screen and sunshine recorder were installed and continuous weather readings obtained from April 15 to May 25. The basic meteorological records at these five glacier sites provide a climatological profile between 16,000 and 22,000 feet (e.g., fig. 4). At the two highest camps test-pit measurements of stratigraphy and density, plus systematic measurements of englacial temperatures, were also obtained.

The Névé-line and Meteorological Details

The 1963 transient snow-line reached 18,500 feet. This represented the late-May névé-line just before the monsoon. Our measurements of net accumulation reveal a positive accumulation above 20,000 feet (figs. 5 and 6). Prime accumulation in the Cwm was found to be by direct snowfall rather than avalanches. Katabatic winds off the Lhotse face remove much snow cover above the 22,500-foot level and redeposit it in the middle and lower sections of the Cwm. Over the past decade the zone of maximum total accumulation has remained in the lower one-third of the Cwm, i.e. at about 21,000 feet. A thickening of ice at the same elevation along the Pumori-Khumbutse rampart (fig. 2) suggests that this is regionally representative. Most accumulation is as monsoonal snow deposited during summer months.

Base-camp meteorological records are plotted in figure 4. Maximum/minimum temperature and precipitation trends are shown, as well as a comparison between total sunshine and incoming/outgoing radiation maxima. Base-camp minimum temperatures in April were seldom below zero (F.), rising to 15° to 20° higher during the afternoons. Surprisingly, the lowest temperatures at Gorak Shep were as much as 15° colder, suggesting strong katabatic wind effects. In May at 18,000 feet night-time minimum temperatures were seldom below 15° F.; the maxima slightly above 32° F. After April 27 pronounced increases in daytime temperatures caused meltwater to form, with substantial runoff after mid-May. Such, however, did not take place above 19,000 feet. At the Cwm camps, ambient temperatures

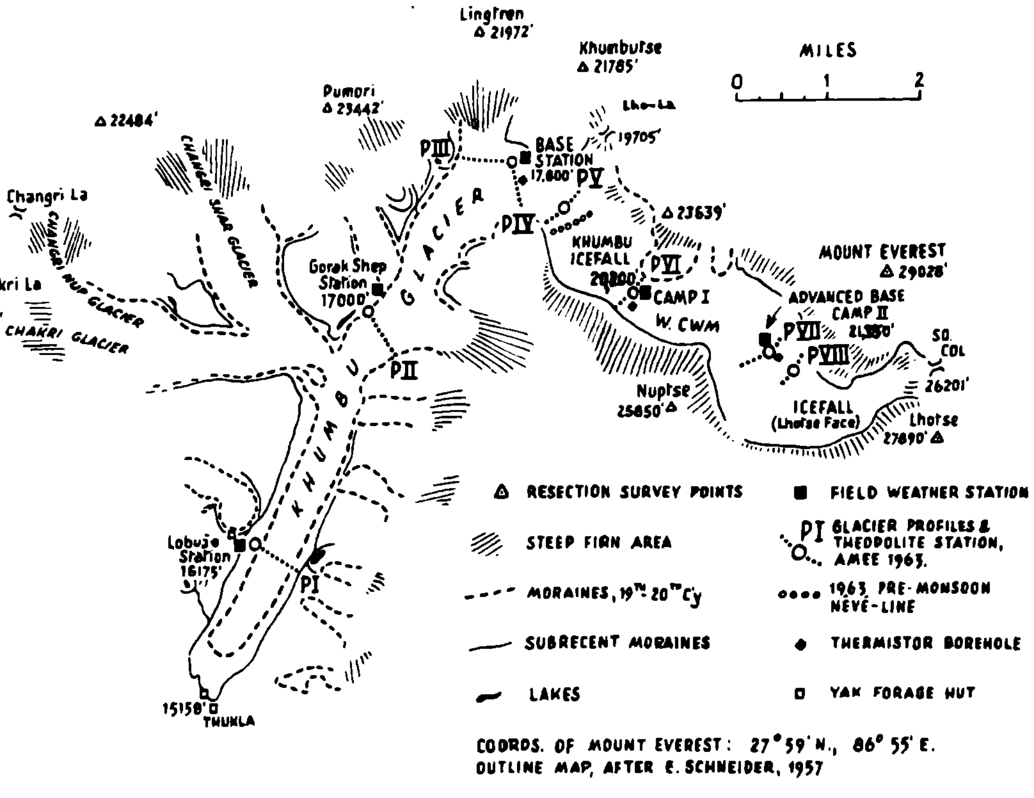

FIG. 2. The Khumbu Glacier System, showing position of geophysical transects and glaciological and meteorological research sites.

in May persisted below 15° F. and were invariably below zero at night. During April the temperatures at 21,000 feet in the Cwm (Camp II) were generally 15° colder than at 18,000 feet (Base).

On May 1, the day of the first summit assault, mid-morning temperatures at the South Col (26,000 feet) registered 18° below zero (F.). At this time the diurnal range at 18,000 feet was 12° to 26° F. (mean 19° F.). Strong differences in orographical control preclude extrapolation of temperatures at higher levels. It was, however, at least 10° colder (about −30° F.) at 1 p.m. when the team attained the summit. At this hour winds were gusting at 60 to 80 mph above 27,000 feet.

Comparison of the spring weather records with those of previous expeditions suggests conditions warmer and drier than in the 1920's. The worldwide climatic amelioration of the past half century has presumably affected this part of the Himalaya with a regional storm-track shift to the south. Related is what seems to be a later arrival of monsoon storms since the early 1950's. This is in contrast to the monsoons reported on expeditions of 30 and 40 years ago. Prior to the premonsoon lull of May 21, wind above 26,000 feet was almost incessant. The May 21-23 lull signified termination of the prevailing westerly gales. As shown in figure 4, early monsoon storms commenced after May 23. These were culminated on June 6 by severe monsoon conditions throughout the eastern Himalaya. Within a week the lower Brahmaputra and Ganges Rivers had flood-crested.

Firn-pack Stratigraphy and Chronology

In the Western Cwm a stratigraphic thickness of 65 feet (20 meters) of retained firn and ice was measured, representing 10 years of accumulation. Melt samples from each stratum were obtained for study of the origin of wind-borne material, including pollen, spores, salts, and other inorganic particulates. Samples were also collected for measurement of tritium (T, radio-active hydrogen, mass 3, with an 18-year average life). Significant variations of this radioactive isotope are known to be produced in periodic outbursts of solar flares, as well as in man-made thermonuclear explosions. Our results, briefly stated below, are based on the laboratory analyses of Dr. W. F. Libby and J. S. Leventhal at the University of California, Los Angeles.

Firn stratigraphy of the upper Khumbu Glacier from 20,000 to 23,000 feet was obtained with samples taken in test pits and shoveled-back crevasse walls. A particularly well-delineated sequence of ice strata was observed (fig. 5). On the initial assumption that these were annual strata, the lowest layers would have corresponded to precipitation during years before nuclear

FIG. 3. B. W. Prather taking reading with double hemispheric radiometer which includes a solarimeter, at 17,800 feet. Camp Khumbu Icefall in background. (Photo by M. M. Miller.)

testing. Thus we believed that we had an opportunity to provide a check on the natural production of tritium. However, with the beginning of fusion weapons testing in the mid-1950's, artificial amounts of T were introduced into the atmosphere and these were large enough to mask its natural production. Because of the polythermal character of this glacier (described in the next section), resulting from a combination of low latitude and high elevation, and in view of the peculiarities of the upper tropospheric meteorology involved, including effects of the jet stream, significance of the stratigraphic interpretations is increased.

Though the original plan to obtain pre-1954 samples failed, we did succeed in dating the strata. Figure 6 represents the data plot against depth below the late-May, 1963, névé surface. Tritium concentration is given in T units ($1TU = T/U \times 10^{18}$). The measurement techniques for tritium have been well established in recent geochemical literature (Von Buttlar and Libby, 1955). Dated bomb-testing peaks are identified on this curve by reference to data from elsewhere in the Northern Hemisphere. Thus, stratum 16, which is 4 feet (1.2 meters) thick, was laid down in the summer of 1954; and stratum 10, which is 2 feet (0.6 meter) thick, was formed in

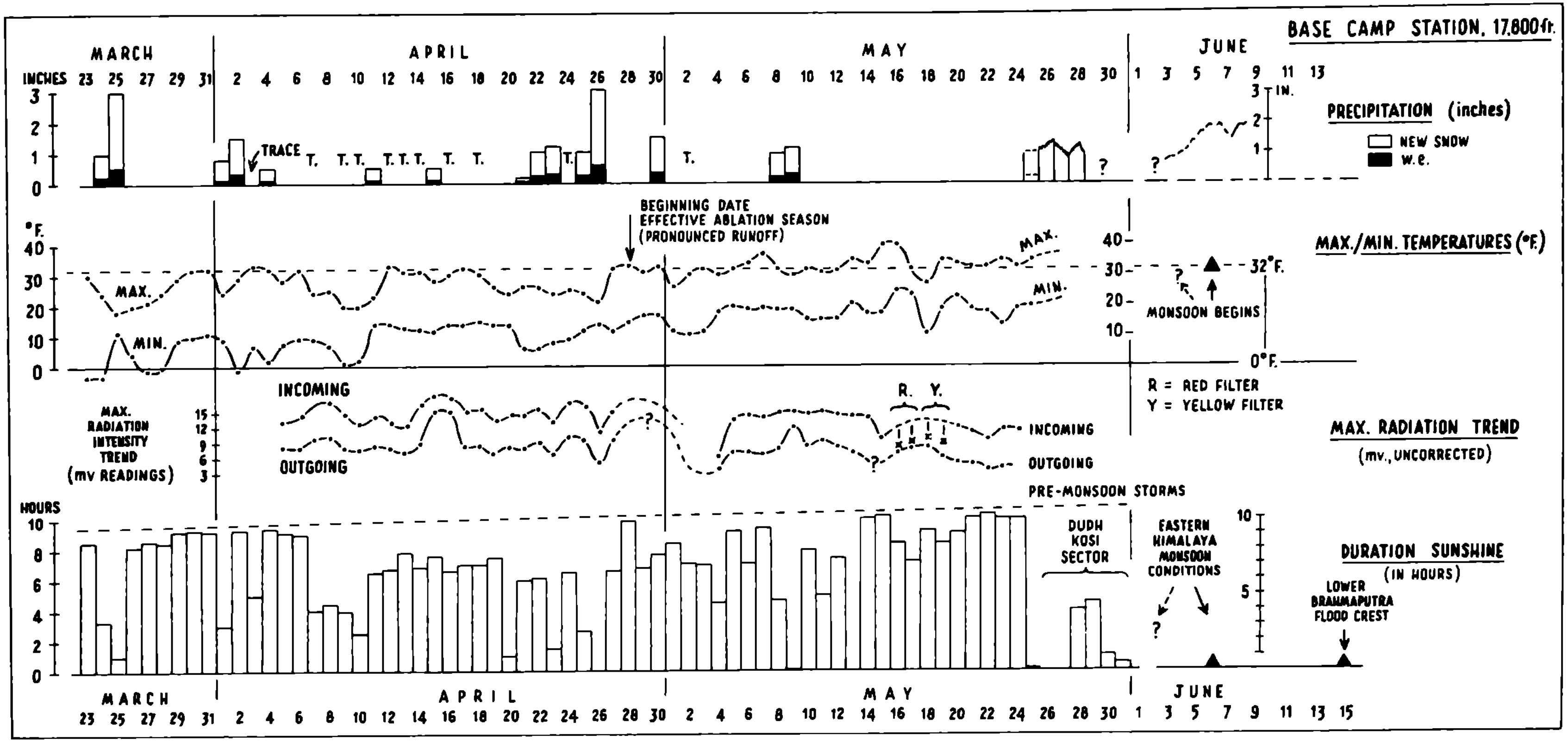

FIG. 4. Daily temperature, precipitation, and sunshine records at 17,800-foot camp on the Khumbu Glacier of Mount Everest, March-June 1963.

1958, following the spring-summer U. S. and Soviet nuclear tests. The net accumulation between these fixed points (1954-58) was 21.8 (6.6 meters) of ice at density of about 0.88 (measured and found to be nearly constant below the top two or three layers), for a total of 19.1 feet (5.8 meters) of water equivalent, or 5 feet (1.5 meters) per year over the 4-year interval. Between the next four years (1958-62) the total was 25.4 feet (7.7 meters) of water equivalent, or 6.3 feet (1.9 meters) per year. In the lower section of the Cwm, this gives an average net accumulation of 5.6 feet (1.7 meters) per year over the preceding 8-year period.

Our interpretation concludes that two strata are deposited each year (see Miller, Leventhal, and Libby, 1965, for further details). One segment represents accumulation during the summer monsoon and the other accumulation during the months of prevailing winter storms. Variations in thickness indicate irregular deposition and ablation, with evaporation, not melting, being the major cause of ablation. This is the result of the low temperatures and high solar radiation effects. It is also indicative of the two main types of accumulation which occur: (1) in the summer monsoon, deposition largely by direct snowfall; (2) in the winter much less total

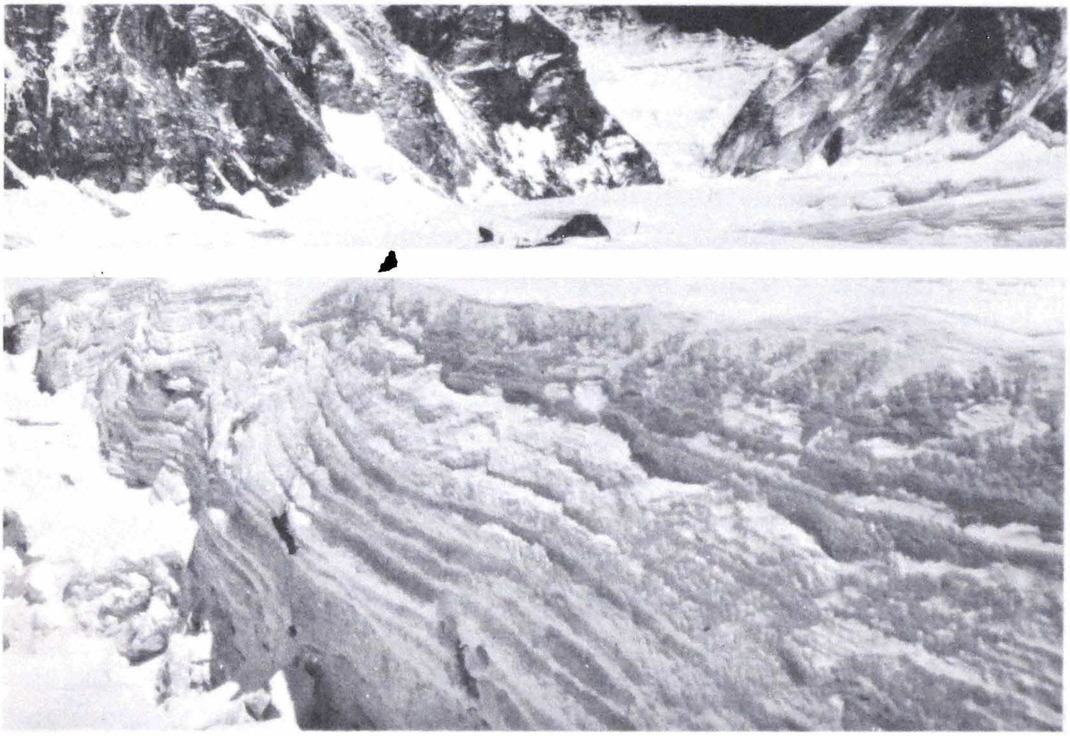

FIG. 5. Exposed Crevasse Wall and glaciological camp on Upper Khumbu Glacier at 20,200 feet, showing layers of primary stratification sampled for tritium, palynological, and particulate analyses.

snowfall but considerable redeposition locally by wind drift from high exposed ledges and faces (Müller, 1959; Pugh, 1962).

In winter another prominent feature of the climatology of this region is the westerly jet stream, which centers at 27 1/2° N. and 12 kilometers altitude. The core of the jet is only 3 kilometers above Everest and, on occasions, may be lower, resulting in very strong winds throughout the winter. The velocity of the winter wind on Mount Everest's summit is estimated to be 40 m/sec. (Koteswarm and Parthasrathy, 1953). This combination provides a plausible explanation of the two mechanisms of deposition described.

Glaciothermal Character and Current Regime Trends

Our geophysical results indicate a polythermal character of the Khumbu Glacier; that is, thermophysical conditions at the highest elevations are geophysically subPolar to Polar, with those at the terminus being sub-Temperate to Temperate. In the Western Cwm the rather severe negative in-ice temperatures indicate ambient temperatures throughout the year which are substantially below freezing and hence with negligible propagated melt-water. As yet we do not know whether there are significant short-term ameliorating effects of the monsoon at high elevation.

Because of the sensitivity of glacier creep to englacial temperature changes, the seismic and surface movement data when worked up should throw more light on the glaciophysical characteristics. Also related is the fact that the accumulation/ablation balance points to an equilibrium regime, verging on slight down-wasting and terminal area retreat. Short-term climatic changes, however, are expressed by pulsations in the icefall zone. This may explain why the glacier in 1963 was unusually active in its upper reaches. It is clear that abnormally difficult serac conditions had developed in this year. Also, the Cwm crevasse wall stratigraphy suggests that a decade ago melt-water played a larger role. Regime-wise the total melt-water effects in 1963 were found to be nil and, in fact, almost totally absent above 24,000 feet.

Neoglacial Pulsations and Epeirogenic Effects

The latest expanded positions of the Khumbu Glacier are twofold and not far from the present glacial position. Corresponding scour zones and associated lateral moraines along the valley walls suggest that these recent pulsations occurred since the 1700's and represent more vigorous advances than have occurred at any time in the past several millennia. The situation has been compared with the regional pattern of Alaskan Cordilleran glaciation (Miller and Prather, 1966).

At present, the Khumbu Glacier terminus rests on a subglacial mantle of older till, bearing out the concept of a strong recent resurgence of the Himalayan Little Ice Age (late Neoglacial), as well as the probability that during the Thermal Maximum (about 5,000 years ago) recession occurred

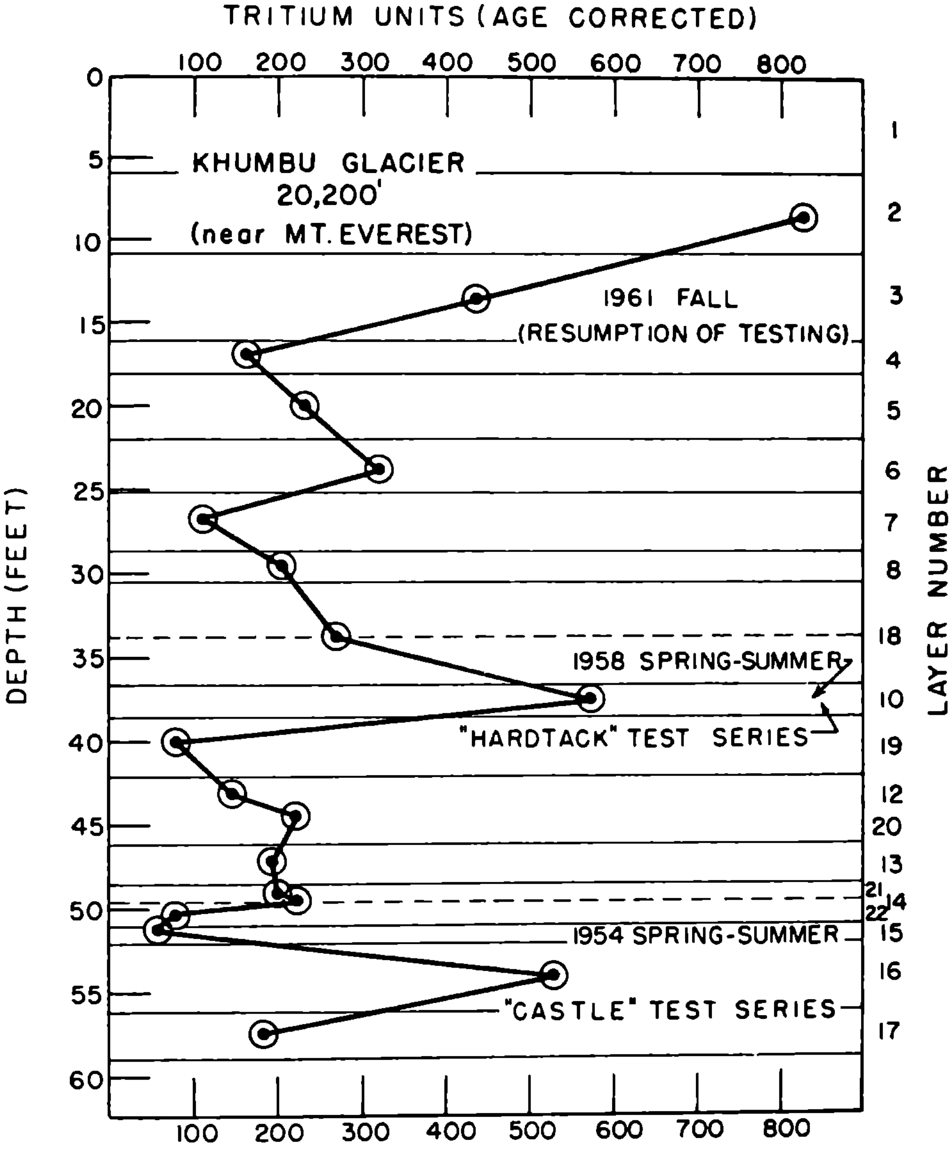

FIG. 6. Tritium concentration on vertical profile at 20,200 feet on upper Khumbu Glacier, Mount Everest.

some distance up-valley from the present frontal positions. Development of a strong upward and northward shift in maximum glacial position in the crestal Himalaya might explain the lack of ice-cut morphological features and moraine deposits of earlier vintage at or above these latest ice limits. In the long fugue of climatic events, a northward shift of centers of accumulation is not compatible with climatic theory, nor does it corroborate the direction of larger storm-track shifts indicated by the loessial deposits which we observed during the approach march. One is left with the alternate possibility that pronounced crustal deformation in recent geologic time has uplifted this part of the Himalaya into a colder climatic condition than the normal atmospheric trends should have produced.

There is little doubt that the Khumbu Glacier reflects a unique character, probably a prototype of the high Himalayan glaciers. It appears to be responding to what are probably the earth's most unusual and complex controls. Our observations in this high and dry region support the proposition that recent tectonic uplift (epeirogeny) and consequent local changes in climate on these high slopes, have taken place. Extensive recent uplift has also been reported in the southern Andes (Flint, 1964) and in coastal Alaska (Miller, 1958; Miller and Prather, 1966). This may explain the paradox of extensive glaciation developed here late in Pleistocene time, in contrast to the early Pleistocene Maxima known in many other formerly glaciated regions.

The apparent Himalayan uplift is corroborated by considerable geomorphic evidence such as oversteepened, convex, and highly terraced valley walls. If this interpretation is correct, it must be presumed to have represented an uplift sufficiently rapid to balance out deglaciation in consequence of the worldwide climatic amelioration of the past 10,000 years. The implication is that upwarp of the eastern Himalaya has been sufficient to maintain these newly elevated surfaces in a glacial condition somewhat out of phase with the worldwide climatic trend. The suggestion of a maximum glaciation in fairly recent time also connotes that the present glacial position in the Everest region and its polythermal character represent a climatic situation only slightly less severe than the more expanded conditions of the Pleistocene.

REFERENCES

BISHOP, BARRY C.

1963. How we climbed Everest. Nat. Geogr. Mag., vol. 125, no. 4, pp. 477-507, illus.

BISHOP, BARRY C.; ÅNGSTRÖM, ANDERS K.; DRUMMOND, ANDREW J.; and ROCHE, JOHN J.

1966. Solar radiation measurements in the High Himalayas (Everest region). Journ. Applied Meteorol., vol. 5, no. 1, pp. 94-104.

Dyhrenfurth, Norman G.
1963. Six to the summit. Nat. Geogr. Mag., vol. 125, no. 4, pp. 460-473, illus.
Flint, Richard F.
1964. Glacial geology of the east flank of the Argentine Andes between lat. 39° 10′ S. and lat. 41° 20′ S. Bull. Geol. Soc. Amer., vol. 75, no. 4, pp. 335-352.
Hornbein, Thomas F., and Unsoeld, William F.
1963. The first traverse. Nat. Geogr. Mag., vol. 125, no. 4, pp. 509-513, illus.
Koteswarm, P., and Parthasrathy, S.
1953. Winds over Mt. Everest. Indian Journ. Meteorol. and Geophys., vol. 4, pp. 187-189.
Miller, Maynard M.
1958. The role of diastrophism in the regimen of glaciers in the St. Elias district, Alaska. Journ. Glaciol., vol. 3, no. 24, pp. 292-297.
1964a. Geology and glaciology (Mt. Everest region). Chap. 16 (pp. 401-412) in "Americans on Everest," by James Ramsey Ullman. J. B. Lippincott & Co., Philadelphia.
1964b. Glacio-meteorology on Mt. Everest in 1963: The Khumbu Glacier of Chomolongma in northeastern Nepal. Weatherwise, vol. 17, no. 4, pp. 168-178, 189.
1965. Mount Everest and the Mahalangur Himal, 1963 (geology and glaciology). Explorers Journ., vol. 43, no. 3, pp. 130-148.
Miller, Maynard M.; Leventhal, Joel S.; and Libby, W. F.
1965. Tritium in Mt. Everest ice—annual glacier accumulation and climatology at great equatorial altitudes. Journ. Geophys. Res., vol. 70, no. 16, pp. 3885-3888.
Miller, Maynard M., and Prather, B. W.
1966. Teleconnection problems in the glaciation of the Himalaya and of the North Pacific Coast Ranges. Proc. 16th (1965) Alaska Sci. Conf., pp. 167-175.
Müller, Fritz
1959. Eight months of glacier and soil research in the Everest region. In "The Mountain World, 1958-59," pp. 191-208. George Allen and Unwin, London, and Harper & Brothers, New York.
Pugh, L. G. C. E.
1962. Himalayan scientific and mountaineering expedition, 1960/61: The scientific programme. Geogr. Journ., vol. 128, pp. 447-456. (Symposium held on April 16, 1962, at the Royal Geographical Society on "Man at High Altitude"; the participants were Charles Evans, L. G. C. E. Pugh, Barry C. Bishop, J. S. Milledge, and M. P. Ward.)
Von Buttlar, Haro, and Libby, W. F.
1955. Natural distribution of cosmic-ray produced tritium, II. Journ. Inorg. and Nuclear Chem., vol. 1, pp. 75-91.

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