Variations of Lewis Glacier, Mount Kenya, 1974-78
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VARIATIONS OF LEWIS GLACIER, MOUNT KENYA, 1974–78.

With 1 map (suppl. IX), 3 figures and 1 table

STEFAN HASTENRATH and ROBERT A. CAUKWELL

1. *Introduction*

A multiannual field project is being conducted on Lewis Glacier, Mount Kenya, aimed at a quantitative understanding of secular glacier behavior and the reconstruction of long-term climatic variations in the tropics. Observations related to the present heat and mass budgets, ice thickness determinations by various techniques, and repeated mappings of the ice surface topography of the glacier are designed to provide the input to computer modelling of the ice dynamics and of long-term glacier and climate variations. This effort is complemented by attempts at reconstructing a net balance and climate chronology on the basis of isotope and microparticle analysis of ice cores.

As part of this project, an aerial photogrammetric survey of the glacier was flown by the Kenya Air Force on 20 February 1974. A map at scale 1:2,500 obtained from this survey has been published in this journal (CAUKWELL and HASTENRATH, 1977). During the 1977/78 field season, it became possible to repeat the survey at about the same time in the mass budget year, namely on 13 February 1978. The resulting 1:2,500 map is presented here, along with an evaluation of glacier changes during this four year period.

2. *The 1974 mapping*

Control points established by the IGY Mount Kenya Expedition on rock outcrops outside the glacier were used for both the 1974 and 1978 mappings. Coordinates of IGY control points are reproduced in Table 1. Points were premarked in the terrain by white paint in preparation for the air photography. The survey was flown with a Caribou of the Kenya Air Force. Frames from a pass at 18,000 feet were chosen for photogrammetric evaluation on the Thompson-Watts First Order Plotter of the University of Nairobi.

3. *The 1978 mapping*

The aerial photogrammetric mapping was patterned closely after the 1974 survey. The same IGY control points identified in Table 1 were premarked with white paint in the terrain. The date of 13 February is close to the time of year when the 1974 survey was flown. The same aircraft and camera were used, with Captain Gathenya again in charge of the photography. Because of turbulence, a flight level of 18,400 feet was chosen in reasonable approximation of the 1974 survey. Mapping was again performed on the same stereoplotter of the University of Nairobi. The same contour interval and symbols were used in the design of the map. The enclosed map is again at scale 1:2,500.

During the 1977/78 field season, an array of 31 stakes was laid out on the glacier for purposes of net balance measurements and the monitoring of surface ice movement by repeated surveying of these poles. These stations plotted in the map were surveyed from IGY control points „L2" and „L3" using optical theodolite (LIETZ T–60D) and electronic distance measuring equipment (Beetle 500 of Precision International, USA). Stations 1 through 15 are situated in the accumulation area and consist of one 3 m bamboo pole each inserted to a depth of about 150 cm. Stations 21 to 26 are located near and somewhat below the equilibrium line. These consist of an assembly of two 2 m wooden stakes linked together by a rubber strip, being inserted to a depth of about 4 m. Stations 31 to 35 further down glacier, consist of three such wooden stakes inserted to a depth of 6 m. Stations 41 to 45 in the lowest portion of the glacier consist of four 2 m wooden stakes inserted to a depth of about 8 m. The location of stake 45 was determined by tape and azimuth bearing from station 44, but not by theodolite.

Four ice pits were dug as indicated in the map. Pits 1 and 4 were used for stratigraphic studies and extend to 2 and 1 m, respectively. Pits 2 and 3 are about 3 m deep and were used for both stratigraphic purposes and the retrieval of 15 m long ice cores. During the 1977/78 expedition, a meteorological station was operated in the vicinity of the net balance station 21.

4. *Changes in ice thickness*

The enclosed map at scale 1:2,500 is presented as a historic documentation for detailed comparison with other epochs. Conspicuous changes are apparent since the 1974 mapping. These were evaluated in separate maps at scale 1:2,500, reproduced in Figs. 1 and 3 at scale 1:7,500.

Fig. 1 shows a greatly decreased Curling Pond, but this water body is known to vary greatly over short time intervals. Fig. 1 also illustrates a particularly drastic ice loss in the lower portion of the glacier. The terminal has receded some 15 m and Nayan Pond has formed since 1978, somewhat above Lewis Tarn. Two large ice caves have developed, extending from the front some 30 m inward, with a ceiling of about 4 m.Also, in 1978 the front was much less step than in 1974 and earlier times. During the 1977/78 field work we walked up the glacier from the very front without use of crampons and ice axe, an undertaking quite impossible in earlier years.

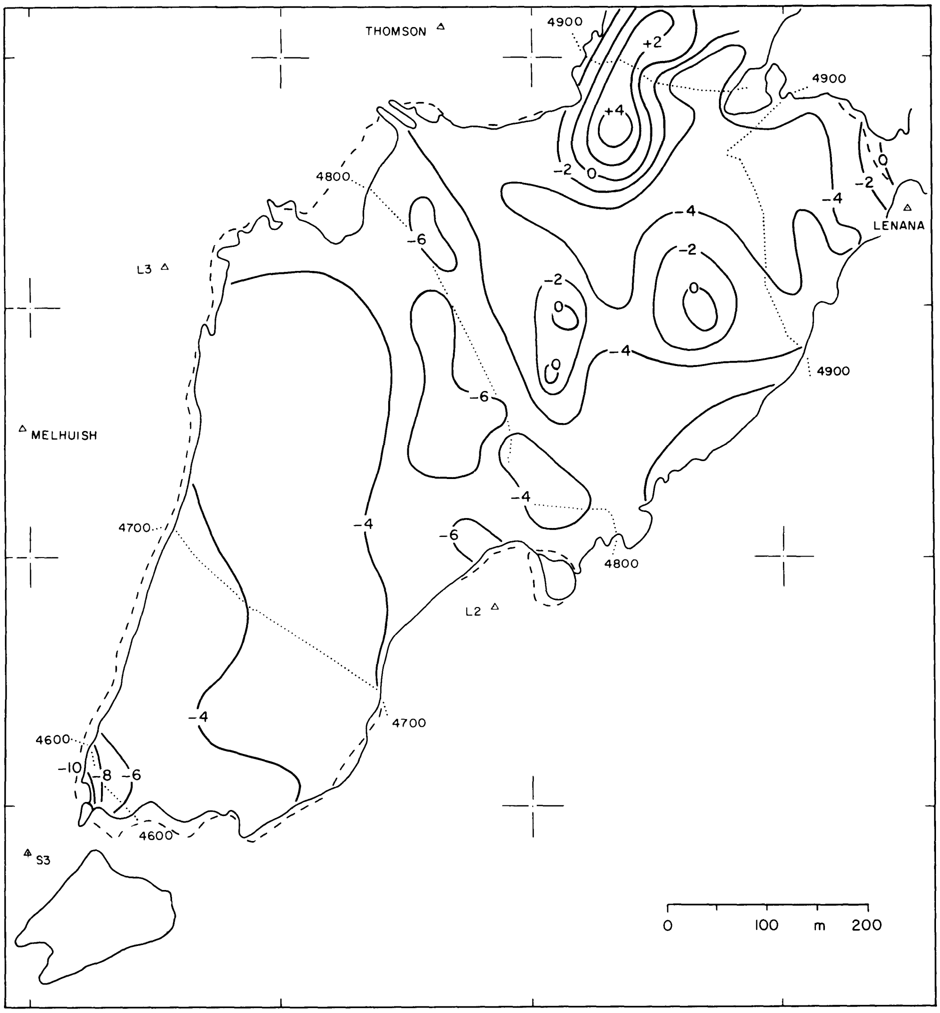

Fig. 1. Changes in ice thickness, February 1978 minus February 1974, in m. Ice rim in 1978 is shown as solid, and in 1974 as broken line. 1978 height contours are entered as dotted lines. Scale 1:7,500.

The decrease in ice thickness during the 1974–78 interval (Fig. 1) is of the order of a few m for the glacier as a whole. However, Fig. 1 shows an organized spatial pattern. Adjacent to the area of largest ice losses in the low, Southwest portion of the glacier is an approximately North-South oriented band with thickness decreases of less than 4 m. This contrasts with an approximately North-Northwest to South-Southeast striking zone at somewhat higher elevation and in a comparatively steep portion of the glacier, where ice losses in part exceed 6 m. Except for a large, broadly westward facing area, most of the upper glacier shows thickness decreases of less than 4 m. In sizeable portions of the upper glacier the decrease is less than 2 m. In fact, an area extending from the col between the two glaciers down to the Gregory Glacier proper is characterized by a distinct increase in topography.

The relative pattern of thickness changes in 1974–78, Fig. 1, is similar to the difference map for 1963–74, not shown here. It is recalled (Hastenrath, 1975; Caukwell and Hastenrath, 1977; *Forschungsunternehmen Nepal-Himalaya,* 1967) that there was a weak indication of a possible increase in ice thickness in limited portions of the upper glacier during the 1963–74 interval. If this increase was real, it did only partly continue into 1974–78. Because of the close duplication of scale and control, comparability of the 1978 and 1974 maps is much superior to the 1963–74 interval.

From 1963 to 1974 the snout retreated vertically by 3 m, the area decreased by 52 x 10^3 m^2, and the volume by 1,000 x 10^3 m^3 (Hastenrath, 1975). For the interval from 1974 to 1978, the lowest point of the glacier rose by another 5 m. Planimetering of Fig. 1 yields a 1974–78 decrease in area of 11 x 10^3 m^2, in average

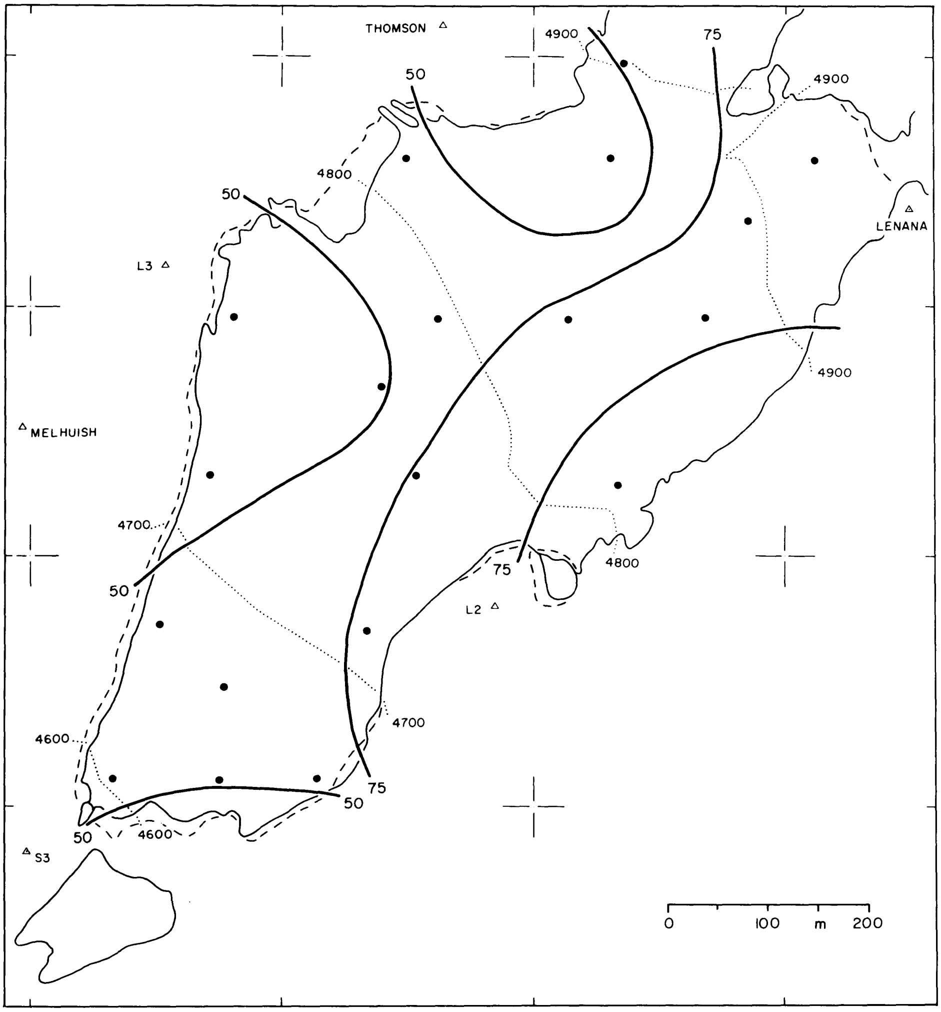

Fig. 2. Annual pattern of direct solar radiation received by (non-horizontal) glacier surface, in W m^{-2}. Crosses indicate the location of points for which calculations were performed. 1978 height contours are entered as dotted lines. Scale 1:7,500.

thickness of about 4 m, and in total volume of 1,200 x 10^3 m^3. The February 1978 area is about 295 x 10^3 m^2, and the volume is estimated to be of the order of 8,500 x 10^3 m^3. It is noted that the volume change in the recent four years alone is comparable to that during the preceding eleven years; and it may amount to more than a tenth of the presently remaining ice mass.

5. Patterns of thickness change and radiation budget

The spatial pattern of changes in ice thickness depicted in Fig. 1 may appear complicated, in that there is no monotonic decrease in ice loss from the lower to the upper glacier. Such a simple dependence on elevation could be expected from the larger number of above zero hours conducive to melting and the smaller albedo at the lower elevations. However, a rather complicated spatial distribution of net radiation must be considered for Lewis Glacier, because its surface varies greatly in azimuth orientation and slope, and the precipitous high mountain relief leads to a differing obstruction of the horizon.

Our measurements in 1977/78 provide some insight into the radition conditions on the mountain. At unobstructed sites outside the glacier, the diffuse contributes only a few percent to the global radiation. The horizontal component of diffuse radiation can be more substantial in complicated terrain configurations on the glacier. Likewise, net longwave radiation is presumably not uniform all over the glacier surface. However, direct radiation must be considered as the dominant factor for the spatial pattern of net allwave radiation at the surface.

Twenty locations (Fig. 2) were chosen on the glacier, so as to represent the pattern of thickness changes (Fig. 1) and ice topography. For each of these locations the slope and azimuth orientation of the glacier surface was determined from our map. The ratio of direct radiation received on these differently oriented surfaces to that impinging on a surface perpendicular to the solar rays was calculated for the hours 7, 9, 11, 13, 15, 17 LT, and for the equinoxes and solstices. The times at which the solar beam would be obstructed by the surrounding orography were determined for each of the twenty locations, using the 1:5,000 map of the entire peak region (*Forschungsunternehmen Nepal Himalaya*, 1967). Direct radiation impinging on the glacier surface was set to zero for these times and locations. On this basis the ratio of direct radiation incident on the actual glacier surface to that on a surface always perpendicular to the solar rays can be calculated for the day as a whole.

At various elevation angles excluding the vicinity of the horizon, direct radiation on a surface perpendicular to the solar rays was measured at Mont Kenya to be of the order of 1.5 cal cm^{-2} min^{-1} = 1,050 W m^{-2}. Accordingly, the aforementined ratios were converted into energy units, and mapped.

It is noted that the effect of clouds on direct radiaton has not yet been considered here. Cloudiness at Mount Kenya is systematically larger in the afternoon than in the morning. To account for this effect, separate calculations were also performed with the afternoon hours set cloudy half of the time.

In particular, annual maps were constructed by weighting the two solstices and the two exquinoxes equally. For the year as a whole, the maps for the „clear“ and „cloudy“ models look similar, except for the absolute magnitude. Only the latter map is reproduced in Fig. 2. For purposes of comparison, the annual values of direct radiation on a horizontal unobstructed surface were calculated to be 314 for the „clear“ and 235 W m^{-2} for the „cloudy“ models. No accuracy is claimed for the absolute values in Fig. 2, but the relative pattern is considered as similar to that of surface net radiation.

Accordingly, Fig. 2 may provide some insight into the rather complex spatial pattern of ice thickness change, Fig. 1. In the following considerations it seems appropriate to compare areas at comparable elevation, so as to partly account for the role of temperature in melting.

In the lowest portion of the glacier, the decrease in thickness loss from West to East is paralleled by a decrease of radiation values in the same sense. In the middle portion of the glacier, say below the line L3–L2, ice loss is smaller to the West where radiation is smaller. The adjacent comparatively steep, approximately southwestward facing portion of the glacier has undergone a particularly drastic change in ice thickness. This coincides in part with a band where radiation values are considerably larger than in adjacent areas. Especially striking is the area of distinct increase in thickness on the col leading from the Lewis to the Gregory Glacier. This is concomitant with particularly small radiation values. In conclusion, the strongly topographically controlled spatial distrubution of direct solar radiation appears to be a major factor in the rather complex pattern of long-term change in ice thickness.

6. *Crevasse pattern*

The location of crevasses in 1974 and 1978 is compared in Fig. 3. In view of the photography at slightly different hour of day and mapping tolerance, a discussion of the small crevasses is not warranted.

In the upper glacier, there are indications of crevasses being displaced towards lower elevations. However, there are also situations where crevasses seem to have formed new at a location somewhat higher than mapped in 1974. These regions of crevasse formation seem to be favored by the bedrock topography.

An ice ridge in the upper glacier has in its Eastern portion a cliff facing northnorthwestward, and in its Western portion a cliff facing in approximately the opposite direction. Both cliffs seem to have moved in the direction in which they are facing.

In the middle portion of the glacier, a large longitudinal crevasse has developed. Longitudinal crevasses continue to prevail in the lower portion of the glacier. A continued tendency for the changeover from transverse to longitudinal crevasses in the middle glacier deserves attention in future surveys, in that this may reflect changes in the flow characteristics.

7. *Concluding remarks*

Methods of the airborne surveys and the subsequent photogrammetric evaluation were closely duplicated for the 1974 and 1978 mappings. The comparability of maps is thus optimal. Conditions around the end of the short dry season, as considered in both surveys, offer the most appropriate reference for year-to-year changes. A drastic decrease of ice thickness and extent is borne out over the time span of only four years. The two maps provide quantitative information representative of the recent imbalance of the glacier mass budget. Such data together with field observations on the recent characteristics of the vertical net balance profile are among the important input parameters for the ongoing computer modelling of ice dynamics, climatic forcing, and glacier response. In view of the unique historical documentation for this equatorial glacier (review in HASTENRATH, 1975; CAUKWELL and HASTENRATH, 1977) which includes maps of ice topography for the epochs 1934, 1958, 1963, 1974 and now 1978, systematic re-surveys would represent a highly desirable contribution to global environmental monitoring.

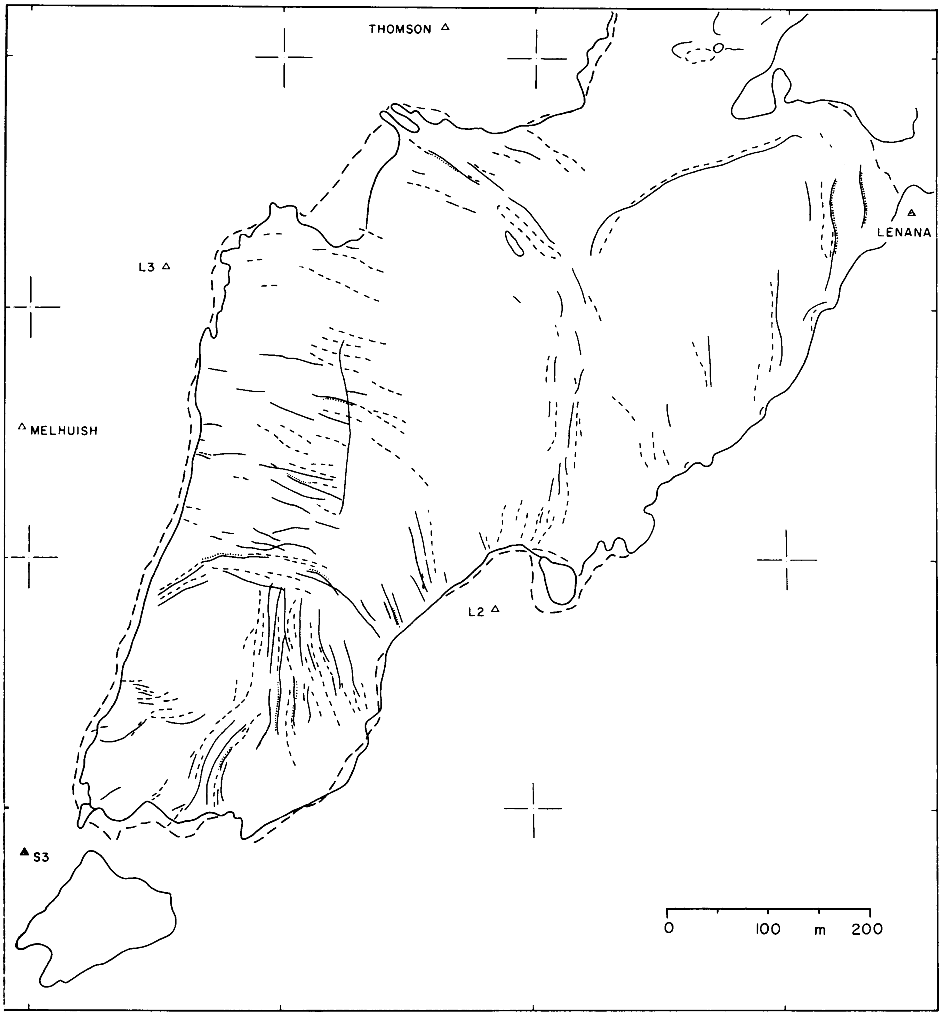

Fig. 3. Changes in crevasse pattern. 1978 solid, and 1974 broken lines. Scale 1:7,500.

Table 1: IGY control points in the vicinity of Lewis Glacier. Marks not identified and not used in the 1973–74 survey are indicated by asterisk. South-North (+Y), West-East (+X) coordinates, and elevation (h) in m.

	+Y	+X	h
L 1*	1,508.0	3,373.9	4,823.1
L 2	1,450,4	3,210.6	4,797.2
L 3	1,791.8	2,884.0	4,792.7
Little John*	1,306.1	2,577.7	4,628.4
Lenana	1,847.9	3,622.1	4,985.0
Melhuish	1,630.6	2,742.2	4,876.5
S 3	1,206.3	2,745.5	4,600.6
Thomson	2,031.0	3,159.7	4,955.1
Top Hut*	1,361.4	3,177.5	4,809.4

Acknowledgments:

The 1977/78 Mount Kenya expedition was supported through U.S. National Science Foundation Grants EAR77–13130 and EAR76–18881. In the expedition participated: S.H. and Phil Kruss, Dept. of Meteorology, University of Wisconsin; Nayan Bhatt, Dept. Geology, and J. K. Patnaik, Dept. of Meteorology, University of Nairobi; Lonnie G. Thompson, Institute of Polar Studies, Ohio State University; Kamau Mwangi and Joseph Karanja, Naro Moru. As during the 1974 survey, Captain Gathenya, Kenya Air Force, was in charge of the air photography, and Samuel W. Kimani, Dept. of Surveying and Photogrammetry, University of Nairobi, performed the stereo-plotting. Approval for this research was obtained from the Office of the President, Republic of Kenya, and the Director of Kenya National Parks. As during 1973/74, the cooperation of Phil Snyder, Assistant Warden of the Mount Kenya National Park was vital to the success of this project. Sincere thanks go to Prof. Douglas Odhiambo, Deputy Vice-Chancellor, Prof. Raouf Rostom, Head of the Department of Surveying and Photogrammetry, and Prof. G. C. Asnani, Head of the Dept. of Meteorology, University of Nairobi;

to staff and students of Hillcrest Secondary School; and especially to Frank Charnley, Nairobi.

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GRUNDSÄTZLICHES ZUM UNTERSCHIED ZWISCHEN TROPISCHEM UND AUSSERTROPISCHEM GLETSCHERHAUSHALT UNTER BESONDERER BERÜCKSICHTIGUNG DER GLETSCHER BOLIVIENS

Mit 6 Abbildungen, z. T. als Beilage X und 9 Photos

EKKEHARD JORDAN

Summary: Some basic considerations of the difference between tropical and extra-tropical glacier economy with special reference to the glaciers of Bolivia

Knowledge of mass economies of tropical glaciers is still very inadequate. Although tropical glaciers cover only 2000–3000 km², thus amounting to only about 1 per cent of the entire montane glaciation, 95 per cent of them are situated in the periodically-humid tropics, and take on the important function of water supply during the dry season. As a result of insufficient precipitation there is transition from the almost perennially-fed glaciers to the complete absence of glaciation in Bolivia, which, with a glacial area of almost 1000 km², belongs to this marginally tropical type.

The distribution of glaciers in Bolivia in their dependence on relief and climate is presented, and the totally different character of the tropical-marginally tropical glacier mass economy derived from the temporal regime of the climate as well as the observations and measurements carried out in 1975 and 1977. The difference from the glaciers of higher latitudes is chiefly to be seen in the absence of a strict annual periodicity, which renders the usage of the natural annual economy absolutely impossible. More exact quantitative proofs can only be achieved on the basis of a series of measurements extending over several years.

In den Gletschern der Erde ist ein Großteil unserer Süßwasservorräte gespeichert. Massenhaushaltsuntersuchungen an Gletschern sind der Schlüssel zur Ermittlung der Wasserreserven der Gletscher. Sie geben einen Einblick in die Beziehungen, die zwischen Gletschern und dem Klima bestehen. Aufgrund des mit derartigen Untersuchungen verbundenen hohen zeitlichen und apparativen Aufwandes ist es nur möglich, einzelne Probegletscher innerhalb ausgedehnter Gletschergebiete zu bearbeiten. Dies wird in den Gebieten traditioneller Gletscherforschung seit einigen Jahrzehnten betrieben, so daß wir für die Gletscher der Zone der gemäßigten Breiten der Nordhemisphäre bereits über recht gute Kenntnisse verfügen. Über die Gletscherhaushalte anderer Klimazonen sind wir weit weniger gut informiert; oft fehlt es dort selbst an der Kenntnis über die genaue Gletscherverbreitung.

Der Verfasser hat sich zur Aufgabe gestellt, Massenhaushaltsuntersuchungen in einer solchen – in diesem Falle tropischen – Gletscherregion durchzuführen und dazu die Gletscher Boliviens ausgewählt. Die Grundlagen der nachfolgenden Ausführungen wurden auf zwei Forschungsreisen nach Bolivien von Juli bis September 1975 und Februar bis Juni 1977[1]) mit Unterstützung durch den Servicio Geologico de Bolivia (GEOBOL) und das Instituto de Geologia Aplicada – UMSA La Paz/FU Berlin erarbeitet. Es soll hier zunächst ein Einblick in den Stand der Erforschung tropischer Gletscher sowie in die Situation derartiger Forschungen in Bolivien mit einem Überblick über die regionalen Verhältnisse gegeben werden und dann einiges zum Massenhaushalt tropisch-randtropischer Gletscher ausgeführt werden.

Der Stand der Erforschung tropischer Gletscher

Während in den Außertropen allein für die Alpen die Literatur zur Gletscherforschung fast unübersehbar ist, ist sie für tropische Gletscher zwar weit verstreut, aber durch ein gutes Dutzend von Aufsätzen bereits erschöpft. Dabei stehen in der älteren Literatur von HAUTHAL, HERZOG, MEYER, SIEVERS etc. zu Anfang des Jahrhunderts Entdeckung und Beschreibung sowie vereinzelt Schneegrenzangaben im Vordergrund. In den bedeutenden Arbeiten von KINZL und TROLL ab Ende der zwanziger Jahre werden dann auch neben der Erschließung von im wahrsten Sinne weißen Flekken, typologische und ursächliche Fragen angesprochen, und es folgen von HUMPHRIES (1959), WHITTOW et al (1963) und PLATT (1966) weitere Angaben zu den tropischen Gletschern Afrikas. Über rein klimato-

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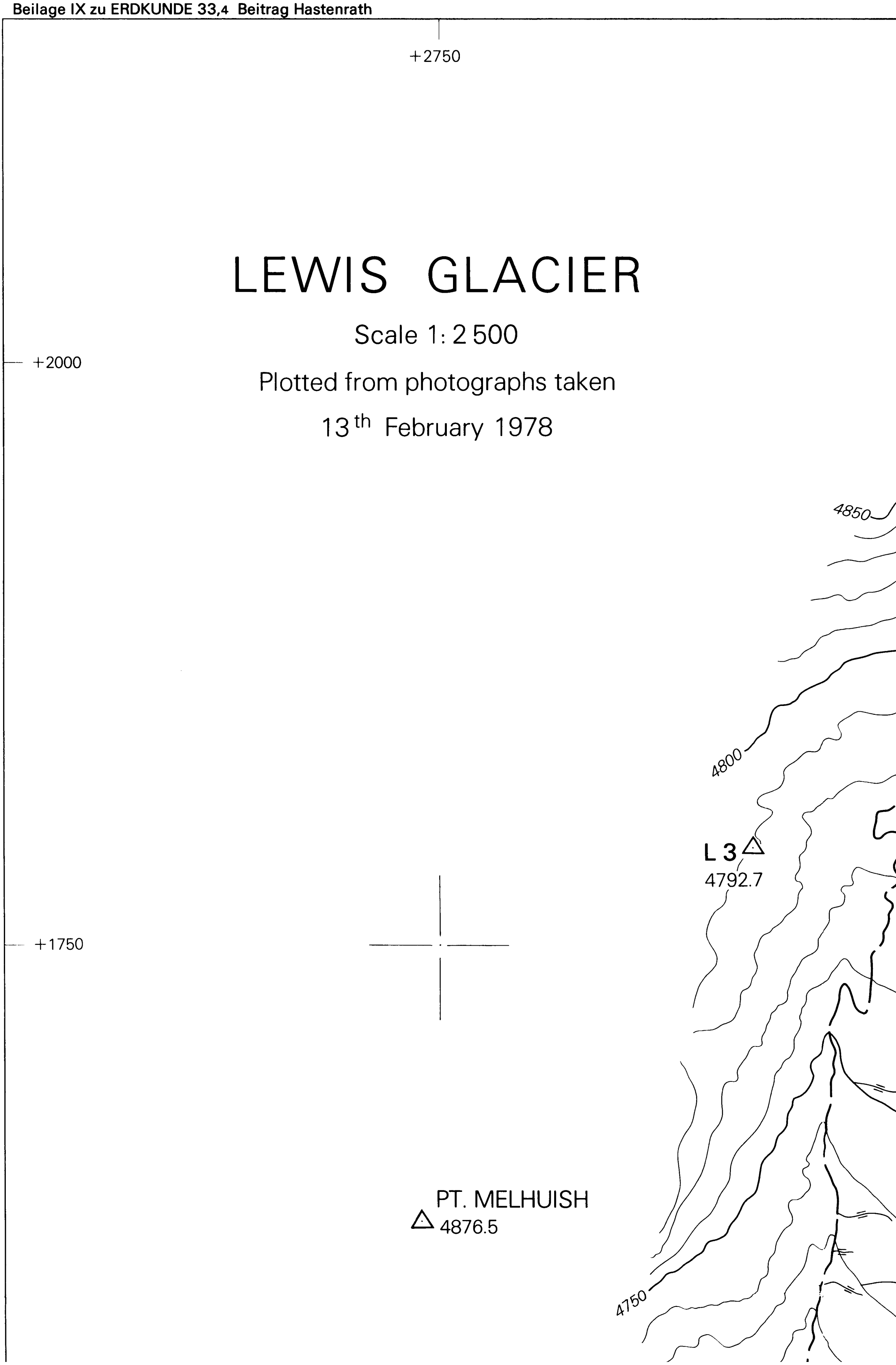
[1]) Für Finanzierung und Förderung sei der Deutschen Forschungsgemeinschaft, den Kreidlerwerken, Kornwestheim, Firma Wassermann, Gehrden, sowie zahlreichen unbenannten Personen und Institutionen in Deutschland und Bolivien herzlich gedankt.

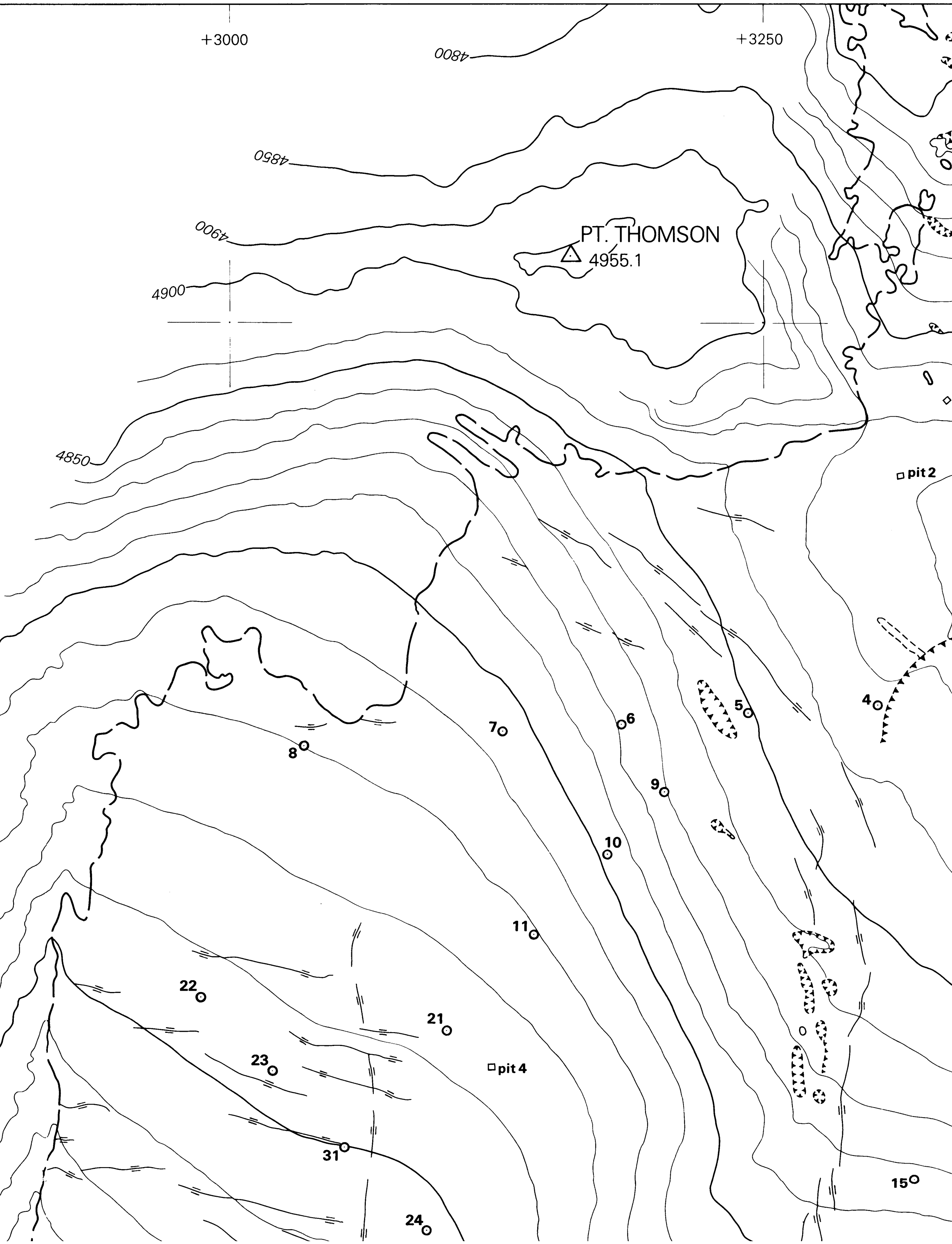


LEWIS GLACIER

Scale 1: 2 500

Plotted from photographs taken

13th February 1978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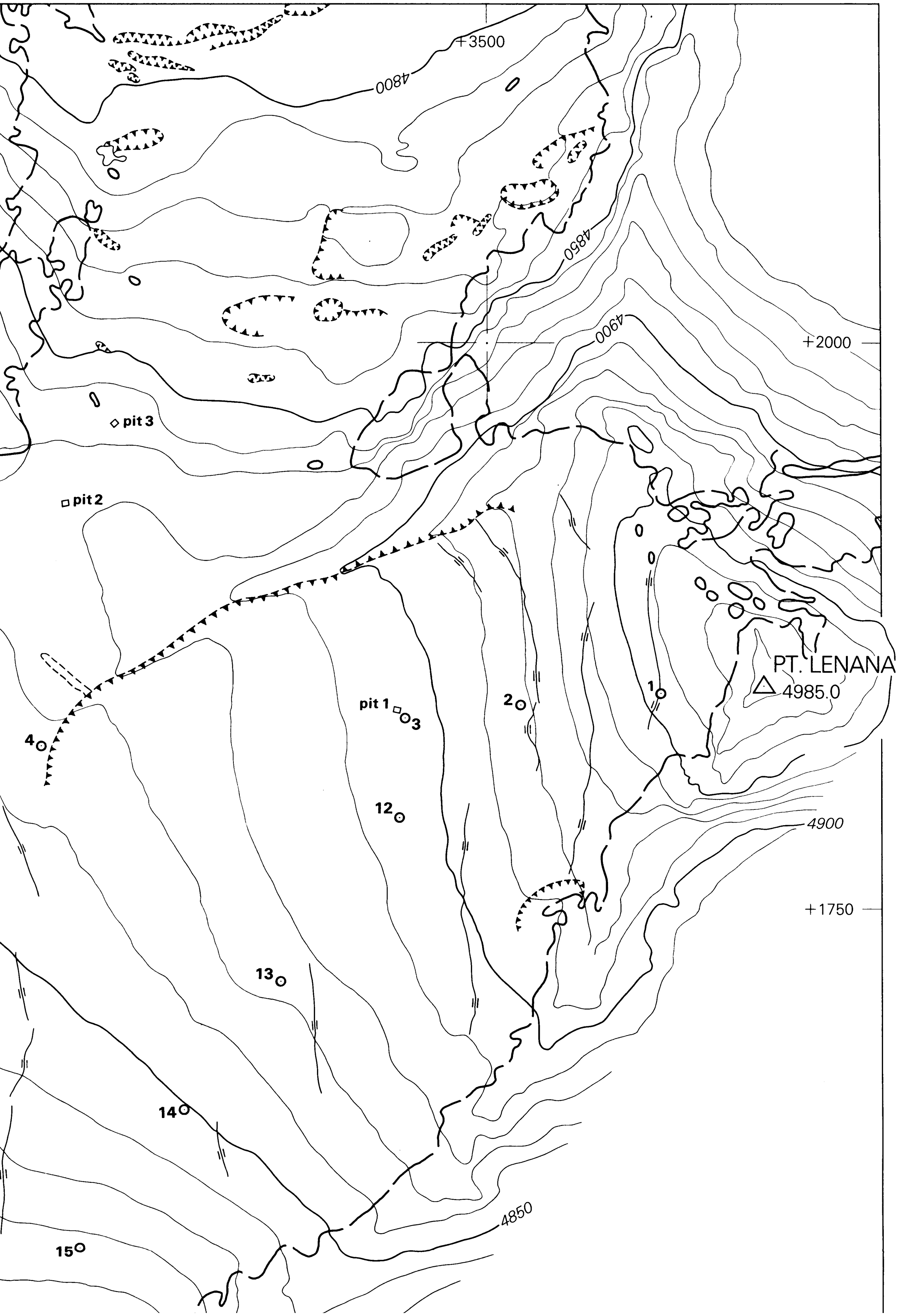
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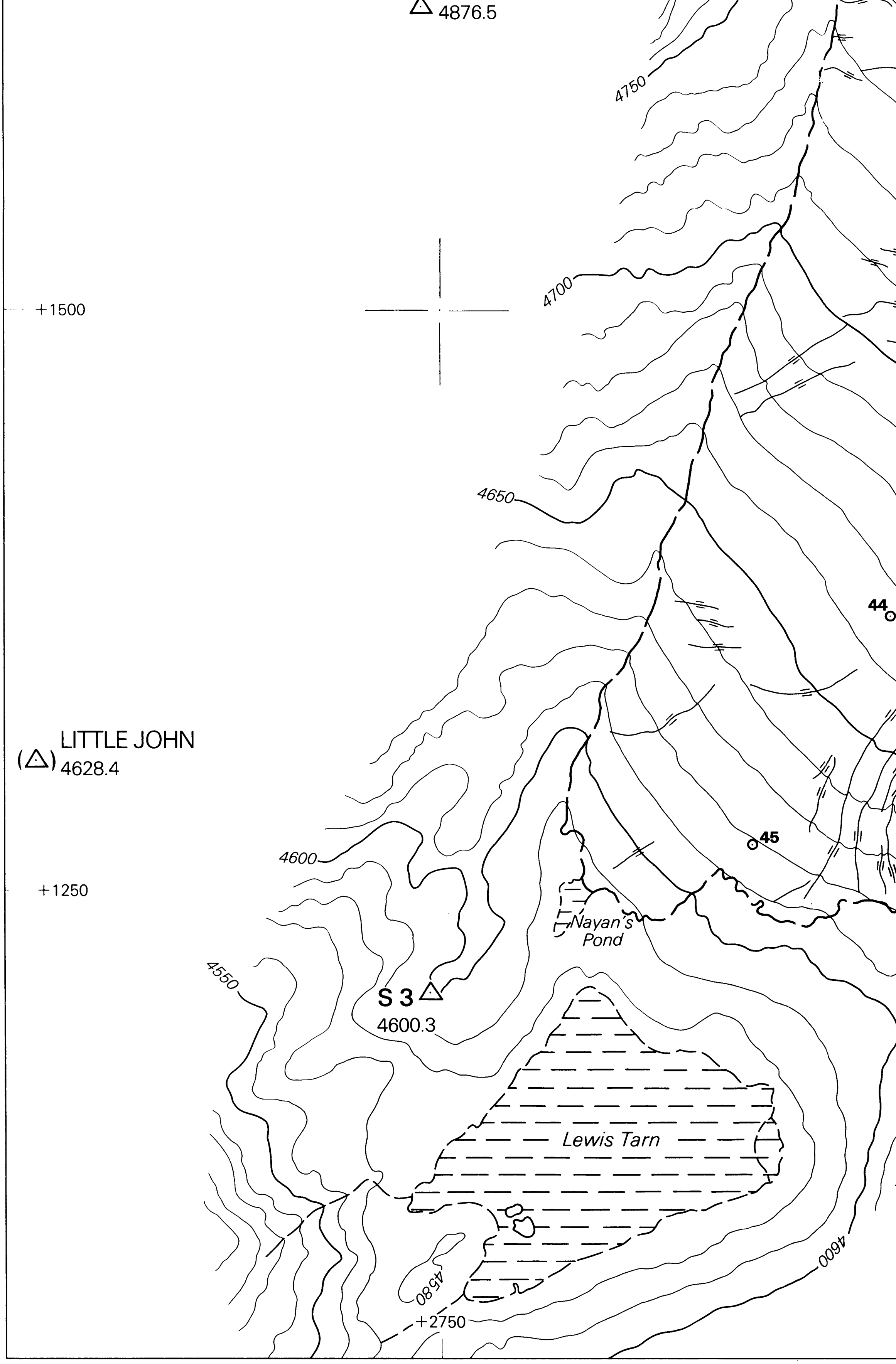
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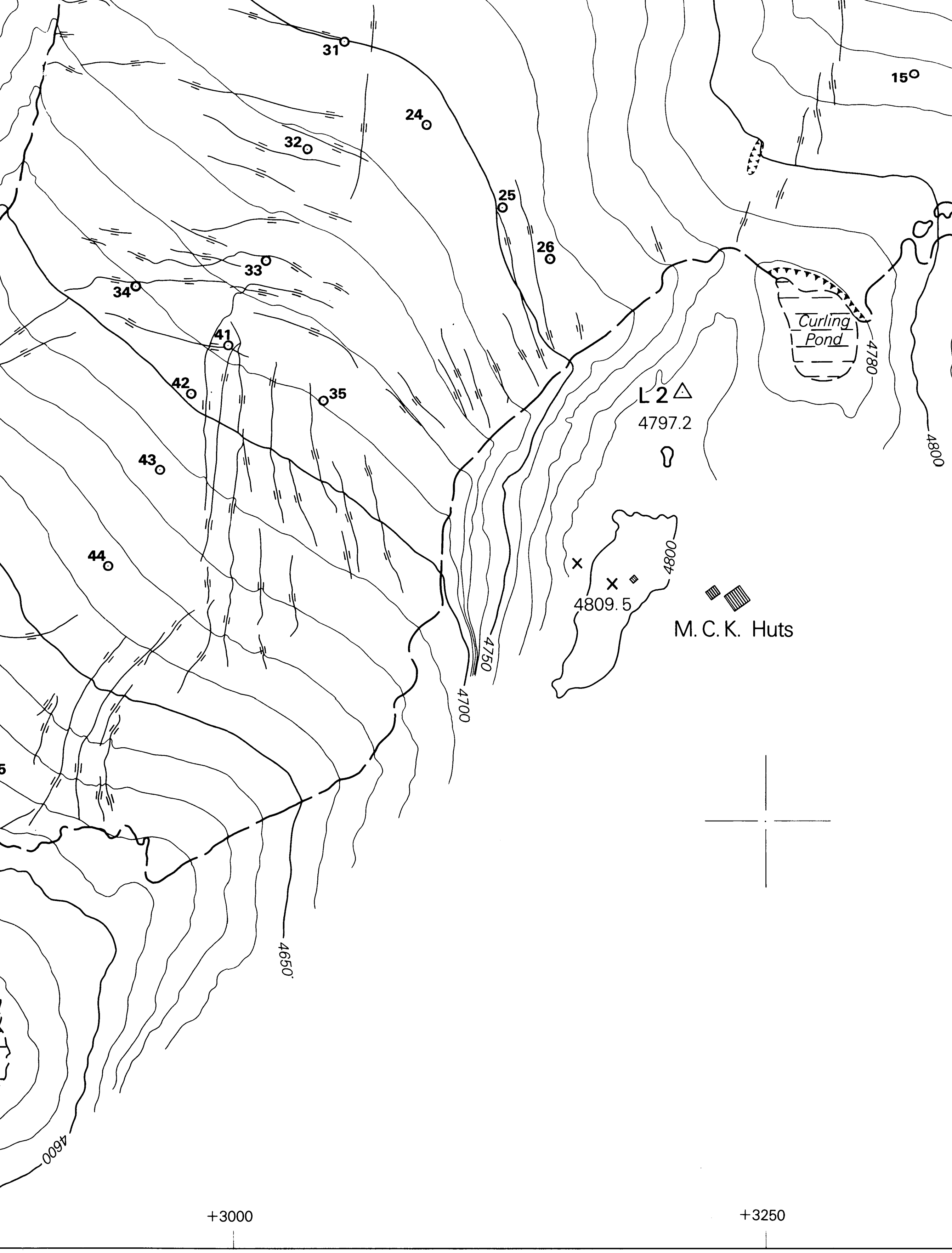
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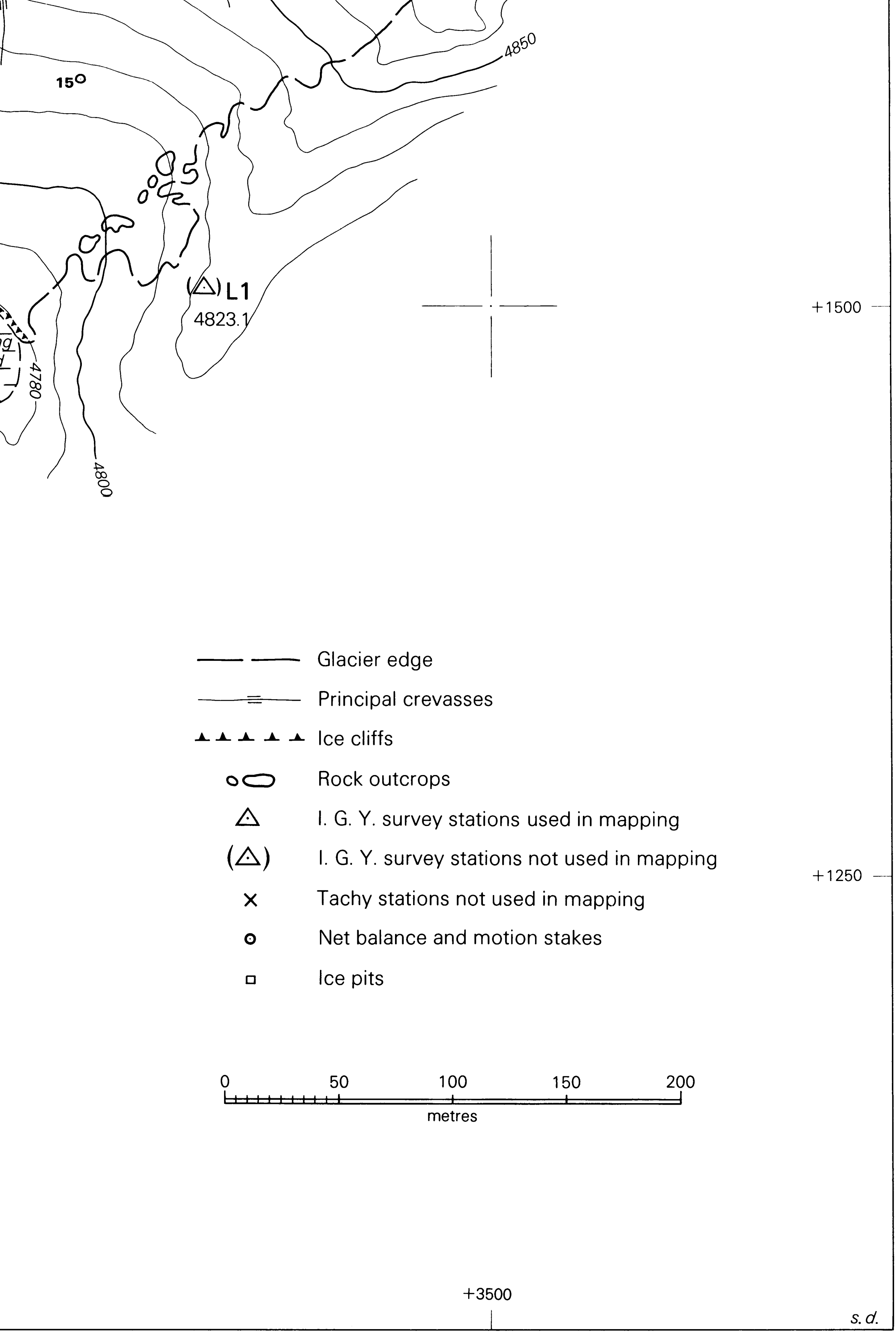
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Glacier edge
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Ice cliffs
Rock outcrops
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I. G. Y. survey stations not used in mapping
Tachy stations not used in mapping
Net balance and motion stakes
Ice pits
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100
150
200
metres
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