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MAPPING THE GLACIERS OF MOUNT KENYA IN 1947

With 3 figures, 4 tables and 1 supplement (IX)

RAOUF S. ROSTOM and STEFAN HASTENRATH

Dedicated to ROBERT A. CAUKWELL

Zusammenfassung: Kartierung der Gletscher des Mount Kenya 1947

Die Karte der Mount Kenya Gletscher 1947 basiert auf einer Auswertung von Luftbildaufnahmen vom Februar 1947 in Kombination mit dem Netz von Bodenkontrollpunkten, das für die aerophotogrammetischen Kartierungen im September 1987 und September 1993 ausgelegt wurde. Zwischen 1947 und 1987 reduzierte sich die eisbedeckte Fläche um 379 000 m², das Volumen um 6 930 000 m³ und die Mächtigkeit um durchschnittlich 8,6 m, das entspricht einer Abnahme um 0,2 m/Jahr und einer entsprechenden Abschmelzenergie von 2 W/m². Im Vergleich dazu betrug die Abnahme im Zeitraum 1987 bis 1993 1 m/Jahr und die Abschmelzenergie 10 W/m². Das weist auf eine Verstärkung der klimatischen Ursachen in den letzten Jahren hin.

1 Introduction

The glaciers of Mount Kenya and their relation to climatic change have been the object of our research since the early 1970's (HASTENRATH 1984, 1991). For the largest, the Lewis Glacier, this has included the

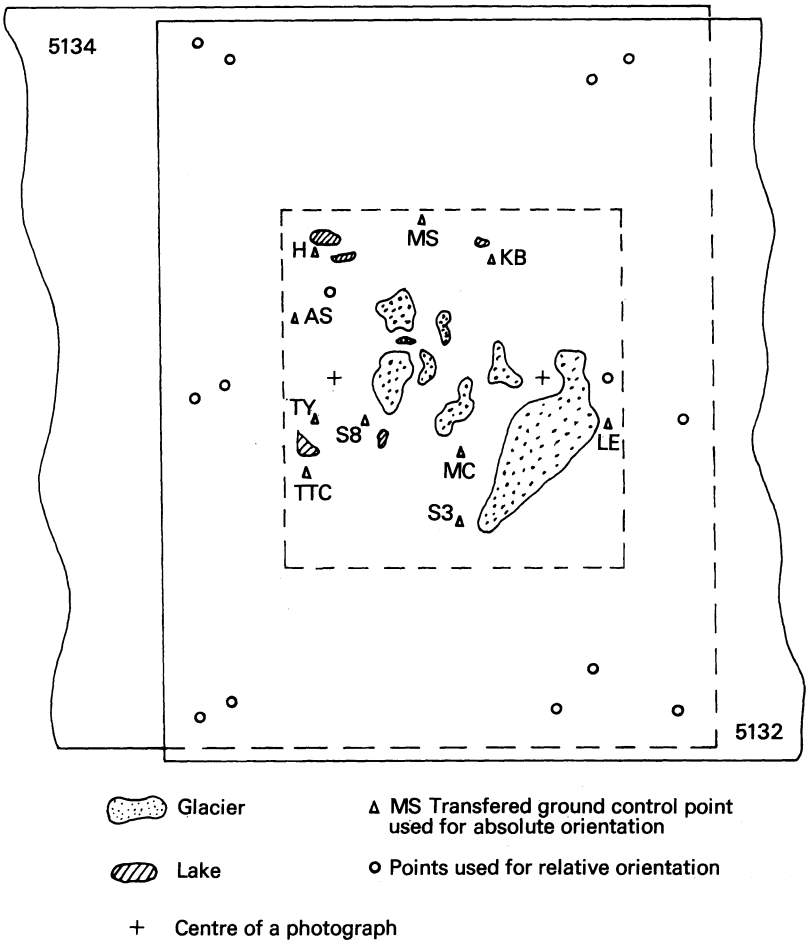

Fig. 1: Sketch map showing the map area and the points used for orientations of the stereopair. Triangles and letter codes denote the terrain control points listed in Table 1

Übersichtskarte der kartierten Fläche und der benutzten Bodenkontrollpunkte. Dreiecke und Buchstaben bezeichnen die in Tabelle 1 aufgelisteten Kontrollpunkte

continuous monitoring of net balance, ice flow velocity, and precipitation, and mappings of the ice surface topography at four-year intervals. The resulting maps at scale 1:2,500 have all been published in this journal (Caukwell a. Hastenrath 1977, 1982; Hastenrath a. Caukwell 1979, 1987; Hastenrath a. Rostom 1990; Rostom a. Hastenrath 1994). For the glaciated peak region as a whole a map at scale 1:5,000 and with date January 1963, based on terrestrial photogrammetry, has been presented by Forschungsunternehmen Nepal-Himalaya (1967). For the same domain and at same scale we produced maps of the glaciers of Mount Kenya from purpose-flown air photography on 3 September 1987 and 9 September 1993, and they have also been published in this journal (Hastenrath et al. 1989; Rostom a. Hastenrath 1994). Expanding on this work, we have evaluated historical air photographs to reconstruct the state of Mount Kenya's glaciers around the middle of the 20th century, and present here a map at scale 1:5,000 and with date February 1947 (Supplement IX).

2 *Air photography*

Air photographs nos. 5131–5136 flown on 21 February 1947 were acquired from the Royal Air Force, U. K. These had also served to compile part of the national topographic map series (Survey of Kenya 1975). The flight level was 27,000 feet, the average scale 1:25,000, and the focal length 154.2 mm. Of these, the stereo-pair of frames 5132 and 5134, with overlap of 75% (Fig. 1) was chosen for stereo-compilation. Over the altitude range from 4,200 m to 5,200 m the scale of the photographs varies from about 1:26,000 to 1:19,000.

Table 1: Coordinates of ground survey stations (m). Triangles indicate points used in mapping and circles points plotted but not used. Code identifies points plotted in map

Koordinaten der Bodenbeobachtungsstationen (m). Dreiecke bezeichnen die bei der Kartierung benutzten und Kreise die für die Kartierung nicht verwendeten Punkte. Der Code identifiziert die in der Karte eingetragenen Punkte

	Name	Code	+Y(N)	+X(E)	Height
△	Melhuish Cross	MC	1637.9	2743.9	4878.1
△	Two Tarn Cross	TTC	1521.2	1518.7	4519.1
△	Molar Saddle	MS	3234.9	2327.8	4615.8
△	Kami Boulder	KB	3015.8	2961.9	4448.5
△	Hausburg	H	2979.3	1708.8	4359.9
△	Lenana	LE	1847.9	3622.1	4985.0
△	S 8	S 8	1794.4	2086.0	4477.5
○	Thomson Cross	TC	2037.8	3165.5	4958.1
○	Gregory	G	2261.3	3303.1	4693.5
○	Arthur's Seat	AS	2404.8	1555.6	4665.6
○	L 2	L 2	1450.4	3210.6	4797.2
○	L 3	L 3	1791.8	2884.0	4792.7
○	Melhuish	ME	1630.6	2742.2	4876.5
○	S 3	S 3	1206.3	2745.5	4600.6
○	Two Tarn	TT	1524.0	1524.0	4519.6
○	Tyndall	TY	1771.1	1751.0	4551.3

3 Ground control

As detailed in our previous reports (Hastenrath et al. 1989; Rostom a. Hastenrath 1994), we established a net of terrain control points with a closure around the mountain, thereby expanding on the set of points from the IGY Mount Kenya Expedition (Charnley 1959). Table 1 lists the coordinates of the points of interest for the present mapping. Wild PUG 4 was used to transfer 10 control points for the 1987 photography at scale 1:10,000 to the 1947 photographs. A total of 16 terrain points are plotted in the new 1947 map and of these 7 were used for mapping. Also shown in the map is point PP 5154, the center of photograph.

4 Orientation

The instruments suitable for this mapping available at Photomap (K) Ltd. were a Wild B-8 Aviograph Stereoplotter with Qasco analytical conversion system and supported by Kork system and automatic drum digital plotter. For interior orientation, the side fiducial marks of the 1947 photographs were placed to coincide with those of a diapositive from a calibrated camera, and then the PUG-4 was used to transfer the corner fiducial marks onto the emulsion of the 1947 diapositives. The diapositives were oriented in the plate holders of the B-8, and each marked corner prick was oberseved twice, with differences not exceeding 4 μm. The interior orientation resulted in defining x and y scales on each plate with root-mean-square error (RMS) of about 60 μm.

For relative orientation, the 14 points shown in Fig. 1 were used, namely 2 points on each standard location and 2 additional points in the extreme y of the model. The RMS of the residual y-parallax after 3

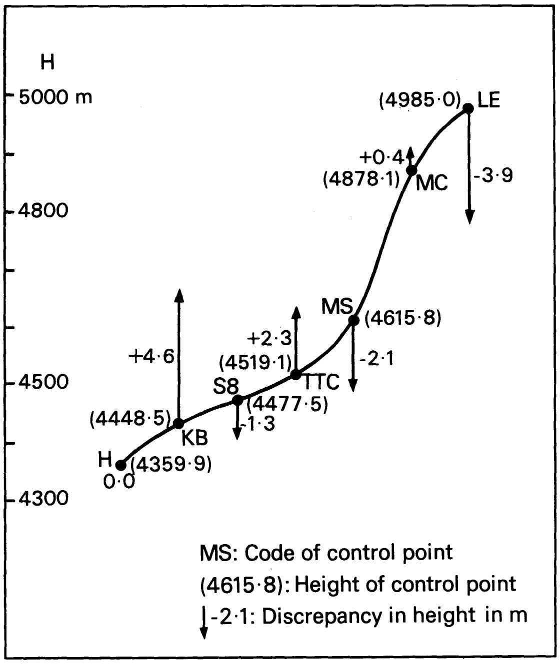

Fig. 2: Residuals in heights at the control points in the model

Höhenresiduen der Kontrollpunkte im Modell

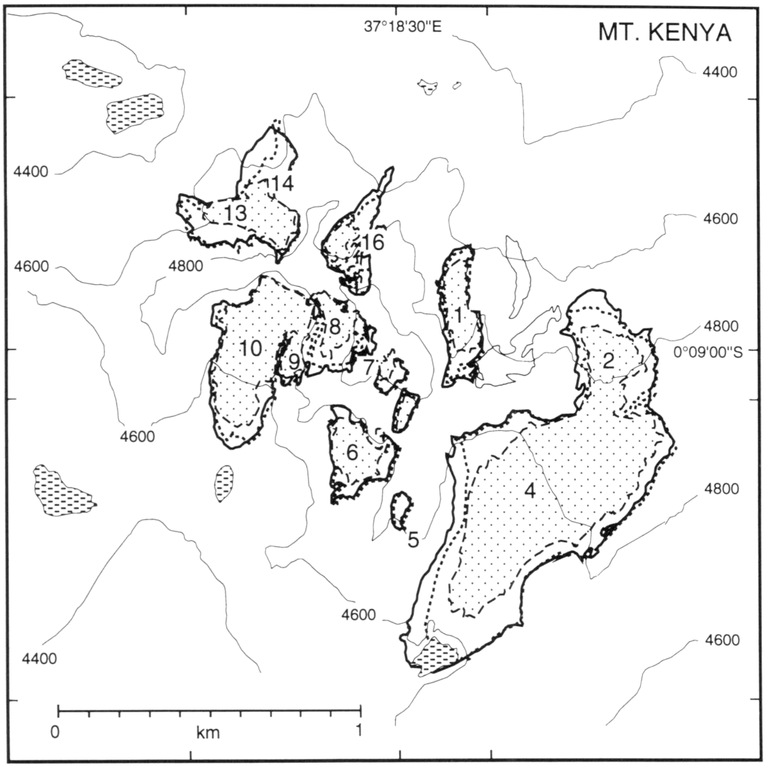

Fig. 3: Orientation map of the glaciers on Mount Kenya. February 1947 solid, January 1963 dotted, and September 1987 broken lines. Thin solid lines indicate snowfields to the East and Southeast of Krapf Glacier in 1947. Scale 1:25,000. Contours at 200 m intervals. Large numbers denote glaciers listed in Tables 2 and 3, as follows: 1 = Krapf, 2 = Gregory, 4 = Lewis, 5 = Melhuish, 7 = Diamond, 8 = Forel, 9 = Heim, 10 = Tyndall, 13 = Cesar, 14 = Joseph, 16 = Northey

Orientierungskarte der Mount Kenya Gletscher. Februar 1947 - durchgezogene, Januar 1963 - gepunktete Linien, September 1987 - gestrichelte Linien. Die dünnen, durchgezogenen Linien begrenzen die Schneefelder im Osten und Südosten des Krapf Gletschers im Jahre 1947. Maßstab 1:25 000; Höhenlinien in 200 m Intervallen. Die Ziffern bezeichnen die in Tabelle 2 und 3 aufgelisteten Gletscher, s. o.

iterations was $\pm 16\ \mu m$. On these grounds the deformation of the model resulting from lens distortion and the errors in the y-scales were considered acceptable.

The absolute orientation of the model with regard to the ground control system depends in this case on the precise setting of the camera focal length, reliable identification of the images of the ground control points, the deformation of the model from relative orientation, and the appropriateness of the x-scales from interior orientation. Initially, the 10 terrain control points shown in Fig. 1 were used for orientation, but then the points S 3, TY and AS, with large departures were excluded. With the remaining 7 points the model gave RMS errors of 4.6 m, 4.5 m, and 2.6 m, in the x, y, and z coordinates, respectively. The analysis of the residuals of these 7 points indicates that they are randomly distributed with respect to height and do not form any systematic pattern (Fig. 2). This corroborates the approach used for the interior orientation. Accordingly, the resulting model was accepted as satisfactory for map production at scale 1:5,000.

5 Mapping

The Wild B-8 combined with the Qasco and Kork systems were used to produce the digital map of the mountain at scale 1:5,000, with contour spacing of 10 m on ice and 20 m on rock outside the glaciers. From tone, texture, and absence of crevasses, snow fields were distinguishable from glaciers. It may be noted that such distinction is not assured in the 1963 map of Forschungsunternehmen Nepal-Himalaya (1967).

In the comparison of the maps for 1947, 1963, and 1987, some details should be noted (Fig. 3). The Melhuish Glacier is found on the 1947 and 1963 but not on the later maps, because it disappeared after 1978 (Hastenrath 1984). To the East and Southeast of the Krapf Glacier some snowfields are indicated on the 1947 and 1963, but not the later maps. The air photographs still show small debris ramparts in the area. To the Southeast of the Diamond, or in fact above the Darwin Glacier, a small ice field is seen in the 1947, 1963, and 1993, but not the 1987 map from which it was omitted inadvertently. The 1987 air photography indeed captures this feature. Finally, a discrepancy should be pointed out with the mapping of the Diamond Glacier, sitting between and below the summits of Batian and Nelion. Its location is consistent between the 1947 and 1963 maps, obtained by different analysts and with different methods. The location also agrees between the 1987 and 1993 maps. However, these latter two maps have its position somewhat more westward as shown for 1947 and 1963. It appears that this inconsistency may have occurred due to an inherent error in the 1987 mapping, carried over into the 1993 map.

Table 2: Characteristic parameters of Mount Kenya's glaciers, 1947

Charakteristische Parameter der Mount Kenya Gletscher 1947

No.	Name	Length [m]	Area [10^3 m^2]	Highest Elevation [m]	Lowest Elevation [m]
1	Krapf	450	43	4930	4600
2	Gregory	540	94	4930	4645
4	Lewis	1195	400	4980	4580
5	Melhuish	220	5	4860	4770
6	Darwin	260	40	4835	4620
7	Diamond	140	7	5150	4965
8	Forel	100	37	5190	4800
9	Heim	80	25	4800	4715
10	Tyndall	570	101	4810	4470
13	Cesar	395	49	4835	4520
14	Joseph	450	34	4795	4555
16	Northey	380	39	5060	4545

6 Glacier inventory for 1947 and 1987

In accordance with the international efforts at glacier monitoring (Temporary Technical Secretariat for World Glacier Inventory of UNESCO-UNEP-IUGG-IASH-ICSI 1977; World Glacier Monitoring Service of IASH-ICSI-UNEP-UNESCO 1993a, b), we present in Table 2 an inventory of the state of Mount Kenya's glaciers in February 1947. The corresponding Table 3 for September 1987 is repeated from our earlier report (Hastenrath et al. 1989).

7 Length, area, and volume changes 1947–1987

Changes over the interval 1947–1987 are presented in Table 4. The length and area changes of glaciers can be reliably retrieved from topographic maps containing accurately traced ice boundaries. More demanding is the estimation of volume changes because this requires a high degree of internal consistency in vertical and horizontal control between

Table 3: Characteristic parameters of Mount Kenya's glaciers, 1987

Charakteristische Parameter der Mount Kenya Gletscher 1987

No.	Name	Length [m]	Area [10^3 m^2]	Highest Elevation [m]	Lowest Elevation [m]
1	Krapf	300	23	4800	4620
2	Gregory	420	45	4890	4715
4	Lewis	950	243	4960	4610
5	Melhuish	0	0		
6	Darwin	200	26	4740	4640
7	Diamond	100	3	5120	4980
8	Forel	100	16	5000	4820
9	Heim	80	16	4800	4720
10	Tyndall	500	78	4790	4510
13	Cesar	300	24	4780	4580
14	Joseph	200	10	4775	4620
16	Northey	150	11	4930	4680

successive mappings. Ice thickness changes were evaluated digitally, with co-registering of control points and using a 2.5 m grid. Topography differences between dates were calculated not only for the glaciers but also for a 50 m wide perimeter around the glaciers, and on this basis glacier thickness changes were adjusted according to apparent discrepancies in rock topography.

Table 4 shows over the 1947–1987 interval the following decreases: as much as 250 m in length; 38×10^4 m^2 in total area; 8.6 m in average thickness, and 69×10^5 m^3 in total ice volume. These results are pertinent to the estimation of the climatic forcing. Thus, the thickness change obtained corresponds to a rate of about 0.2 m/a^{-1}, and it would take 2 W/m^{-2}

Table 4: Decreases in length $\triangle L$ (m), area $\triangle A$ (10^3 m^2), average thickness $\triangle Z$ (m), and volume $\triangle V$ (10^3 m^3) of Mount Kenya's glaciers during 1947–1987

Abnahme der Länge $\triangle L$ (m), Fläche $\triangle A$ (10^3 m^2), durchschnittlichen Mächtigkeit $\triangle Z$ (m) und des Volumens $\triangle V$ (10^3 m^3) der Gletscher am Mount Kenya im Zeitraum 1947–1987

No.	Name	$\triangle L$	$\triangle A$	$\triangle Z$	$\triangle V$
1	Krapf	150	20	2.8	122
2	Gregory	120	49	8.3	784
4	Lewis	245	157	11.7	4692
5	Melhuish	220	5	2.2	11
6	Darwin	60	14	9.6	385
7	Diamond	40	4	3.7	26
8	Forel	9	21		
9	Heim	9	9	0.1	3
10	Tyndall	70	23	3.3	331
13	Cesar	95	25	3.6	176
14	Joseph	250	24	5.1	172
16	Northey	230	28	5.9	228
	all glaciers		379	8.6	6,894

to melt such a column of ice. It is against this background that we should re-visit the results from our 1987 and 1993 mappings (HASTENRATH et al. 1989; ROSTOM a. HASTENRATH 1994). Over that recent time span, the thinning rate was about 1 m/a^{-1}, corresponding to 10 W/m^{-2} for melting. In context then a new map for 1947 served to create a long-term reference against which the evolution over the most recent years can be compared.

8 Concluding remarks

The glaciers of Mount Kenya, right under the Equator, have been the object of our research for more than two decades (HASTENRATH 1984, 1991). In the context of the growing concern for global change at the international level (World Meteorological Organization-ICSU 1988; World Glacier Monitoring Service 1993 a, b), this work acquires an important dimension. The glaciers on the high mountains of the tropics are indeed climatically sensitive components of the environment. For quantitative inferences of the climatic forcing repeated assessments are needed not only of the glacier area but more importantly of the changes in surface topography and ice thickness, because these contain the information needed for energy considerations.

In this project, we have mapped Mount Kenya's glaciers in 1987 and 1993 (HASTENRATH 1994). In scale and domain consistent with these maps, the present retrospective mapping from historical air photography in 1947 extends this documentation back to the middle of the 20th century, thus completing the task proposed in our previous study (ROSTOM a. HASTENRATH 1994). In conjunction, our maps of the glaciers of Mount Kenya for 1947, 1987, and 1993, indicate that the climatic forcing of the glacier recession has accentuated in recent years.

Acknowledgements

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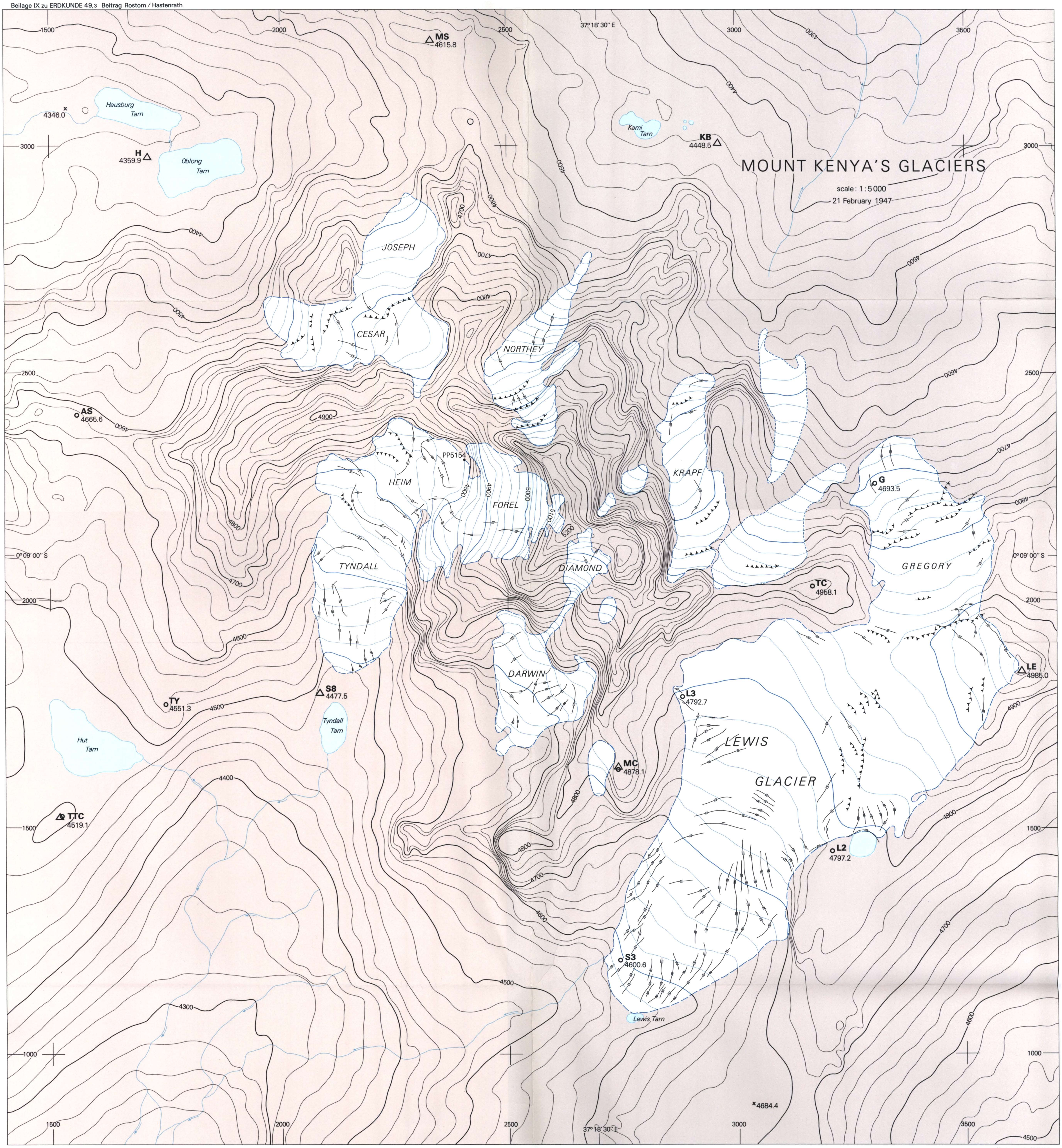

Kartographie: S. Dohmen

△ ground control points used in mapping (transferred to 1947 photogr. from 1987 photographs)

○ ground control points not used in mapping (not transferred to 1947 photography)

glacier boundary

principal crevasses

ice cliff

snow field

lake, pond

stream

0 100 200 300 400
metres