

Glaciers of the Middle East and Africa—

GLACIERS OF AFRICA

By JAMES A.T. YOUNG *and* STEFAN HASTENRATH

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

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Glaciers in Africa are located on two volcanoes, Mount Kenya in Kenya and Kilimanjaro in Tanzania, and on the Ruwenzori massif in Uganda and Zaire and have a total area of 10.7 km²



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GLACIERS OF THE MIDDLE EAST AND AFRICA— GLACIERS OF AFRICA

By JAMES A.T. YOUNG¹ and STEFAN HASTENRATH²

Abstract

The present-day distribution of glaciers in Africa is limited to three specific geographic locations: two volcanoes (Mount Kenya and Kilimanjaro) and one mountain group (the Ruwenzori). The combined area of glaciers in these three regions is about 10 square kilometers. There has been substantial and virtually continuous wastage of the glacier ice for more than 100 years. Mount Kenya (5,202 meters), in central Kenya, has 11 cirque and valley glaciers with a total area of 0.7 square kilometers. Kilimanjaro (5,895 meters), in northern Tanzania, is the highest mountain in Africa. It has 16 named glaciers and 3 ice fields distributed around the Kibo caldera with a total area of about 5 square kilometers. The present occurrence of glacier ice on Kilimanjaro represents the isolated remnants of a more extensive ice cap on Kibo, from which several outlet glaciers extended in a number of locations some hundreds of meters farther downslope, according to observations made in the late 1800's. The Ruwenzori, which sit astride the border between Uganda and Zaire, and whose highest elevation is 5,109 meters, have 44 named glaciers distributed over 6 glacierized mountains. The total area of these glaciers is approximately 5 square kilometers. Because of the small area of the individual glaciers in Africa, the 79-meter pixel resolution of the Landsat multispectral scanner image limits its usefulness for monitoring changes in the areal extent of African glaciers. The Landsat 3 return beam vidicon image, with its pixel resolution of approximately 30 meters, provides considerable improvement. No usable Landsat images were available of the Ruwenzori because of persistent cloud cover. Future monitoring activities and studies of the glaciers of Africa will require image or photographic data from sensors with spatial resolution equivalent or better than 10 meters, such as the Large Format Camera or the French *Système Probatoire d'Observation de la Terre*. Vertical aerial photographs or field surveys, done on a repetitive basis, are still the most effective means of monitoring changes in the glaciers of Africa.

Introduction

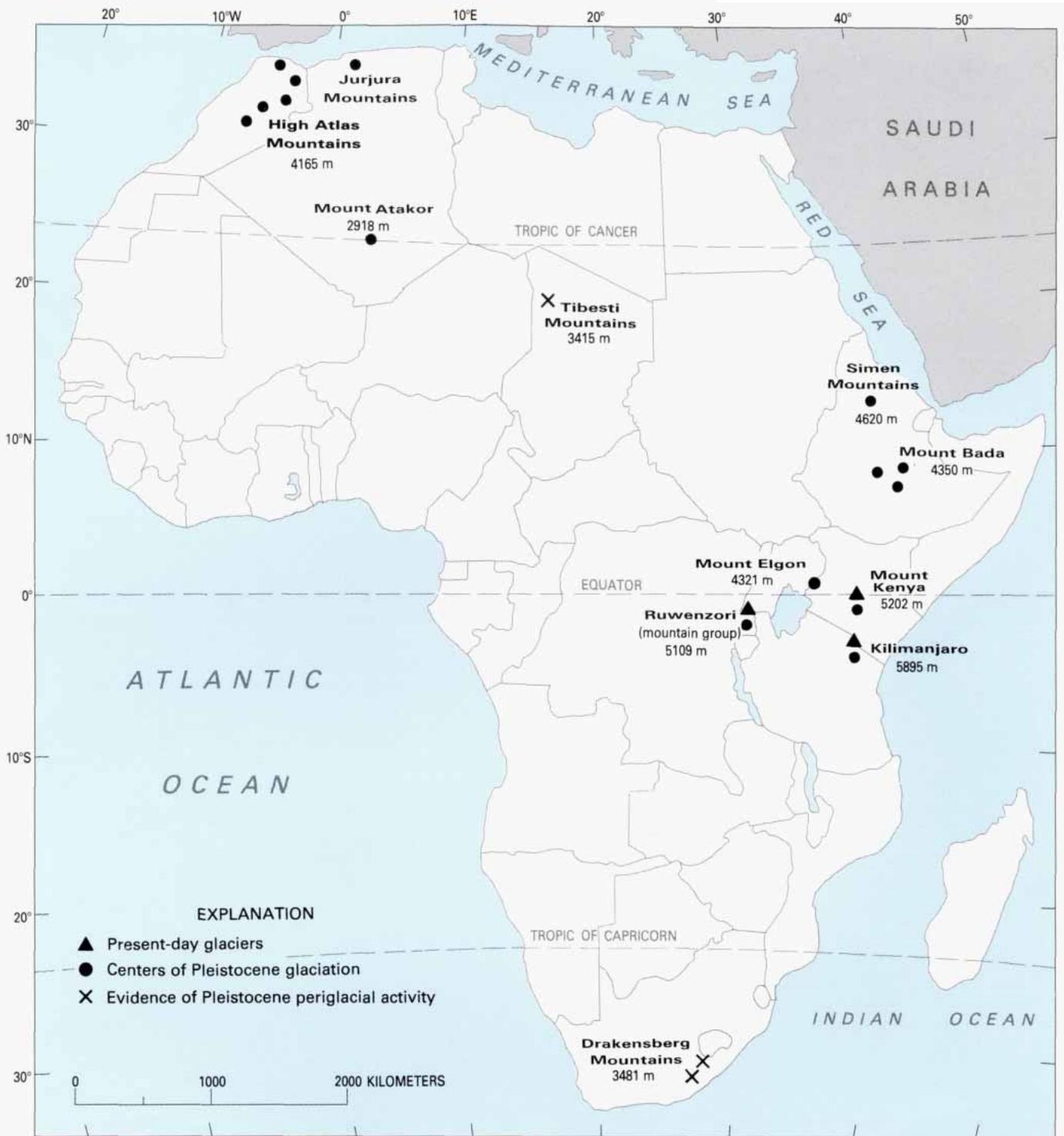
Geomorphological and biological evidence indicates that, during the Pleistocene Epoch, glaciers extended across several hundred square kilometers of the east African mountains and also spread out from the highest peaks in (1) the High Atlas³ Mountains of Morocco, (2) possibly the Mount Atakor massif in southern Algeria, (3) the Simen Mountains of northern Ethiopia (fig. 1), and from the following mountains of southern Ethiopia: Bada, Filfo Terara (Enguolo), Ch'ilalo Terara (Cilalo), K'ech'a Terara (Cacca), and Agal Terara (Bale). Today, glaciers cover less than 10 km² of the topmost reaches of Mount Kenya (5,202 m), Kenya; Kilimanjaro (5,895 m), northern Tanzania; and the Ruwenzori (5,109 m), which straddle the border between Uganda and Zaire (Young, 1980; Hastenrath, 1984).

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³The geographic names used in this subchapter are those approved by the U.S. Board on Geographic Names. Where variations are commonly used, these are given in parentheses.



Ice-clad Kilimanjaro was first sighted in 1848 by the German missionary J. Rebmann (Rebmann, 1849), and Mount Kenya was first sighted in 1849 by J.L. Krapf (Krapf, 1860), but their reports were long disbelieved. When first studied in the latter years of the 19th century, the glaciers were already beginning to retreat from nearby, scantily vegetated moraines. Since then, wastage has been rapid; many of the large glaciers have disintegrated, and some glaciers have disappeared completely. Historical documentation of the glacier recession includes expedition reports, sketch maps, photographs, and field measurements. For some of

Figure 1.—Distribution of present-day glaciers in Africa, location of centers of Pleistocene glacial activity, and areas where there is evidence of Pleistocene periglacial activity (modified from Butzer, 1978).

the glaciated areas there are accurately surveyed maps (Hastenrath, 1975, 1984). The causes of the rapid retreat have puzzled many researchers. Possible variations in precipitation, temperature, and cloud cover, direct evaporation from the surface of the glaciers, and the details of the relief have all been suggested as contributing factors (Spink, 1949; Shepherd, 1959; Osmaston, 1961; Whittow and others, 1963; Platt, 1966; Temple, 1968). However, numerical modeling of the complete causality chain (climate, net balance, ice dynamics, terminus response) of the Lewis Glacier on Mount Kenya, combined with an ongoing field program, identifies a drastic decrease in precipitation in the latter years of the 19th century and a slight warming in the first half of the 20th century as the major factors controlling the observed dramatic recession of the glaciers in east Africa (Kruss, 1983; Hastenrath, 1984).

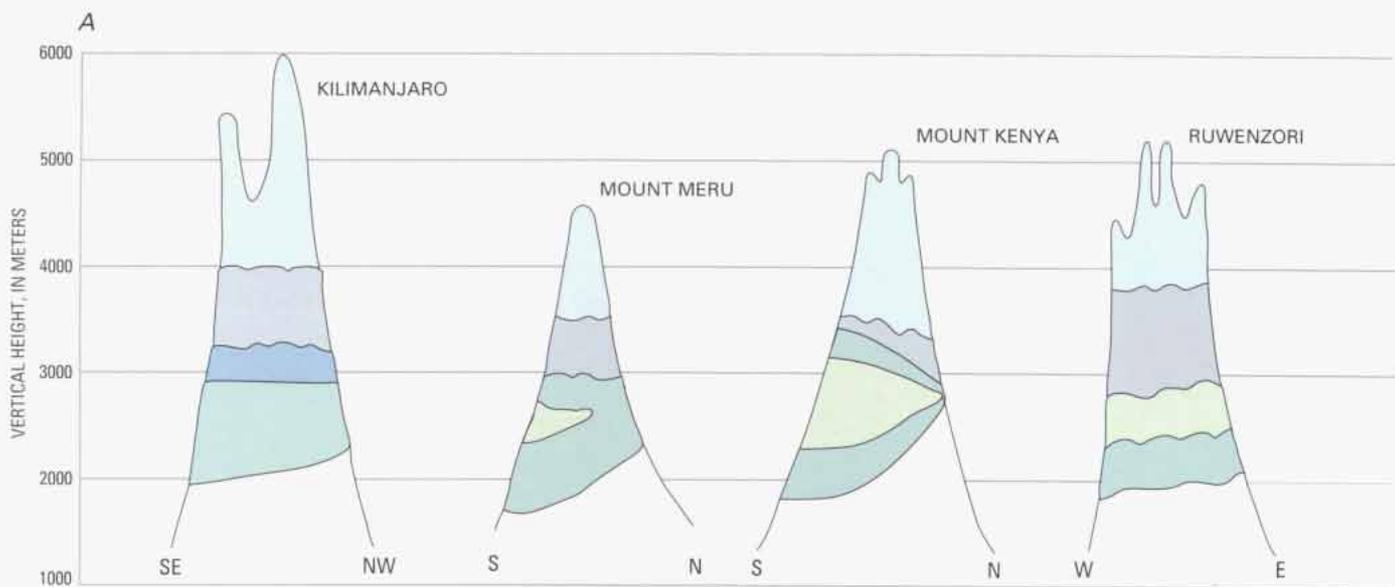
Mount Kenya and Kilimanjaro owe their origins to intense Quaternary volcanic activity, one aspect of the crustal dynamics of this region, which, through faulting, also produced the East African Rift Valley. The Ruwenzori are a horst of Precambrian crystalline rocks produced by upfaulting of a block within the downfaulted Western Rift Valley and are the highest nonvolcanic mountain range in Africa (Buckle, 1978). As is commonly observed on tropical mountains, Kilimanjaro and Mount Kenya possess well-developed altitudinal belts of maximum precipitation. From these belts, conditions change with increased elevation to a relatively dry environment in the summit regions. Moreover, spatially varying circulations that have a daily periodicity dominate the diurnal pattern of cloudiness and precipitation and have a profound effect on the climate and vegetation patterns as well as on the ice distribution (fig. 2).

A search of the literature suggests that, since the east African glaciers were discovered, there have been two periods of most intense investigations. An initial 20 to 25 years of active exploration from the late 1880's was followed by about 40 years during which little research was published. From 1945 to 1960, substantial scientific work was carried out that culminated in investigations associated with the International Geophysical Year (IGY) of 1957-58. Since then, there has been a general dearth of new work, except for a number of studies concentrating on Mount Kenya.

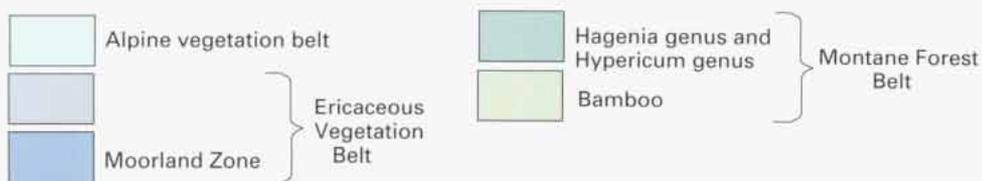
Glaciers of Mount Kenya, Kenya

Mount Kenya is the dissected remnant of a large composite volcano that primarily built up during a period of about 500,000 years, from 3.1 to 2.6 million years B.P., although flank eruptions continued until 40,000 years B.P. (Baker, 1967). Its summit is the center of a broad, shallow cone whose north to south base diameter of 100 km is slightly greater than its west to east axis. Deeply excavated valleys radiate from the summit area, which is composed of a network of arêtes (fig. 3).

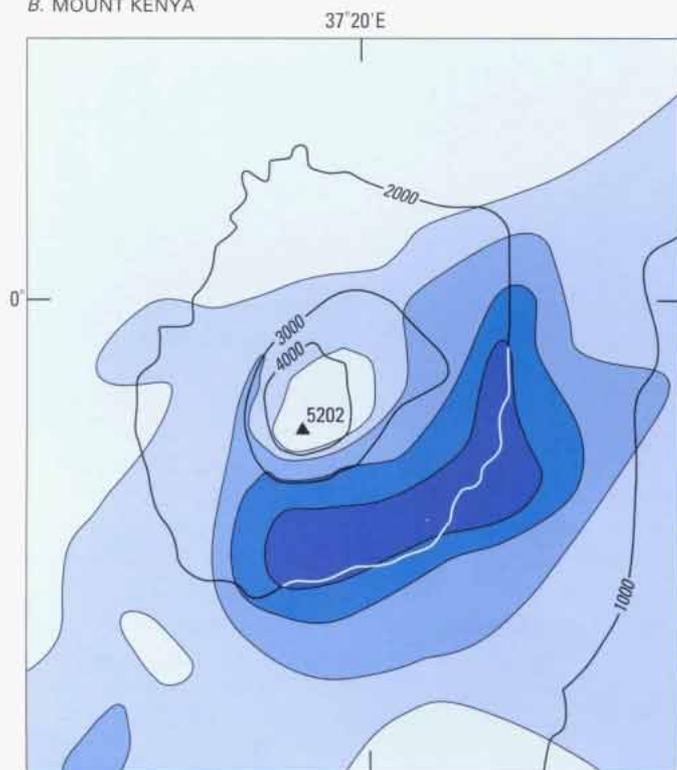
Although Krapf in 1849 was the first European to see the distant snows of Mount Kenya (Krapf, 1849, 1858, 1860), exploration did not begin until 1887, when an expedition climbed to about 4,250 m on the southwestern slopes (Höhnel, 1894). The glaciers were eventually reached in 1893 by Gregory, who initiated scientific work on Mount Kenya (Gregory, 1894, 1896). During the 20th century, the most notable investigations have been those of Nilsson (1931), the IGY expedition (Charnley, 1959), an investigation of the ecology of the alpine zone by Coe (1967), and studies of Mount Kenya glaciers, with particular attention to the Lewis Glacier (Hastenrath, 1975, 1983, 1984; Caukwell and Hastenrath, 1977, 1982; Hastenrath and Caukwell, 1979; Hastenrath and Patnaik, 1980;



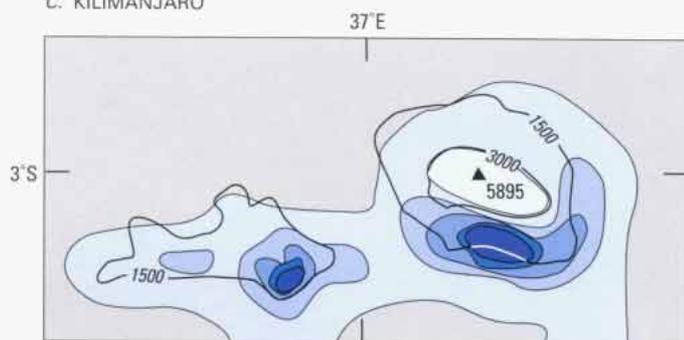
EXPLANATION



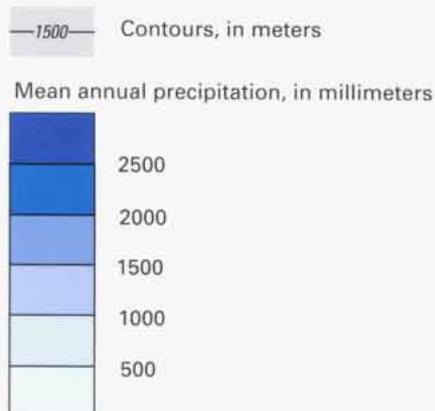
B. MOUNT KENYA



C. KILIMANJARO



EXPLANATION



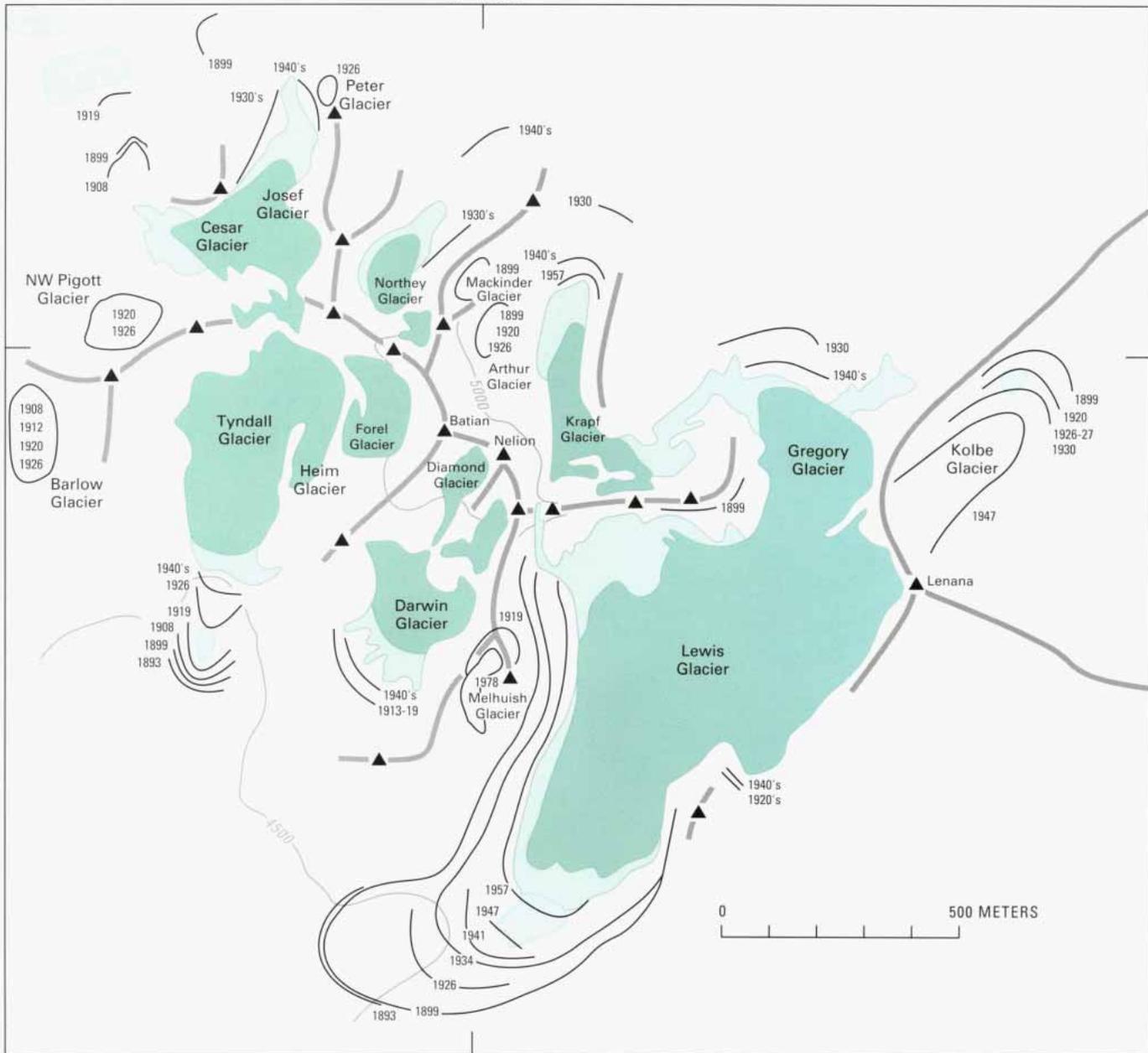
Hastenrath and Kruss, 1981, 1982; Thompson, 1981; Thompson and Hastenrath, 1981; Bhatt and others, 1982).

In the course of the successful expedition to climb Mount Kenya in 1899, a sketch of the peaks and glaciers was produced from a plane-table survey (Mackinder, 1900). Later sketch maps include those by Melhuish and Arthur around 1920, by Dutton (1929), and the Mountain Club of Kenya (Allan, 1981; Hastenrath, 1984). However, accurate topographic mapping has to be traced from Troll and Wien's 1:13,000-scale 1934 terrestrial photogrammetric survey map of the Lewis Glacier that was not published until 1949 (Troll and Wien, 1950). Schneider carried out a terrestrial photogrammetric survey in 1963 and published a superb map of the entire summit region at a scale of 1:5,000 (Forschungsunternehmen Nepal-Himalaya, 1967). The Lewis Glacier was mapped in 1983 also by use of terrestrial photogrammetry methods by Patzelt and others (1985) at a scale of 1:5,000. Maps at 1:25,000 scale (1973), 1:50,000 scale (1974), and 1:125,000 scale (1974) based on aerial photogrammetry are now available for the entire summit area (table 1). The Lewis Glacier was mapped in 1958 by tacheometry at a scale of 1:2,500 (Charnley, 1959) and in 1974, 1978, 1982, and 1985 by aerial photogrammetry at a scale of 1:2,500 (Caukwell and Hastenrath, 1977, 1982; Hastenrath and Caukwell, 1979; Hastenrath, 1984). In view of the six maps produced since the 1930's, numerous photographs acquired during various expeditions, and extensive field research since the 1970's, the Lewis Glacier is now one of the best documented ice masses in the tropics (Hastenrath, 1984).

TABLE 1.—Selected maps for the presently glacierized areas of Africa

Mount Kenya, Kenya
Directorate of Overseas Surveys (U.K.) Tourist Map of Mount Kenya National Park and Environs (from 1:50,000 Series Y731 with additional information supplied by the Survey of Kenya 1972 and 1973) D.O.S 2657 1974, Edition 1, Scale 1:125,000
Survey of Kenya Mount Kenya, East Africa (Kenya) Series Y731, Sheet 121/2, D.O.S. 423 1974, Edition 6-SK, Scale 1:50,000
Survey of Kenya Map of Mount Kenya, Sheet SK 75, D.O.S. 302 1973, Edition 5-SK Scale 1:25,000
Forschungsunternehmen Nepal-Himalaya Mount Kenya, special sheet 1967, Scale 1:5000 Kartographische Anstalt Freytag-Berndt und Artaria, Wien
Kilimanjaro, Tanzania
Directorate of Overseas Surveys (U.K.) Kilimanjaro, East Africa (Tanzania/Kenya) Series, special sheet, D.O.S. 522 1965, Reprinted 1978, Edition 1-DOS, Scale 1:100,000 Directorate of Overseas Surveys for United Republic of Tanzania
Directorate of Overseas Surveys (U.K.) Kilimanjaro, East Africa (Tanganyika) Series Y742, Sheet 56/2, D.O.S. 422 1964, Edition 1, Scale 1:50,000 Directorate of Overseas Survey for the Tanganyika Government
The Ruwenzori, Uganda and Zaire
Directorate of Overseas Surveys (U.K.) Margherita, East Africa (Uganda) Series Y732, Sheet 65/2 (D.O.S. 26) 1958, Edition 3-U.S.D., Scale 1:50,000 Lands and Surveys Department, Uganda
Uganda Department of Lands and Surveys Central Ruwenzori U.S.D. v15 (first edition D.O.S. 326) 1970, Edition 2-U.S.D., Scale 1:25,000

Figure 2.—A, Schematic profiles of the vegetation belts on selected east African mountains. Only the vertical distances are to scale (after Hedberg, 1951). B, Distribution of mean annual precipitation on Mount Kenya (after Thompson, 1966). C, Distribution of mean annual precipitation on Kilimanjaro and Mount Meru (after Coutts, 1969).



EXPLANATION

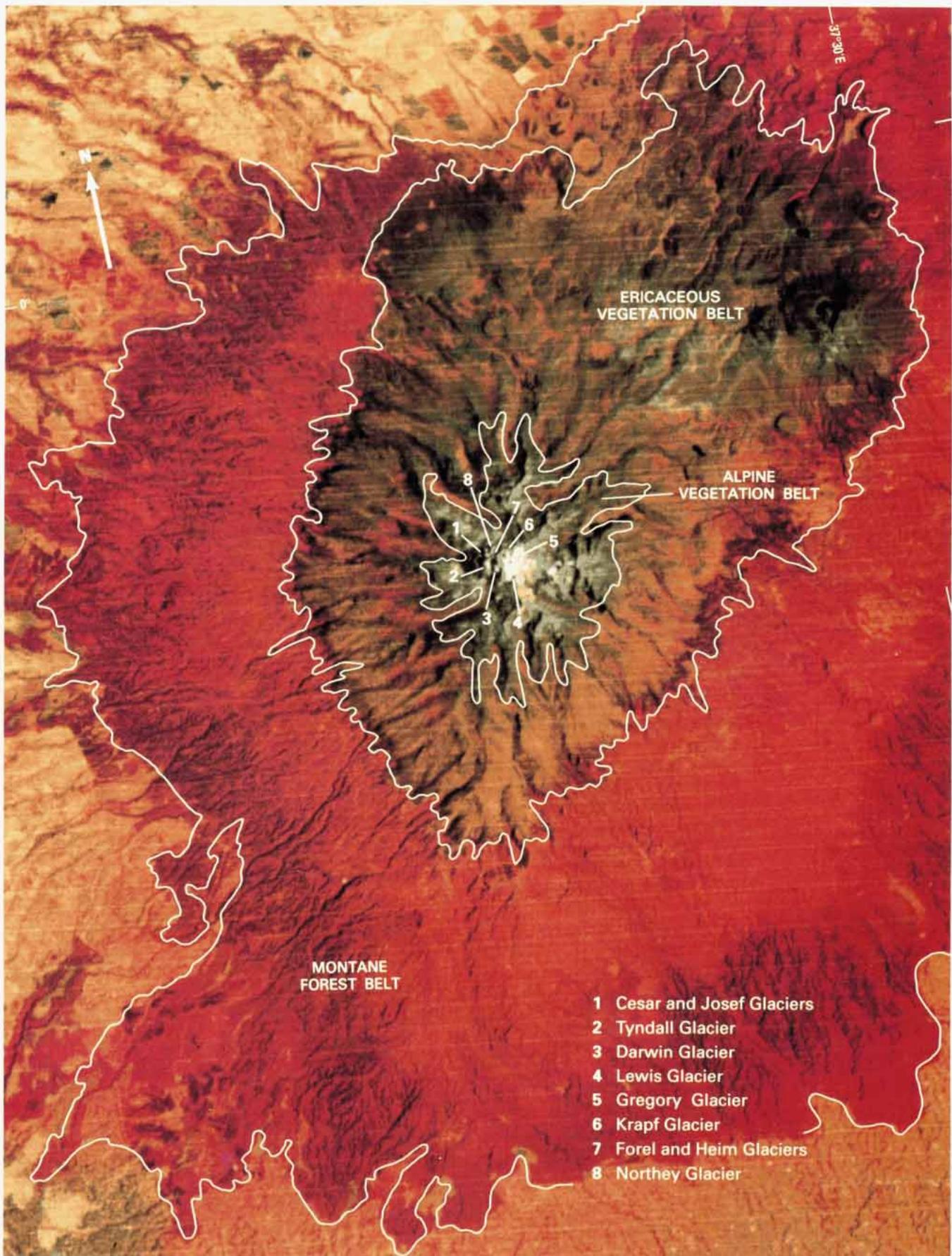
- | | | | |
|---|--|--|--------------------------------------|
|  | Distribution of glaciers in 1973-74 |  | Tarn, or proglacial lake |
|  | Distribution of glaciers in 1963 |  | Dated position of glacier termini |
|  | Glaciers which have disappeared subsequent to the last date indicated. Melhuish Glacier has disappeared since 1978 |  | Ridge crest or divide |
| | |  | Isolated summit or peak (some named) |
| | |  | Contours, in meters |

Figure 3.—The shrinking glaciers of Mount Kenya (modified from Map 4.3:8 in Has-tenrath, 1984).

On his 1893 expedition, Gregory discovered moraines on Mount Kenya at 3,000 m, but he attributed them to the former greater elevation of Mount Kenya, which he believed had been reduced by subsidence and denudation (Nilsson, 1929). It was Meyer (1900) who, from his repeated expeditions to Kilimanjaro, first recognized the climatic significance of fossil moraines in east Africa. Erosional and depositional evidence indicates that glaciers once covered about 200 km² of Mount Kenya and descended to the upper limit of the modern treeline. Palynological studies suggest that the mean annual temperature at 2,400 m about 18,000 years B.P. was 8 °C lower than present and that major warming began 15,862±185 years B.P. (Coetzee, 1964).

The glaciers of Mount Kenya are best developed on the western and southern slopes of the ridges south and east of the summit; these are topographically the most favorable areas for accumulation and survival of snow (figs. 3 and 4). A stronger glaciation in the western as compared to the eastern quadrants is found on many high mountains in the tropics. The major factors for this on Mount Kenya are the precipitation maximum centered on the southeast and the strong daily weather pattern that causes the highest reaches of the mountain to be clear until late morning, then become progressively obscured by clouds that do not dissipate until late afternoon. These vigorous circulations, which have a daily periodicity and enhanced afternoon cloudiness, result in reduction of insolation on the westward-facing slopes. This diurnal weather pattern substantially protects the glaciers and snows on the western summit slopes from the ablativ effects of direct solar radiation that ravage the glacier cover of the eastern slopes. As Mount Kenya is located only a little to the south of the Equator, meridional contrasts of radiation are of subordinate importance. References to the daily weather pattern are found in Allan (1981) and Davies and others (1977). In addition, Thompson (1966) suggests that turbulent overturning of the large-scale Easterlies produces a narrow, poorly defined band of higher precipitation immediately west of the summit (fig. 2B).

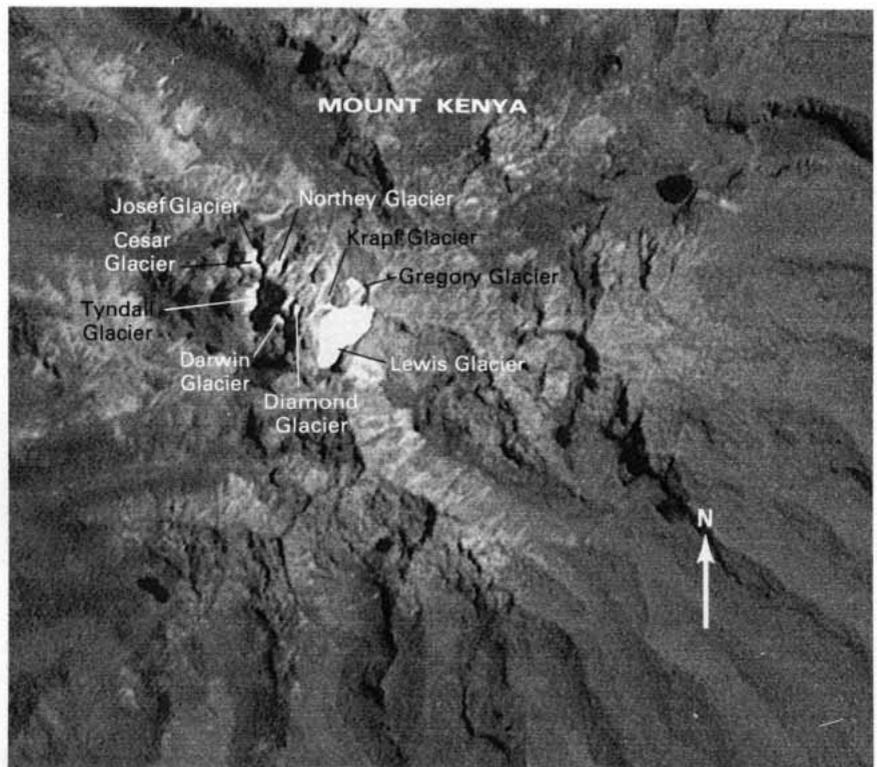
There were 18 cirque and valley glaciers on Mount Kenya at the end of the 19th century (Hastenrath, 1984), and Gregory (1894) described the western side of the summit as almost entirely covered by snow and ice. The Lewis Glacier had recently broken through the closest of its terminal moraines and was estimated by Mackinder (1900) to be 1.6 km long, while the Gregory Glacier was only slightly shorter. Following a period of wastage described by Spink (1945) as "startling," Nilsson (1949) calculated that the total glacier cover was only 1.2 km², of which the Lewis Glacier accounted for 0.36 km². The 1957–58 IGY work showed that the mass losses of the Lewis Glacier through thinning had exceeded those associated with frontal recession (Charnley, 1959). An ongoing field program on the Lewis Glacier has included determinations of ice thickness and bedrock topography by seismological and gravimetric techniques and numerical modeling (Bhatt and others, 1982); assessment of the spatial pattern of surface ice flow velocity by repeated surveying of a network of stakes; estimate of major heat budget terms during intensive short-term measurement programs; establishment of the mass budget characteristics through monitoring of net balance at an array of stakes, measurement of runoff (water), and monthly gaging of precipitation; climatic ice core studies (Thompson, 1981; Thompson and Hastenrath, 1981); and numerical modeling of climatic forcing and ice dynamics (Hastenrath, 1984). During the period 1899–1982 (Hastenrath, 1984), the area of the Lewis Glacier decreased from 630 to 261 × 10³ m², the length of the glacier from about 1,590 m to 995 m, and the terminus elevation moved upward 135 m to 4,600 m (fig. 3). The total ice-covered area of Mount Kenya in the 1980's is of the order of 0.7 km² (Muller, 1977;



Hastenrath, 1984). Of the **18** glaciers at the turn of the century, **11** still exist as of **1986**; one glacier has disappeared since **1978**.

Figure 4, an annotated Landsat image (2367-06573; Path 180, Row 60), depicts Mount Kenya on the morning of 24 January 1976, approximately midway through one of the annual “dry” seasons and, therefore, before ablation has reached a maximum. Accordingly, the glaciers on the north side of the mountain tend to be masked by snow cover, and the west-facing slopes are in shade. Thus, of the glaciers to the north, the Krapf Glacier seems to connect with the Lewis Glacier, and the Gregory Glacier appears large. The evidently shaded Northey, Forel, and Heim Glaciers are not depicted at all, and the Darwin, Tyndall, Cesar, and Josef Glaciers appear rather small. The image is dominated by the largest ice body, Lewis Glacier. An estimated 60 to 70 percent of the snow and ice cover on the satellite image is glacier ice, and 10 of the 12 glaciers remaining at the time can be identified. On the northeastern and eastern sides of the summit, the proportion of snow is probably 50 percent. To the north and northeast of the summit, parasitic volcanic cones can be identified. The vegetation belts are demarcated on the image.

Figure 5 is an annotated Landsat 3 return beam vidicon (RBV) image (30912-06490, subscene C, Path 180, Row 60) depicting the summit area of Mount Kenya on the morning of 2 September 1980, at a time in the year when the midday sun was almost directly overhead and approximately midway through one of the dry seasons but before ablation had reached a maximum. On the southeast side of the mountain, the Lewis and Gregory Glaciers are prominent, although their apparent area is exaggerated by snow cover. Because of their exposure to the sun during the previous months, the north-facing Cesar, Josef, Northey, and Krapf Glaciers appear to be without snow cover, and their areas are therefore more accurately depicted. Shadows cast by the arc of the high summit ridge that curves from northwest to southwest in a clockwise direction



◀ **Figure 4.**—Annotated 1:250,000-scale enlargement of a Landsat MSS color-composite image of Mount Kenya (2367-06573; 24 January 1976; Path 180, Row 60) showing vegetation belts and the distribution of glaciers. Ten of the 12 glaciers remaining at the time can be detected.

Figure 5.—Annotated 1:100,000-scale enlargement of a Landsat 3 RBV image (30912-06490, subscene C; 2 September 1980; Path 180, Row 60) of Mount Kenya showing the distribution of glaciers. The Heim and Forel Glaciers are hidden by the summit's shadow.

mask most of the Tyndall, Darwin, and Diamond Glaciers and hide completely the Heim and Forel Glaciers, all of which lie to the west of this ridge. Possibly 80 to 90 percent of the snow and ice cover of the RBV image is glacier ice; 9 of the 11 remaining glaciers can be identified and are noted on the annotated image. The Landsat 3 RBV image has 30-m picture elements (pixels) compared with 79-m pixels of the Landsat MSS image, a 2½-fold improvement in spatial resolution. As a result it is possible to enlarge the RBV image to a larger scale and to distinguish more easily the small glaciers of Mount Kenya (compare fig. 5 with fig. 4).

Glaciers of Kilimanjaro, Tanzania

Kilimanjaro is the highest mountain in Africa and is the largest of a group of volcanoes that continued to be active until at least the Pleistocene Epoch (Downie and Wilkinson, 1972). In contrast to Mount Kenya, Kilimanjaro is a massive and relatively undissected shield volcano that rises from a 95-km-long by 65-km-wide base, whose longer axis runs east-southeast/west-northwest (fig. 6). There were three main volcanic centers, and, on the basis of their degree of subaerial dissection, it is believed that Shira (4,005 m) was first to cease activity, then Mawenzi (5,140 m), and finally Kibo (5,895 m). However, the latter is not completely extinct, and the same may be true of Mount Meru (4,566 m) immediately to the west (figs. 2 and 6). Kibo has solfataras and steam fumaroles, and Mount Meru is thought to have erupted in the late 19th century (1877? and 1886?) and was active for about 2 months in late 1910 (Simkin and others, 1981); both should be classified as dormant volcanoes. Kibo culminates in a nearly symmetrical cone and contains a 2.5-km-wide caldera whose inner scarps rise 180 to 200 m on the south side; toward the northern side of the caldera (figs. 7–9) are two concentric craters containing a central cone.

Following the first European sighting of the snow-covered summit of Kibo in 1848 by Rebmann (1849), exploration proceeded more rapidly than on Mount Kenya. Several expeditions had visited Kilimanjaro prior to Meyer's initiation of scientific research on the mountain in 1888 and successful ascent of Kibo in 1890 (Meyer, 1890a, 1891). Impressive results flowed thereafter from a series of German expeditions that culminated in the detailed work by Klute (1920). Further pertinent studies about Kilimanjaro's glaciers were published by Gillman (1923) and Nilsson (1931). In 1953, a renewal of interest resulted in the fullest IGY investigation on any of the east African mountains (Humphries, 1959; Downie, 1964; Downie and Wilkinson, 1972).

Maps and sketches published in reports of the early expeditions (Johnston, 1885; Meyer, 1890b, 1891, 1900) are an interesting, generalized record of the relative distribution of snow and ice on Kilimanjaro. The best of the earliest maps was a 1:50,000-scale map (1912) that was based on terrestrial photogrammetry of the upper reaches of the mountain (Klute, 1920), although it was found during the IGY work to be deficient in topographical detail. Sketch maps of the Kibo glaciers are also found in a report of the Mountain Club of East Africa (1932) and in publications of the Mountain Club of Kenya (Allan, 1981; Hastenrath, 1984). An impressive 1:125,000-scale geological map was published in 1965 by the Geological Survey of Tanganyika and includes an inset map of the caldera area of Kibo at 1:50,000 scale. This inset depicts the perennial ice cover in February 1962. The most recent large-scale map is a

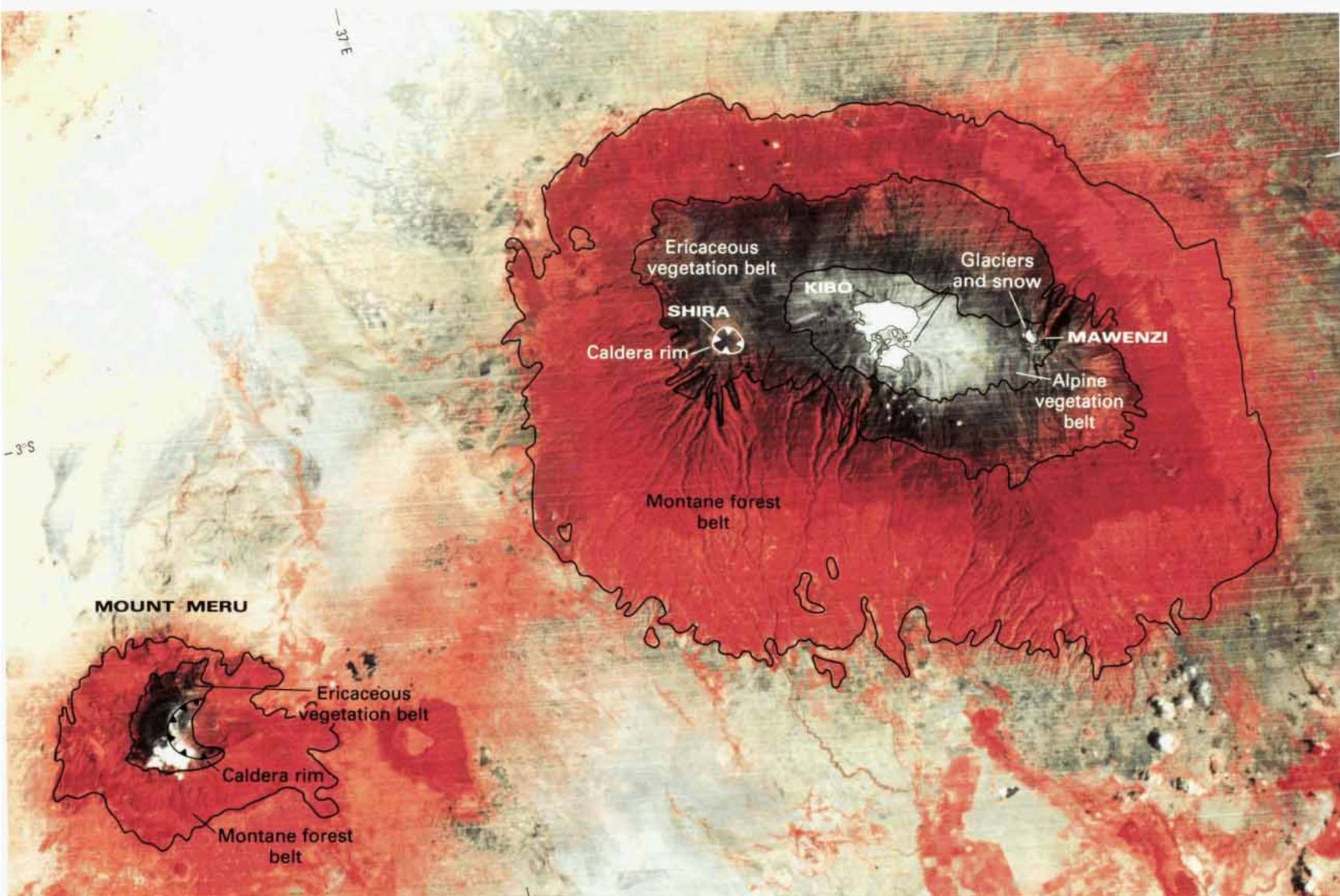


Figure 6.—Annotated 1:500,000-scale enlargement of a Landsat MSS color-composite image (2367-06582; 24 January 1976; Path 180, Row 62) of Kilimanjaro and Mount Meru showing vegetation belts and the distribution of glaciers.

1:50,000-scale sheet (1964). Both the 1:50,000-scale (1964) and a 1:100,000-scale (1978) map were compiled from aerial photogrammetry (table 1).

Moraines, boulder trains, crag-and-tail features, U-shaped valleys, glaciated pavements, roches moutonnées, rock basins, kettle lakes, and cirques all testify to a formerly more extensive cover of glacier ice on Kilimanjaro. The evidence is best developed around the summits of Kibo and Mawenzi. Meyer (1900) traced moraines to 3,600 m on the northern side and 3,800 m on the western and southern sides of Kibo and also assigned a fluvio-glacial origin to sediments overlain by lavas to the north of Shira caldera. Glacial deposits interbedded with lavas were later found on Kibo by Downie (1964), who suggested that there had been six glacial episodes on Kilimanjaro, with volcanic activity separating the earlier episodes. During the period of maximum glacier development, a continuous ice cap covering approximately 400 km² extended across the summits of Kibo and Mawenzi (fig. 8). Depictions of more recent ice extent are found in Allan (1981), Hastenrath (1984), and on the Landsat images of figures 6 and 7.

Kilimanjaro exhibits a prominent belt of maximum precipitation below 2,000 m and a marked upward change to the decidedly dry environment

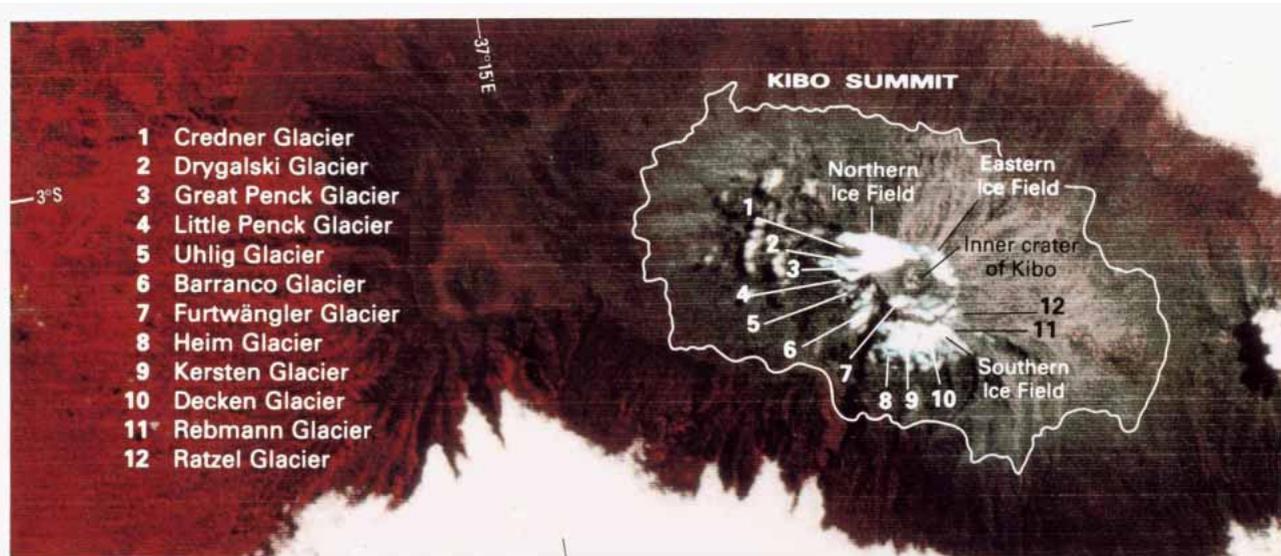


Figure 7.—Annotated 1:250,000-scale enlargement of a Landsat MSS color-composite image (2205-07000; 15 August 1975; Path 180, Row 62) provides information about the distribution of glaciers on the summit region of Kilimanjaro. Twelve of the remaining 16 glaciers and the 3 ice fields can be detected.

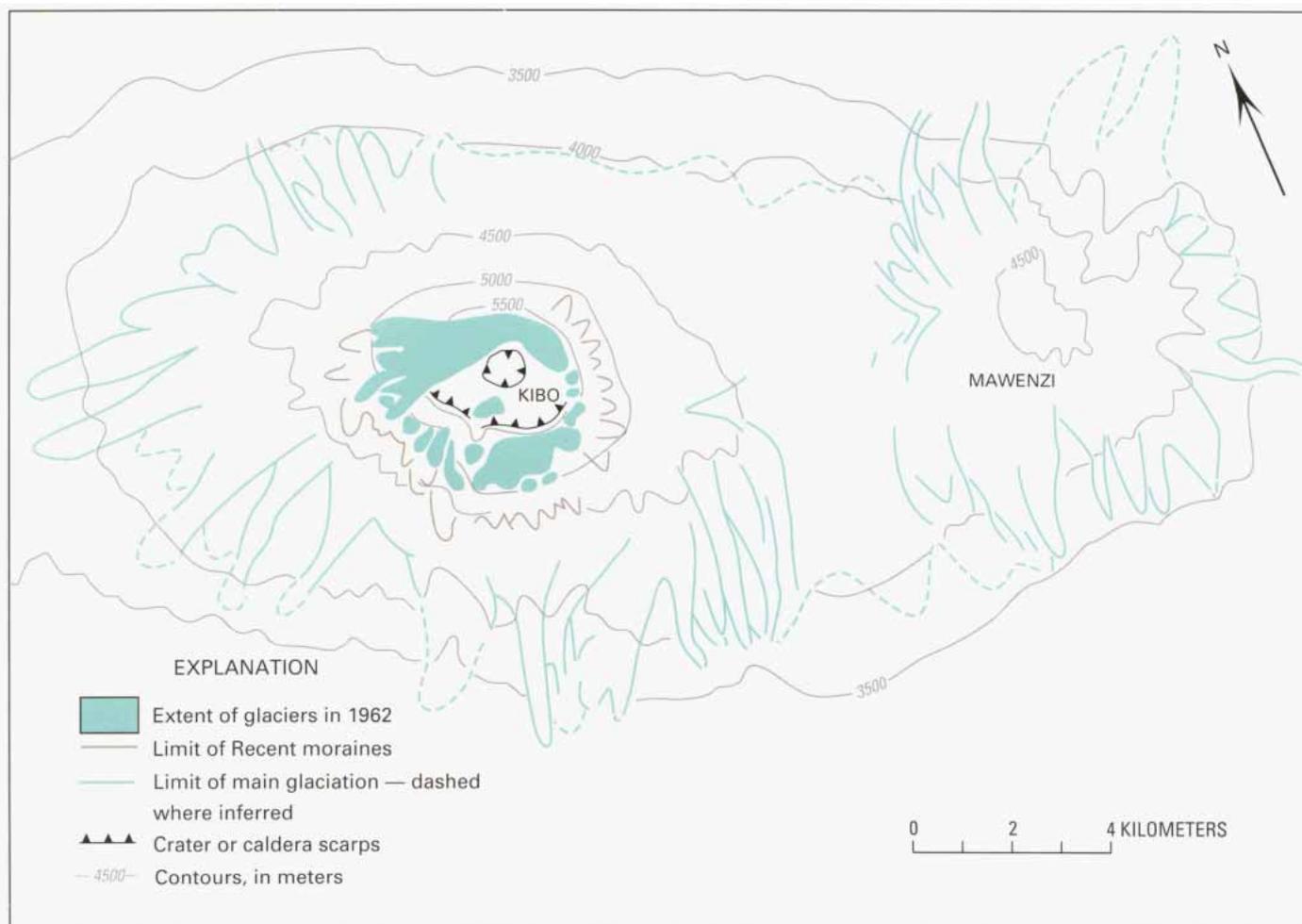


Figure 8.—The shrinking glaciers of Kilimanjaro (after Downie, 1964).

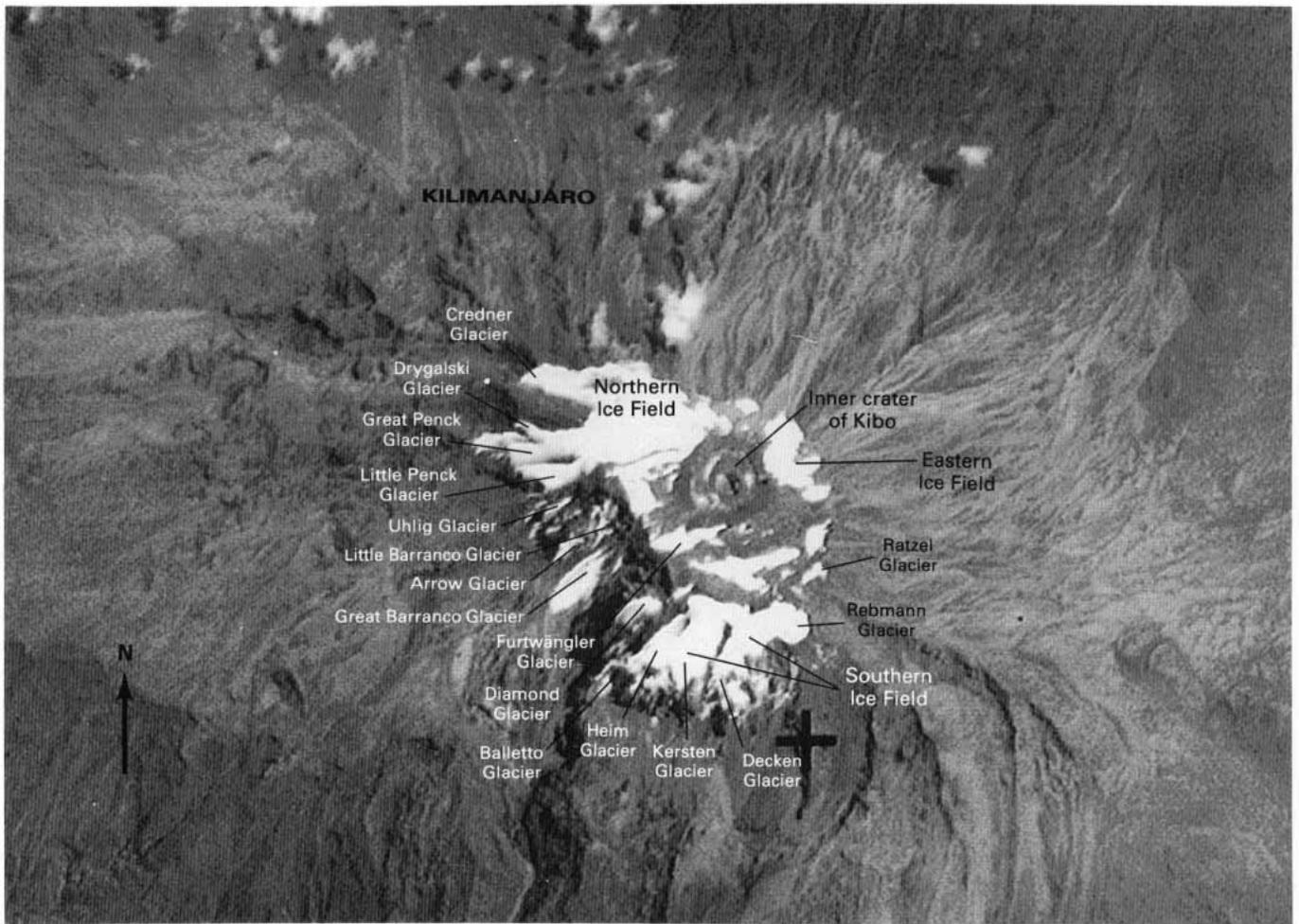


Figure 9.-Annotated 1:100,000-scale enlargement of a Landsat 3 RBV image (30912-06495, subscene D; 2 September 1980; Path 180, Row 62) of Kilimanjaro showing the distribution of glaciers.

of the summit region. A stratiform cloud deck is frequently found with an upper limit around 3,000 to 3,500 m. This is apparent on the satellite image used in figure 7. Within the belt of maximum precipitation, rainfall is considerably more abundant on the southern as compared to the northern slopes. This asymmetry appears related to the southeasterly flow in the lower troposphere during the main rainy season, which lasts from March to May ("long rains"). Only a weak secondary rainfall peak is indicated around December ("short rains"), when the flow in the lower troposphere is from the northeast (Coutts, 1969). The distribution of rainfall (fig. 2C) has a conspicuous effect on the altitudinal belts of vegetation, as illustrated in figure 6. In the drier peak regions, marked asymmetries are apparent in the ice distribution. Most remarkable are the glaciers that reach a comparatively low elevation on the western slopes, contrasting with the now completely ice-free eastern crater rim. This zonal asymmetry is primarily a consequence of the strong diurnal circulation, which leads to abundant cloudiness in the afternoon and reduced insolation on the westward-facing slopes. Also noteworthy is the much larger ice extent on the south as compared to the north side of Kibo. Because Kilimanjaro is located well into the Southern Hemisphere, the geometry of planetary radiation becomes a factor, favoring as it does insolation on the equatorward, northern slopes.

At the time of Meyer's 1888 and 1889 expeditions, the summit of Kibo was completely enveloped by an ice cap from which a series of outlet glaciers cascaded in an unbroken arc extending from northwest to southeast across the western and southern slopes (Meyer, 1890a, 1891). In contrast, the glacier cover on the northeastern rim only descended a

few hundred meters. Excepting the inner cone, the entire caldera of Kibo was buried beneath glacier ice that flowed out through a breach in the western wall of the caldera to feed the glaciers on the southwestern slopes. By the turn of the century, there was no connection between the glaciers inside and outside the caldera, and the breakup of the Kibo ice cap was already underway (Meyer, 1900). Valuable photographic records, sketches, and summaries of the unabated 20th century glacier wastage have been made by Klute (1920), Gillman (1923), Nilsson (1931), Geilinger (1930, 1936) and Spink (1945, 1949). By 1957, the disintegration of the glaciers was so advanced that pessimism about the survival of the remaining 5 km² of glacier ice was being expressed (Humphries, 1959, 1972). Only small, isolated blocks of ice remained in the caldera, and although there was an unbroken ice cover across the northern caldera rim, it varied in thickness from 45 m on the east to 6 to 12 m on the west and was beginning to show signs of fragmentation. The glaciers of the southern and western slopes were still the most extensive, and the 2.4-km-long Great Penck Glacier descended to about 4,750 m in a narrow tongue bordered by 60-m-high Recent lateral moraines; by 1968, the lowest reach of the glacier had become detached at 5,000 to 5,200 m and was dead. Separation of the tongues of many of the other glaciers from their sources of supply and buried ice reflected their widespread state of fragmentation and stagnation. On the southern slopes, the glaciers had largely lost their individual snouts and were best grouped together as a Southern Ice Field. To the east, the Ratzel Glacier was reduced to several fragments and was disappearing rapidly.

Figure 6, a Landsat MSS color-composite image (2367-06582, 24 January 1976; Path 180, Row **62**), depicts a substantial cover of snow on the summit of Kibo at 0958 h local time and gives a false impression of the extent of the Northern Ice Field; there are also large snow patches on the western crags and pinnacles of Mawenzi. A more accurate summary of the glaciers is shown on figure 7 (Landsat MSS color-composite image; 2205-07000; Path 180, Row **62**), which was taken on the morning of 15 August 1975, midway through the main ablation period. Both the January 1976 and August 1975 images have their westward-facing slopes obscured by shadow. The 15 August 1975 image (fig. 7) permits delineation of many of the ice masses that have been mapped previously.

In the northeastern sector of the Kibo crater area, two notches in the ice cover are apparent, separating an unnamed small ice entity from both the Northern and Eastern Ice Fields. The remnant of the Ratzel Glacier (12) in the southern crater rim can be recognized, set apart from the great Southern Ice Field. Separate lobes of the four ice streams emanating from the Southern Ice Field can be distinguished, namely the Rebmann (11), Decken (10), Kersten (9), and Heim (8) Glaciers. A long rock rib, the so-called 'Wedge,' now separating the Rebmann (11) and Decken (10) Glaciers all the way to their snouts, can be delineated on the Landsat image. The Wedge gradually developed from an isolated rock outcrop at the end of the last century. Identification of ice entities in the area to the west is hampered by shading. The ice streams originating from the great Northern Ice Field, namely the Little Penck (4), Great Penck (3), Drygalski (2), and Credner (1) Glaciers, are all well depicted. The rock rib of the "Ravenstein," now separating the Little and Great Penck Glaciers to their snouts, can be clearly made out. An isolated rock outcrop existed here at the end of the last century. Separation of the ice streams by this rock rib was complete by the 1940's. The satellite image also permits recognition of a rock threshold in the lower portion of the Drygalski (2) Glacier. Embedded in the crater of Kibo, one notes the Furtwangler Glacier (7) and an extended snow field to the north of the Southern Ice Field.

In summary, disintegration of the Northern Ice Field and continuing disappearance of the long tongues of glacier ice on the northwestern slopes can be confirmed on the Landsat image (fig. 7). On the western slopes, the once continuous cover of vigorously active ice has been reduced to many fragments. To the south lies the Southern Ice Field, below which separated fragments of the former glacier tongues are stagnating. A sizable patch of snow flanks the minor southern scarps of the caldera that now contains virtually no glacier ice (fig. 8).

Figure 9 is an annotated Landsat 3 RBV image (30912-06495, subscene D; Path 180, Row 62) that was taken on the morning of 2 September 1980, a third of the way through the driest period of the year (August-October) on Kilimanjaro. It depicts very clearly the fragmented nature of the snow and ice cover on the summit of Kibo. For approximately the previous 5 months, the overhead midday sun has been to the north of the mountain, and therefore snow and ice on slopes with northerly exposures have been subjected to their maximum annual depletion as a result of direct solar radiation. Nonetheless, most of the 16 named glaciers and 3 ice fields on the image are snow covered, and snow alone accounts for an estimated 50 percent of this area of snow and ice. Immediately north of the Northern Ice Field, small patches of convectional cloud can be differentiated readily from the snow and ice surfaces because of the shadows that they cast. The summit area of Kibo is more open and covers a larger area in comparison to Mount Kenya, and thus it is easier to identify the individual glaciers on Kibo. These and the ice fields are noted on figure 9.

Glaciers of the Ruwenzori, Uganda and Zaire

The Ruwenzori are a 50-km-wide horst that straddles the Uganda/Zaire border and trends northwestward from the Equator for approximately 100 km. Subaerial erosion has carved out a network of deep valleys and individual mountains. Within the central area of the range, 25 peaks rise above 4,500 m, and the highest point is the Margherita peak on Mount Stanley, which is one of six mountains with a cover of glacier ice. A recent compilation by Hastenrath (1984; see fig. 10) lists 44 named glaciers, although the rapid wastage may alter, and in fact increase, this number.

The Ruwenzori may be the mythical snow-covered *Lunae Montes* where Aeschylus, Ptolemy, and Aristotle believed the Nile had its source (Filippi, 1909). Over the centuries, the mountains continued to be written about, appeared on maps, and were still being sought by 19th century explorers (Jeannel, 1950). The Ruwenzori may have been seen by Europeans as early as 1864, although it is generally agreed that Stanley was first to glimpse their snow-capped peaks in 1888 (Abruzzi, 1907). Photographs of the snow-covered western slopes taken in 1891 clearly depict glaciers that were not recognized (Stuhlmann, 1894), and the existence of glaciers was not documented until 1900 (Moore, 1901). Scientific work was subsequently initiated by the Duke of Abruzzi, whose 1906 expedition identified 30 glaciers and named 20 of them (Abruzzi, 1907; Filippi, 1909). No further investigation of the glaciers was made until the detailed survey of the Speke Glacier in 1949 (Menziés, 1951a,b). A series of small studies followed, which culminated in six expeditions mounted between 1958 and 1961 (Whittow 1959; Whittow and Shepherd, 1959; Osmaston 1961; and Whittow and others, 1963). By 1958, the 37 surviving glaciers had been seen, although some remained unnamed and unvisited. Observation of four of the main glaciers continued until 1967 (Temple, 1968); since that time there has been no substantial scientific work.

A 1:50,000-scale map of the peaks, passes, and glaciers of the Ruwenzori was produced during the 1906 expedition (Abruzzi, 1907); magnificent photographic panoramas of the peaks and glaciers were incorporated into the more detailed account of Filippi (1909). Busk (1954) discussed discrepancies between the photographs and the 1906 map. Stumpp (1952) produced a 1:25,000-scale map of the central peaks based on a 1937–38 terrestrial photogrammetric survey, but this Deutscher Alpenverein expedition excluded the glaciers on the Zaire side of the range. In 1958, a 1:50,000-scale map was published; this was followed in 1962 by a 1:25,000-scale map (reprinted 1970) of the central Ruwenzori that incorporated glaciological detail from the 1958–61 expeditions. These latter two maps, both based on aerial photogrammetry, are listed in table 1. Osmaston and Pasteur (1972) published sketch maps of the peaks.

Livingstone (1962, 1967) suggested that the most recent deglaciation of the Ruwenzori began $14,700 \pm 290$ years B.P., on the basis of a C^{14} date obtained for basal sediments extracted from a kettle lake lying inside massive moraines about 10 km from the contemporary glaciers on Mount Baker. The glaciers, which Nilsson (1931) estimated had locally extended across at least 100 km², have now retreated vertically through 2,400 m from these moraines (Livingstone, 1975).

The Ruwenzori are by far the cloudiest and wettest of all east African mountains. Precipitation is common all year round, with maxima around March–May and September–October. At about 4,300 m, a net accumulation of snow has been reported for these wetter times of the year. Maximum ablation occurs in January–February and June–August (Bergstrom, 1953; Temple, 1968). Livingstone (1967) believes that the western slopes of the Ruwenzori are wetter, but there is little observational evidence on the precipitation distribution in the peak regions; for the eastern slopes, the following annual precipitation totals are given: 1,140 mm at 1,220 m, 2,280 mm at 1,830 m, 2,540 mm at 3,050 m, and above that level values ranging between 1,910 and 2,790 mm. An altitudinal belt of maximum precipitation and daily circulation patterns, if existing at all, is certainly less well developed than on Kilimanjaro and Mount Kenya. The persistent cloud cover must be regarded as a major factor in controlling the diurnal heat budget and hence mountain-valley wind systems. It is interesting that east-west asymmetries in ice extent are less well developed than on Kilimanjaro and Mount Kenya. A further feature of this perennially wet environment is the proximity of glaciers and lush vegetation on the Ruwenzori, compared with Kilimanjaro, where a wide belt having a desertic appearance separates the dense tropical rain forest from the realm of perennial ice. The abundant precipitation and considerable cloud protection are conducive to the development and survival of glaciers on the Ruwenzori. The atmospheric conditions have also prevented acquisition of any usable Landsat images from 1972 to 1985 (see section entitled “Landsat Images” and table 3), although many of the glaciers that presently exist on the six glacierized mountain massifs of the Ruwenzori have dimensions large enough to be discerned on Landsat images.

In 1906, the glaciers were retreating rapidly from adjacent moraines (Abruzzi, 1907; Filippi 1909). Despite unabated 20th century wastage, the glaciers were considered by Spink (1949) to be in a healthier state than those on Mount Kenya and Kilimanjaro. This was confirmed by the glaciologist Bergstrom, who suggested that the loss of glacier ice had not been as catastrophic as had been commonly portrayed. Whittow and others (1963) estimated that the glacier cover was approximately 5 km², with 2 km² on Mount Stanley, 1.62 km² on Mount Speke, 0.67 km² on Mount Baker, 0.25 km² on Mount Gessi, 0.08 km² on Mount Emin, and 0.04 km² on Mount Luigi di Savoia. The Vittorio Emanuele and Speke

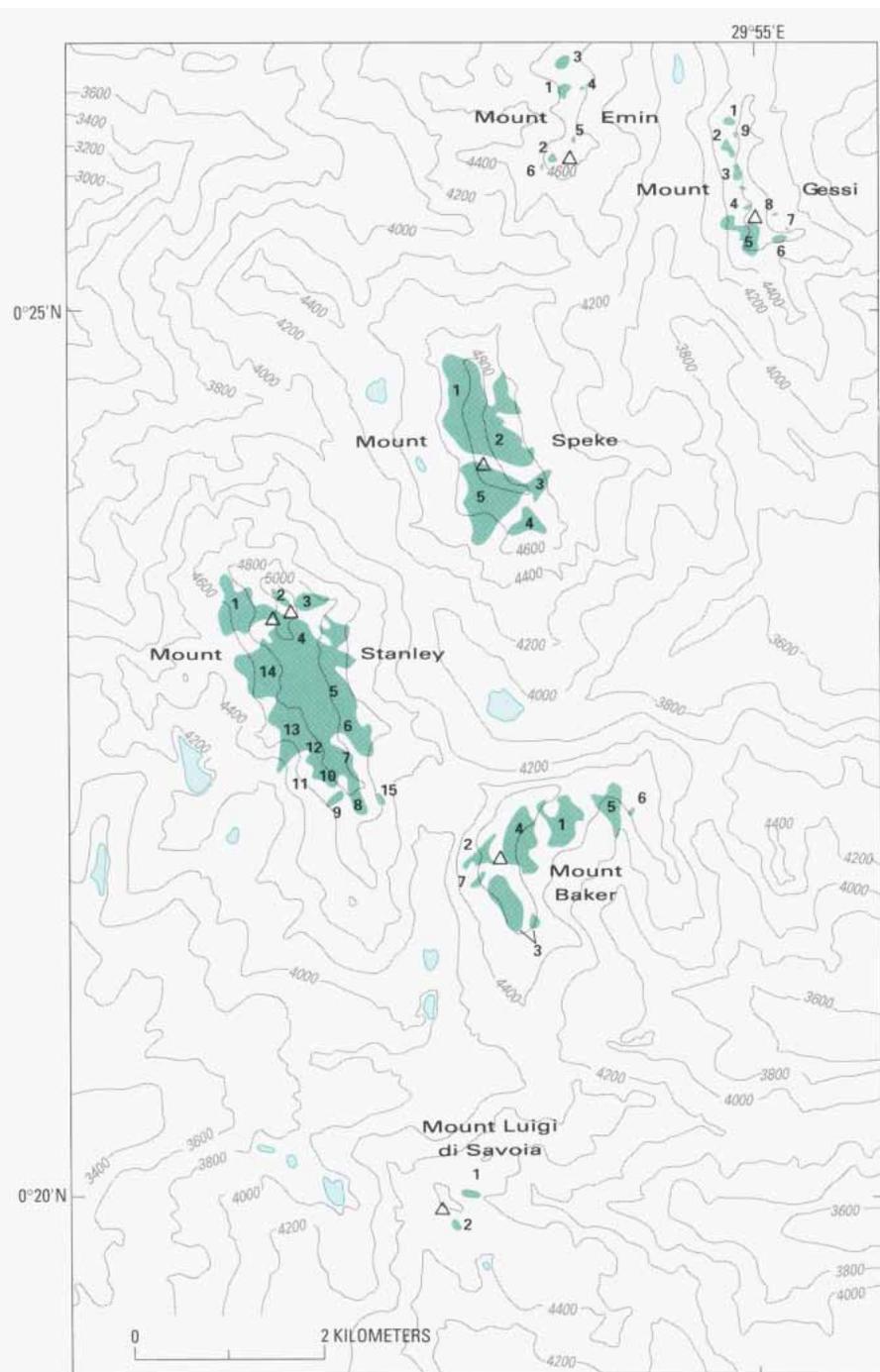
Figure 10.—The peaks (triangles), glacial lakes (blue), and glaciers (green) of the Ruwenzori (modified from Map 4.2:1 in Hastenrath, 1984); data compiled by Hastenrath from maps, photographs, and field observations, and Whittow and others (1963), Temple (1968), and Osmaston and Pasteur (1972). Names of glaciers in the explanation are keyed to numbers on each mountain. Contour interval 200 m.

EXPLANATION

List of names of glaciers
on six peaks in the Ruwenzori

- Mount Emin** 4802 meters
- 1 Kraepelin 1
Umberto (disappeared after 1906)
 - 2 Emin 1
 - 3 North Kraepelin
 - 4 Kraepelin 2
 - 5 Emin2
 - 6 Emin3
one unnamed (disappeared after 1906)
- Mount Gessi** 4769 meters
- 1 Gessi 1
 - 2 Gessi 2
 - 3 Gessi 3
 - 4 Gessi 4
 - 5 Iolanda 1
 - 6 Iolanda 2
 - 7 Iolanda 3
 - 8 Iolanda 4
 - 9 Gessi 0
- Mount Speke** 4891 meters
- 1 Grant
 - 2 Vittorio Emanuele
 - 3 East Johnston
 - 4 Johnston
 - 5 Speke
- Mount Stanley** 5111 meters
- 1 Alexandra
 - 2 Albert
 - 3 Northeast Margherita
 - 4 Margherita
 - 5 East Stanley
 - 6 Elena
 - 7 Coronation
 - 8 Savoia
 - 9 Philip
 - 10 Elizabeth
 - 11 West Elena
 - 12 West Savoia
 - 13 Moebius
 - 14 West Stanley
 - 15 unnamed
- Mount Baker** 4873 meters
- 1 East Baker
 - 2 Y Glacier
 - 3 Edward 1
 - 3 Edward 2
 - 4 West Baker
 - 5 Moore (Mubuku)
 - 6 Wollaston
 - 7 Edward 3
Semper (disappeared after 1943)
- Mount Luigi di Savoia** 4665 meters
- 1 Thomson 1
 - 2 Thornson2
Sella (disappeared after 1906)
Stairs (disappeared after 1906)

Glaciers (fig. 10) were the largest individual glaciers and covered 0.48 km² and 0.375 km², respectively. Few of the glaciers had active valley tongues, and most were either cirque glaciers or part of the summit ice caps. On the lower Mounts Emin, Gessi, and Luigi di Savoia, the glaciers were disappearing rapidly. Regular observations on the Speke, Elena, Savoia, and Moore Glaciers were maintained until 1967; these observations disclosed evidence of minor, nonsynchronous readvances in an overall pattern of clear and even spectacular retreat (Temple, 1968). During a brief visit in 1974, it was estimated that the Speke Glacier had retreated 30 to 40 m and shrunk laterally by 10 to 20 m since 1958 (Hastenrath, 1975).



Imaging of African Glaciers

Aerial Photographs

In all three mountain areas, Mount Kenya, Kilimanjaro, and the Ruwenzori, a variety of ground photographs has been taken by numerous travelers since the end of the last century (Mercer, 1967; Hastenrath, 1984). Evaluation of these pictures and of various oblique aerial photographs in conjunction with other historical sources provides a time-lapse record of a drastic recession of Africa's glaciers that continues to the present (Hastenrath, 1975, 1984). The official topographic maps noted in table 1 are all based on vertical aerial photographs, the first of which were not acquired until 1947. Table 2 provides a list of this vertical aerial photographic coverage. In conjunction with topographic maps and direct field observations, these aerial photographs have proven to be most useful in mapping the modern extent of glaciers in the three areas (Hastenrath, 1975, 1984).

TABLE 2. – *Selected aerial photographs for the presently glacierized areas of Africa*

Date	Mission	Frame numbers
Mount Kenya, Kenya		
14 February 1947	V 13A/RAF/14	5063–5098, 5114–5135, 5140–5153, and 5170–5171
21 February 1947	V 13A/RAF/20	5104–5119, 5129–5138, and 5154–5163
29 January 1963.....	13B/RAF/341	74–76
10 February 1967	VI 3B/RAF/627	60–62
Kilimanjaro, Tanzania		
13 February 1957	V 13A/595	24–30
25 February 1958	V 13A/RAF/686	80–85
2 March 1958.....	13A/RAF/688	9–19, 55–63, and 99–108
The Ruwenzori, Uganda and Zaire		
June 1955	15 UG 13	10–27 and 40–51
June 1955	15 UG 14	8–20
24 September 1955...	15 UG 33	15–26
20 October 1955.....	15 UG 31	5–13 and 21–29

Landsat Images

Figure 11 is an index map showing the nominal scene centers and evaluation of the optimum Landsat images available for the three presently glacierized areas in Africa: Mount Kenya (one useful MSS image and a Landsat 3 RBV subscene), Kilimanjaro (two useful MSS images and a Landsat 3 RBV subscene), and the Ruwenzori (no usable image). Table 3 provides more-detailed information on each of the optimum Landsat images. Landsat imagery has provided some information on the glaciers of Africa, but the limited number of usable images, the spatial resolution of the Landsat MSS and RBV sensors compared with the small size of these glaciers, and the frequent cloud cover in the high peaks have restricted the usefulness of this remote sensing tool. However, digital processing of Landsat computer compatible tapes (CCT's), such as the research by Ian Allison and James Peterson on the "Glaciers of Irian Jaya, Indonesia" (see Chapter H–1 of this Professional Paper), has proven valuable in the study of small tropical glaciers. If, in the next decades, spaceborne sensors with greater spatial resolution and

TABLE 3.--*Optimum Landsat 1,2, and 3 images of the glaciers of Africa*
 [Explanation of symbols used in the "Code" column is provided on figure 11]

Path-Row	Nominal scene center (lat-long)	Landsat identification number	Date	solar elevation angle (degrees)	Code	Cloud cover (in percent)	Remarks
180-60	00°00' 37°47'E.	2367-06573	24 Jan 76	45	●	0	Mount Kenya; color composite available
180-60	00°00' 37°47'E.	30912-06490-C	02 Sep 80	49	●	0	Mount Kenya; Landsat 3 RBV
180-62	02°53'S. 37°07'E.	2205-07000	15 Aug 75	47	●	0	Kilimanjaro; minimum snow; color composite available
180-62	02°53'S. 37°07'E.	2367-06582	24 Jan 76	46	●	0	Kilimanjaro; excessive snow; color composite available
180-62	02°53'S. 37°07'E.	30912-06495-D	02 Sep 80	48	●	0	Kilimanjaro; Landsat 3 RBV
185-60	00°00' 30°37'E.				◐		Ruwenzori
186-60	00°00' 29°11'E.				◐		Ruwenzori

cloud penetrating ability become available to the civilian research community, the usefulness of satellite remote sensing of small tropical glaciers will be greatly improved. Until data are available from much-improved satellite sensing systems that are specially designed for photogrammetric surveys, such as the Large Format Camera (LFC) and the French Système Probatoire d'Observation de la Terre (SPOT), conventional aerial photogrammetry and field work will remain the mainstay of glaciological research on small glaciers in the tropics and other regions.

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