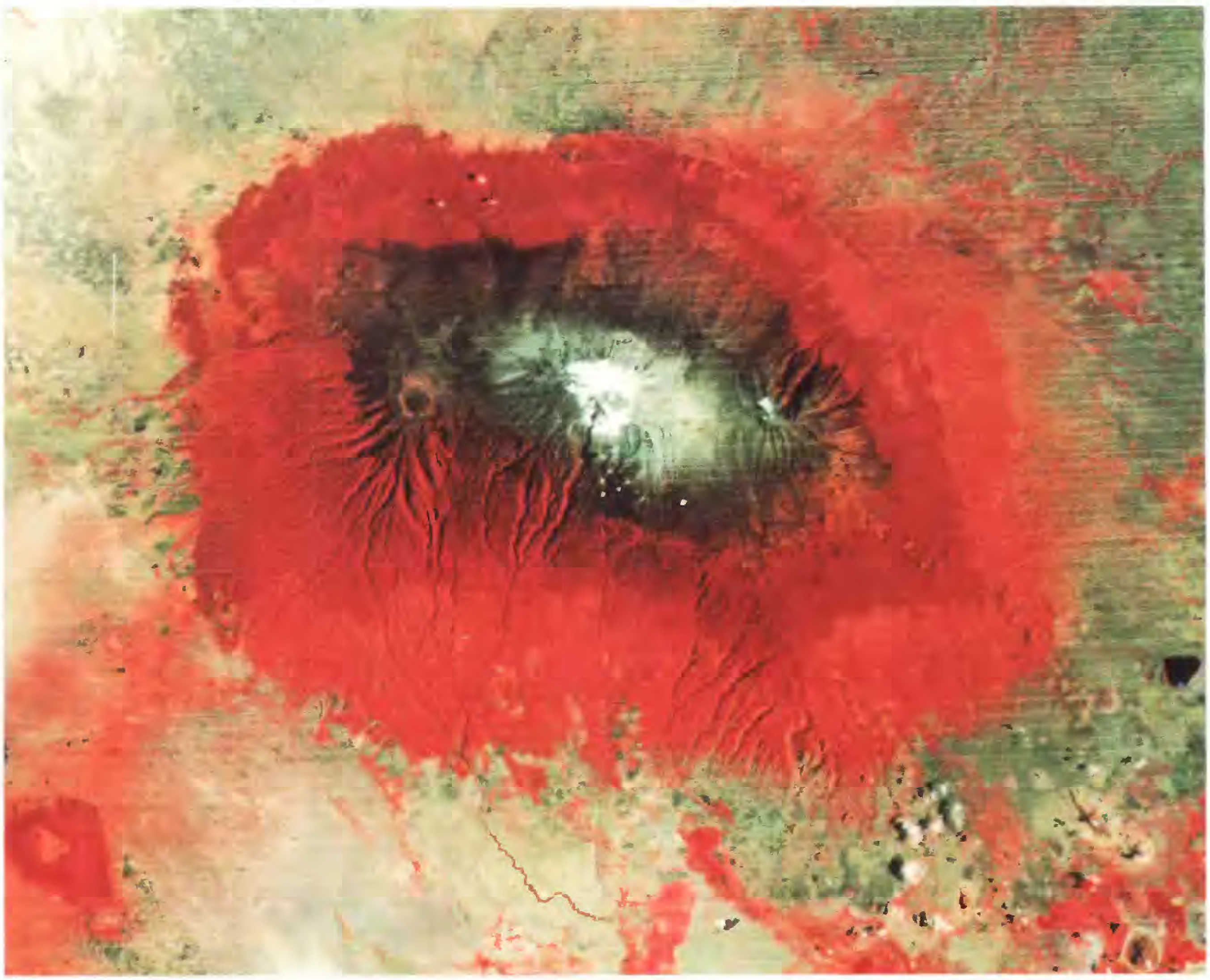
Satellite Image Atlas of Glaciers of the World

MIDDLE EAST and AFRICA



United States Geological Survey
Professional Paper 1386–G

An enlargement of a Landsat MSS color-composite image of Kilimanjaro and Mount Meru showing vegetation belts and the distribution of glaciers. See text page G59.

Cover design by Lynn Hulett.

Glaciers of the Middle East and Africa—

G–1. GLACIERS OF TURKEY
By AJUN KURTER

G–2. GLACIERS OF IRAN
By JANE G. FERRIGNO

G–3. GLACIERS OF AFRICA
By JAMES A.T. YOUNG *and* STEFAN HASTENRATH

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

Edited by RICHARD S. WILLIAMS, Jr., *and* JANE G. FERRIGNO

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1386–G

Landsat images, in conjunction with aerial photographs, maps, and field measurements, were used to locate and describe the areal distribution of and changes in glaciers in Turkey, Iran, and Africa

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1991

U.S. DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, Jr., *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publication Data

(Revised for volume G)
Satellite image atlas of glaciers of the world.
(U.S. Geological survey professional paper ; 1386)
Includes bibliographies.
Supt. of Docs. no. : I 19.16:1386–G
Contents: B. Antarctica / by Charles Swithinbank; with sections on The dry valleys of Victoria Land, by Trevor J. Chinn, and Landsat images of Antarctica, by Richard S. Williams, Jr., and Jane G. Ferrigno — ch. G. Glaciers of the Middle East and Africa. Glaciers of Turkey / by Ajun Kurter. Glaciers of Iran / by Jane G. Ferrigno. Glaciers of Africa / by James A.T. Young and Stefan Hastenrath.
1. Glaciers—Remote sensing. I. Williams, Richard S. II. Ferrigno, Jane G. III. Series: Geological Survey professional paper ; 1386.
GB2401.72.R42S28 1988 551.3′12 87–600497

For sale by the Books and Open-File Reports Section, U.S. Geological Survey, Federal Center, Box 25425, Denver, CO 80225

Foreword

On 23 July 1972, the first Earth Resources Technology Satellite (ERTS 1 or Landsat 1) was successfully placed in orbit. The success of Landsat inaugurated a new era in satisfying mankind's desire to better understand the dynamic world upon which we live. Space-based observations have now become an essential means for monitoring global change.

The short- and long-term cumulative effects of processes that cause significant changes on the Earth's surface can be documented and studied by repetitive Landsat images. Such images provide a permanent historical record of the surface of our planet; they also make possible comparative two-dimensional measurements of change over time. This Professional Paper demonstrates the importance of the application of Landsat images to global studies by using them to determine the current distribution of glaciers on our planet. As images become available from future satellites, the new data will be used to document global changes in glacier extent by reference to the image record of the 1970's.

Although many geological processes take centuries or even millenia to produce obvious changes on the Earth's surface, other geological phenomena, such as glaciers and volcanoes, cause noticeable changes over shorter periods. Some of these phenomena can have a worldwide impact and often are interrelated. Explosive volcanic eruptions can produce dramatic effects on the global climate. Natural or culturally induced processes can cause global climatic cooling or warming. Glaciers respond to such warming or cooling periods by decreasing or increasing in size, thereby causing sea level to rise or fall.

As our understanding of the interrelationship of global processes improves and our ability to assess changes caused by these processes develops further, we will learn how to use indicators of global change, such as glacier variation, to more wisely manage the use of our finite land and water resources. This Professional Paper is an excellent example of the way in which we can use technology to provide needed earth-science information about our planet. The international collaboration represented by this report is also an excellent model for the kind of cooperation that scientists will increasingly find necessary in the future in order to solve important earth-science problems on a global basis.

Dallas L. Peck
Director,
U.S. Geological Survey

Preface

This chapter, consisting of three independently authored subchapters, is the third to be released in U.S. Geological Survey Professional Paper 1386, Satellite Image Atlas of Glaciers of the World, a series of 11 chapters. In each chapter, remotely sensed images, primarily from the Landsat 1, 2, and 3 series of spacecraft, are used to study the glacierized regions of our planet and monitor glacier changes. Landsat images, acquired primarily during the middle to late 1970's, were used by an international team of glaciologists and other scientists to study various geographic areas or discuss glaciological topics. In each geographic area the present areal distribution of glaciers was compared, where possible, with historical information about their past extent. The atlas provides an accurate regional inventory of the areal extent of glacier ice on our planet during the 1970's as part of a growing international scientific effort to measure global change on the Earth's surface.

In Turkey, present-day glaciers are found in the higher elevations of the Eastern Black Sea Coastal Range, in the Middle and Southeastern Taurus Mountains, and on Mounts Erciyas, Süphan, and Ağrı. The total glacier area is estimated to be 22.9 km^2. The southeastern Taurus Mountains have the most glaciers. Modern maps, aerial photographs, and Landsat images are used to document the distribution of glaciers in Turkey, although the spatial resolution of the sensors limits the use of Landsat images to the largest glaciers.

In Iran, glaciers occur in the Elburz Mountains, the Zagros Mountains, and Kūhhā-ye Sabālan. The total glacier area is estimated to be 20 km^2. The largest concentration of glaciers is on the Takht-e Sulaiman massif of the Elburz Mountains. One of the glaciers, Sarchal, is about 7 km long. Five glaciers are present in the Zagros Mountains. Seven glaciers are located on Kūhhā-ye Sabālan. Because of the small size of the glaciers in Iran, Landsat images have only limited usefulness.

In Africa, glaciers are presently limited to two volcanoes, Mount Kenya in Kenya and Kilimanjaro in Tanzania, and one massif, the Ruwenzori, on the border between Uganda and Zaire. Mount Kenya has 11 cirque and valley glaciers totaling 0.7 km^2 in area. Kilimanjaro has 16 named glaciers and 3 ice fields in the Kibo caldera that total 5 km^2 in area. The total glacier area in Africa is 10.7 km^2. No Landsat data were acquired of the Ruwenzori because of persistent cloud cover. Landsat 3 return beam vidicon (RBV) camera images were acceptable for documenting glacier area on the two volcanoes, but vertical aerial photographs combined with field surveys remain the most effective means of monitoring areal changes in the glaciers of Africa. Availability of high-resolution satellite images or photographs would obviate the need for vertical aerial photographs.

Richard S. Williams, Jr.

Jane G. Ferrigno,

Editors

About this Volume

U.S. Geological Survey Professional Paper 1386, Satellite Image Atlas of Glaciers of the World, contains eleven chapters designated by the letters A through K. Chapter A is a general chapter containing introductory material and a discussion of the physical characteristics, classification, and global distribution of glaciers. The next nine chapters, B through J, are arranged geographically and present glaciological information from Landsat and other sources of data on each of the geographic areas. Chapter B covers Antarctica; Chapter C, Greenland; Chapter D, Iceland; Chapter E, Continental Europe (except for the European part of the Soviet Union), including the Alps, the Pyrenees, Norway, Sweden, Svalbard (Norway), and Jan Mayen (Norway); Chapter F, Asia, including the European part of the Soviet Union, China (P.R.C.), India, Nepal, Afghanistan, and Pakistan; Chapter G, Turkey, Iran, and Africa; Chapter H, Irian Jaya (Indonesia) and New Zealand; Chapter I, South America; and Chapter J, North America. The final chapter, K, is a topically oriented chapter that presents related glaciological topics.

The realization that one element of the Earth's cryosphere, its glaciers, was amenable to global inventorying and monitoring with Landsat images led to the decision, in late 1979, to prepare this Professional Paper, in which Landsat 1, 2, and 3 multispectral scanner (MSS) and Landsat 2 and 3 return beam vidicon (RBV) images would be used to inventory the areal occurrence of glacier ice on our planet within the boundaries of the spacecraft's coverage (between about 81° north and south latitudes). Through identification and analysis of optimum Landsat images of the glacierized areas of the Earth during the first decade of the Landsat era, a global benchmark could be established for determining the areal extent of glaciers during a relatively narrow time interval (1972 to 1982). This global "snapshot" of glacier extent could then be used for comparative analysis with previously published maps and aerial photographs and with new maps, satellite images, and aerial photographs to determine the areal fluctuation of glaciers in response to natural or culturally induced changes in the Earth's climate.

To accomplish this objective, the editors selected optimum Landsat images of each of the glacierized regions of our planet from the Landsat image data base at the EROS Data Center in Sioux Falls, S. Dak., although some images were also obtained from the Landsat image archives maintained by the Canada Centre for Remote Sensing, Ottawa, Ontario, Canada, and by the European Space Agency in Kiruna, Sweden, and Fucino, Italy. Between 1979 and 1981, these optimum images were distributed to an international team of more than 50 scientists who agreed to author a section of the Professional Paper concerning either a geographic area or a glaciological topic. In addition to analyzing images of a specific geographic area, each author was also asked to summarize up-to-date information about the glaciers within the area and to compare their present areal distribution with historical information (for example, from published maps, reports, and photographs) about their past extent. Completion of this atlas will provide an accurate regional inventory of the areal extent of glaciers on our planet during the 1970's.

Richard S. Williams, Jr.
Jane G. Ferrigno,
Editors

CONTENTS

Glaciers of the Middle East and Africa—

GLACIERS OF TURKEY

By AJUN KURTER

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

Edited by RICHARD S. WILLIAMS, Jr., *and* JANE G. FERRIGNO

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1386–G–1

The glaciers of Turkey have a total area of 22.9 km² and are located on three mountain ranges and three stratovolcanoes; documentation is provided by maps, aerial photographs, and Landsat images

CONTENTS

GLACIERS OF THE MIDDLE EAST AND AFRICA—

GLACIERS OF TURKEY

By AJUN KURTER[1]

Abstract

Glaciers currently occur in Turkey in the higher elevations of the coastal ranges along the southeastern shore of the Black Sea, in the Middle and Southeastern Taurus Mountains, and on Mounts Erciyes, Süphan, and Ağrı. The total area of the glaciers is estimated to be 22.9 square kilometers, with the greatest concentration occurring in the Southeastern Taurus Mountains. Although a few early glacier studies were carried out just after 1900, modern scientific studies of the glaciers of Turkey did not begin until the 1930's. Precise, reliable modern topographic maps at scales of 1:100,000 and 1:25,000 have become available during the last 30 years. Complete aerial photographic coverage of Turkey has been acquired at 1:35,000 and 1:20,000 scales, but the photographs have limited usability for glacier research because they often contain too much snow cover and there is little repetitive coverage. Landsat imagery can be used for repetitive coverage of the glaciers of Turkey, but the spatial resolution restricts its use to the largest glaciers.

General Introduction

The areas of present glaciation in the Middle East are situated in the northern part of the region and include various types and sizes of glaciers in Turkey and Iran. The primary reasons for this distribution are (1) the decrease in the elevation of the snowline from south to north and (2) the presence of high mountains within these two countries that rise above the snowline altitude. In addition to the prevailing climatic conditions (for example, temperature, wind direction, precipitation), orographic factors, such as slope orientation and degree of landform dissection, are also favorable. By contrast, in the southern part of the Sinai Peninsula of Egypt, which also is a mountainous area, the snowline elevation lies above Mount Sinai (2,287 m), the highest peak in the region. Only during the Pleistocene was the snowline depressed enough to support glaciers in the southern Sinai Peninsula. Neither Syria nor Iraq has high enough mountains or climatic conditions suitable for formation of glaciers. In Lebanon, which is bordered on the west by the eastern Mediterranean Sea, a somewhat different situation exists. Elevations reach above 3,000 m in the Lebanon and Anti-Lebanon Mountains. Although the elevations are below the present snowline (about 3,700 m), there are occasional perennial snow patches at elevations that exceed 3,000 m. During the Würm glacial stage of the Pleistocene, even though the snowline dropped approximately 1,000 m to below 2,700 m, glaciation in this part of the Middle East was not fully developed because of orographic conditions and the degree of landform dissection (Klaer, 1957).

High mountain areas encompass parts of Turkey and Iran. The highest elevation in the Elburz Mountains in northern Iran is 5,670 m on

Manuscript approved for publication May 20, 1988.

[1] Institute of Marine Sciences and Geography, University of Istanbul, Istanbul, Turkey.

Damāvand. The summit of Kūhhā-ye Sabālan, approximately 135 km east of Tabriz, Iran, has an elevation of 4,740 m. Here, the elevation of the snowline has been calculated to be about 4,500 m, so these high mountain systems support small glaciers. The eastern half of Turkey also is a suitable area for the development of glaciers of different sizes and types because of the climate and altitude. Information on the glaciers of Turkey will be given in this section. The glaciers of Iran will be discussed separately in the next section.

Occurrence of Glaciers

Turkey, located between latitudes 36° and 42° N., exhibits different topographic and climatic features from west to east as well as from the coastal to interior regions. For example, high mountain chains extending parallel to the northern and southern coasts prevent penetration of moist air masses to the interior plains and plateaus. Although the elevation of Turkey's interior is considerable, the highest terrain is located in the central and eastern parts, especially in association with the many extinct or dormant volcanoes. Toward the east, different mountain ranges converge to produce a region of increasing elevation. The highest extinct volcanoes are also located in this region. The degree of continentality increases with distance from the coast. Temperature rises toward the interior, while the simultaneous increase in continentality results in lower precipitation toward the east. On the other hand, humid air masses that move over the region during the winter months produce precipitation that exceeds 2 m in the higher elevations. There are a few glaciers on the summits of coastal mountains that have elevations above the snowline. Well-developed glacierization and long valley glaciers are nonexistent in these coastal ranges, however, because of the increased elevation of the snowline, high degree of erosional dissection, and small number of peaks that are above the snowline. Toward the eastern part of Turkey, the elevation of the snowline increases in association with continentality, so that the glaciation in this region seems to be less well developed. The southeastern part of the Toros Dağları (Taurus Mountains)[2] is the foremost glacierized area. Some valley glaciers in this region are 4 km in length (table 1). Ağrı Dağı (Mount Ağrı, or Mount Ararat), near the eastern border, has an elevation of 5,137 m. It is covered with an ice cap that has an area of 10.0 km^2, the largest single glacier in Turkey. Thus, one can say that glaciation in Turkey is developed for the most part in the eastern part of the country (fig. 1). Although no comprehensive studies on glaciation in Turkey have been carried out, in the limited studies that have been done, most scientists have reached similar conclusions. The studies have found some traces of evidence about glaciation in earlier glacial periods, especially Riss. It has also been concluded that extensive glaciation occurred at the beginning of the Würm. In fact, the snowline was at least 1,000 m lower than at present. As a result, valley glaciers developed, descending to an elevation of 2,000 m. Cirque glaciers and small valley glaciers formed on mountains that do not have glaciers today. However, this glaciation disappeared after the end of Würm II. In other words, the present glaciation cannot be considered to be a continuation of the Pleistocene glaciation. During the postglacial interval

[2] The geographic names used in this subchapter are from the Gazetteer of Turkey (U.S. Board on Geographic Names, 1984), the New Atlas of Turkey (Harita Genel Müdürlürlüğü, 1977), and the author.

of warm temperatures, glaciers probably existed only on one or two of the highest mountains. Other glaciers regenerated within historic times (B.C. 2200–1800), and, during this period, the area covered with glaciers is estimated to have been twice the present one. Beginning with the second half of the 19th century, a glacier recession began. In conclusion, one can say that glaciers in Turkey have been subjected to many fluctuations in position of termini and areal extent since the end of the Pleistocene Epoch.

TABLE 1.—*Principal glaciers of Turkey (after Kurter and Sungur, 1980)*

Name of mountain range	Name of mountain or peak	Elevation of mountain or peak (m)	Location (latitude and longitude)	Named glacier(s) (informal names shown in quotation marks)	Type of glacier	Area of glacier(s) (km^2)	Mean length of glacier (km)
Giresun Mountains	Mount Karagöl	3,107	40°30′–40°32′N. 38°08′–38°13′E.	"Northwest"	Mountain	0.08	0.4
Gavur Mountains	Mount Aptalmusa	3,331	40°22′–40°26′N. 39°02′–39°07′E.	Avlıyana	Mountain	.045	.15
Eastern Black Sea Mountains	Varşanba Peak (Mount Verçenik)	3,710	40°40′–40°46′N. 40°54′–41°05′E.	Sinançor and Varşanba Tepe	Valley	.14	.7
Eastern Black Sea Mountains	Mount Kaçkar	3,932	40°50′–41°00′N. 41°08′–41°20′E.	Kaçkar I, II, III, and Krenek II	Valley	.06	.3
Middle Taurus Mountains Bolkar Mountains	Mount Medetsiz	3,524	37°26′–37°33′N. 34°36′–34°50′E.	"North"	Mountain	.06	.3
Middle Taurus Mountains Ala Mountains	Mount Demirkazık	3,756	37°41′–37°55′N. 35°02′–35°16′E.	Lolut	Valley	.5	1.0
Southeastern Taurus Mountains Buzul (Cilo) Mountains	Mount Uludoruk (Reşko)	4,135	37°26′–37°32′N. 43°56′–44°04′E.	Uludoruk and and Mia Havara	Valley	8.0	4.0
Southeastern Taurus Mountains İkiyaka (Sat) Mountains	Mount Dolampar	3,794	37°18′–37°24′N. 44°10′–44°20′E.	Geverok	Valley	.8	1.0
Kavuşşahap Mountains	Mount Hasanbeşir	3,503	38°12′–38°16′N. 42°48′–42°54′E.	"Northwest"	Mountain	.06	.3
	Mount Erciyes	3,917	38°31′–38°34′N. 35°24′–35°28′E.	"Northwest"	Valley	.11	.55
	Mount Süphan	4,058	38°53′–38°55′N. 42°47′–42°52′E.	"South"	Mountain (crater)	3.0	1.5
	Mount Ağrı	5,137	39°41′–39°44′N. 44°15′–44°19′E.		Ice cap	10.0	–
					Total:	22.9	

34°
36°
38°
42°
40°
38°
36°
BLACK SEA
Ordu
Giresun
Giresun Mountains
Mount Karagöl
(3107m)
Mount Aptalmusa
(3331m)
Fig. 3
Path 188–Row 33
Salt Lake
Kayseri
Mount Erciyes
(3917m)
Fig. 9
Path 189–Row 34
Demirkazık Peak
(3756 m)
Ala Mountains
Medetsiz Peak
(3524 m)
Bolkar Mountains
Middle Taurus Mountains
Fig. 5
Eastern
Euphrates
(Firat)
MEDITERRANEAN SEA
0
100
SYRIA

Figure 1.—*Mountain ranges, dormant stratovolcanoes, and the coverage by Landsat images of the glacierized regions discussed in the text.*

Observations of Glaciers

Historical Studies

From a historical viewpoint, published references to glaciers in Turkey are not very old or extensive. Although the presence of glaciers in the southeastern part of the Taurus Mountains was noted in 1842 (Ainsworth, 1842), and similar observations were made in the Doğukaradeniz Dağları (Eastern Black Sea Mountains) (Koch, 1846; Palgrave, 1872), the scientific study of the glaciers of Turkey did not begin until the 20th century. Maunsell (1901) studied glaciers in the Buzul Dağı (Buzul, or Cilo, Mountains) in the Güneydoğu Toroslar (Southeastern Taurus Mountains) in 1901; Penther (1905) studied glaciers on Erciyes Dağı (Mount Erciyes) in 1902. Penther's photograph of one of these glaciers is the oldest known photograph of a glacier in Turkey. Philippson (1906) published an article on this same glacier on Mount Erciyes. However, these initial studies were not followed by additional ones in other glacierized areas of the country. As a matter of fact, after these studies were completed, there was a lengthy hiatus before additional glacier studies were again carried out in Turkey.

Modern Studies

In a real sense, scientific studies on glaciers in Turkey began during the 1930's. During those years additional glacierized areas were discovered. In 1927, Künne (1928) visited the Aladağ (Ala Mountains). During the same year, Stratil-Sauer (1927) studied the Eastern Black Sea Mountains. However, the most remarkable studies in these regions were made by Krenek (1932) and Leutelt (1935). During that period Bartsch (1935) studied the Erciyes Glacier. At the beginning of World War II, Bobek (1940) made an exhaustive study of glaciers in the Buzul Mountains of the Southeastern Taurus Mountains that included good photographic documentation of the glaciers. Bobek's work was the first in which the glaciated areas of Turkey were studied in the context of the Pleistocene. No other detailed studies were made during World War II, with the exception of the general study by Louis (1944). In the years following World War II, Turkish geographers began to play a more active role in glacial studies. In particular, the research by Erinç is recognized as that of the pioneer Turkish glaciologist, with his very detailed studies of Turkey's glaciers (Erinç, 1949a,b, 1951, 1952b, 1953), including the discovery of glaciers on Kaçkar Dağı (Mount Kaçkar) (Erinç, 1949b) and on Süphan Dağı (Mount Süphan). He also made valuable contributions in his studies of variations in snowline altitudes (Erinç, 1952a). Glaciers in the Buzul Mountains were also studied by İzbırak (1951), another Turkish scientist, who was active at the same time. By the 1960's, foreign scientists became more and more interested in the glaciers discovered previously in Turkey. For example, Klaer (1962, 1965, 1969) studied glaciers on Mount Erciyes, Mount Süphan, the Ala Mountains, and the Bolkar Dağları (Bolkar Mountains). Wright (1962) investigated glaciers in the Buzul Mountains. Blumenthal (1938, 1952, 1954, 1955, 1956, 1958) studied glaciers in the Ala Mountains, on Mount Kaçkar, and on Mount Ağrı. Gall (1966) studied glaciers on Varşanba Peak (Mount Verçenik), or Dilek Peak, and Mount Kaçkar. Loffler (1970) investigated glaciers on Mount Verçenik, Mount Kaçkar, and in other parts of the Eastern Black Sea Mountains. Spreitzer (1939, 1956, 1958, 1959, 1971) carried out studies of glaciers on Mount Süphan and in the Ala Mountains. Stratil-Sauer, who initially carried out investigations in the Eastern Black Sea Mountains (1927), continued his studies of Pleistocene glaciation and small modern glaciers in the western part of these ranges (1961, 1964, 1965). Imhof (1956), Ivan'kov (1959), and Arkel (1973) conducted studies of glaciers on Mount Ağrı. In addition, Louis (1938, 1944), Messerli (1964, 1967), and Birman (1968), made observations and published papers about the glacierized areas of Turkey. Birman (1968) also endeavored to conduct a reconnaissance survey of the glacial geology and glaciers of the entire country. Horvath (1975) reviewed the glaciers of Turkey as part of a discussion of the area including Turkey, Armenian S.S.R., and Iran.

Mapping of Glaciers

The Earliest Maps of Glaciers

During the 19th century, accurate large-scale or small-scale maps were not available for glacier studies in Turkey. For this reason, from the middle to the end of the 19th century, all of the scientists who carried out field studies in Turkey had to produce their own base maps. This situation prevailed until the beginning of the 20th century. In the years preceding World War I, maps, such as those made by the German cartographer Kiepert, in which relief features were shown by hachures, became available but were filled with numerous errors (Philippson, 1918). Maps made of the southeastern part of the country at a scale of 1:400,000 by German cartographers and at a scale of 1:250,000 by British mapmakers during this period were used by many explorers after World War I. For example, Bobek (1940) made use of these maps in his glacial studies in the Buzul Mountains and in the İkiyaka (Sat) Dağları (İkiyaka, or Sat, Mountains). However, there is no information about glaciers on the aforementioned maps.

In summary, for glacial geology and glacier studies in Turkey until the beginning of World War II, explorers had to use very small scale maps. These maps did not show any glaciers and also provided erroneous information about peaks, valleys, and landforms, in general. As a result, scientists made many errors on sketch maps of glaciers.

Modern Maps of Glaciers

In the years following World War II, as greater interest was shown in glaciological research, scientists involved in such studies were more fortunate because of the availability of more reliable topographic maps. A 1:200,000-scale topographical map series of Turkey in which contour intervals are shown at 50-m intervals was completed by this time. Unfortunately, topographic maps in this series do not contain correct information on either elevations or geographic place-names. Hence, scientists who used the 1:200,000-scale topographic maps noted that there were inconsistencies in place-names used by earlier explorers and place-names shown on more recently published maps (Gall, 1966; Löffler, 1970). In addition, glaciers are not delineated on this map series. Despite these obvious problems, the 1:200,000-scale maps have been used in almost all recent studies of glaciers. However, explorers made use of these maps only for orientation purposes and finding their locations.

Within glacierized regions each scientist had to draw a large-scale sketch map with an altimeter and a compass. However, errors do exist on these sketch maps because of the inaccurate base maps.

In recent years the situation has been altered considerably because of the availability of very precise topographic maps of Turkey at scales of 1:250,000, 1:100,000, and 1:25,000. When these maps are used, sketch maps drawn by explorers are more precise, especially with regards to delineation of the snowline. Also on recently published 1:25,000- and 1:100,000-scale topographic maps, contour lines on the larger glaciers are drawn in blue. Although the large-scale maps were primarily prepared to support military planning and operations and have some restrictions in their availability, in recent years scientists have been able to use them in their research. For example, Planhol and Bilgin (1964) and Kurter and Sungur (1980) based their research on these maps.

In summary, maps of the glacierized areas of Turkey since World War II have been compiled in the field because of lack of availability of large-scale topographic maps, but most such independently drawn maps contain errors. More recently, however, 1:25,000- and 1:100,000-scale maps have become available for modern field studies, and scientists have begun to make effective use of them.

Imaging of Glaciers

Aerial Photography

In Turkey, aerial photogrammetric methods were used extensively for the first time during the 1950's. The main impetus was to meet the objective of preparing a 1:25,000-scale topographic map series of Turkey. A military unit attached to the General Staff Headquarters was given the responsibility for acquiring complete aerial photographic coverage of Turkey. Vertical aerial photographs of the entire country were taken over a period of several years. The vertical aerial photographs can be used, with some restrictions, for all types of scientific studies, with the exception of mapmaking. Two scales, one at 1:35,000 and the other 1:20,000, are available. The 1:20,000-scale vertical aerial photographs are more suitable for studies of glaciers.

Although aerial photographs are available of the glacierized areas of Turkey, the anticipated increase in glacial and glacier studies in Turkey has not been realized, because the photographs were acquired for topographic mapmaking, not for scientific purposes. Thus, the photographs are generally only of average quality, often lacking in the detail needed to support precise scientific investigations. In addition, another negative factor in their use for glacier studies is the limited opportunity for repetitive coverage. Because the main purpose is for topographic mapmaking, only one or two flights are made over each area to be mapped. Once a usable set of aerial photographs is available for topographic mapmaking, no other survey flights of the area are scheduled. Thus, scientists are deprived of the availability of periodic aerial photographs necessary to determine the advance or retreat of a glacier. Also, because the aerial photographs have not been taken during the time of minimum snow cover, determination of the snowline on the glaciers is very difficult.

In recent years, aerial photographs have also been acquired for forest-management purposes, and 1:10,000- and 1:5,000-scale aerial photographs are available for such studies. However, because glacierized areas do not coincide with forested areas, these aerial photographs are not useful for glacier studies. Arrangements for photographing glacierized areas during a specific season and time can be made with the Harita Genel Müdürlürlügü (General Maps Directorate), the only establishment in Turkey authorized to acquire aerial photographs, but the institution that needs the photographs must pay all costs.

Landsat Imagery

The limitations inherent in using aerial photographs of Turkey for glacier studies do not apply to Landsat imagery. In fact, glaciers could be analyzed during different years on Landsat images available for the period 1972–77 (table 2; figs. 1 and 2). Thus, advance or recession of glaciers could easily be determined. Also, acquisition of images at the end of the melt season increases the chance of having minimum snow cover. In this way, satellite images give some advantages that cannot be derived from aerial photographs. However, delineation of Turkey's glaciers on satellite images is difficult because of the glaciers' small areas and volumes. Although glaciers on the volcanic cones of Mount Erciyes, Mount Süphan, and Mount Ağrı can be seen quite easily on the 1:1,000,000-scale images, small features such as glacierets and firn patches cannot be detected in the mountain ranges, especially on high peaks and steep slopes, even on enlargements of the images. For this reason, only the major glaciers of Turkey could be studied on available Landsat multispectral scanner (MSS) and return beam vidicon (RBV) images, even though they are enlarged to a scale of 1:250,000 or larger. Also, some of the available Landsat MSS and RBV images contain too many clouds and (or) too much snow cover for optimum analysis (table 2).

In the following discussion of Turkey's glaciers, a combination of aerial photographs and Landsat images was used, even though each had its own limitations. Because the aerial photographs of Turkey were taken for other uses, primarily mapmaking, they were not acquired during the optimum time of year (end of the melt season) and do not provide repetitive coverage; therefore, they have only limited value for studies of glaciers. These shortcomings of the aerial photographs are overcome by use of the Landsat images; however, the spatial resolution of the Landsat MSS images restricts its value to studies of only the largest Turkish glaciers.

Glaciers on Landsat Images

In Turkey, various types of glaciers tend to cluster in specific areas, and, in fact, almost all of the glaciers are located in the eastern half of the country (fig. 1). The glaciers are classified as valley, mountain, and rock glaciers. The concentration of glaciers in specific areas presents an opportunity for recording several of them on the same image. However, since some glaciers have developed on the highest peaks in widely separated parts of Turkey, several satellite images must be used to cover all the glacierized regions of Turkey. Eight separate Landsat images are the minimum needed to provide complete coverage, although only seven are shown in figure 1 because of the lack of an adequate image for one region.

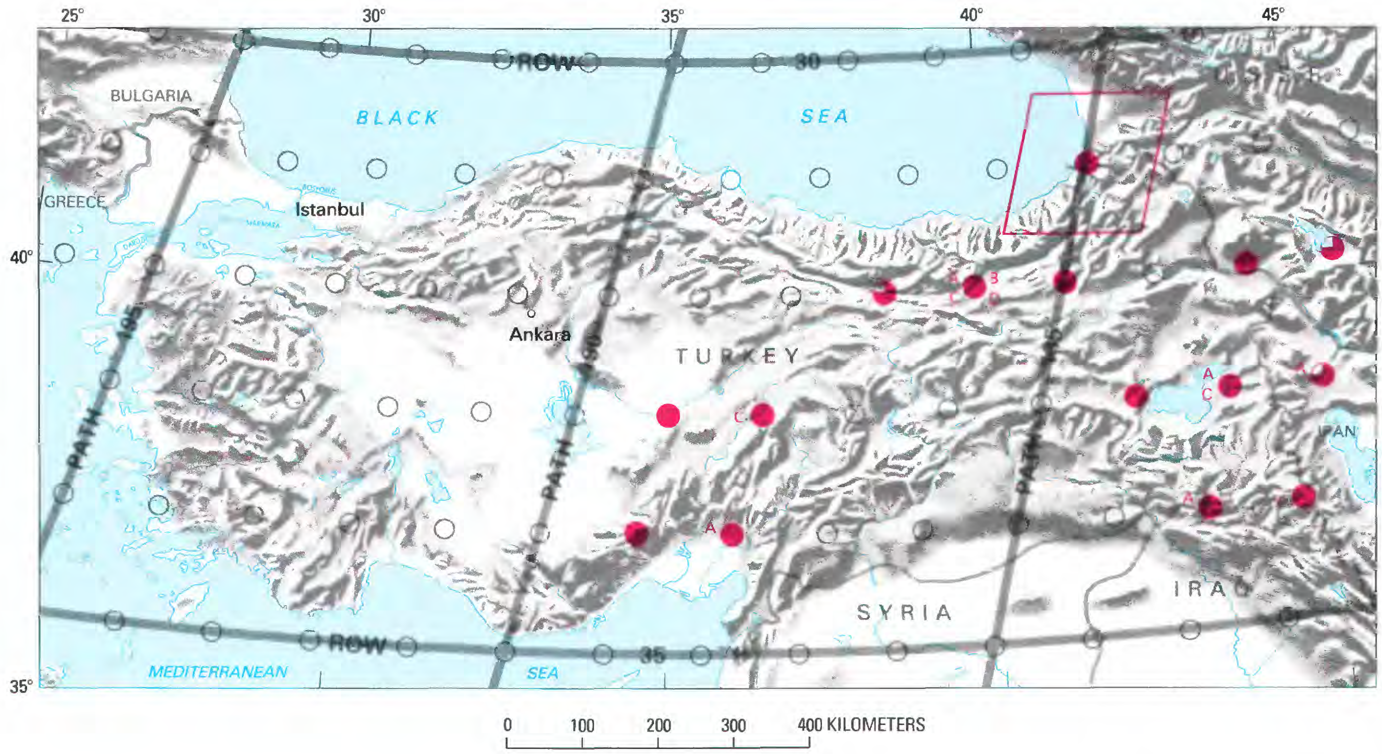
TABLE 2.—*Optimum Landsat 1, 2, and 3 images of the glaciers of Turkey*

[Explanation of symbols used in the "Code" column is provided on figure 2. The single occurrence of a half-filled circle indicates a fair to poor image]

Path-Row	Nominal scene center (lat-long)	Landsat identification number	Date	Solar elevation angle (degrees)	Code	Cloud cover (in percent)	Remarks
182–32	40°14′N. 45°34′E.	2603–06505	16 Sep 76	43	◕	10	Mount Ağrı
182–33	38°49′N. 45°05′E.	2603–06512	16 Sep 76	44	◕	10	Mount Ağrı
182–33	38°49′N. 45°05′E.	30950–06480–A	10 Oct 80	36	●	0	Mount Ağrı; Landsat 3 RBV; figure 13
182–34	37°24′N. 44°37′E.	2189–07002	30 Jul 75	56	●	0	Buzul and İkiyaka Mountains; figure 6
182–34	37°24′N. 44°37′E.	30950–06482–C	10 Oct 80	37	●	0	Buzul and İkiyaka Mountains; Landsat 3 RBV
183–32	40°14′N. 44°08′E.	2586–06570	30 Aug 76	47	◕	10	Mount Ağrı; figure 12
183–32	40°14′N. 44°08′E.	2946–06411	25 Aug 77	46	●	0	Mount Ağrı; color composite available
183–33	38°49′N. 43°39′E.	2946–06414	25 Aug 77	47	●	0	Mount Süphan, Kavuşşahap Mountains; figure 11
183–33	38°49′N. 43°39′E.	2208–07050	18 Aug 75	52	◕	10	Mount Süphan, Kavuşşahap Mountains
183–33	38°49′N. 43°39′E.	30915–06545–AC	05 Sep 80	46	●	0	Mount Süphan, Kavuşşahap Mountains; Landsat 3 RBV
183–34	37°24′N. 43°11′E.	2208–07053	18 Aug 75	53	●	0	Kavuşşahap and Buzul Mountains
183–34	37°24′N. 43°11′E.	30951–06540–A	11 Oct 80	37	●	0	Kavuşşahap Mountains; Landsat 3 RBV
184–33	38°49′N. 42°13′E.	2227–07104	06 Sep 75	48	●	0	Mount Süphan, Kavuşşahap Mountains; color composite available; figure 8
185–31	41°40′N. 41°46′E.	2210–07153	20 Aug 75	50	●	0	Mount Altıparmak area of Eastern Black Sea Mountains; color composite available
185–32	40°14′N. 41°16′E.	2084–07170	16 Apr 75	50	●	0	Mounts At and Kaçkar area of Eastern Black Sea Mountains; heavy snow cover; color composite available
186–32	40°14′N. 39°50′E.	2211–07214	21 Aug 75	51	●	0	Mounts Aptalmusa and Kaçkar areas; color composite available; figure 3
186–32	40°14′N. 39°50′E.	30954–07102–ABCD	14 Oct 80	34	●	0	Mount Aptalmusa and Varşanba Peak; Landsat 3 RBV
187–32	40°14′N. 38°24′E.	2248–07271	27 Sep 75	41	◕	10	Mount Karagöl, Giresun Mountains; color composite available
188–33	38°49′N. 36°28′E.	2933–07110	12 Aug 77	49	●	0	Mount Erciyes; figure 9
188–33	38°49′N. 36°28′E.	2915–07120	25 Jul 77	52	●	0	Mount Erciyes; color composite available
188–33	38°49′N. 36°28′E.	30956–07220–C	16 Oct 80	34	●	0	Mount Erciyes; Landsat 3 RBV

TABLE 2.—*Optimum Landsat 1, 2, and 3 images of the glaciers of Turkey*—Continued

Path-Row	Nominal scene center (lat-long)	Landsat identification number	Date	Solar elevation angle (degrees)	Code	Cloud cover (in percent)	Remarks
188–34	37°24′N. 36°00′E.	2933–07113	12 Aug 77	50	●	0	Ala Mountains; some snow cover
188–34	37°24′N. 36°00′E.	30938–07231–A	28 Sep 80	41	◑	20	Ala Mountains; Landsat 3 RBV
189–33	38°49′N. 35°02′E.	2268–07390	17 Oct 75	36	●	0	Mount Erciyes; fine topographic detail
189–34	37°24′N. 34°34′E.	1146–07525	16 Dec 72	24	●	0	Ala and Bolkar Mountains; some snow cover; figure 5



EXPLANATION OF SYMBOLS

Evaluation of image usability for glaciologic, geologic, and cartographic applications. Symbols defined as follows:

- Excellent image (0 to ≤5 percent cloud cover)
- Good image (>5 to ≤10 percent cloud cover)
- Usable Landsat 3 return beam vidicon (RBV) scenes A, B, C, D refer to usable RBV subscenes
- Nominal scene center for a Landsat image outside the area of glaciers
- Approximate size of area encompassed by nominal Landsat MSS image. Landsat 3 RBV subscenes encompass slightly more than one overlapping quadrant (A, NW; B, NE; C, SW; D, SE) of an MSS nominal scene.

Figure 2.—*Optimum Landsat 1, 2, and 3 images of the glaciers of Turkey. The vertical lines represent nominal paths. The rows (horizontal lines) have been established to indicate the latitude at which the imagery has been acquired.*

Glaciers in Coastal Ranges Along the Black Sea

A series of mountain ranges extends along the coastline parallel to the Black Sea. The snowline is lower on the north-facing than on south-facing slopes of these ranges because of the effect of humid air masses. The elevation of the snowline on the northern slopes is 3,100–3,400 m (Erinç, 1952b). The limited number of peaks that extend above the snowline has been a negative factor in the development of glaciers. Glaciers are located on Karagöl Dağı (Mount Karagöl) in the Giresun Dağları (Giresun Mountains), on Aptalmusa Dağı (Mount Aptalmusa) in the Gavurdağları (Gavur Mountains), and on Varşanba Peak and Mount Kaçkar in the extreme eastern part of the Eastern Black Sea Mountains.

Karagöl Dağı (Mount Karagöl), Giresun Dağları (Giresun Mountains)

The Giresun Mountains are located just to the west of the Eastern Black Sea Mountains. The peaks extend between latitudes 40°30′ and 40°32′ N. and longitudes 38°08′ and 38°13′ E., reaching a maximum elevation of 3,107 m on Mount Karagöl. A small mountain glacier, about 0.08 km^2, exists within a cirque on the northwestern part of this mountain. Some glacierets are also present on north-facing slopes. The elevation of the snowline is at 2,900 m, which is lower than the snowline in the Eastern Black Sea Mountains because of cloudiness and nourishment differences (Planhol and Bilgin, 1964). Except for the largest glacier on the northwestern slope on Mount Karagöl, all of its glacierets are too small to be resolved by the Landsat MSS and cannot be seen on the images under normal conditions.

Gavurdağları (Gavur Mountains)

The southwestern part of the Eastern Black Sea Mountains is known as the Gavur Mountains. There are a few small glaciers on the highest peaks of these mountains, which are situated between latitudes 40°22′ and 40°26′ N. and longitudes 39°02′ and 39°07′ E. The area is located on the western edge of Landsat image 2211–07214, which was acquired on 21 August 1975, at a time of minimum snow cover. On the Landsat image several small mountain glaciers and old cirque lakes extending in a southwest to northeast direction immediately east of the summit of Aptalmusa Dağı (Mount Aptalmusa) (3,331 m) can be delineated (fig. 3). The largest of the mountain glaciers, the Avlıyana Glacier, has a width of 300 m and a length of 150 m. It is contained within a cirque basin that has developed on the northern slope of Mount Aptalmusa. The Avlıyana Glacier takes its name from a creek that flows nearby. The snowline elevation here is estimated to be at 3,100 m.

Doğukaradeniz Dağları (Eastern Black Sea Mountains)

This lofty part of the Eastern Black Sea Mountains is located to the south of the towns of Rize and Ardeşen and has its highest elevations in excess of 3,000 m. The western part of this mountain group is called the Soğanlı Dağları (Soğanlı Mountains), which lie between latitudes 40°25′

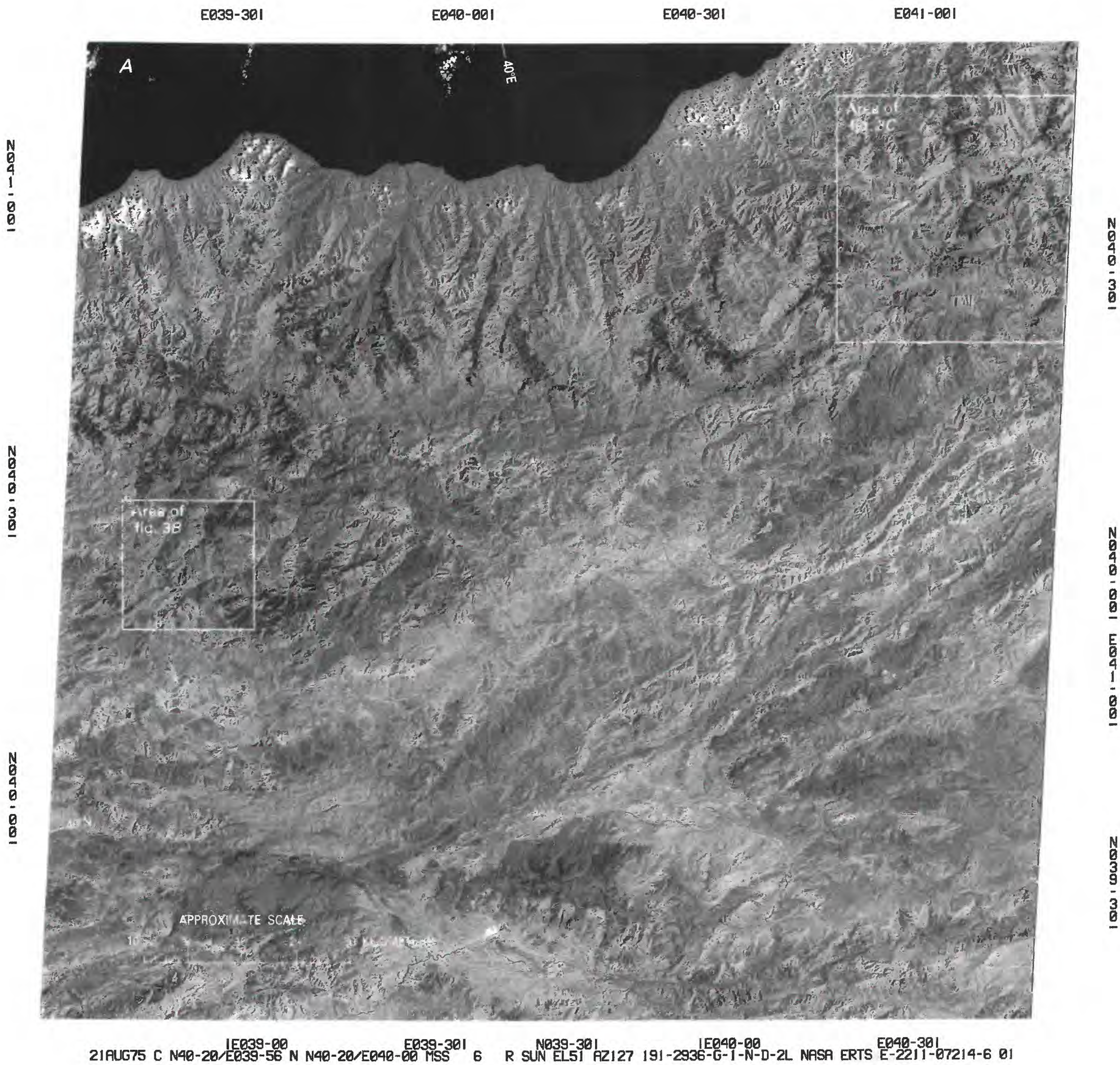
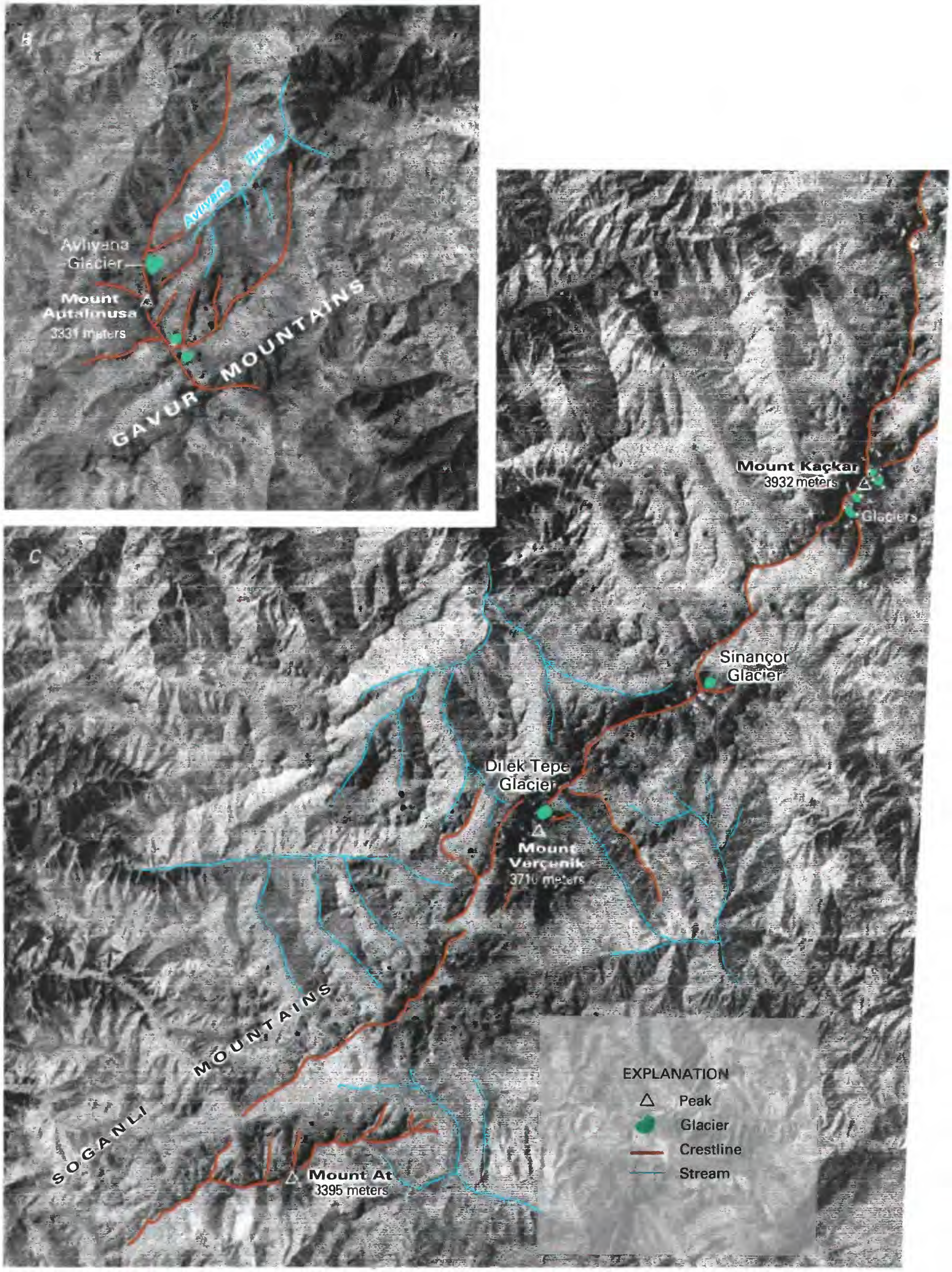


Figure 3.—A, *A 1:1,000,000-scale Landsat MSS image (2211–07214, band 6; 21 August 1975; Path 186, Row 32) of north-central Turkey showing the areas of the annotated enlargements.* B, *An approximately 1:250,000-scale enlargement of 3*A *showing the Avlıyana Glacier and other small mountain glaciers on Mount Aptalmusa in the Gavur Mountains.* C, *An approximately 1:250,000-scale enlargement of 3*A *showing the Soğanlı Mountains with the highest peak, Mount At, and Varşanba Peak (Mount Verçenik) and Mount Kaçkar with their small mountain glaciers (see fig. 1).*


B
Avlıyana River
Avlıyana Glacier
Mount Aptalmusa
3331 meters
GAVUR MOUNTAINS
C
Mount Kaçkar
3932 meters
Glaciers
Sinançor Glacier
Dilek Tepe Glacier
Mount Verçenik
3710 meters
SOGANLI MOUNTAINS
Mount At
3395 meters
EXPLANATION
Peak
Glacier
Crestline
Stream

and 40°45′ N. and longitudes 40° and 40°52′ E. The highest peak, Atdağı (Mount At), has an elevation of 3,395 m and is included within Landsat MSS image 2211–07214, acquired on 21 August 1975 (fig. 3). Although this is the region with the highest annual precipitation in Turkey, cloud cover on the image is negligible, making it very suitable for glacier studies. There are a few glacierets and rock glaciers on this high mountain group that await further investigation.

Toward the east, even higher peaks of the Eastern Black Sea Mountains are situated. Varşanba Tepe (Mount Verçenik) has an elevation of 3,710 m and is located between latitudes 40°40′ and 40°46′ N. and longitudes 40°52′ and 41°05′ E. On Landsat MSS image 2211–07214 (fig. 3), several rock glaciers northeast of the summit of Mount Verçenik and a mountain glacier near the Sinançor area can be delineated. The Sinançor Glacier is approximately 300 m in length and hangs down to the northeast. Dilek Tepe Glacier has a length of 700 m and is located on the north slope of Mount Verçenik. The elevation of the snowline in this area is about 3,500 m, and most of the cirques have developed at the 3,600-m elevation.

The highest part of the Eastern Black Sea Mountains, which includes Mount Kaçkar (3,932 m), is south of the town of Ardeşen between latitudes 40°50′ and 41° N. and longitudes 41°08′ and 41°20′ E. The area is partially covered by Landsat MSS image 2211–07214 of 21 August 1975 (fig. 3). The image includes only the northeast edge of the summit area of Mount Kaçkar. This mountainous region is the part of the Eastern Black Sea Mountains where glaciers are most highly developed. In fact, three valley glaciers are situated on the northern part of the summit of Mount Kaçkar. Kaçkar I Glacier extends 1.5 km in length (fig. 4); Kaçkar II Glacier is almost 1 km long, and Kaçkar III Glacier is slightly shorter. These three valley glaciers originate at an elevation of 3,650 m and terminate at 2,900 m, 2,990 m, and 3,130 m, respectively. The snowline elevation in this part of the range is at 3,400 m. A smaller glacier southwest of the summit, the Krenek II Glacier, extends to the northeast. It originates at an elevation of 3,760 m and terminates at 3,350 m. Kaçkar I and II Glaciers can be delineated clearly on the Landsat image (fig. 3). One other small glacier is situated in the Altıparmak Dağları (Altıparmak Mountains), a little farther east at an elevation of 3,562 m, but this area is outside of the area covered by figure 3.

***Figure 4.**—Kaçkar I Glacier on the northwestern part of the summit of Mount Kaçkar in the Eastern Black Sea Mountains. Photograph taken at 3,000 m.*

Glaciers in the Toros Dağları (Taurus Mountains)

The Taurus Mountains are a group of mountain ranges that extend from the west, running roughly parallel to the Mediterranean coast, in an arc to the east. Maritime air masses move to the north over the Taurus Mountains from the Mediterranean Sea on the south, and numerous glaciers have formed on the sheltered northern slopes of the system of mountain ranges. The Güneydoğu Toroslar (Southeastern Taurus Mountains) contain Turkey's greatest concentration of glaciers, with about two-thirds of the glaciers located in this mountain range. Although the precipitation is lower than in the area of the Eastern Black Sea Mountains, the higher degree of glacierization of the Taurus Mountains can be explained by greater erosion and lesser ablation (Erinç, 1952b). In the Taurus Mountains, glaciers tend to be concentrated in two areas: (1) the Orta Toroslar (Middle Taurus Mountains) and (2) the Güneydoğu Toroslar (Southeastern Taurus Mountains).

Orta Toroslar (Middle Taurus Mountains)

The Middle Taurus Mountains form the part of the Taurus Mountains that extends parallel to the Mediterranean coast. Unfortunately, the available Landsat MSS images of this area generally contain too much cloud and (or) snow cover. The most suitable Landsat MSS images for analysis are Landsat MSS images 2933–07113 of 12 August 1977 (table 2) and 1146–07525 of 16 December 1972 (fig. 5). In the Bolkar Mountains, which are located between latitudes 37°26′ and 37°33′ N. and longitudes 34°36′ and 34°50′ E., a mountain glacier about 300 m in length has developed at an altitude of 3,000 to 3,350 m on Medetsiz Tepe (Medetsiz Peak) (3,524 m); its tongue extends to the north down to an elevation of 2,950 m. The snowline in this area is at 3,450 m. The fact that the glacier on Mount Medetsiz has developed below the snowline can be explained only by unique local climatological and physiographic conditions (Klaer, 1962; Messerli, 1967; Kurter and Sungur, 1980). Glacierization in the Ala Mountains is even more extensive. A number of mountain glaciers have developed on the northern slopes of Demirkazık Tepe (Demirkazık Peak) (3,756 m). There are also several glaciers on the southern flank, including the Lolut Glacier. The Lolut Glacier has a length of 1 km and can be classified as a valley glacier. Demirkazık Peak is situated between latitudes 37°41′ and 37°55′ N. and longitudes 35°02′ and 35°16′ E.

Güneydoğu Toroslar (Southeastern Taurus Mountains)

The Southeastern Taurus Mountains are the most important glacierized region in Turkey. More than 20 glaciers have been identified in this range (Erinç, 1952b). The glaciers are especially well developed on two mountain groups, the first of which is the Buzul Mountains. The Buzul Mountains extend between latitudes 37°26′ and 37°32′ N. and longitudes 43°56′ and 44°04′ E. Glaciers can be delineated on Landsat MSS images 2208–07053 of 18 August 1975 (table 2) and on 2189–07002 of 30 July 1975 (fig. 6). Both images are cloud free and have minimum snow cover. The valley glacier, Uludoruk Glacier, on the north side of Uludoruk Tepe (Uludoruk Peak) (4,135 m), also known as Reşko Tepe (Reşko Peak), can be delineated easily (fig. 6). The Uludoruk Glacier has a length of almost

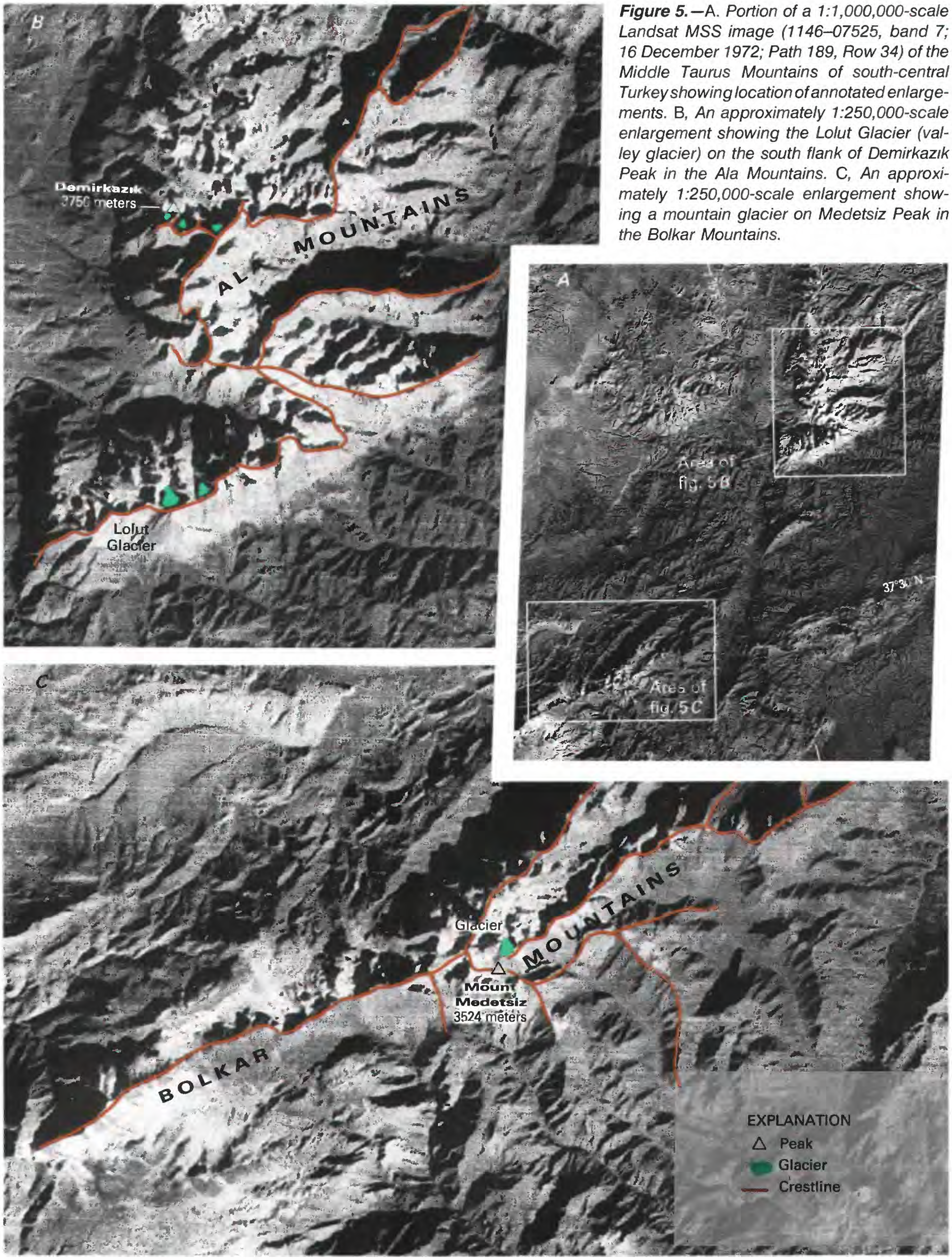


Figure 5.—A. *Portion of a 1:1,000,000-scale Landsat MSS image (1146–07525, band 7; 16 December 1972; Path 189, Row 34) of the Middle Taurus Mountains of south-central Turkey showing location of annotated enlargements.* B, *An approximately 1:250,000-scale enlargement showing the Lolut Glacier (valley glacier) on the south flank of Demirkazık Peak in the Ala Mountains.* C, *An approximately 1:250,000-scale enlargement showing a mountain glacier on Medetsiz Peak in the Bolkar Mountains.*

4 km and extends down to an elevation of 3,000 m (fig. 7). The elevation of the snowline in this mountain group is approximately 3,600 m (Erinç, 1952b). One other glacier, Mia Havara, has advanced to the east and down to the 2,800-m elevation (fig. 6). Lesser numbers of glaciers exist in the İkiyaka (Sat) Mountains, which are situated between latitudes 37°18′ and 37°24′ N. and longitudes 44°10′ and 44°20′ E. and can be seen easily on figure 6. The Geverok Glacier on Dolampar Dağı (Mount Dolampar) (3,794 m) extends in a northwesterly direction and has a length of about 1 km. The elevation of the snowline in this area is 3,500 m.

Kavuşşahap Dağları (Kavuşşahap Mountains)

Glaciers in the Kavuşşahap Mountains, which are located south of Van Gölü (Lake Van) (see fig. 1), have been discovered only recently (Klaer, 1965; Schweizer, 1972, 1975). The Kavuşşahap Mountains, which are situated between latitudes 38°12′ and 38°16′ N. and longitudes 42°48′ and 42°54′ E. include Hasanbeşir Dağı (Mount Hasanbeşir) (3,503 m), the highest peak in the area. Several Landsat MSS images cover the area, but Landsat MSS image 2208–07053 of 18 August 1975 provides good coverage. Landsat MSS false-color composite image 2227–07104 of 6 September 1975 (fig. 8) and Landsat image 2946–06414 of 25 August 1977 are also suitable for analysis. Glacier features on the northern slopes of Mount Hasanbeşir at an elevation of 3,300 m can be delineated on all these images. The mountain glacier on the northwest slope of Mount Hasanbeşir has a length of 300 m and a width of 200 m and is too small to be delineated on the Landsat image. The mean elevation of the snowline in this area is 3,400 m, so that the existing glaciers are the result of unusual local climatological and physiographic conditions.

Glaciers on Dormant Stratovolcanoes

Glaciers have also developed on three dormant stratovolcanoes that are located in the interior parts of Turkey. Although the elevation of the snowline is higher in the interior of the country than on coastal mountain ranges, these volcanoes have sufficient elevation to support the formation of glaciers: Erciyes Dağı (Mount Erciyes) (3,917 m), Süphan Dağı (Mount Süphan) (4,058 m), and Ağrı Dağı (Mount Ağrı) (5,137 m). All three stratovolcanoes are considered by Simkin and others (1981) to have been active during the Holocene; Mount Erciyes, on the basis of anthropological evidence, is considered to have erupted in prehistoric times.

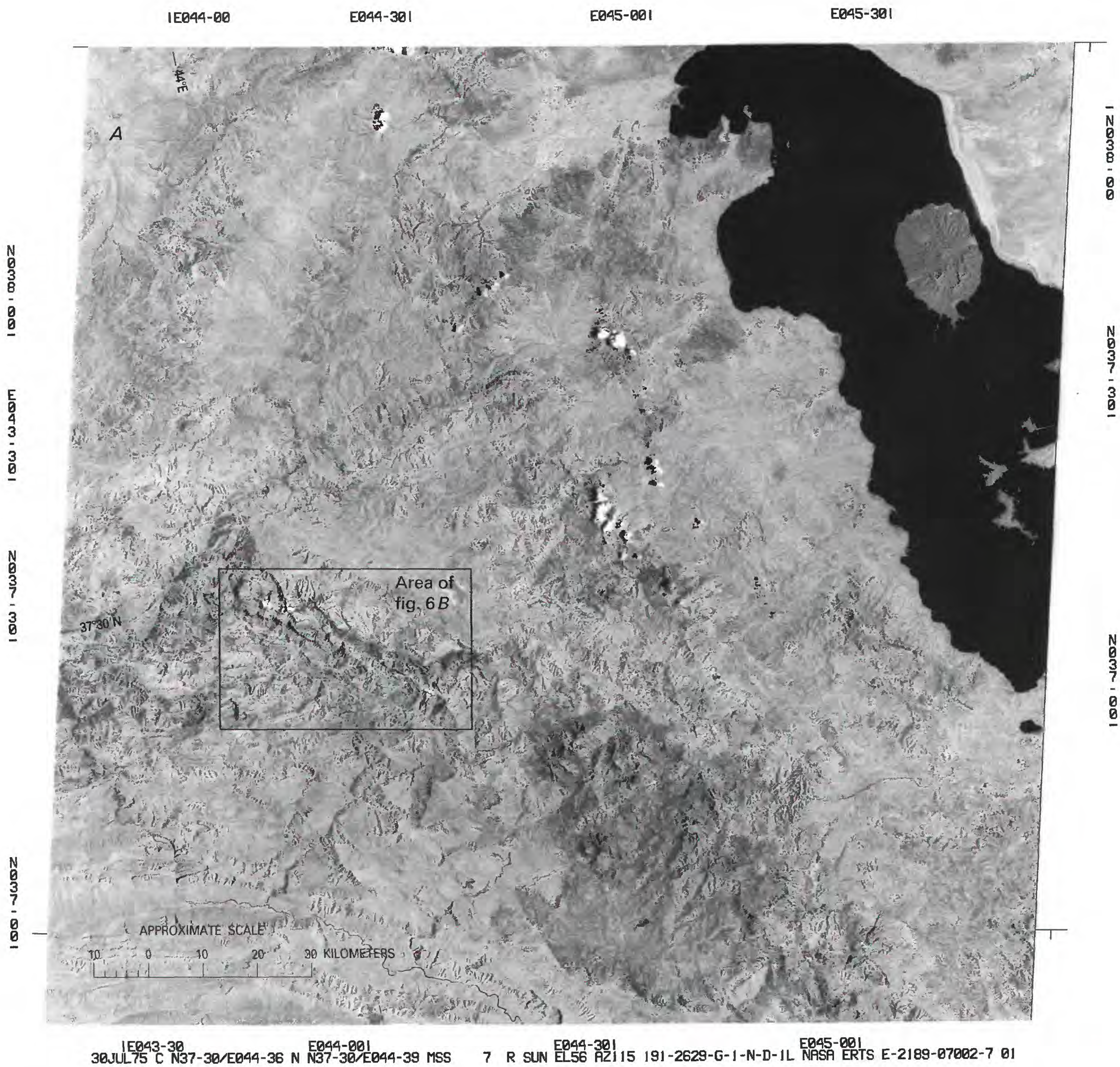


Figure 6.—A, *A 1:1,000,000-scale Landsat MSS image (2189–07002, band 7; 30 July 1975; Path 182, Row 34) of southeastern Turkey showing the area of the annotated enlargement.* B, *An approximately 1:250,000-scale, band 5 enlargement showing the Buzul (Cilo) and İkiyaka (Sat) Mountains and valley glaciers of the Southeastern Taurus Ranges (see fig. 1). Uludoruk Glacier and Mia Havara Glacier on Uludoruk (Reşko) Peak and the Geverok Glacier on Mount Dolampar can be delineated easily.*

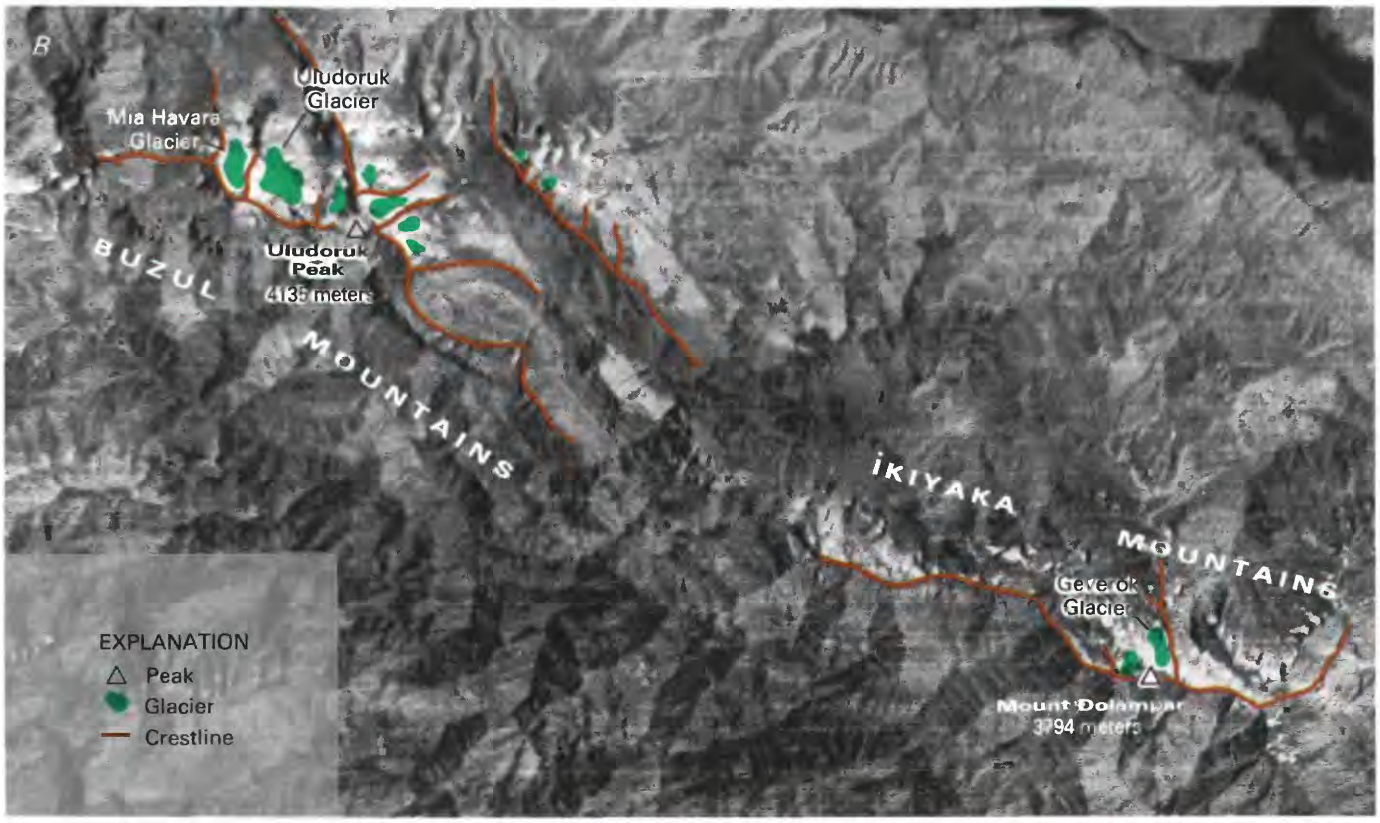


Figure 7.—*Uludoruk Glacier, the largest glacier on Uludoruk Peak, Southeastern Taurus Mountains (photographed by M. Somuncu).*

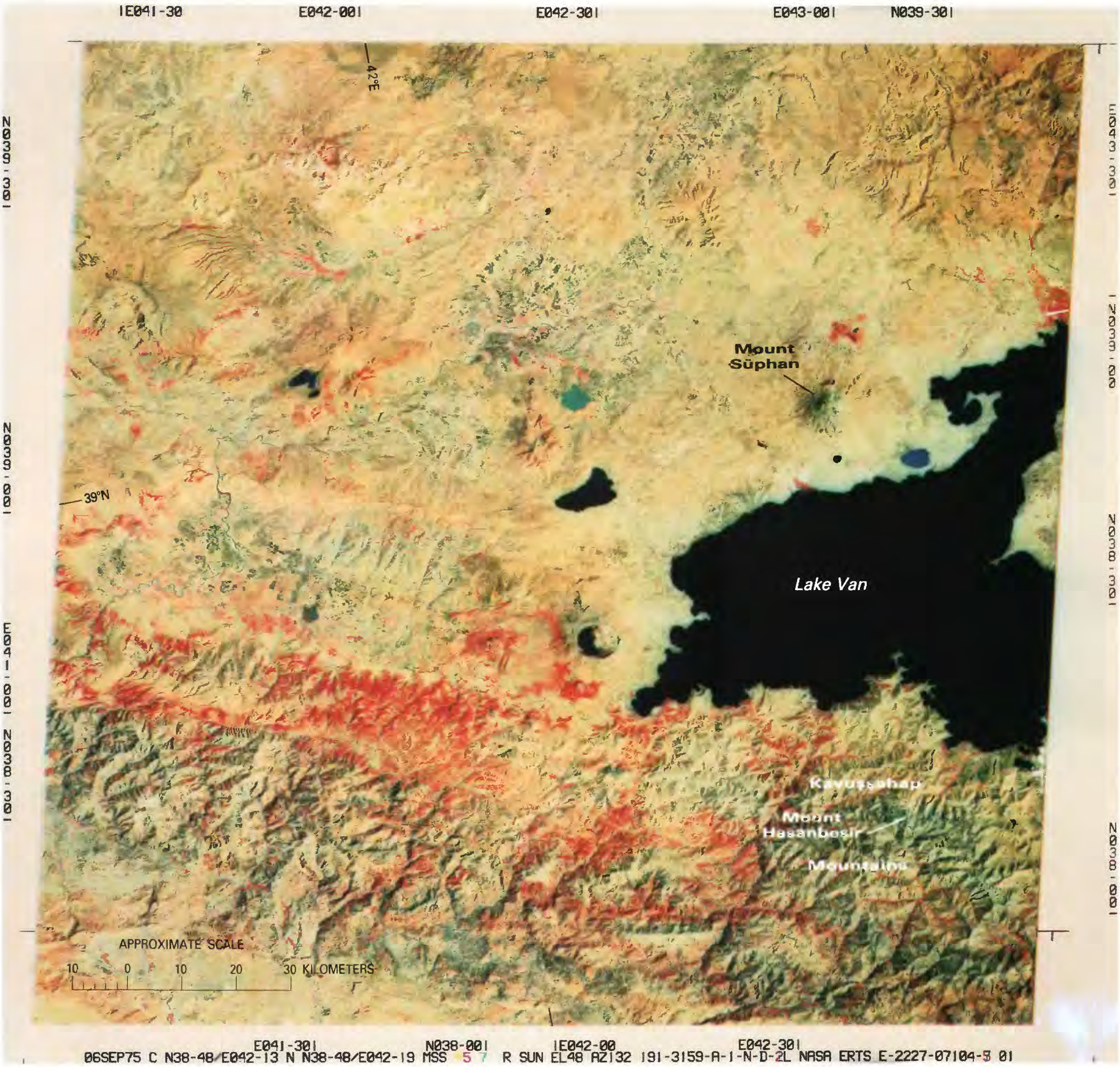


Figure 8.—*Annotated 1:1,000,000-scale Landsat MSS false-color composite image (2227–07104, bands 4, 5, and 7; 6 September 1975; Path 184, Row 33) including Mount Süphan, Lake Van, and Mount Hasanbeşir of the Kavuşşahap Mountains area of southeastern Turkey (see fig. 1).*

Glaciers on Erciyes Dağı (Mount Erciyes)

A glacier has developed on the northern part of the dormant volcanic cone of Mount Erciyes, which is located south of the city of Kayseri between latitudes 38°31′ and 38°34′ N. and longitudes 35°24′ and 35°28′ E. Two useful Landsat images of Mount Erciyes were analyzed. Landsat MSS image 2268–07390 (17 October 1975) (table 2) shows the fine topographic detail of the stratovolcano, while Landsat MSS image 2933–07110 of 12 August 1977 more clearly delineates the glaciers (fig. 9). Of the several glaciers on Mount Erciyes, the one that extends to the northwest has been the most studied (Penther, 1905; Bartsch, 1935; Blumenthal, 1938; Erinç, 1951; Klaer, 1962; Messerli, 1964). The northwest glacier is classified as a valley glacier and extends from 3,800 to 3,400 m (fig. 10). The second glacier, which is also clearly seen on the two Landsat images, extends to the east from a large cirque and appears to be a rock glacier at an elevation of 3,100 m (Güner and Emre, 1983). Various values have been given for the mean elevation of the snowline on Mount Erciyes, but the best estimate is about 3,600 m.

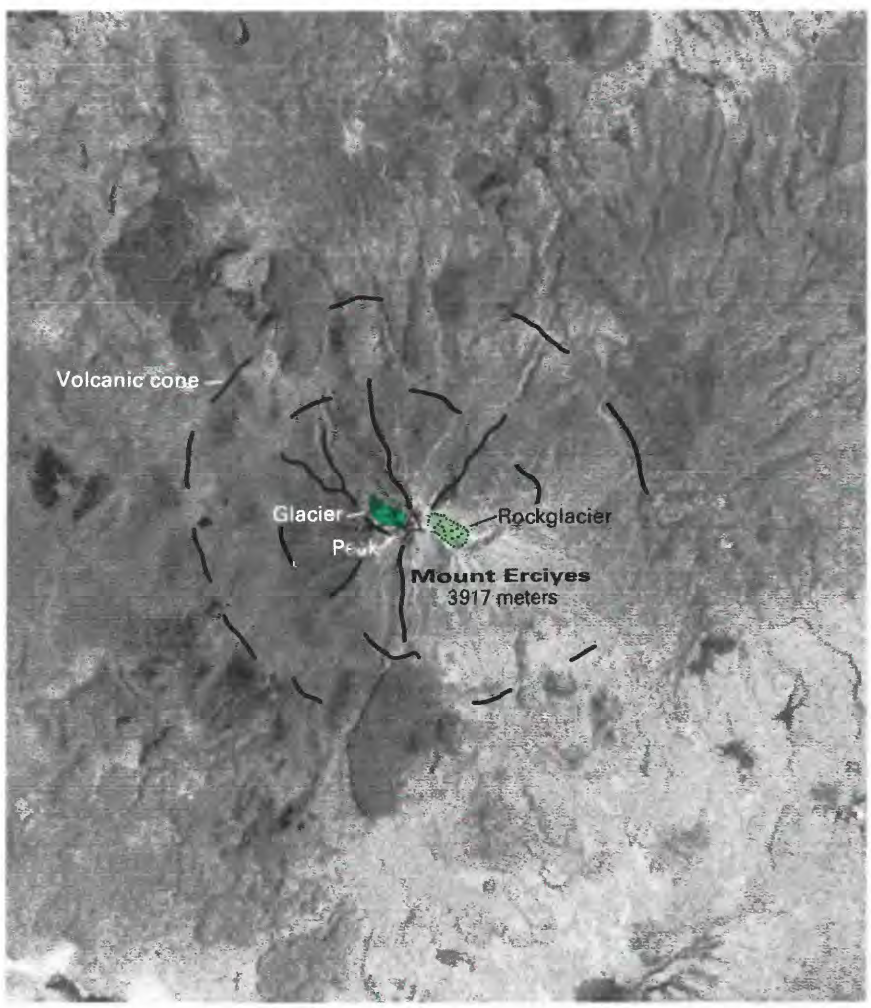


__Figure 9.__—Annotated 1:250,000-scale enlargement of part of a Landsat MSS image (2933–07110, band 7; 12 August 1977; Path 188, Row 33) showing glaciers on the flanks of Mount Erciyes, a dormant stratovolcano in central Turkey (see fig. 1).

Figure 10.—*The valley glacier on the northwest slope of Mount Erciyes viewed from 3,200 m (photographed by M. Somuncu).*

Glaciers on Süphan Dağı (Mount Süphan)

Mount Süphan is located to the north of Lake Van in southeastern Turkey, has a summit elevation of 4,058 m, and also is a dormant stratovolcano (fig. 8). The crater of this volcano, which contains several glaciers, lies between latitudes 38°53′ and 38°58′ N. and longitudes 42°47′ and 42°52′ E. Detailed analyses can be made from two Landsat MSS images, 2208–07050 of 18 August 1975, and 2946–06414 of 25 August 1977 (fig. 11). The best developed glacier, located on the north-facing slope of the crater, has a width of 2 km, has a length of 1.5 km, and extends in a southerly direction. There are also several other smaller glaciers on the northern slope of the crater. The elevation of the snowline on Mount Süphan is around 3,700–4,000 m, with the mean elevation about 3,900 m.

The Ice Cap on Ağrı Dağı (Mount Ağrı, or Ararat)

Mount Ağrı, a dormant stratovolcano, is the highest mountain in Turkey, with the elevation of Büyük Ağrı Dağı (Great Ararat), the highest of its two peaks, at 5,137 m (the other peak, Küçük Ağrı Dağı (Little Ararat), reaches 3,927 m). It is located in the easternmost part of the country near the border with Iran between latitudes 39°41′ and 39°44′ N. and longitudes 44°15′ and 44°19′ E. The summit region of Mount Ağrı is covered by an ice cap (Imhof, 1956). Landsat MSS image 2586–06570 of 30 August 1976 (fig. 12) corresponded to a time of minimum snow cover. Cloudiness is also negligible, although there are small clusters of clouds on the northern slopes that do not affect the analysis of the image. As is evident on the Landsat images, the ice cap is most prominent in a northwesterly direction (figs. 12–14). In the northwest, the ice cap extends down to an altitude of 4,100 m and encompasses an area of 10 km^2 (Kurter and Sungur, 1980). The elevation of the snowline on Mount Ağrı is estimated to be at 4,300 m (Klaer, 1965; Kurter and Sungur, 1980).

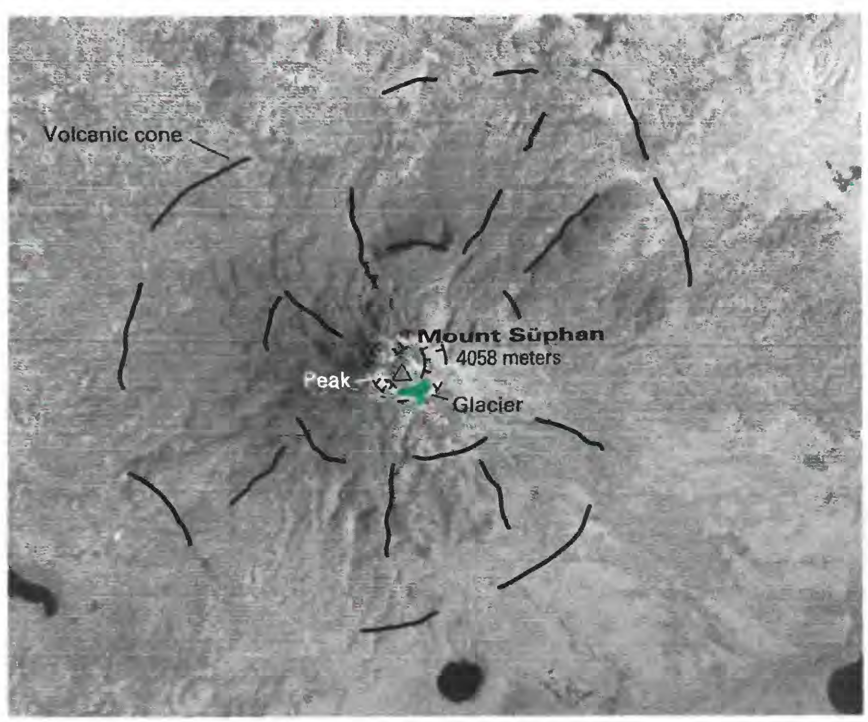


Figure 11.—*An approximately 1:250,000-scale enlargement of part of a Landsat MSS image (2946–06414, band 7; 25 August 1977; Path 183, Row 33) showing mountain glaciers in the crater of the Mount Süphan stratovolcano north of Lake Van in southeastern Turkey (see figs. 1 and 8).*

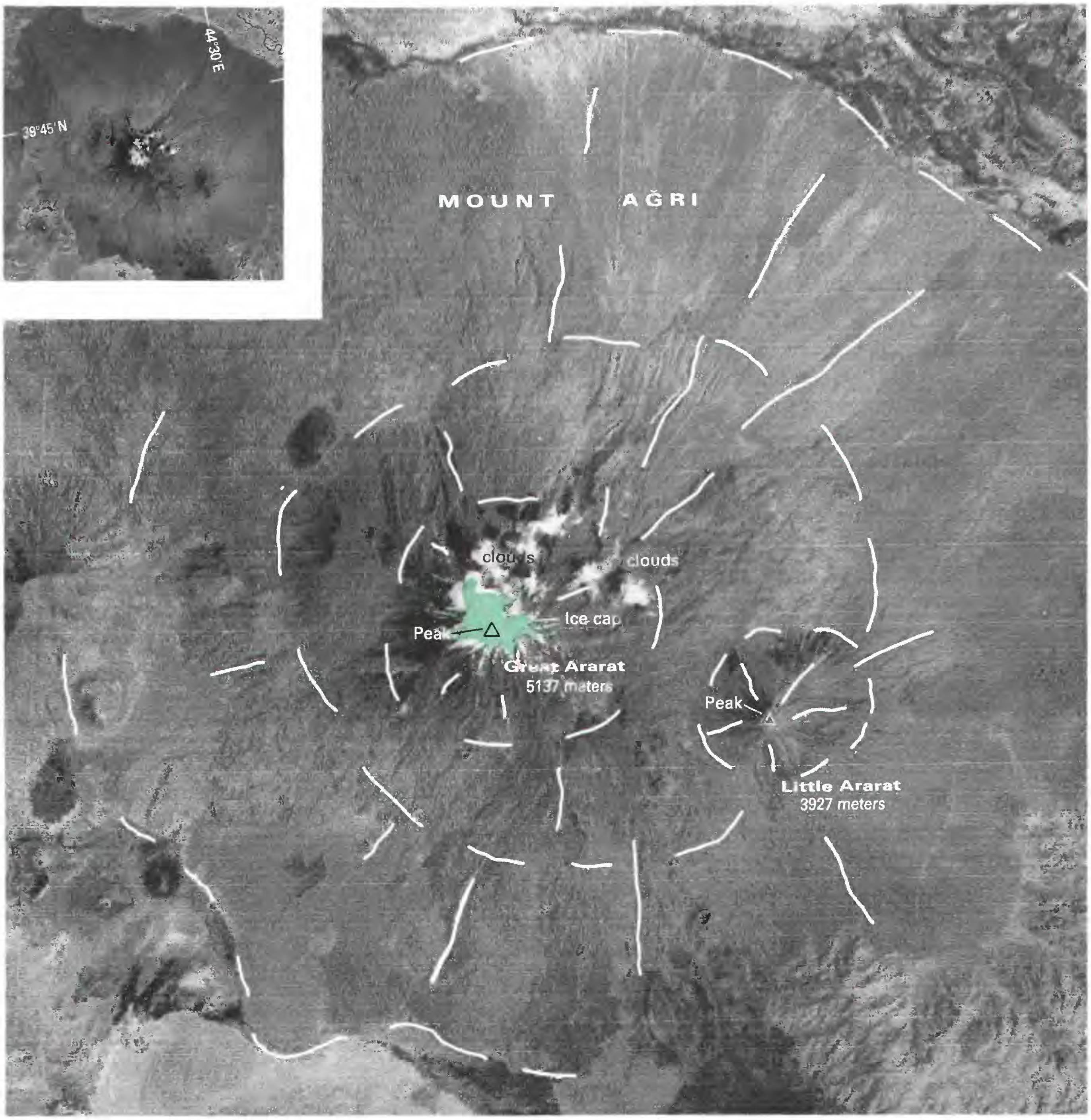


Figure 12.—*Annotated 1:250,000-scale enlargement of part of a Landsat MSS image (2586–06570, band 7; 30 August 1976; Path 183, Row 32) of the ice cap on Mount Ağrı, a dormant stratovolcano and Turkey's highest mountain (5,137 m) (see fig. 1). Inset shows Mount Ağrı at 1:1,000,000 scale.*

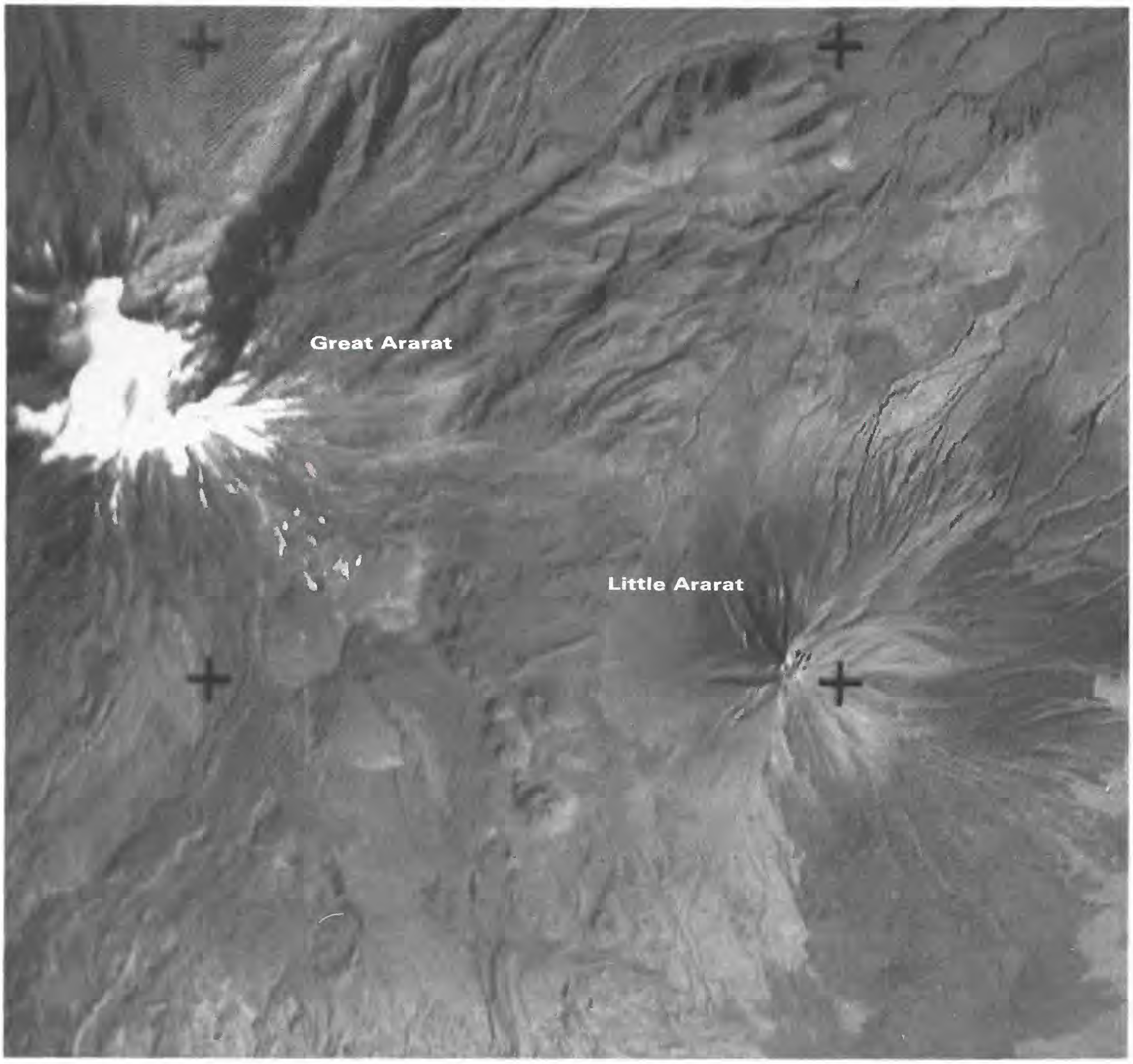


Figure 13.—*Annotated enlargement of part of a Landsat 3 RBV image (30950–06480–A; 10 October 1980; Path 182, Row 33) of Great Ararat and Little Ararat. Approximate scale is 1:100,000.*

Figure 14.—An approximately 1:90,000-scale annotated enlargement of part of a Landsat 5 TM false-color composite image (50209–07140; bands 2, 4, and 7; 26 September 1984; Path 170, Row 32) showing the prominent ice cap on Mount Ağrı. On the image, white clouds partially obscure the upper part of the bluish ice cap. The spatial resolution of the TM image is approximately equivalent to that of a Landsat 3 RBV image (compare figs. 13 and 14). Image courtesy of Nicholas M. Short, National Aeronautics and Space Administration, Goddard Space Flight Center.

References Cited

Ainsworth, W.F., 1842, Travels and researches in Asia Minor, Mesopotamia, Chaldea and Armenia: London, J.W. Parker, v. 1, 364 p.; v. 2, 399 p.

Arkel, N.A. van, 1973, Die gegenwärtige Vergletscherung des Ararat [The present-day glaciation of Ararat]: Zeitschrift für Gletscherkunde und Glazialgeologie, v. 9, no. 1–2, p. 89–103.

Bartsch, G., 1935, Das Gebiet des Erdsciyas Dağı und die stadt Kayseri in Mittel-Aanatolien [The region around Mount Erciyes and the city of Kayseri in central Anatolia]: Jahrbuch der Geographischen Gesellschaft zu Hannover für 1934 und 1935, p. 87–202.

Birman, J.H., 1968, Glacial reconnaissance in Turkey: Geological Society of America Bulletin, v. 79, no. 8, p. 1009–1026.

Blumenthal, M.M., 1938, Der Erdschias-Dagh, 3916 m [Mount Erciyes, 3,916 m]: Die Alpen, v. 14, no. 3, p. 82–87.

———1952, Das taurische Hochgebirge des Aladağ, neuere Forschungen zu seiner Geographie, Stratigraphie und Tektonik [The Taurus Mountains of the Ala Mountains, new investigations of its geography, stratigraphy, and tectonics]: Ankara, Maden Tetkik ve Arama Enstitüsü Yayınlarından-Veröffentlichungen des Institutes für Lagerstättenforschung der Türkei, ser. D, no. 6, 136 p.

———1954, Im südostanatolischen Hochland zwischen dem Van-See und den Cilo-Ketten [In the southeastern Anatolian highlands between Lake Van and Mount Cilo]: Die Alpen, v. 30, p. 223–240.

———1955, Geologie des Hohen Bolkardağ, seiner nördlichen Randgebite und westlichen Ausläufer (Südanatolischer Taurus) [Geology of the Bolkar Mountains, their northern border region and western extension (southern Anatolian Taurus Mountains)]: Ankara, Maden Tetkik ve Arama Enstitüsü Yayınlarından-Veröffentlichungen des Institutes für Lagerstättenforschung der Türkei, ser. D, no. 7, 169 p.

———1956, Die Vergletscherung des Ararat (Nordöstliche Türkei) [The glaciation of Mount Ararat (northeastern Turkey)]: Geographica Helvetica, v. 11, no. 4, p. 263–264.

———1958, Vom Ağrı Dağ (Ararat) zum Kaçkar Dağ. Bergfahrten in nordostanatolischen Grenzlanden [From Mount Ararat to Mount Kaçkar. Mountain trip in the frontier region of northeastern Anatolia]: Die Alpen, v. 34, p. 125–137.

Bobek, H., 1940, Die gegenwärtige und eiszeitliche Vergletscherung im Zentralkurdischen Hochgebirge [The present and Pleistocene glaciation in the central Kurdistan Mountains]: Zeitschrift für Gletscherkunde, v. 27, no. 1–2, p. 50–87.

Erinç, S., 1949a, Eiszeitliche formen und gegenwärtige Vergletscherung im nordostanatolischen Randgebirge [Pleistocene landforms and present glaciation in the northeastern Anatolian border mountains]: Geologische Rundschau, v. 37, p. 75–83.

———1949b, Kaçkardağı grubunda diluviyal ve bugünkü glasyasyon-Eiszeitliche und gegenwärtige Vergletscherung in der Kaçkardağ-Gruppe [Pleistocene and recent glaciation in the Kaçkar mountain group]: İstanbul Üniversitesi Fen Fakültesi Mecmuasi (Revue de la Faculté des Sciences de l'Université d'Istanbul), ser. B, v. 14, no. 3, p. 243–246.

———1951, Glasiyal ve post glasiyal safhada Erciyes glasiyesi [The glacier of Erciyes in Pleistocene and Post-glacial epoches]: İstanbul Üniversitesi Coğrafya Enstitüsü Dergisi (Review of the Geographical Institute of the University of Istanbul): v. 1, no. 2, p. 82–90.

———1952a, Glacial evidences of the climatic variations in Turkey: Geografiska Annaler, v. 34, no. 1–2, p. 89–98.

———1952b, The present glaciation in Turkey: General Assembly and Seventeenth International Congress of the International Geographical Union, 8th Proceedings, Washington, D.C., August 8–15, 1952, p. 326–330.

———1953, Van'dan Cilo Dağlarına [From Lake Van to Mount Cilo]: İstanbul Üniversitesi Coğrafya Enstitüsü Dergisi [Review of the Geographical Institute of the University of Istanbul]: v. 2, no. 3–4, p. 84–106.

Gall, H., 1966, Gletscherkundliche Beobachtungen im Hochgebirge von Lasistan (Nordostanatolischen Randgebirge) [Glaciological observations in the high mountains of Lasistan (northeastern Anatolian border mountains)]: Mitteilungen der Österreichischen Geographischen Gesellschaft, v. 108, no. 2–3, p. 261–286.

Güner, Y., and Emre, Ö., 1983, Erciyes Dağında Pleyistosen Buzullasması ve Volkanizma ile ilişkisi [Pleistocene glaciation on Mount Erciyes and its relation to volcanism]: Ankara, Jeomorfoloji Dergisi [Bulletin of Geomorphology], no. 11, p. 23–34.

Harita Genel Müdürlürlüğü, 1977, Yeni Türkiye Atlasi [New Turkish Atlas]: Ankara, M.S.B., Harita Genel Müdürlürlüğü.

Horvath, E., 1975, Glaciers of Turkey, Armenian S.S.R. and Iran, *in* Field, W.O., ed., Mountain glaciers of the Northern Hemisphere, pt. III, Glaciers of Southern Asia: Hanover, N.H., U.S. Army Cold Regions Research and Engineering Laboratory, p. 343–359.

Imhof, E., 1956, Der Ararat [Ararat]: Die Alpen, v. 32, no. 1, p. 1–14.

Ivan'kov, P.A., 1959, Sovremennoe oledenenie Malogo Kavkaza i Armianskogo Nagor'ia [Present-day glaciation of the Lesser Caucasus and the Armenian highlands]: Izvestiia Akademii Nauk Armianskoi SSR, Seriia Geologiceskoi i Geograficeskoi Nauki, v. 12, no. 2, p. 47–50.

İzbırak, R., 1951, Cilo dağı v Hakkâri ile Vangölü çevresinde coğrafya araştırmaları [Geographical research in Lake Van and in the Hakkari and Cilo Mountains]: Ankara Üniversitesi, Dil ve Tarih-Coğrafya Fakültesi yayımları, no. 67, Coğrafya Enstitüsü (yayınları), no. 4, 149 p.

Klaer, W., 1957, Beobachtungen zur rezenten Schnee- und Strukturbodengrenze im Hochlibanon [Observations on the Holocene snow line and limit of patterned ground in the Lebanon Mountains]: Zeitschrift für Geomorphologie, neue folge, v. 1, no. 1, p. 57–70.

———1962, Untersuchungen sur klimagenetischen Geomorphologie in den Hochgebirgen Vorderasiens [Investigations on the climatogenetic geomorphology of the mountains of the Asian front]: Heidelberger Geographische Arbeiten, no. 11, 135 p.

———1965, Geomorphologische Untersuchungen in den Randgebirgen des Van-See (Ostanatolien) [Geomorphological investigations in the border mountains of Lake Van (eastern Anatolia)]: Zeitschrift für Geomorphologie, neue folge, v. 9, no. 3, p. 346–355.

———1969, Glazialmorphologische Probleme in den Hochgebirgen Vorderasiens [Glaciomorphological problem in the border mountains of the Asian front]: Erdkunde, v. 23, no. 3, p. 192–200.

Koch, K.H.E., 1846, Reise im pontische Gebirge [Trip in the Pontic Mountains]: Weimar.

Krenek, L., 1932, Gletscher im Pontischen Gebirge (Lasistan) [Glacier in the Pontic Mountains (Lasistan)]: Zeitschrift für Gletscherkunde, v. 20, no. 1–3, p. 129–131.

Künne, G., 1928, Die deutsche alpine Taurusexpedition 1927 (Ala Dagh in Zilizien) [The German alpine expedition to the Taurus Mountains in 1927 (Ala Mountains in Cilicia)]: Petermanns Mitteilungen, v. 74, no. 9–10, p. 273–276.

Kurter, A., and Sungur, K., 1980, Present glaciation in Turkey, *in* World Glacier Inventory, Proceedings of the workshop at Riederalp, Switzerland, 17–22 September 1978: International Association of Hydrological Sciences, Publication 126, p. 155–160.

Leutelt, R., 1935, Glazialgeologische Beobachtungen im Lasistanischen Hochgebirge [Glacial geology observations in the mountains of Lasistan]: Zeitschrift für Gletscherkunde, v. 23, no. 1–3, p. 67–80.

Loffler, E., 1970, Untersuchungen zum eiszeitlichen und rezenten klimagenetischen Formenschatz in den Gebirgen Nordostanatoliens [Investigations of Pleistocene and Holocene climato-genetic relict landforms in the northeastern Anatolian Mountains]: Heidelberger Geographische Arbeiten, no. 27, 162 p.

Louis, H., 1938, Eiszeitliche Seen in Anatolien [Pleistocene lakes in Anatolia]: Zeitschrift der Gesellschaft für Erdkunde zu Berlin, v. 73, no. 7–8, p. 267–285.

———1944, Die Spuren eiszeitlicher Vergletscherung in Anatolien [The evidence for Pleistocene glaciation in Anatolia]: Geologische Rundschau, v. 34, no. 7–8, p. 447–481.

Maunsell, F.R., 1901, Central Kurdistan: Geographical Journal, v. 18, no. 2, p. 121–144.

Messerli, B., 1964, Der Gletscher am Erciyas Dagh und das Problem der rezenten Schneegrenze im anatolischen und mediterranen Raum [The glacier on Mount Erciyes and the problem of the Holocene snow line in the Anatolian and Mediterranean region]: Geographica Helvetica, v. 19, no. 1, p. 19–34.

———1967, Die eiszeitliche und die gegenwärtige Vergletscherung im Mittlemeerraum [The Pleistocene and the Holocene glaciation in the Mediterranean region]: Geographica Helvetica, v. 22, no. 3, p. 105–228.

Palgrave, W.G., 1872, Vestiges of the glacial period in north-eastern Anatolia: Nature, v. 5 (April 1872), p. 444–445.

Penther, A., 1905, Eine Reise in das Gebiet des Erdschias-Dagh (Kleinasien), 1902 [A trip to the Mount Erciyes region (Asia Minor) in 1902]: Abhandlungen der K. K. Geographischen Gesellschaft in Wien, v. 6, no. 1, 48 p.

Philippson, A., 1906, Ein Gletscher am Erdschias-Dagh (Argaeus) in Kleinasien [A glacier on Mount Erciyes (Argaeus) in Asia Minor]: Zeitschrift für Gletscherkunde, v. 1, no. 1, p. 66–68.

———1918, Kleinasien. Handbuch der regionale Geologie [Asia Minor. Handbook of regional geology]: Heidelburg, C. Winters Universitätsbuchhandlung, v. 5, no. 2 (no. 22), 183 p.

Planhol, X. de, and Bilgin, T., 1964, Glaciaire et périglaciaire quaternaires et actuels dans le massif du Karagöl (Chaînes pontiques-Turquie) [Quaternary and present glacial and periglacial (landforms) in the Karagöl massif (Pontic Mountains of Turkey)]: Revue de Géographie Alpine, v. 52, no. 3, p. 497–512.

Schweizer, G., 1972, Klimatisch bedingte geomorphologische und glaziologische Züge der Hochregion vorderasiatischer Gebirge (Iran und Ostanatolien) [Climatically based geomorphological and glaciological characteristics of the high-altitude regions of Near Eastern mountain areas (Iran and eastern Anatolia)], *in* Geoecology of the high-mountain regions of Eurasia: Erdwissenschaftliche Forschung, v. 4, p. 221–236.

———1975, Untersuchungen zur Physiogeographie von Ostanatolien und Nordwestiran [Investigations of the physical geography of eastern Anatolia and northwestern Iran]: Tübinger Geographische Studien, v. 60, Special Issue 9, 145 p.

Simkin, T., Siebert, L., McClelland, L., Bridge, D., Newhall, C., and Latter, J.H., 1981, Volcanoes of the world: New York, Van Nostrand Reinhold, 232 p.

Spreitzer, H., 1939, Bergfahrten und Forschungen im Ala Dag (Südostanatolien). Deutsche Taurus-Bergfahrt 1938 des Zweiges Klagenfürt. Die Kundfahrt und ihre Ergebnisse [Mountain trip and investigations in the Ala Mountains (southeastern Anatolia). German expedition to the Taurus Mountains in 1938 of the Zweiges Klagenfürt. The scientific expedition and its results]: Zeitschrift des Deutschen Alpenvereins, v. 70, p. 50–52.

———1956, Untersuchungen im Kilikischen Ala Dag im Taurus [Investigations on Kilik, Ala Mountains of the Taurus Mountains]: Mitteilungen des Österreichischen Geographisches Gesellschaft, v. 98, no. 1, p. 57–64.

———1958, Frührezente und rezente Hochstände der Gletscher des Kilikischen Ala Dag im Taurus [Pre-Holocene and Holocene positions of the glacier on Kilik, Ala Mountains of the Taurus Mountains]: Innsbruck, Universitätsverlag Wagner, Geographische Forschungen (Festschrift zum 60. Geburtstag von Hans Kinzl), no. 190, p. 265–281.

———1959, Fussflächen am Kilikischen Ala Dağ im Taurus [Base level of Kilik, Ala Mountains of the Taurus Mountains]: Mitteilungen des Österreichischen Geographisches Gesellschaft, v. 101, no. 2, p. 183–201.

———1971, Rezente und eiszeitliche Grenzen der glazialen und periglazialen Hohenstufen im Zentralen Taurus (vornehmlich am Beispiel des Kilikischen Ala Dağ) [Holocene and Pleistocene limits of the glacial and periglacial elevation levels in the Middle Taurus Mountains (particularly the example on Kilik, Ala Mountains)]: Mitteilungen des Naturwissenschaftlichen Vereines für Steiermark, v. 101, p. 139–162.

Stratil-Sauer, G., 1927, Der östliche Pontus [The eastern Pontic Mountains]: Geographische Zeitschrift, v. 33, no. 9, p. 497–519.

———1961, Beobachtungen im Ostpontischen Gebirge unter besonderer Berücksichtigung der Kaltzeitlformen [Observations in the eastern Pontic Mountains, with particular reference to Pleistocene landforms]: Mitteilungen des Österreichischen Geographischen Gesellschaft, v. 103, no. 1, p. 1–24.

———1964, Beobachtungen im Ostpontischen Gebirge unter besonderer Berucksichtigung der Kaltzeitformen. Teil II [Observations in the eastern Pontic Mountains, with particular reference to Pleistocene landforms. Part 2]: Mitteilungen des Österreichischen Geographischen Gessellschaft, v. 106, no. 1, p. 16-44.

———1965, Beobachtungen im Ostpontischen Gebirge unter besonderer Berucksichtigung der Kaltzeitformen (Teil III) [Observations in the eastern Pontic Mountains, with particular reference to Pleistocene landforms (Part 3)]: Mitteilungen des Österreichischen Geographischen Gesellschaft, v. 107, no. 1–2, p. 20–44.

U.S. Board on Geographic Names, 1984, Gazetteer of Turkey: Defense Mapping Agency, Washington, D.C., 1,502 p.

Wright, H.E., 1962, Pleistocene glaciation in Kurdistan: Eiszeitalter und Gegenwart, v. 12, p. 131–164.

Glaciers of the Middle East and Africa—

GLACIERS OF IRAN

By JANE G. FERRIGNO

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

Edited by RICHARD S. WILLIAMS, Jr., *and* JANE G. FERRIGNO

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1386–G–2

Glaciers are situated in two mountain ranges and on one volcano in Iran and have an estimated total area of 20 km^2; Landsat images are of limited usefulness because of glacier size

CONTENTS

GLACIERS OF THE MIDDLE EAST AND AFRICA—

GLACIERS OF IRAN

By JANE G. FERRIGNO

Abstract

Glaciers occur in the higher elevations of the Elburz Mountains of north-central Iran, the Zagros Mountains in the southwest, and Kūhhā-ye Sabālan in the northwestern part of the country. The glaciers have a total area estimated to be about 20 square kilometers. The greatest concentration of glaciers exists in the western part of the Elburz Mountains in the region of the Takht-e Sulaiman massif on steep northward-facing slopes. The largest glacier, the Sarchal, is estimated to be 7 kilometers long with much of the surface entirely covered with rock debris. In the eastern Elburz Mountains, two small glaciers are located on Qōlleh-ye Damāvand, the highest peak in Iran. In the Zagros Mountains, five glaciers have been described, with the largest about 500 meters wide and spanning an elevation of about 150 meters. The Sabālan area has seven glaciers located on the northern, eastern, and western slopes of the summit peaks. During the Pleistocene, glaciation was much more extensive in Iran and included the present-day centers of glaciation and three other mountain areas. During that time the climatic snowline was 600 to 1,100 meters lower than the present level. The temperature structure was thought to be similar except that the mean temperature was 4 to 5 °C lower and the precipitation/evaporation ratio was higher. Cloud-free Landsat data exist for all the glacier areas of Iran. However, Landsat data are of limited usefulness for glacier studies and monitoring in Iran because of the resolution of the spacecraft sensors, the size of the glaciers, and the prevalent snow and debris cover.

Introduction

Before 1930, the consensus was that there were no present-day glaciers in Iran. Although Europeans had traveled widely in the country since the mid-1800's, including the high mountain areas, and published reports of their expeditions, either they had not seen the glaciers, had not recognized them, or their reports had been overlooked. The first European who recognized the presence of glaciers in the Elburz Mountains was Busk (1933). He was closely followed by Hans Bobek, who traveled widely throughout Iran. He carried out studies of the extent of contemporaneous and previous glaciation and published the results of his observations (Bobek, 1934, 1937). Since the 1930's, the Iranian glaciers have decreased in size but are still found in the same four main areas: in the higher elevations of the Reshteh-ye Kūhhā-ye Alborz (Elburz Mountains)[1] in the vicinity of Takht-e Sulaiman and Alam Kūh in the west, on Qōlleh-ye Damāvand in the east, on Kūhhā-ye Sabālan in the northwestern part of the country, and on Zard Kūh in the Kūhhā-ye Zagros (Zagros Mountains) in the southwest (fig. 1). The "General Introduction" that precedes the subchapter "Glaciers of Turkey" gives climatic and historical background on glacier occurrence in the Middle East.

Manuscript approved for publication April 12, 1988.

[1] The geographic names used in this subchapter are from Gazetteer No. 19, Iran (U.S. Board on Geographic Names, 1956). Familiar names are given in parentheses. Where there are no officially approved names for a geographic feature, the name commonly accepted in the English scientific literature is used.

***Figure 1.**—Location of present-day glaciers in Iran.*

The Elburz Mountains

The Elburz Mountains lie along the northern border of Iran at the southern shore of the Caspian Sea and extend about 650 km from west to east. The mountain range includes Qōlleh-ye Damāvand (5,670 m), the highest peak in Iran, and several other peaks that have summits higher than 3,000 m. The annual average precipitation in the vicinity of the range varies from 20 to 30 cm at Tehrān just south of the mountains to 30 to 50 cm midway through the range to 150 cm at Chālūs, north of the mountains. The prevailing winds, usually from the south, and the intense solar radiation prevent snow from accumulating on southward-facing slopes. As a result, large amounts of snow tend to accumulate, and glaciers and snow patches are most likely to occur on north-, northeast-, and northwest-facing slopes. The large accumulations of snow also create the potential for serious avalanches (Roch, 1961).

The Western Elburz Mountains

The greatest concentration of glaciers in Iran exists in the western part of the Elburz Mountains, in the region of the Takht-e Sulaiman massif (lat. 36°25′ N., long. 50°57′ E.) about 90 km northwest of Tehrān. The highest peak of the massif, Alam Kūh (4,840 m), is the second highest peak in Iran. The massif consists of several peaks over 3,000 m in elevation that are joined by high, narrow summit ridges (fig. 2). The glaciers are found mostly on the steep, northward-facing slopes of these peaks and ridges. The first European to travel in the Elburz Mountains and recognize the presence of glaciers was Busk (1933, 1935). He was followed by Bobek, who noted in 1934 the existence of several small cirque glaciers and a 3-km-long tongue glacier. He estimated the snowline to be at 4,000 m. In 1937 he described the tongue glacier more thoroughly. He said that it originated at about 4,200 m in a 2-km-wide cirque high on the north slope of Alam Kūh. The approximately 1-km-wide glacier gradually disappeared under an increasing cover of rock debris so that it was impossible to precisely locate the terminus, although it probably was between 3,700 and 3,600 m. The glacier became known as the Sarchal, named after the region in which it is located (fig. 3). Bobek located the snowline at 4,000 to 4,100 m.

In 1956, a group from Cambridge University climbed in the area and drew a sketch map (Harding, 1957). They mentioned four main glaciers in the area: the Sarchal Glacier, located northeast of the summit of Alam

Figure 2.—*Top, Panorama of Takht-e Sulaiman massif from the east with Alam Kūh (center) and Takht-e Sulaiman (right) (from Harding, 1957).*

Figure 3.—*Bottom, Alam Kūh (left), Takht-e Sulaiman (right), and the head of Sarchal Glacier as photographed by Bobek in 1936 (from Busk, 1937).*

Kūh, a northwest glacier, and two glaciers to the south of the summit, the Hazarchal and the Hazarcham (fig. 4). They also noted two small, unnamed glaciers. The sketch map produced by Harding and those made by earlier travelers (Busk, 1935) were the only available maps of the area until 1957, when Bobek produced an excellent map at 1:100,000 scale of the Takht-e Sulaiman region (Bobek, 1957). It remains the only map of Iran that shows the occurrence of glaciers.

In 1958, Péguy, a member of a French expedition in Iran, described and sketched the glaciers in the vicinity of Alam Kūh, although he concentrated on the Sarchal Glacier (fig. 5) (Péguy, 1959). He described the Sarchal as forming from the confluence of three unequal segments. He estimated its length at 7 km with two-thirds of the surface entirely covered with rock debris. In describing its motion, he said that the eastern third consisted of active ice bounded by an active lateral moraine and covered by debris 0.5 to 1.5 m thick. The other two-thirds was mostly

Figure 4.—*The glaciers in the Takht-e Sulaiman massif region (from Harding, 1957).*

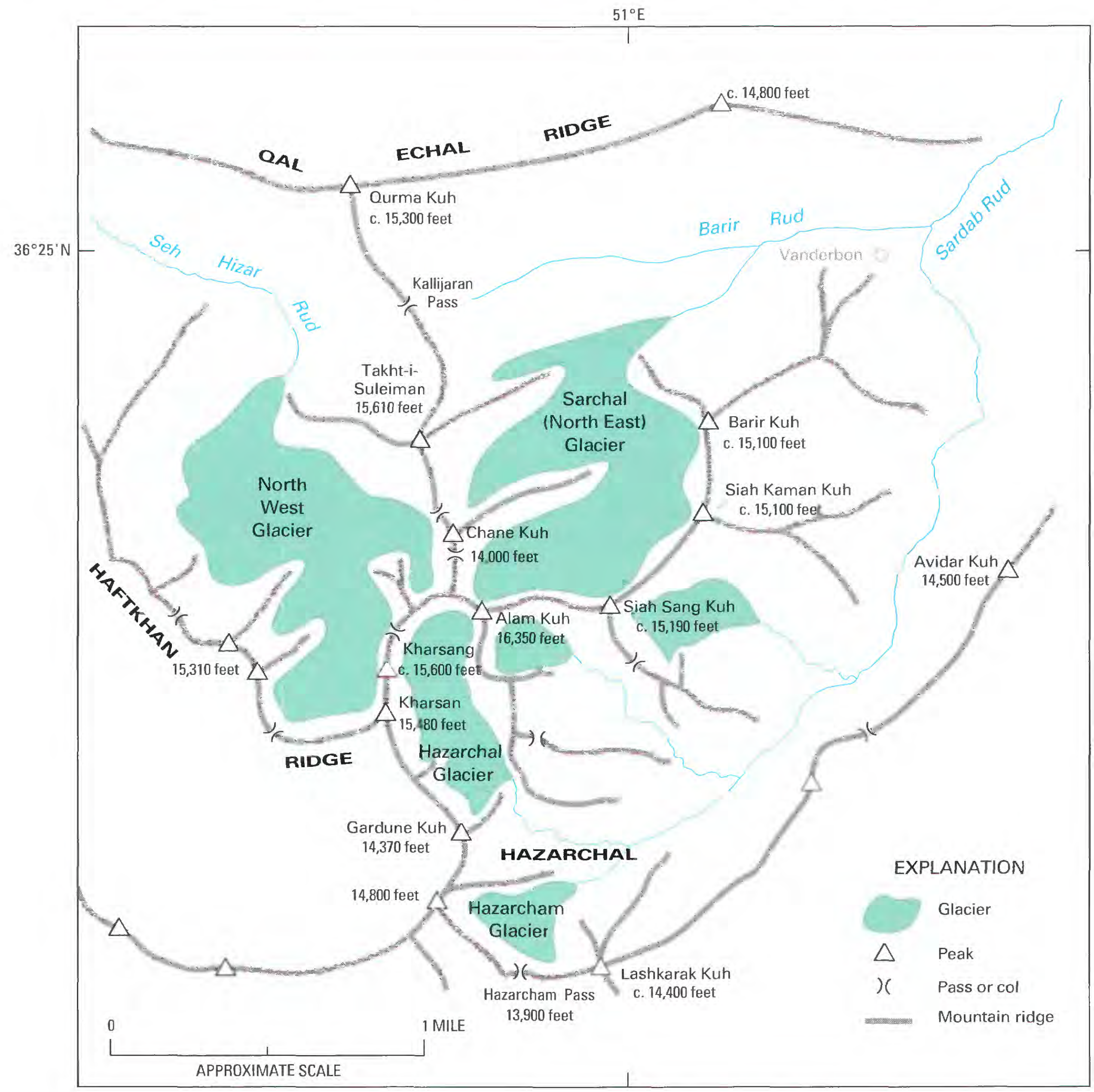
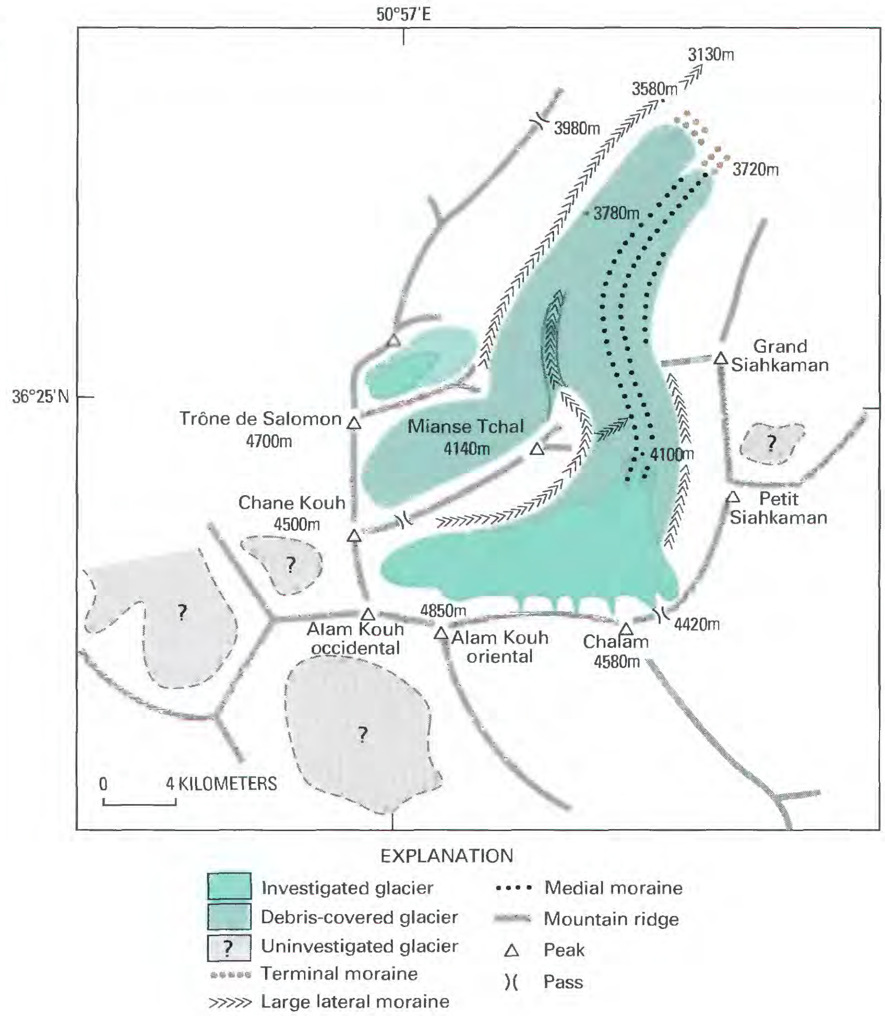


Figure 5.—Sarchal Glacier, Takht-e Sulaiman massif (from Péguy, 1959).



inactive ice covered with several meters of inert cover. The most recent data for the area (Schweizer, 1972) locate the snowline at 4,150 m. This estimate is based on the work of Bout and others (1961).

The Eastern Elburz Mountains

At present all of the glaciers in the eastern Elburz are located on Qōlleh-ye Damāvand (lat. 35°56′ N., long. 52°08′ E.). Damāvand, a dormant stratovolcano, is located about 70 km northeast of Tehrān. Because it is the highest peak in Iran and because it is not difficult to reach from the south, it has been climbed repeatedly. Notes of a visit by Watson in 1861 described a summit covered by snow and sulfur (Watson, 1862). He found places where there were sulfur fumes and the ground was too hot to sit on for more than a few minutes. It was not until Bobek's visit with the German climbing expedition of 1936, however, that the glaciers were mentioned (Bobek, 1937). He described the peak as almost entirely covered by firn above 4,500 m. The firn was continuous in the highest regions and separated into deeply eroded bands of snow and ice farther down. He recognized two small glaciers, one on the east slope, the other on the north slope (fig. 6). The eastern glacier descended from the peak to the steep, fragmented cliff walls at the head of the Talu Valley

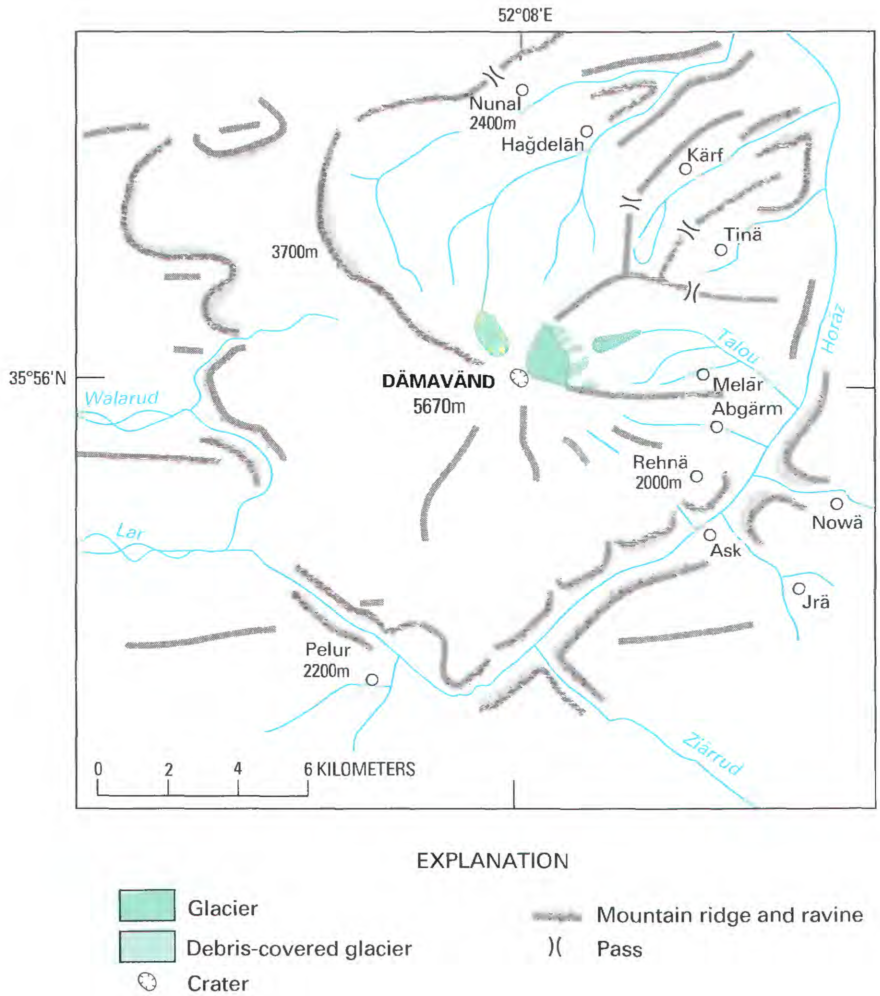


Figure 6.—*The glaciers on Damāvand (from Bobek, 1937).*

at about 4,800 to 5,000 m elevation. Here the glacier broke off cleanly, and the thickness was seen to be about 50 m. Glacier ice accumulated at the foot of the cliffs at about 3,900 m in ice debris cones and extended downward to about 3,400 m. The glacier on the northern slope started 600 to 800 m below the summit, extending downslope to about 4,400 m. At the lower elevations the glacier was broken and fragmented. Bobek placed the snowline at 4,500 m.

In September 1958, Péguy climbed the volcano with the French group and described the summit region (Péguy, 1959). He described a northeastern glacier (probably Bobek's eastern glacier) having a surface area of about 2 km^2. It formed a little below the summit at about 5,550 to 5,600 m and ended at about 5,100 m. The glacier was covered with large penitentes and a series of crevasses. There was not much debris cover. Penitentes, an annual phenomenon of snow sublimation related to solar radiation and arid climate, occur only on selected peaks in the region; they do not occur on similar peaks in nearby Turkey. Although penitentes form on the highest peaks in Iran—Damāvand, Alum Kūh, and Sabālan—climate is more important than elevation to their formation. The incidence angle of the Sun, the intensity of the radiation, and the dryness of the air in late summer and early fall, the time of maximum development, determine the occurrence, size, and shape of the penitentes (Schweizer, 1972). In addition, Péguy noted the southern side of the summit crater was covered by ice. Here and on the southern slope of the volcanic cone were penitentes 50 to 80 cm or more in height. The most recent data on the area are given by Schweizer (1972). He described the southern slope above 4,800 m and the summit crater of Damāvand as covered with firn and penitentes (fig. 7).

South of Damāvand a small glacier referred to as a "tonsurgletscher" was observed on Tare Mumedsch at 3,035 m in September 1936 (Heybrock, 1940). However, no mention of the glacier has been made since that time, and it has most likely disappeared.

Figure 7.—*Penitentes in the summit crater of Damāvand (photograph by E. Durr, 7 September 1968; from Schweizer, 1972).*

Kūhhā-ye Sabālan

The Sabālan area (lat. 38°15′ N., long. 47°49′ E.) has a continental climate with hot, dry summers and extremely cold, snowy winters (Schweizer, 1970). Although there are no meteorological stations on the mountain itself, Schweizer was able to estimate the annual precipitation to be between 400 and 700 mm, on the basis of the elevation of the mountain and extrapolation of data from surrounding stations. The precipitation, which falls almost exclusively as snow in the late autumn, winter, and spring, nourishes the glaciers on the highest peaks. During the arid summer, there is considerable ablation, however.

The presence of glaciers on Sabālan (4,740 m) was first recognized in 1885 by Sjögren (1888), who described a small cirque glacier that was about 1 km long, 0.33 km wide, and descended to about 3,800 m. However, his report was not widely known. In 1934, Bobek observed the glaciers from a distance and estimated the snowline to be between 3,900 and 4,000 m (Bobek, 1934). A few years later, Bobek (1937) listed the height of the snowline on the north side of Sabālan as 4,000 to 4,100 m.

In September 1955, a German mountain climbing group climbed the peak and photographed and described the glaciers (Klebelsberg, 1958). On the northwest slope, there were large, interconnected glaciers extending from the summit downward to 4,000 m. On the south to southwestern sides there were only limited snow fields.

In 1968 and 1969, Schweizer carried out extensive fieldwork in the area (Schweizer, 1970, 1972). His description of the glaciers is very detailed, and he included information on glacier size and orientation and the maximum and minimum elevations of the ice (table 1). He counted seven glaciers and sketched their locations (fig. 8). The largest glacier is located on the steep north slope of the principal, or east, peak. Slightly east of this glacier lies a narrow, twisting couloir that is partially filled with a small glacier, one of the smallest of the group. The middle and western summits contain the remaining glaciers observed by Schweizer. The only glacier that has an eastern exposure is a small cirque glacier, the most southerly of the cirque glaciers. There are three small glaciers side by side on the steep north wall of these peaks. The last glacier is a small ice patch on the western slope of the western peak. The glaciers on Sabālan are often characterized by a heavy, continuous debris cover, and many glaciers appear to grade into and (or) continue as rock glaciers. Schweizer listed the height of the snowline as 4,500 m. Penitentes are also found on the summit of Sabālan between 4,200 and 4,300 m and are best developed above 4,500 m.

The Zard Kūh Area

The climate of the Zagros Mountains is typically Mediterranean, with dry summers and precipitation in the fall, winter, and spring. The spring and summer precipitation is caused by cyclonic storms that move as cold fronts and are characterized by snow at higher elevations. The winter precipitation is a result of anticyclonic, more gentle fronts. The precipitation increases generally with the elevation of the land area and ranges from 300 mm per year in the outer foothills to more than 1,000 mm per year in the highest part of the range (Wright, 1962).

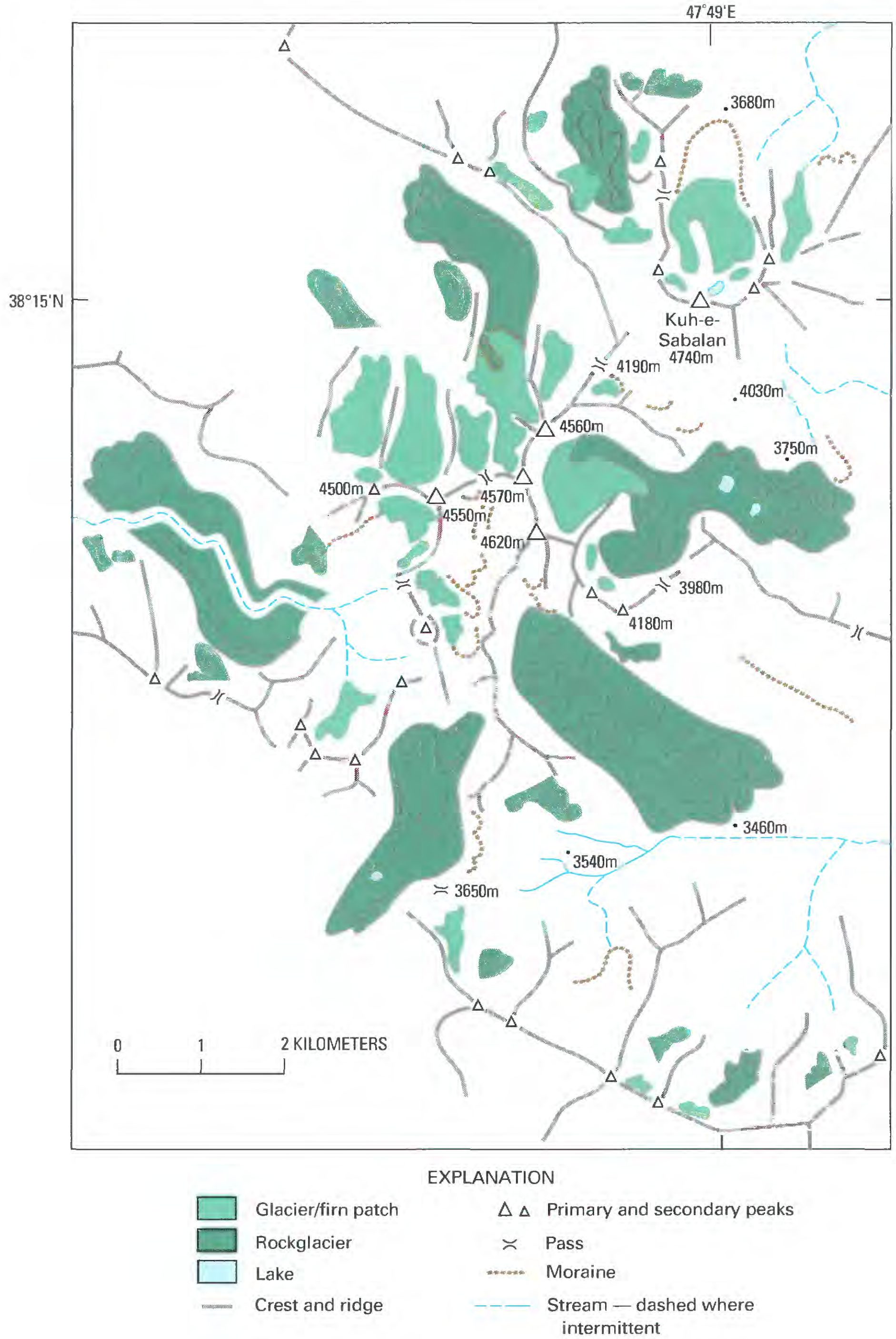
Small glaciers were first observed in the Zagros Mountains on the northern slopes of Zard Kūh (4,268 m) (lat. 32°22′ N., long. 50°04′ E.) during August 1933 (Desio, 1934b). Desio described, photographed, and named four small glaciers with a combined area of 150 hectares (ha). The largest glacier, which he called "Ghiacciaietto del Kulang-ci," had an area

TABLE 1.—*The recent glaciers of Kūhhā-ye Sabālan*

[Modified from Schweizer, 1970; —, no data; do., ditto]

Glacier	Glacier type	Orientation	Highest ice occurrence (m)	Lowest occurrence of clean ice (m)	Average height of surrounding ridges (m)	Orographic snowline (m)	Visible firn line (mid-Sept. 1968)	Maximum length (m)	Maximum width (m)
Large North Glacier	Cirque	North	4,700	3,980	4,700	4,340	4,000	900	650
North Couloir Glacier	Couloir	North	4,500	4,000	4,600	4,200	—	750	150
East Glacier	Cirque	East-northeast	4,250	4,020	4,500	4,260	4,100	750	600
Eastern Northwest Glacier	Slope	North	4,400–4,500	4,000	4,480	4,230	not continuous	850	550
Middle Northwest Glacier	Slope	North	4,540	4,050	4,550	4,300	....do...	850	450
Western Northwest Glacier	Slope	North	4,420	4,000	4,500	4,210	....do...	800	450
West Summit Glacier	Plateau	West	4,500	4,460	4,520	4,490	—	400	350

Figure 8.—The occurrence of glaciers on Kūhhā-ye Sabālan (modified from Schweizer, 1972).



of 70.4 ha. Each glacier occupied a span of about 200 m elevation, with the minimum occurring at about 3,600 m and the maximum at 4,200 m. In 1937, Bobek listed the snowline at 4,000 to 4,100 m. In 1963, Dr. H. McQuillan (1969) photographed the "Ghiacciaietto" (fig. 9). He estimated its width at 400 m. Comparison of his photograph with Desio's sketch shows that the glacier had thinned considerably and that the toe had receded at least 20 m of the total 100 m elevation it spanned.

In 1972, Schweizer used the work of others and his own analysis of aerial photographs to estimate the height of the snowline at Zard Kūh at 4,050 m. In 1975, Grunert and others (1978) studied the glaciers, firn patches, snowline, and climate of the Zard Kūh area. They described and

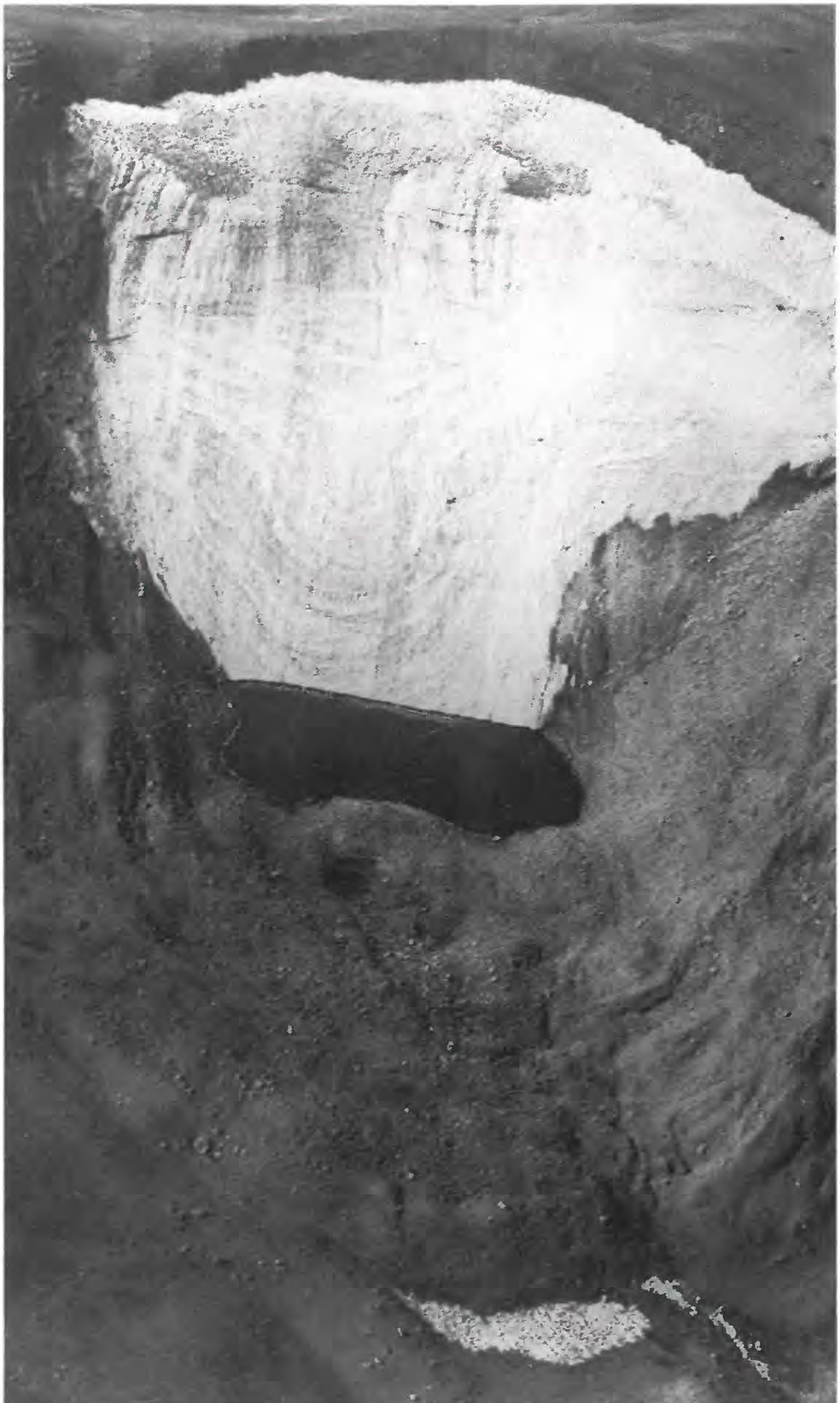
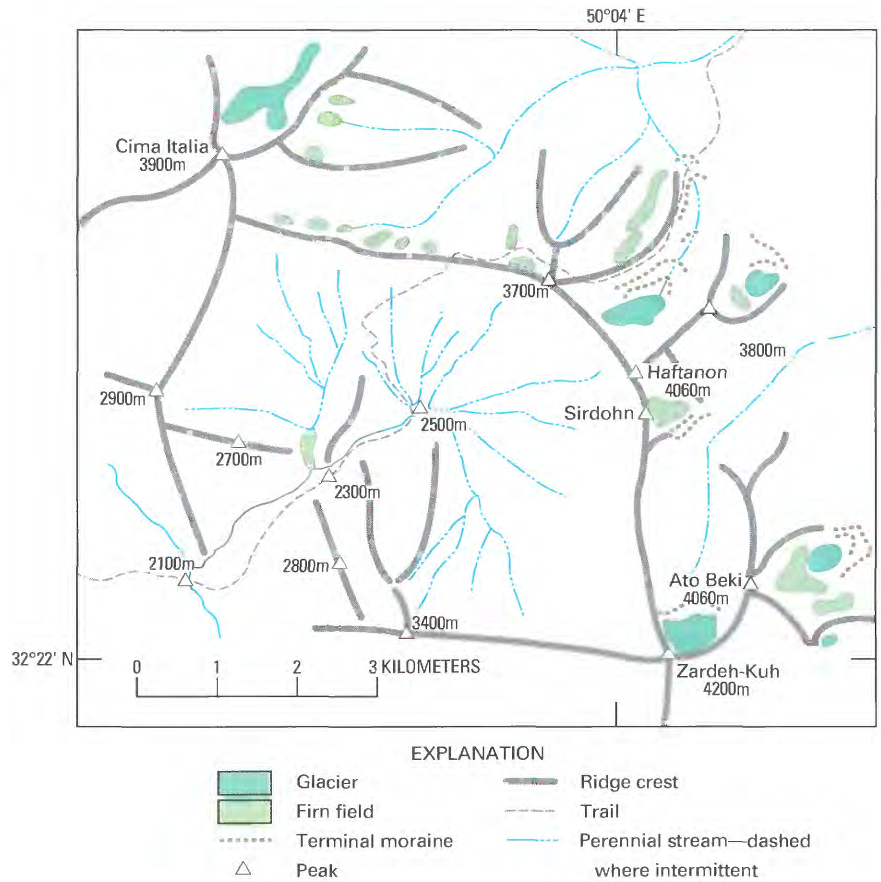


Figure 9.—*The largest glacier on the north slopes of Zard Kūh as photographed by H. McQuillan, 1963 (from McQuillan, 1969).*

Figure 10.—The glaciers of Zard Kūh (modified from Grunert and others, 1978).



sketched the location of five glaciers (fig. 10). The largest was described as 500 m wide and spanned an elevation of 150 m from 3,900 to 4,050 m. On the basis of the location and condition of the glaciers and firn patches, they concluded the snowline had dropped to 3,900 m. They noted that the Zagros Mountains contain glaciers, while equally high mountains to the east do not because of the weather pattern. Other areas eastward fall within the precipitation shadow of the Zagros Mountains and are much more arid.

Glacier Fluctuation

During the Pleistocene, there were six centers of glaciation in Iran, according to Bobek (1963), including the central Elburz Mountains, Kūhhā-ye Sabālan, Zard Kūh, and three other mountain areas. The most important single area was the Takht-e Sulaiman massif of the central Elburz. Here the Sarchal Glacier, currently the largest in Iran at about 7 km, extended between 20 and 25 km. Two other glaciers, one 13 km and the other 11 km long, also were present. Bobek (1963) also maintained that during the Pleistocene the climatic snowline throughout the country was 600 to 800 m lower than the present level and that the temperature structure was similar to current patterns except that the mean temperature was 4 to 5 °C lower. On the basis of a study of the playas, Krinsley concluded that, during the Würm maximum, the outward-facing slopes of the northern Zagros and Elburz Mountains had mean annual temperatures 5 to 8 °C colder than at present. The snowline was depressed as much as 1,800 m (Krinsley, 1970). Krinsley also (1968) added that the Pleistocene climate of Iran was more compartmented than in other countries in similar latitudes. He stated that, although the Pleistocene climate of northern Iran was similar to the present climate, the precipitation/evaporation ratio was higher because of decreased evaporation resulting from lower summer temperatures (Krinsley, 1972). Schweizer (1970) compared Pleistocene and present snowlines on the basis of his own and earlier studies (table 2). Since the end of the Pleistocene, there is evidence of a series of stadial retreats and readvances of the glaciers as the climate cycle progressed. The cool, dry climate of the Pleistocene gave way to a warm, dry climate, and the level of precipitation increased slowly during the Hypsithermal until about 5,500 years ago (Wright, 1968). This period was followed by the colder temperatures of the Neoglacial. Minor temperature fluctuations occurred until the generally cooler times of the "Little Ice Age" of the 16th and 18th centuries. Since the 19th century the glaciers of Iran have probably followed the same general pattern as described for Turkey by Erinç (1952). He stated the trend has been toward general recession interrupted by periods of growth. Since 1930, the rate of recession has accelerated. The contemporary glaciers, however, are not relict but have regenerated in post-Pleistocene times and at one time covered an area twice their present size.

Information on the total areal coverage of glaciers in Iran is nonexistent. Previous reviews of Iran's glaciers have discussed occurrence, but not areal extent (Klebelsberg, 1949; McCauley, 1958; Horvath, 1975). Drygalski and Machatschek (1942) estimated the total glacier area of Turkey, Armenia, and Iran to be about 100 km^2. Recent estimates by Kurter for the total glacier area of Turkey, included elsewhere in this chapter, are 22.9 km^2. A very rough estimate for the current size of Iran's glaciers is 20 km^2. This estimate is based on estimates of 14 km^2 for the glaciers of the Takht-e Sulaiman massif made from sketch maps listed on table 3, 2.0 km^2 for Damāvand (Péguy, 1959), 2.4 km^2 for Sabālan (Schweizer, 1970), and 1.5 km^2 for Zard Kūh (Desio, 1934b).

TABLE 2.—*The height of the present and Pleistocene snowlines in selected mountain areas of Iran*

[Modified from Schweizer, 1970]

Mountain area	Summit height (m)	Present snowline (m)	Pleistocene snowline (m)	Source
Takht-e Sulaiman	4,840	4,000–4,100	3,000	Bobek, 1937; Bout and others, 1961.
Damāvand	5,670	4,500	3,700–3,800	Bobek, 1937; Bout and others, 1961.
Sabālan	4,740	4,500	3,600–3,700	Schweizer, 1970.
Zard Kūh	4,268	3,900	3,350–3,400	Desio 1934a; Grunert and others, 1978.

Available Data for Glacier Studies

Maps

There are a very limited number of maps available for glacier studies of Iran. The first maps available were the sketch maps produced by early travelers and climbers. Later researchers also produced sketch maps because of the absence of accurate maps showing glacier occurrence. The only published map that shows the occurrence of glaciers is a map by Bobek at a scale of 1:100,000 of the Takht-e Sulaiman massif area, published in 1957. Later maps, which have been produced at various scales, do not show the glaciers but depict the topography of each of the glacier areas. Information about the available maps is given in table 3.

TABLE 3.—*List of maps covering the glacier areas of Iran*

Map or author	Scale	Glacier areas covered
Published maps and charts		
U.S. Defense Mapping Agency–Operational Navigation Chart ONC G-5	1:1,000,000	All areas
U.S. Defense Mapping Agency–Joint Operations Graphic, Series 1501	1:250,000	
Sheet NJ 39–14, 15		Takht-e Sulaiman
Sheet NI 39–3		Damāvand
Sheet NJ 38–8		Sabālan
Sheet NI 39–14		Zard Kūh
Kartog Anstalt Freytag-Berndt und Artaria, Vienna–Karte der Takht-e Sulaimangruppe in mittleren Alburzgebirge, Nordiran	1:100,000	Takht-e Sulaiman
Geological Survey of Iran–Geological Map of the Central Alborz Sheet Damāvand	1:100,000	Damāvand
Sketch maps		
Busk, 1935	~1:90,000	Takht-e Sulaiman
Harding, 1957	~1:90,000	Takht-e Sulaiman
Péguy, 1959	~1:50,000	Takht-e Sulaiman
Bobek, 1937	~1:300,000	Damāvand
Schweizer, 1972	~1:70,000	Sabālan
Grunert and others, 1978	~1:90,000	Zard Kūh

Aerial Photographs

Some aerial photographs were acquired by the U.S. Air Force for the U.S. Army Map Service in the late summer and fall of 1955 and 1956 and the summer of 1970. The photographs are valuable for getting an accurate view of the glaciers at that time. The photographs that cover the glacier areas are listed in table 4. The photograph taken of Damāvand in August 1955 is particularly good (fig. 11). It was taken at a time of minimum snow cover, and the two glaciers described by Bobek are clearly visible.

TABLE 4.—*Aerial photographic coverage of the glacierized areas of Iran*

Date	Project	Sortie	Frame	Approximate scale
Takht-e Sulaiman area				
03 Oct 55	158	M99	15938–15940	1:60,000
03 Oct 55	158	S99	15937A–15940	1:30,000
03 Oct 55	158	S99	15904–15909	1:30,000
Damāvand area				
13 Sept 56	158	M231	33578	1:45,000
01 Aug 55	157	LS23A	3736–3736A	1:30,000
Sabālan area				
08 Jun 70	NW-IRAN	R25	1553–1555	1:60,000
Zard Kūh area				
31 Aug 55	158	R64A	10774A–10775	1:30,000
31 Aug 55	158	R64	10773–10775	1:60,000
29 Aug 55	158	R59A	9861A–9862A	1:30,000
29 Aug 55	158	59	9951–9953, 9961–9963	1:50,000

Figure 11.—*Aerial photograph of the glaciers on Damāvand acquired in August 1955 by the U.S. Air Force for the Army Map Service, Project 157, Frame 3736A. Approximate scale 1:30,000.*

TABLE 5.—*Optimum Landsat 1, 2, and 3 images of the glaciers of Iran*

[A filled-in circle in the "Code" column means an excellent image, 0 to ≤5 percent cloud cover over glacier areas]

Path-Row	Nominal scene center (lat-long)	Landsat identification number	Date	Solar elevation angle (degrees)	Code	Cloud cover (in percent)	Remarks
176–35	35°58′N. 52°45′E.	21263–06052	08 Jul 78	55	●	0	Damāvand; color composite available
177–35	35°58′N. 51°19′E.	2580–06240	24 Aug 76	50	●	0	Damāvand, Takht-e Sulaiman
177–37	33°07′N. 50°26′E.	1044–06443	05 Sep 72	53	●	0	Zard Kūh
180–33	38°49′N. 47°57′E.	1083–07001	14 Oct 72	38	●	0	Sabālan
180–34	37°24′N. 47°29′E.	2187–06485	28 Jul 75	56	●	0	Sabālan; color composite available

Satellite Imagery

Cloud-free Landsat data exist for all the glacier areas of Iran (table 5, fig. 12). However, standard Landsat multispectral scanner (MSS) photographic data have limited usefulness for glacier studies in Iran. The glaciers are all very small, with only a few (Sarchal and the northwest glacier on Alam Kūh and the northeast glacier on Damāvand) being larger than 0.5 km^2, and they are difficult to resolve on standard Landsat imagery. The situation is made more difficult by the fact that snow cover and debris cover, which are common on most of Iran's glaciers, make glacier features harder to discern. Photographic enlargements and color composites make it easier to see the glaciers, but the glacier features are still hard to distinguish (figs. 13 and 14). Figure 13, a section of a color composite image, shows the snow and ice cover on Damāvand, but it is impossible to separate snow from ice. Figure 14, a 1:250,000-scale enlargement of band 7 MSS image of Sabālan clearly shows some of the individual snow and ice patches, but detailed features and glacier areas covered by debris or hidden by shadow are not distinguishable. Digital enhancement techniques have been successfully used for glacier studies in some areas such as described in the subchapters on Irian Jaya, Indonesia, and the Italian Alps. Such techniques have not been tried in Iran but might offer additional information.

In some areas it is possible to use Landsat imagery to (1) delineate glacier distribution, (2) map glacier outlines, (3) monitor glacier fluctuations, (4) distinguish transient snowlines, (5) inferentially determine changes in mass balance, and (6) indicate the former extent of glaciers by showing the location of abandoned moraines or by showing traces of glacial erosion such as cirques, arêtes, or glaciated valleys. However, the size of glaciers in Iran and conditions of snow cover, debris cover, and, in the case of Damāvand and Sabālan, surrounding recent igneous rocks that are resistant to glacial erosion, make this difficult. Data from sensors having greater spectral and (or) spatial resolution are becoming available, including data from the Landsat Thematic Mapper (TM), the Large Format Camera (LFC), and the French Système Probatoire d'Observation de la Terre (SPOT). Such new data will be able to contribute to glacier studies and monitoring in Iran and in other glacierized regions of the world where the resolution of the Landsat MSS sensor is not adequate.

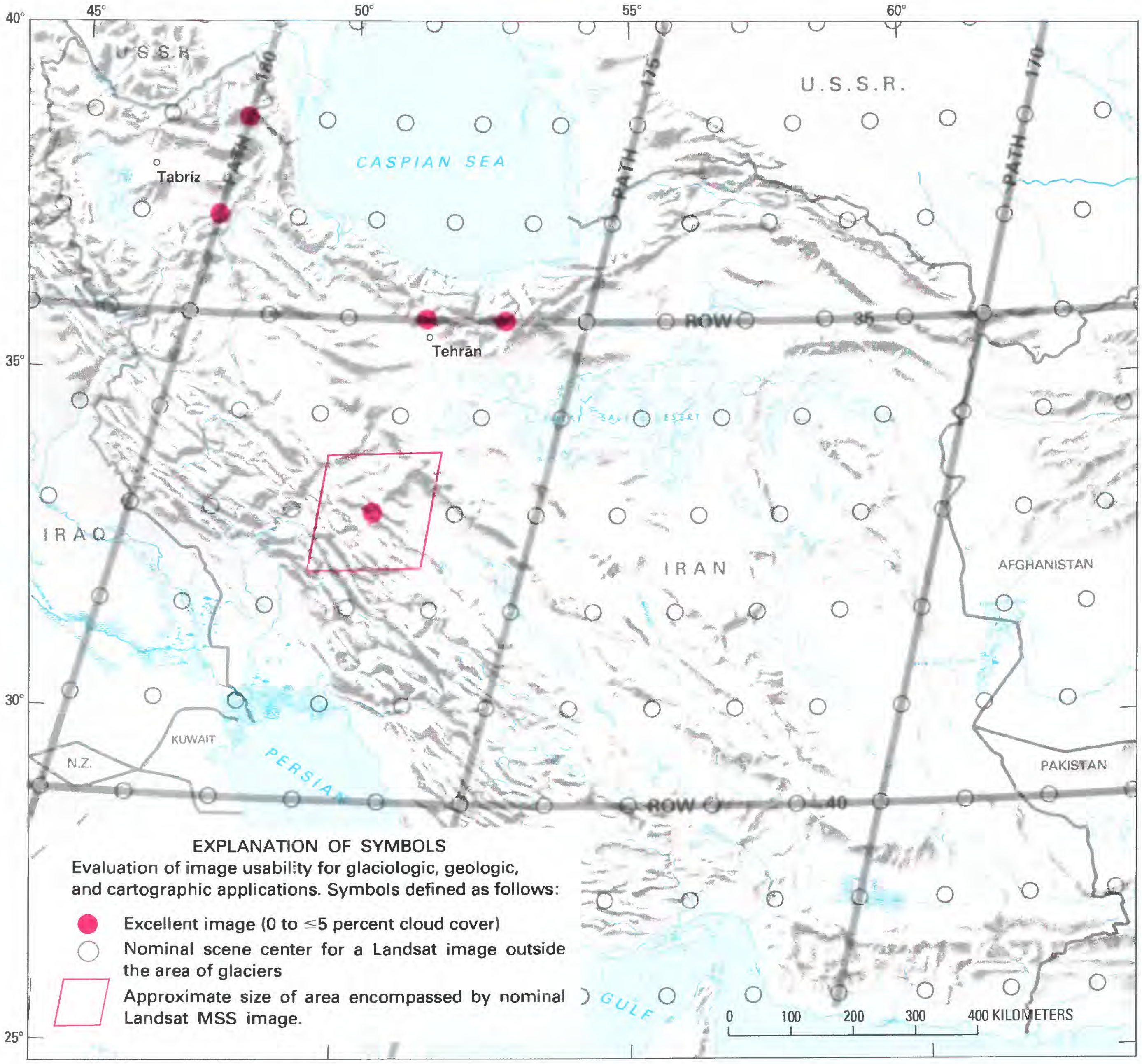
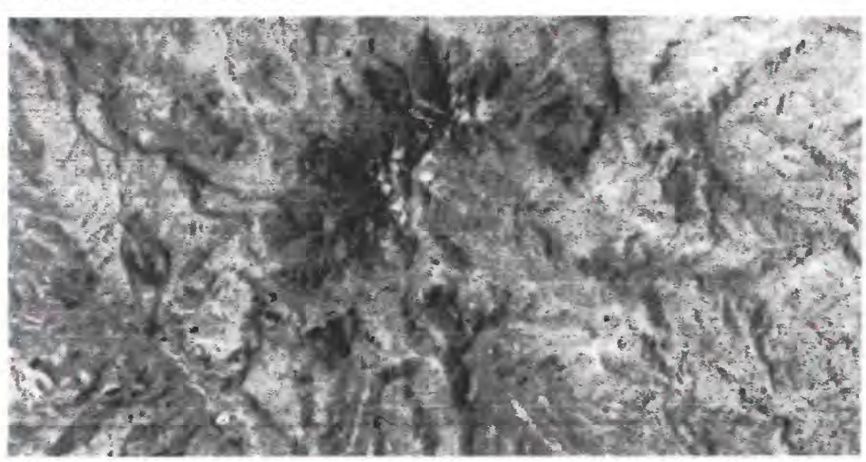


Figure 12.—*Optimum Landsat 1, 2, and 3 images of the glaciers of Iran. The vertical lines represent nominal paths. The rows (horizontal lines) have been established to indicate the latitude at which the imagery has been acquired.*



Acknowledgment

The author wishes to thank N. Tamberg for assistance in translating some of the German references.

References Cited

Bobek, H., 1934, Reise in Nordwestpersien 1934 [Travel in northwest Persia 1934]: Zeitschrift der Gesellschaft für Erdkunde zu Berlin, v. 9/10, p. 359–369.

———1937, Die Rolle der Eiszeit in Nordwestiran [The role of the ice age in northwestern Iran]: Zeitschrift für Gletscherkunde, v. 25, p. 130–183.

———1957, Die Takht-e Sulaimāngruppe im mittleren Alburzegebirge, Nordiran, *in* Wiche, K., ed., Festschrift zur Hundertjahrfeier der Geographischen Gesellschaft in Wien 1856–1956 [Anniversary Publication for the Centennial of the Geographical Society of Vienna 1856–1956]: Geographische Gesellschaft Vienna, p. 236–264.

———1963, Nature and implications of Quaternary climatic changes in Iran, *in* Changes of climate, Proceedings of Symposium on Changes of Climate with Special Reference to Arid Zones: Rome, 1961, UNESCO, p. 403–413.

Bout, P., Derruau, M., Dresch, J., and Péguy, Ch.P., 1961, Observations de geographie physique en Iran septentrional. Expedition 1958 sous les auspices du C.N.R.S. [Observations on the physical geography of northern Iran. Expedition of 1958 under the auspices of C.N.R.S.]: Memoires et Documents 8, Paris, p. 9–112.

Busk, D.L., 1933, Climbing and ski-ing in the Elburz Range, North Persia, 1931–2: Alpine Journal, v. 45, no. 247, p. 334–341.

———1935, Climbing in the Takht-i-Suleiman Group, N. Persia: Alpine Journal, v. 47, no. 251, p. 299–309.

———1937, The German expedition in the Elburz Range, N. Persia: Alpine Journal, v. 49, no. 255, p. 245–247.

Desio, A., 1934a, Appunti geografici e geologici sulla catena dello Zardeh Kuh in Persia [Geographic and geologic information concerning the Zard Kūh mountains in Persia]: Memorie Geologiche e Geographiche di G. Dainelli, 4, p. 141–167.

———1934b, Sull'esistenza di piccoli ghiacciai nella Persia occidentale [Concerning the existence of small glaciers in western Persia]: Bollettino del Comitato Glaciologico Italianao, no. 14, p. 39–52.

Drygalski, E. von, and Machatschek, F., 1942, Enzyklopädie der Erdkunde: Gletscherkunde [Encyclopedia of Earth Sciences: Glaciology]: Wien, Franz Deuticke, 261 p.

Erinç, S., 1952, Glacial evidences of the climatic variations in Turkey: Geografiska Annaler, v. 34, no. 1–2, p. 89–98.

Grunert, J., Carls, H.-G., and Preu, C., 1978, Rezente Vergletscherungsspuren in zentraliranischen Hochgebirgen [The present-day glaciers of the central Iranian high mountains]: Eiszeitalter und Gegenwart, v. 28, p. 148–166.

Harding, J.G.R., 1957, Cambridge Expedition, 1956, to the Elburz Mountains, Iran: Himalayan Journal, v. 20, p. 112–121.

◀ ***Figure 13.***—Left, *Section of a 1:1,000,000-scale Landsat 2 MSS color-composite image 21263–06052 (Path 176, Row 35, acquired 8 July 1978) showing Damāvand.*

◀ ***Figure 14.***—Right, *A 1:250,000-scale enlargement of a section of Landsat MSS image 2187–06485 (band 7; Path 180, Row 34, acquired 28 July 1975) showing some of the glaciers and snow patches on Sabālan.*

Heybrock, W., 1940, Naturwissenschaftliche Beobachtungen in Iran: Petermanns Geographische Mitteilungen 86, no. 4, p. 124–131.

Horvath, E., 1975, Glaciers of Turkey, Armenian S.S.R. and Iran, *in* Field, W.O., ed., Mountain glaciers of the Northern Hemisphere, pt. III, Glaciers of Southern Asia: Hanover, N.H., U.S. Army Cold Regions Research and Engineering Laboratory, p. 343–359.

Klebelsberg, R. von, 1949, Handbuch der Gletscherkunde und Glazialgeologie [Handbook of glaciology and glacial geology]: Wien, Springer-Verlag, 1028 p.

———1958, Von der Vergletscherung des Kuh-i-Sawalan (4,821 m), Nordwest-Persien [The glaciers of Kūhhā-ye Sabālan (4,821 m) northwest Persia]: Zeitschrift für Gletscherkunde und Glazialgeologie, v. 4, no. 1–2, p. 119–120.

Krinsley, D.B., 1968, Geomorphology of three kavirs in northern Iran, *in* Neal, J.T., ed., Playa surface morphology: Miscellaneous investigations, chap. 5: Air Force Cambridge Research Laboratory, Environmental Research Papers, no. 283, p. 105–130.

———1970, A geomorphological and paleoclimatological study of the playas of Iran: U.S. Geological Survey Interagency Report IR–Military–1, 329 p.

———1972, The paleoclimatic significance of the Iranian playas, *in* Zinderen Bakker, E.M. van, ed., Palaeoecology of Africa, v. 6: Cape Town, A.A. Balkema, p. 114–120.

McCauley, C., 1958, Glaciers of Turkey, Iran, and Soviet Armenia, *in* Glaciation in the Northern Hemisphere, pt. 6, Western, arctic, and eastern Asia: New York, American Geographical Society, p. 6.1.1–6.1.4.

McQuillan, H., 1969, Small glacier on Zardeh Kuh, Zagros Mountains, Iran: Geographical Journal, v. 135, pt. 4, p. 639.

Péguy, Ch.P., 1959, Les glaciers de l'Elbourz [The glaciers of the Elburz Mountains]: Bulletin de l'Association de Géographes Français, no. 284–285, p. 44–49.

Roch, A., 1961, Avalanche danger in Iran: Journal of Glaciology, v. 3, no. 30, p. 979–983.

Schweizer, G., 1970, Der Kuh-e-Sabalan (Nordwestiran). Beiträge zur Gletscherkunde und Glazialgeomorphologie vorderasiatischer Hochgebirge [Kūhhā-ye Sabālan (northwest Iran). Contributions on the glaciology and glacialgeomorphology of the high mountains of the Near East], *in* Beiträge zur Geographie der Tropen und Subtropen: Tübinger Geographische Studien, no. 34, p. 163–178.

———1972, Klimatisch bedingte Geomorphologische und Glaziologische Züge der Hochregion vorderasiatischer Gebirge (Iran und Ostanatolien) [Climatically based geomorphological and glaciological characteristics of the high-altitude regions of Near Eastern mountains (Iran and Eastern Anatolia)]: Erdwissenschaftliche Forschung, v. 4, p. 221–236.

Sjögren, H., 1888, Beiträge zur Geologie des Berges Savelan in nördlichen Persien [Contributions to the geology of the Sabālan Mountains in northern Persia]: Verhandlungen der Russisch-Kaiserlichen Mineralogischen Gesellschaft zu St. Petersberg, Series 2, v. 24, p. 36–66.

U.S. Board on Geographic Names, 1956, Gazetteer No. 19, Iran: Washington, D.C., U.S. Government Printing Office.

Watson, R.G., 1862, Notes of a visit to the Elburz Mountains and ascent of Demavend: Royal Geographic Society Proceedings, v. 6, p. 103–105.

Wright, H.E., Jr., 1962, Pleistocene glaciation in Kurdistan: Eiszeitalter und Gegenwart, v. 12, p. 131–164.

———1968, Climatic change in the Eastern Mediterranean region: Limnological Research Center, University of Minnesota, Minneapolis, 15 p.

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

Edited by RICHARD S. WILLIAMS, Jr., *and* JANE G. FERRIGNO

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1386–G–3

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

CONTENTS

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

GLACIERS OF THE MIDDLE EAST AND AFRICA—

GLACIERS OF AFRICA

By JAMES A.T. YOUNG[1] *and* STEFAN HASTENRATH[2]

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 Atlas[3] 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 km^2 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).

Manuscript approved for publication February 3, 1987.

[1]Department of Geography, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, Scotland, U.K.

[2]Department of Meteorology, University of Wisconsin, 1225 West Dayton Street, Madison, WI 53706.

[3] The 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.

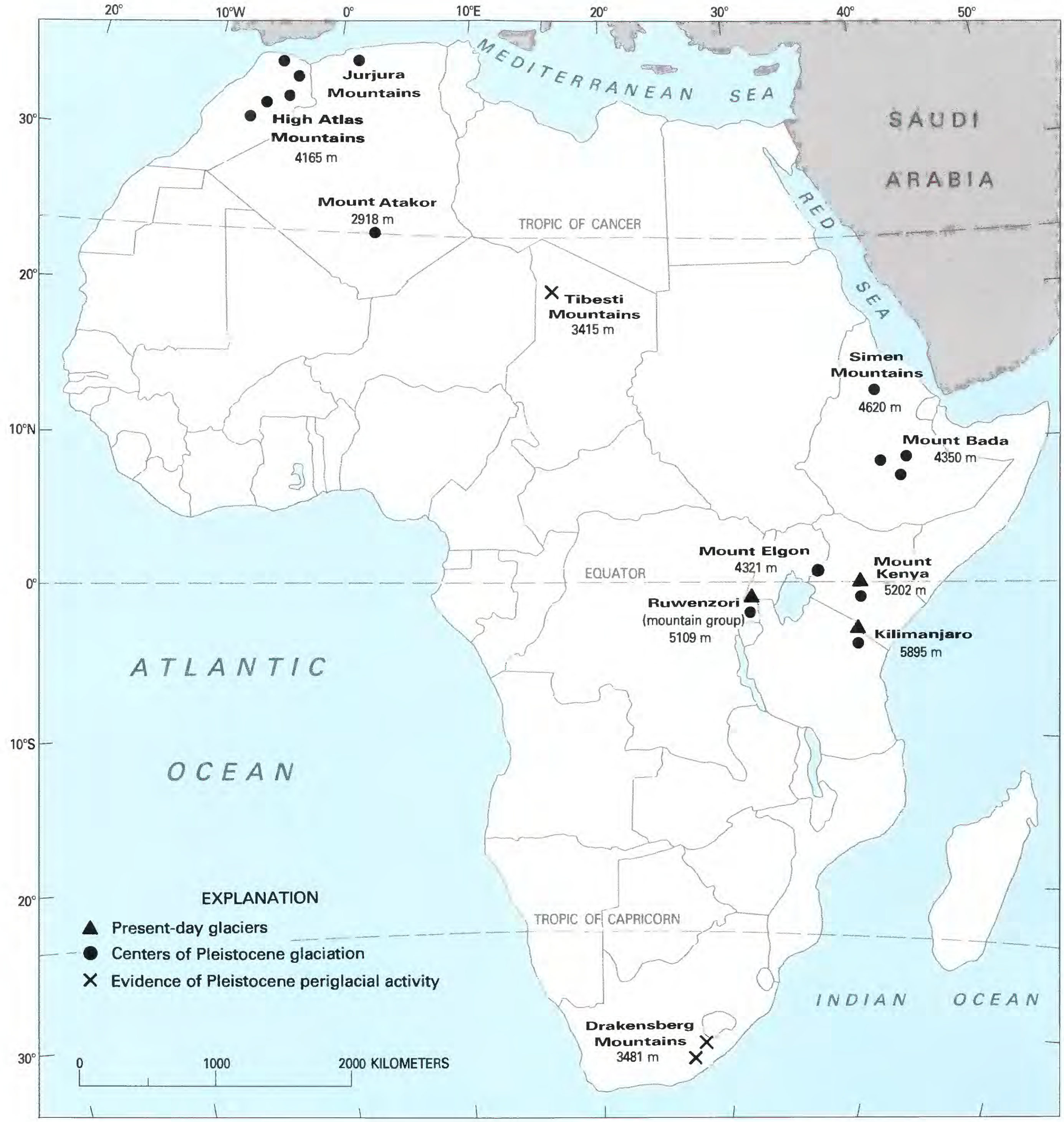


Figure 1.—*Distribution of present-day glaciers in Africa, location of centers of Pleistocene glacial activity, and areas where there is evidence of Pleistocene periglacial activity (modified from Butzer, 1978).*

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 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).

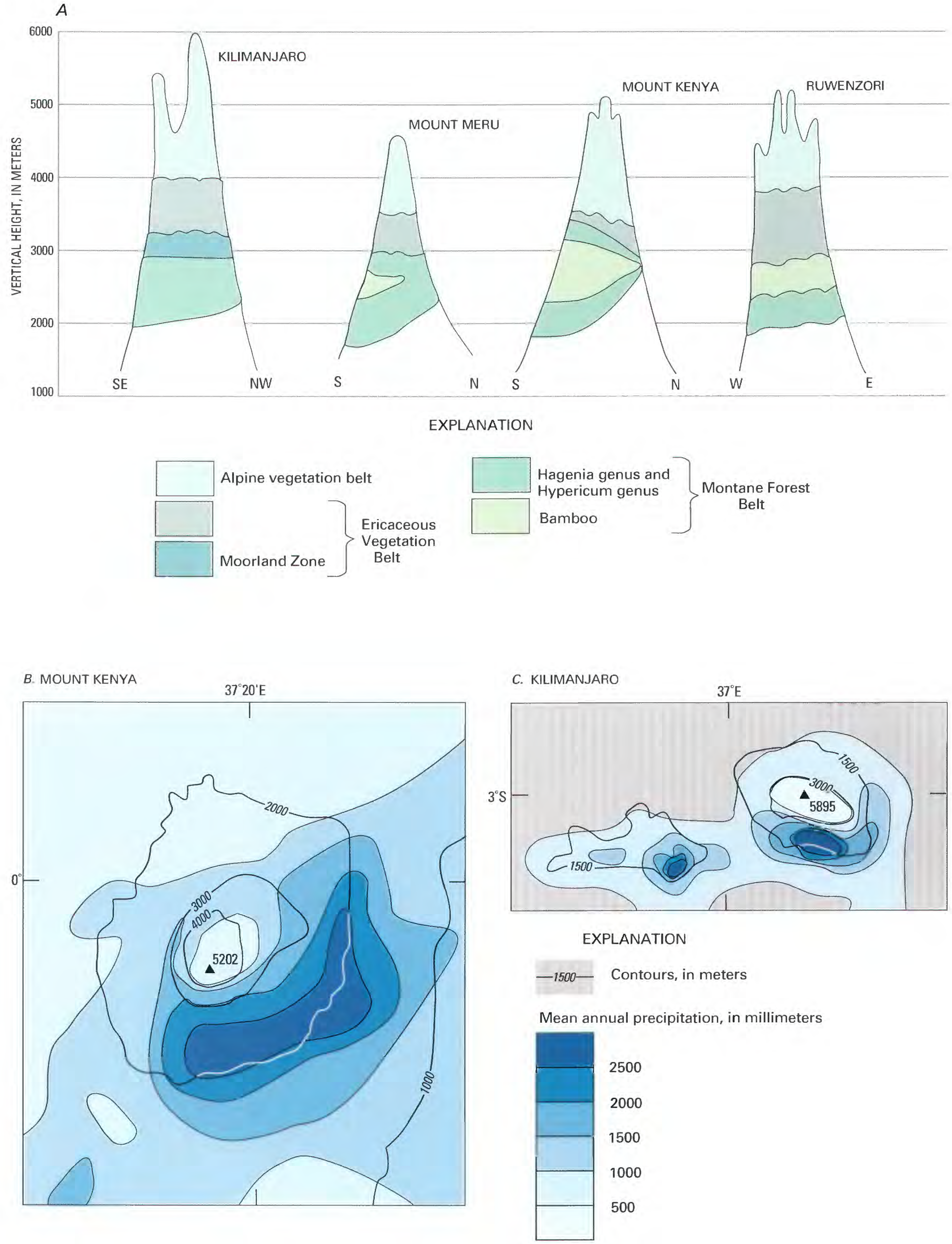
Mount Kenya and Kilimanjaro owe their origins to intense Quaternary volcanic activity, one aspect of the crustal dynamics of this region, which, through faulting, also produced the East African Rift Valley. The Ruwenzori are a horst of Precambrian crystalline rocks produced by upfaulting of a block within 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;


A
6000
5000
4000
3000
2000
1000
VERTICAL HEIGHT, IN METERS
KILIMANJARO
MOUNT MERU
MOUNT KENYA
RUWENZORI
SE
NW
S
N
S
N
W
E
EXPLANATION
Alpine vegetation belt
Moorland Zone
Ericaceous Vegetation Belt
Hagenia genus and Hypericum genus
Bamboo
Montane Forest Belt
B. MOUNT KENYA
37°20'E
0°
2000
3000
4000
5202
1000
C. KILIMANJARO
37°E
3°S
1500
3000
5895
1500
EXPLANATION
1500 Contours, in meters
Mean annual precipitation, in millimeters
2500
2000
1500
1000
500

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 1:5,000
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).*

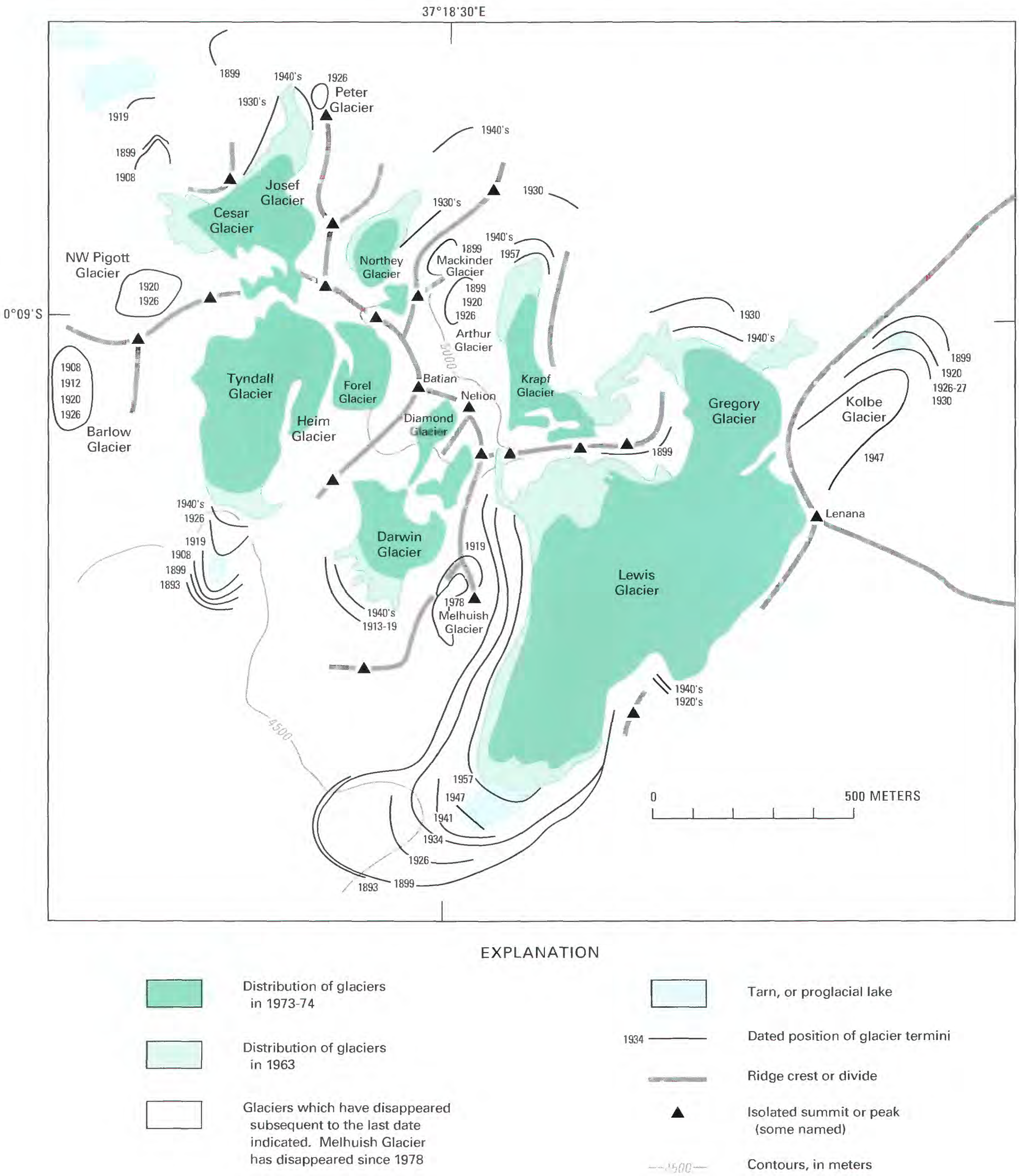
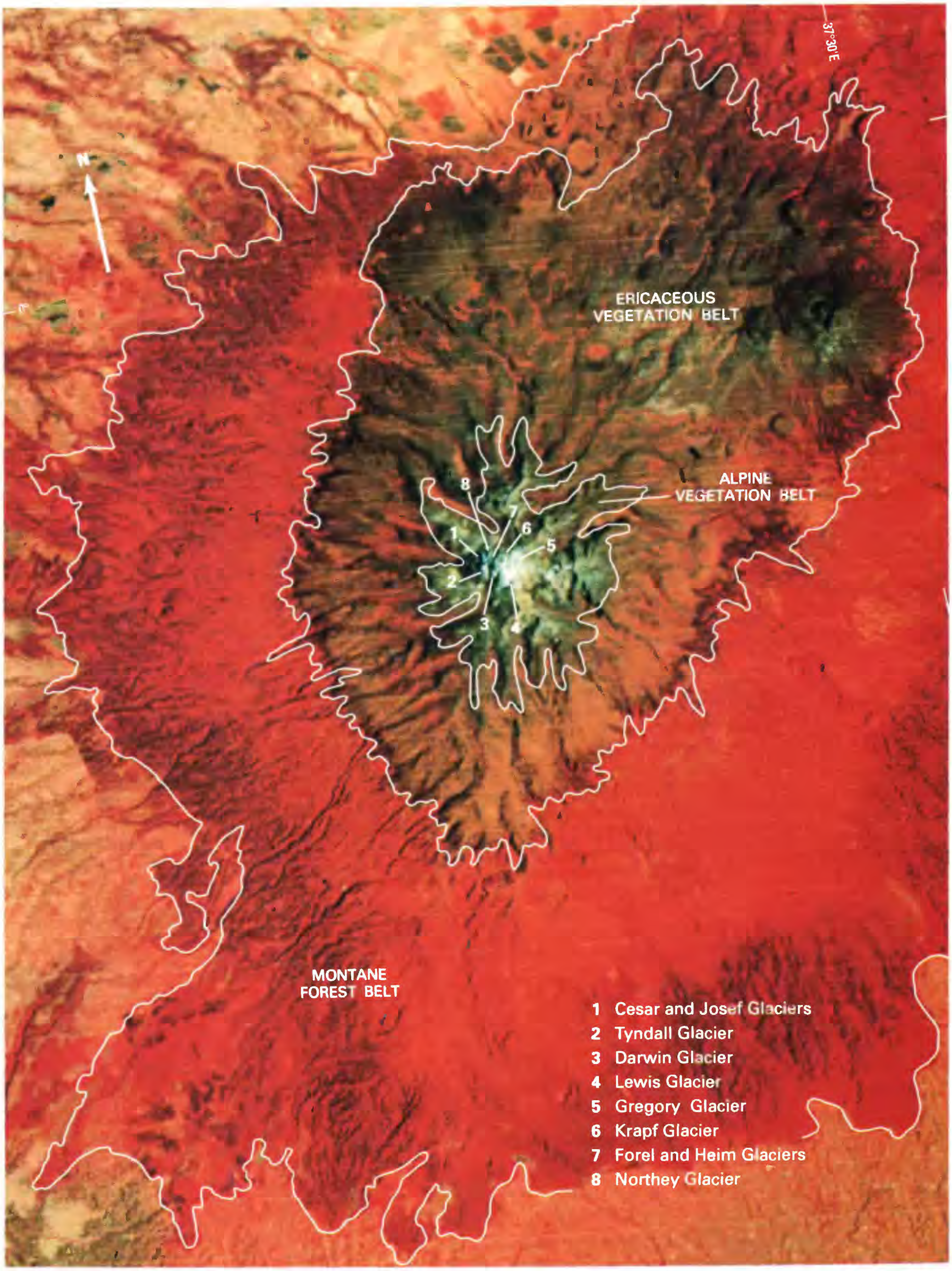


Figure 3.—*The shrinking glaciers of Mount Kenya (modified from Map 4.3:8 in Hastenrath, 1984).*

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 km^2 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 ablative 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. 2*B*).

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 km^2, of which the Lewis Glacier accounted for 0.36 km^2. 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 × 10^3 m^2, 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 km^2 (Müller, 1977;



37°30'E
N
ERICACEOUS VEGETATION BELT
ALPINE VEGETATION BELT
MONTANE FOREST BELT
1 Cesar and Josef Glaciers
2 Tyndall Glacier
3 Darwin Glacier
4 Lewis Glacier
5 Gregory Glacier
6 Krapf Glacier
7 Forel and Heim Glaciers
8 Northey Glacier

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.*

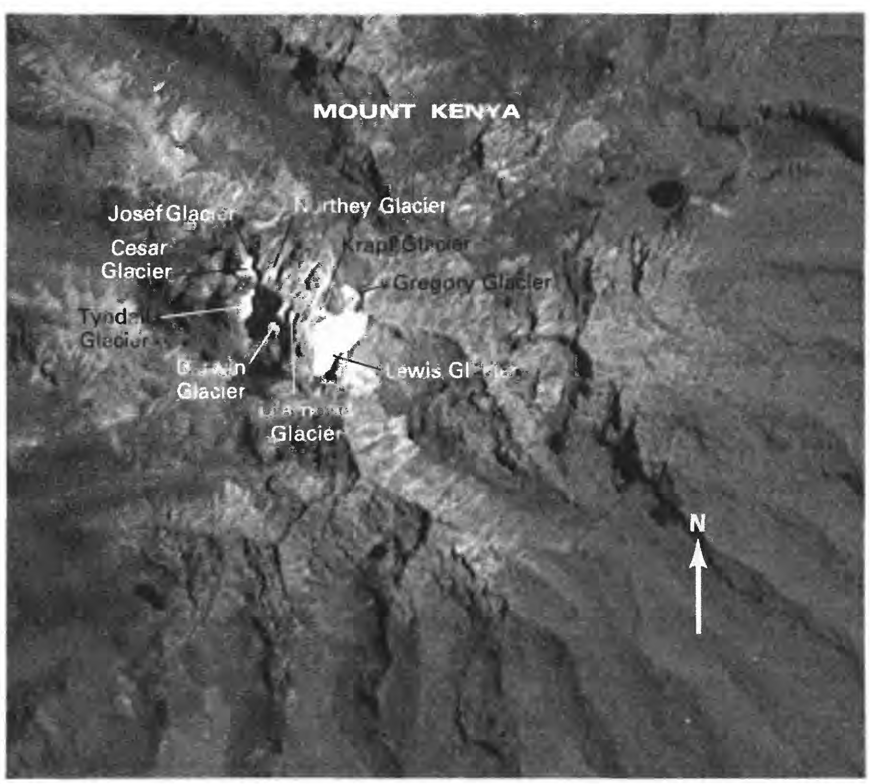


Figure 5.—Annotated 1:100,000-scale enlargement of a Landsat 3 RBV image (30912–06490, subscene C; 2 September 1980; Path 180, Row 60) of Mount Kenya showing the distribution of glaciers. The Heim and Forel Glaciers are hidden by the summit's shadow.

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

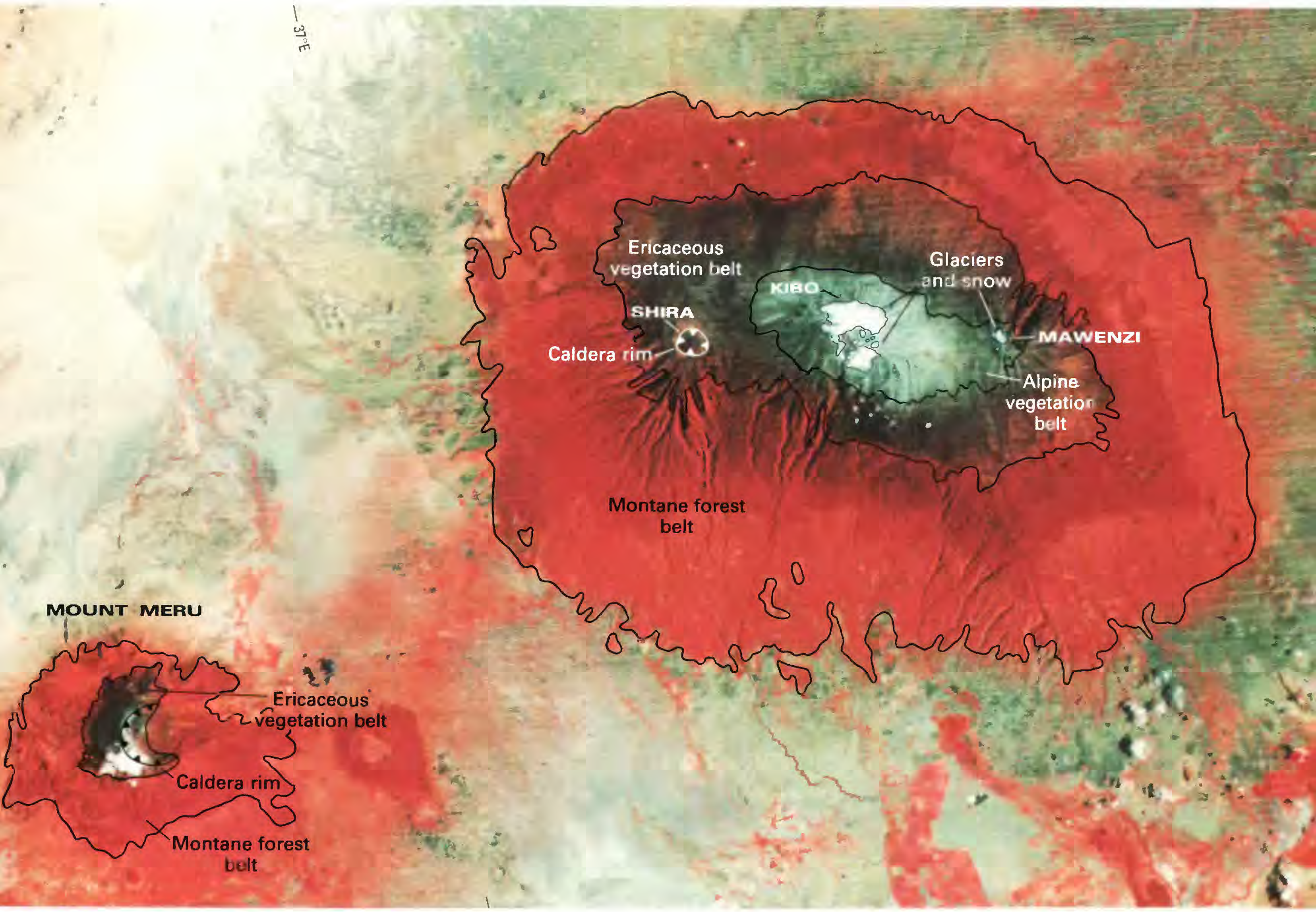


Figure 6.—*Annotated 1:500,000-scale enlargement of a Landsat MSS color-composite image (2367–06582; 24 January 1976; Path 180, Row 62) of Kilimanjaro and Mount Meru showing vegetation belts and the distribution of glaciers.*

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 fluvioglacial 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 km^2 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.*

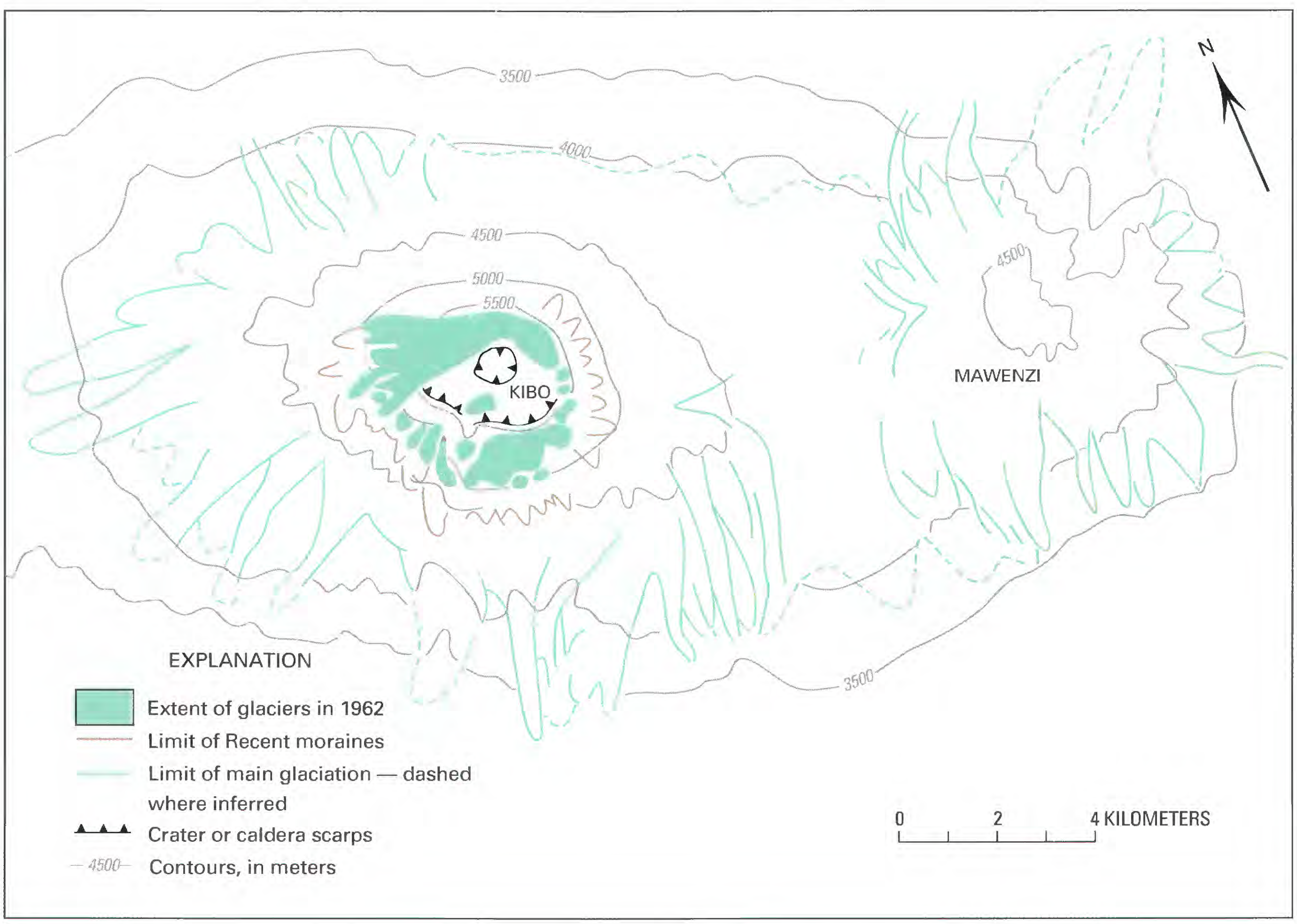


Figure 8.—*The shrinking glaciers of Kilimanjaro (after Downie, 1964).*

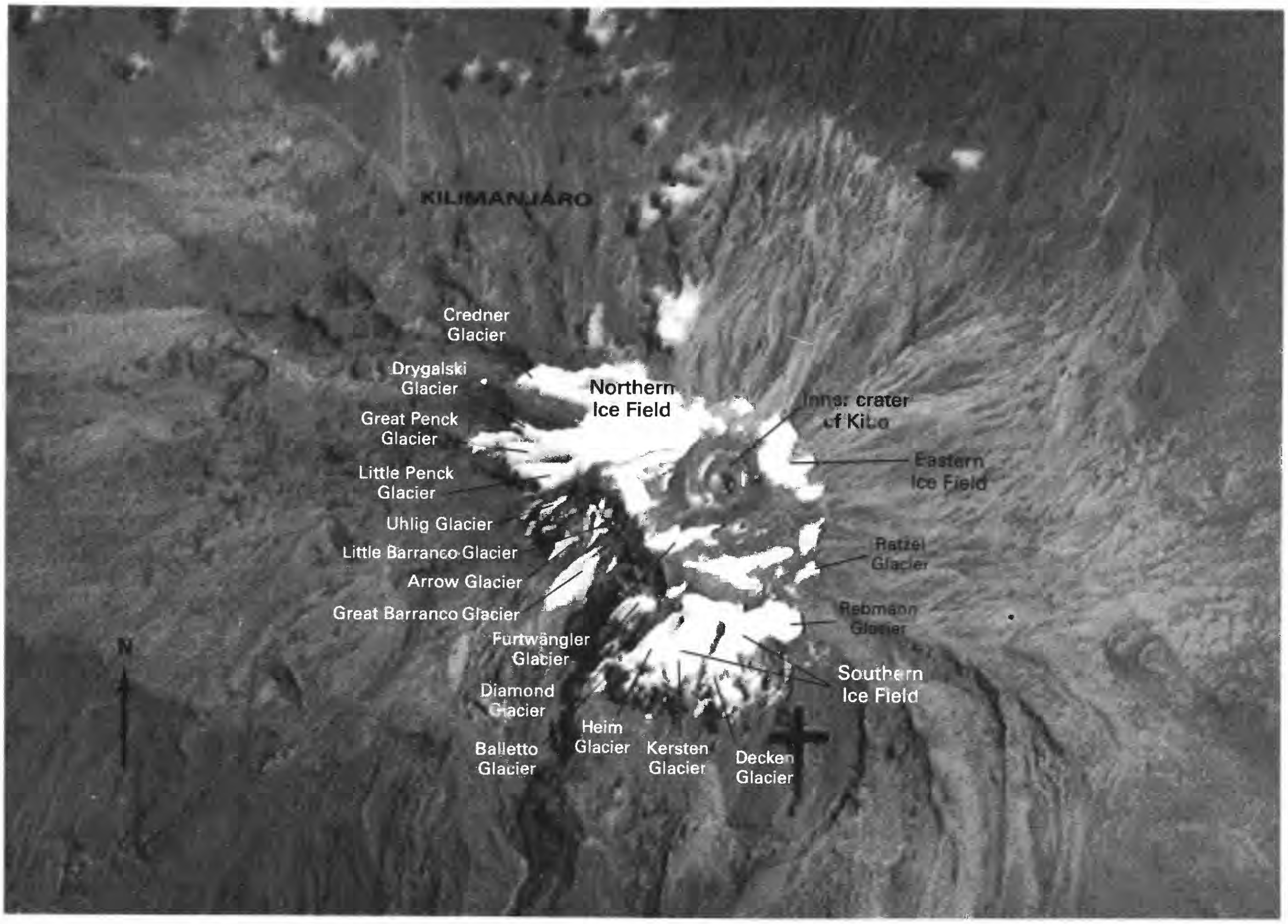


Figure 9.—*Annotated 1:100,000-scale enlargement of a Landsat 3 RBV image (30912–06495, subscene D; 2 September 1980; Path 180, Row 62) of Kilimanjaro showing the distribution of glaciers.*

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. 2*C*) 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 km^2 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 Furtwängler 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 (Menzies, 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±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 km^2, 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 km^2, with 2 km^2 on Mount Stanley, 1.62 km^2 on Mount Speke, 0.67 km^2 on Mount Baker, 0.25 km^2 on Mount Gessi, 0.08 km^2 on Mount Emin, and 0.04 km^2 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.* ▶

Glaciers (fig. 10) were the largest individual glaciers and covered 0.48 km^2 and 0.375 km^2, 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).

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 Emin 2
6 Emin 3
  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

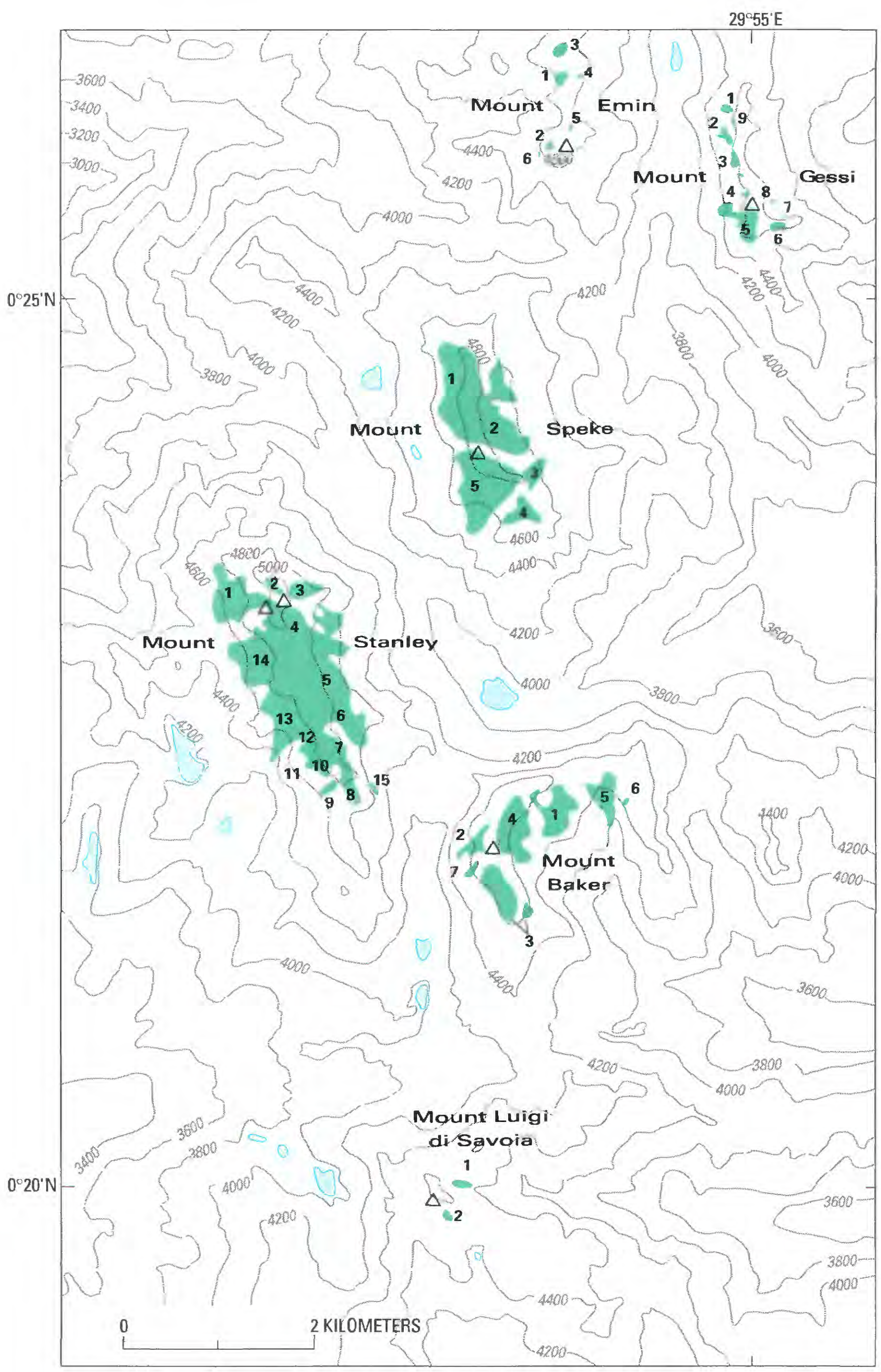
1 Alexandra
2 Albert
3 Northeast Margherita
4 Margherita
5 East Stanley
6 Elena
7 Coronation
8 Savoia
9 Philip
10 Elizabeth
11 West Elena
12 West Savoia
13 Moebius
14 West Stanley
15 unnamed

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 Thomson 2
  Sella (disappeared after 1906)
  Stairs (disappeared after 1906)



Imaging of African Glaciers

Aerial Photographs

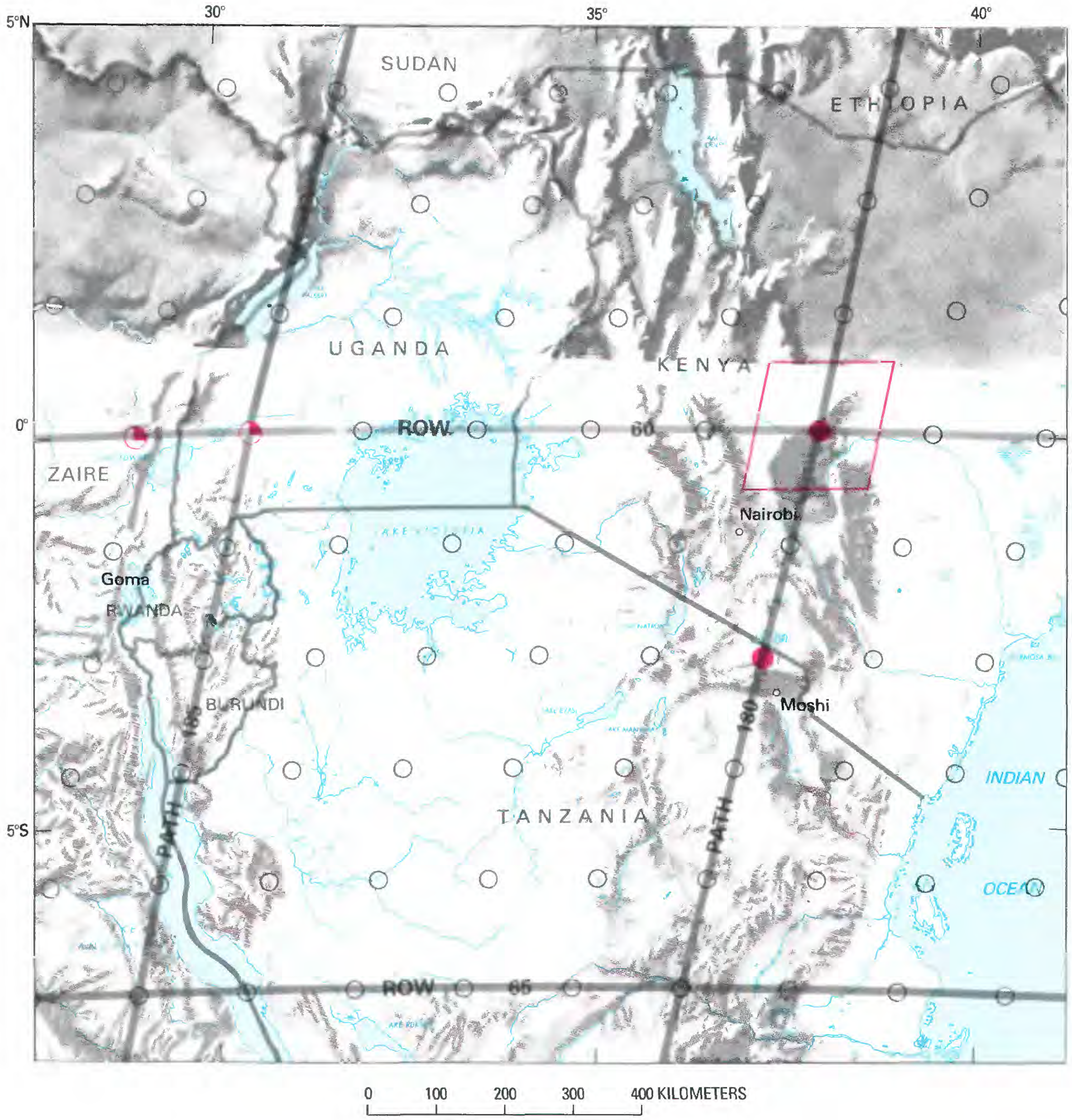
In all three mountain areas, Mount Kenya, Kilimanjaro, and the Ruwenzori, a variety of ground photographs has been taken by numerous travelers since the end of the last century (Mercer, 1967; Hastenrath, 1984). Evaluation of these pictures and of various oblique aerial photographs in conjunction with 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



EXPLANATION OF SYMBOLS

Evaluation of image usability for glaciologic, geologic, and cartographic applications. Symbols defined as follows:

- Excellent image (0 to ≤5 percent cloud cover)
- Unusable image (100 percent cloud cover)
- Nominal scene center for a Landsat image outside the area of glaciers
- Approximate size of area encompassed by nominal Landsat MSS image.

Figure 11.—*The optimum Landsat 1, 2, and 3 images of the glaciers of Africa. The vertical lines represent nominal paths. The rows (horizontal lines) have been established to indicate the latitude at which the imagery has been acquired.*

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.

References Cited

Abruzzi, H.R.H., the Duke of, 1907, The snows of the Nile. Being an account of the exploration of the peaks, passes, and glaciers of Ruwenzori: Geographical Journal, v. 29, no. 2, p. 121–147.

Allan, I., ed., 1981, Guide to Mount Kenya and Kilimanjaro (4th ed.): Nairobi Mountain Club of Kenya, 284 p.

Baker, B.H., 1967, Geology of the Mount Kenya area: Geological Survey of Kenya Report No. 79, 78 p.

Bergstrom, E., 1953, Som glaciolog på Ruwenzori [As a glaciologist in the Ruwenzori]: Ymer, v. 73, no. 1, p. 1–23.

Bhatt, N., Hastenrath, S., and Kruss, P., 1982, Ice thickness determination at Lewis Glacier, Mount Kenya: Seismology, gravimetry, dynamics: Zeitschrift für Gletscherkunde und Glazialgeologie, v. 16, no. 2 (1980), p. 213–228.

Buckle, C., 1978, Landforms in Africa—An introduction to geomorphology: London, Longman, 249 p.

Busk, D., 1954, The southern glaciers of the Stanley Group of the Ruwenzori: Geographical Journal, v. 120, pt. 2, p. 137–145.

Butzer, K.W., 1978, Climate patterns in an un-glaciated continent: Geographical Magazine, v. 51, no. 3, p. 201–208.

Caukwell, R.A., and Hastenrath, S., 1977, A new map of Lewis Glacier, Mount Kenya: Erdkunde, v. 31, no. 2, p. 85–87.

———1982, Variations of Lewis Glacier, Mount Kenya: Erdkunde, v. 36, no. 4, p. 299–303.

Charnley, F.E., 1959, Some observations on the glaciers of Mt. Kenya: Journal of Glaciology, v. 3, no. 26, p. 483–492.

Coe, M.J., 1967, The ecology of the Alpine zone of Mount Kenya: The Hague, Dr. W. Junk, 136 p.

Coetzee, J.A., 1964, Evidence for a considerable depression of the vegetation belts during the upper Pleistocene on the East African mountains: Nature, v. 204, no. 4958, p. 564–566.

Coutts, H.H., 1969, Rainfall of the Kilimanjaro area: Weather, v. 24, no. 2, p. 66–69.

Davies, T.D., Brimblecombe, P., and Vincent, C.E., 1977, The daily cycle of weather on Mount Kenya: Weather, v. 32, no. 11, p. 406–417.

Downie, C., 1964, Glaciations of Mount Kilimanjaro, northeast Tanganyika: Geological Society of America Bulletin, v. 75, no. 1, p. 1–16.

Downie, C., and Wilkinson, P., 1972, The geology of Kilimanjaro; the results of the Joint Sheffield University–Tanzania Geological Survey Expeditions in 1953 and 1957: Sheffield, University of Sheffield, Department of Geology, and the Geological Survey of Tanzania, 253 p.

Dutton, E.A.T., 1929, Kenya mountain: London, Jonathan Cape, 218 p.

Filippi, F. de, 1909, Ruwenzori; an account of the expedition of H.R.H. Prince Luigi Amedeo of Savoy, duke of Abruzzi: Second printing (first printing, 1908), London, A. Constable and Co., Ltd., 407 p.

Forschungsunternehmen Nepal-Himalaya, 1967, Mount Kenya: Wien, Austria, Kartographische Anstalt Freytag-Berndt und Artaria, 1:5,000 scale.

Geilinger, W., 1930, Der Kilimandjaro, sein Land und seine Menschen [Kilimanjaro, its land and its people]: Bern-Berlin, H. Huber, 182 p.

———1936, The retreat of the Kilimanjaro glaciers: Tanganyika notes and records, no. 2, p. 7–21.

Gillman, C., 1923, An ascent of Kilimanjaro: Geographical Journal, v. 61, no. 1, p. 1–27.

Gregory, J.W., 1894, Contributions to the geology of British East Africa, pt. 1, The glacial geology of Mount Kenya: Quarterly Journal of the Geological Society of London, v. 50, p. 515–530.

———1896, The great rift valley; being the narrative of a journey to Mount Kenya and Lake Baringo, with some account of the geology, natural history, anthropology and future prospects of British East Africa: London, J. Murray, 422 p.

Hastenrath, S., 1975, Glacier recession in East Africa, *in* Proceedings of the World Meteorological Organization/International Association of Meteorology and Atmospheric Physics, Symposium on Long-term Climatic Fluctuations (Norwich, 1975): WMO Publication No. 421, p. 135–142.

———1983, Net balance, surface lowering, and ice-flow pattern in the interior of Lewis Glacier, Mount Kenya, Kenya: Journal of Glaciology, v. 29, no. 103, p. 392–402.

———1984, The glaciers of equatorial East Africa: Dordrecht/Boston/Lancaster, D. Reidel Publishing Company, 353 p.

Hastenrath, S., and Caukwell, R.A., 1979, Variations of Lewis Glacier, Mount Kenya, 1974–78: Erdkunde, v. 33, no. 4, p. 292–297.

Hastenrath, S., and Kruss, P., 1981, Dynamics of crevasse pattern at Lewis Glacier, Mount Kenya: Zeitschrift für Gletscherkunde and Glazialgeologie, v. 15, no. 2, p. 201–207.

———1982, On the secular variation of ice flow velocity at Lewis Glacier, Mount Kenya, Kenya: Journal of Glaciology, v. 28, no. 99, p. 333–339.

Hastenrath, S., and Patnaik, J.K., 1980, Radiation measurements at Lewis Glacier, Mount Kenya, Kenya: Journal of Glaciology, v. 25, no. 93, p. 439–444.

Hedberg, O., 1951, Vegetation belts on the East African mountains: Svensk Botanisk Tidskrift, v. 45, no. 1, p. 140–202.

Höhnel, L.R. von, 1894, Discovery of Lakes Rudolf and Stephanie; a narrative of Count Samuel Teleki's exploring and hunting expedition in eastern equatorial Africa in 1887 and 1888, by his companion Lieutenant Ludwig von Höhnel: London, Longmans, Green and Co., 2 v. (translation of 1892 ed. (877 p.) published by A. Holder, Wien, Austria).

Humphries, D.W., 1959, Preliminary notes on the glaciology of Kilimanjaro: Journal of Glaciology, v. 3, no. 26, p. 475–482.

———1972, Glaciology and glacial history, *in* Downie, C., and Wilkinson, P., eds., The geology of Kilimanjaro; the results of the Joint Sheffield University-Tanzania Geological Survey Expeditions in 1953 and 1957: Sheffield, University of Sheffield, Department of Geology, and the Geological Survey of Tanzania, p. 31–71.

Jeannel, R., 1950, Hautes montagnes d'Afrique, vers les neiges èternelles sous l'équateur [High mountains of Africa, everlasting snows at the Equator]: Publications du Muséum National d'Histoire Naturelle, Supplement No. 1, 253 p.

Johnston, H.H., 1885, The Kilimanjaro expedition: Proceedings of the Royal Geographical Society and Monthly Record of Geography, v. 7, no. 3, p. 137–160.

Klute, F., 1920, Ergebnisse der Forschungen am Kilimandscharo 1912 [Results of investigations on Kilimanjaro in 1912]: Berlin, Dietrich Reimer, 136 p.

Krapf, J.L., 1849, Von der afrikanischen Ostküste [The African East Coast]: Zeitschrift der Deutschen Morgenländischen Gesellschaft, v. 3, p. 310–321.

———1858, Reisen in Öst-Afrika ausgeföuhrt in den Jahren 1837–1855 [Travels in East Africa during the years 1837–1855]: Kornthal: Im Selbst verlage des Verfassers; Stuttgart: In Commission bei W. Stroh, v. 1 (505 p.), v. 2 (521 p.).

———1860, Travels, researches, and missionary labors, during an eighteen years' residence in eastern Africa. Together with journeys to Jagga, Usambara, Ukambani, Shoa, Abessinia, and Khartum; and a coasting voyage from Mombaz to Cape Delgado. By the Rev. Dr. J. Lewis Krapf...With an appendix respecting the snow-capped mountains of Eastern Africa; the sources of the Nile; the languages and literature of Abessinia and Eastern Africa, etc. etc. and a concise account of geographical researches in Eastern Africa up to the discovery of the Uyenyesi by Dr. Livingstone in September last, by E.G. Ravenstein: London, Trubner and Co., 566 p.

Kruss, P., 1983, Climatic change in East Africa: numerical modelling from the 100 years terminus record of Lewis Glacier, Mount Kenya: Zeitschrift für Gletscherkunde und Glazialgeologie, v. 19, no. 1, p. 43–60.

———1984, Terminus response of Lewis Glacier, Mount Kenya, Kenya to sinusoidal net balance forcing: Journal of Glaciology, v. 30, no. 105, p. 212–217.

Kruss, P., and Hastenrath, S., 1983, Variations of ice velocity at Lewis Glacier, Mount Kenya, Kenya: Verification midway into a forecast: Journal of Glaciology, v. 29, no. 101, p. 48–54.

Livingstone, D.A., 1962, Age of deglaciation in the Ruwenzori Range, Uganda: Nature, v. 194, no. 4831, p. 859–860.

———1967, Postglacial vegetation of the Ruwenzori Mountains in equatorial Africa: Ecological Monographs, v. 37, no. 1, p. 25–52.

———1975, Late Quaternary climatic change in Africa: Annual Review of Ecology and Systematics, v. 6, p. 249–280.

Mackinder, H.J., 1900, A journey to the summit of Mount Kenya, British East Africa: The Geographical Journal, v. 15, no. 5, p. 453–486.

Menzies, I.R., 1951a, The glaciers of Ruwenzori: Uganda Journal, v. 15, no. 2, p. 177–181.

———1951b, Some observations on the glaciology of the Ruwenzori Range: Journal of Glaciology, v. 1, no. 9, p. 511–512.

Mercer, J.H., 1967, Glaciers of East Africa, *in* Southern hemisphere glacier atlas: Technical Report 67–76–ES by the American Geographical Society, New York, for the Earth Sciences Laboratory, U.S. Army Natick Laboratories, Natick, Massachusetts, Series ES–33, June, p. 169–196.

Meyer, H., 1890a, Die Besteigung des Kilimandscharo [The ascent of Kilimanjaro]: Petermanns Mitteilungen, v. 36, no. 1, p. 15–22.

———1890b, Ostafrikanische Gletscherfahrten Forschungsreisen im Kilimandscharo-Geibiet [East African glacier expedition. Research trip to the Kilimanjaro area]: Leipzig, Duncker and Humblot, 376 p.

———1891, Across East African glaciers; an account of the first ascent of Kilimanjaro: London, George Philip and Son, 404 p.

———1900, Der Kilimandjaro. Reisen und Studien [Kilimanjaro. Expeditions and Studies]: Berlin, Dietrich Reimer, 436 p.

Moore, J.E.S., 1901, To the Mountains of the Moon, being an account of the modern aspect of Central Africa, and of some little known regions traversed by the Tanganyika expedition in 1899 and 1900: London, Hurst and Blackett, Ltd., 350 p.

Mountain Club of East Africa, 1932, The icecap, v. 1 (publisher unknown).

Müller, F., 1977, Fluctuations of glaciers 1970–1975: Compiled for the Permanent Service on the Fluctuations of Glaciers of the International Union of Geodesy and Geophysics–Federation of Astronomical and Geophysical Sciences/International Commission on Snow and Ice, International Association of Hydrological Sciences and United Nations Education, Scientific and Cultural Organization (Unesco), Paris, v. 3, 269 p. (with 12 special topographic maps of glaciers).

Nilsson, E., 1929, Preliminary report on the Quaternary geology of Mount Elgon and some parts of the Rift Valley: Geologiska Föreningens Stockholm Förhandlingar, v. 51, no. 2 (no. 377), p. 253–261.

———1931, Quaternary glaciations and pluvial lakes in British East Africa: Geografiska Annaler, v. 13, no. 4, p. 249–349.

———1949, The pluvials of East Africa. An attempt to correlate Pleistocene changes of climate: Geografiska Annaler, v. 31, no. 1–4, p. 204–211.

Osmaston, H.A., 1961, Notes on the Ruwenzori glaciers: Uganda Journal, v. 25, no. 1, p. 99–104.

Osmaston, H.A., and Pasteur, D., 1972, Guide to the Ruwenzori; the Mountains of the Moon: Kampala, Mountain Club of Uganda, 200 p.

Patzelt, G., Schneider, E., and Moser, G., 1985, Der Lewis-Gletscher, Mount Kenya, Begleitworte zur Gletscher-karte 1983 [Lewis Glacier, Mount Kenya, comments on the 1983 glacier map]: Zeitschrift für Gletscherkunde und Glazialgeologie, v. 20 (1984), p. 177–195.

Platt, C.M., 1966, Some observations on the climate of the Lewis Glacier, Mount Kenya, during the rainy season: Journal of Glaciology, v. 6, no. 44, p. 267–287.

Rebmann, J., 1849, Narrative of a journey to Jagga, the snow country of East Africa: Church Missionary Review, v. 1, p. 12–23.

Simkin, T., Siebert, L., McClelland, L., Bridge, D., Newhall, C., and Latter, J.H., 1981, Volcanoes of the world: Stroudsberg, Pennsylvania, Hutchinson Ross Publishing Company, 233 p.

Spink, P.C., 1945, Further notes on the Kibo inner crater and glaciers of Kilimanjaro and Mount Kenya: Geographical Journal, v. 106, no. 5–6, p. 210–216.

———1949, The equatorial glaciers of East Africa: Journal of Glaciology, v. 1, no. 5, p. 277–281.

Stuhlmann, F., 1894, Mit Emin Pascha ins Herz von Afrika [With Emin Pascha into the heart of Africa]: Berlin, Dietrich Reimer, 901 p.

Stumpp, A., 1952, Kartierungsarbeiten im Ruwenzorigebirge [Survey work in the Ruwenzori]: Allgemeine Vermessungs-Nachrichten, no. 6, p. 142–147.

Temple, P.H., 1968, Further observations on the glaciers of the Ruwenzori: Geografiska Annaler, v. 50A, no. 3, p. 136–150.

Thompson, B.W., 1966, The mean annual rainfall on Mt. Kenya: Weather, v. 21, no. 2, p. 48–49.

Thompson, L.G., 1981, Ice core studies from Mt. Kenya, Africa, and their relationship to other tropical ice core studies: International Association of Hydrological Sciences Publication No. 131, p. 55–62.

Thompson, L.G., and Hastenrath, S.L., 1981, Climatic ice core studies at Lewis Glacier, Mount Kenya: Zeitschrift für Gletscherkunde and Glazialgeologie, v. 17, no. 1, p. 115–123.

Troll, C., and Wien, K., 1950, Der Lewisgletscher am Mount Kenya [The Lewis Glacier on Mount Kenya]: Geografiska Annaler, v. 31, no. 1–4 (1949), p. 257–274.

Whittow, J.B., 1959, The glaciers of Mount Baker, Ruwenzori: Geographical Journal, v. 125, pt. 3–4, p. 370–379.

Whittow, J.B., and Shepherd, A., 1959, The Speke Glacier, Ruwenzori: Uganda Journal, v. 23, no. 2, p. 153–161.

Whittow, J.B., Shepherd, A., Goldthorpe, J.E., and Temple, P.H., 1963, Observations on the glaciers of the Ruwenzori: Journal of Glaciology, v. 4, no. 35, p. 581–616.

Young, J.A.T., 1980, The glaciers of East Africa, *in* World Glacier Inventory (Proceedings of the Workshop at Riederalp, Switzerland, 17–22 September 1978): International Association of Hydrological Sciences, Publication No. 126, p. 213–217.