Diabase Sheets of the Taylor Glacier Region Victoria Land, Antarctica

GEOLOGICAL SURVEY PROFESSIONAL PAPER 456-B

Work done in cooperation with the National Science Foundation

Diabase Sheets of the Taylor Glacier Region Victoria Land, Antarctica

By WARREN HAMILTON

With sections on PETROGRAPHY

By WARREN HAMILTON, PHILIP T. HAYES, *and* RONALD CALVERT

And sections on CHEMISTRY

By WARREN HAMILTON, VERTIE C. SMITH, PAUL S. D. ELMORE,
PAUL R. BARNETT, *and* NANCY CONKLIN

CONTRIBUTIONS TO THE GEOLOGY OF ANTARCTICA

GEOLOGICAL SURVEY PROFESSIONAL PAPER 456–B

Work done in cooperation with the
National Science Foundation

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1965

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

ILLUSTRATIONS

TABLES

CONTRIBUTIONS TO THE GEOLOGY OF ANTARCTICA

DIABASE SHEETS OF THE TAYLOR GLACIER REGION, VICTORIA LAND, ANTARCTICA

By Warren Hamilton

ABSTRACT

Thick sills and inclined sheets of quartz diabase were intruded during Jurassic time into the nearly undeformed Beacon Sandstone in the area now occupied by the mountains west of McMurdo Sound. Each sheet has a subuniform thickness ranging between 300 and 1,500 feet or more and has alternating concordant and discordant segments; each in places cuts obliquely through several thousand feet of strata. The thick peneplain sill intruded along or just above the planar depositional contact between the Beacon and the underlying plutonic basement complex, and the basement sill follows subhorizontal exfoliation joints formed during pre-Beacon time in the basement rocks. Aggregate thickness of sills and sheets in single sections is about 3,000 feet.

Single sheets maintain subuniform thicknesses over areas of at least a thousand square miles. Roof plates of this area floated on the molten sheets. Density of molten diabase and solid roof rocks was similar, and roof pressure squeezed the magma out into the vast sheets.

The entire Beacon Sandstone has been metamorphosed slightly by the diabase sheets, but strong metamorphic effects are limited to contact zones a few feet thick.

The diabase sheets, the sandstone they intrude, and the underlying basement rocks have been arched into a broad north-trending dome whose apex is in the high Royal Society Range. A few normal faults that have maximum displacements of about 1,500 feet break the section.

Published paleomagnetic studies of diabase from many Antarctic diabase localities indicate a Jurassic south magnetic pole near lat 54° S., long 136° E. During Jurassic time, Antarctica apparently lay between lat 30° and 70° S.

The basement sill was sampled systematically where it is about 700 feet thick. Chilled margins of the sill are aphanitic basalt free of megascopic phenocrysts. The chilled basalt at the base grades upward through diabase to gabbro, which forms the bulk of the sill. Diorite pegmatite veins are common in the upper part of the gabbro. Above the gabbro is a layer of granophyre 10–15 feet thick whose top is 30–40 feet below the top of the sill. The upper chilled zone grades downward to diabase, not to gabbro; and the lower part of the zone, above the granophyre, was metasomatized intensely by silicic materials which rose into it. Plagioclase in the diabase and gabbro is mostly calcic labradorite and sodic bytownite. Pigeonite, subcalcic augite, augite, and hypersthene are present in varying combinations. Hypersthene is most abundant and clinopyroxene least abundant in the lower part of the gabbro, which is impoverished in magnetite, ilmenite, and interstitial granophyre as compared with the chilled margins and the upper part.

Chilled-zone specimens have a nearly constant composition, containing about 55 percent SiO_2 and, by comparison with other basaltic rocks, small amounts of alkalis and titanium. They are more silicic than most other tholeiites; their most obvious mineralogic distinction is that they contain relatively little magnetite and ilmenite. As the rocks are composed largely of pyroxene and calcic plagioclase, there is no question regarding their basaltic character despite their high silica content.

The gabbro contains less silica, alumina, ferric iron, alkalis, and titanium, and a little more calcium and much more magnesium, than do the chilled-border rocks. The schlieren of diorite pegmatite in the upper part of the gabbro contain more silica, ferric iron, total alkalis, and titanium, and less aluminum, magnesium, and calcium, than do either the chilled borders or the gabbro.

The granophyre is more granitic than the pegmatite, and it is richer in ferric iron and titanium than are common rocks of comparable silica content elsewhere. The granophyre zone probably represents both silicic material differentiated within the sill and reconstituted xenoliths of the quartz monzonitic wallrocks, and it has the only rocks in the sill that have a potassium to sodium ratio greater than one.

Many of the minor elements in the basement sill show systematic variations also. Late differentiates are enriched, and the lower gabbro impoverished, in barium, chlorine, fluorine, strontium, zirconium, and probably beryllium. The reverse is true for cobalt, chromium, nickel, and vanadium. Copper, phosphorus, and scandium vary in more complex fashion.

The margins of the sheet crystallized from magma that was almost entirely liquid at the time of intrusion. Gravitational differentiation obviously produced the systematic changes within the sill, but conventional explanations in terms of crystal settling or filter pressing cannot account for them. The pyroxene is more magnesian and the plagioclase more calcic in the lower part of the gabbro than in the chilled margins; this seems explicable only in terms of their crystallization from a liquid of different composition from that of the margins. The dominant process of fractionation seems to have been liquid fractionation due to the migration upward of the more volatile components before, during, and after intrusion; the magma seems to have fractionated into a liquid of graded composition presumably in response to pressure and temperature gradients which resulted in the upward migration of volatile-rich liquid.

Random sampling was done of other sills, inclined sheets, and thin dikes. The other thick sheets are also of diabase and gabbro, but they contain little orthopyroxene. One sheet has a diorite-pegmatite zone near its top but no silicic granophyre. These other sheets also are of highly silicic (SiO_2=54.5–56.0 percent) diabase that has a low content of alkalis and opaque minerals. Thin dikes are aberrant in having more oxidized (but not total) iron than do the thick sheets; mineralogically, the dikes have a higher content of magnetite.

Samples taken inward from the base of a moderately inclined thick sheet show slight but systematic differentiation: aluminum, ferric iron, potassium, and titanium increase, where-

as magnesium and calcium decrease and sodium and ferrous iron show little change. The interior is richer in volatile components than is the margin. Liquid fractionation may have operated here also, the volatiles having moved upward from the lower bulk of the sheet.

Similar great sheets of quartz diabase are virtually coextensive with the Beacon Sandstone in most parts of the Transantarctic Mountains. Correlative formations of the Gondwana systems, extensively intruded by sills of quartz diabase similar to those of Antarctica, are widespread in eastern Australia, southern and central Africa, peninsular India, and South America. All these sills are of tholeiitic type, containing less alkalis, titanium, and phosphorus, and more silica, than does alkali olivine basalt. Within Antarctica, tholeiite sills in the McMurdo Sound region—including those described here—contain more silica than do those in most other known regions. The least differentiated Antarctic diabases contain about 52–56 percent silica. Labradorite is commonly in excess of pyroxene, which is dominantly monoclinic. Interstitial granophyre is almost invariably present; opaque minerals are of minor abundance; and olivine is rare.

Differentiation of tholeiitic magma by liquid fractionation rather than by crystal settling or filter pressing could account for much differentiation in many regions and in varied geologic environments. The studies published on differentiated quartz diabase sills in other areas show that differentiation there can be explained in terms of liquid fractionation. Several aspects of the petrology, eruptive sites, and history of bimodal volcanic provinces of basalt and rhyolite also indicate the likelihood of significant liquid fractionation.

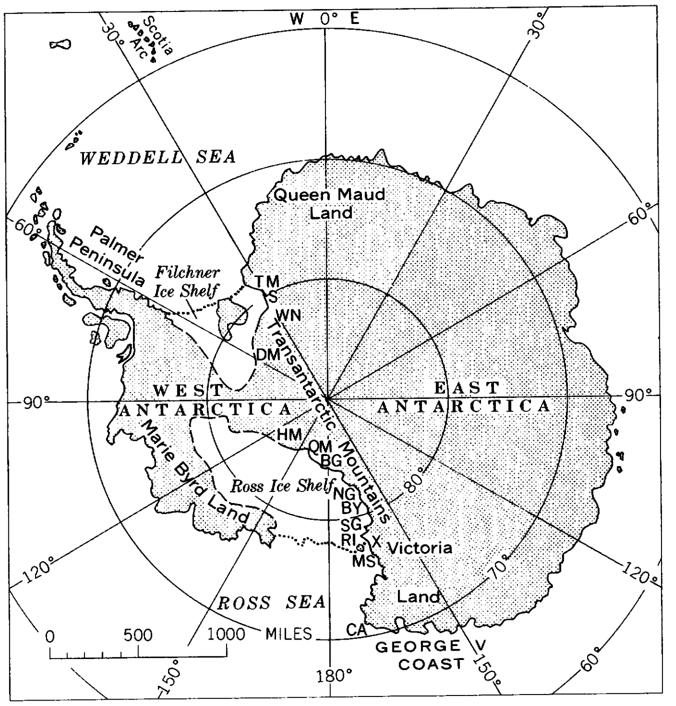


FIGURE 1.—Antarctica. X, area of this report; BG, Beardmore Glacier; BY, Byrd Glacier; CA, Cape Adare; DM, Dufek Massif; HM, Horlick Mountains; MS, McMurdo Sound; NG, Nimrod Glacier; QM, Queen Maud Range; RI, Ross Island; S, Shackleton Range; SG, Skelton Glacier; TM, Theron Mountains; WN, Whichaway Nunataks.

INTRODUCTION

LOCATION

The Taylor Glacier region lies in the mountains west of McMurdo Sound at the head of the Ross Sea (fig. 1). Between the sea and the inland ice plateau, 50 miles to the west, high mountains dam the plateau ice. Taylor Glacier is one of the outlet glaciers flowing eastward from the plateau toward the sound (fig. 2).

This report presents field and laboratory information on diabase sheets intrusive into nearly flat sandstone and into basement plutonic rocks on both sides of Taylor Glacier within the area bounded by parallels 77°40′ and 77°55′ S. and by meridians 160° and 163° E. Further information based on reconnaissance from the air and on study of aerial photographs is given for the larger area between lat 77°25′ and 78°10′ S. and between the same limiting meridians.

PRESENT WORK

The fieldwork for this report was done during November and December 1958 from four camps. One camp was established by ski-equipped Otter airplane on upper Taylor Glacier near Beacon Heights. The other three camps were placed by helicopter on dry ground: one at Bonney Lake, the second near Suess Glacier in Taylor Dry Valley, and the third in Solitary Dry Valley between the upper and lower parts of Taylor Glacier. Four observation flights over the region were made in addition to the flying connected with placing and moving camps. A brief summary of the geology was published by Hamilton and Hayes (1960) and data from the present report were summarized by Hamilton (1963c, 1964).

This report describes the diabase sheets intrusive into sandstone and the underlying plutonic basement rocks. One thick sheet was sampled systematically from bottom to top, and other sheets were sampled wherever they were reached during reconnaissance. Forty specimens of diabase and allied igneous rocks were collected; most samples were studied petrographically, and 27 were analyzed chemically for both major and minor elements. Exposures are superb in many parts of the mountains, and much additional information was obtained during various flights ranging from Skelton Glacier (south of the area shown in fig. 2) to Granite Harbor (north of area shown in fig. 2).

About 1,500 Navy aerial photographs, vertical and oblique, were studied for geologic information after the fieldwork was completed. The geologic map of plate 1 was prepared by photogrammetric methods from vertical photographs. My own low-altitude aerial photographs supplied further data.

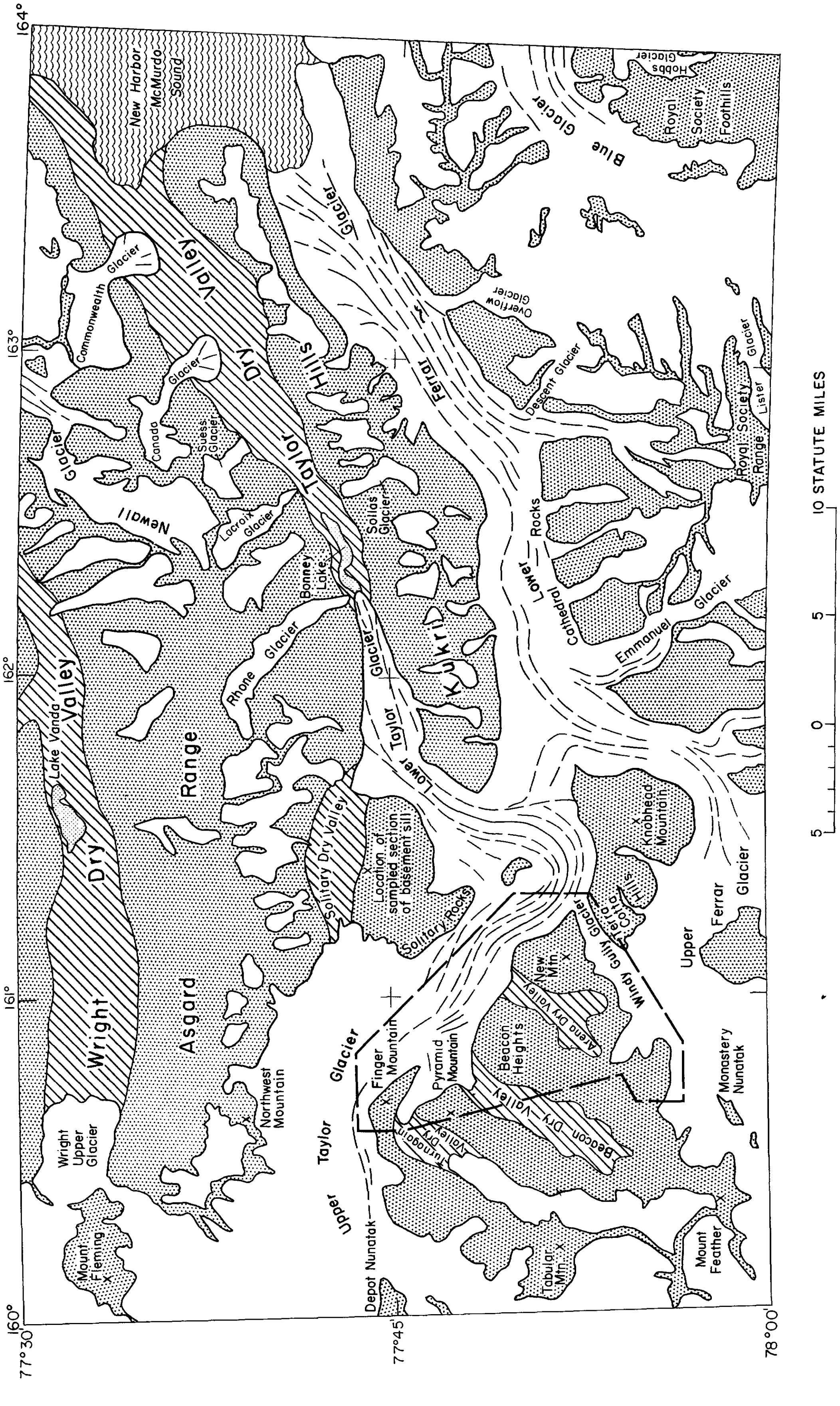


FIGURE 2.—Taylor Glacier region, Antarctica. Dashed line indicates area of geologic map (pl. 1).

ACKNOWLEDGMENTS

Many people and organizations contributed to the success of this study. Philip T. Hayes was my companion and able coworker in the field. Financial support came from the Antarctic Research Program of the National Science Foundation. The fieldwork was operationally part of the U.S. Navy's Deep Freeze IV Expedition (1958–59). Transportation to and from the Antarctic and quarters and meals at the operating base of Williams Naval Air Facility on Ross Island in McMurdo Sound were provided by the Navy. Logistic support in the field—the placing of camps from ski-equipped aircraft and helicopters, and reconnaissance flights about the region—was given by Navy Squadron VX–6. Operational planning while I was in the Antarctic was facilitated by Philip M. Smith of the National Science Foundation, and by Kendall M. Moulton who was then of the International Geophysical Year organization. Radio contact with the Navy was maintained from the field camps through Peter Yeates at New Zealand's Scott Base.

Philip T. Hayes and Ronald Calvert did some of the petrographic work reported here and are coauthors of the appropriate sections. Chemical analyses were made by Vertie C. Smith, Paul R. Barnett, Nancy M. Conklin, Paul S. D. Elmore, I. H. Barlow, S. D. Botts, and G. Chloe, of the U.S. Geological Survey; some of these analysts are also coauthors of several sections. Many of the accompanying aerial photographs were taken by the U.S. Navy, some of them expressly for our use. Photomicrographs were made by Ernest P. Krier and Charles Fiola of the U.S. Geological Survey.

Discussions and correspondence with other geologists who have worked in the Antarctic have contributed much to some of the material presented here. Particularly relevant to the present study has been the cooperation of Bernard M. Gunn of the University of Otago, New Zealand, who made a detailed study (Gunn, 1962) of the petrography and chemistry of several diabase sheets in the same region and who shared his data in advance of publication. P. Jon Stephenson of the Commonwealth Trans-Antarctic Expedition supplied unpublished data on diabase sheets in the Weddell Sea sector. Other less direct contributors to this study include H. J. Harrington and Barrie C. McKelvey of the University of New England, Australia; Peter N. Webb of the Geological Survey of New Zealand; Troy L. Péwé of the University of Alaska; William E. Long and Colin Bull of Ohio State University; Edward J. Zeller of the University of Kansas; and Robert L. Nichols of Tufts College.

Discussions of petrography with Preston E. Hotz, Ray E. Wilcox, and Howard G. Wilshire of the U.S. Geological Survey, and of chemistry with Frank W. Dickson of the University of California, Riverside, and with Julian J. Hemley, Lee C. Peck, Howard A. Powers, and Wilshire, all of the U.S. Geological Survey, have also been most helpful.

OTHER STUDIES

The Taylor Glacier region was first visited during Capt. Robert Falcon Scott's "Discovery" expedition of 1901–04. Hartley T. Ferrar, the expedition's young geologist, with several companions traversed Ferrar and upper Taylor Glaciers from McMurdo Sound to the inland ice plateau. Ferrar (1907) published reconnaissance geologic information, including several photographs of the diabase sills in the Beacon Sandstone and a geologic sketch map of the region. His rock specimens were described by Prior (1907). Benson (1916) described more fully some of the same specimens in a report devoted largely to erratics of diabase collected from moraines on Ross Island, on the east side of McMurdo Sound; his report long remained the primary source of information on the petrology of diabase from the Antarctic.

Additional geological reconnaissance studies in the region were made during Sir Ernest Shackleton's expedition of 1907–09. Geologists were T. W. Edgeworth David, Douglas Mawson, and Raymond E. Priestley, none of whom, however, studied the diabase sheets.

Scott returned to McMurdo Sound with the "Terra Nova" expedition of 1910–13, during which he perished. Geologists Griffith Taylor (for whom Taylor Glacier and Taylor Dry Valley were named) and Frank Debenham visited Taylor Dry Valley and, although concerned primarily with surficial geology, collected bedrock samples. A little information on the diabase sheets, based on the fieldwork and samples of Taylor and Debenham, was given by Smith (1924).

No ground party visited the region again until the International Geophysical Year of 1957–58. During and since that year, New Zealand and American parties have made geological studies in the Taylor Glacier region. McKelvey and Webb (1959, 1962), Webb and McKelvey (1959), Allen and Gibson (1962), Gunn (1962), and Gunn and Warren (1962) gave information on the diabase sheets.

REGIONAL SETTING

The Ross and Weddell Seas and their respective Ross and Filchner Ice Shelves nearly divide Antarctica into two parts. West Antarctica is the smaller part and lies mostly in west longitudes, south of the Pacific Ocean and South America. Seismic soundings of the ice cap show that, were the Antarctic ice to melt, West Antarctica would consist of several large islands even after isostatic rise had compensated for the offloading of the ice (Bentley and others, 1960). West Antarctica is formed largely of metavolcanic and metasedimentary rocks and of granitic plutons intruded into them during Paleozoic and Mesozoic time (Hamilton, 1960a, 1963b).

East Antarctica is the large part of the continent, lying chiefly in east longitudes, south of New Zealand, Australia, the Indian Ocean, and Africa. East Antarctica would probably stand as an unbroken land mass were its ice melted (Crary, 1959). Rock is exposed above the continental ice sheet chiefly around the outer coast and in the nearly continuous, high Transantarctic Mountains, which bound the Ross and Weddell Seas and their ice shelves against the inland region. The outer coast is largely formed of rocks of a Precambrian shield, and so, probably, is most of the interior; but the Transantarctic Mountains in substantial part mark the site of early Paleozoic geosynclinal sedimentation, orogeny, metamorphism, and granitic intrusion (Hamilton, 1960a, 1963b). Present in most parts of the mountain system above the basement rocks is the little deformed Beacon Sandstone of Carboniferous(?), Permian, Triassic, and Early Jurassic age (Gunn and Warren, 1962). Almost coextensive with the Beacon are great intrusive sheets of quartz diabase of later Jurassic age (McDougall, 1963), some of which form the subject of this report.

The Transantarctic Mountains form a dam against the inland ice plateau, and most of the interior ice flows northward toward the Southern Ocean rather than toward the Ross and Weddell Seas. The mountains are breached by transverse valleys, however, through which flow outlet glaciers. Some of these, such as the Beardmore Glacier, are of great size.

GEOGRAPHY

The Transantarctic Mountains are 50–120 miles wide along the west side of McMurdo Sound (figs. 1, 2). Prominent peaks are typically 7,000–9,000 feet high, but summits in the Royal Society Range reach 13,000 feet above sea level. Altitudes rise gradually westward for 15–20 miles inland from the coast, beyond which summit levels vary irregularly. The inland ice plateau has an altitude of about 7,000 feet along the west side of the range (figs. 3, 14).

Among the outlet glaciers flowing eastward from the plateau toward McMurdo Sound are the Taylor and Ferrar Glaciers (fig. 2). Both glaciers were much thicker during repeated earlier glaciations and at such times coalesced with a great ice sheet filling McMurdo Sound (Péwé, 1960). The Ferrar now reaches the sea, but the Taylor ends in a valley 20 miles from the sound at an altitude of about 500 feet. The eastern part of the valley of Taylor Glacier is now ice free, except for small sidehill glaciers coming into it from cirques on the flanking divides, and is known as Taylor Dry Valley. Taylor and Ferrar Glaciers meet near Knobhead; an increment of Ferrar ice joins the Taylor through Windy Gully (figs. 8, 9), and another joins it north of Knobhead as the Taylor turns to pass the west end of Kukri Hills. The upper and lower parts of Taylor Glacier were previously joined by two other ice streams that cut through the now dry region enclosed within the sharp bend of the Taylor. Ice now flows from the main glacier into both the lower and upper ends of the two dry valleys left by recession of the ice. The northern valley (fig. 18), which was unvisited before our work, is here named Solitary Dry Valley because of its proximity to Solitary Rocks, which were named by the early British expeditions.

North of the upper Taylor and lower Ferrar Glaciers for about 40 miles the mountains are largely ice free. There are many small alpine glaciers (fig. 13) in the region; valley glaciers such as the lower Taylor and upper Wright project short distances into the valleys; and a large piedmont glacier covers the coastal lowlands in the northern part. The region, however, is mostly clear even of snow at least during the summer months. Between the lower Ferrar Glacier and Taylor Dry Valley is the sharp-crested ridge of the Kukri Hills (figs. 2, 8), 35 miles long and only 5 miles wide, which reaches an altitude of 7,000 feet. The straight north wall of Taylor Dry Valley similarly stands 5,000–6,000 feet above the valley floor, but extending north from this, and north of the upper Taylor Glacier, is an irregular upland area, 5–10 miles broad, which ends against Wright Dry Valley. Only a small apron glacier now flows into the head of Wright Dry Valley from the inland ice plateau (fig. 14); most of the valley is ice free (fig. 17), although it has repeatedly been filled by ice in the past (Nichols, 1961). The lower end of the valley is blocked by a piedmont glacier (fig. 20) flowing southward along the coastal lowlands from MacKay Glacier and sending a prong, Wright Lower Glacier, westward up Wright Dry Valley. Victoria Dry Valley is north of Wright Dry Valley, and each valley has ice-free tributaries.

South of the upper Taylor and lower Ferrar Glaciers, large and small mountain masses are separated by streams of ice. The largest and highest block is that of the Royal Society Range (figs. 9, 19), which is largely separated from the coastal foothills by the Blue Glacier (fig. 12) and is cut off from mountains farther inland by the Ferrar Glacier on the northwest and by the Skelton Glacier on the southwest. A nearly equidimensional mountain block about 20 miles in diameter lies between the upper Taylor and upper Ferrar Glaciers and the inland plateau; its peaks, including East and West Beacon Heights and Pyramid Mountain, rise typically to about 8,000 feet, and north-northeast-trending Beacon and Arena Dry Valleys are ice free (figs. 2, 6, 8). This mountain mass is separated from the smaller mass of Knobhead to the east only by shallow Windy Gully Glacier (fig. 9). Many nunataks project through the ice south and west of the Beacon Heights mountain mass. Plate 1 is a geologic map of part of this mountain block.

Dry valleys are common in this region but rare elsewhere in the Antarctic. The dry valleys west of McMurdo Sound are ice free, except for small hanging glaciers flowing into them from flanking crests, and largely lack snow cover during at least the summer months. Many nearby ridges are mostly covered by snow and ice, but there are large areas of bare ground at altitudes as high as 6,000 feet. Many of these dry areas are shown in the accompanying photographs: Wright Dry Valley in figures 14, 17, and 20; Solitary Dry Valley in figures 13 and 18; Beacon Dry Valley and its ice-free neighboring highlands in figures 6 and 8; and the basin adjoining Northwest Mountain in figure 15. These bare areas are markedly warmer than nearby snow-covered terrain at similar altitudes; an average temperature differential of perhaps 20° in the summer, and possibly in the winter, is suggested by scanty data. The dry valleys have been referred to as "oases," but this term in misleading as their air temperatures rise above freezing only on occasional summer days.

The mountains act as a dam holding back the ice of the interior plateau. From this plateau, outlet glaciers flow eastward toward McMurdo Sound. Figure 3 shows the head of Taylor Glacier, one such outlet glacier, which flows only into Taylor Dry Valley (fig. 2), where its snout is at frozen Bonney Lake. The floor of Taylor Dry Valley is mantled by till, which extends 3,000 feet vertically up the valley sides and a comparable distance above lower Taylor Glacier. Along upper Taylor Glacier in the Beacon Heights area near the ice plateau (fig. 8), till—including erratics of basement plutonic rocks, which are not exposed above the ice anywhere upstream to the west—rises 1,200 feet above the present ice surface. As manifested by the till, Solitary Dry Valley (figs. 13, 18) once was filled with ice to a depth of about 2,000 feet. Lower Ferrar Glacier (fig. 19) still reaches the sea, but its surface is perhaps 3,500 feet below past levels. Wright Dry Valley was also filled deeply by ice. Péwé (1960) and Nichols (1961) described evidence for repeated glaciation of the region, which shows that the ice during each stage reached far above present levels. The height at which past levels of ice stood above present levels decreases westward across the mountains, and this decrease in the difference in height indicates that fluctuations in altitude of the plateau ice were much less than were those of the lower reaches of the outlet glaciers. A change of a few hundred feet in the ice level on the plateau seems adequate to account for the great changes in ice level in the lower valleys.

The bedrock lips at the east margin of the interior ice plateau thus have a threshold effect upon the outlet glaciers. These lips are close enough to the present ice surface so that relatively small changes in thickness of the inland ice produce great changes in ice flow into the outlet glaciers and, hence, great changes in thickness of ice in the lower valleys. The most striking display of the threshold effect in the region is illustrated by figure 14: the inland ice is now only slightly above the bedrock lip at the head of Wright Dry Valley, and the flow over the lip produces only the small ice apron of Wright Upper Glacier. The high bedrock lips are formed of the thick diabase sills and of the cliff-forming sandstone of Pyramid Mountain (figs. 3, 14).

Similar conclusions were reached by Clark (1960) and by Bull (1962).

Air temperatures in the dry valleys are warmer than those of nearby snow-covered areas and must be an effect rather than a cause of deglaciation. With the lowering of the ice surface comes enormously increased absorption of solar heat by the exposed rock and till—ground temperatures are well above air temperatures in the summer—and thus also a changed local climate that inhibits accumulation of snow. The region is a cold desert probably receiving only a few inches of equivalent water in snow each year, so that the transition from areas in which snow accumulates to areas in which it does not is likely to represent a very sensitive equilibrium.

GEOLOGY[1]

Most diabase sheets of the Taylor Glacier region are intruded into the little-deformed Beacon Sandstone. The sandstone and coextensive diabase form nearly all the exposed western third of the mountains, cap the ridges of the central third, and are largely lacking in the eastern third, near the coast. A sheet of diabase is also present in many places within the basement rocks; there it follows exfoliation joints beneath the erosion surface upon which the Beacon was deposited. This basement sill, as it will be called here, is present in massive granitic rocks but is generally absent in gneisses and schists. Metamorphic rocks underlie most of the east-

[1] Sources include Ferrar (1907), David and Priestley (1914), Smith and Debenham (1921), Taylor (1922), Smith (1924), Webb and McKelvey (1959), McKelvey and Webb (1959), Hamilton and Hayes (1960), Gunn and Warren (1962), and my unpublished data.

ern third of the mountains within the area of figure 2; grantic rocks underlie the central third. The basement sill correspondingly is present in most of the central third, where the basement rocks are exposed. About 30 miles north of the area of figure 2, at Granite Harbor, massive granitic rocks reach the coast, and here the basement sill is present only a few hundred feet above sea level.

BEACON SANDSTONE

The Beacon Sandstone, a formation of little-deformed clastic rocks, is widely distributed through the mountains of south Victoria Land. The formation was named by Ferrar (1907) for exposures in Beacon Heights (fig. 2; pl. 1). Philip T. Hayes and I studied the central part of the formation in its type locality at Beacon Heights, and the basal part in Solitary Dry Valley. We combined our data with those of a published description of the lower part of the Beacon near Windy Gully (pl. 1), just east of the type area, by Zeller and others (1961), and with those of a published account of the upper part of the formation west of Beacon Dry Valley (pl. 1), just west of the type locality, by McKelvey and Webb (1959), and compiled (Hamilton and Hayes, 1963) a complete section of the exposed strata in the vicinity of Beacon Heights.

The Beacon in its type section is about 4,000 feet thick, exclusive of diabase sheets. It consists largely of light-colored medium- to coarse-grained quartzose and feldspathic sandstone, much of it crossbedded. Interbeds of fine-grained sandstone and siltstone are subordinate. Carbonaceous strata bearing elements of the *Glossopteris* flora occur high in the formation, dating that part of the sandstone as of Permian age. The middle part of the formation throughout its type region is a cliff-forming sandstone, easily recognizable from a distance (figs. 6, 8, 13, 14, 15), which we called the sandstone of Pyramid Mountain. The less resistant lower part of the formation, consisting in part of finer grained and thinner bedded rocks and in part of less well cemented thick-bedded sandstone, we named the sandstone of New Mountain; the similar upper part of the formation, which contains the plant fossils (fig. 5), we called the sandstone of Finger Mountain. The three subdivisions are distinguished on plate 1.

Still younger units, not present in the type section, are of Triassic and Early Jurassic age.

BASEMENT ROCKS

The crystalline rocks upon which the Beacon Sandstone lies consist of a composite batholith of varied granitic rocks in the west and of metasedimentary schist and gneiss in the east. The granitic rocks range from quartz diorite to light-colored quartz monzonite and locally to granite. The metasediments include both carbonate and clastic types. The metamorphic rocks are probably of late Precambrian and Early Cambrian age, and the granitic rocks, of Late Cambrian or Ordovician age (Hamilton, 1960a, 1963b).

FORM OF DIABASE SHEETS

The diabase intrusions are exposed throughout the region as sills, inclined sheets, and steep dikes. Most of the sills and inclined sheets are 300–1,500 feet thick or more, but most of the steep dikes are only a few feet thick. Concordant sills are dominant, but all the intrusives have crosscutting segments that are inclined moderately or, less commonly, steeply, and many sheets are locally extremely irregular. The discordant segments are referred to here as inclined sheets. Some of the diabase sheets are illustrated on the map and cross sections (pl. 1) and in the photographs (figs. 3–20). Most of the intrusions lie within Beacon Sandstone. One sill, the peneplain sill, is widely present along or near the unconformity between the Beacon and the plutonic basement complex beneath. Another widespread sheet, the basement sill, follows subhorizontal exfoliation joints in granitic rocks beneath the unconformity. Exposures of diabase sills are probably better in this region than anywhere else in the world, and details of their form can be seen that are not generally visible elsewhere.

SHEETS IN BEACON SANDSTONE

Thick sills and inclined sheets of diabase cut the Beacon Sandstone in all exposed sections in the region of the report. In the following discussion, these diabase intrusions are described in geographical order—eastward south of the upper Taylor and lower Ferrar Glaciers and thence westward to the north of these glaciers (fig. 2)—through a counterclockwise circuit around the region. (Description of the peneplain and basement sills, and of thin dikes, is reserved for following sections.) P. T. Hayes and I studied on the ground the sheets in the Beacon in the mountain block along the southwest side of upper Taylor Glacier (pl. 1) and also north of Solitary Dry Valley (fig. 2). Description of diabase in the Beacon of other areas is based on my ground and air observations from a distance and on study of about 1,500 U.S. Navy vertical and oblique photographs taken during flights crisscrossing the region.

The most spectacular exposures of the block southwest of upper Taylor Glacier (pl. 1) are those of Finger Mountain (figs. 3, 4, 5). This mountain is a high, narrow ridge, along whose 2,500-foot-high north face Taylor Glacier flows as it leaves the interior ice plateau (fig. 3). The south side of the ridge is 3,000 feet high and is almost equally well exposed, so that the three-dimensional shapes of the intrusions are clear. The west end of the mountain is a dip slope (figs. 3, 5), eroded on the upper side of an inclined 1,000-foot-thick sheet of diabase, which cuts obliquely upward through the sandstone and, at the top of the mountain, turns into a concordant, flat sill. Fingers of diabase were injected into the sandstone along the base of the sheet, and long plates of sandstone form xenoliths within it (fig. 5). The sheet also truncates the lower sill of the mountain. Columnar joints are perpendicular

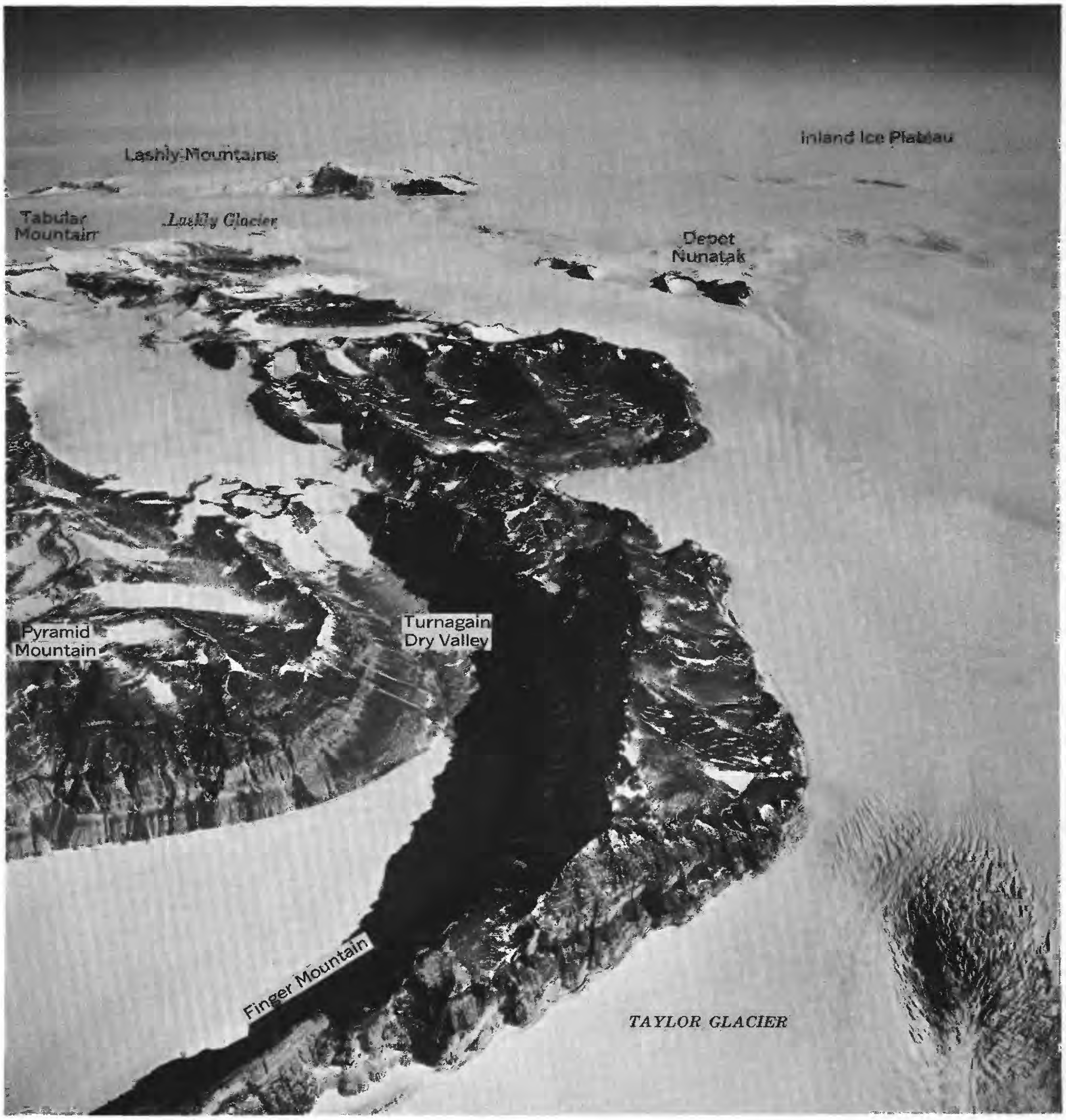


FIGURE 3.—View west-southwestward over Finger Mountain to head of Taylor Glacier and the inland ice plateau, showing diabase sheets and sandstone. The smooth dark slope extending from the crest of Finger Mountain to Taylor Glacier is the stripped upper surface of a thick inclined sheet of diabase (fig. 5). Lower Turnagain Valley is filled by ice flowing up the valley from Taylor Glacier; upper Turnagain Valley in filled by local ice heading at Tabular Mountain. Lashly Mountains are 20 miles from Finger Mountain. U.S. Navy photograph, November 1959.

to the walls of the inclined sheet and to the walls of the sill into which it changes, as they are also in the lower, older sill. The concordant segment of the upper sheet is within the sandstone of Finger Mountain, whereas the lower sheet lies within the cliff-forming sandstone of Pyramid Mountain.

The lower sill of Finger Mountain maintains an even thickness of 700 feet to a point about 1 mile westward from its truncation by the upper sill, and there a dike 150 feet thick diverges downward into the sandstone and forks, one branch tapering out (fig. 4). The main lower sill, thinned to 500 feet, continues southeastward for several thousand feet more, then abruptly turns into an inclined sheet that dips about 40° E. (fig. 4; pl. 1). There is no change in thickness of the sill where it ends against a vertical contact of sandstone; yet on the southwest face of the mountain, many sandstone beds can be seen to continue beneath this vertical contact without any break. The sill ends against a fault along which the roof rocks were raised but which did not break the floor rocks.

Nearby Pyramid Mountain (pl. 1; figs. 6, 7) displays the same thick dike and sill that is exposed as the lower sheet of Finger Mountain. The dike is about 500 feet thick at Pyramid Mountain and there dips about 45° E. and has an irregular lower contact (fig. 7). It inflects to a sill which encloses a long wedge of sandstone on the northeast face of the mountain (fig. 6); near the inclined segment, the sandstone is 200 feet thick, and the upper and lower parts of the concordant sill are 700 and 200 feet thick, respectively. These parts merge farther west along the mountain into a single sheet 900 feet thick. Above this branching sill, and separated from it by thin discontinuous lenses of sandstone (fig. 6), is another sill, 700 feet thick. Resting directly upon this, without intervening sandstone, is a third sill, 400 feet thick, distinguished from the underlying middle sill by its different color and by a discontinuity in columnar jointing.

The lower sill of Pyramid Mountain maintains its stratigraphic position within the sandstone of Pyramid Mountain for about 4 miles to the south along the west wall of Beacon Dry Valley (fig. 6), beyond which it is irregular and cuts up and down through at least 1,000 feet of sandstone. The upper two sills of Pyramid Mountain rise abruptly in the section southward along the valley and are present in the sandstone of Finger Mountain in the crest west of the inner valley wall but not in the valley wall (fig. 6).

The eastward-dipping sheet at the east end of both Finger and Pyramid Mountains disappears beneath Beacon Dry Valley and Taylor Glacier. The actual contact between the sandstone of Pyramid Mountain and the sandstone of New Mountain is 500–1,000 feet higher on the east side of the valley than its position projected updip from the west. (See section *D–D′*, pl. 1.) Although a fault whose west side is dropped down might lie beneath Beacon Dry Valley, the offset more likely is due to the raising of the strata east of the valley by the hidden diabase sheet. The inclined sheet in Finger and Pyramid Mountains probably becomes a sill beneath the exposed section in Beacon Heights and is probably part of either the peneplain sill or the basement sill as exposed farther east.

Two sills lie within the upper part of the sandstone of Pyramid Mountain in West Beacon Heights, east of Beacon Dry Valley (pl. 1; fig. 8). The lower of these sills lies at about the same stratigraphic position as the middle sheet in Pyramid Mountain and is likely to be part of the same sill. Beneath this sill, the lower 3,000 feet of sandstone section exposed in West Beacon Heights is barren of sills and is cut only by several small, thin, steep dikes of diabase. The lower of the two sills in West Beacon Heights is exposed also in East Beacon Heights at the same stratigraphic level, and its thickness is about 400 feet in both peaks. It is exposed continuously along ridges to the southwest of East Beacon Heights, and it remains concordant, or nearly so, to the sandstone to where it pinches out about 2 miles from East Beacon Heights (pl. 1). One mile south of East Beacon Heights, several intersecting inclined sheets (perhaps interpreted incorrectly on pl. 1) of diabase are poorly exposed low in the section at stratigraphic levels which on the lower slopes of East Beacon Heights are barren of diabase except for several thin dikes.

A gently undulating sill having a general thickness of 700 feet is exposed for 4 miles along Taylor Glacier from Arena Dry Valley to Windy Gully Glacier (fig. 9). This is the peneplain sill; it is intruded nearly along the unconformity between sedimentary rocks and the underlying crystalline basement complex. A further discussion of the peneplain sill follows.

In the Beacon Sandstone above the peneplain sill in the area from Taylor Glacier to Windy Gully Glacier and between Arena Dry Valley and upper Ferrar Glacier—at total area of about 15 square miles—is an extensive and exceedingly complexly formed sheet of diabase (pl. 1; fig. 9). Except for the peneplain sill and a few small dikes, all the diabase exposed in this area probably belongs to this one sheet, no part of which maintains a constant orientation for more than a few thousand feet. By Taylor Glacier near Arena Dry Valley, the sheet is mostly in concordant contact with the peneplain sill but is partly separated from the sill by thin lenses of sandstone; yet this irregular sheet is

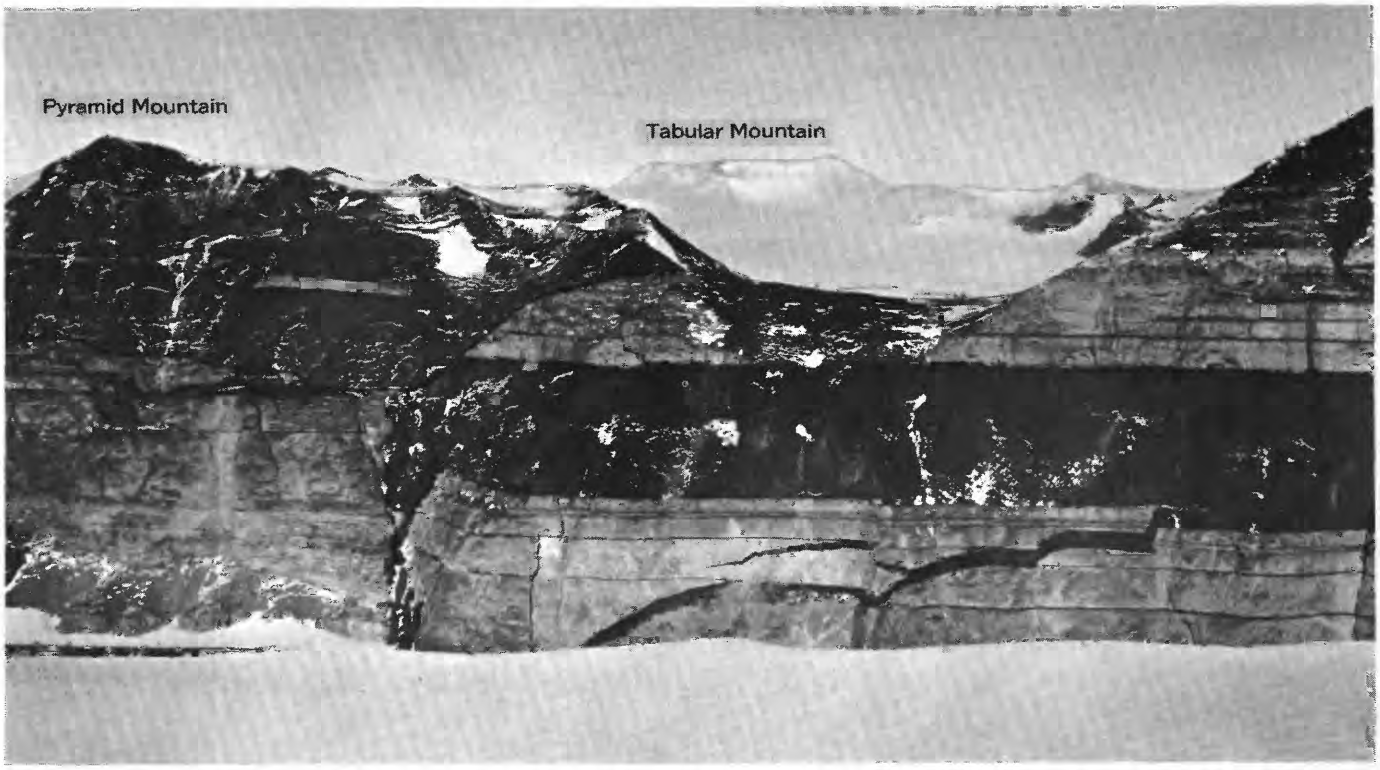


FIGURE 4.—Diabase sheets in northeast face of Finger Mountain. The concordant sill in the center of the face sent discordant tongues into its floor; it turns abruptly into a thick dike toward the left side. A concordant sheet of diabase caps Finger Mountain on the right skyline, but it becomes crosscutting just to the right of the pictured area (fig. 5). Carbonaceous strata above the lower sill at the right edge are truncated against a scoured channel filled by massive light-colored sandstone. Aerial photograph by Warren Hamilton, November 1958.

3,000 feet higher 2 miles away at New Mountain. Between the glacier and New Mountain, the sheet inflects abruptly into different attitudes at several places. Most of these diversely oriented segments are straight rather than curved. One mile north of New Mountain, the sheet inflects to a horizontal concordant attitude and attains a thickness of 1,100 feet. This concordant segment ends against a vertical contact 1,500 feet north of New Mountain, but the underlying sandstone is not offset (No. 5, fig. 9). Here, as at Finger Mountain, a fault has raised the roof of the sheet without breaking its floor. A mile and a half west of New Mountain the sheet has the form of a shallow canoe. The sheet is only slightly oblique to bedding along the ridge to a point about 1½ miles southwest of New Mountain, but at that point it turns into a thick irregular dike with a generally southwest strike. The dike continues, forming several nunataks, for an exposed length of 5 miles. There is no apparent systematic orientation to the axes of the many inflections of this great sheet of diabase.

Diabase sheets injected before and after normal faulting form an intricate pattern in the Terra Cotta Hills (fig. 9) just east of Windy Gully Glacier. I saw this complex from a nearby point on Taylor Glacier and from the air but was unable to study it on the ground; however, its character is mostly clear on the many oblique aerial photographs that show it from all sides. (The distant photograph of fig. 9 is reproduced here because it shows the entire complex and its relation to surrounding areas.) A normal fault with a displacement of about 1,500 feet and a southeastward dip of about 45° exposes the peneplain and basement sills and the basement granitic rocks only in its footwall. Distinctive variegated strata can be matched layer for layer on opposite sides (No. 2, fig. 9). The horizontal sandstone of the hanging wall near the fault is injected by a swarm of thin dikes parallel to the fault (No. 3, fig. 9). The fault is apparently cut by a thick sheet of diabase (No. 4, fig. 9) that is inclined steeply westward, although the actual contact of fault and sheet is hidden by talus.

The lower part of the Beacon Sandstone east of the dike swarm contains a concordant sill of diabase (fig. 9) that is not present in the dike-swarm complex toward which it directly trends; whether the discontinuity is due to faulting or to irregularity of the intrusion is not clear. Several thinner, inclined sheets of variable attitude lie higher in the sandstone of the Terra Cotta Hills and nearby Knobhead. On the east face of Knobhead

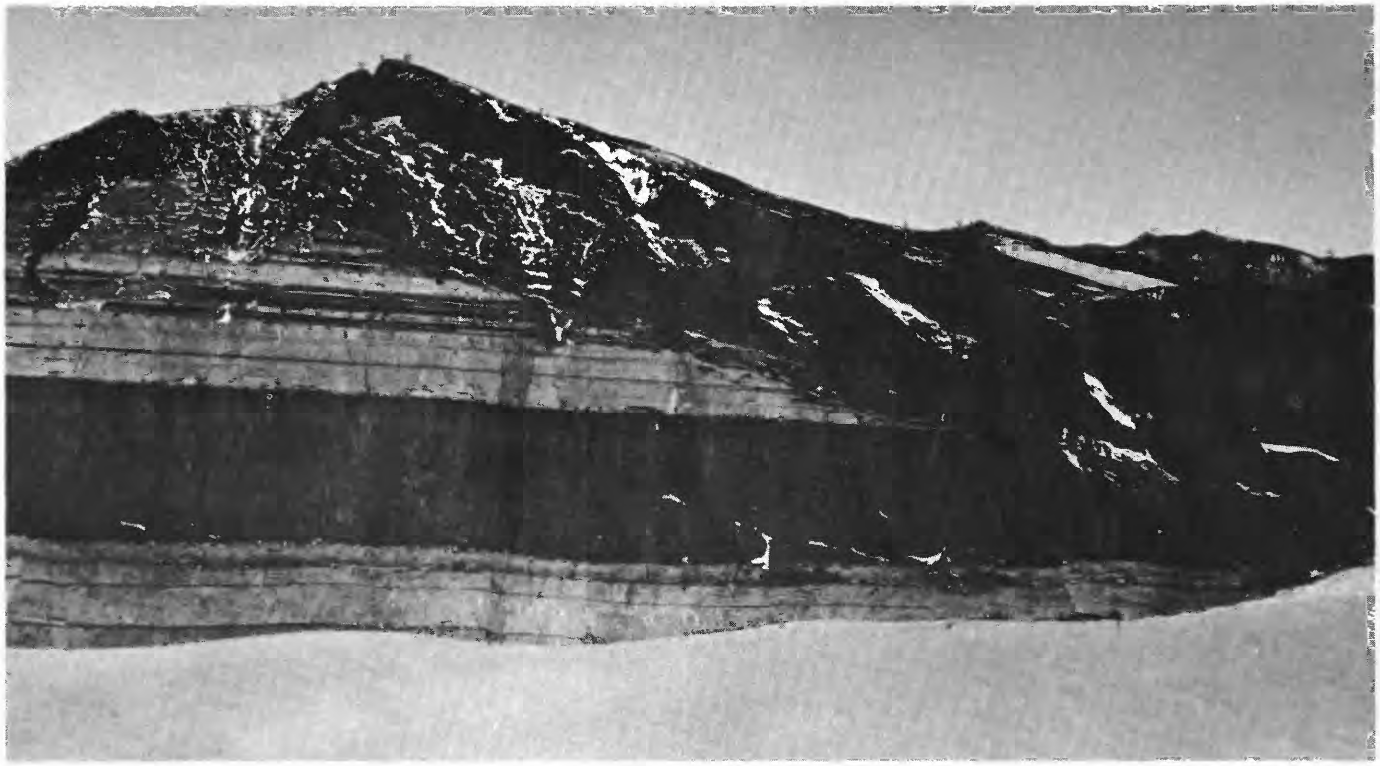


FIGURE 5.—West end of north face of Finger Mountain. The lower sill is cut obliquely by an inclined sheet which turns into a concordant sill at top of mountain. (See also pl. 1 and fig. 4.) Carbonaceous sediments stripe the sandstone between the diabase sheets. Note banding in lower sill. Figure 4 overlaps this picture from the left. Aerial photograph by Warren Hamilton, November 1958.

(fig. 10), an inclined sheet of diabase about 1,500 feet thick cuts through 3,000 stratigraphic feet of sandstone and concordant diabase while maintaining a uniform dip of about 35°; the mountain face is in part the stripped upper surface of this sheet. Columnar joints are perpendicular to the contact of the sheet.

East and south of Ferrar Glacier, the high Royal Society Range and its surrounding foothills are largely covered by snow and ice; but where exposures are good, the diabase sheets are seen, as elsewhere, to have both concordant and discordant segments. One ridge projecting between glaciers tributary to the upper Ferrar south of Knobhead is faced by a crosscutting sheet having a moderate northeast dip (fig. 11, left). The eastern part of the next ridge south displays a sill about 1,000 feet thick low in the Beacon (fig. 11, center), but in the central part of the ridge the sheet becomes abruptly inclined and rises through 1,500 feet of section; it is concordant at the higher level for a short distance, beyond which it again becomes oblique and rises out of the exposed section; this sheet cuts across at least 3,000 stratigraphic feet of sandstone in its two oblique segments.

The main crest of the Royal Society Range rises to summit altitudes of 13,000 feet, and even its great cliffs are largely covered by snow and ice. The broad structure of the range is domical, as is discussed below, and the base of the Beacon Sandstone lies at altitudes of about 8,000 feet along the crest. Exposures are good along the west side of the north end of the crest (fig. 12), and here the usual combination of alternately concordant and crosscutting segments are shown by a thick diabase sheet. The mountain face is capped by a concordant to gently discordant sill; but at both ends of the peak, the sheet inflects to markedly discordant segments which cut downward through exposed thicknesses of about 2,500 feet of sandstone.

No more than the basal few hundred feet of the Beacon Sandstone is preserved in the Kukri Hills, the long mountain block between lower Ferrar Glacier and Taylor Dry Valley (fig. 2). The basement and peneplain sills, discussed below, are widely exposed.

A thick section of Beacon is exposed in the western half of the Asgard Range—the mountain block north of Taylor Dry Valley, Solitary Dry Valley, and Upper Taylor Glacier, and south of Wright Dry Valley (fig. 2). Diabase sheets are widespread in the sandstone, but in this mountain block they are largely concordant sills; inclined sheets are much less conspicuous than in the areas described previously.

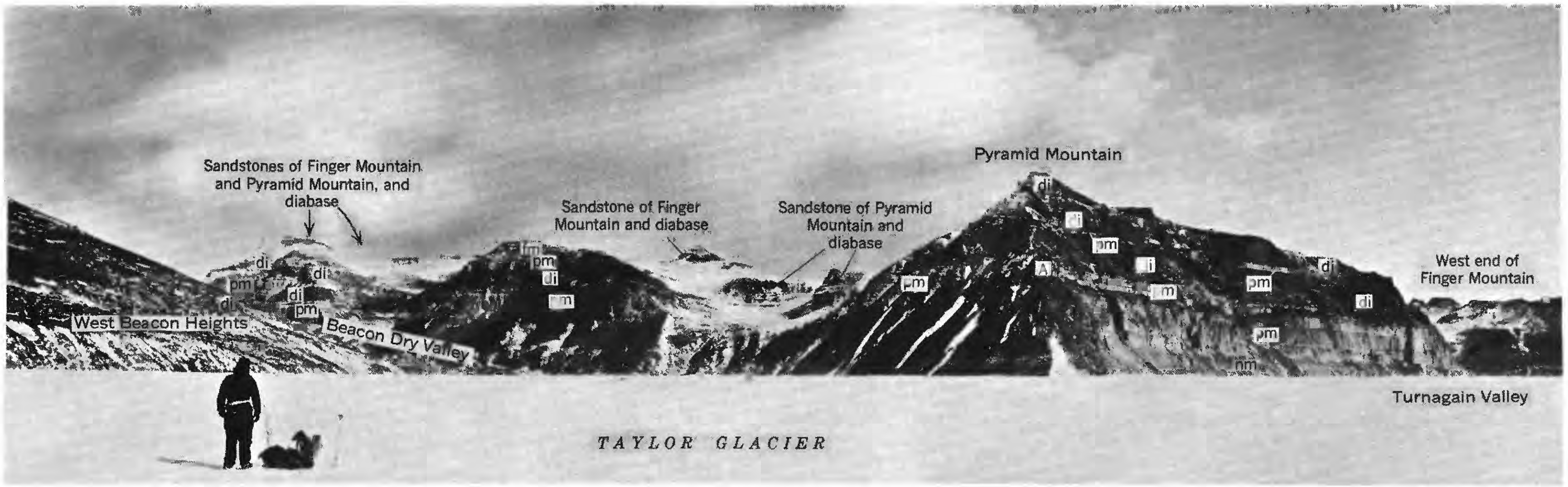


FIGURE 6.—Pyramid Mountain and west wall of Beacon Dry Valley. A diabase dike turns into a sill that encloses a large wedge of sandstone to right of point A. The lower diabase sill of the east (right) face of Pyramid Mountain maintains its stratigraphic position along the wall of Beacon Dry Valley. The upper two sills of Pyramid Mountain rise in the section to the south (left) and are present in the crest beyond the inner valley wall. The base of the cliffs marks the contact between the sandstone of Pyramid Mountain and the sandstone of New Mountain. Units in the Beacon Sandstone: fm, sandstone of Finger Mountain; pm, sandstone of Pyramid Mountain (forming cliffs); and nm, sandstone of New Mountain. Diabase, di. Photograph by P. T. Hayes, November 1958.

FIGURE 7.—Irregular basal contact of inclined sheet of diabase (above and left) against sandstone. View southwest at east buttress of Pyramid Mountain; cliffs within picture are 1,000 feet high. Photograph by Warren Hamilton, November 1958.

In the Asgard Range, we did fieldwork on the Beacon and the diabase sheets only in Solitary Dry Valley. North of the valley (fig. 13), all but the uppermost part of the Beacon Sandstone is exposed, and two sills are present within it in addition to the peneplain and basement sills beneath. One sill in the sandstone of New Mountain is stratigraphically low, and the other is near the top of the sandstone of Pyramid Mountain. Just left (west) of the area shown in figure 13, the upper of these sills descends abruptly through about 500 feet of section to the middle of the sandstone of Pyramid Mountain, and another sill is exposed high in the sandstone of Finger Mountain.

On both sides of Wright Upper Glacier and between this glacier and upper Taylor Glacier, a thick sill of diabase is widely exposed near the top of the sandstone of Pyramid Mountain. At Wright Upper Glacier the sill apparently lies along the upper contact of this unit (fig. 14); other, higher sills are visible in the distant crests (fig. 14). At Northwest Mountain, just north of upper Taylor Glacier (fig. 2), the sill is slightly lower in the section, being a little below the top of the sandstone of Pyramid Mountain (fig. 15). Other sills lie higher in the section.

PENEPLAIN SILL

Wherever the base of the Beacon Sandstone was seen in the region, a thick sill of diabase lay along or a short distance above the unconformity between the Beacon and the underlying plutonic basement rocks. This sill is referred to in this report as the peneplain sill, after the usage of New Zealand geologists; the erosional surface at the base of the Beacon is certainly one of low relief, although as is explained below, the term "peneplain" may not be altogether proper. The thickness of the peneplain sill ranges from about 700 to about 1,500 feet.

The regional dip of the Beacon is gently westward, so that its base is exposed at generally lower altitudes westward through the mountains. The Beacon is missing altogether in the eastern foothills. It is exposed above basement rocks along the crests through the central part of the mountains. The western mountains expose only Beacon and diabase. The base of the Beacon and the peneplain sill are preserved at altitudes of 6,000–7,000 feet in the central mountains, and they disappear underground or under ice at altitudes of 3,000–4,000 feet in the west.

The peneplain sill is exposed on both sides of Windy Gully Glacier (pl. 1; fig. 9) and, farther east, between Emmanuel and Ferrar Glaciers (fig. 2) and in the Royal Society Range. The sill forms much of the crest of the western part of the Kukri Hills (fig. 16) and is widely exposed in the mountains north of Taylor Glacier from the longitude of Bonney Lake westward to Solitary Dry Valley (figs. 13, 18) and Solitary Rocks. In Wright Dry Valley, it crops out from east of Lake Vanda (figs. 17, 20) westward to the head of the valley (fig. 14). Its known area extends 30 miles north-south and the same distance east-west, and its minimum volume is about 150 cubic miles.

In many places the peneplain sill apparently lies directly upon basement rocks (figs. 11, 13, 16, 18, and probably 17). In others, it intrudes the basal strata, and a few feet to several hundred feet of sandstone intervene between it and basement rocks (figs. 9, 22). Nowhere were basement rocks seen above the sill.

The erosion surface on the plutonic rocks of the basement complex is one of remarkably low relief. Although basement hills as high as 100 feet are exposed locally at the unconformity, as near Windy Gully Glacier (Zeller and others, 1961), the surface is commonly nearly a plane (fig. 17). Variations in the character of the strata overlying the unconformity, however, suggest that this plane may have had 1,000 feet or more of broad relief. For example, the cliff-forming sandstone of Pyramid Mountain forms the middle part of the Beacon Sandstone wherever that part is seen westward from Knobhead and Solitary Dry Valley to the inland ice plateau (figs. 6, 8, 9, 13, 14, 15), and the recessive-weathering sandstone of New Mountain—sandstone with subordinate siltstone—forms a thick,

FIGURE 8.—Diabase sheets of Beacon Dry Valley–New Mountain area. The dark diabase (di) is conspicuous in the light-colored sandstone (ss). The sandstone of Pyramid Mountain (pm) forms cliffs across the center of the picture. Arrows show direction of ice flow. The far peak of Ross Island is 125 miles east of the foreground area. U.S. Navy photograph, November 1959.

lower unit; thin strata of quite different character, and possibly much older than the Beacon proper, are present locally beneath this unit. In the Kukri Hills, by contrast, the basal part of the Beacon—the only part of the formation present—is cliff-forming sandstone (fig. 16) similar to the sandstone of Pyramid Mountain. If these similar units are correlative, which would indicate onlap of the Beacon, then one interpretation of the cause of onlap is that the Kukri Hills mark the site of a broad basement high upon which the basal part of the Beacon was not deposited. The thinness of the section in the Kukri Hills may be due in part to lack of deposition as well as to subsequent erosion.

The term "peneplain" has genetic as well as geometric significance, for it is defined as a nearly plane surface formed by subaerial erosion. It has yet to be proved that the gentle surface beneath the Beacon was produced by such erosion rather than by, for example, marine erosion that yielded a broad strandflat. The extensive sill of diabase along the unconformity is referred to

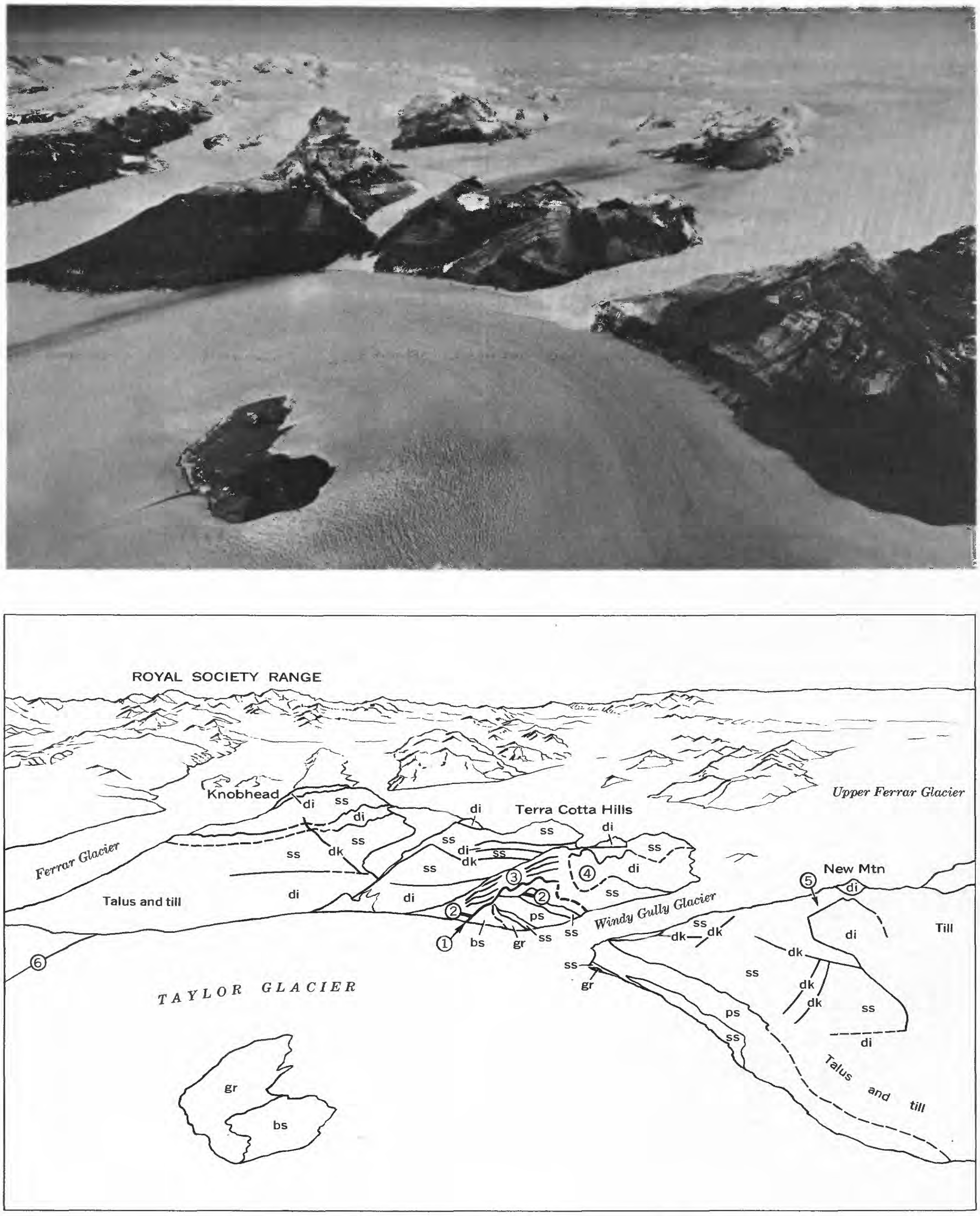


FIGURE 9.—Diabase sheets of Knobhead–New Mountain area as viewed south-southwestward from above Solitary Rocks. ss, Beacon Sandstone; gr, granitic basement rocks; bs, basement sill; ps, peneplain sill; di, higher sheets, concordant or inclined, of diabase; dk, diabase dikes, mostly less than 100 feet thick. Dark talus from diabase sheets and dikes covers sandstone in many places. 1, Normal fault formed during period of diabase intrusion; left side dropped down about 1,500 feet. 2, Distinctively variegated strata, offset by fault, marked by bars extending from circles. 3, Swarm of diabase dikes parallel to fault, injected into horizontal sandstone. 4, Thick dike of diabase injected after faulting. 5, Vertical contact bounding segment of gently dipping diabase sheet; roof raised, but floor not faulted; sheet continues as the cap of New Mountain. 6, Medial moraine at junction of Ferrar and Taylor Glaciers; an increment of ice from the Ferrar joins the Taylor to flow into Taylor Dry Valley. Knobhead rises nearly 5,000 feet above Taylor Glacier. U.S. Navy photograph, December 1956.

here as the peneplain sill for the sake of consistency with reports by others, but a nongenetic term would perhaps be preferable.

Webb and McKelvey (1959, p. 134, fig. 2) and Allen and Gibson (1962) found two extensive diabase sills in the area of Victoria Dry Valley, the next valley system north of Wright Dry Valley. Granitic basement rocks underlie the lower sill and lie between it and the upper one, which is the highest structural unit recorded. Balham (1960, p. 7), however, reported a thick section of Beacon Sandstone immediately north and also west of

FIGURE 10.—Diabase sheets in sandstone, east face of peak 2 miles south of Knobhead. The summit and left ridge are formed of a thick sheet that dips about 35° E. (left). Horizontal sandstone crops out on the right. A concordant sill forms a dark bench below center, but most of the foreground slopes are mantled by till having polygonal ground structure. The inclined sheet is seen from another direction along the crest of Knobhead in figure 9. The peak stands about 3,500 feet above the ice. View southwestward along middle part of Ferrar Glacier. Aerial photograph by Warren Hamilton, November 1958.

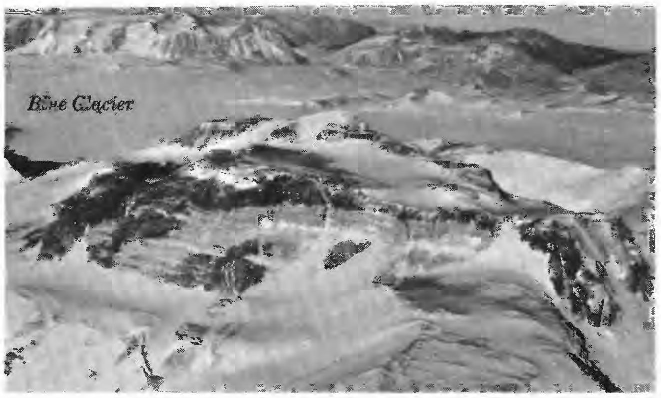


FIGURE 12.—Sheet of diabase in Beacon Sandstone of Royal Society Range. Sheet is a concordant sill along most of the ridgetop but turns into an inclined sheet at both ends. Irregular dark areas below sheet are diabase talus over sandstone. View eastward toward main crest of range, near north end. U.S. Navy photograph, November 1959.

the area seen by Webb and McKelvey. The lower diabase sheet noted by Webb and McKelvey and by Allen and Gibson is the basement sill, and the upper one, the peneplain sill. The peneplain sill was found on both sides of the valley system as far north as the limit of the area visited, about lat 77°45′ S., or about 20 miles north of Lake Vanda in Wright Dry Valley. If this 20 miles is added to the 30 miles of north-south extent of the peneplain sill described in the present report, giving a minimum length of 50 miles with neither end yet known, the minimum volume of the sill is increased correspondingly to about 250 cubic miles. It is of course possible that different sills intruded fortuitously at the same stratigraphic position have been seen in the separate areas, but no discontinuities to suggest this alternative have yet been recognized.

FIGURE 11.—Inclined sheets of diabase in sandstone at south side of Ferrar Glacier. The sheet along the left side of the foreground ridge is entirely discordant, whereas the sheet on the near side of the distant ridge is discordant on the right but concordant on the left along the glacier. View southward across the middle part of Ferrar Glacier; the near ridge lies above Knobhead in figure 9, and the far ridge lies to the right of that mountain. The far ridge rises 3,500 feet above Ferrar Glacier. Aerial photograph by Warren Hamilton, November 1958.

FIGURE 13.—View north across Solitary Dry Valley toward diabase sheets. A fault is believed to trend left across the picture beyond the ridge of the middle distance; the far side may have been dropped down about 2,000 feet. qm, pre-Devonian quartz monzonite; nm, sandstone of New Mountain; pm, sandstone of Pyramid Mountain; fm, sandstone of Finger Mountain; bs, basement sill of diabase; ps, peneplain sill of diabase: di, other sills of diabase. Relief in picture, 5,000 feet. Photograph by P. T. Hayes, December 1958.

BASEMENT SILL

Less regular than the peneplain sill but equally extensive is the huge basement sill (fig. 18), a sheet of diabase 600 to at least 1,500 feet thick intruded along horizontal and gently dipping exfoliation joints in granitic rocks beneath the unconformity at the base of the Beacon Sandstone. The joints are closely spaced high in the basement rocks, but they become progressively wider spaced and less regular downward and are generally inconspicuous at depths greater than 3,000 feet beneath the unconformity. As these joints are followed by the sill, it is apparent that they were formed mostly before intrusion, presumably in response to erosional unloading during the period that produced the broad plain upon which the Beacon was deposited. The basement sill was seen at most places where granitic rocks are exposed at the appropriate levels; but it was not seen where, as in the eastern third of the Kukri Hills, metamorphic rocks are extensive. Structures in the metamorphic rocks are irregular but generally steep, and the restriction of the sill to granitic rocks probably is due to the much better development of flat joints in the granitic rocks.

The term "basement sill" is also accepted in this report, with reservations, for the sake of consistency with usage by New Zealand geologists. The name is derived from the restriction of the sill to the pre-Beacon basement complex, and there is no objection to the term when this is understood. The sill, however, was intruded after deposition of the Beacon Sandstone and is

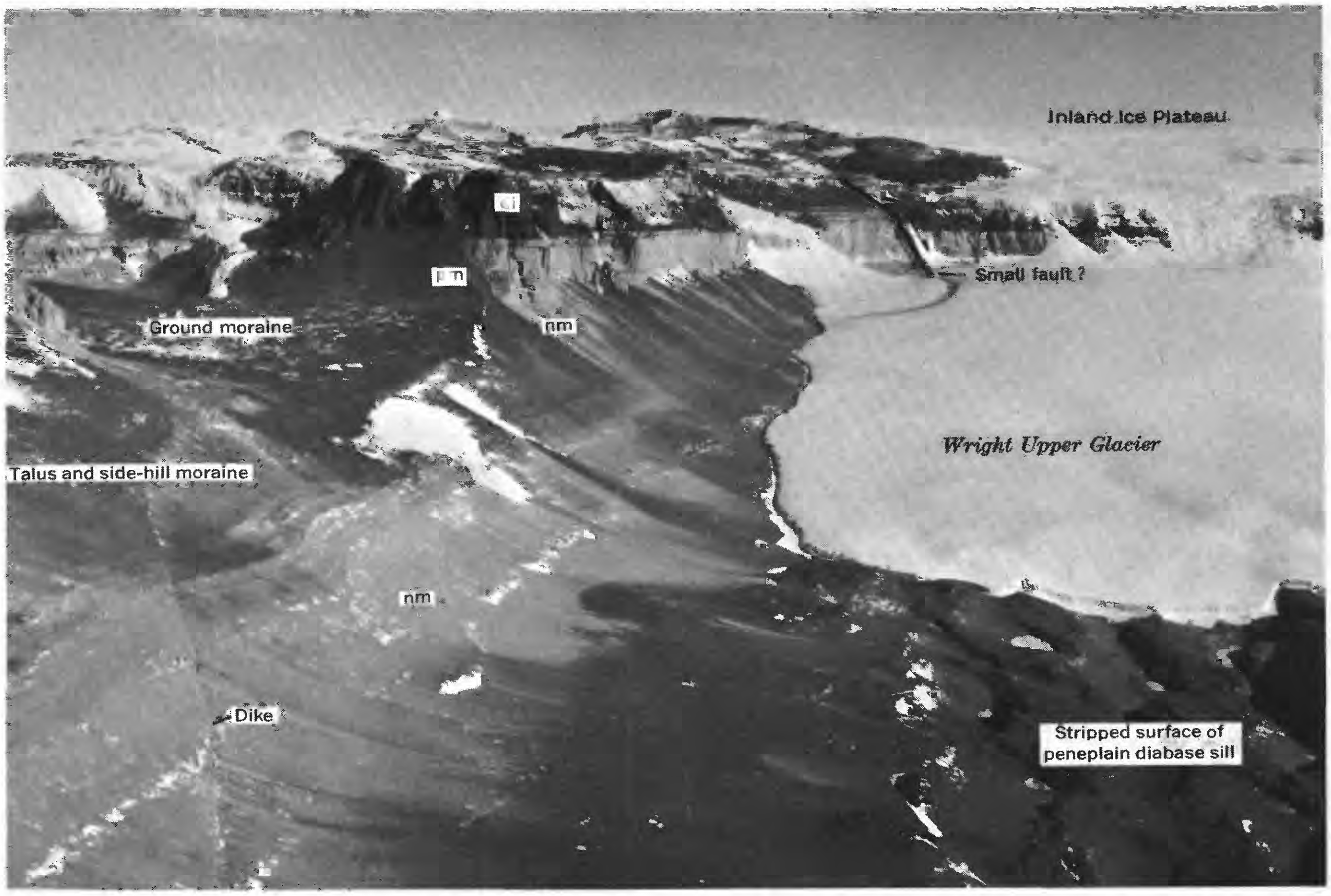


FIGURE 14.—Diabase (di) and sandstone, viewed west over Wright Upper Glacier. Ice from the inland plateau spills over the mountain crest to form the small apron of Wright Upper Glacier, but the inland ice surface has dropped almost to the level of the rock sill so that there now is little overflow. The ice margin is a continuous ice cliff. The inland ice stood higher during parts of Pleistocene time, and its overflow repeatedly filled the now bare valley to depths of several thousand feet; the hanging valley at the left was filled at such times also. The ice-scoured surface of the peneplain sill is shown also in figure 17. Units in the Beacon Sandstone: pm, sandstone of Pyramid Mountain; nm, sandstone of New Mountain. Relief in picture, 5,000 feet. Aerial photograph by U.S. Navy for U.S. Geological Survey, November 1958.

far younger than the basement complex; it is not part of the basement, as might be inferred erroneously from its name.

The basement sill is exposed most continuously along the north side of the western half of the Kukri Hills (fig. 16), where it is particularly thick (1,200–1,500 ft). It undulates gently up and down in the basement rocks, maintaining one trend or the other for long distances. Its most common depth beneath the unconformity is 500–1,500 feet (figs. 13, 18, 19), but it ranges from as high as the unconformity itself (fig. 9) to as low as 4,000 beneath it.

The basement sill is exposed in the Terra Cotta Hills (fig. 9), the Solitary Rocks, and the low bedrock mass in Taylor Glacier between them (fig. 9); in Cathedral Rocks along the south side of the lower Ferrar Glacier (fig. 19), where it is less than 1,000 feet thick; along the east side of the Royal Society Range; in the Kukri Hills on the north side of the Ferrar Glacier opposite Cathedral Rocks and westward; on both sides of Taylor Dry Valley and lower Taylor Glacier, westward from the longitude of Sollas Glacier, and around Solitary Dry Valley (figs. 13, 18); and along the middle reaches of Wright Dry Valley (fig. 20) at least from 5 miles west of Lake Vanda to 10 miles east of it. The sill thins to less than a few hundred feet in lower Wright Dry Valley (fig. 20) and ends a short distance beyond the area visible in the photograph. The basement sill crops out over a known area of 25 by 30 miles, and, if one assumes all exposures to be of the same sheet, has a minimum volume of 100 cubic miles.

Webb and McKelvey (1959, p. 134; fig. 2) found two diabase sheets separated by granitic rocks near Lake Vida in the Victoria Dry Valley system about 12 miles northeast of Lake Vanda in Wright Dry Valley. As noted previously, the lower of these sills is equivalent to the basement sill of this report; if it is part of the same sheet, another 10 miles is added to the northward

FIGURE 15.—View west to Northwest Mountain. The concordant diabase sill (di) maintains about the same stratigraphic position that it has from Beacon Dry Valley (fig. 6), Pyramid Mountain (fig. 4), and Finger Mountain (fig. 3) to Wright Upper Glacier (fig. 14). Units in the Beacon Sandstone: fm, sandstone of Finger Mountain; pm, sandstone of Pyramid Mountain; nm, sandstone of New Mountain. The cliffs in center and right background are 1,500–2,000 feet high. Aerial photograph by U.S. Navy for U.S. Geological Survey, November 1958.

extent of the sill. Balham (1960, p. 8) reported its thickness to be about 800 feet in Victoria Dry Valley.

I saw from the air a thick diabase sill high in granitic basement rocks in the coastal headlands north of the floating tongue of MacKay Glacier in Granite Harbor, 50 miles north of the mouth of Taylor Dry Valley and 30 miles north of the Lake Vida occurrences noted just above. If the Granite Harbor mass is part of the same sheet as that of the Ferrar Glacier–Taylor Dry Valley–Wright Dry Valley region, then its north-south extent is increased to 65 miles and neither end is yet known.

Ferrar (1907, p. 36–38 and geologic map) misinterpreted the granite lying above the basement sill in the Kukri Hills to be younger than the sill, and to be injected between the sill and the overlying sandstone and peneplain sill. This misconception seems to be based on the misinterpretations that pink granite overlies the still, whereas gray granite underlies it, and that the pink granite intrudes masses of diabase.

The basement complex of the western half of the Kukri Hills consists of a composite batholith in which the separate plutons become progressively more potassic westward. A large pluton of silicic pink quartz monzonite is exposed around Solitary Dry Valley, and it also (Ferrar, 1907; Prior, 1907; and Smith, 1924) forms the western part of Kukri Hills and the western part of Cathedral Rocks along the south side of Ferrar Glacier. In Taylor Dry Valley eastward from a point at least 1 mile west of Bonney Lake almost to Suess Glacier and Nussbaum Riegel, several plutons are present, all of gray rock, dominantly granodiorite; near Suess Glacier and Nussbaum Riegel the granitic rocks give way to a gneissic border zone along the west side of the metasedimentary belt that continues eastward to McMurdo Sound (Hamilton and Hayes, 1960). Ferrar's misconception that pink granite overlies the basement sill whereas gray rocks underlie it probably is due to his having collected samples many miles apart along Ferrar Glacier, and having sampled the eastern gray plutons beneath the sill and the western pink one above it, both at ice level because of the general westward dip of the sill. In Solitary Dry Valley the pink quartz monzonite above the sill is identical with that beneath

FIGURE 16.—Basement and peneplain sills on north side of Kukri Hills. The tabular peak is capped by cliff-forming Beacon Sandstone, beneath which is the thick, columnar-jointed peneplain sill. This sill lies directly against granitic rocks of the basement complex, apparently without intervening sandstone. The less exposed basement sill of diabase trends downward to the right; its base is a short distance above Taylor Glacier to the right of the tributary hanging glacier. Relief in picture is 4,500 feet. Aerial photograph by U.S. Navy for U.S. Geological Survey, November 1958.

it; the quartz monzonite at the upper contact of the sill is metasomatized by the diabase, and many xenoliths of quartz monzonite occur within the upper part of the sill.

Ferrar's idea that the pink granite intrudes diabase was apparently based upon the finding of a large xenolith of mafic rock within the granite near the west end of Kukri Hills, and upon the assumption that this mafic rock was diabase. Prior (1907, p. 128) studied Ferrar's specimens and recognized that the dark rock in question was highly metamorphosed and completely unlike the diabase of the region. Smith (1924, p. 184–185) also recognized Ferrar's error and stated correctly that abundant field relations proved that the diabase intruded the granite. Ferrar (1925) apparently realized his error, for he later emphasized that dikes in the granitic rocks are older than the Beacon Sandstone and are truncated at the great unconformity; but he made no specific statement in this later report regarding the relation of the granite to the basement sill.

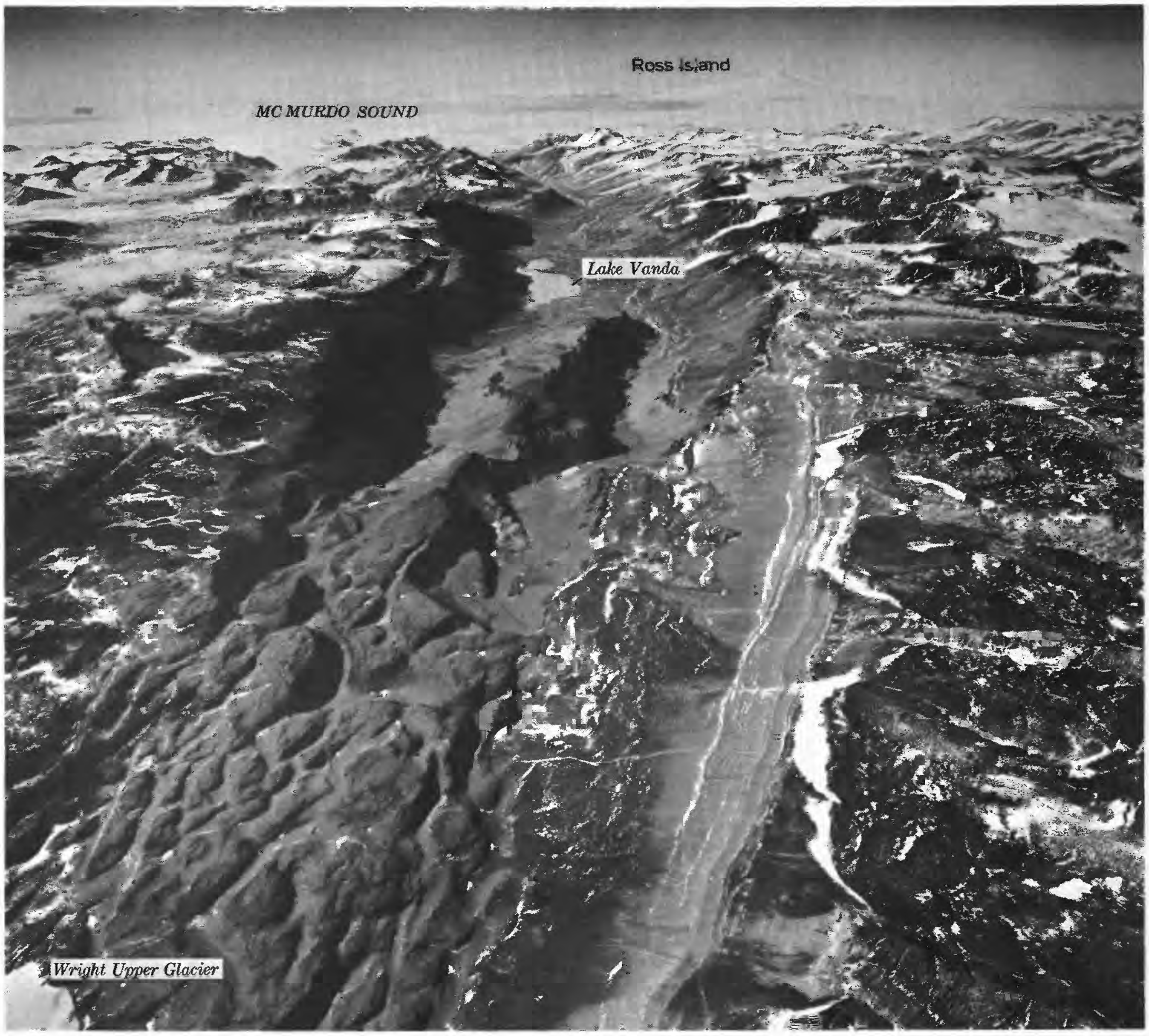


FIGURE 17.—The peneplain sill in the upper part of Wright Dry Valley, viewed eastward from above head of valley. The ice-scoured upper surface of the sill forms the platform extending from lower left to center, and the sill continues beyond as cliff-forming headlands above the inner valleys, carved in granitic rocks. The recessive-weathering lower part of the Beacon Sandstone forms the striped terrain to the right of the platform and less conspicuous areas to the left of it. Diabase sills and Beacon Sandstone form the peaks and ridges along both sides of the picture. The ice-stripped platform resembles topographically the Channeled Scablands of Washington, which are formed on thick flows of Columbia River Basalt, similar mechanically to this diabase sheet. The Scablands were formed by erosion by a catastrophic flood, and possibly this topography formed similarly. The area of figure 14 (view in the opposite direction) overlaps that of the bottom of this picture. U.S. Navy photograph, November 1959.

SMALL DIKES

The Beacon Sandstone is cut by locally numerous straight, steep dikes 2–50 feet thick and random in strike. These dikes are much thinner than the sills and inclined sheets and dip more steeply than any but a few of the inclined sheets. They are illustrated on plate 1 and in figures 9, 14, and 17 (right of bottom center). They are rare in cliff-forming sandstone and occur largely in the recessively weathering units.

The basement complex is injected by innumerable dark straight dikes such as those along the south side of Wright Dry Valley (fig. 20). These dikes are particularly plentiful in the broad contact zone between granitic and metamorphic rocks. Without any exception of which I know, these dikes are older than the Beacon Sandstone and bear no relation to the diabase intrusions. The dike rocks that were studied petrographically are thoroughly altered, completely different

749-445 O—65——4

FIGURE 18.—Basement and peneplain sills in south wall of Solitary Dry Valley. The lower (basement) sill, 700 feet thick, was sampled in the area near the center of the photograph. The light-colored wallrock is massive uniform quartz monzonite. The basement sill was injected along exfoliation joints in the quartz monzonite related to the pre-Beacon Sandstone erosion surface. The peneplain sill caps the crest. The foreground rubble is ground moraine deposited by a branch of Taylor Glacier that formerly flowed directly through the valley as well as through the now ice-filled lower valley. Photograph by Warren Hamilton, December 1958.

mineralogically from the diabase. The dikes in many places—for example, in spectacular exposures upon Nussbaum Riegel—are fragmented complexly by intricately intersecting minor faults. They are truncated against the unconformity at the top of the basement rocks and against the basement and peneplain sills, wherever these contacts were seen.

MODE OF INTRUSION

Each of the large sheets of diabase in the Beacon Sandstone is alternately concordant and discordant. Sheets inflect to concordant sills above and below segments which cut sharply across several thousand feet of beds. Segments of some sheets end against vertical contacts that are faults along which the roof rocks were raised but which did not cut the floor rocks. The significance of such crosscutting in South Africa was emphasized by Du Toit and Haughton (1953), and similar relationships were recognized in Tasmania by Carey (1958b). These features are particularly obvious in the Taylor Glacier region because of the excellent exposures. In areas of poor exposures, many inflections or intrusive offsets of sheets such as these could easily be misinterpreted to be faults cutting the sheets.

Individual diabase sheets extend over areas of at least 1,000 square miles and yet maintain subuniform thicknesses. The magma from which they formed was obviously highly fluid. The even thickness probably is due to roof pressure which caused the magma to spread out into vast sheets as it was intruded and which thus caused subuniform altitudes of the ground surface to be maintained. Fluid diabase and solid sandstone and granite probably had about the same density, and the balance was not affected by crosscutting segments of the sheets.

Areas of a thousand square miles or more of roof rocks must have floated upon single molten sheets. The transgressive parts of the sheets would, however, have prevented much sliding about of the floating plates.

The diabase sheets appear to be most continuously concordant where intruded along surfaces of massive rocks Particularly widespread sills are intruded in the middle of the cliff-forming sandstone of Pyramid Mountain; sheets in the thinner bedded sandstone of New Mountain are in general less regular. The peneplain sill, intruded along or very near the top of the granitic

FIGURE 19.—Basement sill along lower Ferrar Glacier. Cathedral Rocks—the triangular headlands facing the glacier—are 3,000–4,000 feet high and are formed of granitic and gneissic basement rocks overlain by remnants of the diabase sheet. Structure rises gradually toward the 13,000-foot crest of the Royal Society Range of the center skyline; broad structure of the range is domical, and view is south-southeastward up the long axis. The stratovolcano Mount Discovery is 9,000 feet high and 60 miles distant. U.S. Navy photograph, December 1956.

basement complex, is the most uniformly positioned sheet in the region. The basement sill, which follows exfoliation joints in the granitic complex beneath the pre-Beacon erosion surface, varies in position through a vertical interval of 4,000 feet.

No dikes of diabase, large or small, were found cutting the basement rocks of the region; but dark dikes of varied porphyries and lamprophyres, none of which are diabasic, a few feet to a few tens of feet thick cut the basement rocks in all parts of the region (as, fig. 20) The enormous basement sill is the only intrusion of diabase seen in the basement rocks. There is thus no evidence available to suggest that the basement sill and the diabase sheets in the overlying Beacon Sandstone were intruded from deep sources within the report region. There are abundant crosscutting sheets and small dikes in the Beacon, but all these need indicate only injections of or from the far-traveled sheets themselves.

CONTACT METAMORPHISM

METAMORPHISM OF BEACON SANDSTONE

The entire Beacon Sandstone near its type section has been slightly metamorphosed thermally by the diabase sheets. This metamorphism is obvious in the field chiefly in the hornfelsed or metasomatized rocks within a few feet of the sheets. The appearance of rocks farther away as seen in hand specimens is chiefly that of unaltered sedimentary rocks, but, nevertheless, pervasive metamorphism is apparent in thin sections. Argillaceous fractions are reconstituted to fine-grained mica, and most of the quartz has been recrystallized marginally to form mosaics and, locally, interlocking grains. Much feldspar has been converted to fine-grained mica. The bituminous to anthracitic character of the coal in the Beacon probably is due to this thermal metamorphism.

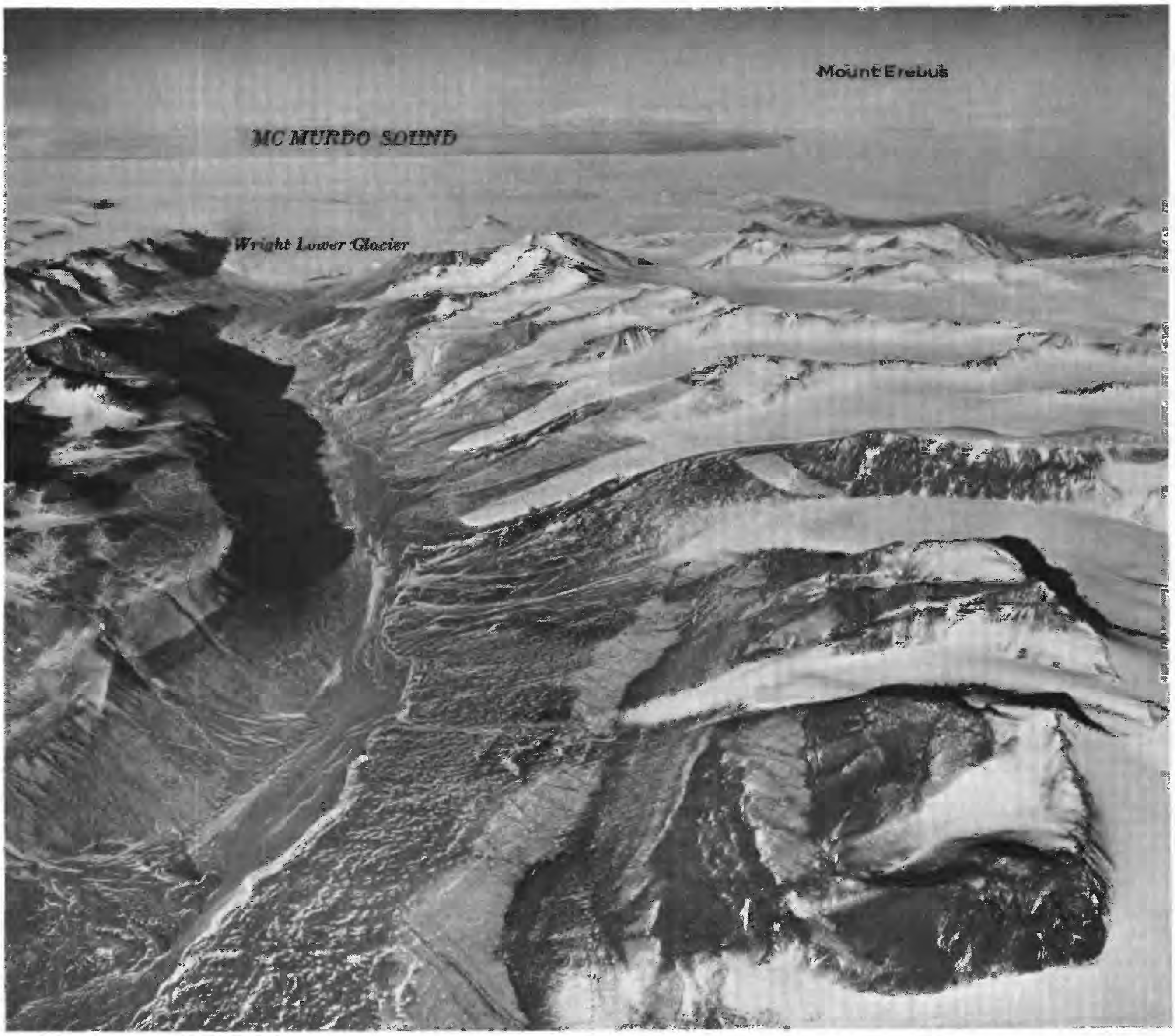


FIGURE 20.—Basement and peneplain sills in Wright Dry Valley. The irregular basement sill forms the dark band high on the wall on the left side of the inner valley and the broader band along the right side trending upward in the photograph from bottom center. The peneplain sill forms the dark ridges from lower right to right center. Beacon Sandstone caps the long, dark ridge just above right center. The granitic basement rocks are cut by many thin dark dikes unrelated to the diabase sheets. Lower slopes of the inner valley are mantled by talus and till. Wright Lower Glacier protrudes into the mouth of the valley from a coastal piedmont ice sheet. The broad bend in the valley is that beyond Lake Vanda in figure 17. View eastward; 13 miles of ice-free valley are shown, and the peaks stand 5,000–6,000 feet above it. U.S. Navy photograph, November 1959.

The diabase sheets were intruded at temperatures near 1000°C, and their total thickness approaches that of the Beacon itself. Temperatures near cooling intrusive sheets were calculated by Jaeger (1957), who allowed for the heat of crystallization within the intrusives. His calculations for a sheet 200 meters thick suggest a probable time of about 600 years for cooling from 1,000° to 800°C—the range within which crystallization of quartz diabase should largely occur; thus, temperature of the sheet and its wallrocks would be held substantially above original temperatures for several thousand years. Maximum wallrock temperatures due to conduction of heat away from the sill—both up and down from a sill under thick cover—should reach 450°C at 100 meters from the contacts of a 200-meter sill, 350°C at 200 meters from it, and 250°C at 300 meters. (These values were scaled from Jaeger's fig. 4.) As most of the Beacon Sandstone of the region is within 300 meters of some thick diabase sheet, its pervasive recrystallization is thus easily explained. The actual temperatures would be higher in proportion to the geothermal heat present in the section prior to intru-

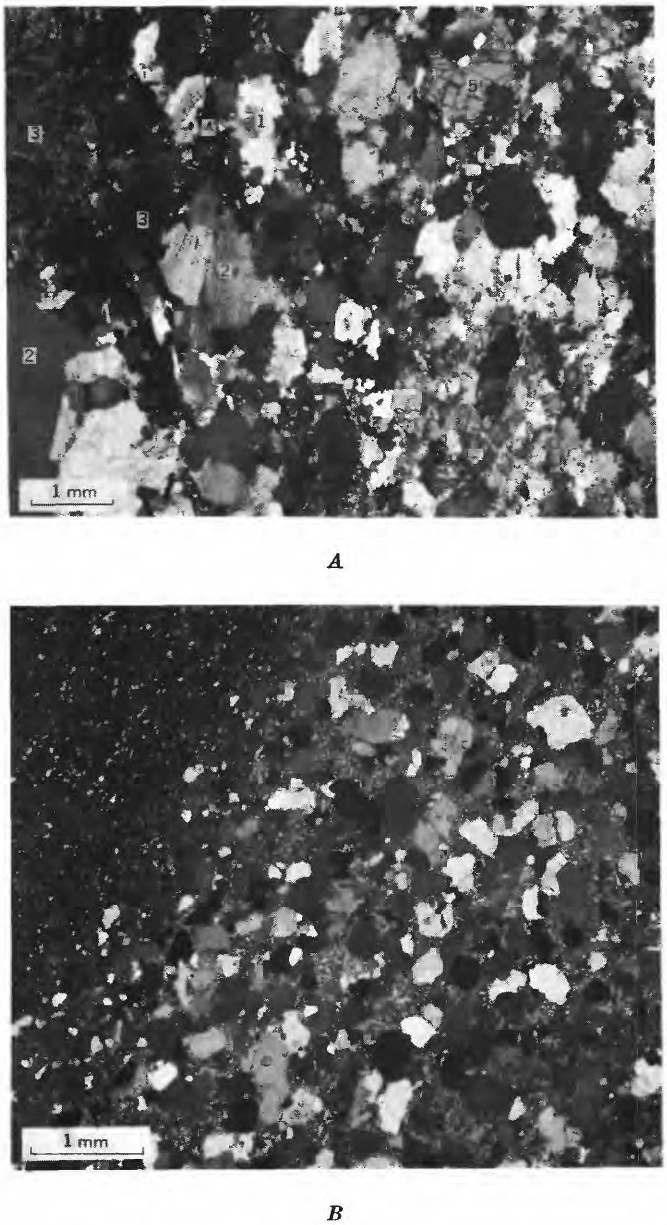


FIGURE 21.—Photomicrographs of sandstone. *A*, Metasomatized and sheared sandstone near contact with inclined sheet of diabase at east end of Pyramid Mountain. Metasomatism was largely accomplished before the shearing that produced the cataclstic foliation, which is here vertical. 1, quartz grain recrystallized to a granular mosaic; 2, oligoclase, either clastic or metasomatic; 3, hornblende, 4, biotite, and 5, sphene, all of metasomatic origin. Nicols oblique. *B*, Hornfelsed argillaceous sandstone. Quartz and feldspar sand grains have been recrystallized marginally and have sutured edges but retain their clastic dimensions. The argillaceous matrix has been recrystallized into randomly oriented fine-grained muscovite. Carbonaceous siltstone (upper left) was changed little in grain size. Specimen was collected from a thin septum between two diabase sheets beside Taylor Glacier just east of Beacon Dry Valley. Nicols oblique.

sion. Temperatures could be further increased by ground-water movement or by the intrusion of one sheet before the warming effects of the previous one had been dissipated and a stable geothermal gradient established.

Relatively intense metamorphism affected the feldspathic sandstone near the west (lower) contact of the thick inclined sheet at the east end of Pyramid Mountain. Pods and lenses of green-spotted rock were produced in coarse-grained feldspathic sandstone within several tens of yards of the diabase sheet. The green spots are composed principally of large poikilitic anhedral grains of hornblende, which is green both in hand specimen and in thin section (fig. 21*A*), but they also include subordinate biotite, which is brown in thin section. As the unspotted sandstone contains very little mafic material, the hornblende probably was added metasomatically. Part of the locally abundant oligoclase (fig. 21*A*) in the spotted sandstone may have been added also. Some of the spotted sandstone, including the specimen illustrated, was sheared cataclastically after the formation of hornblende but before final crystallization of biotite, quartz, and oligoclase.

Such metasomatism is uncommon even at this contact. The general effect observed in the sandstone here was the bleaching and baking of the normally tan-weathering sandstone to hard white quartzite within a few feet of the contact. Quartz grains largely retain their clastic size in the quartzite but are recrystallized into a tightly fitted, although not interlocking, mosaic. The sparse argillaceous matrix is now fine-grained muscovite. Bedding is easily visible in the baked rock and is continuous without deformation from the less altered sandstone.

Beside Taylor Glacier just east of Beacon Dry Valley, thoroughly hornfelsed sediments form a horizontal septum 3–15 feet thick between the basement sill and the diabase sheet overlying it. The sediments are now hard, flinty rocks, many of which are darkly carbonaceous, but bedding laminae are clearly preserved in the fine-grained strata. Both quartz and felspar clastic grains in the sandy rocks were recrystallized marginally and have sutured edges (fig. 21B); the here-abundant argillaceous matrix material was converted to randomly oriented muscovite in flakes 0.02–0.05 mm (millimeter) long. The originally argillaceous or silty rocks show similar preservation of general size and shape of sand grains, but in these rocks the new mica tended to crystallize mimetically parallel to bedding.

Similar but less marked reconstitution and recrystallization has affected the Beacon Sandstone throughout the Beacon Heights section and in the other localities where P. T. Hayes and I observed it. Marginal recrystallization of quartz grains, and frequently of feldspar, and reconstitution of the interstitial clay fraction to randomly oriented muscovite are ubiquitous.

METAMORPHISM OF BASEMENT ROCKS

The crystalline basement rocks show obvious thermal metamorphism only adjacent to the diabase sheets. The pink quartz monzonite intruded by the basement sill in Solitary Dry Valley shows upon casual field inspection no obvious effects of metamorphism at either its upper or lower contact. A specimen collected 6 inches beneath the lower contact of the sill shows in thin section considerable clouding of both oligoclase and perthite, much but incomplete chloritization of hornblende, only slight recrystallization of quartz, and apparently no recrystallization of feldspar. Another specimen collected 5 feet above the upper contact shows considerably more alteration in thin section, though scarcely more is apparent in hand specimen. The hornblende was altered completely to biotite, chlorite, and magnetite; biotite was partly chloritized; and quartz and mafic minerals were slightly recrystallized; but, as at the base, feldspar was only clouded.

Xenoliths of quartz monzonite lie in the granophyric layer near the top of the basement sill and have been highly metasomatized. The xenoliths occur as lenses and highly irregular masses; their shape presumably is due to flow after thermal softening. The metagranite has an obscurely granitic aspect in hand specimen, for the vague outlines of its original coarse grains can be seen although the color is changed from the pink of the unaltered rock to mottled greenish gray. In thin section the metagranite is seen to be largely a mosaic of tiny poikilitic crystals of quartz and clouded feldspar, with subordinate biotite and a little chlorite and pale hornblende; the original granitic texture is preserved in scattered less altered feldspar grains and in slight variations in proportions of the different minerals. No xenoliths were noted within the chilled margins.

As is described elsewhere, the most silicic granophyre of the granophyric layer in the basement sill may have formed in part by still more thorough metasomatism of granitic wallrocks. The intermediate granophyre probably also includes material of xenolithic and xenocrystic origin.

Away from the basement and peneplain sills, the basement rocks show no effects demonstrably due to metamorphism by the sills. The basement rocks generally show only slight chloritization of mafic minerals and slight sericitization of feldspars, and they are similar to granitic rocks that would not be considered altered elsewhere in the world. The sills perhaps contributed to this alteration.

The published paleomagnetic studies reported in another section of this paper show that both Beacon and basement rocks share the same paleomagnetic orientation as do the diabase sills in this region. Certainly all the Beacon samples considered and probably all the basement rocks are within about 2,000 feet of large diabase sheets, and it is likely that this consistent magnetic orientation is due to heating by the intrusive sheets.

AGE

The diabase sheets can be dated stratigraphically as younger than the Beacon Sandstone because they are instrusive into all parts of the Beacon. The uppermost part of the Beacon is of Early Jurassic age (Gunn and Warren, 1962).

The enormity and continuity of the diabase sheets and their compositional similarity throughout the vast part of Antarctica in which they occur suggest that they are of approximately the same age throughout the continent. This is confirmed by age determinations. McDougall (1963) made 10 potassium-argon determinations on plagioclase and pyroxene from various diabase sheets in the Victoria Dry Valley, Skelton Glacier, and Beardmore Glacier regions and found them to range only from 147 to 163 m.y. in calculated age; 8 of the determinations are within the range 150 to 159 m.y.. These sheets are of Middle Jurassic age.

Diabase sheets of about this same age are intrusive into strata of southern Africa and southeastern Australia that are correlative with and very similar to the Beacon Sandstone of Antarctica. Eleven potassium-argon determinations made on separated minerals and chilled rock from a diabase sill in Tasmania indicated an age of about 165 m.y. (McDougall, 1961). The comparable Karroo diabase sheets of southern Africa are closely associated with the compositionally similar Stormberg basalts of Late Triassic (Walker and Poldervaart, 1949, p. 598–599) or Early Jurassic (Du Toit and Haughton, 1953) age and are presumably correlative, although only provable stratigraphically to be pre-Cretaceous (Du Toit and Haughton, 1953, p. 353, 369, 370). Diabase sheets and basaltic lavas, again associated with Beacon-like strata, are present also in South America but cannot yet be dated by precisely, although an Early Jurassic age is inferred by available data. At least some of the similar igneous rocks of India are of Jurassic age, although others may be as young as Cretaceous.

STRUCTURE

The diabase sheets have been little deformed in the Taylor Glacier region. The sheets, the Beacon Sandstone which they intrude, and the underlying basement rocks have been arched into a broad north-trending dome and have been broken by a few normal faults. Many faults in the basement rocks do not break the sandstone or diabase and are older than the peneplain(?) surface upon which the sandstone was deposited. Few faults are seen in sandstone and diabase even where large areas are exposed in continuous outcrop.

Basement rocks, sandstone, and diabase in the Terra Cotta Hills (pl. 1; fig. 9) are dropped about 1,500 feet on the south side of a fault that strikes west-southwestward and dips moderately southward. This fault does not cut the sandstone or diabase of the Beacon Heights mountain mass within the area of plate 1; hence it must be hidden beneath the upper Ferrar Glacier to the west-southwest of the Terra Cotta Hills. East of the hills the fault projects into the lower course of the Ferrar Glacier and is not exposed on either side of the valley containing the glacier. The top of the basement complex is perhaps 1,000 feet higher in the west end of the Kukri Hills than it is on the opposite side of the Ferrar Glacier and this offset is presumably due to the same fault, hidden beneath the glacier. The fault, however, has little or no displacement as far east as Cathedral Rocks, for the basement sill and the top of the basement complex are at similar altitudes on both sides of the Ferrar Glacier.

Another fault, its north side downdropped approximately 1,500 feet, is inferred to strike west-northwestward beneath Solitary Dry Valley. The peneplain sill in the hanging wall apparently is brought even with the basement sill in the footwall. This fault probably continues east-southeastward beneath lower Taylor Glacier, for the top of the basement complex is about 500 feet higher in the west end of the Kukri Hills than in the mountains north of Taylor Valley; however, the basement and peneplain sills are at similar altitudes on opposite sides of the snout of Taylor Glacier, so the fault has little or no displacement that far east. West of Solitary Dry Valley the fault is hidden beneath upper Taylor Glacier.

A possible fault striking northeastward, its northwest side dropped down, is shown north of Solitary Dry Valley in figure 13. This structure was not recognized on aerial photographs farther northeast, and primary irregularities in diabase sheets, rather than faulting, may account for the apparent truncations and offsets along the indicated line.

Two small faults cut the rocks at the west end of Kukri Hills (fig. 22). A small fault is shown on plate 1 southwest of East Beacon Heights, and a possible similarly small fault south of Wright Upper Glacier is marked in figure 14.

The broad anticline which is the dominant structural feature of the mountains of the Taylor Glacier region is defined by the attitude of the Beacon Sandstone and the diabase sheets in the western two-thirds of the mountains and by the inferred altitude of the basement peneplain in the eastern one-third. The pre-Beacon erosion surface on the basement rocks was certainly one of low relief, and it may have been approximately a horizontal plane throughout the area shown in figure 2 at the start of Beacon deposition. (As noted in a previous section, the western Kukri Hills area may have stood a little above the general level; if it did, then the inferences made above regarding faults on opposite sides of the western Kukri Hills are incorrect.) The erosion surface is exposed throughout most of the central half of the area shown in figure 2, and it is remarkably even; it is not generally exposed near the east or west edges of the area.

The Beacon Sandstone and the underlying erosion surface dip in general gently westward throughout the region west of the longitude of the crest of the Royal Society Range. The base of the Beacon stands at 8,000–9,000 feet in the Royal Society Range, is inflected downward in a monocline at the west side of the main crest, and drops generally westward to disappear beneath the ice at altitudes of 3,000–4,000 feet about 20 miles west of the crest. The continued westward dip of the Beacon beyond this point of disappearance indicates that the base of the formation is near an altitude of 1,500 feet beneath the west edge of the mountains at the east margin of the interior ice plateau.

The anticlinal crest of the Royal Society Range plunges gently northward to the Ferrar Glacier, on both sides of which the top of the basement complex stands at an altitude of about 6,000 feet. The basement surface maintains about this altitude northward across the area of figure 2 along the crest of the anticline. To the west of this part of the anticline, as to the west of the highest part of the Royal Society Range, the Beacon and the basement surface dip gently westward.

The Beacon Sandstone is not preserved in the eastern third of the area of figure 2, so less direct evidence for the structure must be adduced. East of the main crest of the Royal Society Range, both basement and peneplain sills are exposed in grantic rocks and dip eastward, which indicates that the top of the basement complex drops about 3,000 feet in 5 miles from the crestal cliffs. North of the area of figure 2, peneplain and basement sills approach the coast and reach altitudes lower than those shown in figure 2, thereby defining the broadly anticlinal structure of the range. The altitudes of ridges in the eastern third of the area of figure 2 appear to be not far beneath the pre-Beacon surface, for exposures of the Beacon feather out eastward along the ridges. The known position of the pre-Beacon surface north of the area figured is consistent with this. If this inference is correct, then the top of the basement complex dips gently eastward to an altitude of about 3,000

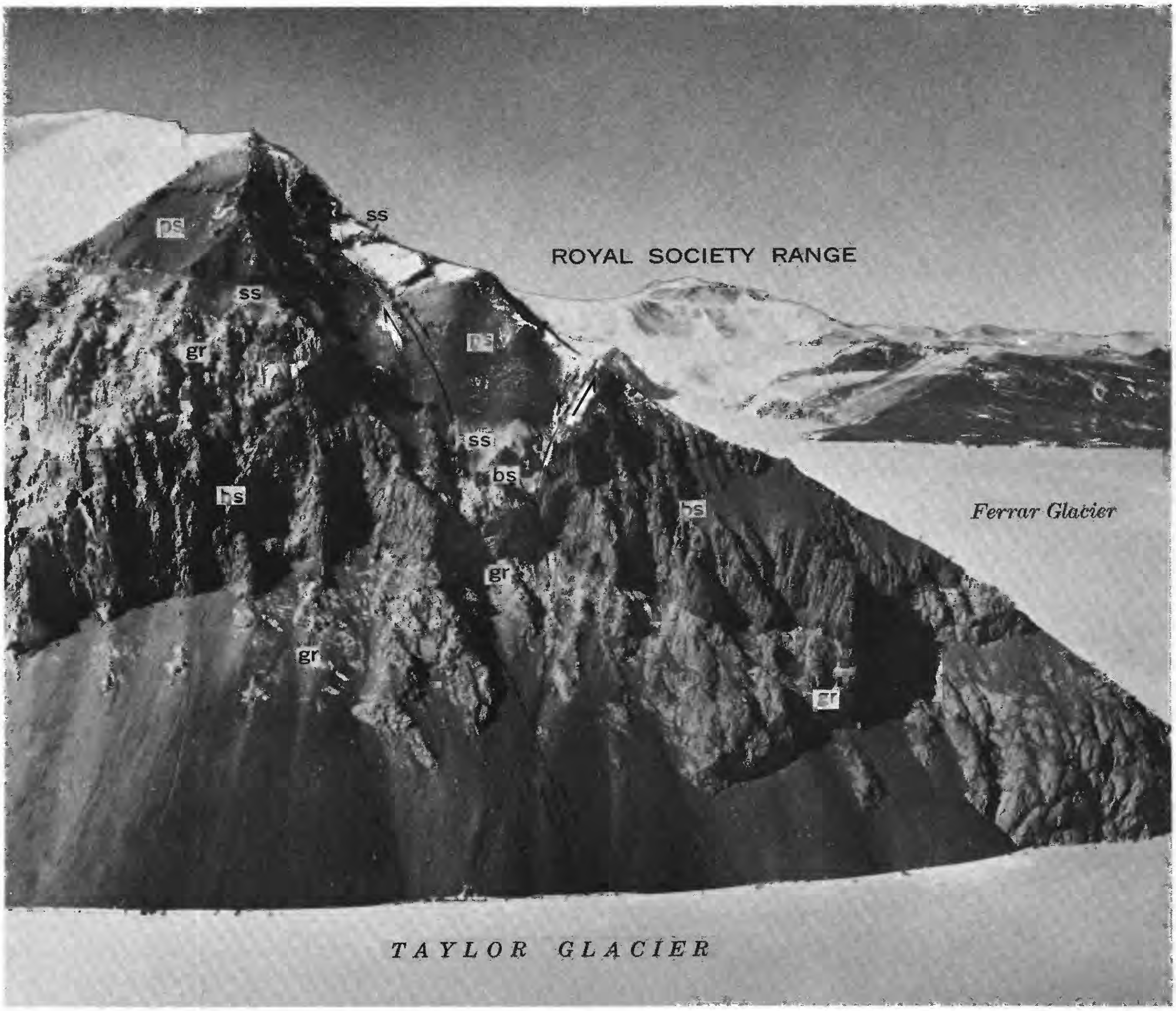


FIGURE 22.—Structure of peneplain and basement sills in north face, 4,000 feet high, of west end of Kukri Hills. Irregular intrusive contacts have been complicated by normal faults for which an interpretation is shown. Faults are indicated by lines, and arrows show directions of relative displacements. ss, Beacon Sandstone; ps, peneplain sill; bs, basement sill; gr, granite of basement complex. Aerial photograph by U.S. Navy for U.S. Geological Survey, November 1958.

feet near the coast from the Blue Glacier northward. South of the Blue an anticline raises the basement surface to altitudes of about 5,000 feet in the coastal foothills. A syncline separates the Royal Society Range from the foothills, and along this syncline flows the Blue Glacier.

PALEOMAGNETISM

Published studies by workers in different laboratories agree on the position of the paleomagnetic pole indicated by remanent magnetism of the diabase sheets intrusive into the Beacon Sandstone in several parts of Antarctica (fig. 23). Turnbull (1959, p. 155) reported on 57 samples from 5 localities near the upper Ferrar Glacier; all were magnetized normally and were grouped about a magnetic south pole at lat 58° S., long 141° W., in present earth coordinates. One sample from the Queen Maud Range was magnetized about 12° from this direction, but its plot was well within the scatter to be expected of single observations, so that the difference cannot be considered significant (Turnbull, 1959). Bull and Irving (1960a, b) made 12 measurements on samples from several localities in the basement and peneplain sills near Lake Vanda in Wright Dry Valley and found a close grouping around a pole at lat 51° S., long 132° W. Blundell and Stephenson (1959) reported measurements on samples from seven diabase sheets in a broad region in the Theron Mountains, Shackleton Range, and Whichaway Nunataks and found mostly normal polarities but some reversed; their measurements showed an average south paleomagnetic pole at about lat 54° S., long 136° W.

These three independent studies show remarkably close agreement on a paleomagnetic pole near lat 54° S., long 136° W., which falls in the southwest Pacific about 1,500 miles east-southeast of New Zealand. Paleomagnetic latitude lines indicated by this pole are drawn in figure 23.

Despite the separation between the present magnetic and geographic poles, and despite the nondiametric opposition of the present north and south magnetic poles, measurements by many workers on rocks from all parts of the world show middle and late Cenozoic paleomagnetic-pole determinations to cluster about the present geographic poles (Cox and Doell, 1960, pp. 736–739). "The earth's average magnetic field throughout post-Eocene time was that of a dipole parallel to the present axis of rotation" (Cox and Doell, 1960, p. 739). Although some geophysicists have speculated that the earth's field has been nondipolar in ages farther past, there is little basis for this hypothesis in the data available for testing it. The close agreement between the different groups of Antarctic determinations cited above suggests strongly that the continent lay in lower latitudes in Early Jurassic time than it does now and that it has moved 35° relative to the rotational axis in the intervening period. As Blundell and Stephenson (1959), Turnbull (1959), and Bull and Irving (1960b) emphasized, these determinations from Antarctica, when considered with the very different poles indicated for each of the other continents having approximately correlative diabase sills and basalts (India, Australia, southern Africa, and South America), are consistent with continental drift along the general lines suggested by Du Toit (1937) and Carey (1958a). The data seem irreconcilable with assumptions of either a stable earth grid or of a shifting crust upon which the continents are fixed in relative position. Although the geology of Antarctica was long so little known that it was inadequate for use in arguments either for or against continental drift, the relatively abundant new data obtained during the past few years provide strong support for drift (Hamilton 1960a, 1961, 1963a).

Turnbull (1959) also determined the paleomagnetic pole indicated by contact-metamorphosed Beacon Sandstone near diabase sheets and found a magnetic direction within a few degrees of that of the sheets themselves. He further measured the direction in variegated red and green argillaceous sandstone, not recognized as contact metamorphosed, and found the same magnetic orientation. He did not specify the localities nor describe the stratigraphy represented by his samples, and

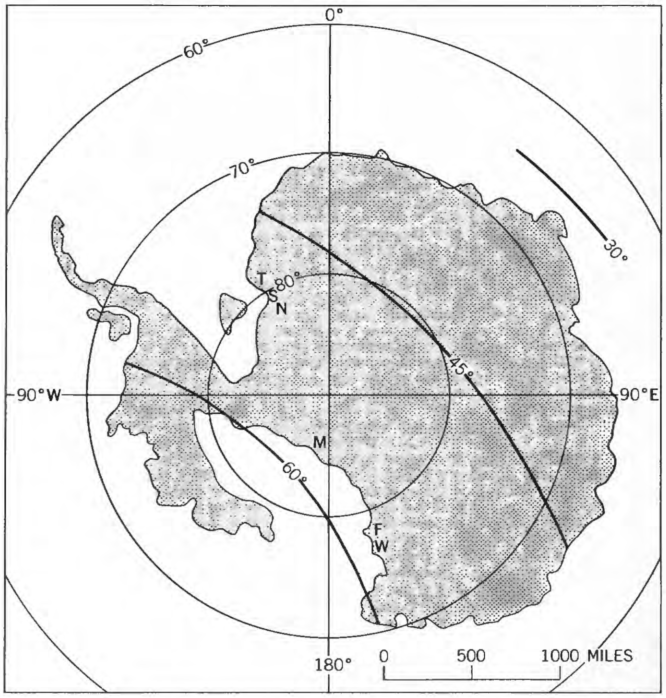


FIGURE 23.—Latitude of Antarctica at time of intrusion of diabase sheets, as indicated by paleomagnetic studies. Location of specimens for which paleomagnetic-pole positions have been published: W, Wright Dry Valley; F, Ferrar Glacier; M, Queen Maud Range; N, Whichaway Nunataks; S, Shackleton Range; T, Theron Mountains. Determinations agree on a south magnetic pole near lat 54° S., long 136° W., in present earth coordinates. Heavy lines show paleolatitudes corresponding to this pole position.

the lithologies he mentioned could be matched in either the upper unit of the Beacon, the sandstone of Finger Mountain of known Permian age, or in the lower unit, the sandstone of New Mountain which is not yet dated; but the variegated samples could not have come from the middle unit, the sandstone of Pyramid Mountain. The difference in age from variegated sandstone to sill is thus at least that from Permian to Jurassic time. Paleomagnetic studies on other continents normally show marked changes in paleomagnetic-pole positions within this interval, and it is likely that a similar actual change occurred in Antarctica. The lack of any shift apparent in these data is consistent with the conclusion reached in the present report that the entire Beacon Sandstone has been metamorphosed thermally by the diabase sheets, even though this widespread metamorphism is not obvious in the field.

PETROLOGY OF BASEMENT SILL

The basement sill was sampled systematically in Solitary Dry Valley (fig. 18), where the sill is about 680 feet thick. Specimens were collected at heights of 1, 5, 18, and 60 feet above the base by Philip T. Hayes, and at heights of 350, 480, 520, 630, 650, 665, and 680 feet by me. (The overall thickness and that of some of the intervals

749–445 O—65——5

were measured by aneroid altimeter; short intervals were estimated by the height-of-eye method.) The interval between 60 and 350 feet above the base was covered by surficial deposits where we crossed the sill, but continuous columnar joints throughout exposures of the entire sill a short distance to the southwest show that only one sill is present. Chemical and mineralogic analytical data are shown in table 1 and in figures 29–39.

The margins of the sill are chilled to aphanitic basalt free of megascopic phenocrysts. The lower chilled basalt grades upward through diabase to gabbro, and the total thickness of basalt and diabase is more than 18 feet but less than 60 feet, as bracketed by samples at those heights. The upper chilled basalt also coarsens inward, but only to rock having a diabasic texture, which has a sharp contact 30–40 feet below the top of the sheet with a layer of granophyre. The diabase and basalt of the upper chilled layer also differ from those at the base in being much altered metasomatically. The alteration decreases from the bottom of the layer to the top and is clearly a result of upward streaming of volatiles into the chilled top of the sill. The contact between granophyre and upper chilled zone is an undulatory surface rather than a horizontal plane and is marked by a layer of rock of intermediate composition about one-half inch thick.

The granophyre layer is 10–15 feet thick and consists of fine-grained gray blotchy granophyre containing abundant irregular masses of coarser and lighter colored granophyre that commonly has a pinkish cast. At the basal contact of the granophyre zone is a layer of transitional rock no more than an inch thick.

The remainder of the sill, between the diabase of the chilled basal zone and the layer of granophyre near the top, consists of massive medium-grained gabbro of uniform aspect. The upper 120 feet of this interior gabbro also contains abundant schlieren of coarse-grained mafic pegmatite 1 inch to 3 feet thick and a few inches to 50 feet long which make up 1–2 percent of the volume of that part of the sill.

PETROGRAPHY

By Warren Hamilton, Philip T. Hayes, and Ronald Calvert

The chilled base of the sill is of dark-gray aphanitic basalt (table 1, col. 1). The rock is a felted haze of tiny granules and prisms of inclusion-clouded pigeonite and augite and poorly shaped labradorite and contains about 3 percent microphenocrysts, shorter than 0.5 mm, of clear, calcic, slightly normal zoned labradorite. Maximum length of pyroxene crystals is about 0.2 mm. Opaque minerals occur as disseminated tiny (0.005 mm) granules.

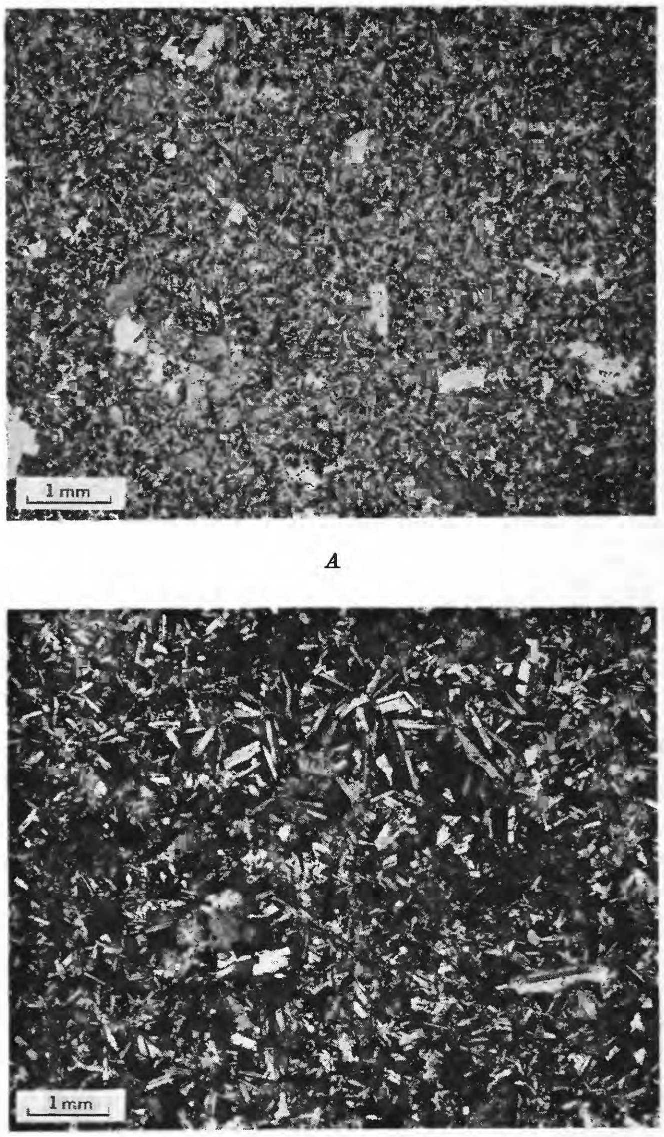


Figure 24.—Photomicrographs of diabasic basalt and diabase near base of basement sill. *A*, Diabasic basalt 5 feet above base. Microphenocrysts of labradorite (clear) and of augite, pigeonite, and hypersthene (gray) lie in a fine-grained matrix of labradorite laths and subophitic pigeonite. Plane-polarized light. Analysed specimen (table 1, col. 2). *B*, Diabase 18 feet above base. Euhedral laths of calcic labradorite lie in ophitic clinopyroxene. Crossed nicols. Analyzed specimen (table 1, col. 3).

This rock grades smoothly upward within a few feet into coarser and clearer diabasic basalt that is composed of sparse microphenocrysts of labradorite, subcalcic augite, pigeonite, and subordinate hypersthene in a groundmass of subophitic pigeonite and labradorite in 0.1–0.2 mm laths (table 1, col. 2; fig. 24*A*). Plagioclase phenocrysts have narrow, even, sodic rims. The pyroxene is partly altered to fibrous green hornblende and subordinate biotite and chlorite. Tiny plates of ilmenite are the dominant opaque constituent.

TABLE 1.—*Chemical and mineralogic analyses of rocks of differentiated diabase sill intruded into quartz monzonite*

[Specimens, collected about 6 miles northwest of west end of Kukri Hills, are described in text. Chemical analyses 1, 4, 5, 7, 8, 11, and 14 by gravimetric methods by Vertie C. Smith, U.S. Geol. Survey, Denver, 1959; others by colorimetric methods by P. S. D. Elmore, I. H. Barlow, S. D. Botts and G. Chloe, U.S. Geol. Survey, Washington, D.C., 1960. All analyses for chlorine and fluorine by Vertie C. Smith, Denver, 1959 and 1960. Spectrographic analyses 1, 4, 5, 7, 8, 11, and 14 by quantitative methods, using internal standards, by Paul R. Barnett, U.S. Geol. Survey, Denver, 1959; analyses 2, 9, and 13 by Barnett, 1960, and 3, 6, 10, and 12 by Nancy M. Conklin, U.S. Geol. Survey, Denver, 1959, using rapid visual-comparison semiquantitative methods, values reported as midpoints of logarithmic-third divisions; d, element detected but not measureable. Modes determined by point counting by Philip T. Hayes and Warren Hamilton and reported as volume percent. Powder densities measured by Vertie C. Smith]

	Lower chilled zone			Gabbro				Diorite pegmatite schlieren		Granophyre zone		Upper chilled zone			Averages, volatile free	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	A	B
Feet below top	≈680	≈675	≈660	≈620	≈330	200	160	160	160	50	50	30	15	0.1	Chilled margins (1, 2, 13, 14)	Gabbro (4, 5, 6, 7)
Feet above base	1	5	18	60	≈350	≈480	≈520	≈520	≈520	≈630	≈630	≈650	≈665	≈680		
SiO_2	55.00	55.6	54.9	53.65	53.09	53.9	53.42	57.61	59.4	63.0	69.22	57.6	55.6	55.27	55.8	54.0
Al_2O_3	14.56	14.6	14.7	14.02	14.34	14.8	12.42	13.14	12.2	17.8	13.95	14.9	15.0	14.67	14.8	14.0
Fe:																
Fe_2O_3	2.49	2.1	2.2	1.74	.73	1.8	1.49	3.12	3.8	1.2	1.38	2.2	2.3	1.03	2.0	1.5
FeO	6.99	7.4	7.4	7.57	7.26	6.7	8.39	7.38	7.5	3.8	2.27	7.4	7.0	8.57	7.6	7.6
Sum as FeO	9.2	9.3	9.4	9.1	7.9	8.3	9.7	10.2	10.9	4.9	3.5	9.4	9.1	9.5	9.4	9.0
Mgo	5.70	6.0	6.0	7.06	9.78	8.6	9.00	3.34	3.2	1.0	.77	3.7	4.5	5.93	5.6	8.7
CaO	9.92	10.1	10.1	10.78	11.72	11.4	11.46	7.93	7.0	3.6	1.99	7.8	10.1	10.22	10.2	11.4
Na_2O	2.20	2.0	1.8	1.71	1.38	1.6	1.32	2.80	2.0	3.8	3.48	2.2	2.0	2.18	2.1	1.5
K_2O	.91	.95	.92	.31	.48	.66	.56	.83	1.5	5.2	5.32	1.7	1.0	.71	.9	.5
TiO_2	.70	.70	.64	.63	.43	.48	.58	1.08	1.3	.68	.38	.72	.72	.71	.7	.5
P_2O_5	.07	.12	.12	.06	.03	.08	.08	.18	.24	.24	.08	.16	.14	.10	.11	.06
MnO	.18	.18	.18	.18	.17	.18	.20	.18	.19	.10	.07	.18	.19	.18	.18	.2
H_2O+	.71	1.3	1.4	1.78	.34	.70	.65	1.53	1.9	.92	.59	1.7	1.2	.25		
H_2O-	.33			.41	.18		.33	.29			.24			.12		
CO_2	.12	<.05	<.05	.02	.01	<.05	.02	.40	<.05	<.05	.02	<.05	<.05	.01		
F	.04	.02	---	.02	.01	---	.02	.03	.03	---	.08	---	.02	.03		
Cl	.01	.02	---	.01	.02	---	.01	.03	.03	---	.07	---	.05	.03		
Sum	99.93	---	---	99.95	99.97	---	99.95	99.87	---	---	99.91	---	---	100.01		
Less O	.02	---	---	.01	.01	---	.01	.02	---	---	.05	---	---	.02		
Total	99.91	101	100	99.94	99.96	100	99.94	99.85	100	100	99.86	100	100	99.99		
Ba	0.029	0.03	0.015	0.013	0.016	0.007	0.016	0.034	0.03	0.15	0.062	0.03	0.03	0.024		
Be	<.0001	.0007	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	.00015	.00015	.0005	<.0001	.0003	<.0001		
Co	.0046	.003	.0015	.0047	.0047	.0015	.0058	.0038	.003	.0007	.0008	.003	.003	.0044		
Cr	.010	.015	.003	.018	.046	.007	.034	.0014	.0003	.0007	.0005	.0015	.007	.012		
Cu	.011	.015	.007	.011	.007	.007	.010	.014	.015	.0003	.002	.007	.015	.010		
Ga	.0016	.0007	.0003	.0016	.0013	.0003	.0013	.0016	.0015	.0015	.0017	.0007	.0007	.0015		
Nb	.002	<.01	<.01	.002	.002	<.01	.002	.003	<.01	<.01	.003	<.01	<.01	.002		
Ni	.0067	.007	.003	.0084	.012	.007	.014	.0029	.003	.002	.0006	.003	.007	.0063		
Pb	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	.0015	<.001	d	<.001	<.001		
Sc	.0044	.007	.003	.0047	.0045	.003	.0066	.0043	.007	.0007	.0010	.003	.007	.0048		
Sr	.018	.03	.015	.017	.014	.007	.012	.022	.015	.07	.028	.015	.03	.018		
V	.022	.07	.015	.022	.020	.015	.028	.018	.015	.003	.004	.03	.03	.021		
Y	.003	.003	.0015	.003	.002	d	.003	.006	.003	.0015	.004	.003	.0015	.003		
Yb	.0005	.0003	.00015	.0004	.0004	d	.0005	.0006	.0007	.00015	.0004	.0003	.0003	.0005		
Zr	.016	.007	.007	.014	.009	.003	.012	.024	.007	.03	.030	.007	.007	.017		
Plagioclase	51	48	50	50	47	51	45	33	36	41	45	44	51	53		
(Percent An)	(65)	(65)	(65)	(70)	(75)	(70)	(70)	(50)	(50)	(32)	(23)	(55)	(65)	(65)		
Augite and subcalcic augite	47	18	15	15	10	10	13	15	12	.7	.5	13	15	41		
Pigeonite		25	18	12	21	24	30	---	8	---	---	8	23			
Hypersthene	---	5	10	13	15	7	2	.1	---	.1?	---	---	---	2		
Opaque minerals	2	2	2	1.5	.7	.9	.9	4	4	1.0	1.2	1.0	3	1		
Quartz	.4	.1	1.5	2.5		1.2	1.7	17	17	15	20	13	3	2		
Alkali feldspar	---	---			---	1.4	2.0	2	15	31	26	7	2			
Hornblende	---	1	.4	1	.2	.4	.4	.3	.2	7	4	.6				
Chlorite, chrysotile, saponite, and others	---	1	2.5	4	.3	2	4	7	6	2	2	13	2	---		
Biotite	---	---	.2	.4	2	1.0	.5	.2	.7	1.0	.3	4	1.2	.3		
Muscovite	---	---	---	---	---	---	.1	2	.2	---	.1	---	---	---		
Powder density	2.93	2.95	2.93	2.93	3.01	3.01	3.01	2.88	2.88	2.73	2.67	2.88	2.95	2.99		
Field No.	A42A	A42C	A43	A44	A50	A51	A52A	A52B	A52C	A53B	A53A	A53C	A53D	A53E		
Laboratory Nos.	F2502	156222 G2981	154594 272410	F2503	F2505	154596 272412	F2506	F2507	156223 G2982	154597 272413	F2508	154598 272414	156244 G2983	F2509 F2509		

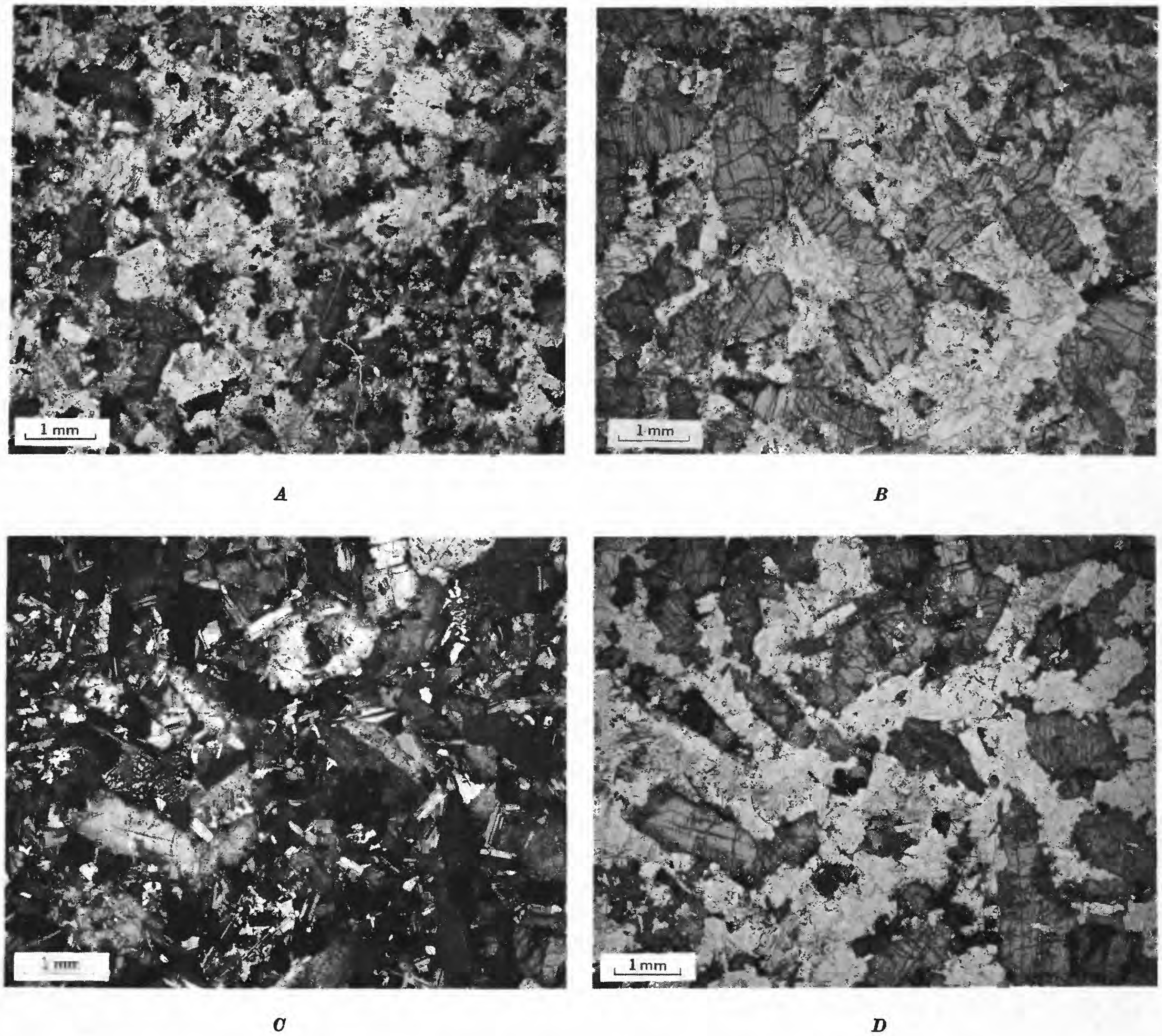


FIGURE 25.—Photomicrographs of gabbro of basement sill. *A*, Gabbro 60 feet above base. Poorly shaped prisms and subophitic plates of pyroxene (gray) are surrounded by subhedral plagioclase (white). Plane-polarized light. Analyzed specimen (table 1, col. 4). *B*, Gabbro 350 feet above base. Irregular prisms of pyroxene photograph gray. Exsolution lamellae form a herringbone pattern in the large prism of pigeonite near lower-left corner. Plane-polarized light. Analyzed specimen (table 1, col. 5). *C*, Gabbro 520 feet above base. Prisms of pyroxene (mottled, high relief), are much larger than crystals of plagioclase (striped by albite twinning). Micrographic intergrowths of quartz and alkali feldspar are present left of center and at top near right edge. Crossed nicols. Analyzed specimen (table 1, col. 7). *D*, Same field as in *C*. Plane-polarized light.

The diabase continues to coarsen upward, and 18 feet above the base its ophitic texture is very pronounced and it contains a little interstitial micropegmatite (table 1, col. 3; fig. 24*B*). The laths of unzoned calcic labradorite are 0.2–1 mm long and thus are larger than the microphenocrysts nearer the base. Most of the pyroxene is clear, pale-brown pigeonite and subcalcic augite, but there is considerable hypersthene, largely altered to brown chrysotile. Both ilmenite plates and magnetite granules are present.

Within 30–40 feet above the base of the sill, the diabase has graded into gabbro and the color has changed from dark gray to the dark greenish gray that is maintained throughout the interior gabbro. The gabbro at a height of 60 feet has a general grain size of about 1 mm (table 1, col. 4; fig. 25*A*). Augite and pigeonite are irregularly intergrown, in mottled aggregates of varying colors, birefringence, and optical orientation; some augite crystals have pigeonitic cores, and many pigeonite grains enclose irregular relicts of hypersthene.

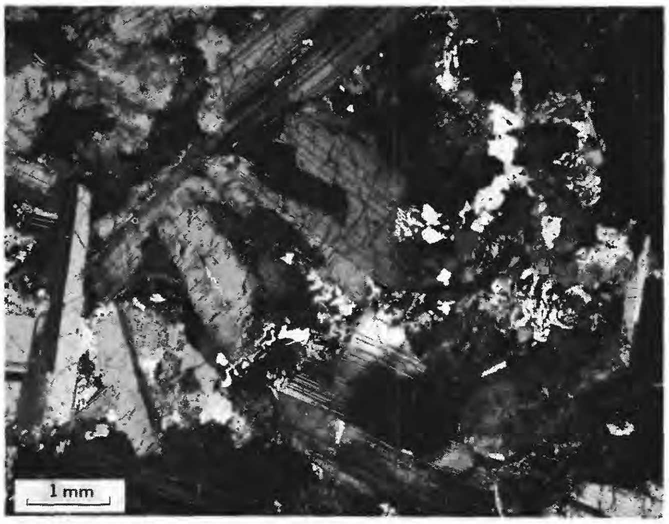


FIGURE 26.—Photomicrograph of granophyric diorite pegmatite. Large crystals of plagioclase (ruled by albite twinning) partly enclose altered augite (irregular dark grains) left of center. Granophyric quartz and alkali feldspar form the right-central part of the field and smaller areas elsewhere. Part of a long prism of augite extends along the right edge from the top of the picture. Crossed nicols. Analyzed specimen (table 1, col. 9).

Whereas the clinopyroxene is but a little altered to chlorite and fibrous hornblende, the subordinate hypersthene is much altered to chlorite. Pyroxenes, particularly hypersthene, have abundant exsolution lamellae. Plagioclase shows strong progressive zoning.

From 350 to 625 feet above the base, the sill consists of greenish-gray equigranular gabbro (table 1, cols. 5, 6, 7; figs. 25*B*, *C*, *D*) of uniform aspect which is coarser grained than any of that described previously. The average grain size is 1–2 mm. Plagioclase composition is An_{70-75}. Pigeonite, subcalcic augite, and hypersthene are all present; exsolution lamellae are highly developed in much of the hypersthene. Relicts of hypersthene are abundant in pigeonite. Several percent of interstitial quartz and micropegmatite are present. Ilmenite plates and magnetite granules total only about 1 percent by volume. Secondary minerals—brown biotite, chrysotile, green chlorite, and pale-green hornblende—have replaced orthopyroxene more than clinopyroxene.

Such gabbro encloses abundant schlieren of granophyric diorite pegmatite between 500 and 625 feet above the base of the sill. Low in this pegmatite-bearing zone, the pegmatite occurs as lenses and very irregular but generally subhorizontal masses 1 inch to 2 feet thick and as much as 40 feet long, and it forms perhaps 2 percent of the volume of the sill at this level. Higher in the zone the pegmatite schlieren are smaller but more numerous, hence of similar total abundance, and are oriented irregularly in all directions including vertically. Grain size and mineral proportions vary irregularly within the pegmatites, but all are distinguished by long thin prisms of black augite strewn through white plagioclase; finer grained pyroxene and alteration products of both pyroxene and plagioclase are distributed irregularly. Two analyses of the pegmatite are given in table 1 (cols. 8, 9), and a specimen is illustrated in figure 26. Augite prisms are as long as 1.5 cm (centimeters); augite is dark, mottled, and much altered. Plagioclase (An_{50}) crystals are as long as 1 cm. Quartz-alkali feldspar micropegmatite makes up about 40 percent of the pegmatite. Antigorite was seen in the sill only in these specimens.

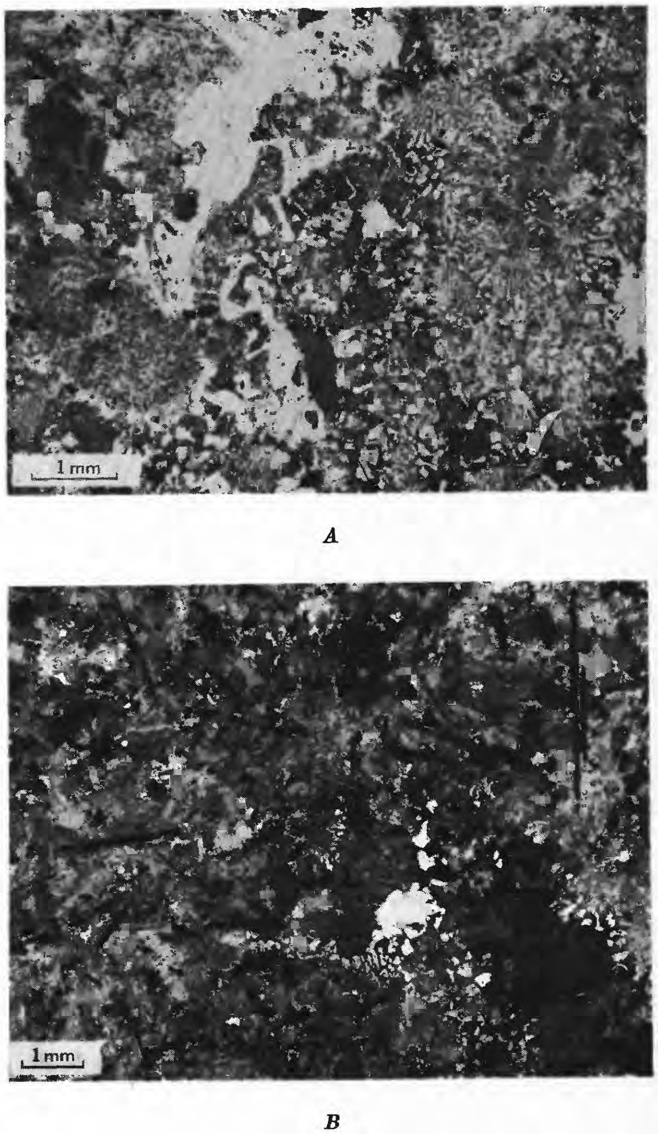


FIGURE 27.—Photomicrographs of silicic granophyre near top of basement sill. *A*, Right half consists largely of granophyric quartz and alkali feldspar. Quartz forms white area extending from top center downward to left. A large ovoid crystal of altered oligoclase is near lower-left corner. Plane-polarized light. Analyzed specimen (table 1, col. 11). *B*, Same specimen. Needles of sodic pyroxene(?), largely altered to hornblende, project through variably granophyric quartz and feldspar. Nicols oblique.

Between 625 and 640 feet above the base of the sill is a sharply bounded layer of granophyre 10–15 feet thick. Although the top and bottom of the layer are slightly undulating, its contact zones of mixed or intermediate-composition rocks are only ¼–1 inch thick. Most of the granophyre layer consists of fine-grained light-greenish-gray rock (table 1, col. 10) speckled by 3-mm ellipsoids of gray quartz. About 50 percent of this rock consists of xenomorphic and micropegmatitic quartz and alkali feldspar in 0.05–0.5-mm crystals, and 10 percent consists of granules, small needles, and clusters and veinlets of variably altered green hornblende. The remainder of the rock is of large (1–4 mm) crystals and aggregates of quartz, oligoclase, and potassic feldspar. The quartz ellipsoids are of aggregates of recrystallized granules and have discontinuous reaction rims of granular hornblende. The large oligoclase crystals are generally rectangular grains with carlsbad twinning, suggestive in appearance of oligoclase in granitic rocks, but are completely recrystallized into mottled chessboard mosaics. Similarly, the large crystals of potassic feldspar are now finely mottled mosaics. These large crystals and aggregates are apparently xenocrysts from the quartz monzonite into which the sill is intruded.

Intermixed with this dominant type of granophyre are small irregular, vaguely bounded masses of more silicic granophyre (table 1, col. 11). This silicic granophyre consists of slightly pinkish, sodic oligoclase, in 0.5–2.5 mm crystals, and micropegmatite (fig. 27*A*), laced by mafic needles (fig. 27*B*) that are 2–5 mm long and green in hand specimen. The needles consist of thin ragged rims of pale hornblende surrounding cores of brown cryptocrystalline secondary material, locally enclosing remnants of a little-altered mineral which appeared to be a sodic pyroxene ($-2V$ moderate, $Z \wedge c$ about 45°, nearly colorless, high relief, birefringence about 0.015). The rock is mottled by lighter colored and coarser grained patches which lack the mafic needles and contain instead large stubby prisms of hornblende that is black in hand specimen and green in thin section. Reaction textures are widely developed, and the similarity in composition between this silicic granophyre and the quartz monzonitic wallrocks of the sill suggests that this granophyre is the product primarily of reconstitution of wallrocks rather than of differentiation.

The upper chilled zone of the sill is 30–40 feet thick and is in sharp contact with the granophyre. Within the upper zone there is a textural gradation similar to that at the base of the sill; in addition, there is a compositional gradation from abnormally silicic and alkalic greenish-gray diabase low in the upper zone to dark-gray basalt of normal composition at the top. The lower part of this upper zone consists of metasomatized diabase (table 1, col. 12), consisting of laths of sodic labradorite mostly about 0.5 mm long, and subophitic augite and pigeonite that are much altered to chlorite, chrysotile, and biotite; this rock contains about 20 percent of micropegmatite. The finer grained diabase

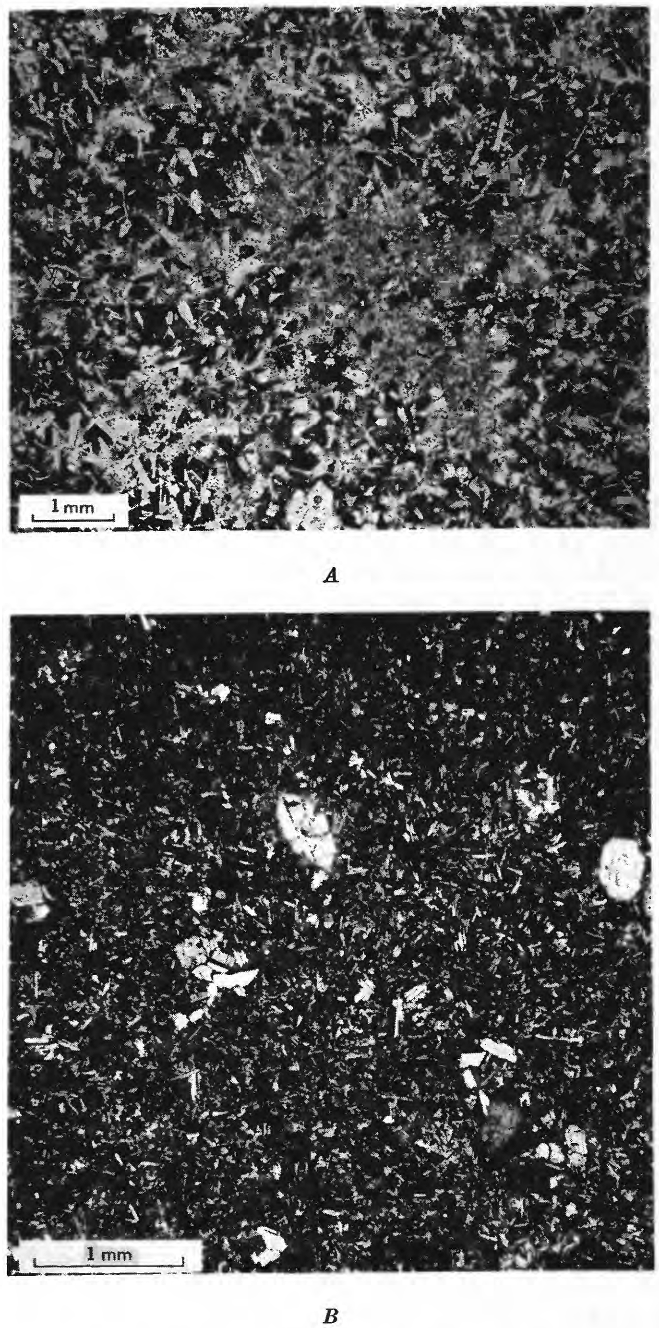
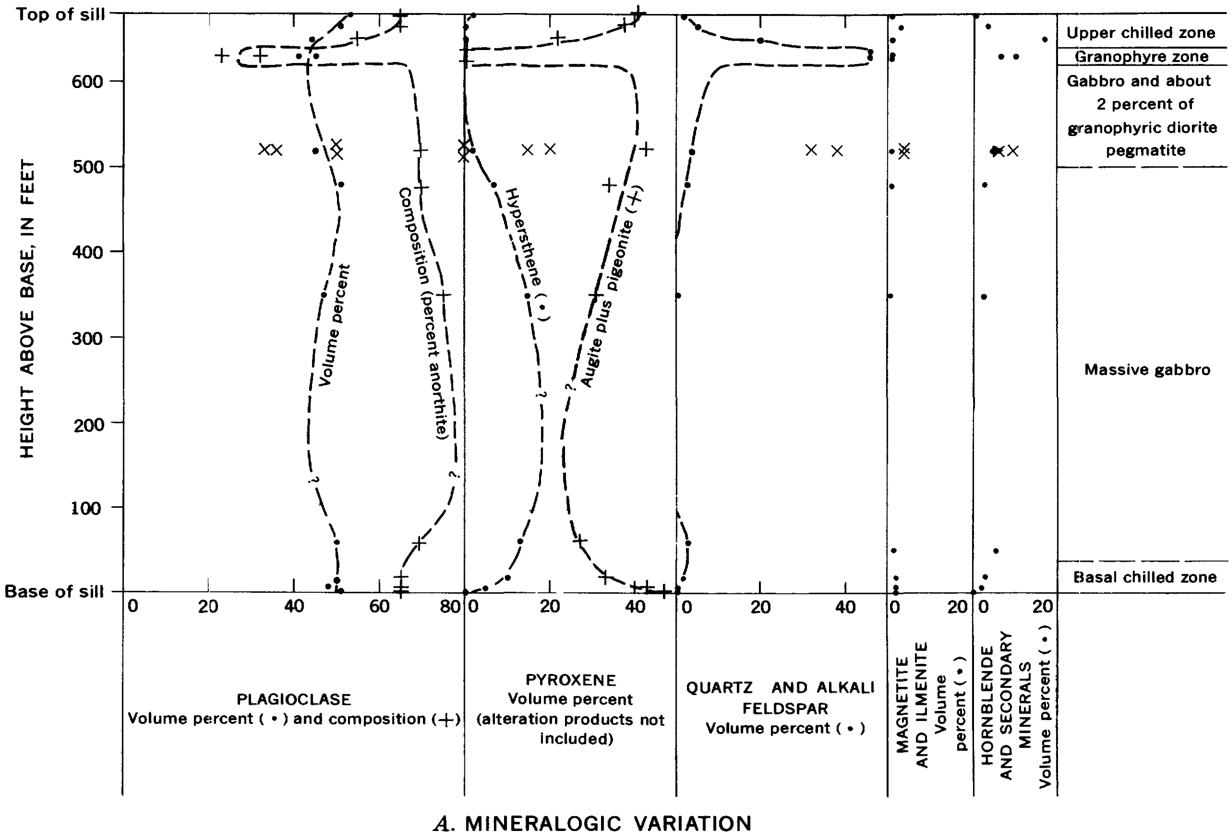


FIGURE 28.—Photomicrographs of diabase and basalt in basement sill. *A*, Diabase in upper chilled zone, 15 feet below top of sill. Laths of clear calcic labradorite are enclosed in subophitic plates of pigeonite. Plane-polarized light. Analyzed specimen (table 1, col. 13). *B*, Chilled basalt at top of sill. Microphenocrysts of pigeonite and hypersthene are strewn through a groundmass of small laths of labradorite and granules of clinopyroxene. Crossed nicols. Analyzed specimen (table 1, col. 14).



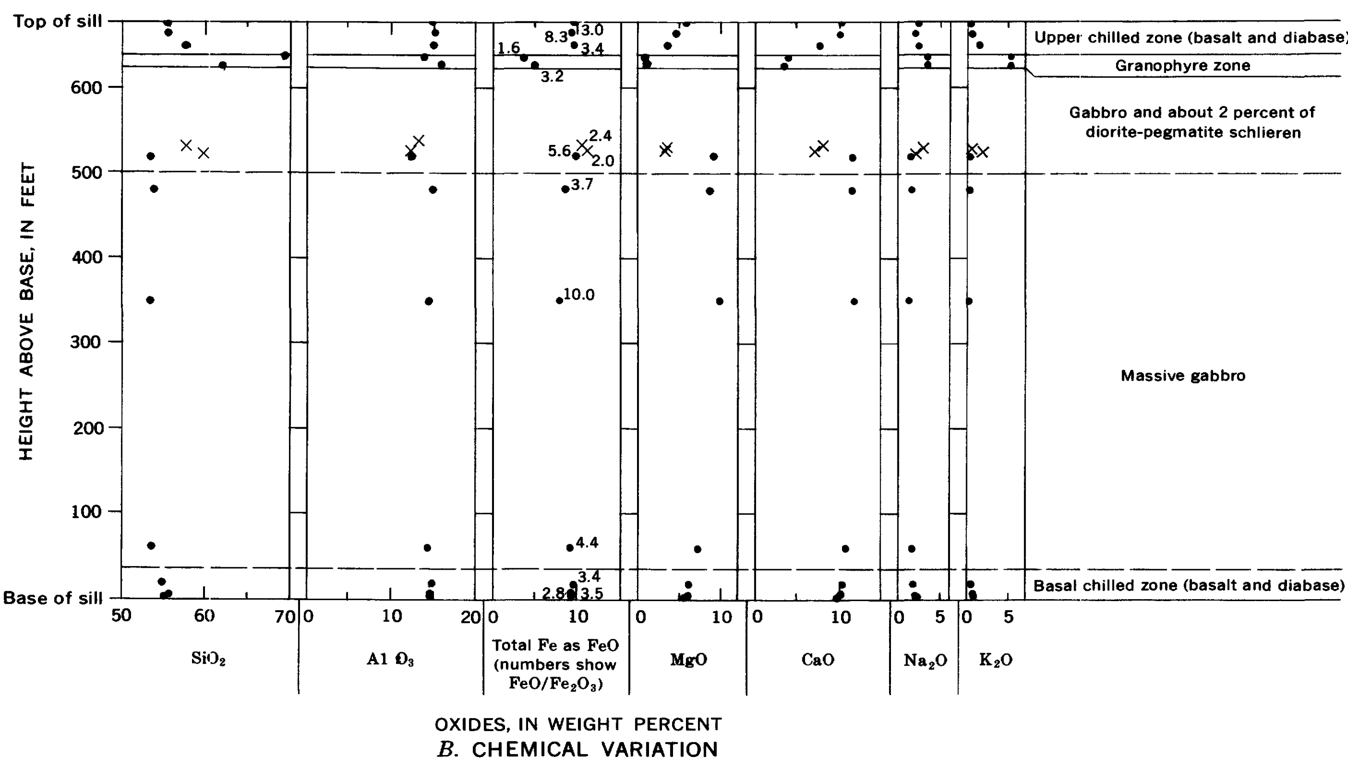


Figure 29.—Mineralogic and chemical variations with height in basement sill. ×, pegmatite. Data from table 1.

nearer the top (table 1, col. 13; fig. 28*A*) is of normal composition and consists largely of labradorite and little-altered clinopyroxene; the rock contains but little micropegmatite. The chilled basalt at the top of the sill (table 1, col. 14; fig. 28*B*) is quite different petrographically from that at the base; it consists of clear, distinct laths of labradorite and tiny clear granules of greenish clinopyroxene and is sparsely sprinkled by microphenocrysts of pigeonite, hypersthene, and labradorite. The completely chilled aphanitic rock is only about 1 inch thick.

The upper chilled zone thus changes downward in composition, becoming more silicic and richer in alkalis and more altered toward the granophyre layer. It is likely that this progression is due to metasomatism by fluids streaming into, but generally not through, the upper zone from the differentiating mass beneath.

Cutting irregularly through the upper chilled zone are short lenses of white granophyre that are less than half an inch thick and are sharply bounded against the dark diabase. These constitute much less than 1 percent of the zone.

Mineralogic variations with increased height in the sill are shown in figure 29*A*. Plagioclase is more calcic and possibly less abundant in the interior gabbro than in the chilled margins, and it is much less calcic and less abundant in the pegmatite schlieren and granophyre zone than in any of the mafic rocks. Hypersthene and clinopyroxene vary in complementary fashion, the hypersthene increasing in abundance in the interior gabbro at the expense of augite and pigeonite; pyroxene is a minor constituent in the pegmatite and is virtually lacking in the granophyre. Quartz and alkali feldspar increase in abundance in the upper part of the sill toward the granophyre layers, in which they reach their maximum concentration. Opaque minerals are more abundant in chilled zones than in interior gabbro or granophyre, and more abundant in pegmatite than in either gabbro or granophyre. Hornblende and secondary minerals are most abundant in the upper part of the sill.

Gunn (1962) sampled the basement sill on the south side of the Kukri Hills, about 10 miles southeast of the location described here. Although he could not reach either chilled zone or the granophyre zone, he did see the lower interior part of the sheet, which was missed in the present study, so that our studies are to some extent complementary. He found the rock 200–300 feet about the base of the sill to contain about 60 percent of pyroxene, of which half is hypersthene partly inverted from pigeonite(?) and the other half is augite and subordinate pigeonite; the remainder of the rock is mostly fine-grained interstitial bytownite. His findings elsewhere in the sill are similar to those reported here.

MINERALOGY

The dominant mineral of the basement sill is plagioclase, mostly calcic labradorite and sodic bytownite. Although locally sericitized or veined by secondary minerals, the plagioclase is generally fresh even where adjacent pyroxene is thoroughly altered. The plagioclase is mostly euhedral or nearly so and is tabular parallel to [010]. The compositions listed in table 1 and plotted in figure 29*A* are the averages of extinction-angle determinations, made in thin sections, based on low-temperature curves. Although this plagioclase certainly crystallized well above the temperatures of high-low optical inversion, calculations show that the low-temperature curves yield determinations agreeing much better with the chemical analyses than do the high-temperature curves. Presumably the plagioclase cooled so slowly in this great sill that the inversion to low-temperature optics was largely accomplished. Plagioclase is near An_{65} in the chilled margins and An_{70-75} in the gabbroic interior. Slight even normal zoning is typical.

Gunn (1962, p. 835) presented refractive-index determinations for plagioclase in nine specimens of gabbro from heights of 80–520 feet above the bottom of the basement sill in the Kukri Hills. He found the most calcic parts of the crystals to have a composition near An_{80} in samples taken between 80 and 300 feet—a range which includes the hypersthene-rich zone and the underlying hypersthene-poor gabbro—and to become progressively less calcic at higher levels. At 400 feet above the base, the most calcic composition of crystals present was determined as An_{77}; at 500 feet, as An_{75} in one specimen and as An_{69} in another; and at 600 feet, as An_{66}. The most sodic parts of the crystals in these various specimens vary less regularly in composition with height.

Most slides show two or even three pyroxenes, which are commonly distinguishable only with difficulty; although the total amounts of pyroxene listed in table 1 were determined by point counting, the proportions of different species were estimated on the basis of the 15–40 grains for which specific determinations were made. In many slides the pyroxene varieties are rather uniform in appearance, although this appearance varies from slide to slide. Most of the clinopyroxene is clear pale green or pale brown. Some is mottled and darker, but even the dark types are virtually nonpleochroic. Exsolution lamellae of different pyroxenes are highly developed in some specimens, particularly in hypersthene, but inconspicuous in others. Hypersthene was recognized by its straight extinction and negative optic sign. The clinopyroxenes all have positive sign and were distinguished on the basis of optic angle (estimated from interference figures) as pigeonite ($+2V=15°$–$30°$), subcalcic augite ($+2V=35°$–$40°$), and augite ($+2V=50°$–$70°$). Pigeonite shows a higher interference color as viewed in basal sections than does augite. Degree of alteration—of augite mostly to chlorite and green hornblende and subordinately to biotite, and of pigeonite and hypersthene mostly to chrysotile—is slight in the chilled margins, generally moderate in the gabbroic interior, and relatively high in the pegmatite, granophyre, and the lower part of the mafic zone above the granophyre layer. Hypersthene occurs both as distinct crystals and as irregular relicts enclosed in clinopyroxene.

Gunn (1962, p. 835) found the n_y index of augite in his specimens from the basement sill generally to increase upward in systematic fashion: at 80 feet, $n_y=$ 1.686; at 100, 1.688; at 200, 1.692; at 300, 1.691; at 400, 1.698; at 500, 1.700; and at 600, 1.707. Optic angle varies only within the range 43°–49°. These data indicate that the augite becomes markedly more ferroan and less magnesian upward, and probably a little less calcic. Gunn suggested compositions of $Ca_{44}Mg_{47}Fe_8$ for the augite in the lowest specimen and $Ca_{39}Mg_{34}Fe_{27}$ for that in the highest. This progression is uninterrupted through the hypersthene-rich zone at 200–300 feet.

Gunn's data for pigeonite, which he considers to have partly inverted to hypersthene in the lower half of the sill, are more ambiguous but indicate that the lower interior of the sill has pigeonite which is less magnesian than that of the hypersthene-rich zone but more magnesian than that of the gabbro above the hypersthene zone.

Quartz and alkali feldspar are present throughout the sill and are mostly intergrown micropegmatically. They exceed a combined amount of a few percent only in the pegmatite schlieren, granophyre layer, and the metasomatized lower part of the upper chilled zone. The alkali feldspar is clear, unlike the hematite- and clay-clouded feldspar of granophyres of many regions.

Opaque minerals are remarkably sparse in most of the sill and make up less than 1 percent by volume of most of the specimens; the notable exceptions are the basic pegmatites, which contain 3–4 percent opaque minerals. The opaque oxides form tiny granules in the chilled basalt at the base and top of the sill. In the diabase and gabbro, compact masses of magnetite and plates and skeletal grains of ilmenite are generally about equally abundant, and they clearly crystallized relatively late. Magnetite is the dominant opaque mineral in pegmatite and granophyre.

Apatite is the most conspicuous trace accessory mineral, and it occurs generally in small stubby prisms. The pegmatite and granophyre, however, contain abundant long needles of chlorapatite(?). Apparently primary sphene is largely limited to a few of the mafic rocks and even in them is not abundant, but minute granules of sphene are scattered through chlorite and chrysotile that have replaced pyroxene. Zircon is most plentiful in the pegmatite and granophyre and is accompanied by pleochroic halos in some minerals, notably chlorite.

MAJOR OXIDES

By WARREN HAMILTON, VERTIE C. SMITH, and PAUL S. D. ELMORE

Chemical analyses of 14 specimens from the basement sill are presented in table 1. Seven of the specimens were analyzed by Vertie C. Smith by standard silicate gravimetric methods; the other seven were analyzed by P. S. D. Elmore, I. H. Barlow, S. D. Botts, and G. W. Chloe by colorimetric methods similar to those described by Shapiro and Brannock (1956).

Most components of the sill vary systematically in abundance with position in the sill, and many inferences regarding the trends of differentiation and crystallization can accordingly be drawn. A silica-variation diagram of the analyses is shown by figure 30, and the data are plotted against height in sill in figure 29*B*. Relationships between various oxides in the analyses are shown by figures 31–34; data from other diabase sheets sampled (table 2) are also included in some of these diagrams.

The chilled-zone specimens (table 1, cols. 1, 2, 3, 13, 14, and A) have a nearly constant composition. (The lowest specimen—col. 12—from the upper chilled zone is much altered metasomatically and differs correspondingly from the other chilled specimens.) Silica content is remarkably high—55 percent—for basaltic rocks; but as the rocks are composed largely of pyroxene and calcic plagioclase, there is no question about the propriety of the rock names. The most obvious mineralogic expression of the high-silica composition is in the very low content—about 2 percent by volume—of opaque minerals. Most basalt, gabbro, and diabase have more ilmenite and magnetite. Were several percent of opaque minerals added to the basement sill, its composition would be similar to that of tholeiitic basalt and diabase in many other parts of the world.

The gabbro (table 1, cols. 4–7 and B) that forms the greater part of the basement sill contains a little less silica, alumina, ferric iron, alkalis, and titanium, but a little more calcium and much more magnesium, than do the chilled borders. The schlieren of granophyric diorite pegmatite (table 1, cols. 8, 9) high in the gabbroic interior of the sill contain more silica, ferric iron,

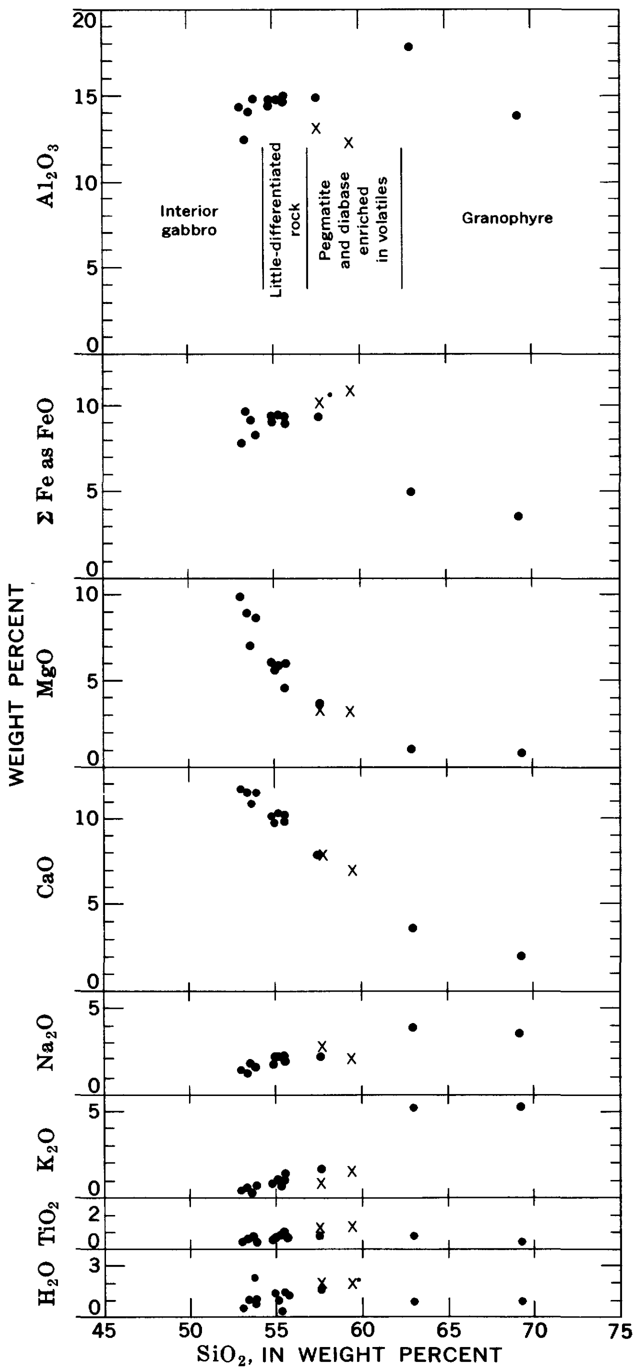


FIGURE 30.—Silica-variation diagam of analyses of specimens from basement sill. ×, pegmatite. Data from table 1.

total alkalis, and titanium and less alumina, magnesium, and calcium than do either the chilled borders or the gabbro.

Both the mafic granophyre (table 1, col. 10) and the silicic granophyre (col. 11) are more granitic in most components than the pegmatite. They differ from common calc-alkaline granitic rocks of similar silica content in batholithic complexes by having a relatively low content of calcium and a relatively high content of ferric iron and titanium.

The silica-variation diagram (fig. 30) shows the systematic change of many components. Total iron increases as silica increases from the interior gabbro through the chilled margins to the diorite pegmatite, and it decreases in the granophyre. Magnesium and calcium decrease evenly as silica increases. Sodium and potassium increase evenly with increasing silica from gabbro through chilled margins to pegmatite, but are erratically high in the granophyre. Titanium reaches a peak in the intermediate-silica rocks—the diorite pegmatites. Least systematic is aluminum, which varies irregularly within a limited range in the mafic rocks, and decreases regularly as silica increases in the granophyres.

The oxides vary systematically with position in the sill (fig. 29*B*). There is less silica in the interior gabbro than in the chilled margins, but more in the pegmatite schlieren, and much more in the granophyre than in the margins. Alkalis tend to behave in the same way, although the correspondence is better when total alkalis are considered than when sodium and potassium are considered alone. Magnesium and calcium display the opposite behavior: there is more in the gabbro than in the margins, but less in the pegmatite and much less in the granophyre. Aluminum is nearly constant in both margins and gabbro, but there is less in the pegmatite, silicic granophyre, and the highest gabbro sample. There is less total iron in the gabbro than in the margins, but more in the pegmatite and less in the granophyre than in either of these.

The effect of metasomatism of the chilled roof zone of the sill is clearly shown in figure 29*B*. Whereas the oxides show little change with height in the basal chilled zone, most of them show systematic variation in the texturally similar upper chilled zone. In both places there is a gradation inward from aphanitic basalt through diabasic basalt to increasingly coarse diabase, but the lower and coarsest rocks of the upper chilled zone are much altered. Silica and potassium increase markedly downward in the upper chilled zone, whereas magnesium and calcium decrease. These changes are due to the obvious metasomatism of the roof rocks by granophyric materials. The upper part of the upper chilled zone does not show either chemical or petrographic evidence of appreciable alteration: the volatiles streaming upward into the lower part of the zone were apparently unable to penetrate to the top of it.

Total iron decreases as magnesium increases (fig. 31) in the basement sill and in the other diabase sheets of the region. This is due primarily to the behavior of

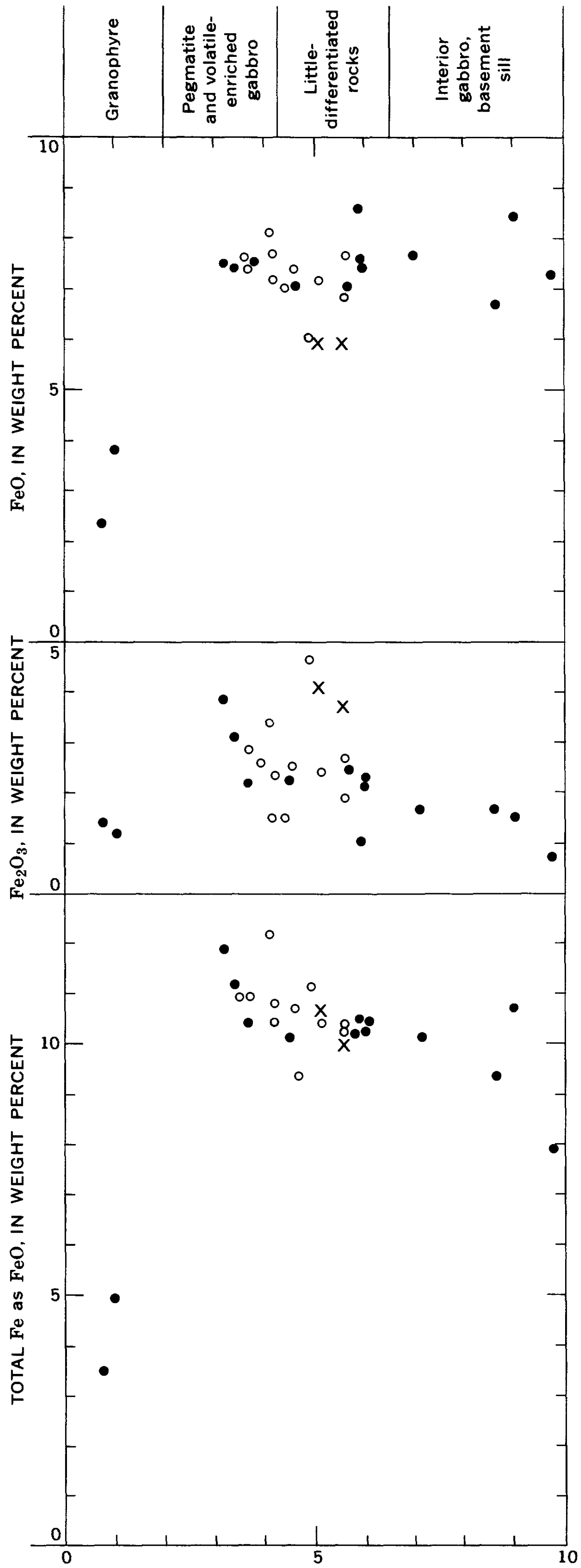


FIGURE 31.—Ratios of ferric, ferrous, and total iron to magnesium in diabase sheets of Taylor Glacier region. •, basement sill; o, other sheets; ×, dikes.

ferric iron which, particularly for the basement sill alone, shows a nearly linear inverse correlation with magnesium; ferrous iron is nearly constant whatever the magnesium content. The two granophyre specimens stand as obvious exceptions to these generalizations: the granophyres have a low content of magnesium and a high content of iron, both ferric and ferrous, and thus have much higher ratios of ferric, ferrous, and total iron to magnesium than do the other rocks. The ratio, by weight, of total iron as FeO to MgO is about 5:1 in the granophyres, 5:1.7 in the diorite pegmatite and in the volatile-enriched diabase and gabbro, 5:3 in the chilled margins, and 5:4 in the interior gabbro.

Ferric iron varies little with ferrous iron (fig. 32*A*) in rocks having less than 9 percent total iron as FeO; in these low-iron rocks, Fe_2O_3 ranges only from 1 to 2 percent of the rock. In high-iron rocks (total FeO = 9–12 percent), total iron increases only slightly faster than does ferric iron. This is another effect of the more limited variation of ferrous iron (except in the granophyres) than of ferric iron.

On a triangular plot of FeO (not total iron), MgO, and Na_2O+K_2O (fig. 33), values from analyses of all samples from the basement sill except those from the granophyres fall near a straight line. The values from analyses of chilled-margin rocks plot between those for interior gabbro on the one hand and those for the pegmatite and metasomatized diabase on the other. The trend is controlled by the nearly constant FeO content and by the inverse correlation between MgO and alkalis. The ratio $MgO:Na_2O+K_2O$ is about 2:1, by weight, in the chilled zones, 4:1 or 5:1 in the interior gabbro, and slightly less than 1:1 in pegmatite and metasomatized diabase. The ratio is near 1:10 in the granophyres, whose plots are thrown far from the linear plot of the other specimens in the diagram by their much higher ratios of alkalis to both iron and magnesium and of iron to magnesium.

Plots of CaO and K_2O (fig. 32*C*) and of CaO, Na_2O, and K_2O (fig. 34) similarly show linear arrays of points. The plots representing chilled margins are intermediate between those for pegmatites and metasomatized rocks in one direction and that of the interior gabbro in the other, and the plot for granophyres is off the main trend. The ratio $K_2O:CaO$, by weight, is about 1:15–1:30 in the interior gabbro, 1:10 in the chilled margins, 1:5 in the pegmatite and metasomatized diabase, and 5:3 in the granophyre. The ternary diagram $CaO-Na_2O-K_2O$ (fig. 34) is similar in the geometry of its point groupings to figure 32*C*, because sodium varies much less than do calcium and potassium.

Gunn (1962, p. 837) presented five analyses of rocks from the basement sill in the Kukri Hills, where, as in

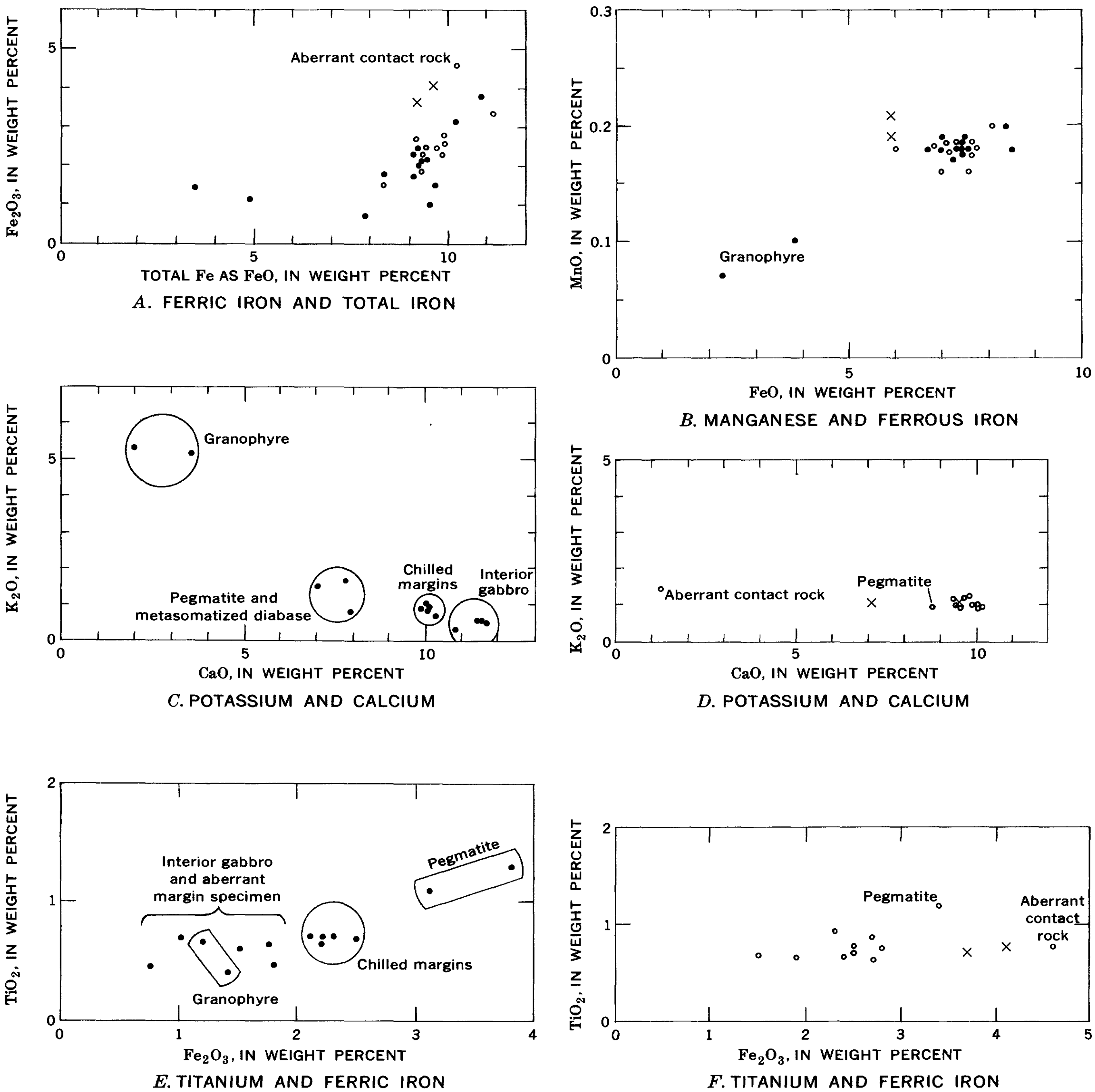


Figure 32.—Chemical variations in diabase sheets. •, basement sill; ○, other sheets; ×, dikes. Data from tables 1 and 2.

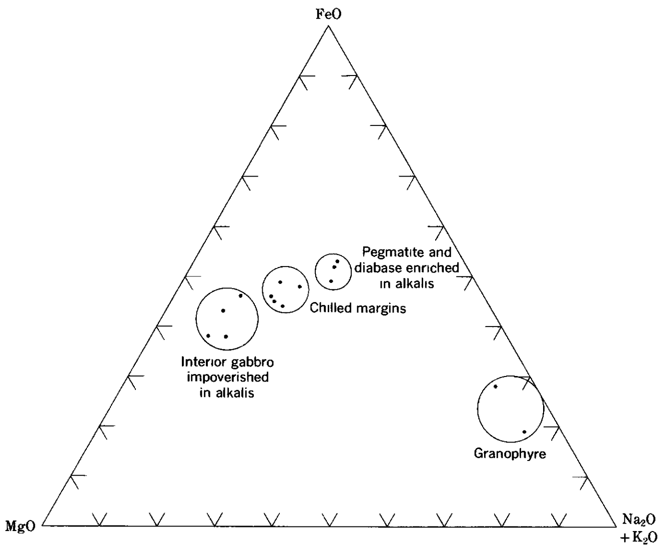


FIGURE 33.—Ternary diagram of weight-percent content of MgO, FeO, and Na_2O+K_2O in basement sill. Sums of components plotted are 16.6–19.3, 14.5–17.4, 14.2–15.0, and 11.8–13.8 for points within circles from left to right, respectively.

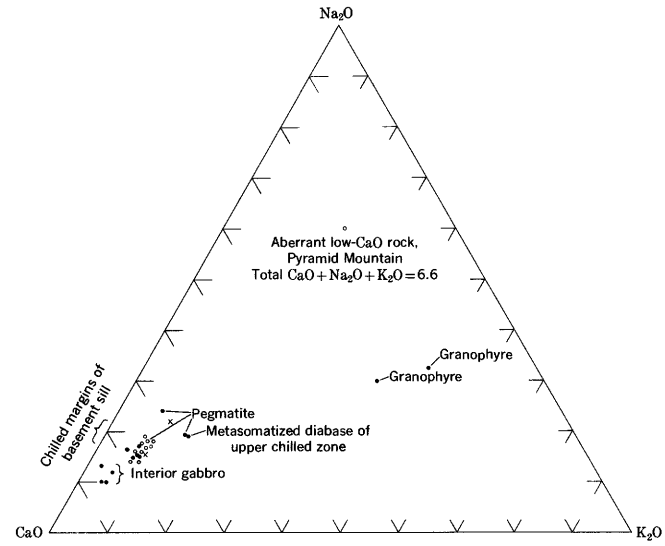


FIGURE 34.—Ternary diagram of weight-percent content of CaO, Na_2O, and K_2O in diabase sheets of Taylor Glacier region. Sum of the three components are between 10.5 and 12.8 except at the one point noted. •, basement sill; o, other sheets; ×, dikes.

the locality sampled in the present study, the sill is about 700 feet thick. These analyses, in weight percent, are repeated below.

Analyses of rocks from basement sill, Kukri Hills

	1	2	3	4	5
Feet above base	80	200	500	520	600
Density	3.00	3.06	2.92	2.85	2.82
SiO_2	52.68	52.90	53.47	56.36	56.68
Al_2O_3	13.34	11.69	16.86	14.32	16.20
TiO_2	.51	.39	.71	.81	.78
Fe_2O_3	1.81	1.64	2.34	3.51	1.18
FeO	7.36	7.74	7.21	6.89	7.94
MnO	.15	.18	.18	.19	.19
MgO	10.00	13.41	4.84	5.35	3.78
CaO	12.40	9.38	10.73	8.24	8.68
Na_2O	1.17	1.16	1.58	2.15	2.16
K_2O	.40	.39	.66	1.01	1.27
P_2O_5	.02	.05	.10	.10	.10
H_2O+	.28	.65	.84	1.03	.82
H_2O-	.33	.22	.20	.58	.48
Total	100.45	99.80	99.72	100.54	100.26

The rock of the first column is pigeonite-augite-bytownite gabbro of Gunn's lower pigeonite zone. Number 2 is pigeonite-augite-hypersthene-bytownite gabbro, containing about 30 percent hypersthene, from the hypersthene zone. Numbers 3–5 are from Gunn's upper pigeonite zone; 3 is pigeonite-augite-labradorite leucogabbro that is more feldspathic than is typical of rock at this height according to Gunn. Number 4 is granophyric gabbro pegmatite, and 5 is granophyric pigeonite-augite-labradorite gabbro.

The hypersthene gabbro (2) is markedly richer in magnesium and poorer in aluminum and calcium than is the clinopyroxene gabbro (1) beneath it. The highest specimen (5) is conspicuously richer in silica, aluminum, titanium, alkalis (particularly potassium), and phosphorus, and much lower in magnesia, than are any other of Gunn's or my nonpegmatitic gabbros in the sill. Gunn's pegmatite analysis (4) shows more magnesium than do my analyses (tables 1, cols. 8, 9), but is generally similar to them.

BULK COMPOSITION

The composition of the rock groups sampled in this study of the sill can be summarized as follows, the averages being recalculated to 100 percent for the components listed:

	Interior gabbro	*Chilled margins*	*Intermediate granophyre*
SiO_2	54.3	56.1	62.9
Al_2O_3	14.0	14.8	17.8
Fe_2O_3	1.5	2.0	1.2
FeO	7.6	7.6	3.8
MgO	8.7	5.6	1.0
CaO	11.4	10.2	3.6
Na_2O	1.5	2.1	3.8
K_2O	.5	.9	5.2
TiO_2	.5	.7	.7

Influencing the bulk composition of the sill to a lesser degree are these rock types, also recalculated to 100 percent:

	Diorite pegmatite	*Silicic granophyre*	*Altered diabase* [1]
SiO_2	60.0	70.2	58.7
Al_2O_3	13.0	14.1	15.2
Fe_2O_3	3.5	1.4	2.2
FeO	7.6	2.3	7.5
MgO	3.4	.8	3.8
CaO	7.6	2.0	8.0
Na_2O	2.5	3.5	2.2
K_2O	1.2	5.3	1.7
TiO_2	1.2	.4	.7

[1] The altered diabase is that of the lower part of the upper chilled zone, as represented by table 1, col. 12.

An estimate of the bulk composition of the sill can be obtained by combining these specific compositions in the following proportions, the figures representing the feet of thickness of each type: Interior gabbro, 593; chilled margins, 60; intermediate granophyre, 12; metasomatized diabase of upper chilled zone, 10; diorite pegmatite, 3; and silicic granophyre, 2. It is not a course inferred that the precision of such numbers is significant—uncertainty regarding both the proportions of the different rocks in the sill and the compositions properly assignable to the types make the true accuracy far less than this expressed precision. The bulk composition of the basement sill calculated from these proportions and specific compositions is:

	Percent		Percent
SiO_2	54.7	CaO	11.1
Al_2O_3	14.3	Na_2O	1.6
Fe_2O_3	1.5	K_2O	.6
FeO	7.5	TiO_2	.5
MgO	8.2		

This computed total bulk composition is more like the average composition of the interior gabbro than like the average composition of the chilled margins in all components except FeO, which is the same in gabbro, margins, and computed bulk. Obviously, then, either the sill did not simply differentiate in place from magma of the composition of the chilled margins (either magma—fresh or partly differentiated—more mafic than the margins was introduced, or silicic materials differentiated at this locality migrated away) or the assumptions regarding composition and proportions of the varying rock types are much in error. Uncertainty exists as to the thickness assigned to the lower chilled zone, but if this thickness has been underestimated, any correction would change the discrepancy between bulk and chilled compositions only slightly. The granophyre zone is so clearly defined that there could be no significant error in its thickness, and its rock types also are distinctive enough so that sampling inadequacies are unlikely to introduce major errors into the calculations. Increasing the allowance for granophyre in the calculations would make the discrepancy smaller for most oxides other than ferric iron, but such an increase in the allowance could only be small. The allotment for altered diabase in the lower part of the upper chilled zone could similarly be increased but little, and, again, such an increase could not much change the results. If differentiates more mafic than in the average interior gabbro were overlooked in the lower part of the sill, the discrepancy would be larger than that calculated. The remaining apparent place to account for the discrepancy in terms of compositional assumptions is in the upper part of the interior gabbro, which contains pegmatite segregations of minor total volume. Excellent exposures of the upper part of the interior gabbro were examined; it appeared to be uniform from the last-sampled locality 520 feet above the base of the sill (table 1, col. 7) to its top at 620 feet. If, however, the actual composition of the top 100 feet of the interior gabbro approximates more nearly the composition of the diorite pegmatite schlieren than it does the rest of the gabbro, the discrepancy calculated between bulk and margin compositions would be much reduced.

No evidence was recognized to support the possible interpretation of movement of differentiated silicic material from this section of the sill into the wallrocks. The wallrock quartz monzonite at both upper and lower contacts shows no apparent metasomatism, such effects being limited to xenoliths within the sill, and no dikes or veins of material from the sill were seen in the granite.

Gunn (1962, p. 837) sampled the lower interior part of the basement sill—the interval missed in the present work. He found it to contain 10 percent MgO at 80 feet above the base and 13.4 percent at 200 feet. Thus, it is more magnesian than any part of the sill reported here, and its inclusion further accentuates the contrast between bulk composition and chilled margins. Comparison of Gunn's data with those in this report indicates that part of the discrepancy between bulk composition and composition of chilled margins of the basement sill as calculated here may be due to changes within the upper 100 feet of the interior gabbro. This part of the gabbro was sampled by Gunn but not by me; he found it to be a little higher in silica and alkalis and markedly lower in magnesia than the rest of the gabbro.

The differentiation of the sill can thus be considered only in terms of data which do not balance. The section studied is not a closed differentiation system.

MINOR ELEMENTS

By Warren Hamilton, Paul R. Barnett, Vertie C. Smith, and Nancy M. Conklin

Analyses for minor elements in the basement sill are listed in table 1. Chlorine and fluorine were determined chemically by Vertie C. Smith; titanium and manganese were determined as oxides by the silicate analysts; and the other elements were measured spectrographically by P. R. Barnett and Nancy M. Conklin. The data are plotted in figure 35 against height within the sill. Many of the elements show correlation with rock type and degree of differentiation in the rocks.

Late differentiates are enriched in barium, chlorine, fluorine, strontium, zirconium, and probably beryllium. All these are most abundant in the granophyre zone and

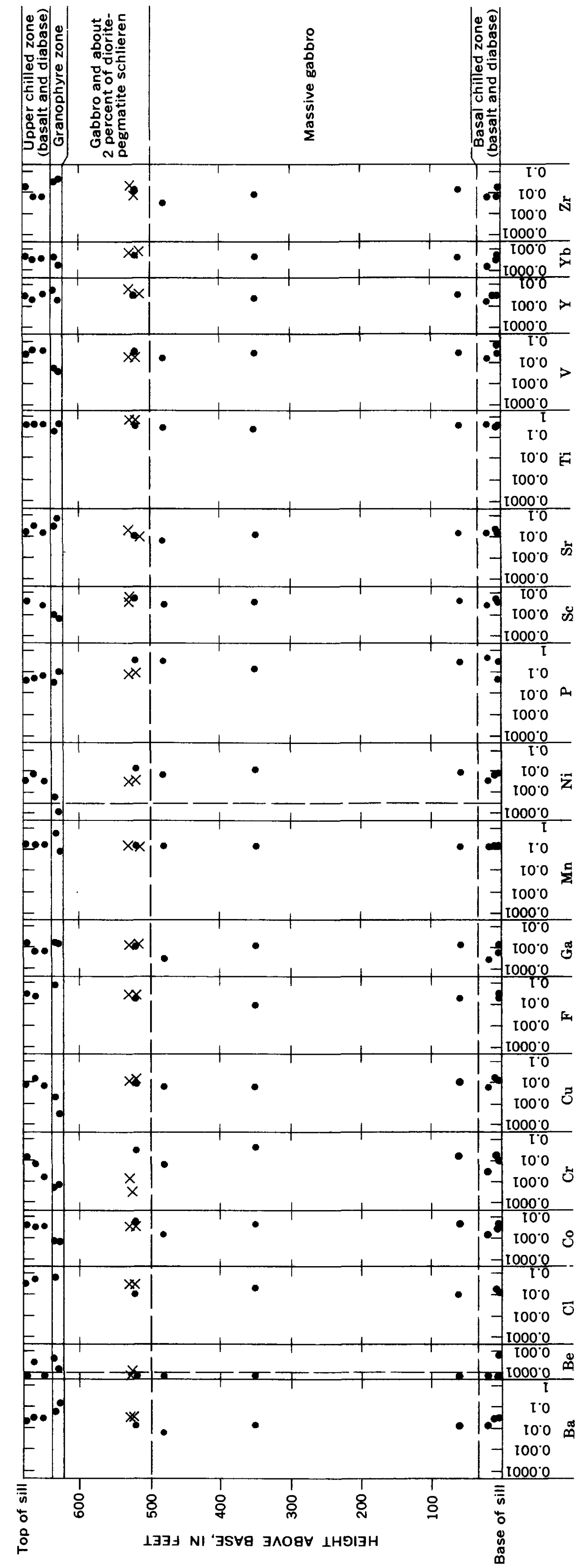


FIGURE 35.—Variation diagram for minor elements in basement sill. X, pegmatite. Data from table 1.

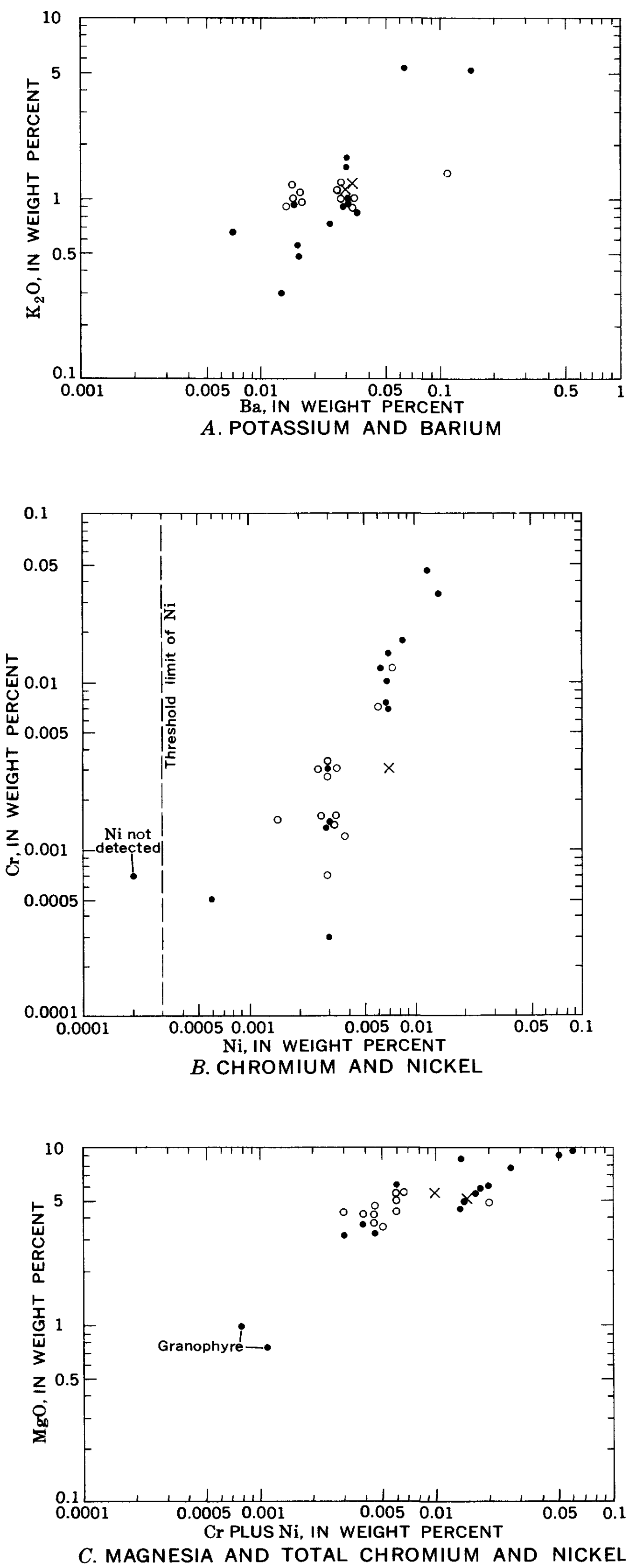


FIGURE 36.—Log-log plots of major and minor elements. •, basement sill; o, other sheets; ×, dikes. Data from tables 1 and 2.

are generally more abundant in the diorite pegmatite schlieren than in other mafic rocks. Barium shows a marked decrease upward from the chilled base into the main gabbro; fluorine and strontium show slight decreases; and chlorine and zirconium show no apparent change. Chlorine is much more abundant in the upper chilled zone than in the lower, consistent with the demonstrated streaming into the upper chilled zone.

Behaving in the opposite manner are cobalt, chromium, nickel, and vanadium, which are least abundant in the granophyre and are less abundant in the diorite pegmatite schlieren than in the gabbro. Each of these elements is about 10 times more plentiful in the mafic rocks than in the granophyre, and 2–10 times more abundant in the gabbro than in the diorite pegmatite.

More complex variation is shown by copper, phosphorus, and scandium. Copper shows moderate enrichment in the intermediate differentiate, diorite pegmatite, relative to the gabbro and chilled margins, but marked impoverishment in the final differentiate, granophyre. Phosphorus content is irregularly high in the basal chilled zone and in the main gabbro, but it is low in the diorite pegmatite, granophyre, and upper chilled zone. Scandium is nearly uniformly abundant in all rocks except the granophyre, in which it is conspicuously low.

Still another group of elements lacks obvious variation patterns through the sill. These elements that vary little in abundance are gallium, manganese, yttrium, and ytterbium. An intensive study by quantitative methods might, of course, demonstrate systematic variations not apparent in the data available.

Interrelations between various elements in the basement sill are shown graphically in figures 36 and 37. Data from other sills, inclined sheets, and dikes are included in some graphs. The log-log graph of barium and potassium (fig. 36*A*) demonstrates clustering of the values from basement sill analyses about a line sloping nearly 45°, thus constituting a linear correlation.[2] Barium and potassium each ranges through a 20-fold variation, and K_2O is about 50 times as abundant as is barium. Discrepant values were reported by Barnett and Conklin; Barnett's analyses, made largely by quantitative methods, cluster about a steeper line than do Conklin's semiquantitative analyses. As the specimens analyzed by the two analysts were generally taken

[2] On a log-log graph, a direct linear correlation is indicated by clustering of points along a line sloping 45°. Clustering about a straight line having any other slope demonstrates a simple exponential relation with the general equation

$$Y=aX^b$$

where b is the slope and a is the Y intercept. As the slope approaches the vertical or the horizontal, the correlation approaches the purely random. Clustering about a curve rather than a straight line demonstrates a correlation that is neither linear nor simply exponential.

alternately through the basement sill, an analytical bias rather than a true scatter seems indicated. Such a bias is shown more strongly by the analyses of samples from other sheets and dikes of diabase in the region, which are also plotted on the same figure. Nearly all these analyses for barium were made by semiquantitative methods, and again each analyst worked with generally alternate rather than systematically different samples; Conklin's value of 0.015 percent Ba for all samples but one is only half as large as the 0.03 percent determined by Barnett in all but one of his analyses of closely similar rocks. The random correlation between potassium and barium suggested for these other dikes and sills by the plot thus is probably illusory rather than real.

Cobalt, chromium, and nickel show the expected correlation with iron and magnesium. The correspondence for cobalt is particularly good when only the quantitative analyses from the basement sill are considered; among the semiquantitative determinations for rocks from the basement sill and from the other intrusions, Conklin's values are generally lower than Barnett's. Chromium and nickel show marked correlation (fig. 36*B*), but interpretation is again clouded by probable analytical biases. Of Conklin's nine semiquantitative analyses of both basement sill and other specimens, seven show identical amounts of chromium and nickel, and thus a perfect 1:1 correlation. Barnett's analyses for the basement sill, which are largely quantitative, show by contrast a general dominance of chromium over nickel by a factor of 2 or more, whereas his determinations for specimens from other sheets and dikes, which are mostly semiquantitative, show a general dominance of nickel over chromium by the same amount. Because of these variations, the sum of chromium and nickel contents may be more accurately known than is that of either element alone. Combined chromium and nickel are plotted against MgO in figure 36*C*. Correlation of these parameters is fairly good, and all determinations except those for the granophyres fall in a broadly linear group showing that the ratio (Cr+Ni) : MgO increases as the amount of each component increases. There is about 1,000 times as much magnesia as there is combined chromium and nickel in rocks having only 3 or 4 percent MgO, but only 150 times as much in rocks having 9–10 percent MgO. The low-magnesia granophyres plot beneath the projected trend of the other analyses; they have about 1,000 times as much MgO as they do chromium plus nickel.

Manganese shows little variation; determined by either colorimetric or gravimetric methods, MnO content in all samples of both the basement sill (table 1) and the other diabase intrusions (table 2), except the two granophyre specimens from the basement sill, is within the narrow range 0.16–0.20 percent. The granophyre contains only 0.07–0.10 percent MnO. There is an excellent correlation between manganese and ferrous iron (fig. 32*B*); the abundance of FeO is about 40 times as great, by weight, as that of MnO; there is no apparent correlation in most specimens between the amounts of magnesium or ferric iron and manganese. The manganese is probably in silicate minerals in Fe^{+2} positions.

Titanium varies systematically with ferric iron (fig. 32*E*). The ratio by weight of $TiO_2:Fe_2O_3$ is consistently about 1:3. The abundance of both oxides correlates well with that of opaque minerals (table 1); granophyre and interior gabbro contain only about 1 percent by volume of magnetite and ilmenite, whereas the chilled margins contain about 2 percent and the diorite pegmatite contains about 4 percent. Most of the ferric iron and titanium is present in magnetite and ilmenite rather than in silicate minerals. The distribution of these components within the sill demonstrates that they crystallized late in the sequence and that they migrated upward with alkalis. A different aspect of the distribution of titanium and ferric iron is shown by figure 37, in which the proportions of these elements are plotted against that of magnesium. The systematic change in the proportion of titanium plus ferric iron to magnesium is apparent on this diagram: the proportion is lowest in the volatile-impoverished interior gabbro, low in the chilled margins, moderate in the metasomatized roof, high in the pegmatite, and very high in the granophyre. The linear array of the points in figure 37 is due, of course, to the nearly constant ratio of titanium to ferric iron.

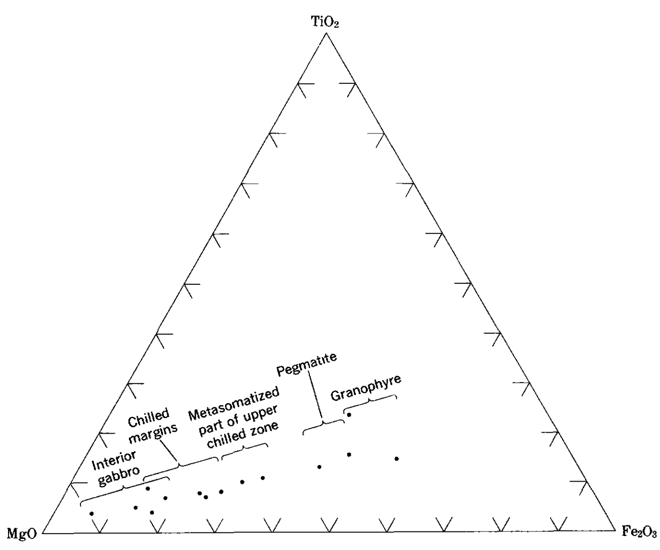


FIGURE 37.—Variation of $MgO–TiO_2–Fe_2O_3$ proportions in basement sill.

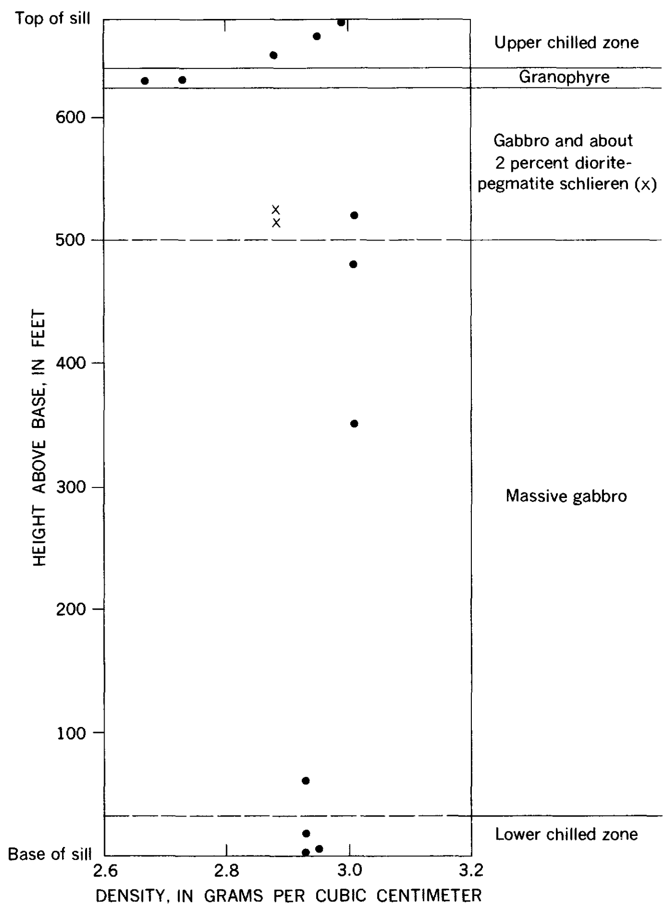


FIGURE 38.—Variation of powder density with height in differentiated diabase sill intruded into quartz monzonite. Data from table 1.

DENSITY

The rocks of the sill vary in density by more than 0.3 g per cc (grams per cubic centimeter) (table 1), the differences being related systematically to position in the sill (fig. 38). The lower 60 feet of the sill has a uniform density of about 2.94 g per cc. The upper chilled zone has a density graded from less than 2.9 just above the granophyre layer to almost 3.0 at the chilled top. The three gabbro specimens from the upper-middle part of the sill all have a density of 3.01. The diorite pegmatites are lighter (2.88), and the granophyres lighter yet (about 2.7). These density contrasts and trends are predictable from the variation of mineralogic and chemical compositions.

DIFFERENTIATION

The dominant mechanism of differentiation of the basement sill seems to have been liquid fractionation whereby fluid gabbroic magma developed a vertically graded composition in response to pressure and temperature gradients. This fractionation process continued in the magma throughout the period when it was wholly or in any part fluid: before, during, and after intrusion into its present position, and before and during crystallization. The term "volatile transfer" has been used by some authors to explain effects such as those discerned here, but the term is at least in part invalid in its thermodynamic connotations and is rejected in favor of the nonspecific term "liquid fractionation." Liquid immiscibility, an effect producing liquid fractionation, may account for minor differentiation, but it is much subordinate to diffusion processes. Perhaps superimposed on liquid fractionation have been the subordinate effects of crystal settling and filter pressing.

Many aspects of igneous differentiation conventionally assumed to be due to crystal settling and filter pressing may instead be products of liquid fractionation. Theoretical and experimental thermodynamic considerations indicate that any magma having either finite vertical extent or nonuniform temperature must fractionate as a liquid in the directions called upon here, but quantitative evaluation of these effects is not yet possible on a thermodynamic basis. These matters are discussed under a subsequent heading; the immediate discussion is limited to the more empirical features of differentiation of the basement sill.

The chilled marginal zones of the sill are each about 30 feet thick and consist of basalt grading inward to increasingly coarse diabase. The aphanitic basalt at the outer contacts contains only a few percent of microphenocrysts and hence crystallized from magma that was almost entirely liquid at the time of intrusion. The lower chilled zone has a uniform composition throughout, which indicates that it crystallized without loss or addition of components from equally liquid components. Subsequent to crystallization the lower part of the upper chilled zone was much altered by upward-streaming material.

The great bulk of the sill lies between the chilled zones and crystallized from the bottom upward. Progressively lower temperature assemblages are found at greater heights in the interior; and the granophyre zone, containing the most extreme silicic differentiates, lies directly beneath the upper chilled zone. In chilled-margin rock of basaltic and diabasic texture, plagioclase crystallized largely before pyroxene. Plagioclase crystals are well shaped, whereas pyroxene grains are molded about them. Ilmenite and magnetite are molded in turn about pyroxene. The crystallization sequence is more ambiguous in the gabbro, where the interference textures present might be interpreted to indicate either simultaneous crystallization of plagioclase and pyroxene or variable recrystallization after magmatic crystallization was largely complete. Plagioclase crystals are in general smaller but better shaped than pyroxene, and irregular contacts suggesting simultaneity are widespread. Opaque minerals and interstitial micropegmatite obviously crystallized late.

The bulk composition of the sill has been demonstrated by the combined studies of Gunn (1962) and me to be markedly more mafic than that of the chilled margins. The gabbro which forms the greater part of the interior of the sill contains less silica, alumina, ferric iron, alkalis, and titania, and more magnesia and lime (figs. 29, 31, 39) than do the margins. The interior of the sill must have crystallized from a liquid more mafic than did the margins, and yet joints continuous across the sill in cliff outcrops show that the sheet is not composite in the normal sense of the term. The first magma intruded formed the chilled margins and was less mafic than was the remainder of the magma. If the magma first intruded lay above that intruded last in some deeper magma chamber, then differentiation within that chamber resulted in a magma of graded composition prior to intrusion into the present position.

The same conclusion is indicated by the mineralogy of marginal and interior rocks. The plagioclase is more calcic in the gabbro (An_{70-75}) than in the chilled margins (An_{65}) and hence crystallized from a more calcic liquid (unless crystallization of the chilled-margin plagioclase was at the composition of the liquidus for its temperature, rather than at the composition of the solidus). The pyroxenes are more magnesian and less ferroan in the gabbro than in the margins; hence they crystallized from a more magnesian liquid. Had the gabbro crystallized from magma like that of the chilled margins, its minerals should be those of the margins, differences in bulk composition then being explicable in terms of mechanical separation of crystals and residual liquid, but this is not the case.

Gunn (1962) found a thick hypersthene-rich zone below the middle of the sill in a height interval I was unable to sample. He explained the hypersthene concentration as a result of gravitational settling of crystals; but whether or not this is correct, the hypersthene must have crystallized from a liquid different from that of the chilled margins, for the margins contain little hypersthene. Gunn found the plagioclase in the hypersthene zone, and in one gabbro sample between it and the lower chilled zone, to be more calcic (near An_{80}) than that either higher in the sill or in either chilled margin; I infer again that crystallization from a different liquid is indicated. The complementary abundances of hypersthene and clinopyroxene, which have like densities, also suggest crystallization from different liquids.

Gunn's data showing progressive increase upward in the iron magnesium ratio in augite throughout his suite of samples again leads to the conclusion that a different liquid was present at each level as crystallization progressed upward.

I see no evidence for gravitational settling of early crystals anywhere in the sill. Olivine forms layers near the base of some such sills, but no olivine nor pseudomorphs after it were found here in either margins or interior. Plagioclase and pyroxene probably overlapped broadly in their time of crystallization, so that neither could have sunk independently.

The schlieren of granophyric diorite pegmatite in the upper part of the gabbro are poorer than is the bulk of the gabbro in those oxides in which the border zone is enriched, and richer than the gabbro in oxides in which the border zone is relatively poor. The relationships are nearly linear. The removal of the components of the pegmatite from chilled-margin magma would leave material trending directly toward the composition of the interior gabbro. The proportions of the various rock types are, however, such that closed-system differentiation within the section is inadequate to explain the bulk composition of the sill; upward removal of pegmatitic and granophyric constituents would leave the mafic residium needed to form the magsian interior of the sill, but only if the differentiating liquid was different from the chilled-margin magma.

Pegmatite or granophyre or both are richer in silica, ferric iron, sodium, potassium, and titanium than is gabbro. The enrichment is shown mineralogically by such features as the high contents of micropegmatite and opaque minerals and by more sodic plagioclase in the more silicic rocks. Both pegmatite and intermediate granophyre are also enriched in barium, beryllium, lead(?), phosphorus, strontium, and zirconium. These elements were somehow removed subuniformly from the lower 500 feet of the interior gabbro and were concentrated in the upper 100 feet of the gabbro and in the immediately overlying thin layer of granphyre. These upward-migrated components are those to be expected in a late-crystallizing residium from chilled-margin magma, and probably most petrologists would accordingly infer their separation by mechanical means—filter pressing or crystal settling—from early-crystallized plagioclase and pyroxene. The mineralogical and chemical data seem to me, however, to preclude the possibility that this explanation is applicable to more than a subordinate part of the differentiation.

The components now concentrated high in the sill share another attribute in addition to their being typical of late residua: they are also the components most soluble in water, and they have the lowest crystallization temperatures. A process which will tend to separate water and relatively soluble rock components from the more refractory part of the magma *as a liquid* could thus explain not only the concentration of the soluble materials in the upper part of the sheet but also the changes in mineral compositions within the gabbro which require crystallization from different liquids. Such a process, the formation of concentration gradients within a magma in response to temperature and pressure gradients, is discussed at length in a subsequent section.

The enrichment of pegmatite and granophyre in the most soluble, most volatile, and coolest-crystallizing components of the diabase is illustrated by the ternary diagram CaO–Na_2O–K_2O (fig. 39). The interior gabbro and the pegmatite and granophyre are complementary in composition, and the chilled-margin rocks are intermediate between them. Similar relationships can be seen in most of the major-oxide diagrams in this report: the ternary plots of MgO–FeO–Na_2O+K_2O (fig 33) and of MgO–TiO_2–Fe_2O_3 (fig. 37), the binary plot of CaO and K_2O (fig. 32*C*), and the variation diagrams plotted against silica (fig. 30) and height in the sill (fig. 29*B*). The minor-element data show similar relationships.

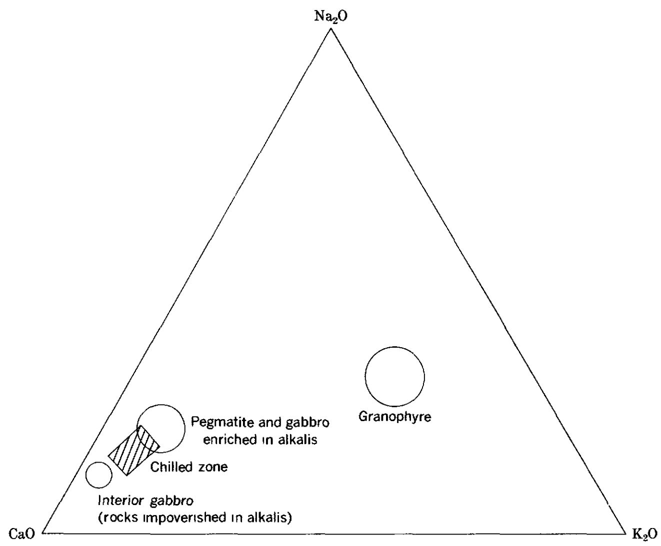


FIGURE 39.—Differentiation in basement sill due to migration of alkalic fluids, as illustrated by changes in proportion of weight percentages of CaO, Na_2O, and K_2O. Compare with figure 34.

The granophyre zone contains the most silicic and alkalic rocks of the sill, but neither the silicic nor the intermediate granophyre is related in linear fashion to the other rock types in many components. On the diagrams this is shown by the offset of the granophyre points from the trends established by the other rock types. Factors more complex than linear complementary change are indicated for the granophyre. Although most of the granophyre is interpreted as a magmatic rock produced by fractionation of basaltic magma, some of the granophyre formed by reconstitution and assimilation of wallrock granite. Xenoliths of highly altered wallrock quartz monzonite are present in the granophyre zone, and textural and compositional peculiarities of the granophyre suggest that a considerable part of it formed by metasomatic reconstitution of such quartz monzonite. The silicic granophyre ($SiO_2=69$ percent in the analyzed specimen) may represent largely xenolithic material, and the more abundant intermediate granophyre ($SiO_2=63$ percent), which encloses the silicic granophyre, appears from petrographic study to have a considerable proportion of xenolithic quartz and feldspar.

The basement sill, where sampled, is intrusive into a large pluton of coarse-grained pink biotite quartz monzonite varying to granite. Chemical analysis of specimens from the pluton gave these results:

	1	2		1	2
SiO_2	69.24	69.8	H_2O+	0.54	0.88
Al_2O_3	14.93	15.2	H_2O-	.05	
Fe_2O_3	.55	.7	CO_2	.03	<.05
FeO	2.48	1.9	Cl	.03	-------
MgO	.43	.35	F	.15	.10
CaO	1.84	1.5			
Na_2O	3.78	3.6	Sum	99.88	100
K_2O	5.34	6.0	Less O	.07	
TiO_2	.33	.27			
P_2O_5	.09	.08	Total	99.81	
MnO	.07	.06			

Both specimens have pink orthoclase microperthite as their dominant mineral and also include abundant quartz and intermediate oligoclase, minor biotite, even less hornblende, and trace amounts of allanite, fluorite, apatite, zircon, and opaque minerals. No. 1 was collected from the north side of Solitary Dry Valley near its east end, beneath the basement sill; No. 2 was collected from the south side of the central part of the valley, near the sampled section through the basement sill and several hundred feet beneath it. No. 1 was analyzed by standard silicate methods by Vertie C. Smith in 1959 (lab. No. F2510, field No. A54). No. 2 was analyzed by rapid colorimetric methods by P. S. D. Elmore, I. H. Barlow, S. D. Botts, G. W. Chloe, and W. D. Goss in 1960 (lab. No. 154593, field No. A41).

The silicic granophyre differs from this wallrock notably by being lower in alumina and higher in ferric iron and magnesia. The plutonic rock is so uniform in aspect—despite the slight variation in sodium-potassium ratio that warrants calling some quartz monzonite and some, only slightly different, granite—that this difference is probably real and not an illusion due to sampling deficiencies. If the granophyre was formed by metasomatic alteration of granite inclusions, then at least the alumina, ferric iron, and magnesia were moved in the process; more likely, the granophyre represents a combination of substantial amounts of both xenolithic and introduced material. Deductions are complicated because the intermediate granophyre, interpreted to be more completely magmatic in origin, differs from the granite less than does the silicic granophyre in ferric iron, and it has much more alumina than does the granite.

PETROLOGY OF OTHER DIABASE SHEETS

Other sills, inclined sheets, and dikes were sampled near the south side of Taylor Glacier in the vicinity of New Mountain, Beacon Heights, and Pyramid Mountain (pl. 1). It was not possible to sample systematically through any large sheet of diabase and gabbro here, and the specimens represent different parts of a number of sheets. The pegmatitic zone near the top of the peneplain sill, the chilled base of the irregular New Mountain sheet, the sills of Pyramid Mountain, the thick inclined sheet at the east end of Pyramid Mountain, and small steep dikes of West Beacon Heights are represented. No differentiates more silicic than gabbro pegmatite were seen, and pegmatite was found only in the peneplain sill.

Thirteen specimens from these sheets were analyzed chemically and modally. Data are listed in table 2, and specimens are described below. The mineralogy of these rocks is much like that of the basement sill. Apatite is ubiquitous and is not mentioned in the following descriptions.

PETROGRAPHY

By WARREN HAMILTON and PHILIP T. HAYES

The peneplain sill was sampled only in its upper, pegmatitic part, beside Taylor Glacier just east of the mouth of Arena Dry Valley, at the base of the north spur of New Mountain. The rock here is medium-grained gabbro which contains abundant large irregular masses of gabbro pegmatite, some of it of very coarse texture. No granophyre was seen. Above the gabbro and pegmatite is the upper chilled zone of basalt and metasomatically altered diabase. Three specimens from the gabbro and pegmatite zone, about 50–100 feet below the top of the sill, were analyzed (table 2, cols. 1–3); petrographic descriptions follow.

The first analysis (col. 1) is of medium-grained gabbro with abundant micropegmatite, showing patchy variation of composition and texture. Greenish-black pyroxene is conspicuous against the light-gray feldspar. Labradorite shows slight normal zoning; tablets are thin and euhedral to subhedral, and most are 1–2 mm long, but some are as much as 4 mm long. Augite occurs partly as skeletal crystals as much as 1.5 cm. long (fig. 40*A*), enclosing and intergrown with plagioclase, and partly as small compact prisms and anhedra. Pigeonite and the minor hypersthene are mostly in better shaped small prisms. The abundant micropegmatite is partly interstitial and partly replaces plagioclase (fig. 40*A*); alkali feldspar in it is clouded. Plagioclase has mica-lined fractures but is otherwise unaltered. Pyroxene is considerably altered and exsolved. Ilmenite and magnetite are partly interstitial and partly in skeletal intergrowths with secondary hornblende and chlorite after pyroxene.

The second analyzed specimen (table 2, col. 2) is of very similar gabbro which also contains abundant granophyre. The slightly zoned labradorite is partly replaced by micropegmatite but is otherwise unaltered. The pyroxene—about equally augite and pigeonite—is poorly shaped and is in part much altered. Alkali feldspar is clouded.

Coarse-grained granophyric gabbro pegmatite is represented by column 3. This rock has blotchy variations of texture and composition. The coarsest parts have prisms of augite and pigeonite as large as 0.5 by 3 cm and discontinuous needles as large as 0.2 by 6 cm; many large crystals are in roughly radial clusters. Labradorite crystals (fig. 40*B*) are poorly shaped, are as long as 1 cm, and are much replaced by micropegmatite. The large grains of clinopyroxene each consist of several intergrown skeletal crystals; elements of most crystals are discontinuous in the plane of a single thin section (fig. 40*B*). Many crystals appear in section as scattered small islands or blebs showing optical and crystallographic continuity but separated completely by other minerals, mostly labradorite. Pyroxene is altered mostly to chlorite, and alkali feldspar is generally clouded, but plagioclase is little altered where not wholly replaced. The photomicrograph is atypical for the specimen in showing little micropegmatite. The specimen is so irregularly variable that the tabulated mode (based on 2,000 points counted in one thin section) is much less representative than is the chemical analysis.

Gunn (1962, p. 822) described several samples from the lower and middle part of the peneplain sill at Solitary Rocks, where it is about 1,350 feet thick. Six samples taken from 35 to 560 feet above the base are rather uniform in composition and contain 40±2 percent pyroxene (generally more augite than pigeonite; no hypersthene), 44.5±1.5 percent plagioclase (sodic bytownite–calcic labradorite; no systematic change in composition with height), 10.5±1.5 percent micropegmatite, 0.7–3 percent biotite and hornblende, and 0.9–5 percent opaques. Higher samples, taken at 600 and 1,090 feet, have a similar amount of plagioclase and accessories but

TABLE 2.—*Chemical and mineralogic analyses of rocks of diabase sills, inclined sheet, and dikes intruded into Beacon Sandstone*

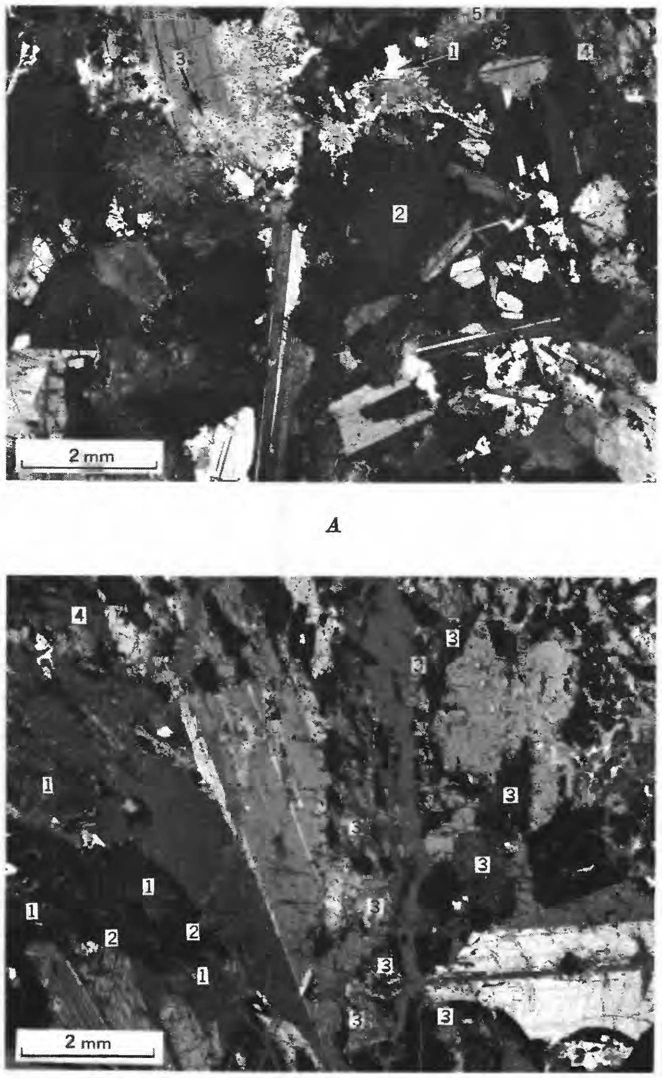
[Major-oxide analyses of columns 1–7, 9, 10, 12, and 13 by colorimetric methods by P. S. D. Elmore, I. H. Barlow, S. D. Botts, and G. W. Chloe, U.S. Geol. Survey, Washington, D.C., 1960; columns 8 and 11 by gravimetric methods by Vertie C. Smith, U.S. Geol. Survey, Denver, Colo., 1959; all analyses for fluorine and chlorine also by Vertie C. Smith. Spectrographic analyses 8 and 11 by quantitative methods, using internal standards, by Paul R. Barnett, U.S. Geol. Survey, Denver, 1960; Nos. 1, 3, 4, 12, and 13 by Barnett, Denver, 1960, and Nos. 2, 5, 6, 7, 9, and 10 by Nancy M. Conklin, U.S. Geol. Survey, Denver, 1959, using visual-comparison semiquantitative methods; values reported as midpoints of logarithmic-third divisions. Modes determined by point counting by Philip T. Hayes and Warren Hamilton, and reported as volume percent. Powder densities measured by Vertie C. Smith.]

	Sills							Inclined sheet				Thin dikes		Average of 4–7 and 9–13 (volatile free)
	Peneplain sill			New Mountain sheet	Sills of Pyramid Mountain			East end Pyramid Mountain				Beacon Heights		
	Gabbro		Pegmatite					Distance from edge						
								0.1 ft	1.5 ft	20 ft	100 ft			
	1	2	3	4	5	6	7	8	9	10	11	12	13	A
SiO_2	55.4	56.1	56.5	56.0	54.6	54.7	54.9	55.26	54.9	55.2	55.07	55.0	55.2	55.8
Al_2O_3	15.0	14.7	13.3	16.2	16.3	16.0	15.0	15.06	14.7	15.2	15.88	14.8	15.5	15.7
Fe:														
Fe_2O_3	2.5	2.3	3.4	1.5	2.5	2.8	2.7	4.60	1.9	2.4	2.59	3.7	4.1	2.8
FeO	7.4	7.7	8.1	7.0	7.2	7.4	6.8	6.03	7.6	7.2	7.56	5.9	5.9	7.0
Sum as FeO	9.7	9.8	11.2	8.3	9.4	9.9	9.2	10.2	9.3	9.4	9.9	9.2	9.6	9.5
MgO	4.6	4.2	4.1	4.4	4.2	3.7	5.6	4.91	5.6	5.1	3.61	5.6	5.1	4.9
CaO	9.9	9.4	8.8	9.7	10.0	9.6	10.2	1.26	10.1	9.8	9.33	9.6	7.1	9.6
Na_2O	2.0	2.2	2.2	2.3	2.1	2.4	1.8	3.93	2.1	2.2	2.16	2.0	2.3	2.2
K_2O	1.0	1.0	.94	1.2	1.0	.92	.94	1.40	.96	1.0	1.16	1.1	1.1	1.0
TiO_2	.79	.92	1.2	.68	.70	.76	.62	.77	.64	.66	.86	.74	.79	.7
P_2O_5	.12	.14	.15	.14	.14	.14	.12	.10	.12	.13	.11	.13	.14	.13
MnO	.18	.18	.20	.16	.18	.18	.18	.18	.18	.18	.16	.18	.22	.18
H_2O+	1.3 (with H_2O-)	1.8	1.8	.94	1.6	1.6	1.5	3.96	1.4 (with H_2O-)	1.2	.92	1.8 (with H_2O-)	3.3	--------
H_2O-								1.12			.39			
CO_2	<.05	<.05	<.05	<.05	.05	<.05	<.05	.04	<.05	<.05	.03	<.05	<.05	--------
F	.02	.03	.03	--------	--------	--------	--------	.05	--------	--------	.03	.04	.03	--------
Cl	.01	.03	.01	--------	--------	--------	--------	.04	--------	--------	.01	.01	.01	--------
Sum	--------	--------	--------	--------	--------	--------	--------	99.71	--------	--------	99.87	--------	--------	--------
Less O	--------	--------	--------	--------	--------	--------	--------	.03	--------	--------	.01	--------	--------	--------
Total	101	101	101	100	100	100	100	99.68	100	100	99.86	101	101	--------
Ba	0.03	0.03	0.03	0.015	0.015	0.015	0.015	0.11	0.03	0.015	0.028	0.03	0.03	
Be	.0003	.0007	<.0001	<.0001	<.0001	<.0001	<.0001	.0007	.0001	<.0001	<.0001	.0003	.0003	
Co	.003	.0015	.0015	.003	.0007	.0015	.0015	.0052	.0015	.0015	.0044	.015	.003	
Cr	.0015	.0015	.0007	.003	.0015	.0015	.003	.012	.003	.003	.0012	.003	.007	
Cu	.015	.015	.015	.007	.007	.007	.007	.014	.007	.007	.014	.015	.015	
Ga	.0007	.0007	.0015	.0007	.0003	.0003	.0003	.0016	.0007	.0003	.0016	.0015	.0015	
Nb	<.01	<.01	<.01	<.01	<.01	<.01	<.01	.002	<.01	<.01	.002	<.01	<.01	
Ni	.003	.003	.003	.003	.0015	.003	.003	.0074	.003	.003	.0038	.007	.007	
Sc	.007	.007	.007	.003	.0015	.003	.003	.0046	.003	.003	.0042	.007	.007	
Sr	.03	.07	.015	.015	.015	.015	.015	.028	.015	.015	.016	.03	.03	
V	.03	.03	.03	.03	.007	.03	.015	.019	.015	.015	.021	.03	.07	
Y	.003	.003	.0015	.003	.0015	.0015	.0015	.004	.0015	.0015	.004	.0015	.003	
Yb	.0003	.0003	.0003	.0003	.00015	.0003	.00015	.0004	.0003	.0003	.0005	.0003	.0003	
Zr	.007	.007	.007	.007	.003	.007	.007	.018	.007	.007	.018	.007	.007	
Plagioclase	43	45	43	57	51	55	50		≈45	59	63	50	≈50	
(Percent An)	(60)	(55)	(60)	(65)	(55)	(55)	(55)		(65)	(65)	(60)	(55)	(50)	
Augite and subcalcic augite	18	15	8	11	4	9	4		≈15	15	4	6	≈5	
Pigeonite	14	14	11	24	26	16	28		≈20	18	18	26	≈25	
Hypersthene	3	.4	.9	.6	--------	.7	--------		--------	.3	.1	--------	--------	
Opaque minerals	2.5	1.4	4	.7	2.6	2.4	2.5	[1]		1.8	1.6			
Quartz	5	9	12	2.5		10	6				4			
Alkali feldspar and oligoclase	11	12	16	2.8	8 (quartz and alkali feldspar)		5		≈20 (opaque minerals through chlorite)	3 (quartz and alkali feldspar)	2.5	18 (opaque minerals through chlorite)	≈20	
Chlorite, nontronite, and others	1.3		4	.6	8	7	5			.5	4			
Hornblende	1	2.8 (chlorite through muscovite)	.2	.1	.2	.2	--------		--------	.2	.4	--------	--------	
Biotite	1		.2	.8	--------	--------	--------		--------	2.5	2.3	--------	--------	
Muscovite	.2		.1	.1	.2	--------	--------		--------	.1	.1	--------	--------	
Powder density	2.92	2.92	2.93	--------	2.90	2.90	2.93	2.72	--------	2.89	--------	2.90	2.82	
Field No.	A14C	A14A	A14B	A14D	A19C	A19D	A19A	A15C	A15D	A15E	A15F	A-I-8	A-I-2	
Laboratory No.	156221 G 2980	156219 G 2978	156220 G 2979	154569 272385	154573 272389	154574 272390	154572 272388	F 2498	154570 272386	154571 272387	F 2499	156218 G 2977	156217 G 2976	

[1] Specimen too fine grained for counting.

contain 16–19 percent micropegmatite and only about 35 percent clinopyroxene.

The extremely irregular New Mountain sheet is represented by one analysis (table 2, col. 4) of uniform medium-grained diabase (fig. 41) from the lower chilled zone. The specimen was collected from a small talus cone next to Taylor Glacier east of the mouth of Arena Dry Valley and beneath inaccessible cliff exposures of the diabase sheet; the exact outcrop position of the sample is unknown, but analogy with the basement sill suggests a position 15–20 feet above the base. The New Mountain sheet is concordant to bedding in the Beacon Sandstone at this locality, and this analysis accordingly is listed with "sills" in table 2 although the sheet is largely crosscutting in this area. The specimen is a speckled greenish-black and light-gray rock. Labradorite laths are typically euhedral and about 0.5 mm long; the subophitic plates and poorly shaped prisms of clinopyroxene are 0.5–1.5 mm long. Augite and pigeonite are mostly in distinct grains, but many crystals have augitic cores and pigeonitic rims separated by vague, gradational boundaries. Ilmenite is partly in plates, but it and magnetite are mostly anhedral. The rock is but slightly altered.



B

FIGURE 40.—Photomicrographs of gabbro and gabbro pegmatite. *A*, Gabbro with abundant micropegmatite. Analyzed specimen (table 2, col. 1) from pegmatitic zone near top of peneplain sill. Point of arrow (1) marks original corner of large labradorite crystal, (2), now replaced by micropegmatite; end of another labradorite crystal partly replaced by micropegmatite, (3); long prism of augite, (4); partly resorbed short prism of pigeonite, (5). Crossed nicols. *B*, Gabbro pegmatite near top of peneplain sill. Analyzed specimen (table 2, col. 3). Large irregular labradorite crystals photograph gray and show albite-twin lamellae. The individual small areas of clinopyroxene are parts of very large crystals that are so extremely irregular that they are discontinuous in the plane of the section. Parts of one clinopyroxene crystal, (1); elements of another crystal intergrown with it, (2); isolated elements of another large clinopyroxene crystal, (3). The small dark blebs above and left of the number 4 belong to another single crystal. Nicols oblique.

The sills of Pyramid Mountain (table 2, cols. 5–7) are also known only from talus samples. The specimens were collected beside Taylor Glacier at the north foot of Pyramid Mountain a short distance west of the large inclined sheet of gabbro at the east end of the mountain (fig. 6). The samples were chosen to represent the varied textural types present in the talus, but it is not known which of the sills of the mountain are included. Medium-grained diabase and diabasic gabbro compose all the specimens; nearly aphanitic rock, presumably from chilled margins, was seen but not collected. Neither pegmatite nor granophyre was found during a brief search. The specimens are composed of sodic labradorite, ophitic pigeonite and subordinate augite (and almost no hypersthene), and abundant interstitial material.

The first of the specimens (table 2, col. 5) is medium-grained diabasic gabbro. The dominant mineral is unaltered sodic labradorite which occurs in well-shaped tablets mostly about 0.5 mm long showing slight smooth normal zoning. The pyroxene is entirely monoclinic and is largely pigeonite ($+2V=0°–30°$; single grains show large ranges of optic angle) but is partly augite ($+2V$ about 45°). The pyroxene occurs in poorly shaped prisms mostly 1–2 mm long, many of which have ophitic margins enclosing plagioclase. About one-tenth of the pigeonite has been replaced irregularly by a reddish-brown flaky mineral ($2V=0°$) parallel to exsolution lamellae in the pyroxene. There is abundant fine-grained and cryptocrystalline interstitial material. Much of this is irregularly textured micropegmatite laced by tiny laths of oligoclase; both the oligoclase and the alkali feldspar are darkly clouded by secondary minerals. Also abundant interstitially is nontronite (?)—greenish-yellow to olive-green pleochroic material in semiradial aggregates of straight-extinguishing elongate granules. The opaque minerals are largely in the interstitial material and in part have extremely irregular and skeletal shapes.

The specimen of column 6, table 2, is also diabasic gabbro with abundant interstitial material. Plagioclase is slightly zoned sodic labradorite in subhedral tablets commonly 0.5 mm long. Pyroxene is largely pigeonite ($+2V=10°–30°$) and subcalcic augite ($+2V=30°–40°$) and is highly altered to olive-green fine-grained and cryptocrystalline material; crystals are larger but poorer shaped than those of plagioclase. The interstitial material consists of cloudy very fine grained quartz, alkali feldspar, and oligoclase, abundant green saponite (?), and granules of magnetite and and poorly shaped plates of ilmenite.

The third specimen analyzed (table 2, col. 7) from the Pyramid Mountain sills is a medium-grained diabase.

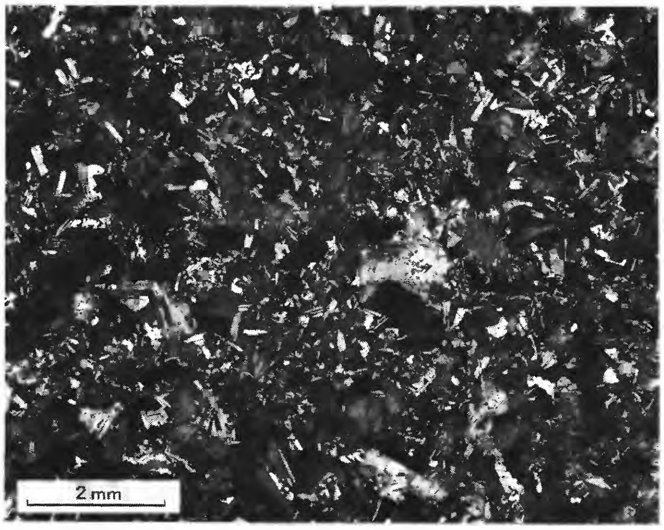


FIGURE 41.—Photomicrograph of diabase from chilled base of New Mountain sheet. Analyzed specimen (table 2, col. 4). Euhedral laths of labradorite are partly enclosed in larger but poorer shaped prisms of augite and pigeonite. Small areas of feathery aspect are vermicular micropegmatite. Crossed nicols.

Like the other two specimens, its dominant mineral is slightly zoned sodic labradorite in 0.5-mm subhedral tablets; unlike the other two, its pyroxene is ophitic. The pyroxene is dominantly pigeonite and subcalcic augite and no orthopyroxene was seen. Plates and prisms of pyroxene are 1–2 mm long; many have good general crystal shapes, but all invariably have ophitic margins; many crystals are extremely irregular and appear in thin section to be a dozen or more disconnected patches interstitial to plagioclase. The pyroxene is irregularly altered to olive-green and reddish-brown material. Several crystals have completely exsolved and highly altered cores which might have originally been orthopyroxene. The interstitial micropegmatite is unclouded, and much of it shows regular micrographic intergrowths. Also present in interstices is abundant saponite(?) and other green crystocrystalline material.

The thick inclined sheet of diabase and gabbro at the east end of the north face of Pyramid Mountain was sampled systematically from its aphanitic lower, east-dipping margin inward for 100 feet. The margin sample (table 2, col. 8) has an unusual composition. The other three samples (table 2, cols. 9–11) show progressive changes inward in most oxides. Textural changes are also marked.

The sheet is chilled within an inch or two of its margin to aphanitic rock (table 2, col. 8) which has a semiconchoidal fracture, greasy luster, and grayish olive-green color. The rock consists largely of a felted haze of pyroxene blades, wholly replaced by secondary minerals, and oligoclase laths. Pyroxene and oligoclase are interlayered in aggregates having radial tendencies; grains are mostly 0.05–0.2 mm long. The oligoclase is little altered, but the pyroxene is entirely pseudomorphed by fine-grained to cryptocrystalline greenish-yellow minerals in aggregates extinguishing parallel to the original pyroxene elongation. Tiny granules of magnetite and tiny ragged plates of ilmenite are scattered throughout but tend to outline oligoclase and pyroxene grains. Also present are sparse microphenocrysts of oligoclase, partly replaced by greenish-yellow material, and of pyroxene; pyroxene phenocrysts are mostly replaced by penninite and saponite(?), but a very few retain unaltered augite.

This unusual marginal rock grades inward within a few inches to rock of normal composition. The rock 1.5 feet from the edge of the sheet is fine-grained normal, medium-gray diabase (table 2, col. 9). Calcic labradorite forms subhedral laths, mostly only 0.05–0.2 mm long and sparse small phenocrysts. Pyroxene is entirely monoclinic, high-2V pigeonite ($+2V=10°–30°$) being more abundant than low-2V augite ($+2V=40°-45°$). Pyroxene occurs in thin plates and irregular grains larger than the labradorite laths and in ophitic relation to them. The abundant mesostasis is very fine grained and consists of quartz, alkali feldspar, saponite(?) and other cryptocrystalline materials, and opaque dust and granules. Most of the scattered pyroxene microphenocrysts are fresh or are altered only marginally. Others are wholly replaced by secondary minerals and might have originally been orthopyroxene.

Twenty feet from the edge of the inclined sheet of Pyramid Mountain, the diabase (table 2, col. 10) is coarse enough to have a finely speckled appearance, plagioclase and pyroxene being separately visible without a hand lens, and to have accordingly a lighter gray color than the nearly aphanitic rock closer to the contact. Most laths of calcic labradorite are about 0.5 mm long. Grains of clinopyroxene, which consists of nearly equal proportions of pigeonite and augite, are larger than those at the margin and are very irregular ophitic plates; many crystals are highly discontinuous in the plane of the section. Rare grains have irregular cores of hypersthene. The pyroxene shows considerable marginal alteration to reddish-brown biotite and subordinate amounts of other brown and green materials. The opaque granules tend to cluster along pyroxene boundaries. The interstitial micropegmatite is very fine grained but is little clouded by either mica or opaque dust.

The rock 100 feet into the inclined sheet is medium-grained gabbro (table 2, col. 11) speckled by 1–3 mm crystals of greenish-black clinopyroxene. Labradorite tablets are mostly only about 0.5 mm long but are thicker than those in the finer grained diabase nearer the edge. The labradorite shows smooth normal zoning. The clinopyroxene is in generally compact tablets having a marginal ophitic relationship with plagioclase. The pyroxene is much altered marginally to biotite (green rather than brown as in the previous specimen), green hornblende, saponite(?), and other green and brown secondary minerals, plus extremely irregular intergrown opaque minerals. The interstitial micropegmatite is largely in the form of single crystals of quartz filling spaces between plagioclase and pyroxene grains and enclosing vermicular intergrowths of alkali feldspar.

Several thin steep diabase dikes were sampled along the north foot of Pyramid Mountain and on the north slopes of West Beacon Heights. The two analyzed specimens (table 2, cols. 12, 13) from the latter locality are petrographically representative of these dikes. Margins of all the dikes are aphanitic, and many have green rock with greasy luster within an inch of their contacts. Dike interiors are of fine-grained diabase that has abundant interstitial material.

The fine-grained diabase whose analysis is given in column 12, table 2, is from the center of a 30-foot dike—one of the thickest of the steep dikes seen. Thin laths of sodic labradorite, mostly near 0.2 mm in length, and sparse microphenocrysts of similar labradorite are partly enclosed in small, highly ophitic grains of pigeonite and subordinate augite, and in abundant interstitial material. The mesostasis consists of cryptocrystalline green minerals and fine-grained quartz and alkali feldspar, clouded prevasively by tiny opaque dendrites.

The specimen of column 13, table 2, was collected from the center of a steep dike only 4 feet thick. The laths of sodic labradorite are of the same size—near 0.2 mm—as those of the preceding specimen, but the clinopyroxene is in smaller grains, many of which are highly altered to cryptocrystalline material. Microphenocrysts of clinopyroxene are common, and of labradorite, uncommon. The fine-grained to cryptocrystalline mesostasis owes its dark color to its abundant opaque granules and dendrites.

CHEMISTRY

By Warren Hamilton, Vertie C. Smith, and Paul S. D. Elmore

Chemical analyses of 13 specimens are given in table 2. Eleven of these specimens were analyzed by rapid colorimetric methods by P. S. D. Elmore, I. H. Barlow, S. D. Botts, and G. W. Chloe, and two were analyzed by standard gravimetric methods by Vertie C. Smith. All fluorine and chlorine determinations are also by Smith. Also listed in the table are spectrographic analyses for minor elements, made by P. R. Barnett and Nancy M. Conklin; these minor-element data were discussed in the preceding section on the basement sill and will not be considered further here.

In major-element composition, most of these specimens vary little from the average of all. The four specimens obviously aberrant relative to this average are the pegmatite of the peneplain sill(table 2, col. 3), the contact specimen of the inclined sheet of Pyramid Mountain (col. 8), and the two thin dikes (cols. 12, 13). The remaining nine specimens vary only within the ranges SiO_2=54.6–56.1; Al_2O_3=14.7–16.3; total iron as FeO=8.3–9.9; MgO=3.6–5.6; CaO=9.3–10.2; Na_2O=1.8–2.4; K_2O=0.9–1.2; and TiO_2=0.6–0.9. This constancy reflects the relatively undifferentiated character of this suite of rocks.

The two thin dikes are aberrant chiefly because of their high ratio of ferric to ferrous iron. This ratio is expressed mineralogically in the high content of magnetite in the mesostasis of these fine-grained rocks. The thinner (table 2, col. 13) of the dikes also has an unusually high ratio of sodium to calcium. Both of the dikes are a trifle richer in potassium than are most of the other specimens. These same peculiarities of high-oxidation state of iron, and high sodium and potassium and low calcium, are shown more strikingly by the very unusual rock (table 2, col. 8) at the aphanitic margin of the thick inclined sheet at the east end of Pyramid Mountain. It accordingly appears likely that the unusual chemistry of these rocks was caused by reactions with the sandstone wallrocks. Metasomatism near the inclined sheet of Pyramid Mountain was described previously, but the materials (hornblende, subordinate biotite, probably oligoclase) added to the sandstone are not obviously the components whose removal from normal diabase would yield the aberrant rocks.

The gabbro pegmatite (table 2, col. 3) of the peneplain sill is similar to the pegmatites of the basement sill (table 1, cols. 8, 9) in having, relative to the undifferentiated rocks, high silica content, low alumina, high ferric and total iron, low calcium, and high titania; but most of these differences are less in rocks of the peneplain sill than those of the basement sill, and are surprisingly small in view of the completely different texture of the pegmatite.

The nine near-average specimens recorded in table 2 are like the chilled-margin specimens of the basement sill in most of their components and chemical relationships. This can be seen in the several diagrams, accompanying the basement-sill discussion, upon which both sets of data are plotted: figure 31 (ferrous, ferric, and total iron, against magnesia); figure 32*A* (ferric iron against total iron); figure 34 (ternary diagram, CaO–Na_2O–K_2O). In absolute contents of potassium and calcium (fig. 32*D*), all of the specimens in table 2 except for the pegmatite, the thinnest dike, and the aberrant contact rock from Pyramid Mountain cluster within or near the chilled-margin group of the basement sill (fig. 32*C*). Other plots, not reproduced here, of the data of table 2 show similar relations to the chilled-margin analyses from Pyramid Mountain and cluster within or near the chilled-margin group of analyses from the basement sill.

The tendency toward correlation of ferric iron and titania is much less pronounced in the intrusions into Beacon Sandstone (fig. 32*F*) than in the basement sill (fig. 32*E*). In the sheets in the Beacon, the bulk of the rocks show only a slight irregular increase of TiO_2 with increasing Fe_2O_3; the pegmatite specimen has high contents of both and is analogous to the pegmatites of the basement sill. The three aberrantly oxidized specimens in the Beacon—the two thin dikes and the contact specimen from the big inclined sheet of Pyramid Mountain—have only average contents of titanium and total iron and plot far from the general trend.

Gunn (1962, p. 827) presented seven analyses of specimens from the peneplain sill at Solitary Rocks, where it is about 1,350 feet thick, which showed that the lower and middle part of the gabbro—the top was not sampled—was more basic than the basal chilled zone. This fact is illustrated by the averages listed below: column 1 is the average, recalculated to 100 percent, of analyses of two specimens at 0 and 35 feet above the base, and column 2 gives the average and range of analyses of five specimens at 100, 350, 500, 600, and 1,090 feet above the base.

	1	2		1	2
SiO_2	55.6	54.3 ±0.3	Na_2O	2.3	2.0 ±0.4
Al_2O_3	16.0	15.3 ±0.3	K_2O	1.1	.9 ±0.1
Fe_2O_3	1.8	1.3 ±0.2	TiO_2	.8	.8 ±0.1
FeO	8.0	7.6 ±0.3	P_2O_5	.1	.07±0.06
MgO	4.2	6.1 ±0.5	MnO	.17	.18±0.02
CaO	8.4	10.0 ±0.5	H_2O	1.5	1.5 ±0.3

The interior of the peneplain sill may, like that of the basement sill, be more mafic than its chilled margins. Silica, ferric and possibly ferrous iron, the alkalis, and phosphorus are less abundant in the gabbro than in the margins, and magnesium and calcium are more abundant. The gabbro samples (averaged in col. 2), however, show no obvious systematic compositional change with vertical position except that P_2O_5 increases progressively from 0.01 percent in the lowest sample to 0.10 percent in the highest. Gunn reported the higher part of the sampled gabbro to have markedly less pyroxene and more micropegmatite, but such a contrast is not apparent from the chemical data.

DIFFERENTIATION

The available data do not suggest that any of the diabase sheets intrusive into the Beacon Sandstone are as highly differentiated as is the basement sill. The peneplain sill, where sampled in its upper part, contains coarse pegmatite which is compositionally less different from the chilled rock than is the pegmatite in the basement sill, and there is no granophyre in the peneplain sill where sampled. Gunn's data also show that there is only slight differentiation in the peneplain sill. The sills of Pyramid Mountain are known only from talus shed from them; no pegmatite, granophyre, or highly magnesian gabbro were recognized. Light-colored layers in the lower sill of Finger Mountain (fig. 5) may be zones of differentiates, but they were not sampled; this sill is part of the same sheet as are the lower sills and inclined sheet of Pyramid Mountain, where no marked differentiates were found in talus.

The analyzed rocks from sheets intrusive into the Beacon Sandstone, except for the pegmatite specimen and the aberrant contact rock of the Pyramid Mountain sheet, are much like the chilled margins of the basement sill in composition:

	Sheets in Beacon Sandstone (table 2, col. A)	*Chilled zones of basement sill (table 1, col. A)*
SiO_2	55.8	55.8
Al_2O_3	15.7	14.8
Fe:		
Fe_2O_3	2.8	2.0
FeO	7.0	7.6
Total as FeO	9.5	9.4
MgO	4.9	5.6
CaO	9.6	10.2
Na_2O	2.2	2.1
K_2O	1.0	.9
TiO_2	.7	.7
P_2O_5	.13	.1
MnO	.18	.2

(Both averages are, as in the tables, recalculated to 100 percent for the oxides listed. Data are in weight percent.) As compared with the basement-sill margins, the sheets in the Beacon are on the average a little higher in aluminum and lower in magnesium and calcium, and higher in the ratio of ferric to ferrous iron but not in total iron.

At least part of this difference is due to the presence of rocks slightly differentiated toward the silicic and alkalic end of the local magmatic series in the suite of samples from the sheets in the Beacon Sandstone. The data demonstrate such differentiation directly only in the thick inclined sheet of Pyramid Mountain. Four samples were taken inward from the lower contact of the sheet (table 2, cols. 8–11). The specimen at the aphanitic margin was discussed previously; it is highly aberrant, presumably because of wallrock reactions. The other three specimens were taken at distances of 1.5, 20, and 100 feet horizontally from the contact and show systematic differentiation. Aluminum, ferric iron, potassium, and titanium increase inward, whereas magnesium and calcium decrease. Sodium and ferrous iron show little change. The interior of the inclined sheet is richer in lower melting components than is the margin. Although the sampling was done near the lower contact of the sheet, these variations are those to be expected in the upper part of the magmatic mass, which suggests that the sampled part of the mass has received light differentiates from below.

That the sills of Pyramid Mountain into which the inclined sheet inflects participated in this differentiation-exchange system is suggested by the slight differences between the compositions of the samples shown in columns 5 and 6 of table 2 and the averages tabulated above. These two samples differ from the average in the same manner as does the interior gabbro of the inclined sheet. The samples were collected a short distance west of the western limit of the inclined sheet from talus derived from the concordant sills.

The pegmatite of the peneplain sill differs from the average rocks in the same direction in most components as do the pegmatites of the basement sills. A similar origin by enrichment in low-melting components is indicated.

The differentiation pattern of the diabase sills and the inclined sheet intrusive into Beacon Sandstone is similar to but less marked than that of the basement sill. A similar mechanism of differentiation by diffusion within the largely liquid interiors of the magmatic masses is proposed: volatiles, notably water, and low-melting components migrated upward as liquids within the melts after crystallization of insulating border zones and were slightly concentrated within the levels sampled. For at least the peneplain sill, as for the basement sill, magma also was probably differentiated as a liquid prior to intrusion, inasmuch as the bulk composition seems to be more mafic than the composition of the chilled margins.

COMPARATIVE PETROLOGY

Enormous sheets of quartz diabase are virtually coextensive with the Beacon Sandstone in most parts of the Transantarctic Mountains. The Beacon is one of the rock units of the famed Gondwana system. Correlative formations of late Paleozoic and early Mesozoic age that are similar in many respects occur in Australia, southern and central Africa, peninsular India, and South America; and in many regions of these continents also, great sheets of quartz diabase of about the same age as those of Antarctica are injected into the clastic rocks. There are many other sheets of comparable mafic rocks elsewhere in the world.

ANTARCTICA

McMURDO SOUND REGION

During expeditions for the Commonwealth Trans-antarctic Expedition and the Geological Survey of New Zealand, Bernard M. Gunn collected specimens from diabase sheets in a large region west of McMurdo Sound, including the area reported on here. Gunn (written commun., 1960–62) generously made his modal and chemical analyses available to me prior to their publication, but much of his material has since been published (Gunn, 1962; Gunn and Warren, 1962). His data for the basement and peneplain sills were summarized in the preceding discussions of those sheets.

Gunn's (1962, p. 836–841) few samples from the upper Escalade sill—a sheet about 1,000 feet thick at Escalade Peak, near 78°40′ S., 159°20′ E., west of upper Skelton Glacier—show that it is similar to the basement sill. The chilled base (col. 1 below) consists of pigeonite-augite-labradorite (An_{60}) diabase with 15 percent interstitial micropegmatite and 5 percent opaque minerals. Two samples (cols. 2, 3) from the lower interior of the sill are of augite-hypersthene-bytownite (An_{80}) noritic gabbro containing less than 1 percent opaques and only a few percent micropegmatite. The mineralogic differences are clearly reflected in the chemical data. Gunn also described a granophyre lens (col. 4), high in the sill, containing 65 percent micropegmatite, 7 percent ferroaugite, 9 percent andesine (An_{40}), 14 percent biotite plus hornblende, and 4 percent opaques. Gunn's (1962, p. 843) analyses follow:

Analyses of samples from upper Escalade sill (Gunn, 1962, p. 843)

	1	2	3	4
Height above base ____ feet	5	300	350	800
Density ____ g per cc	2.89	2.96	2.99	2.73
SiO_2	55.54	51.09	49.81	67.40
Al_2O_3	14.70	20.82	17.71	10.11
Fe_2O_3	3.72	.34	1.02	5.45
FeO	6.81	5.87	7.11	3.86
MgO	4.22	6.76	10.38	.91
CaO	8.91	11.84	10.51	3.86
Na_2O	2.17	1.54	1.61	2.43
K_2O	1.11	.56	.46	2.51
TiO_2	.88	.44	.30	.77
P_2O_5	.09	.09	.05	.23
MnO	.16	.14	.13	.14
H_2O+	.75	.50	.79	1.53
H_2O-	.91	.21	.24	.72
Total	99.97	100.20	100.12	99.92

As in the basement sill, the noritic zone of this upper Escalade sill is markedly more mafic in both bulk and mineral compositions than are the chilled margins. Plagioclase is more calcic and pyroxene more magnesian in the norite and hence must have crystallized from different liquids. (Gunn, however, explained the variation as due to crystal settling.) There is also marked impoverishment of the norite in titania and alkalis, particularly potassium. The granophyre differs from the chilled margin in most components in the opposite manner from the norite.

Gunn (1962, p. 843) gave four analyses but no descriptions of rock from an 800-foot sill in Mount Egerton, near 80°50′ S., 158°30′ E., near Byrd Glacier. The chilled base of the sill has a density of 2.94 and the following composition:

	Percent		Percent
SiO_2	53.41	K_2O	0.81
Al_2O_3	16.53	TiO_2	.67
Fe_2O_3	.88	P_2O_5	.09
FeO	7.73	MnO	.18
MgO	6.61	H_2O	.59
CaO	10.90		
Na_2O	1.78	Total	100.18

Samples from higher in the sill appear from their analyses to be norite (MgO=17 percent) at 200 feet, extremely bytownite-rich gabbro (CaO=16 percent) at 400 feet, and leucogabbro at 600 feet. The compositions suggest that the differentiation contrasts noted in the basement sill are in considerable part present here also.

Gunn (1962, p. 846) gave six analyses of samples from a vertical range of 1,400 feet high in a huge inclined sheet in Detour Nunatak, near 77°10′ S., 161°00′ E., in MacKay Glacier. Beneath the chilled top (col. 1 below) of the sheet, the rocks vary unsystematically with height but are all richly granophyric (26–47 percent micropegmatite); column 2 gives ranges in the five analyses of granophyric rocks.

	1	2
SiO_2	53.43	55 –63
Al_2O_3	15.63	11.6 –17.2
Fe_2O_3	1.53	2.9 – 5.6
FeO	7.64	6.3 – 8.3
MgO	6.42	.8 – 3.7
CaO	10.69	4.5 – 9.4
Na_2O	1.80	2.2 – 2.8
K_2O	.80	1.1 – 2.3
TiO_2	.66	.9 – 1.4
P_2O_5	.07	.08– .21
MnO	.18	.13– .18
H_2O	1.42	1.6 – 1.9
Total	100.27	

The differences here between chilled zone and silicic differentiates are similar to those described previously for the basement sill except that this silicic rock forms a large mass at the top of an inclined sheet of great vertical range. The silicic rock is enriched in silica, ferric iron, alkalis, titanium, and phosphorus and is impoverished in magnesium and calcium.

The great concentration of granophyric components high in this inclined sheet emphasizes the inadvisability of considering differentiation only in terms of single sections across diabase sheets. The differentiation systems are closed only on a scale much larger than that of single sections.

Gunn (1962) presented a total of four analyses of chilled-margin rocks, two of which are much like those of the chilled margins of the basement sill (table 1, col. A,) and like the average of specimens from sheets in the Beacon Sandstone (table 2, col. A). Gunn's other two margin analyses show markedly less silica, sodium, potassium, and titanium, and more magnesium and calcium. Gunn believed the contrast to be due to the existence of two primary magma types in the region, one having an SiO_2 content near 55 percent, the other near 53.5 percent. The averages of Gunn's two analyses in each category, recalculated anhydrous, are presented in columns 3 and 4 of table 3.

The similarity of the low-silica chilled margins to the interior gabbro of the basement sill (table 1, cols. 4–7 and B) is so great that a common origin for the low-silica chilled margins and such interior gabbro is quite possible. I concluded that prior to intrusion the magma forming the basement sill had differentiated as a liquid at its present position and that the first magma injected at the sampled locality was more silicic, alkalic, et cetera, than was the subsequent liquid. A corollary of this conclusion is that the more mafic liquid of the interior should elsewhere also produce chilled margins where it outran the initial silicic magma—and this may be the cause of the low-silica margins found by Gunn. Both low-silica and high-silica margins are virtually nonporphyritic, so that whatever differentiation accounts for their differences was accomplished in the liquid phase.

Prior (1907) described several specimens of diabase and gabbro from near the south side of upper Taylor Glacier. Depot Nunatak, carved entirely from a part of a single sheet more than 500 feet thick (Ferrar, 1907), consists of diabasic gabbro composed largely of colorless augite and plagioclase. One erratic collected at Depot Nunatak contains olivine intergrown with purple titanaugite. A specimen collected from a moraine at the base of Knobhead was not described petrographically but was analyzed chemically (Prior, 1907, p. 137); analytical errors are apparent in the high sum and the very low value reported for ferric iron, and the analysis is not repeated here.

Benson (1916) described specimens of diabase from Antarctica which included several collected in the Taylor Glacier region, although most were collected from moraines on Ross Island and elsewhere. The rocks are composed essentially of calcic plagioclase and pyroxene, chiefly monoclinic; pigeonite ("enstatite-augite") is abundant. Plagioclase (commonly very fresh) is in excess over pyroxene and occurs in thick plates tabular parallel to {010}; it shows progressive zoning that is nowhere oscillatory. Orthopyroxene and clinopyroxene are in distinct crystals in some rocks but are intergrown in others. Orthopyroxene is commonly better shaped than clinopyroxene, but both may be ophitic. Where intergrown by exsolution, orthopyroxene forms the matrix, and small strips of clinopyroxene either are scattered about it or are in two sets optically continuous with it and elongate parallel to the base and vertical to the skeletal clinopyroxene. Pigeonite is the dominant pyroxene; it is commonly singly twinned on {100} and striated parallel to the base, the striations showing as a herringbone effect in grains twinned on {100}. Rhombic pyroxene alters to pale-green fibers parallel to the vertical axis and growing inward from margins and cracks, whereas pigeonite alters to greenish-brown fibers parallel to the base. Dense mats of fibers form by increasing alteration. Ilmenite anhedra and plates are more abundant in aphanitic rocks than in phaneritic ones. Olivine is present in uncommon specimens. The rocks are very similar to those of the diabase sheets of Tasmania.

Benson presented two chemical analyses of erratics from Cape Royds. The specimen analyzed in column 1 below is a porphyritic quartz diabase that contains bronzite, whereas that of column 2 is an aphanitic quartz diabase:

	1	2		1	2
SiO_2	54.17	54.16	TiO_2	0.64	0.70
Al_2O_3	14.90	15.08	P_2O_5	Trace	Trace
Fe_2O_3	1.09	.79	MnO	.15	.14
FeO	7.74	8.08	H_2O+	.53	.36
MgO	10.66	7.14	H_2O-	.17	.20
CaO	8.79	10.57			
Na_2O	1.27	1.60	Total	100.65	99.93
K_2O	.54	1.11			

Despite the high total of the first column, these two analyses appear internally reasonable.

McKelvey and Webb (1959) described a specimen of three-pyroxene (hypersthene, pigeonite, and augite) gabbro collected east of Knobhead, presumably from the thick inclined sheet shown in figure 10 of this report. They, as did Allen and Gibson (1962), mistakenly considered thermal metamorphism of the Beacon Sandstone to be limited to a zone a few inches wide along the contacts with diabase sheets. Webb and McKelvey (1959) reported sampling the basement sill at 200-foot vertical intervals where the sill is 1,400 feet thick in Victoria Dry Valley, but they made only brief mention of the findings. Hypersthene is the dominant pyroxene near the center of the sill. McKelvey and Webb (1962) stated that the peneplain sill in Wright Dry Valley consists largely of three-pyroxene gabbro.

EAST ANTARCTICA

OCCURRENCE OF DIABASE

Diabase sheets occur within the Beacon Sandstone throughout most of the Transantarctic Mountains. Some of the regions in which diabase and sandstone occur together are listed here in order from the Pacific end of the mountain system to the Atlantic end. Erratics of quartz dolerite are common in moraines at Cape Adare, on the coast, near 71° S. (Smith, 1924). Aerial photographs of mountains near 72° S., 160° E. (Weihaupt, 1960), show horizontal sedimentary rocks that contain dark layers which may be thin diabase sills; these rocks have not been studied on the ground. In the vicinity of 74°–75° S., basement rocks lie near the coast; but Beacon Sandstone and diabase form higher inland peaks, and fine-grained amygdaloidal basalt possibly correlative with the diabase sheets has been found in moraines (Smith, 1924). The widespread diabase sheets of the Granite Harbor–McMurdo Sound–Skelton Glacier region, from 77° to 79° S., have been described in other sections of this report. In the vicinity of 80° S., diabase and Beacon lie more than 40 miles inland at altitudes above 8,000 feet; the lowest diabase sill in the north follows the Beacon peneplain, but the lowest one in the south lies above 2,000 feet of Beacon Sandstone (Laird and Skinner, 1961). North of Nimrod Glacier, near lat 82° S., Beacon and diabase occur similarly only in the high inland peaks, at altitudes above 10,000 feet (Laird and Skinner, 1961). Sills also lie in the Beacon between Nimrod and Beardmore Glaciers (Gunn and Walcott, 1962). In the inland mountains along Beardmore Glacier near 85° S., 170° E., several sills appear within the Beacon (Debenham, 1921; Wright, 1923; Smith, 1924). The Queen Maud Range near the Ross Ice Shelf at 85° S., 170° W., displays, above altitudes of 6,000 feet, a section of about 5,000 feet of Beacon Sandstone into which are intruded diabase sills having an aggregate thickness of about 2,000 feet (Gould, 1935). Capping the 3,000–4,000 feet of sandstone and allied sediments of the central range of the Horlick Mountains at 85° S., 114° W., is a diabase sill 600 feet thick (Long, 1962). The Dufek Massif, at 83°30′ S., 51° W., consists of a subhorizontal lopolith of which a

1,500-foot section was studied by Aughenbaugh (1959); this complex may be a particularly thick sheet of the Mesozoic diabase suite. The Whichaway Nunataks, Shackleton Range, and Theron Mountains, in the general region of 80° S., 30° W., contain Beacon Sandstone intruded by sills of diabase which were sampled during the Commonwealth Trans-Antarctic Expedition (P. Jon Stephenson, written commun., 1961). In western Queen Maud Land, between 71° and 75° S., and between 2° E. and 12° W., sandstone and other strata lying above the basement complex are intruded by numerous diabase sills, some more than 600 feet thick. All the sills are locally crosscutting, generally following bedding of thick-bedded rocks but breaking through incompetent fine-grained rocks. Altered andesitic(?) volcanic rocks are interbedded with the higher strata and overlie the sedimentary section (Roots, 1953).

During a geologic reconnaissance of northeastern Victoria Land in November 1964, Dwight F. Crowder and I found Beacon Sandstone and coextensive diabase sills to extend as far northeast as a line trending northwest from 165°00′ E., 72°10′ S., to 163°30′ E., 71°30′ S., and to be considerably faulted and tilted near that limit. An extreme outlier of Beacon alone caps a peak at 168°03′ E., 71°53′ S.

Occurrences of diabase dikes and sills that may be correlative with those in the Beacon Sandstone are not extensive elsewhere in East Antarctica. Rock is exposed around much of the outer coast of East Antarctica and in mountains generally close to the coast, but most of the continental interior between these coastal exposures and the Transantarctic Mountains is deeply buried beneath the ice sheet. The following occurrences are noted in order from the Ross Sea westward around to the Weddell Sea. At Horn Bluff, on the George V Coast near 150° E., sandstone is intruded by a diabase sill whose exposed thickness is 500 feet and whose top is missing (Browne, 1923). Uncommon diabase dikes mostly only a few feet thick are injected into the Precambrian crystalline complexes of the coastal region in the vicinity of 155° E.; a dike specimen yielded a whole-rock potassium-argon age of 170 m.y. (Starik and others, 1959). Several hundred steep dikes of diabase cut Precambrian rocks within an area of 150 square miles near the coast at 75° E., although such dikes are uncommon elsewhere in that region; these dikes may be correlative with the sills in the Beacon Sandstone (Crohn, 1959). Crohn also found fossiliferous Permian sandstone, correlative with the Beacon, near 70° S., 68° E., but no diabase cuts these strata. In the Lützow-Holm Bay region, along the coast between 35° and 40° E., only plutonic and metamorphic rocks are exposed in place, but erratics of basalt indicate inland volcanic fields (Yoshikawa and Toya, 1957). A few thin dikes of diabase cutting gneissic and metamorphic rocks in the mountains near the coast between 10° and 18° E. might be correlative with the diabase sheets in the Beacon (Ravich, 1959).

No exposures of the Beacon Sandstone or of diabase likely to be correlative with those in the Beacon are known anywhere in West Antarctica. Basalt lies upon Lower(?) Jurassic sandstone above the Beacon Sandstone northwest of the area shown in figure 2 (Gunn, 1962; Gunn and Warren, 1962). The section consists of pillow lavas, lava flows, water-laid tuff, and probably volcanic mudflows which, however, were called tillite by Warren (Gunn and Warren, 1962, p. 117). The fresh volcanic rock is microporphyritic pigeonite-augite-labradorite basalt with or without hypersthene. The one analysis of the basalt (Gunn, 1962, p. 846) resembles that of the low-silica rock type of the diabase sheets and suggests genetic and temporal correlation.

During a brief study of the aerial photographs of northern Victoria Land, I found that a high plateau extending from about 72°40′ to 73°30′ S., and from 161° to 164° E., consists wholly of uniformly dark volcanic rocks. These rocks are virtually undeformed and lie above Beacon Sandstone. This volcanic plateau may be formed of quartz basalt correlative with that of the sills in the Beacon elsewhere and thus may be comparable to the Basutoland Plateau of South Africa.

PETROLOGY

Only a little petrologic information has yet been published on the diabase sheets of Antarctica other than those in the McMurdo Sound region. I know of only four published chemical analyses, and these are reproduced below. Column 1 is an analysis of subophitic gabbro from Horn Bluff (Browne, 1923). Browne described the rock as containing 54 percent plagioclase, 33 percent pyroxene, 2 percent opaques, and 11 percent mesotasis. The other three columns are quoted from Stewart (1934a) and are of specimens collected by L. M. Gould in the Queen Maud Range. Stewart gave no petrographic descriptions, but he listed the rocks as diabase (col. 2) containing 57 percent feldspar, 51 percent mafic minerals, and 2 percent quartz; gabbro (col. 3) containing 66 percent feldspar and 34 percent mafics; and "melabasalt" (col. 4), said to contain 42 percent feldspar, 2 percent quartz, and 56 percent mafics. The name "melabasalt" and Stewart's generalized mode for this last rock are, however, incompatible with the chemical analysis, which is of a tholeiite that must have more plagioclase than pyroxene.

	1	2	3	4
SiO_2	53.05	53.64	52.67	52.41
Al_2O_3	16.95	14.56	13.17	15.53
Fe_2O_3	.79	1.81	.74	1.79
FeO	6.69	8.12	6.75	6.64
MgO	6.91	6.14	11.81	8.03
CaO	11.56	10.39	12.01	10.74
Na_2O	2.05	1.87	1.03	1.64
K_2O	.97	.50	.39	.62
TiO_2	.65	.82	.43	.55
P_2O_5	tr	.15	.12	.07
MnO	.07	.17	.17	.14
H_2O+	.49	1.65	.57	1.36
H_2O-	.43	.41	.25	.65
Total	100.61	100.23	100.11	100.17

The rock of column 1 was collected from talus beneath the outcrop of the Horn Bluff sill, so that its position within the sill is unknown. Its subophitic texture probably precludes origin within either chilled zone, for a strongly developed ophitic texture is to be expected in those zones. Comparison of the mode given by Browne (1923) with the modes in the detailed studies of the quanitative mineralogy of Tasmanian diabase sheets by Joplin (1958) and McDougall (1958) suggests that the Horn Bluff specimen probably came from about one-third of the way up in the sill and that its composition demonstrates considerable differentiation. The analysis shows that the Horn Bluff specimen has substantially more aluminum and calcium than have either chilled rocks or all but a few of the known differentiates in the McMurdo Sound region. The modal content of plagioclase is surprisingly low, if these oxides are determined correctly, and analytical errors may account for the discrepancy; the high analytical total indicates erroneously high determinations for some components. The reported values for ferric iron and phosphate are possibly too low, and, as these components are precipitated with aluminum in analysis, low determinations for them would result in erroneously high aluminum values. This analysis should not be incorporated in any chilled-margin averages intended to reflect original magmatic compositions.

Stewart (1934a) did not specify the location within diabase sheets of the specimens whose analyses are given above in columns 2, 3, and 4, but the misnamed "mela-basalt" (col. 4) is presumably from a chilled zone. The chemical composition of the diabase of column 2, and Stewart's generalized mode of it, suggest that it also is relatively little differentiated. The gabbro (col. 3), on the other hand, appears in both mineralogy (56 percent mafic minerals, not divided by Stewart into specific varieties) and chemistry (for example, 12 percent MgO, 0.4 percent K_2O) to be a highly differentiated rock occurring low in a sill. The average of columns 2 and 4 is accordingly listed in column 6 of table 2 as probably approximating a chilled-margin composition, whereas the obvious differentiate of column 3 above is omitted from the average.

Smith (1924) reported that the diabases of the Beardmore Glacier region are quartz bearing and very similar to those of the McMurdo Sound region, but he did not describe them. Fragmentary modes given by Stewart (1934b) apparently indicate that some of the diabase from the Queen Maud Range contains both orthorhombic and monoclinic pyroxenes but that other diabase contains only monoclinic ones. Although the specimens probably include those analyzed (Stewart, 1934a), inconsistencies between his two reports prohibit correlation. Two-pyroxene gabbro was reported by Gunn and Walcott (1962) north of Beardmore Glacier.

In his preliminary report on the geology of western Queen Maud Land, Roots (1953) said that the thicker diabase sheets there are almost invariably differentiated and have thin mafic or ultramafic lower zones, thick central diorite or gabbro, upper zones progressively more feldspathic toward highly feldspathic pegmatite or granophyre. He reported that tops and bottoms are chilled and that the rocks are mostly fresh although locally epidotized.

Eleven chemical analyses have been made of specimens collected by P. Jon Stephenson (written commun., 1961) in the Whichaway Nunataks and Theron Mountains. Stephenson's permission to cite these analyses is gratefully acknowledged. The range of silica content of the specimens is 51.5–56.0 percent. Two chilled-margin specimens from the Theron Mountains are the least silicic of those analyzed and have the average composition, recalculated anhydrous, indicated by column 7 of table 3.

Browne (1923) found the diabase of the sill at Horn Bluff, George V Coast, to consist largely of fresh-zoned plagioclase, mostly labradorite, and pyroxene that is almost entirely monoclinic, both augite and pigeonite being abundant. The pigeonite typically shows undulatory extinction. Pyroxene crystals are tabular parallel to the front pinacoid. The mesostasis consists largely of tiny rods of plagioclase in a background of orthoclase and includes some micropegmatite. Opaque minerals composed only 1–2 percent of the rocks. Some augite grains in a specimen taken 6 feet above the base of the sill contain cores of orthopyroxene. Small fibrous aggregates in the same specimen were thought by Browne to be pseudomorphs after olivine. Browne also described several specimens of quartz diabase collected from moraines in the same region.

The lopolith sampled by Aughenbaugh (1959) is subhorizontally layered and consists largely of labradorite and pyroxene in varying proportions. The pyroxene is mostly augite and orthopyroxene, although pigeonite is probably present also. Small lenses of ultramafic rocks formed largely of spinel and olivine occur throughout the complex. Light-colored layers contain abundant quartz and oligoclase. The section described by Aughenbaugh (1959, p. 177) of about 1,500 feet of the complex shows no obvious upward change in overall composition, so this thickness may be but a small part of a very large mass. The freshness and composition of the rocks permit correlation with the diabase sheets intrusive into the Beacon Sandstone in other ranges in the same region, but no direct evidence for such correlation has been recognized.

MAGMA TYPES

The Tertiary volcanic rocks of Scotland are dominated by silica-saturated basalts on the one hand and by undersaturated basalts on the other. W. Q. Kennedy (for example, 1933) concluded that these are fundamentally different magma types recognizable throughout the world and called them, respectively, the tholeiitic and olivine-basalt magma types. The terms have come into wide use and are employed in this report. It has become increasingly apparent that the dictinction is more semantic than real, for many basaltic provinces are of intermediate character. Basalt forms a broad compositional spectrum within which magma-type assignments are in part quite arbitrary (Green and Poldervaart, 1955; Gilluly, 1955). The terms are nevertheless valuable for splitting basalts, however arbitrarily, into two groups whose investigation has much petrogenetic significance.

The ambiguities in definition of tholeiitic and olivine-basaltic magma types are to some extent brought out by the conflicting average compositions calculated for them by different investigators, among which are those indicated in the tabulation below.

Calculated by	Tholeiite			Olivine basalt	
	W. Q. Kennedy (1933)	Nockolds (1954)	Green and Poldervaart (1955)	W. Q. Kennedy (1933)	Nockolds (1954)
SiO_2	50	51.3	51.0	45	46.1
Al_2O_3	13	14.2	15.6	15	14.8
Fe_2O_3	13	2.9	1.1	13	3.2
FeO		9.1	9.8		8.8
MgO	5	6.4	7.0	8	9.4
CaO	10	10.5	10.5	9	10.8
Na_2O	2.8	2.3	2.2	2.5	2.7
K_2O	1.2	.9	1.0	.5	1.0
TiO_2	----------	2.0	1.4	----------	2.6
P_2O_5	----------	.2	.2	----------	.4
MnO	----------	.2	.2	----------	.2

Contrast between the two assemblages would be increased if averages for quartz-diabase provinces (for example, those of table 3) were incorporated in the tholeiite average, and if analyses from olivine-basalt provinces (for example, the Snake River Plain of southern Idaho, assigned to "Oregonian basalts" by Washington (1922) and probably treated as tholetite by compilers) were excluded from it. Among other changes, this would lower the percentage of alkalis and titanium and increase the percentage of silica in the composite tholeiite. W. Q. Kennedy (1933) erred in considering tholeiite to be richer in potassium than is most olivine basalt.

Tholeiite, loosely defined, was thought by Kennedy to be present exclusively on the continents, whereas olivine basalt was thought to form both in oceans and continents. Tilley (1950), Gilluly (1955), Engel and Engel (1963), and others have shown that, on the contrary, tholeiite occurs in ocean basins as well as on continents. The petrology of an oceanic occurrence of silica-saturated basalt is summarized in a subsequent section because of its significance for petrologic theory.

SUMMARY

The diabase sheets of East Antarctica are of tholeiitic rocks mostly within the silica range 52–56 percent. Labradorite is commonly in excess over pyroxene, which is dominantly monoclinic. Detailed studies suggest that pigeonite is more abundant than augite, and that both are present together in most rocks. Interstitial quartz and alkali feldspar are almost invariably present, opaque minerals are of minor abundance, and olivine is rare. Available chemical analyses cluster about two silica peaks: one at 53–54 percent, the other at 55–56 percent. Differentiation effects are so complex and samples so few that this bimodality may be illusory, and the rocks may actually represent a compositional spectrum. Marked differentiation characterizes the thicker diabase sheets. Even the most mafic rocks commonly contain abundant quartz and alkali feldspar.

Chemical compositions of chilled rocks are summarized in table 3 from data presented in the preceding text and in tables 1 and 2. Three of the averages of chilled (cols. 1, 2, 3) and little-differentiated rocks (col. 2) in the McMurdo Sound region are uniformly high (55.8 percent) in silica and differ little in other components. Their average content of SiO_2 of 56 percent in anhydrous analyses is remarkably high for basaltic rocks.

Contrasted with this high-silica rock type is one a little lower in silica (about 54 percent). It differs correspondingly in other oxides: magnesium is substan-

TABLE 3.—*Average compositions, recalculated to sum 100, of little-differentiated diabase and basalt of Triassic and Jurassic age from Antarctica and other regions*

	Antarctica								Other continents		
	McMurdo Sound					Queen Maud Range	Theron Mountains	Average of 5–7	Tasmania	South Africa	United States
					Average of 1–4						
	1	2	3	4	5	6	7	8	9	10	11
SiO_2	55.8	55.8	56.3	53.9	55.5	54.0	52.9	54.1	53.8	52.2	52.4
Al_2O_3	14.8	15.7	15.3	16.2	15.5	15.3	16.4	15.7	15.5	15.5	14.9
Fe_2O_3	2.0	2.8	3.0	1.2	2.3	1.8	1.4	1.8	.8	1.6	1.5
FeO	7.6	7.0	7.7	7.7	7.5	7.5	7.7	7.6	8.4	9.0	9.0
MgO	5.6	4.9	4.3	6.5	5.3	7.2	7.8	6.8	6.8	7.5	7.5
CaO	10.2	9.6	8.9	10.9	9.9	10.8	9.8	10.2	11.1	10.0	10.5
Na_2O	2.1	2.2	2.2	1.8	2.1	1.8	2.1	2.0	1.7	1.9	2.0
K_2O	.9	1.0	1.1	.8	.9	.6	.7	.8	1.0	.8	.7
TiO_2	.7	.7	.9	.7	.8	.7	.9	.8	.7	1.0	1.1
P_2O_5	.11	.13	.09	.08	.10	.11	.20	.14	.08	.1	.13
MnO	.18	.18	.16	.18	.17	.16	.15	.16	.15	.2	.17

1. Average of four analyses of chilled margins of basement sill, Solitary Dry Valley (col. A, table 1).
2. Average of nine analyses of little-differentiated rocks from sheets intruded into Beacon Sandstone (col. A, table 2).
3. Average of two analyses of high-silica chilled rocks (Bernard M. Gunn, written commun., 1961).
4. Average of two analyses of low-silica chilled rocks (B. M. Gunn, written commun., 1961).
5. Average composition of undifferentiated rocks of McMurdo Sound region.
6. Average of two analyses of probably chilled rocks (Stewart, 1934a).
7. Average of two analyses of chilled rocks from sills (P. Jon Stephenson, written commun., 1961).
8. Average Antarctic chilled diabase.
9. Average composition of chilled diabase (McDougall, 1962, table 7).
10. Average composition of diabase and basalt (Walker and Poldervaart, 1949, table 17, cols. 3–5).
11. Average composition of chilled diabase of eastern United States: average of chilled borders of three sills in Pennsylvania and New Jersey (Hotz, 1953, table 5, cols. 1–5).

tially higher, and calcium less so, and alkalis and titania are lower than in the high-silica type. Columns 4 (McMurdo Sound region) and 6 (Queen Maud Range) illustrate this lower-silica type.

The average of two analyses provided by P. Jon Stephenson of chilled margins of sills in the Theron Mountains is given in column 7 of table 3. This average is lower in silica and higher in magnesia and alumina than any of the other Antarctic averages cited, and it is intermediate in most other components.

Column 8 gives the average of the averages and is as good a tabulation as can now be given of the average composition of Antarctic chilled diabase. As the separate averages vary from place to place about the continent, the overall average probably does not indicate any single magma type. It is nevertheless superior to previously published averages of Antarctic diabase, for these averages have been based in too large a part on a few analyses of highly differentiated rocks.

Too few analyses are available to place confidence in the suggestion, but the data summarized suggest a compositional progression along the trend of the Transantarctic Mountains. Most silicic is the diabase of the McMurdo Sound region (table 3, cols. 1–3). Both north (MacKay Glacier) and south (Mount Egerton) of the McMurdo Sound region, and in the Queen Maud Range farther south, the chilled diabase is less silicic (table 3, cols. 4, 6). Still less silicic is the diabase of the Theron Mountains, 1,000 miles farther toward the Weddell Sea along the mountain system.

The specimens from the George V Coast, described by Browne (1923) are so similar petrographically to rocks from Tasmania (table 3, col. 9) that are described in the literature that it is likely that these two suites are closely similar chemically. Diabase of Tasmania, George V Coast, Queen Maud Range (col. 6), and the regions north and south of McMurdo Sound (col. 4) appear very similar. The chilled diabase of the Theron Mountains (col. 7) is on the other hand closely similar to that of South Africa (col. 10) and Eastern United States (col. 11).

The compositional progression in diabase along the Transantarctic Mountains can thus be suggested to be from high-silica rock in the McMurdo Sound region (in the area of the present report) to intermediate diabase of Tasmanian type farther north in Victoria Land. Southward from McMurdo Sound and beyond the pole to the Weddell Sea, the meager data suggest a progression from high-silica rock through intermediate diabase to more mafic (but still silicic in comparison with most basaltic rocks) diabase of South African type. The diabase nearest Australia on the one hand and South Africa on the other is much like that of those continents. This relationship is consistent with continental drift as postulated by Du Toit (1937) and Carey (1958a) and is another of the many features of Antarctic geology which is perhaps better explained in terms of drift than in terms of stable continents (Hamilton, 1963a).

OTHER CONTINENTS

Great sills of quartz diabase occur in several other parts of the world and are generally intruded, like those of Antarctica, into continental clastic sediments. At least approximately correlative with the sheets intrusive in the Beacon Sandstone in Antarctica are similar sheets in Beacon-like formations in Australia and South Africa. Equivalent lavas are widespread in South Africa and South America. Early Mesozoic quartz diabase and basalt are abundant also in the Eastern United States.

The literature on these and similar tholeiite provinces will not be reviewed in detail here. The petrology of the rocks in these provinces has been summarized by Turner and Verhoogen (1960), Frederick Walker (1958), and many others, including some of the authors whose detailed papers are cited here. Among the papers on the diabase sheets of Tasmania are those by Edwards (1942), Joplin (1958), and McDougall (1958, 1962). The occurrence of the South African sheets is summarized by Du Toit and Haughton (1953), and the petrology of these sheets is described by Walker and Poldervaart (1949). Differentiated diabases of Eastern United States are described by Frederick Walker (1940), Hotz (1953), and others.

Average compositions of chilled-margin rocks in the three provinces just noted are given in table 3 (cols. 9–11). Variations within each province are generally comparable to those within Antarctica, but the highly silicic McMurdo Sound diabase (cols. 1–3) probably is not matched by extensive rocks in the other provinces. The Tasmanian average (col. 9) is almost identical with that of the intermediate diabase of Antarctica (cols. 4, 6) although it has slightly more potassium and its iron is a little less oxidized. The Theron Mountains average (col. 7) is much like that of diabase of South Africa (col. 10) and is practically identical with that of some South African subprovinces. The majority of tholeiite provinces, however, consist largely of rocks less silicic than those of the provinces tabulated.

The reports noted above and many others have established that the general trend of differentiation in tholeiite sheets is chemically much like that of the sills of the McMurdo Sound region. The ternary diagrams of FeO–MgO–(Na_2O+K_2O) given for many tholeiitic provinces by Walker and Poldervaart (1949) and McDougall (1962), for example, display about the same pattern as does figure 33 of this report. The upper parts of tholeiite sheets are typically enriched in silica, ferric iron, alkalis, and titanium relative to the chilled margins, whereas the lower parts are impoverished in these components and enriched in magnesium and to a lesser extent in calcium.

Mineralogic and textural variations within sills are also similar to those of the Antarctic sheets. Such silicic differentiates as are present are concentrated high in the interior of each sill, beneath the upper chilled zone. The bulk of each sill is gabbro. Olivine, if present, is concentrated in the basal part of the interior gabbro. Pyroxene is most abundant and the most magnesian, and plagioclase the most calcic, in the lower part of the interior gabbro. Subophitic textures are typical of the interior gabbro, and plagioclase crystal size generally increases upward within it.

CAUSE OF DIFFERENTIATION

The systematic vertical variation in chemical and mineralogical composition of thick diabase sheets has long been recognized as due to differentiation of initially more uniform magma by factors operating in response to gravity. Components crystallizing at high temperatures are concentrated low in the sills, whereas those crystallizing at low temperatures are concentrated high in the sill. This differentiation has been ascribed largely to the mechanical process of settling of crystals and upward displacement of residual fluid.

Solidification of the interior of a diabase sheet must progress from the bottom upward, although this does not of itself require that the crystallization occur at the bottom of the liquid part of the sheet. The compositional changes are in the direction of progressively lower crystallization temperatures upward. Plagioclase grain size typically increases upward and may thus reflect increasingly hydrous environments of crystallization; if so, then the difference in temperature of crystallization between the lower and upper interior parts of a sill is greater than would be inferred from refractory considerations alone. Extreme silicic and alkalic differentiates are concentrated beneath the upper chilled zone and thus show that the top of the interior mass crystallized last.

Traditional theory has it that crystallization occurs mostly high in the liquid part of the sheet and that the crystals then sink and displace the remaining liquid upward. Such theory is no stronger than the hypothesis of crystal settling and, as is discussed later in this report, is not in accord with thermodynamic considerations. It is more plausible that most crystallization proceeds from the bottom upward and that crystals generally do not move far after forming.

CRYSTAL FRACTIONATION

The olivine-rich zones near the base of some low-silica tholeiites may be explicable in terms of settling of crystals through largely liquid magma, as most petrologists now assume, although Drever (1952) disputes the assumption. Even if the process operates, it can account for only a very small part of the differentiation within olivine-bearing sills and for none within olivine-free ones. Frederick Walker (1940) speculated that the olivine-rich layer low in the Palisade sill of New Jersey formed from olivine crystallized both before and after intrusion of the melt. His (Walker, 1940, table 1) micrometric data show, however, that olivine phenocrysts are the same size (about 0.2 mm) in both chilled margins and olivine layer and that olivine makes up about 2 percent of the chilled margins but only between 0.5 and 0.8 percent of the sill as a whole. Accordingly, it seems probable that any olivine accumulated by settling into the olivine layer was already crystallized in the magma when it was intruded, and that about two-thirds of the olivine crystals in the initial liquid were entirely resorbed.

No olivine has been reported in diabase collected in place in the McMurdo Sound region although olivine was found in glacial erratics of unknown source studied by Prior (1907) and Benson (1916). Olivine is rare in the diabase of Tasmania (Edwards, 1942; McDougall, 1962) but is a minor accessory phenocryst mineral in the chilled borders of many of the sheets of South Africa and Eastern United States (Walker and Poldervaart, 1949; Frederick Walker, 1940). A chilled-margin silica content of about 53 percent (in analyses recalculated anhydrous) is roughly the boundary between these olivine-bearing and olivine-free tholeiites.

That the chief mechanism of differentiation of tholeiite sills is the settling of crystals of early-forming magnesian pyroxene was the conclusion reached by Frederick Walker (1940, 1958), Edwards (1942), Turner and Verhoogen (1960), Gunn (1962), and others. Edwards (1942) and Walker and Poldervaart (1949) suggested that in some instances plagioclase settles.

Textural evidence for early crystallization of pyroxene, as required by the hypothesis of pyroxene settling, is however, generally lacking. The typically subophitic textures of the interior gabbros show that the plagioclase crystallizes no later than the pyroxene. Mainly for this reason, petrologists (for example, Hotz, 1953; Walker and Poldervaart, 1949; and McDougall, 1962) in increasing number have concluded that the primary mechanism of tholeiite differentiation is the upward migration of silicic, alkalic, ferric liquid remaining after crystallization of pyroxene and calcic plagioclase. Filter pressing and other mechanical processes have been suggested as the means by which movement is accomplished.

An hypothesis integrating crystal settling with crystallization sequence was proposed by Jaeger and Joplin (1955), reiterated by Joplin (1958), and partly endorsed by McDougall (1962): pyroxene and plagioclase sink together as clots. To explain the apparent lack of clots in the rocks, they speculated that the clots tend to break up and form uniform precipitates.

Hess (1960) noted that the lack of dimensional orientation of pyroxene in diabase sheets shows that it has not settled gravitationally. He speculated that crystallization in the interior of a diabase sheet proceeds from the bottom upward because convection of magma keeps the hottest materials at the top, and that crystallization is largely accomplished at a sharp interface between largely solid material beneath and largely liquid magma above. Hess further hypothesized that the residual liquid would diffuse upward the small fraction of an inch needed to put it into the main magma and would then be swept convectively to the top of the chamber. McDougall (1962) pointed out that the lack of alinement of mineral grains, which should be brushed out at the top of the crystalline material by the magma flowing along it, is evidence against Hess' conjectures. Another flaw in Hess' hypothesis is that it cannot account for the zoned feldspars which characterize diabase sheets and demonstrate crystallization over considerable temperature ranges. Hess' mechanism requires that crystallization proceed virtually to completion within a very narrow thickness between wholly crystallized and wholly liquid material; this requires in turn that crystallization be virtually isothermal, which has not been the situation.

LIQUID FRACTIONATION

The possibility of liquid fractionation (the term may have been first used by me [Hamilton, 1963c]) as a significant magmatic process has received relatively little attention in the many years since the mutual miscibility of magmas was first demonstrated in the laboratory, but various petrologists have nevertheless explained some rock associations in terms of separation of a liquid into liquids of different compositions. Evans (1914) suggested that as water is more soluble in silicic magma than in mafic magma, separation might occur into water-rich and water-poor fractions. Powers (1932) called upon "limited miscibility" to explain globules in rhyolite. Lindgren (1933) proposed that highly alkaline lavas resulted from the upward streaming of alkalis and volatiles in large magma chambers, the upper parts of which produced the erupted magma. Broderick (1935) concluded that "volatile transfer" of low-melting components was the primary mechanism operating to produce rhyolitic magma from basaltic liquid in the differentiation of the lavas of the Keweenawan of Michigan. Drever (1952) cited evidence to show that many olivine-rich rocks, normally ascribed to settling of olivine crystals, crystallized instead from liquids depleted in silicic liquid by an unspecified process. Drever (1960) considered globules forming a layer high in a picritic intrusion in Greenland to demonstrate separation of one liquid phase from another by immiscibility. Wilshire

(1961) presented evidence for volatile transport of alkalis in an analcite gabbro. Hamilton and Wilshire (1964) suggested that liquid fractionation may be important in most basaltic differentiation. Boone (1962) and Jahns and Tuttle (1963) concluded that liquid fractionation in response to pressure gradients is important in silicic magmas.

Tomkeieff (1937) showed that crystal fractionation could account for only part of the variations in the basalts and diabases of the upper Paleozoic of the Midland Valley of Scotland and concluded that "diffusion differentiation" had been a major process. Diffusion upward in response to pressure gradients of volatile components, including alkalis, resulted in the concentration of alkalis high in magma chambers and their impoverishment low in the chambers. Flett (1932) made a similar argument for liquid fractionation in another British sill.

Other workers have presented thermodynamic explanations of such phenomena. Goranson (1937), Saether (1948), and Verhoogen (1949) recognized that content of water and volatiles a magma must vary with pressure (and hence with depth in the chamber) and with temperature: volatiles will diffuse through a magma chamber to concentrate in the cooler and higher parts. Wahl (1946) argued that the Soret effect (differential diffusion of components in a liquid in response to a thermal gradient) might be highly active in magmas when combined with convection, and he refuted the assertions by N. L. Bowen and others that Soret diffusion is insignificant. Neumann (1948) theorized that a water-rich phase should separate from a crystallizing magma and migrate upward, carrying with it abundant material whose composition would vary with the composition of the residual magma, to form pegmatites and hydrothermal deposits.

G. C. Kennedy (1955) noted that sodium, potassium, and some other components should migrate with the water to the cooler and lower pressure parts of the chamber, and he affirmed Lindgren's theory that alkaline lavas are erupted from the upper parts of magma chambers so differentiated. Kennedy suggested that the eruptive behavior of volcanoes such as Paricutin indicated the action of such a mechanism of concentration of volatiles high in the chamber. Early Paricutin eruptions came from the top of the chamber and were volatile rich and highly explosive; but, during the 9 years of activity of the volcano, its eruptions became progressively poorer in volatiles.

The upward migration of volatiles in response to static pressure differentials was called upon by Dickson (1958) to explain the rise of a batholith by melting of the roof (the melting point of which is lowered by accumulation of volatiles high in the magma chamber) balanced thermally by crystallization low in the chamber, where the solidification temperature is raised by loss of volatiles. Katsui (1962) explained the progression from mafic to felsic eruptions from some Hokkaido calderas thus: "* * * water tended to be concentrated in the apices of the magma column of low pressure and temperature, bringing together alkalis and silica." Separation of phenocryst-poor rhyolites from porphyritic quartz latites and dacites was ascribed by Peterson and Roberts (1962) to similar liquid fractionation plus crystal settling.

Experimental studies show that such processes do operate. The most significant work for its bearing on differentiation is perhaps that of Orville (1963), who demonstrated by both experimental and theoretical thermodynamic methods that the existence of a thermal gradient on a feldspathic liquid will produce concentration gradients such that potassic feldspar is enriched in the cool part and sodic feldspar in the warm part. Other variables complicating the equilibrium are absolute temperature, pressure, bulk composition, and structural state of the crystalline phases; for example, the presence of calcic feldspar components in the liquid increases the concentration gradients of sodium and potassium.

Kennedy and others (1962) found that in the system silica–water, solid silica is in equilibrium with two fluids, one rich in silica and the other rich in water, at high temperature and pressure. Compositions of these fluids converge gradually with increasing pressure until a pressure of about 8,000 bars is reached, beyond which they converge rapidly to merge at 9,500–10,000 bars (which corresponds to a depth on the order of 35 km). An inference to be drawn from this is that a homogeneous magma rising through the pressure region of rapidly converging equilibrium compositions could split into immiscible phases as the pressure decreased; slight changes in pressure and temperature could greatly alter the composition of the phases, and quite different differentiation trends could result. The experimental pressures of the critical region are much too high for application to differentiation within a shallow diabase sheet, but related phenomena perhaps occur. The mechanism might also find application in the explanation of diversification and differentiation of basaltic magmas as they rise through the earth's crust.

Sodium and potassium metasilicate and disilicate are highly soluble in water (although feldspars are relatively insoluble), and the transportation of them by water in a magma will result in a transported liquid proportionately richer in alkalis and silicon and poorer in aluminum than is the original liquid (Morey and Hesselgesser, 1951, 1952; Morey, 1957). Ferrous iron is oxidized under high steam pressure and is then transferred easily as ferric iron (G. C. Kennedy, 1948; Robert C. Newton, oral commun., 1962). Magnesium, calcium, and aluminum have very low solubilities in steam, in contrast to the high solubilities of silicon, potassium, and sodium (Robert C. Newton, oral commun., 1962).

Differential diffusion results in greater fractionation of minor components than of the major components with which they are associated (Wahl, 1946). The typically exponential rather than linear abundance relations between minor and major elements in igneous-rock suites can thus be explained in terms of diffusion fractionation.

Diffusion in response to pressure and temperature gradients within a magma chamber should result in the dilution of magma high in the chamber by upward-migrating liquid richer in water, alkalis (particularly potassium), silicon, and ferric iron than is the original magma, while the magma remaining in the lower part of the chamber consequently becomes richer in magnesium, calcium, and aluminum. The magnitude of this effect cannot yet be assessed quantitatively by thermodynamic means.

The mechanism operates in the direction needed to account for the differentiation of quartz diabase sills such as those described in this report. Minor elements also behave in the manner predicted by such an explanation. (For some elements, notably titanium, laboratory data do not yet seem complete enough to test their conformity to the theory.) Pressure differences within a sill a thousand feet thick would of course be small—far smaller than in the several-miles-high magma chamber suggested by G. C. Kennedy (1955) as one likely to undergo moderate diffusion differentiation. Available data cannot be cited to support quantitatively the explanation that marked differentiation can take place in a chamber so limited in height. Nevertheless, the consistency of the elemental distributions to those predictable in terms of diffusion does suggest that diffusion may have been the major factor operating toward producing magmatic variations.

Interior gabbro and chilled margins of the basement sill described in this report crystallized from different liquids. Pyroxenes are more magnesian and plagioclase is more calcic in the interior, and the bulk composition of the sill is markedly more mafic than the composition of the margins. Differentiation had progressed considerably before intrusion of the magma sheet to its present position, and no evidence available suggests that differentiation was accomplished by fractional crystallization.

The dominant process of differentiation in the basement sill was probably the upward migration due to differential static pressure, and possibly to differential temperature, of much of the most volatile fraction of the liquid interior of the sill before and during intrusion and during crystallization of the gabbro. Relative to the undifferentiated melt, this wetter, migrating melt was much enriched in potassium; moderately enriched in silicon, sodium, ferric iron, and titanium; a little impoverished in ferrous iron; more impoverished in calcium; and much impoverished in magnesium. The migrating material should contain those components which normally crystallize at the lowest temperature from the most hydrous environment and, hence, be much the same as the residual fluids remaining after normal magmatic crystallization of most of the components of a basaltic liquid. This migrating fluid would dilute and displace the basaltic magma previously present high in the liquid interior of the sill.

Gabbroic intrusions may be in general like the basement sill of this report: markedly more mafic in bulk composition than in chilled margins. Smith and Kapp (1963) showed this to be true of the Muskox intrusion in Canada and of some other complexes. Differentiation prior to intrusion at final levels is probably indicated, and liquid fractionation may well be the dominant process.

This fractionation of the liquid interior of the sill would result in its crystallization from the bottom upward. Loss of volatiles in the lower part of the sill would raise the freezing point there to above the temperature of the liquid and would thus force crystallization. (Part of the difference in composition between pyroxene and plagioclase of margins and interior might be explained in such terms.) Addition of volatiles high in the sill would delay crystallization there by lowering the melting point. If heat is lost at a greater rate from the top of the sill than from the base, the resulting temperature gradient would increase the concentration gradients produced by diffusion within the sill. As the liquid would be density stratified, convection would probably be limited to narrow vertical ranges and would not destroy the thermal gradient.

Gunn's (1962) findings can be interpreted similarly. He found that the basement and Mount Egerton sills contain much more magnesian pyroxene and much more calcic plagioclase in the lower interior than in the chilled margins. His data thus also indicate that the lower interior crystallized from a different liquid than did the chilled margins and that fractionation was largely accomplished before appreciable crystallization of the interior. Gunn, however, invoked the conventional explanation of differentiation by gravitational settling of early-crystallizing hypersthene.

Few studies of variations in mineral compositions through diabase sheets have been published. Frederick Walker (1940, figs. 4, 5) found that plagioclase is markedly more calcic in the lower 50 feet or so of the interior of the Palisade sill of New Jersey than it is in the chilled margins; the remainder of the sill is reported to have plagioclase more sodic than that of the margins. Wager and Deer (1939) found the same plagioclase in the lowest exposed layers of the funnel-shaped Skaergaard intrusion of east Greenland as in the chilled margins, and a systematic decrease in anorthite content above those layers; possibly plagioclase more calcic than that of the margins is hidden in the lower part of the funnel. Augite has nearly uniform optical properties in the lower half of the Mount Wellington sill of Tasmania and in the coarser part of the basal chilled zone of that sill, but it becomes progressively richer in iron in the upper half (Edwards, 1942, table 11). Some of these data are favorable and some are unfavorable for the hypothesis of liquid fractionation. Much more information is needed.

Other igneous variations can be explained partly in terms of differentiation of liquid magma. The well-known eruptions of Paricutin volcano, Mexico, provide an example. Wilcox (1954) found a systematic progression in composition of the eruptions, the rocks changing gradually from basaltic olivine andesite (SiO_2=55 percent) in early eruptions to orthopyroxene andesite (SiO_2=60 percent) in the final ones. Aluminum, ferrous iron, magnesium, and calcium decreased, potassium doubled, and ferric iron, sodium, titanium, and phosphorus showed little change. Wilcox demonstrated that crystal fractionation was inadequate to explain this progression and proposed assimilation of granitic wallrocks as its major cause. Migration of components in response to pressure and temperature gradients, the least refractory moving upward within the melt, is another possible explanation. If there was such migration, it proceeded more slowly than did the migration of water; on the basis of G. C. Kennedy's (1955) reasoning, water was concentrated at the top of the chamber by the time of the initial eruptions, whereas potassium was lowest in the initial lavas but highest in the final ones. Progressive liquid fractionation in the chamber during the period of eruptive activity is permitted by the data, the final eruptions being the most silicic and potassic because they represent the longest period of accumulation of upward-migrating materials.

Differentiation by liquid fractionation provides a mechanism for the derivation of rhyolitic magmas in bimodal volcanic provinces of basalt and rhyolite, such as the Keweenawan (Precambrian) of the Lake Superior region, the British-Arctic Cenozoic province, and the Snake River–Yellowstone province (Pliocene and Quaternary) of Idaho and Wyoming. The rhyolites of such provinces differ markedly from the rhyolites of andesitic provinces. Whereas the andesitic associations consist of basalt, andesite, dacite, and rhyolite, have a broad frequency-distribution peak in andesite, and have rhyolite as only the end member of a compositional spectrum, the basalt-and-rhyolite provinces have silicic rocks of limited—remarkably limited in some places—compositional range. The andesite-association rhyolites are richly aluminous and typically carry hornblende and biotite; the basalt-association rhyolites are low in aluminum and generally lack aluminous accessory minerals, carrying instead clinopyroxene or even fayalite. These and other characteristics of the basalt-associated rhyolites suggest that they have differentiated from basaltic magmas. I have noted some of these features elsewhere (Hamilton, 1960b). The lack of mafic cumulate lavas—that is, rocks interpretable as crystal cumulates complementary to rhyolite magma—in the basalt-and-rhyolite provinces argues against the possibility of fractionation by crystallization processes, as Broderick (1935) emphasized for the Lake Superior region.

The coexistence of rhyolite and basalt magmas in single magma chambers is difficult to explain by any terms other than liquid fractionation. An example of such an occurrence is the Island Park caldera (Hamilton, 1965), in the eastern Snake River Plain of Idaho. A circular mass, 18 miles in diameter, of a rhyolite shield built during Quaternary time sank into the underlying magma chamber. During the sinking, first rhyolite, then basalt and rhyolite, and then basalt alone were erupted about the the caldera rim and from numerous vents interspersed within the caldera: rhyolite magma apparently overlay basalt magma in a single large magma chamber.

Liquid fractionation of basaltic magma also seems the best explanation of the volcanic assemblage of Iceland. The exposed rocks of Iceland are entirely volcanic. These were long thought to rest upon a platform of continental rocks representing either a foundered North Atlantic continent or a plate of continental structure sundered by continental drift. However, geophysical work (Bath, 1960; Einarsson, 1960; Eysteinn Tryggvason, 1962) shows that no crustal layers of rocks in which seismic-wave velocities are appropriate for continental materials are present beneath the lavas. Only basaltic rocks seem to be present above the Mohorovicic discontinuity, which is at a depth of 25–30 km. The lower Tertiary succession of eastern Iceland contains about 85 percent basalt (tholeiite> olivine basalt> bytownite porphyry basalt), 3 percent andesite, and 8 percent dacite and rhyolite (G. P. L. Walker, 1958). One rhyolite tuff having a volume of nearly 1 cubic mile contains ubiquitous bubbles of basalt that make up about 2 percent of the rock and prove simultaneous eruption of liquid basalt and liquid rhyolite from the same vent (G. P. L. Walker, 1962). Composite lava flows of rhyolite and basalt, extruded simultaneously from single vents, are also known (Gibson and Walker, 1963). The Quaternary succession of central Iceland consists of about 80 percent low-olivine low-alkali basalt and 20 percent rhyolite that has relatively high titanium content and a relatively high ratio of alkalis to alumina (Hoppe, 1938; Tomas Tryggvason, 1943; Thorarinsson, 1960). Fissure eruptions are basaltic, but stratovolcanoes erupt both basaltic and rhyolitic rocks; silica content increases directly with the duration of the preceding dormant period of the volcano, and differentiation of rhyolite within basaltic magma chambers is obviously indicated (Thorarinsson, 1962).

Iceland thus is a petrographic province of bimodal volcanism in which 10–20 percent of the rocks are rhyolitic and the remainder are basaltic. The dominant basalt is intermediate in composition between typical tholeiite and olivine basalt: it has intermediate silica content but has the low content of alkalis and titania characteristic of tholeiite. The silicic rocks resemble differentiates of basaltic magmas known elsewhere (Hamilton, 1960b) in their bimodal relation to basalt, generally limited compositional range, and low alumina and high titania contents. This suite has been produced in an oceanic structural environment. There appears to be no support here for the assertion frequently found in the literature (for example, Hess, 1960) that at most negligible quantities of silicic rocks can be produced from basaltic magma without the assimilation of continental granitic rocks in that magma. A contrary conclusion appears justifiable: given oceanic basaltic volcanism far more extensive than is represented by the typical oceanic-island volcanoes, silicic differentiates can form in large quantity.

The slight variations in the voluminous "primitive" semitholeiitic basalts of the Hawaiian Islands have been explained mostly in terms of the settling of large quantities of crystals of olivine, clinopyroxene, orthopyroxene, and plagioclase in varying combinations (Macdonald, 1949a,b; Tilley, 1960, 1960b; Powers, 1955). Among the primitive lavas, however, both those hypothesized to have been enriched by settled crystals and those hypothesized to have lost crystals are generally lacking in phenocrysts other than microscopic ones which show by their lack of complex zoning or reaction that their history has been simple. Other obstacles to the theory of dominance of crystal fractionation are that inordinately large amounts of initial magma material must be removed in crystalline form while leaving behind residual magma not greatly different from the original composition, and that the proportions of different minerals removed bears little relation to either proportions or crystallization sequences of the same minerals in the rocks. Macdonald and Katsura (1961) found wholly liquid lava that contained 10 percent normative olivine and that can not be explained in terms of crystal settling unless marked superheat is involved.

Tilley (1960a) presented eight analyses of tholeiitic basalt from the 1955 flank eruption of Kilauea and demonstrated systematic changes with time in nearly all components during the three-month eruptive period. The first eruption was markedly higher than the last eruption in potassium, titanium, and phosphorus, moderately higher in total iron and sodium, and slightly higher in silica; but it was moderately lower in calcium and markedly lower in magnesium. (Aluminum remained nearly constant.) Intermediate eruptions were systematically intermediate in composition. As the highest lava in the magma column was erupted first, the chronologic sequence is also a sequence of position in the initial magma chamber, and the changes indicate that the magma was vertically graded in composition. The most obvious mineralogic change during the eruption was the progressive increase in the abundance of olivine, but the changes in bulk composition were such that they cannot be explained in terms of olivine movement. Tilley (1960b) called on the settling of large quantities of phenocrysts of plagioclase and clinopyroxene from the upper (early) magma into the lower (later) magma; but the late rocks contain virtually no phenocrysts (Howard A. Powers, oral commun. 1963), so that the process is entirely hypothetical.

The changes in composition within the 1955 magma column are similar to those ascribed in this report on both petrologic and thermodynamic grounds largely to a mechanism of liquid fractionation by which a graded composition results from migration of components in response to pressure and temperature gradients. The same mechanism is accordingly suggested to be the dominant means of differentiation within the Hawaiian tholeiites. Had the 1955 Hawaiian magma produced a sill rather than a flow, its composition would have been analogous to that of the basement sill of the present report in that the first-intruded chilled margins would be less mafic than was the later intruded bulk of the sill. Such contrasts may typify basaltic sills.

The alkaline, silica-undersaturated olivine basalts and associated varied alkaline rocks of the Hawaiian Islands form thin veneers atop the tholeiite shields, are erupted in small volumes at widely spaced localities, and are interbedded with the upper tholeiites (Tilley, 1950; Powers, 1955; Macdonald and Katsura, 1962). These alkaline rocks represent the declining stages of volcanism and are best explained in terms of stagnation, with resultant strong differentiation or contamination, of tholeiitic magma.

Yoder and Tilley (1962) and others have hypothesized that the trifling volumes of alkaline rocks were produced from very different parent magmas generated in a different part of the mantle than were the tholeiites. This speculation seems contradicted by the time and volume relationships of the rocks, by the strong differentiation which they universally show, and by the difficulty of explaining simultaneously such compositional peculiarities as the combination of high alkalis with low silica and high magnesium of the alkaline rocks. The Yoder-Tilley speculation is based upon the assumption that the only differentiation mechanism operative in basaltic magma is crystal fractionation; since the other petrologists noted above had demonstrated quantitatively that the Hawaiian alkaline rocks cannot be produced by separation of crystals from the tholeiite magma, Yoder and Tilley then concluded that some other magma must have produced the alkaline rocks. The Yoder-Tilley mechanism would account for the observed difference in alkali content between the two basaltic magma types, but the silica change would be opposite to that required; hence their mechanism cannot operate as postulated.

The Hawaiian alkaline rocks contain abundant phenocrysts that have a complex history, and crystal settling is shown within many lava flows. Crystal-cumulate nodules (lacking in primitive lavas) are numerous in many of the alkaline flows and even more so in associated pyroclastics (Powers, 1955). These magmas are clearly fractionated in part by crystal settling. Relative to the semitholeiitic primitive basalt, the declining-phase basalt is enriched in alkalis (particularly potassium), titanium, and magnesium and has more highly oxidized iron but is impoverished in silica. The changes in abundance of alkalis, titanium, and iron suggest that liquid fractionation has somehow operated here to produce much of the differentiation of alkaline basalt from semitholeiitic basalt. Macdonald and Katsura (1961, 1962) drew a similar inference.

The major Hawaiian differentiate, alkaline basalt, is extremely different from the rhyolite of Iceland, but this may be due to the different compositions of the primitive basalts. The Hawaiian primitive lava is richer in silica than is the modern Icelandic basalt, but it also is conspicuously richer in magnesium and poorer in aluminum and calcium. The different ionic associations in the original melts caused by these differences could perhaps result in the migration of different groups of elements. Other factors, such as oxidation ratios of iron, might contribute to differentiation trends.

Alkaline olivine basalts have long been considered to be typical of oceanic volcanism. An obvious contrary inference to be drawn from Hawaii and Iceland is that the well-known alkaline rocks of the ocean islands are only late-stage differentiates that form veneers over far more extensive silica-saturated basalt. Engel and Engel (1963) found tholeiite to dominate the lavas of the floor of the northeastern Pacific basin. Tholeiite may be the dominant magma type both in oceans and in continents.

REFERENCES CITED

Allen, A. D., and Gibson, G. W., 1962, Outline of the geology of the Victoria Valley region, pt. 6 *of* Geological investigations in southern Victoria Land, Antarctica; New Zealand Jour. Geology and Geophysics, v. 5, no. 2, p. 234–242.

Aughenbaugh, N. B., 1959, Preliminary report on the geology of the Dufek Massif: Ohio State Univ., USNC-IGY Antarctic glaciological data, Field Work 1957–58, Rept. 1, p. 164–208.

Balham, R. W., 1960, Immediate report on the Victoria University of Wellington Antarctic Expedition (1959–60): Wellington, New Zealand, Victoria Univ., 15 p. (mimeographed).

Bath, Markus, 1960, Crustal structure of Iceland: Jour. Geophys. Research, v. 65, no. 6, p. 1793–1807.

Benson, W. N., 1916, Report on the petrology of the dolerites collected by the British Antarctic expedition, 1907–1909: British Antarctic Exped. 1907–09, Sci. Invs. Repts., Geology, v. 2, pt. 9, p. 153–160.

Bentley, C. R., Crary, A. P., Ostenso, N. A., and Thiel, E. C., 1960, Structure of West Antarctica: Science, v. 131, p. 131–136.

Blundell, D. J., and Stephenson, P. J., 1959, Paleomagnetism of some dolerite intrusions from the Theron Mountains and Whichaway Nunataks, Antarctica: Nature, v. 184, p. 1860.

Boone, G. M., 1962, Potassic feldspar enrichment in magma: Origin of syenite in Deboullie district, northern Maine: Geol. Soc. America Bull., v. 73, no. 12, p. 1451–1476.

Broderick, T. M., 1935, Differentiation in lavas of the Michigan Keweenawan: Geol. Soc. America Bull., v. 46, no. 4, p. 503–558.

Browne, W. R., 1923, The dolerites of King George Land and Adelie Land: Australasian Antarctic Exped. 1911–14, Sci. Repts., Geology, ser. A., v. 3, pt. 3, p. 245–258.

Bull, C., 1962, Development of ice-free valleys in South Victoria Land, Antarctica [abs.]: Geol. Soc. America Spec. Paper 68, p. 309–310.

Bull, C., and Irving, E. I., 1960a, Palaeomagnetism in Antarctica: Nature, v. 185, no. 4716, p. 834–835.

——— 1960b, The palaeomagnetism of some hypabyssal intrusive rocks from south Victoria Land, Antarctica: Royal Astron. Soc. Geophys. Jour., v. 3, no. 2, p. 211–224.

Carey, S. W., 1958a, A tectonic approach to continental drift, *in* Carey, S. W., ed., Continental drift—a symposium: Hobart, Australia, Tasmania Univ., p. 177–355.

Carey, S. W., 1958b, The isostrat, a new technique for the analysis of the structure of the Tasmanian dolerite, *in* Carey, S. W., ed., Dolerite—a symposium: Hobart, Australia, Tasmania Univ., p. 130–164.

Clark, R. H., 1960, Geological work in Antarctic dry valleys: Internat. Geol. Cong., 21st, Norden 1960, Rept., pt. 21, p. 105–109.

Cox, Allan, and Doell, R. R., 1960, Review of paleomagnetism: Geol. Soc. America Bull., v. 71, no. 6, p. 645–768.

Crary, A. P., 1959, Antarctica: Am. Geophys. Union Trans., v. 40, no. 4, p. 331–339.

Crohn, P. W., 1959, A contribution to the geology and glaciology of the western part of Australian Antarctic Territory: Australian Natl. Antarctic Research Expeds. Repts., ser. A, v. 3, 103 p.

David, T. W. E., and Priestley, R. E., 1914, Reports on the scientific investigations, glaciology, physiography, stratigraphy, and tectonic geology of South Victoria Land, British Antarctic Expedition 1907–1909: London, W. Heinemann, 319 p.

Debenham, Frank, 1921, The sandstone, etc., of the McMurdo Sound, Terra Nova Bay, and Beardmore Glacier regions: British Antarctic ("Terra Nova") Exped. 1910, Nat. History Rept., Geology, v. 1, no. 4a, p. 103–119.

Dickson, F. W., 1958, Zone melting as a mechanism of intrusion—a possible solution of the room and superheat problems [abs.]: Am. Geophys. Union Trans., v. 39, no. 3, p. 513.

Drever, H. I., 1952, The origin of some ultramafic rocks—a preliminary survey of the evidence for and against gravitative accumulation of olivine: Dansk Geol. Foren. Medd., v. 12, no. 2, p. 227–230.

——— 1960, Immiscibility in the picritic intrusion at Igdlorssuit, West Greenland: Internat. Geol. Cong., 21st, Norden 1960, Rept., pt. 13, p. 47–58.

Du Toit, A. L., 1937, Our wandering continents; an hypothesis of continental drifting: Edinburgh, Oliver and Boyd, 366 p.

Du Toit, A. L., and Haughton, S. H., 1953, The geology of South Africa: New York, Hafner, 611 p.

Edwards, A. B., 1942, Differentiation of the dolerites of Tasmania: Jour. Geology, v. 50, p. 451–480, 579–610.

Einarsson, Trausti, 1960, The plateau basalt areas in Iceland, *in* Askelsson, J., and others, On the geology and geophysics of Iceland: Internat. Geol. Cong., 21st, Norden 1960, Guide A2, p. 5–20.

Engel, C. E., and Engel, A. E. J., 1963, Basalts dredged from the northeastern Pacific Ocean: Science, v. 140, no. 3573, p. 1321–1324.

Evans, J. W., 1914, [Untitled discussion] *in* Pt. 2, Discussion sur la différentiation dans les magmas ignés [Discussion on diffrentiation in igneous magmas]: 12th Internat. Geol. Cong., Comptes Rendus, p. 248–249.

Ferrar, H. T., 1907, Report on the field geology of the region explored during the "Discovery" Antarctic Expedition, 1901–04: London, Natl. Antarctic Exped., Nat. History, v. 1, Geology, p. 1–100.

——— 1925, The geological history of Ross Dependency: New Zealand Jour. Sci., v. 7, p. 354–361.

Flett, J. S., 1932, The Stankards sill: Great Britain Geol. Survey Progress Rept., 1931, pt. 2, p. 141–156.

Gibson, I. L., and Walker, G. P. L., 1963, Some composite rhyolite/basalt lavas and related composite dykes in eastern Iceland: Geol. Assoc. London proc., v. 74, pt. 3, p. 301–318.

Gilluly, James, 1955, Geologic contrasts between continents and ocean basins, *in* Poldervaart, Arie, ed., Crust of the earth—a symposium: Geol. Soc. America Spec. Paper 62, p. 7–18.

Goranson, R. W., 1937, Silicate-water systems—the "osmotic pressure" of silicate melts: Am. Mineralogist, v. 22, no. 5, p. 485–490.

Gould, L. M., 1935, Structure of Queen Maud Mountains, Antarctica: Geol. Soc. America Bull., v. 46, no. 6. p. 973–984.

Green, Jack, and Poldervaart, Arie, 1955, Some basaltic provinces: Geochim. et Cosmochim. Acta, v. 7, nos. 3–4, p. 177–188.

Gunn, B. M., 1962, Differentiation in Ferrar dolerites, Antarctica: New Zealand Jour. Geology and Geophysics, v. 5, no. 5, p. 820–863.

Gunn, B. M., and Walcott, R. I., 1962, The geology of the Mt. Markham region, Ross Dependency, Antarctica: New Zealand Jour. Geology and Geophysics, v. 5, p. 407–426.

Gunn, B. M., and Warren, Guyon, 1962, Geology of Victoria Land between the Mawson and Mulock Glaciers, Antarctica: New Zealand Geol. Survey Bull. 71, 157 p.

Hamilton, Warren, 1960a, New interpretation of Antarctic tectonics, *in* Short papers in the geological sciences: U.S. Geol. Survey Prof. Paper 400–B, p. B379–B380.

——— 1960b, Silicic diffentiates of lopoliths: Internat. Geol. Cong., 21st, Norden 1960, Rept. pt. 13, p. 59–67.

——— 1961, Petrochemistry of probable Paleozoic granitic rocks from the Ross Sea region, Antarctica, *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–C, p. C209–C212.

——— 1963a, Antarctic tectonics and continental drift, *in* Munyan, A. C., ed., Paleontological and mineralogical aspects of continental drift: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 10, p. 74–93.

——— 1963b, Tectonics of Antarctica, *in* Childs, O. M., ed., The Backbone of the Americas: Am. Assoc. Petroleum Geologists Mem. 2, p. 4–15.

——— 1963c, Diabase sheets differentiated by liquid fractionation, Taylor Glacier region, Antarctica [abs.]: Sci. Comm. Antarctic Resources Bull., no. 15, p. 275–276.

——— 1964, Diabase sheets differentiated by liquid fractionation, Taylor Glacier region, South Victoria Land [Antarctica] *in* Adie, R. J., ed., Antarctic geology: SCAR Cape Town Symposium of Antarctic Geology.

——— 1965, Geology and petrogenesis of the Island Park caldera of rhyolite and basalt, eastern Idaho; U.S. Geol. Survey Prof. Paper 504–C. (In press.)

Hamilton, Warren, and Hayes, P. T., 1960, Geology of Taylor Glacier–Taylor Dry Valley region, South Victoria Land, Antarctica, *in* Short papers in the geological sciences: U.S. Geol. Survey Prof. Paper 400–B, p. B376–B378.

——— 1963, Type section of the Beacon Sandstone of Antarctica: U.S. Geol. Survey Prof. Paper 456–A, 18 p.

Hamilton, Warren, and Wilshire, H. G., 1964, Liquid fractionation of basaltic magma [abs.]: Rocky Mountain Sec., Geol. Soc. America, Program 1964 Ann. Mtg., p. 25.

Hess, H. H., 1960, Stillwater igneous complex, Montana: Geol. Soc. America Mem. 80, 230 p.

Hoppe, H. J., 1938, Chemische und mikroskopische Untersuchungen an isländischen Gesteinen [Chemical and microscopic studies of Icelandic rocks]: Chemie der Erde (Linck), v. 11, no. 4, p. 457–479.

Hotz, P. E., 1953, Petrology of granophyre in diabase near Dillsburg, Pennsylvania: Geol. Soc. America Bull., v. 64, no. 6, p. 675–704.

Jaeger, J. C., 1957, The temperature in the neighborhood of a cooling intrusive sheet: Am. Jour. Sci., v. 255, no. 4, p. 306–318.

Jaeger, J. C., and Joplin, G. A., 1955, Rock magnetism and the differentiation of dolerite sills: Geol. Soc. Australia Jour., v. 2, p. 1–19.

Jahns, R. H., and Tuttle, O. F., 1963, Layered pegmatite-aplite intrusives: Mineral. Soc. America Spec. Paper 1, p. 78–92.

Joplin, G. A., 1958, The problem of the quatz dolerites—some significant facts concerning mineral volume, grain size, and fabric, *in* Carey, S. W., ed., Dolerite—a symposium: Hobart, Australia, Tasmania Univ., p. 38–51.

Katsui, Yoshio, 1962, Evolution and magmatic history of some Krakatoan calderas in Hokkaido, Japan [abs.]: Internat. Symposium Volcanology, Tokyo, Abstracts, p. 25–26.

Kennedy, G. C., 1948, Equilibrium between volatiles and iron oxides in igneous rocks: Am. Jour. Sci., v. 246, no. 9, p. 529–549.

——— 1955, Some aspects of the role of water in rock melts, *in* Poldervaart, Arie., ed., Crust of the Earth—a symposium: Geol. Soc. America Spec. Paper 62, p. 489–503.

Kennedy, G. C., Wasserburg, G. J., Heard, H. C., and Newton, R. C., 1962, The upper three-phase region in the system SiO_2–H_2O: Am. Jour. Sci., v. 260, p. 501–521.

Kennedy, W. Q., 1933, Trends of differentiation in basaltic magmas: Am. Jour. Sci., 5th ser., v. 25, no. 147, p. 239–256.

Laird, M. G., and Skinner, D. N. B., 1961, Antarctic fieldwork, summer 1960–61—Geological reconnaissance in the Nimrod Glacier–Byrd Glacier area: Geol. Soc. New Zealand Newsletter, no. 10, p. 9–10.

Lindgren, Waldemar, 1933, Differentiation and ore deposition, Cordilleran region of the United States, *in* Ore deposits of the Western States (Lindgren volume): Am. Inst. Mining Metall. Engineers, p. 152–180.

Long, W. E., 1962, Sedimentary rocks of the Buckeye Range, Horlick Mountains, Antarctica: Science, v. 136, no. 3513, p. 319–321.

Macdonald, G. A., 1949a, Hawaiian petrographic province: Geol. Soc. America Bull., v. 60, no. 10, p. 1541–1595.

——— 1949b, Petrography of the island of Hawaii: U.S. Geol. Survey Prof. Paper 214–D, p. 51–96.

Macdonald, G. A., and Katsura, Takashi, 1961, Variations in the lava of the 1959 eruption of Kilauea Iki: Pacific Sci., v. 15, no. 3, p. 358–369.

——— 1962, Relationship of petrographic suites in Hawaii, *in* Crust of the Pacific Basin: Am. Geophys. Union Geophys. Mono 6, p. 187–195.

McDougall, Ian, 1958, A note on the petrography of the Great Lake dolerite sill, *in* Carey, S. W., ed., Dolerite—a symposium: Hobart, Australia, Tasmania Univ., p. 52–60.

——— 1961, Determination of the age of a basic igneous intrusion by the potassium-argon method: Nature, v. 190, no. 4782, p. 1184–1186.

——— 1962, Differentiation of the Tasmanian dolerites—Red Hill dolerite-granophyre association: Geol. Soc. America Bull., v. 73, no. 3, p. 279–316.

——— 1963, Potassium-argon age measurements on dolerites from Antarctica and South Africa: Jour. Geophys. Research, v. 68, no. 5, p. 1535–1545.

McKelvey, B. C., and Webb, P. N., 1959, Geology of upper Taylor Glacier region, Pt. 2 *of* Geological investigations in southern Victoria Land, Antarctica: New Zealand Jour. Geology and Geophysics, v. 2, no. 4, p. 718–728.

McKelvey, B. C., and Webb, P. N., 1962, Geology of Wright Valley, Pt. 3 *of* Geological investigations in southern Victoria Land, Antarctica: New Zealand Jour. Geology and Geophysics, v. 5, no. 1, p. 143–162.

Morey, G. W., 1957, The solubility of solids in gases: Econ. Geology, v. 52, no. 3, p. 225–251.

Morey, G. W., and Hesselgesser, J. M., 1951, The solubility of some minerals in superheated steam at high pressures: Econ. Geology, v. 46, no. 8, p. 821–835.

——— 1952, The system H_2O–Na_2O–SiO_2 at 400°C: (Bowen volume), Am. Jour. Sci., pt. 2, p. 343–371.

Neumann, Henrich, 1948, On hydrothermal differentiation: Econ. Geology, v. 43, no. 2, p. 77–83.

Nichols, R. L., 1961, Multiple glaciation in the Wright Valley, McMurdo Sound, Antarctica [abs.]: Pacific Sci. Cong., 10th, Honolulu 1961, Abstracts of symposium papers, p. 317.

Nockolds, S. R., 1954, Average chemical compositions of some igneous rocks: Geol. Soc. America Bull., v. 65, no. 10, p. 1007–1032.

Orville, P. M., 1963, Alkali ion exchange between vapor and feldspar phases: Am. Jour. Sci., v. 261, no. 3, p. 201–237.

Peterson, D. W., and Roberts, R. J., 1962, Relations between crystal content of welded tuffs and the chemical and magnetic composition [abs.]: Internat. Symposium Volcanology, Tokyo, Abstracts, p. 59–60.

Péwé, T. L., 1960, Multiple glaciation in the McMurdo Sound region, Antarctica—a progress report: Jour. Geology, v. 68, no. 5, p. 498–514.

Powers, H. A., 1932, The lavas of the Modoc Lava Bed quadrangle, California: Am. Mineralogist, v. 17, no. 7, p. 253–294.

——— 1955, Composition and origin of basaltic magma of the Hawaiian Islands: Geochim. et Cosmochim. Acta, v. 7, nos. 1–2, p. 77–107.

Prior, G. T., 1907, Report on the rock-specimens collected during the "Discovery" Antarctic Expedition, 1901–04: London, Natl. Antarctic Exped., Nat. History, v. 1, Geology, p. 101–140.

Ravich, M. G., 1959, Kratkie svedeniya o geologicheskom stroenii vostochnoi chasti gor na Zemle Korolevy Mod v vostochnoi Antarktide: Akad. Nauk SSSR Doklady, v. 128, no. 1, p. 152–155. (1960, ***English translation entitled*** "A brief report on the geologic structure of the eastern part of the mountains in Queen Maud Land in eastern Antarctica," *in* Proceedings of the Academy of Sciences of the U.S.S.R.: Am. Geol. Inst., v. 128, nos. 1–6, p. 848–850.).

Roots, E. F., 1953, Preliminary note on the geology of western Dronning Maud Land: Norsk Geol. Tidsskr., v. 32, no. 1, p. 18–34.

Saether, Egil, 1948, On the genesis of peralkaline rock provinces: Internat. Geol. Cong., 18th, England, 1960, Rept., pt. 2, sec. A, p. 123–130.

Shapiro, Leonard, and Brannock, W. W., 1956, Rapid analysis of silicate rocks: U.S. Geol, Survey Bull. 1036–C, p. 19–56.

Smith, C. H., and Kapp, H. E., 1963, The Muskox intrusion, a recently discovered layered intrusion in the Coppermine River area, Northwest Territories, Canada: Mineralog. Soc. America Spec. Paper 1, p. 30–35.

Smith, W. C., 1924, The plutonic and hypabyssal rocks of South Victoria Land: British Antarctic ("Terra Nova") Exped. 1910–13, Nat. History Rept., Geology, v. 1, no. 6, p. 167–227.

Smith, W. C., and Debenham, Frank, 1921, The metamorphic rocks of South Victoria Land—The metamorphic rocks of the McMurdo Sound region: British Antarctic ("Terra

Nova") Exped. 1910–13, Nat. History Rept., Geology, v. 1, no. 5a, p. 133–144.

Starik, I. Ye, Ravich, M. G., Krylov, A. Ya., and Silin, Yu I., 1959, Ob obsolyutnom vozraste porod Vostochno-Antarkticheskoy platformy [On the absolute age of the rocks of the East-Antractic platform]: Akad. Nauk SSSR Doklady, v. 126, no. 1, p. 144–146.

Stewart, D. R., Jr., 1934a, The petrography of some Antarctic rocks: Am. Mineralogist, v. 19, no. 4, p. 150–160.

——— 1934b, Petrography of South Victoria Land: Am. Philos. Soc. Proc., v. 74, p. 307–310.

Taylor, T. G., 1922, The physiography of the McMurdo Sound and Granite Harbour region, British Antarctic ("Terra Nova") Expedition 1910–13: London, Harrison and Sons, Ltd., 246 p.

Thorarinsson, Sigurdur, 1960, The tephralayers and tephrochronology, *in* Askelsson, J., and others, On the Geology and geophysics of Iceland: Internat. Geol. Cong., 21st, Norden 1960, Guide A2, p. 55–60.

——— 1962, The nature of some Icelandic eruptions in relation to the length of the preceding interval of quiescence [abs.]: Internat. Symposium Volcanology, Tokyo, Abstracts, p. 74–75.

Tilley, C. E., 1950, Some aspects of magmatic evolution: Geol. Soc. London Quart. Jour., v. 106, p. 37–61.

——— 1960a, Differentiation of Hawaiian basalts; some variants in lava suits of dated Kilauean eruptions: Jour. Petrology, v. 1, pt. 1, p. 47–55.

——— 1960b, Kilauea magma, 1959–60: Geol. Mag., v. 97, no. 6, p. 494–497.

Tomkeieff, S. I., 1937, Petrochemistry of the Scottish Carboniferous-Permian igneous rocks: Bull. Volcanol., ser. 2, v. 1, p. 59–87.

Tryggvason, Eysteinn, 1962, Crustal structure of the Iceland region from dispersion of surface waves: Seismol. Soc. America Bull., v. 52, no. 2, p. 359–388.

Tryggvason, Tomas, 1943, Das Skjaldbreidh-Gebeit auf Island; eine petrographische Studie: Upsala Univ. Geol. Inst. Bull., v. 30, p. 273–320.

Turnbull, G., 1959, Some palaeomagnetic measurements in Antarctica: Arctic, v. 12, no. 3, p. 151–157.

Turner, F. J., and Verhoogen, Jean, 1960, Igneous and metamorphic petrology: 2d ed., New York, McGraw-Hill Book Co., 694 p.

Verhoogen, Jean, 1949, Thermodynamics of a magmatic gas phase: California Univ. Dept. Geol. Sci. Bull., v. 28, p. 91–136.

Wager, L. R., and Deer, W. A., 1939, The petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland, Pt. 3 *of* Geological Investigations in East Greenland: Copenhagen, Medd. om Grønland, v. 105, no. 4, p. 1–352.

Wahl, W. A., 1946, Thermal diffusion-convection as a cause of magmatic differentiation, Pt. 1: Am. Jour. Sci., v. 244, no. 6, p. 417–441.

Walker, Frederick, 1940, Differentiation of the Palisade diabase, New Jersey: Geol. Soc. America Bull., v. 51, no. 7, p. 1059–1106.

——— 1958, The causes of variation in dolerite intrusions, *in* Carey, S. W., ed., Dolerite—a symposium: Hobart, Australia, Tasmania Univ., p. 1–25.

Walker, Frederick, and Poldervaart, Arie, 1949, Karroo dolerites of the Union of South Africa: Geol. Soc. America Bull., v. 60, p. 591–706.

Walker, G. P. L., 1958, Geology of the Reydarfjördur area, eastern Iceland: Geol. Soc. London Quart. Jour., v. 114, p. 367–394.

——— 1962, Tertiary welded tuffs in eastern Iceland: Geol. Soc. London Quart. Jour., v. 118, no. 471, p. 275–293.

Washington, H. S., 1922, Deccan traps and other plateau basalts: Geol. Soc. America Bull., v. 33, no. 4, p. 765–804.

Webb, P. N., and McKelvey, B. C., 1959, The Geology of Victoria Dry Valley, Pt. 1 *of* Geological investigations in South Victoria Land, Antarctica: New Zealand Jour. Geology and Geophysics, v. 2, no. 1, p. 120–136.

Weihaupt, J. G., 1960, Reconnaissance of a newly discovered area of mountains in Antarctica: Jour. Geology, v. 68, no. 6, p. 669–673.

Wilcox, R. E., 1954, Petrology of Parícutin Volcano, Mexico: U.S. Geol. Survey Bull. 965–C, p. 281–353.

Wilshire, H. G., 1961, Sedimentary xenoliths and dolerite patch pegmatites from an analcite basalt intrusion: Am. Jour. Sci., v. 259, no. 4, p. 260–279.

Wright, C. S., 1923, Physiography of the Beardmore Glacier region, British ("Terra Nova") Antarctica Expedition 1910–13: London, Harrison and Sons, Ltd., 25 p.

Yoder, H. S., Jr., and Tilley, C. E., 1962, Origin of basalt magmas—an experimental study of natural and synthetic rock systems: Jour. Petrology, v. 3, pt. 3, p. 342–532.

Yoshikawa, Torao, and Toya, Hiroshi, 1957, Report on geomorphological results of the Japanese Antarctic Research Expedition, 1956–57: Tokyo Antarctic Record, no. 1, p. 1–13.

Zeller, E. J., Angino, E. E., and Turner, M. D., 1961, Basal sedimentary section at Windy Gully, Taylor Glacier, Victoria Land, Antarctica: Geol. Soc. America Bull., v. 72, no. 5, p. 781–786.