Geology of the Ohio Range–Liv Glacier Area

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Introduction

Between the Ohio Range and the Liv Glacier the Transantarctic Mountains trend east-northeast and act as a barrier to the northward flow of ice from the polar plateau to Marie Byrd Land and the Ross Ice Shelf. Rocks crop out in isolated nunataks and in steep flat-topped escarpments that are dissected by glacier-filled valleys. Relief is locally as much as 2100 m, but is generally only 900 to 1200 m.

The Ohio Range–Liv Glacier area was discovered in 1934 during the Second Byrd Antarctic Expedition. At that time the Horlick Mountains were observed from the air by Kenneth L. Rawson, and general surface observations were made along Scott Glacier by a geological party under Quin A. Blackburn (1937). During Operation Highjump, 1946–1947, a plane flew up the Reedy Glacier. In December 1958 on the Marie Byrd Land oversnow traverse, William E. Long and Fred Darling sampled the basement complex at the northeast end of the Wisconsin Range and later, with Charles Bentley and Jack Long, climbed Mt. Glossopteris in the Offo Range. Subsequently, systematic geologic studies within this range and other areas to the northwest were undertaken by The Ohio State University Institute of Polar Studies. The expeditions were:

SEASON	AREA	FIELD PARTY
1960–1961	Ohio Range	W. E. Long (leader), G. A. Doumani, J. H. Mercer, L. L. Lackey; part season: R. P. Goldthwait
1961–1962	Ohio Range	W. E. Long (leader), G. A. Doumani, M. D. Higgins, J. Ricker, C. J. Skinner; part season: R. Oliver, J. M. Schopf, S. B. Treves
1962–1963	Scott Glacier	G. A. Doumani (leader), L. L. Lackey, V. H. Minshew, C. J. Skinner; part season: C. H. Summerson
1963–1964	Nilsen Plateau	W. E. Long (leader), D. McLelland, C. J. Skinner; part season: R. P. Goldthwait
1964–1965	Wisconsin Range	G. Faure (leader), J. H. Mercer, V. H. Minshew, J. Murtaugh, J. Teller; part season: H. Gair, C. J. Skinner

During the 1963–1964 season a four-man geological party from the New Zealand Antarctic Research Program spent a month in the area between the Axel Heiberg and Liv Glaciers.

Basement complex

The basement complex includes all rocks below the flat-lying middle and upper Paleozoic sedimentary rocks and consists of wide-spread intrusives and less common metamorphosed sedimentary and volcanic rocks.

Intrusive rocks. The intrusive rocks are primarily granitic with local variations in composition, fabric, and age. In the Ohio Range a gray granodiorite is intruded by a more widespread pink porphyritic quartz monzonite (Treves, 1965); inclusions of biotite schist, metavolcanics, metadiorite, and metadiabase commonly occur in the granodiorite but are less common in the quartz monzonite. In the Wisconsin Range porphyroblastic quartz monzonite, with biotite and locally abundant xenoliths of probable metasediments, grades into a more equigranular homogeneous granodiorite (Faure and Murtaugh, personal communication). Near the head of Reedy Glacier two small masses of hornblendite intrude these rocks. Both the granitic rocks and the mafic masses are intruded by fine- to medium-grained, equigranular granites with muscovite. Along the Scott Glacier the chief intrusive rock is a medium- to coarse-grained, light-gray granite and quartz monzonite (Doumani and Minshew, 1965). The gray color commonly grades into red, especially near intrusive contacts. In the Nilsen Plateau medium- to coarse-grained, locally porphyritic granodiorite and several quartz monzonite bodies have been identified, mapped, and classified by McLelland (1967) into pre-, syn-, and post-tectonic rocks which form a composite batholith. The youngest intrusive, a quartz monzonite with large pink phenocrysts of potassium feldspar, is similar in appearance and composition to the quartz monzonite in the Ohio Range and to porphyritic granite in the Long Hills and along the north-facing escarpment of the Wisconsin Range. In the Strom Glacier area the intrusive rocks are primarily coarse-grained granodiorite and porphyritic quartz monzonite (McGregor, 1965). All granitic rocks are cut by aplites and pegmatites; black tourmaline is conspicuous in pegmatite dikes in the Wisconsin Range, along the Scott Glacier, and in the Liv Glacier area.

Metasedimentary rocks. In the LaGorce Mountains gray granite intrudes an estimated 5000 m of metagraywacke, slate, and phyllite which dip vertically and strike eastward. These metasediments, now in the greenschist facies, are the oldest rocks in the area, and constitute the LaGorce Formation (Minshew, 1967). Steeply dipping, lithologically similar rocks in the ridges and nunataks north of the Wisconsin Range escarpment, in the area of the Reedy Glacier, in the Strom Glacier area (including the Duncan Formation of McGregor, 1965), and in the northern part of the Nilsen Plateau are probably equivalent to the LaGorce Formation. The strike of these rocks in the Nilsen Plateau, however, is north to north-northwestward rather than eastward as it is elsewhere. North of the Leverett Glacier the gray granite intrudes a 1500-m sequence of limestone, sandstone, and rhyolite which makes up the Leverett Formation (Minshew, 1967). These rocks dip 30° to 45° northward and, because of the much gentler dips and generally slight metamorphism (only to the zeolite facies), may overlie the LaGorce Formation with an angular unconformity. Along the strike near O'Brien Peak and in the Duncan Mountains exposures of limestone and sandstone (including the Henson Marble of McGregor, 1965), though more metamorphosed than those north of the Leverett Glacier, are presumably equivalent as are similar rocks in an isolated nunatak at the head of Reedy Glacier. A thin bed of trilobite fragments in the limestone at Leverett Glacier is suggestive of a Middle Cambrian age' (A. R. Palmer in letter to V. H. Minshew, November 19, 1965). In the same nunatak, rhyolite stratigraphically above the trilobite-bearing bed gives an age of 472±11 m.y., and apparently equivalent rhyolite on Todd Ridge in the Long Hills gives an age of 498±45 m.y., both based on the Rb-Sr method applied to whole rock isochrons (Faure, Murtaugh, and Montigny, 1967). The southernmost nunatak at the head of Reedy Glacier is composed of intensely metamorphosed sedimentary or volcanic rocks, now an amphibolite, which may be the oldest rocks in the map area (Murtaugh, personal communication).

Metavolcanic rocks. Metavolcanic rocks in the central part of the Scott Glacier are black, fine-grained, massive, and structureless, with large grains of primary quartz and sodic plagioclase. This unit, which lacks bedding or flow structures but may be several thousand meters thick, constitutes the Wyatt Formation (Minshew, 1967). The unit, which is intruded by gray granite at Mt. Gardiner but by an earlier quartz monzonite in the Reedy Glacier area, may lie stratigraphically between the LaGorce and Leverett Formations.

Metavolcanic rocks in the Nilsen Plateau have a relict porphyritic texture and a composition suggesting that the original igneous rock was a rhyodacite or quartz latite (McLelland, 1967). In one locality at the northern end of the plateau the contact is discordant to the bedding of the metasedimentary rocks equivalent to the LaGorce Formation, and at the contact the metavolcanic unit has a narrow, chilled zone. In the same locality the metavolcanic unit has been intruded by the youngest of several quartz monzonites.

Age and correlation. Radiometric age determinations obtained on some of the igneous rocks in the basement complex are given in Table 1. The discordant ages suggest that redistribution of radiogenic daughter isotopes has occurred among the minerals of some of the granitic rocks. The grouping of dates around 470 m.y. suggests a metamorphic episode during Late Cambrian to Middle Ordovician time. The Lonely Ridge granodiorite, and perhaps others, crystallized as long ago as 846 m.y. The real antiquity of the igneous rocks and distinct age differences between the various plutons may be masked by the effects of later metamorphism. At least two episodes of granitic intrusion, one in the Precambrian and the other in the Cambrian to Ordovician, seem probable. The Leverett Formation is partly Cambrian and probably partly latest Precambrian. Thus the Wyatt Formation is late Precambrian in age. The LaGorce Formation may be distinctly older than the Leverett Formation; the age of 846 m.y. for the crystallization of the Lonely Ridge granodiorite that intrudes metagraywacke and slate presumed to be equivalent to the LaGorce Formation is probably a minimum age.

Sedimentary Rocks

In the map area flat-lying sedimentary rocks about 600 to 1200 m thick rest nonconformably upon the basement complex; the erosion surface has a relief of as much as 37 m. Most of these sedimentary rocks are considered Permian, though rocks of Early Devonian age occur in the Ohio Range; a Triassic age has been suggested for beds in the Nilsen Plateau but is not yet proven. The sedimentary section includes the temporal equivalents of the Beacon rocks of southern Victoria Land, but the use of the name Beacon is not considered appropriate in the Ohio Range–Liv Glacier area (Mirsky, 1964). The correlation diagram accompanying the map shows composite stratigraphic sections for five areas, giving characteristic lithology and formation names.

Devonian rocks. In the Ohio Range the Horlick Formation, ranging in thickness from 0 to 50 m, consists of interbedded feldspathic and quartzitic sandstone and dark carbonaceous siltstone and silty shale (Long, 1965a). Fossils in the sandstone include brachiopods, pelecypods, bryozoans, cephalopods, and trilobites, and indicate deposition in a near-shore marine environment. The shale contains primitive psilophytic plants, which are indicative of a paludal environment. An Early Devonian age for the Horlick Formation is indicated by the brachiopods (Boucot *et al.*, 1963) and by spores found in the shale (Schopf in Long, 1964).

Late Paleozoic hiatus. In the Ohio Range the rocks overlying the Horlick Formation are probably Permian. Therefore, a major unconformity representing much of the Devonian and most or all of the Carboniferous exists here. This late Paleozoic unconformity is recognized in most of the Transantarctic Mountains between the Ohio Range and Victoria Land (Mirsky, 1964; Harrington, 1965). Throughout the map area, except in the Ohio Range, rocks of probable Permian age lie directly on the basement complex, the upper surface of which rises stratigraphically northwestward (see correlation diagram).

Late Paleozoic glacial beds. The basal part of the upper Paleozoic section consists of glacial or glacier-associated beds which, in the Ohio Range, disconformably overlie the Horlick Formation but elsewhere rest nonconformably on the basement. The glacial unit is thickest in the east and generally thins westward. It consists of tillite and interbedded sandstone and shale, which appear to be glaciofluvial and glaciolacustrine deposits. Striated and polished pavements, boulder pavements, striated and faceted pebbles, varvites, and crag and tail forms are common. Directional features indicate that the late Paleozoic glaciers moved southeast in the Nilsen Plateau (Long, 1967) and east in the Wisconsin (Minshew, 1966, 1968?) and Ohio (Long, 1965a) Ranges, though Frakes *et al.* (1966) believe the evidence indicates an opposite movement direction. At Mt. Fridtjof Nansen a poorly sorted basal conglomerate, 0 to 3 m thick, is also considered to be of glacial origin (Barrett, 1965).

Intermediate rocks. An intermediate sequence of dark, fine-grained clastic rocks overlies the glacial beds, conformably in the Wisconsin Range, along the Watson Escarpment, and at Mt. Fridtjof Nansen, but with a slight disconformity elsewhere. The clastics grade upward from fine grain to coarse grain except in the Nilsen Plateau, where the two rock types are separated by a disconformity. The finer clastics are typically dark gray to black, carbonaceous and micaceous shale and silty shale. Trails of unknown animals are common, and lenticular calcareous and sideritic ironstone concretions are present. The coarser clastics are mostly buff to gray, massive, cross-bedded arkosic sandstone, with interbedded siltstone and shale. Ripple marks and vertical animal burrows are common; some carbonaceous layers, plant debris, and wood fragments are present. Locally, the upper part consists of black carbonaceous shale, which may contain a *Glossopteris* flora and one or two thin coal beds. These rocks appear to have been deposited in an initially large but restricted body of water within a low-lying, inactive land area. As the water level regressed, the environment of deposition became first deltaic and then fluvial and lacustrine on a broad plain over which streams flowed southeastward in the area of the Nilsen Plateau (Long, 1967) and Scott Glacier (Minshew, 1967) and eastward in the areas of the Ohio Range (Long, 1965a) and Wisconsin Range (Minshew, 1967).

Coal measures. A succession of interbedded arkosic sandstone, siltstone, shale, and coal overlies the intermediate rocks. The sandstone is typically fluvial with channel structure, large-scale trough cross-bedding, ripple marks, and quartz pebble lenses. It contains partings of shale, coal, or carbonaceous debris, sideritic ironstone lenses, and fossil leaves and tree trunks, many still upright. Many of the dark shales are carbonaceous and contain abundant fossil leaves, seeds, and stems of a *Glossopteris* flora. Coal, ranging from low volatile bituminous to semi-anthracite (Long, 1965a), occurs in beds as much as 3.5 m thick. The main coal-bearing strata begin with a quartz-pebble conglomerate at the base of the Queen Maud Formation and about 150 m above the base of the Mt. Glossopteris Formation (see correlation diagram). Below the quartz-pebble conglomerate, for at least 90 to 120 m, the dominant lithology is sandstone with coal and fossil plants in a few localities. Above the quartz-pebble conglomerate the section appears more like typical 'coal measures'; siltstone and shale are characteristic, and coal and fossil plants are common. On the Nilsen Plateau the chief rock type of the Queen Maud Formation is blocky mudstone; beds of coal and coaly shale, restricted to the southern part of the plateau, are less well developed than at Mt. Weaver and in the Ohio Range. The top of the coal measures is seen only on the Nilsen Plateau, where the 600-m unit thins in a short distance to only 100 to 200 m. The coal measures represent deposition in a fluvial, swamp, and floodplain environment on a coastal plain where streams flowed generally eastward (Long, 1965b, 1967; Minshew, 1967). The northern part of the Nilsen Plateau apparently was beyond the northwest limits of the main basin where coal formed or was a local site within the basin which was unsuitable for coal.

Post-coal-measures rocks. The Nilsen Formation, which lies disconformably on the Queen Maud Formation, consists of conglomerate and sandstone with interbedded siltstone and mudstone, which were deposited in a floodplain environment. It varies in thickness from 170 m to as much as 460 m (Long, 1967). Outcrops are known near the southern and northern extremities of the Nilsen Plateau, but the formation probably is also present on some of the higher flat-topped peaks in the intervening area. The conglomerate beds occur at several levels, including the basal unit of the formation, and contain some water-worn cobbles of *Glossopteris* shales from the underlying Queen Maud Formation. Cross-bedding, which is common, indicates that currents flowed to the northwest (Long, 1965b), nearly opposite to the current directions inferred from the underlying Queen Maud and Amundsen Formations. The finer clastics include minor units of interbedded mudstone, shale, and siltstone. Fossil wood occurs in several of the sandstone units, and linear plant fossils occur in the mudstone.

Age and correlation. Spores in dark shale in the upper part of the Buckeye Tillite in the Ohio Range are probably Permian (Schopf in Long, 1965a), which is also the likely age for the rest of the unit and for the Buckeye and Scott Glacier Formations found farther west. Glacial beds of later Carboniferous age may be present, but there is as yet no specific supporting evidence. The *Glossopteris* flora indicates a Permian age for the Mt. Glossopteris Formation of the Ohio Range (Schopf, 1962; Cridland, 1963). Conchostracans from near the top of the Mt. Glossopteris Formation have been assigned to the middle to upper Permian (Lower Beaufort) (Doumani and Tasch, 1963). At Mt. Gran in southern Victoria Land similar coal measures are also considered to be Permian (Mulligan *et al.*, 1963). The same age probably applies to the Queen Maud Formation. Thus most of the sedimentary rocks overlying the basement in this map area appear to be Permian, with the exception of the thin Horlick Formation and possibly the upper part of the Nilsen Plateau, which might extend into Early Triassic (Long, 1967).

Diabase Sills and Dikes

Except in the Wisconsin Range, diabase sills and related dikes intrude the sedimentary succession with the number of intrusions decreasing eastward (see correlation diagram); outcrops of diabase south of Mt. Howe are the southernmost rocks known in Antarctica. The sills range in thickness from less than a meter to about 300 m; most are more than 100 m thick, and some can be traced laterally for kilometers. The diabase is a dark greenish black, but it weathers to brownish red. Detailed analyses by Treves (1965) and McLelland (1967) show that the diabase consists of plagioclase, pyroxene (augite, pigeonite, and hypersthene), and lesser amounts of opaques and apatite. Olivine occurs at the base of two sills in the Nilsen Plateau (McLelland, 1967). To the northwest, in Victoria Land, similar diabase sills that intrude Paleozoic rocks have been radiometrically dated as Late Jurassic (McDougall, 1963). The sills in the map area are also considered Jurassic.

Volcanic Rocks of Cenozoic Age

Mt. Early, a cone-shaped mountain in the upper Scott Glacier, is composed chiefly of black, vesicular, olivine basalt flows, with associated explosion fragments of roy basalt, tuff, and tuff breccia (Doumani and Minshew, 1965). The age of this volcano, the most southern presently exposed in Antarctica, is unknown, but it may be Pleistocene to Recent (S. B. Treves, personal communication). Volcanic rocks are found in only one other outcrop, just south of Mt. Saltonstall in the upper Scott Glacier. The rocks are chiefly basalt flows, scoria, and tuff breccia. The number of thin flows suggests numerous mild eruptions. The age is not known but may also be Pleistocene to Recent (S. B. Treves, personal communication).

Structure

The modern mountain ranges appear to be isolated blocks differentially elevated during post-Jurassic epeirogeny. The bounding faults are ice covered, but in the Ohio Range a major northeast trend with a secondary northwest cross-trend is indicated by known and inferred faults and by the joint pattern in the upper 200 m of the Mt. Glossopteris Formation (Long, 1965a). Above the basement complex large folds are absent, and most small ones are due to penecontemporaneous deformation or fault drag. Large folds in the metagraywacke and slate sequence trend northward to north-northwestward in the Nilsen Plateau and in the Liv Glacier areas and eastward in the Scott Glacier area and the Wisconsin Range. Foliation and cataclastic zones within the granite rocks trend northwestward throughout the area.

Geologic History

A thick series of sedimentary and volcanic rocks deposited in the late Precambrian were intruded by granitic rocks possibly about 850 m.y. ago, perhaps in the latest Precambrian, but certainly in Cambrian time, another series of sedimentary and volcanic rocks was deposited on the moderately dipping underlying strata; the trilobite remains indicate that at least the enclosing carbonates were deposited in a Middle Cambrian marine environment. In the latest Cambrian and continuing until the Middle Ordovician (520–450 m.y.) during an extensive orogeny, the area was intruded by granitic rocks, deformed, and metamorphosed. A long erosional interval followed, during which lower Paleozoic sedimentary rocks which were not protected in synclinal remnants were stripped away. Deposition was renewed in the Early Devonian, with sediments accumulating in a shallow sea and on the adjacent land. A major mid- to late-Paleozoic erosional phase removed all Devonian and Carboniferous rocks from the area, with the exception of a thin remnant of Lower Devonian in the Ohio Range. The late-Paleozoic hiatus ended in the earliest Permian—or possibly in the latest Carboniferous—when glacial and glacier-associated sediments were deposited by continental glaciers which advanced eastward and southeastward. After a short erosional interval, dark, fine-grained clastics were laid down in a restricted body of water which covered the area. As the water receded, the area became a delta and then a floodplain, where increasingly coarser grained clastics were deposited. Coal-forming swamps with a Permian *Glossopteris* flora developed on the floodplain, and east-flowing streams brought conglomeratic material from highlands to the west. During the Late Permian, and possibly during the Early Triassic, there appears to have been another erosional interval of unknown length succeeded by another floodplain environment, but one in which, because of renewed tectonism to the southeast, streams reversed their direction and flowed northwest. Diabase sills and dikes were emplaced during the Jurassic.

The rest of the geologic history is less well known. The present Horlick and Queen Maud Mountains formed by uplift and associated block faulting, probably in the middle or late Cenozoic. Pleistocene or Recent volcanism in the upper Scott Glacier area may have occurred during a late phase of this uplift. Continental glaciation marking the beginning of the Antarctic ice sheet began, at the latest, during the late Pliocene but probably earlier (Mercer, 1967).

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TABLE 1. RADIOMETRIC AGE DETERMINATIONS

Location	Lithology	Method and Material	Age (m.y.)	Ref.
Lonely Ridge 86°22'S, 160°01'W	Granodiorite	Rb-Sr Biotite	846±35	4
		K-Ar Biotite	472±10	4
Metavolcanic Mountain 86°13'S, 125°40'W	Metavolcanic rocks	Rb-Sr Whole rock isochron	633±13	2
Ridge east of Olentangy Glacier 86°02'S, 125°22'W	Granodiorite	Rb-Sr Whole rock isochron	627±22	2
	Quartz monzonite	Rb-Sr Whole rock isochron	479±10	2
O'Brien Peak 85°27'S, 157°15'W	Granite	Rb-Sr Microcline	520±30	5
		Rb-Sr Whole rock	490±20	5
		Rb-Sr Muscovite	460±20	5
		Rb-Sr Biotite	450±20	5
Discovery Ridge and Treves Butte 84°45'S, 114°40'W	Quartz monzonite	Rb-Sr Whole rock	516±72	1
		K-Ar Biotite	472±24	1
		Rb-Sr Feldspar	471±49	1
Todd Ridge 85°16'S, 119°10'W	Rhyolite	Rb-Sr Whole rock isochron	498±45	2
East side of Leverett Glacier 85°39'S, 144°45'W	Rhyolite	Rb-Sr Whole rock isochron	472±11	2
Mt. Wilbur 86°59'S, 152°30'W	Gray granite	K-Ar Biotite	470±14	3
On coast between Axel Heiberg and Strom Glaciers 85°17'S, 163°20'W	Pegmatite dike cutting Henson Marble	K-Ar Muscovite	445±13	6

1. Treves (1965)
2. Faure, Murtaugh, and Montigny (1967)
3. Minshew (1965)
4. McLelland (1967)
5. Craddock *et al.* (1964)
6. McDougall and Grindley (1965)

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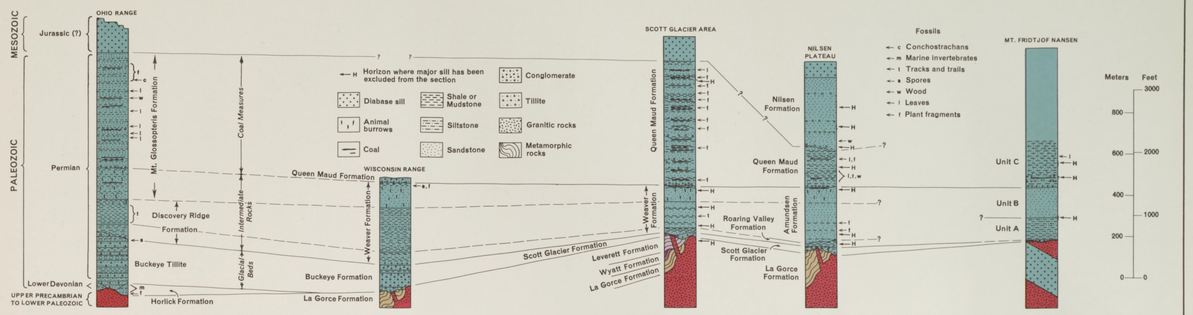
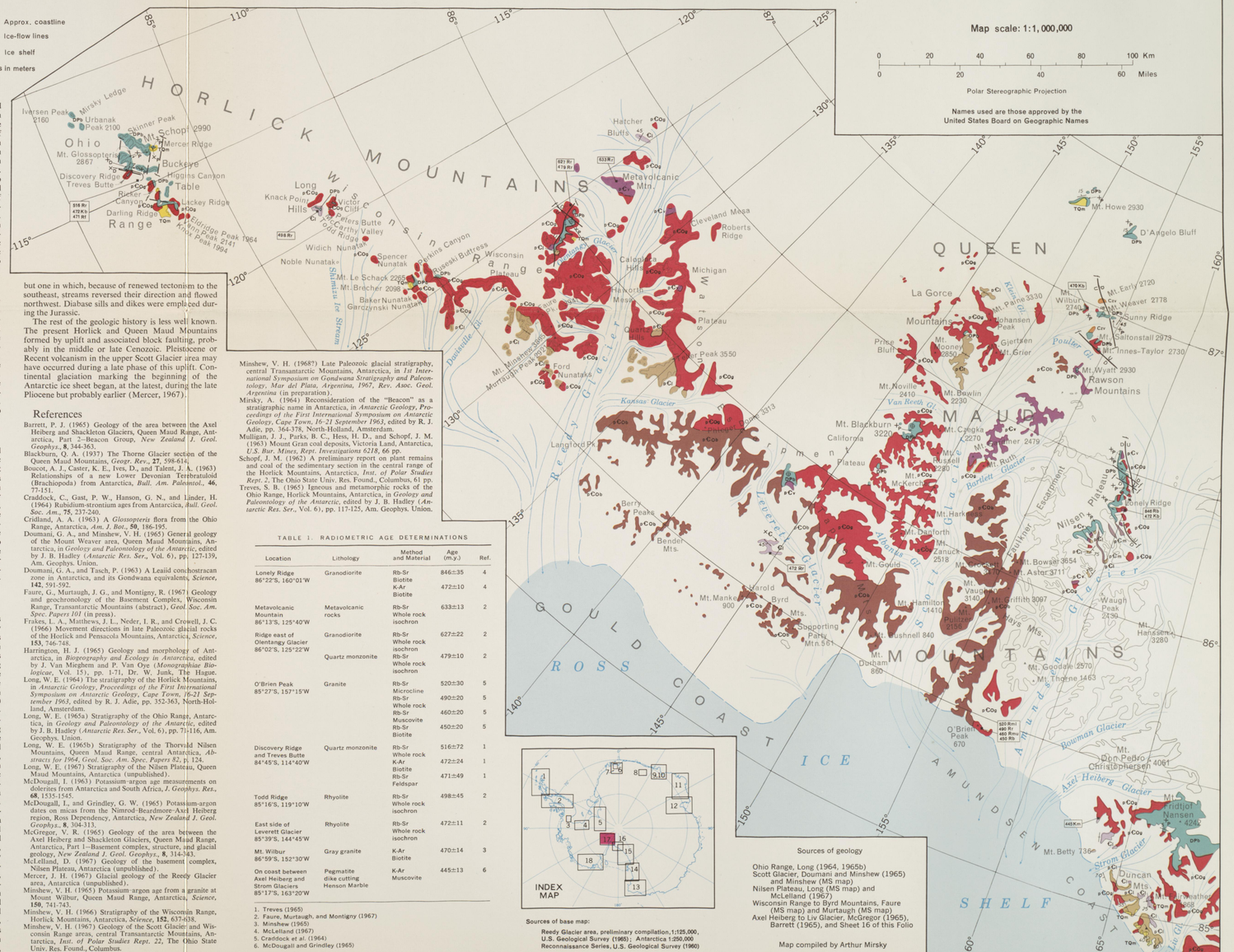
EXPLANATION

CENOZOIC	Pliocene to Pleistocene	TQm — *Morainal deposits*
CENOZOIC	Pliocene (?) to Pleistocene(?)	Czv — *Volcanic rocks*
PALEOZOIC TO MESOZOIC(?)	Jurassic (?) Triassic(?) Permian Lower Devonian	DPb — *Flat-lying sedimentary rocks with sills and dikes; equivalent to* Beacon *rocks of southern Victoria Land (formations and lithologies indicated in correlation diagram)*
	Unconformity (Kukri Peneplain)	
PALEOZOIC	Upper Precambrian(?) to Cambrian	Cl — *Deformed limestone, sandstone, and rhyolite, locally metamorphosed (includes* Leverett Formation *and* Henson Marble*)*
PRECAMBRIAN	Upper Precambrian(?)	pCv — *Metavolcanic rocks (includes* Wyatt Formation *and* Fairweather Formation*)*
	Upper Precambrian	pCl — *Metasedimentary rocks: metagraywacke, slate, phyllite, schist (includes* La Gorce Formation, Duncan Formation, *and* Goldie Formation*)*
		pCm — *Undifferentiated metamorphic rocks*
	Precambrian to Ordovician	pCOg — *Intrusive rocks, mostly granitic in composition*
		pCOb — *Undifferentiated Basement Complex*

BASEMENT COMPLEX

Geologic contact, dashed where inferred
Limits of land forms rising above the surface of the surrounding ice with varying amounts of rock exposure
Fault with sense of displacement, dashed where inferred
Strike and dip of bedding
Horizontal bedding
Strike of vertical bedding
Strike of vertical foliation
Syncline, with plunge of axis
Radiometric age determination showing age in m.y., method (K=K–Ar, R=Rb–Sr), and material (b=biotite, f=feldspar, mu=muscovite, mi=microcline, r=whole rock)
Animal fossil site (Є=Cambrian, D=Devonian, P=Permian)
Plant fossil site (D=Devonian, P=Permian)
Approx. coastline
Ice-flow lines
Ice shelf
Elevations in meters

CORRELATION DIAGRAM OF COLUMNAR SECTIONS