TABLE 1. RADIOMETRIC AGE DETERMINATIONS

Location	Lithology	Method and Material	Age (m.y.)	Ref.
Near Bull Pass, Wright Valley	Porphyry dike	Rb-Sr Whole rock	1000	1
		Rb-Sr Feldspar	942	1
		Rb-Sr Biotite	477	1
Granite Harbor	Aplite	Rb-Sr Whole rock	535	2
	Irizar Granite	Rb-Sr Biotite	486	1
		Rb-Sr Feldspar	475	1
Marble Point	Mafic dike	K-Ar Biotite	524	2
	Marble from metamorphic series	K-Ar Biotite	500	3
	Diorite	K-Ar Biotite	496	2
Nussbaum Riegel, Taylor Valley	Lamprophyre dike (two specimens)	K-Ar Biotite	520, 458	2, 3
	Monzonitic gneiss	K-Ar Biotite	425	3
Gneiss Point	Biotite hornblende paragneiss	K-Ar Biotite	501	4
Mt. Loke, Wright Valley	Porphyritic granite	Rb-Sr Biotite	495, 479	5
Lake Vanda, Wright Valley	Gneiss (two specimens)	Rb-Sr Biotite	494, 481	1
Near Mt. Theseus, Wright Valley	Schist	Rb-Sr Biotite	494	1
Mt. Doorly, Wright Valley	Porphyritic granite	Rb-Sr Biotite	487	1
Near Mt. Theseus, Wright Valley	Pegmatite	Rb-Sr Biotite	435	1
Olympus Range	Schist	Rb-Sr Biotite	345, 338	1
Southeast of Lake Vida, Victoria Valley	Silicic dike intruding granodiorite	K-Ar Feldspar	222	5
		K-Ar Biotite	211	5
	Granodiorite (Vida Granite)	K-Ar Biotite	185	5
South of Lake Vida	Granodiorite (Vida Granite)	K-Ar Biotite	210	5
North of Lake Vashka, Victoria Valley	Ferrar Dolerite in granodiorite	K-Ar Pyroxene	163	5
	Ferrar Dolerite intruding Vida Granite	K-Ar Feldspar	162	6
Southwest of Lake Vida, Victoria Valley	Ferrar Dolerite in granodiorite	K-Ar Feldspar	162	5
Southeast of Lake Vashka, Victoria Valley	Ferrar Dolerite in granodiorite	K-Ar Feldspar	159	5
Escalade Peak	Ferrar Dolerite intruding Beacon Group	K-Ar Feldspar	158	5
		K-Ar Pyroxene	153	5
Stepaside Spur, Skelton Glacier	Pegmatitic dolerite (Ferrar Dolerite) intruding basement rock	K-Ar Feldspar	154, 150	5

1. Deutsch and Webb, 1964
2. Pearn, Angino, and Stewart, 1963
3. Angino, Turner, and Zeller, 1962
4. Goldich, Nier, and Washburn, 1958
5. McDougall, 1963
6. Evernden and Richards, 1962

Geology of the Terra Nova Bay–McMurdo Sound Area Victoria Land

Guyon Warren[1]

Introduction

This map sheet covers that part of the Transantarctic Mountains lying west of the Ross Sea and McMurdo Sound, from the Campbell Glacier at 74°S to the Mulock Glacier at 79°S. The first investigations in the area were made in 1902 during Scott's first expedition, and all the major ranges have now been examined at least at the reconnaissance level. A number of little-modified Cenozoic volcanic cones occupy the southeastern part of the area. They are dominated by the 4000-m Mt. Erebus, which together with two other major volcanic centers forms Ross Island. To the south small volcanic islands and a long peninsula stretching from Mt. Discovery to Minna Bluff constitute a major local barrier to the northward movement of the Ross Ice Shelf. Wide piedmont glaciers, maintained principally by summer snowfall from the Ross Sea region, fringe the foothills of the Royal Society Range and form a coastal platform along much of the western side of the Ross Sea. To the north of the Royal Society Range, the mountains decrease in height and in east–west width, and only small areas of rock are exposed above the continental ice sheet in the sector between the Mawson and David Glaciers. The ice sheet for the most part has a surface altitude of about 2000 m immediately west of the mountains, and for 300 km south of the Mawson Glacier only relatively minor amounts of ice reach sea level in outlet glaciers breaching the ranges. West of McMurdo Sound a large area of ice-excavated valley systems is now wholly ice free below about 1000 m, due partly to reduction of ice supply from the continental ice sheet and partly to increased ablation due to climatic changes.

Previous work. The bases of a number of British expeditions were located on the shores of Ross Island in the period 1901–1917, and since 1957 this area has been the headquarters of the United States and New Zealand Antarctic programs. The map area includes several classical sections of East Antarctic stratigraphy, and many regions have now been examined in considerable detail. The principal reports of the early expeditions are those of Ferrar (1907), David and Priestley (1914), and those of the 1910–13 'Terra Nova' expedition, including detailed accounts by Debenham, Priestley, Seward, Smith, Woodward, and Wright. A complete list of these papers appears in Gunn and Warren (1962, p. 19).

The geology of the area south of the Mawson Glacier was mapped by Gunn and Warren during the 1956–58 Transantarctic Expedition (Gunn and Warren, 1962), and that north of the Mawson by Ricker and Skinner (Ricker, 1964). Besides these regional surveys, many papers dealing with more restricted areas or topics have appeared since 1958 and the more important of these are given in the reference list below. Data from all these sources have been used in the compilation of the map.

Stratigraphy

Basement complex. The basement complex comprises large thicknesses of deformed metasedimentary rocks, probably all pre-Ordovician, that have been extensively invaded and metamorphosed by igneous (chiefly granitic) rocks of various ages. The basement complex is exposed chiefly near the coast and at relatively low altitude, and for this sheet has been mapped in five units:

- p€m — Deformed metasedimentary and igneous rocks, assumed to underlie the other basement metasedimentary rocks unconformably.
- €rg — Quartzo-feldspathic geosynclinal metasedimentary rocks.
- €rl — Metamorphosed limestone, quartzite, and rare conglomerate beds. Units €rg and €rl together comprise the Ross Supergroup (Grindley and Warren, 1964; Warren, 1965).
- €Ogs — Granitic rocks, developed shortly before or during the main period of deformation of the sedimentary rocks.
- €Ogp — Post-tectonic granitic rocks. Units €Ogs and €Ogp together constitute the Granite Harbour Intrusives (Gunn and Warren, 1962).

North of the Mawson Glacier the Priestley Formation of Ricker (1964) has been tentatively correlated with other geosynclinal metasedimentary rocks of the Ross Supergroup by Grindley and Warren (1964) and is mapped as €rg and €rl. It consists of up to 1500 m of tightly-folded, unfossiliferous, hornfelsic argillite, fine graywacke, and limestone. High-grade quartzo-feldspathic biotite and garnet schist, banded paragneiss, and migmatite also crop out in the Terra Nova Bay area. Some of these rocks show evidence of regional as well as thermal metamorphism, and are more intensely deformed than the typical rocks of the Priestley Formation. On this basis they are tentatively inferred to predate the Ross metasedimentary rocks and are mapped as p€m.

Undeformed post-orogenic granitic rocks (€Ogp) predominate in the area on the northern side of the Priestley Glacier, and they have recently been examined by a New Zealand party. Seven lithologically distinct intrusive units have been recognized (R. G. Adamson, personal communication), of which the oldest is a very coarse-grained biotite granite with large orthoclase phenocrysts. Three other biotite granites, a garnetiferous granite, a hornblende granite, and a quartz diorite have also been recognized. Most occur in northwest-trending belts parallel to the strike or foliation of the included and nearby metasedimentary rocks.

South of the Priestley Glacier the granitic rocks include the widely developed Larsen Granodiorite (€Ogs), named (Gunn and Warren, 1962) from Mawson's locality in Backstairs Passage, southeast of Mt. Larsen. This rock is in most places a uniform gray biotite granodiorite and crops out as a major batholith from Terra Nova Bay for several hundred kilometers to the south. In the Mawson–Priestley area it intrudes the Priestley Formation, but it has a distinct gneissic texture, is intruded by younger granites, and clearly predates at least the later part of the Ross Orogeny (Ordovician).

The post-orogenic Irizar Granite (€Ogp) has its type locality at Cape Irizar, south of the David Glacier, and is well exposed in several localities north of the Mawson Glacier. It is an undeformed, coarse-grained, pink-weathering biotite granite, commonly with hornblende, and in many places contains large pink or red orthoclase phenocrysts. Other bodies of post-orogenic biotite granite and quartz diorite have been recognized by Ricker (1964), and granitic and lamprophyric dikes of various ages are also present.

South of the Mawson Glacier there is also uncertainty as to the age of the oldest rocks in the basement complex. Coarse-grained orthogneiss and metadiorite crop out in many areas between the Mackay and Koettlitz Glaciers, in most places in close association with Ross Supergroup metasedimentary rocks or as inclusions in Larsen Granodiorite. These rocks are structurally and mineralogically altered to a degree comparable to that of the most deformed and metamorphosed of the Ross metasedimentary rocks, and are therefore clearly older than the Ross Orogeny. Some are intrusive into the Ross strata, but it seems likely that others may be remnants of the basement on which the sediments of the Ross Supergroup were deposited. All, however, are mapped as €Ogs.

The basement sedimentary rocks, in the area south of the Mawson Glacier, have been described in two groups: the Skelton Group (Gunn and Warren, 1962) and the Koettlitz Group (Blank *et al.*, 1963; Grindley and Warren, 1964). Although these two groups have slightly different metamorphic grades and histories, it is possible that they are in part correlatives. The Skelton Group consists of 2000 m of hornfelsic graywacke and argillite (Teall Graywacke, €rg), and 3000 m of well-bedded, impure crystalline limestone (Anthill Limestone, €rl). Both formations are complexly folded and thermally metamorphosed to a comparable degree, but no contacts between them are exposed.

Objects believed to be poorly preserved archeocyathids, suggesting an Early Cambrian age, occur in Koettlitz Group marble west of the mouth of the Koettlitz Glacier (Blank *et al.*, 1963). No other fossils have been recognized in the basement metasedimentary rocks within this map sheet.

More widely developed than the metasedimentary rocks, except in the southern part of the sheet, are the various granitic bodies invading them. The weakly gneissic Larsen Granodiorite and younger Irizar Granite (see above) predominate, but granite, adamellite, granodiorite, and diorite bodies of restricted extent, all younger than the Larsen Granodiorite, have been described (Gunn and Warren, 1962). Dikes of widely ranging age and composition (including aplite, pegmatite, and lamprophyre) intrude the basement complex throughout the area.

Beacon Group (DJb). Following the Ross Orogeny (see below), the rocks of the basement complex were deeply eroded and reduced to low relief in the area covered by this map sheet, and over wide areas of the East Antarctic continental mass in general. On this surface—the Kukri Peneplain (Gunn and Warren, 1962)—were deposited the clastic sediments of the Beacon Group, a sequence dominated by terrestrial quartz arenite and arkose, with varying thicknesses of interbedded till, carbonaceous siltstone, coal, and thin beds of limestone and fluviatile conglomerate.

The name of this group is derived from Beacon Heights, twin hills on the southwestern side of the upper Taylor Glacier, where good exposures were first examined (Ferrar, 1907; Harrington and Speden, 1962).

Lithologies are highly variable near the base of the group. West of McMurdo Sound, coarse round-stone conglomerate, breccia, interbedded arkosic sandstone and siltstone, probably all of Silurian or Devonian age, overlie the basement rocks. Farther north the Beacon strata are very thin, the only known fossils are of Triassic age, and it is probable that erosion of the Kukri surface continued, at least intermittently, into the late Paleozoic or early Mesozoic.

Massive and cross-bedded quartz arenite with minor siltstone dominates the lower part of most sections and in some places is as much as 1000 m thick. It contains rare Devonian plants (Plumstead, 1962) and a thin band of purple and green pebbly siltstone containing fragmentary Middle to Late Devonian fresh-water fish remains (Gunn and Warren, 1962). The lower Permian glacial beds recognized farther south in the Transantarctic Mountains are not present in the map area, but it is possible that they are represented by a post-Devonian disconformity, as suggested by Mirsky *et al.* (1965). Overlying the quartz arenite, without, in most places, any sign of a major disconformity, are up to 400 m of fluviatile cross-bedded arkosic sandstone, carbonaceous siltstone, and seams of anthracitic high-ash coal. Permian plants (*Glossopteris* flora), including silicified logs up to 70 cm in diameter, are present in several richly fossiliferous horizons (Plumstead, 1962; Townrow, 1967). Barren sandstones overlie these Permian beds, and in the Mackay–Mawson area grade upwards into sandstones with bands of *Dicroidium*-bearing (Triassic) carbonaceous silt. Nearby, an isolated area of brown lacustrine siltstone, interbedded with Ferrar Group volcanics (Jk, see below), contains Jurassic plants, ostracods, and conchostracans. In the northern section of the map sheet, where Beacon strata are only about 150 m thick, Late Triassic or Early Jurassic spores are present in siltstone within a 120-m band of cross-bedded arkosic sandstone (Gair *et al.*, 1965).

A yellow-brown unsorted blocky to clay-grade conglomerate, locally 500 m thick, overlies the deeply channelled surface of Permian to Triassic Beacon sandstones in the Mawson–Mackay area. It was described as the Mawson Tillite by Gunn and Warren (1962), but its depositional origin remains problematical. It is partly older than the earliest local extrusion of Ferrar Group lavas, that is, not younger than early Late Jurassic.

Ferrar Group. Almost coextensive with the Beacon Group strata, and mapped with them (DJb), are massive intrusions (predominantly in the form of sills) of tholeiitic quartz dolerite (Ferrar Dolerite) and related extrusive and pyroclastic rocks (Kirkpatrick Basalt, Jk). Together these constitute the Ferrar Group. Dolerite sheets intrude the pre-Beacon basement rocks in many places, and a thick sill invading the basement–Beacon contact (Kukri Peneplain) is almost universally present. One to three thick sills (to 450 m each) and minor thin sills and dikes are common within and overlying the Beacon beds.

Petrographically, the sills fall into three groups (Gunn, 1966): olivine (rare), hypersthene, and pigeonite tholeiites. These are believed to belong to three separate periods of intrusion. The hypersthene tholeiite sills are strongly differentiated, ranging in composition from a central hypersthene gabbro to felsic and pegmatoid zones. The more siliceous pigeonite tholeiite sills, which include the peneplain sill in most places, are less strongly differentiated. The petrography of the dolerites has recently been studied in considerable detail and is discussed by Gunn (1962, 1963, 1965, 1966) and Hamilton *et al.* (1965).

No flows of Kirkpatrick Basalt are present in the southern part of the sheet, but from the Mackay Glacier northward increasing thicknesses of lava with minor interbedded pyroclastics remain on the higher western peaks. Just north of the sheet as much as 1500 m of basalt may be present.

Little detailed information is available on the Kirkpatrick Basalt flows in the map area; those on Carapace Nunatak (upper Mackay Glacier) are described by Gunn and Warren (1962) and outcrops north of the Mawson Glacier are described by Ricker (1964). In both localities the lowest flows are interbedded with lenses or bands of fossiliferous upper Triassic or Jurassic terrestrial sedimentary rocks and show glassy margins and pillow structure. The chemical composition of the basalts closely approximates that of the intrusives.

The ages indicated for the extrusives by their interbedding with plant and conchostracan bearing strata (Gunn and Warren, 1962; Gair *et al.*, 1965) agree closely with those now available from radiometric dating of the dolerites (summarized in Webb and Warren, 1965), all of which fall within the range Late Triassic to early Late Jurassic (See Table 1).

McMurdo Volcanics (Czv). Quaternary and possibly late Tertiary alkali-rich volcanic rocks (McMurdo Volcanics), including olivine basalt, trachyte, phonolite, and kenyte, with associated pyroclastics, crop out in a north–south coastal belt subparallel to the Victoria Land ranges. The young volcanic cones, Mt. Erebus and Mt. Discovery, dominate an extensive area of lavas and pyroclastics at the southern limit of this belt. Mt. Erebus (Beck, 1965) releases a small but nearly constant steam plume from its summit crater within the rims of several older and much larger craters, but no lava or ash has been erupted within historic times. The stratigraphy of the cone is poorly known, but Smith (1954) has described the petrography of many of the lavas. North of Ross Island only the small volcanic remnants of Beaufort and Franklin Islands link the McMurdo Sound volcanoes with the large area of volcanics north of Terra Nova Bay, dominated by the high symmetrical cone of Mt. Melbourne. Recent examination has shown that steaming ground is present near the summit of Mt. Melbourne (Nathan and Schulte, 1967), and recent volcanic activity is indicated by ash layers in ice nearby (Adamson and Cavaney, 1967).

In the extreme south, tuffaceous early Pleistocene marine sediments (see below) set a minimum age for the inception of volcanism, but many or most of the present volcanic landforms must be the result of post-glacial eruptions.

Superficial deposits (Qm). Small outcrops of lower Pleistocene marine sandstone and grit, and of unconsolidated upper Pleistocene or Holocene marine sand, have been described from the McMurdo Sound area by Speden (1962). Lateral and recessional moraines are present in the deglaciated valleys west of McMurdo Sound, and the age and correlation of the various glacial features have been discussed by Bull *et al.* (1962) and Black and Berg (1964). Fluvioglacial deposits (for example, Speden, 1960) and sand dunes are developed locally in the same area.

Structure

Folding in the basement metasedimentary rocks is predominantly about steeply-plunging axes that trend northward or northwestward, but wide divergence from this regional grain is common near the base of the Royal Society Range. Axial-plane cleavage and schistosity in the metasedimentary rocks, and planar structures in most of their associated pre-tectonic intrusives, are closely parallel to the bedding and probably resulted from the same orogenic movements—the main phase of the Ross Orogeny (? Early Ordovician). Direct evidence limiting the age for the beginning of the Ross Orogeny is given only by the presence of archeocyathid remains (Cambrian) in the folded and metamorphosed sedimentary rocks. The intrusion of the Skelton Granodiorite took place during the later stages of this folding, and was followed by the formation of post-tectonic granites and granodiorites. These are confidently dated as Ordovician on radiometric evidence (Table 1) from many rock units and areas throughout the Transantarctic Mountains.

The Beacon Group was fragmented into discrete sheets and blocks by the injection of immense laterally discontinuous sills during the Jurassic Ferrar Intrusive Phase. The present gentle northwest to southwest dip of the Beacon rocks, however, probably results largely from the later, predominantly vertical movement of the Victoria Orogeny. Uncertainly dated as late Tertiary or Quaternary, this orogeny formed the north–south Victoria Land mountain system and Ross Sea depression along a complex of longitudinal and transverse faults, and was probably accompanied, and certainly followed, by extrusion of McMurdo Volcanics.

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