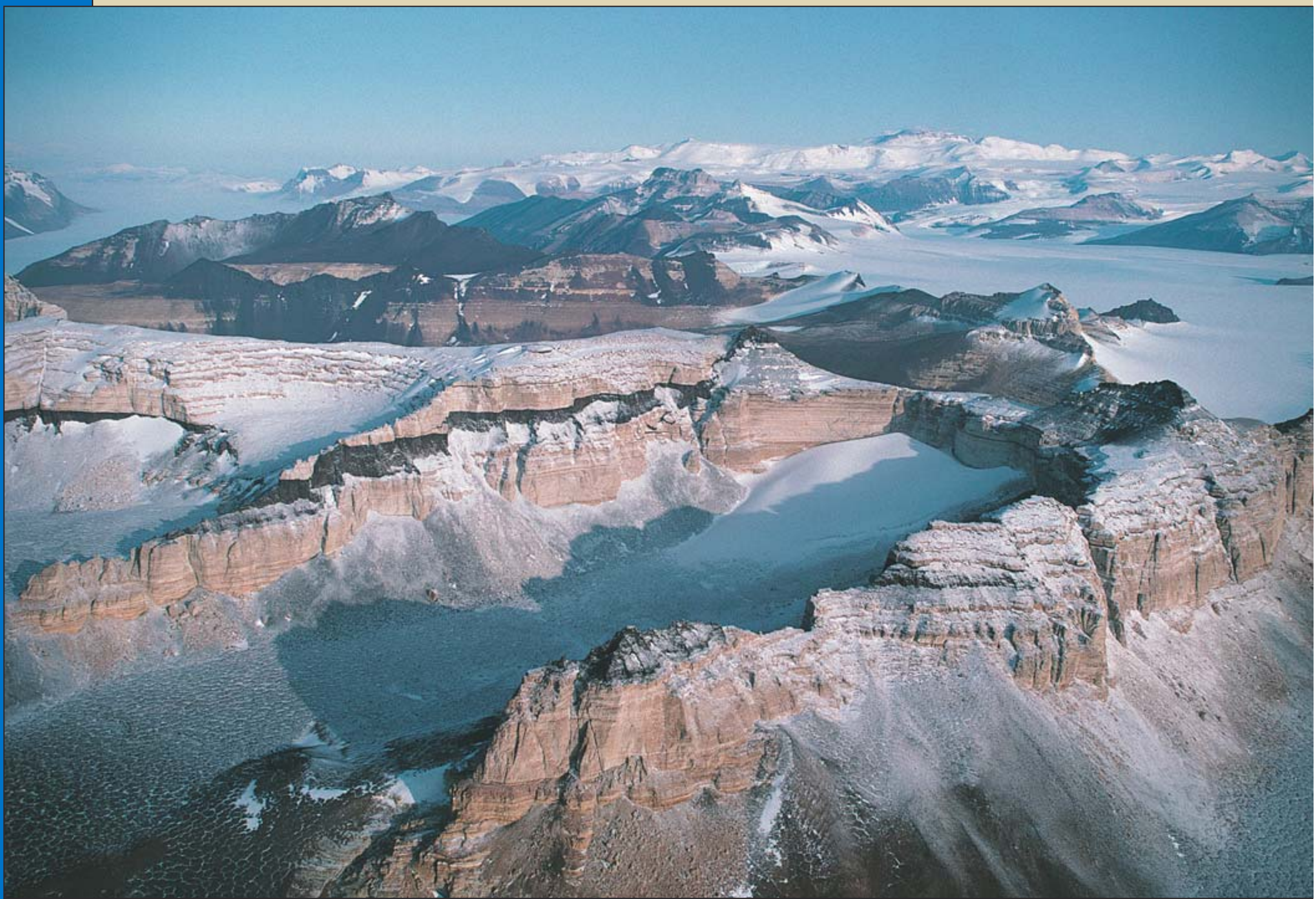
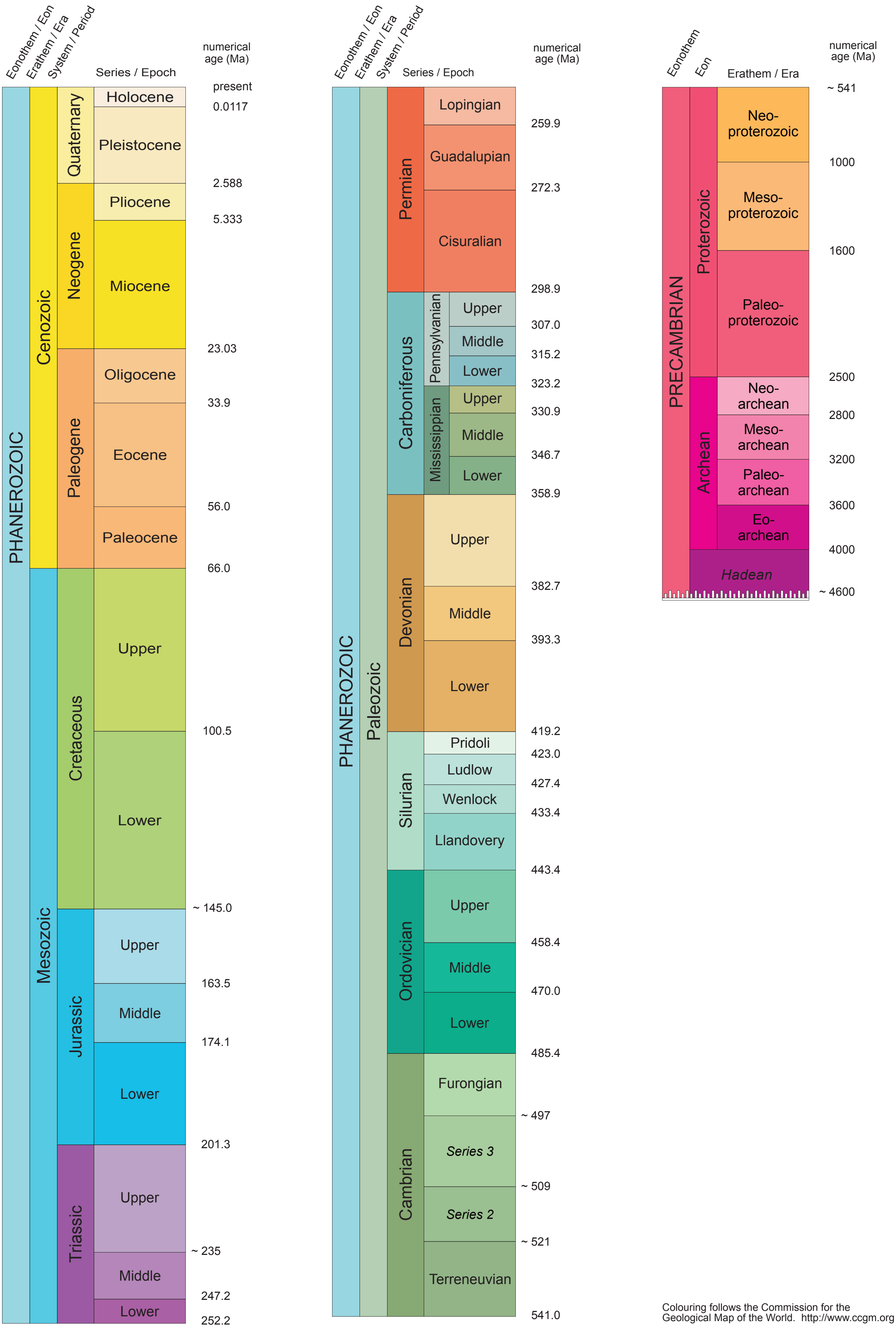
1:250000 Geological Map 22

Geology of southern Victoria Land Antarctica



S.C Cox
I.M. Turnbull
M.J. Isaac
D.B. Townsend
B. Smith Lyttle
(compilers)

GNS Science
Te Pū Ao



Colouring follows the Commission for the Geological Map of the World. http://www.ccgm.org

Geology of southern Victoria Land, Antarctica

Scale 1:250 000

S.C. Cox
I.M. Turnbull
M.J. Isaac
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B. Smith Lyttle
(COMPILERS)

Institute of Geological & Nuclear Sciences 1:250 000 Geological Map 22

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Lower Hutt, New Zealand

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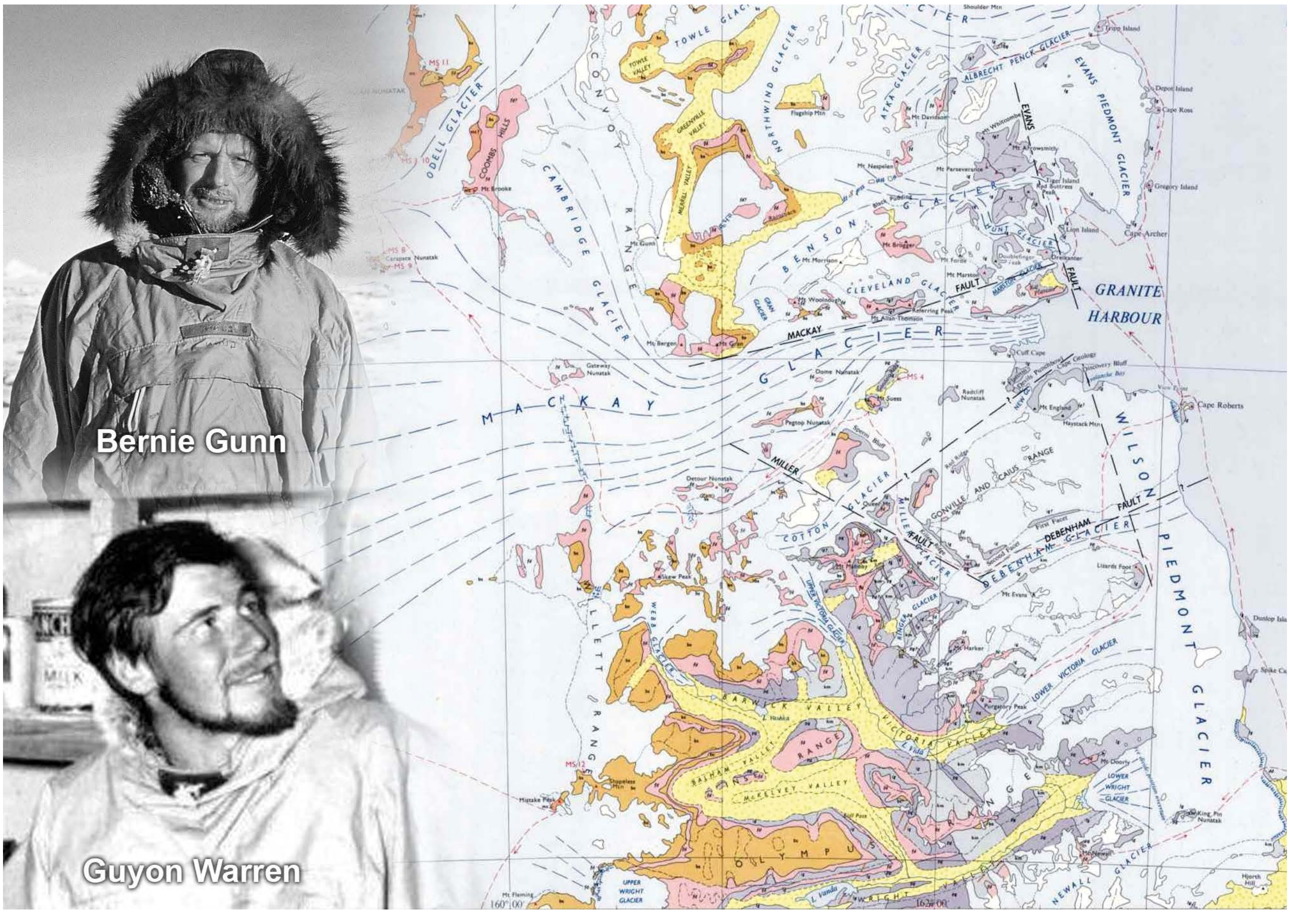
FRONT COVER

Aerial view east from University Valley along the Quartermain Mountains towards Mt Lister (4025 m) in the Royal Society Range. Beacon Supergroup sandstone (pale yellow Beacon Heights Orthoquartzite) is intruded by sills of Ferrar Dolerite (dark brown).

Photo: K. Westerskov/Hedgehog House.



Geologists Bernie Gunn and Guyon Warren, accompanied by Richard Brooke and Murray Douglas, undertook an impressive geological and topographical survey during the spring and summer of 1957–1958. Their 1500 km dog-sled journey explored the McMurdo coastline and piedmont glaciers, climbed the Mawson Glacier, traversed the edge of the Polar Plateau, then descended the Skelton Glacier, with numerous side forays and minimal external support. The resulting 1:250 000 geological map, published as a New Zealand Geological Survey Bulletin in 1962, has remained a valuable reference work for 50 years. As we replace Gunn & Warren (1962) with this new edition "Geology of southern Victoria Land", which has benefitted from aerial and satellite-based topographic surveys, years of further research, and considerably more logistic support, we remain in awe of the achievement of Bernie Gunn and Guyon Warren. Theirs was a remarkable contribution to Antarctic science.

FOREWORD

QMAP 22, Geology of southern Victoria Land, is the last of the New Zealand geological map series that was a key mission for GNS Science from 1993 to 2011. The main purpose was to update the 1st edition of the 1950s 1:250 000 geological map of New Zealand, incorporating new field work and discoveries, but it also allowed the development of a single seamless digital geological database for the whole country. QMAP 22 had as its predecessor the NZ Geological Survey Bulletin n.s. 71 “Geology of Victoria Land between the Mawson and Mulock Glaciers, Antarctica”, published in 1962. This also covered the same 230-km-long sector of the Transantarctic Mountains that included historic McMurdo Sound and the Dry Valleys. This first 1:250 000 regional geological map was based largely on field work from dog-sled journeys along the coast and across the back of the mountains by geologists Bernie Gunn and Guyon Warren, but supplemented by over 100 references including many from the Heroic Era.

In the last 50 years, the nature and purpose of Antarctic exploration has changed enormously. From the Heroic Era to the 1960s the focus of geological exploration was mapping itself, discovering and recording the character of the region. By the time the Gunn & Warren map was published the basic geological framework had been established in both space and time, reflected in the Antarctic-wide map compilation of Craddock et al. (1970) just a few years later. But in the decades that followed research became increasingly focused on particular issues, rocks or time periods: basement granites, Beacon sandstone, Erebus Volcano, ice sheet history, tectonic history, landscape evolution. In addition new techniques for remote-sensing, sampling and dating rocks were developed, and the rise of microbiology and genomics has revealed previously unknown biota on and within soil and rock, interesting biologists in the age and nature of these materials.

QMAP 22 has done the Antarctic science community a singular service in this masterful and authoritative compilation of the wide range of geological data published and unpublished over this period. The accompanying text provides a brief, non-technical introduction to the region and its history of geological exploration, including key developments in recent years, followed by a summary of geological formations (age, extent, significance) from Precambrian to Holocene. The focus has been on accurate documentation, with significant differences within the scientific community fairly acknowledged. A feature of the work is the effort made by the compilers in consulting the extensive literature (over 500 papers and 190 maps cited), months of field-checking, and distribution for external review to a dozen or so experts. The accompanying map is a masterpiece of clarity and detail considering it covers an area of ~50 000 square km and represents over 200 different rock units. It will have value both on walls or tables for big picture conversations, or as enlarged segments for specific projects. The map and database will also be welcomed as a framework for adding either new data or data from new categories by the present and future generations of researchers in the region.

P.J. Barrett
November 2012

CONTENTS

ABSTRACT

The "Geology of southern Victoria Land" is a 1:250 000 map and monograph describing the geology of the largest ice-free area in Antarctica. Covering the region between the Fry Glacier in the north and the Skelton Glacier in the south (~76°30'S–78°45'S), and from the Polar Plateau to Ross Island (158°E–170°E), the map replaces a 1:250 000 map published in 1962. Geological information has been obtained from published and unpublished mapping by researchers from GNS Science, New Zealand universities and the United States Antarctic Program. The accompanying illustrated text summarises the geology and landforms of the area, as well as previous geological exploration. An appendix includes a lexicon of adopted stratigraphic names, unit codes and descriptions. All geological data are held in a Geographic Information System, and are available in digital format.

The region is crossed by a major rift basin, its uplifted shoulder forming the Transantarctic Mountains escarpment. Associated with this rift are large stratovolcanoes on Ross Island and on the mainland nearby. In the Transantarctic Mountains, Neoproterozoic and Paleozoic granitoids and their host rocks are overlain by a thick sequence of Devonian-Triassic sedimentary rocks, and intruded by Jurassic dolerite sills. Eocene to Holocene deposits in the Dry Valleys and beneath the Ross Sea, including the products of Miocene and later volcanism, preserve a record of ice sheet and glacier fluctuations.

The map differentiates Neoproterozoic Skelton Group, comprising metasedimentary rocks of greenschist to amphibolite facies, from late Proterozoic to early Paleozoic granitic plutons of the Granite Harbour Intrusive Complex, which are classified into four petrogenetic suites. These basement rocks, truncated by the Kukri Erosion Surface, have been overlain by sedimentary rocks of the Beacon Supergroup which includes the Devonian Taylor Group and the Permian to Triassic Victoria Group, together differentiated into 12 constituent formations. Jurassic Ferrar Group dolerite sills and dikes intrude both basement and Beacon Supergroup rocks. The extrusive Mawson Formation and Kirkpatrick Basalt of the Ferrar Group are exposed locally. The map shows Cenozoic volcanic rocks (McMurdo Volcanic Group) of Mt Erebus/Ross Island and the southern Ross Sea region in the context of the Transantarctic Mountains and Dry Valleys. Structural features of the intervening offshore Victoria Land Basin are depicted on the cross-section. Miocene-Holocene glacial deposits (tills and drift), lacustrine, coastal, and slope deposits have been differentiated based on lithology content, weathering, geomorphological criteria and the limited dating available.

Keywords

Ross Sea Drift; ice sheet till; local alpine till; scree; colluvium; glaciolacustrine; Prospect Formation; Sirius Group; Taylor Drift; Wilson Drift; Bull Drift; Quartermain Till; Peleus Till; McMurdo Volcanic Group; basanite; phonolite; trachyte; Victoria Land Basin; Ferrar Dolerite; Basement Sill; Peneplain Sill; Asgard Sill; Mount Fleming Sill; Kirkpatrick Basalt; Mawson Formation; Beacon Supergroup; Taylor Group; Victoria Group; Pyramid Erosion Surface; Kukri Erosion Surface; Granite Harbour Intrusive Complex; pluton; granite; granodiorite; orthogneiss; DV2 Suite; Vanda Dikes; DV1a Suite; hornblende-biotite granodiorite; Bonney Pluton; DV1b Suite; biotite granite; Koettlitz Glacier Alkaline Suite; Skelton Mafic Intrusives; Hillary Granitoids; Skelton Group; marble; schist; McMurdo Sound; Ross Island; Mt Erebus; Mt Terror; Mt Bird; White Island; Black Island; Mt Discovery; Mt Morning; Brown Peninsula; Ferrar Glacier; Koettlitz Glacier; Skelton Glacier; Mackay Glacier; Allan Hills; Convoy Range; Quartermain Mountains; Royal Society Range; Dry Valleys; Victoria Valley; Wright Valley; Taylor Valley; Beacon Valley; Arena Valley; Miers Valley.

The southern Victoria Land region of Antarctica borders the Ross Sea at the northern margin of the vast Ross Ice Shelf. It includes a part of the Transantarctic Mountains, one of the largest mountain ranges on earth, and extends inland to the Polar Plateau. Southern Victoria Land is a relatively accessible part of Antarctica, for in late summer suitable ships can travel south down McMurdo Sound as far as Ross Island (latitude 77°10'S to 77°51'S). This ease of access attracted the attention of the early 20th century explorers Robert Falcon Scott and Ernest Shackleton, whose expeditions built huts on Ross Island, explored the immediate area, and set out from there on their marches to the South Pole.

New Zealand and the United States of America currently operate bases on Ross Island (Scott Base and McMurdo Station respectively) in support of scientific research. These are the modern gateways to much of the Pacific sector of Antarctica. The "heroic era" history of southern Victoria Land, the wildlife, the spectacular landforms and scenery, and ease of access have resulted in the region becoming a focus for Antarctic tourism.

The geology is remarkable. The region is crossed by a major rift basin, the uplifted western shoulder of which forms the Transantarctic Mountains escarpment. Large stratovolcanoes associated with the rift are present on Ross Island and on the mainland nearby, and there are many smaller volcanic centres throughout the area. In the Transantarctic Mountains, Neoproterozoic and Paleozoic granitoids and their host metasedimentary rocks are overlain by a thick sequence of sedimentary rocks intruded by extensive dolerite sills and exposed in spectacular outcrops of the ice-free Dry Valleys, the mountain range crest, and the nunataks which project through the ice of the Polar Plateau. The Eocene to Holocene deposits in the Dry Valleys and beneath the Ross Sea preserve a record of ice sheet and glacier fluctuations, from which the history of Antarctic and global climate change can be inferred.

The first geological maps of this area were made over a hundred years ago. More intensive exploration, mapping and interpretation began during the International Geophysical Year of 1957–1958, with detailed work by earth scientists from New Zealand, the United States of America, Italy, Australia, and Russia in the following decades. This new geological map and monograph, covering the area from the Convoy Range to the Skelton Glacier (76°30'S to 78°45'S) and from the Polar Plateau to Ross Island (158°00'E to 170°00'E; Fig. 1), incorporates fieldwork undertaken as part of the International Polar Year 2007–2008 celebrations. It commemorates the achievements of the geologists of the "heroic era" (1901–1917), and marks 50 years of earth science research in southern Victoria Land since the seminal work of Gunn & Warren (1962).

GEOLOGICAL EXPLORATION IN SOUTHERN VICTORIA LAND

Geology in the "heroic era"

In 1839–1843 an expedition led by Captain (later Sir) James Clark Ross of the Royal Navy ventured south through the Antarctic pack ice in the ships HMS *Erebus* and *Terror* and into the open water beyond, now known as the Ross Sea. After charting the western coastline and dredging samples from the sea bed, on the 27th of January 1841 he sighted Ross Island, named the high volcano Mt Erebus and its companion peak Mt Terror, and reported that Erebus was in eruption, "emitting flame and smoke in great profusion" (Ross 1847).

The British National Antarctic (Discovery) Expedition of 1901–1904 was the first official British exploration of the continent since James Clark Ross. Commanded by Robert Falcon Scott, the expedition established a base on Ross Island, from where they made exploratory sledging journeys to the south and west. The party included Hartley Travers Ferrar, a recent geology graduate, who in the austral spring of 1902, with Ernest Shackleton and Edward Wilson, made the first major journey of the expedition. With great difficulty, the inexperienced trio man-hauled a laden sledge to White Island, recording that it is formed of relatively young volcanic rocks. The same year, a party led by Albert Armitage travelled west across the McMurdo Ice Shelf to the Antarctic continent, ascending a glacier which crosses the Transantarctic Mountains escarpment to reach an elevation of 8200 feet (2500 m). In so doing they discovered the Polar Plateau. The following year a party which included both Scott and Ferrar retraced Armitage's western journey and extended it, naming the glacier which they followed the Ferrar Glacier. The first of the Dry Valleys was discovered when, returning from the Polar Plateau in thick cloud, Scott, William Lashly and Edgar Evans sledged northeast along the Taylor Glacier, instead of bearing east down the Ferrar. The Taylor Glacier terminates close to a large frozen lake in an otherwise ice-free valley and, since it was not feasible to man-haul their sledge down this valley, they had to retrace their steps.

Ferrar collected carbonised plant remains from rocks which he named the Beacon Sandstone Formation (after prominent peaks named Beacon Heights by Armitage; see front cover) and recognised that plant remains implied a much warmer climate at some time in the past. Ferrar had collected fossils of great significance—one of the many samples lodged with the Natural History Museum in London was in 1928 split open by Dr W.N. Edwards to reveal fossil leaves of the Gondwanan tree *Glossopteris*, of Permian age. From his own observations and the samples collected by others, Ferrar summarised the geology (Ferrar 1907, 1925). Though he was major author of the field geology descriptions (1907), which also covered the moraines, geomorphology, land ice and sea ice, "the scientific descriptions of the specimens... ...[were] entrusted to Dr G.T. Prior" at the British Museum (Prior 1907). With the help of surveyor and cartographer Lieutenant George

Figure 1 Location map showing the part of the Transantarctic Mountains and Ross Sea covered by this "Geology of southern Victoria Land" 1:250 000 map.

Mulock, Ferrar completed a beautiful map at a scale of 1:291 840 (Fig. 2). It covers an area of ice shelf, sea and land measuring about 60 000 km^2, from the Polar Plateau margin to Cape Crozier at the eastern extremity of Ross Island, and from Mt Cocks and Mt Morning in the south as far north as Cape Bernacchi. The map and report established a fundamental five-fold subdivision of the solid geology ("Gneiss and Crystalline Limestone; Granite; Beacon Sandstone; Dolerite; Recent Volcanic Rocks") which is still applicable more than a century later.

Tannatt William Edgeworth David, Professor of Geology at the University of Sydney, joined Ernest Shackleton's British Antarctic (Nimrod) Expedition to southern Victoria Land in 1907 and was appointed director of the scientific staff. Four other geologists (Raymond Priestley, Leo Cotton, Philip Brocklehurst and Douglas Mawson) were also included, though officially Mawson was the physicist. Edgeworth David, Mawson and three others made the first ascent of Mt Erebus and recorded their observations, though "for the greater part of the time of our visit a vast column of steam and sulphurous gas obscured everything at the bottom of the crater". Edgeworth David and Mawson, with the expedition doctor Alistair Mackay, man-hauled north along the Victoria Land coast and recorded the geology on their way to an ascent of the Drygalski Ice Tongue and glacier, by which they reached the South Magnetic Pole. Edgeworth David & Priestley (1909) gave a general account of the Nimrod observations, and, with others (e.g. Priestley 1909; Edgeworth David & Priestley 1914; Benson 1916) described other aspects of the geological work, although no map was published. Their observations included the recognition of raised beaches and an elegant cross section of Mt Erebus.

Scott's 1910–1913 British Antarctic (Terra Nova) Expedition included the geologists Raymond Priestley, T. Griffith Taylor and Frank Debenham, plus Charles Wright, engaged as physicist and glaciologist and whose work included gravity measurements. With Edgar Evans, Taylor, Debenham and Wright explored and mapped the Transantarctic Mountains and valleys. The so-called western journeys of 1911–1912 covered an area between the Koettlitz and Mackay glaciers and included a trip to the Walcott Glacier, a circumnavigation of the Kukri Hills, a traverse of the Wilson Piedmont Glacier, and a partial ascent of the Mackay Glacier (Taylor 1913). Fossil fish remains discovered by Debenham in moraine northeast of Mt Suess (their Gondola Ridge) were later dated as Devonian by Arthur Smith-Woodward of the Natural History Museum (Young & Long 2005), providing some age constraint for at least a part of Ferrar's Beacon Sandstone Formation. Debenham also found coal in the moraine. Other samples were later found to include *Glossopteris* (Seward 1914).

The scientific reports from the Terra Nova expedition, published in two volumes by the British Museum of Natural History, gave an accurate account of the general geology, and included papers by the expedition geologists and numerous other experts on fossil fish, metamorphic, sedimentary, volcanic and plutonic rocks, and fossil plants. Debenham's map of Granite Harbour remains the best geological map of that site (Smith & Debenham 1921; Smith 1924). The geological work suggested a "Gondwana" age for the Beacon rocks, and noted the similarity of the Transantarctic Mountains covering strata to the Carboniferous-Permian and Triassic-Jurassic rocks of southeast Tasmania and New South Wales. When studying the dolerite samples collected, Benson (1916) also drew attention to the similar occurrences of quartz dolerite in Tasmania, South Africa, South America and elsewhere in Antarctica. These observations provided early support for the concept of a Gondwana supercontinent. Petrologic descriptions of volcanic samples were subsequently published by Smith (1954).

Shackleton's Imperial Trans-Antarctic Expedition of 1914–1917 (*Endurance* and *Aurora*) saw the Ross Sea party establish depots south from McMurdo Sound, but their efforts left no time for scientific research. Following this ill-fated expedition, and the subsequent rescue of the remaining personnel by Ernest Shackleton in 1917, the "heroic era" of exploration came to a close and southern Victoria Land saw no further exploration for 30 years.

International Geophysical Year and the Transantarctic Expedition

Although the United States Navy 'Operation Highjump' of 1946–1947 collected aerial photographs of southern Victoria Land, ground-based observations did not begin until 1955, when the United States Navy began establishing facilities in McMurdo Sound to support work for the International Geophysical Year (IGY). McMurdo Station was built beside the Discovery Expedition hut on Ross Island, a land runway was built at Marble Point, and an ice runway constructed on the Ross Ice Shelf (Williams Field). A programme of trimetrogon (TMA) aerial black and white photography was established by the United States Navy, and later inherited by United States Geological Survey (USGS), and these photos remain a valuable mapping resource. New Zealand's Scott Base, opened in early 1957, was established as the Ross Sea base for the Commonwealth Transantarctic Expedition headed by the British explorer Vivian Fuchs; the New Zealand Ross Sea support team was led by Edmund Hillary. From Scott Base, using United States air support where feasible, a new era of geological and other scientific investigations began. Over the period 1955 to 1958, much of southern Victoria Land was explored by field parties either man-hauling or using dog teams. The Northern Survey Party (Richard Brooke, Murray Douglas, and geologists Bernie Gunn and Guyon Warren) spent the spring and summer of 1957–58 in a geological and topographical survey of the Victoria Land mountains, after which Gunn and Warren published a seminal 1:250 000 geological map and accompanying text (Gunn & Warren 1962). First published in New Zealand, their bulletin was subsequently republished under the auspices of the Commonwealth Transantarctic Expedition. Their map covered a region between the Mawson and Mulock glaciers, an area of about 62 500 km^2, and has remained a valuable reference work for over 50 years.

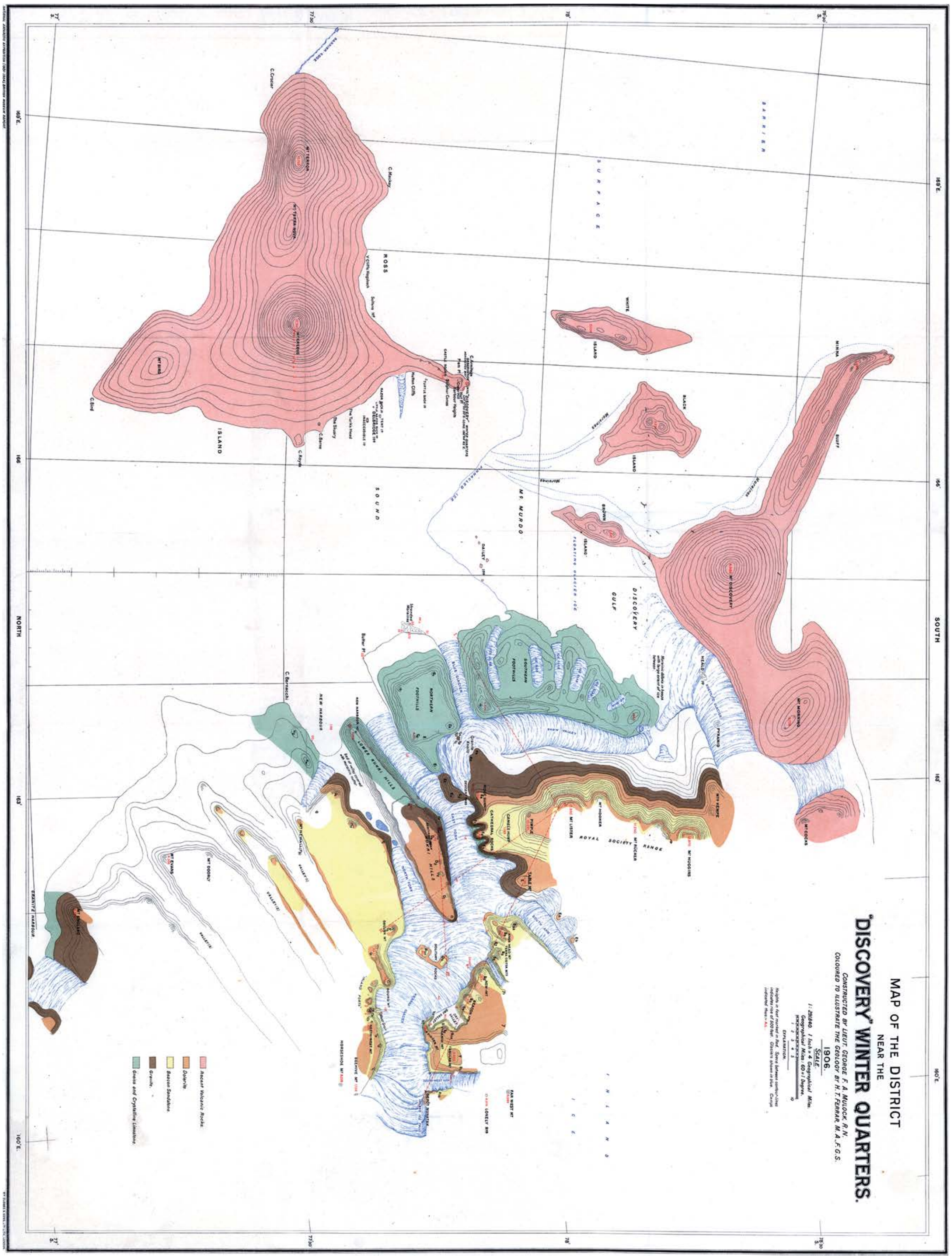


Figure 2 This magnificent hand-drawn and hand-coloured map is the result of Hartley Ferrar's geological work in McMurdo Sound and the Royal Society Range during Scott's Discovery Expedition, and was published in 1906. Geological mapping was continued by Taylor, Debenham and Priestley during the Terra Nova Expedition. This map was the starting point for geological explorations of southern Victoria Land. Colours on the map represent 'Recent Volcanic Rocks' (pink), 'Dolerite' (orange), 'Beacon Sandstone' (yellow), 'Granite' (brown) and 'Gneiss and crystalline limestone' (green).

Reconnaissance work, 1960–1980

Following the successful Commonwealth Transantarctic Expedition and the establishment of permanent bases and air support facilities, the New Zealand and United States governments continued to support scientific work in Antarctica. Much of the earth science work was done by geologists from the New Zealand Geological Survey or by university staff and students, particularly from Victoria University of Wellington. The Victoria University Antarctic Expeditions (VUWAE) began in 1958, when Barrie McKelvey and Peter-Noel Webb were flown into the Taylor Glacier area by United States helicopter, and continued the following year when they returned in a team that mapped in the Wright and Victoria Dry Valleys (Bull 2009). During the summer of 1960–1961, a team traversed the area between the Koettlitz and Blue glaciers and produced a valuable 1:100 000 map that showed the complexity of moraines as well as the lithological variety of basement rock (Blank et al. 1963). American geologists also visited the Dry Valleys region (Hamilton & Hayes 1960, 1963), with a focus on the Ferrar Dolerite (Hamilton 1965). These studies overlapped with Gunn & Warren (1962), who absorbed and incorporated the reconnaissance mapping by McKelvey, Webb and others (McKelvey & Webb 1959, 1962; Webb & McKelvey 1959). Joint US-Russian field parties also visited the region and produced a summary geological map (Lopatin 1972), which updated parts of an earlier 1:1 000 000 map by Warren (1970). These successive expeditions were given logistic support through the New Zealand Antarctic Research Programme (NZARP, later Antarctica New Zealand) and United States Antarctic Research Programme (USARP, later USAP).

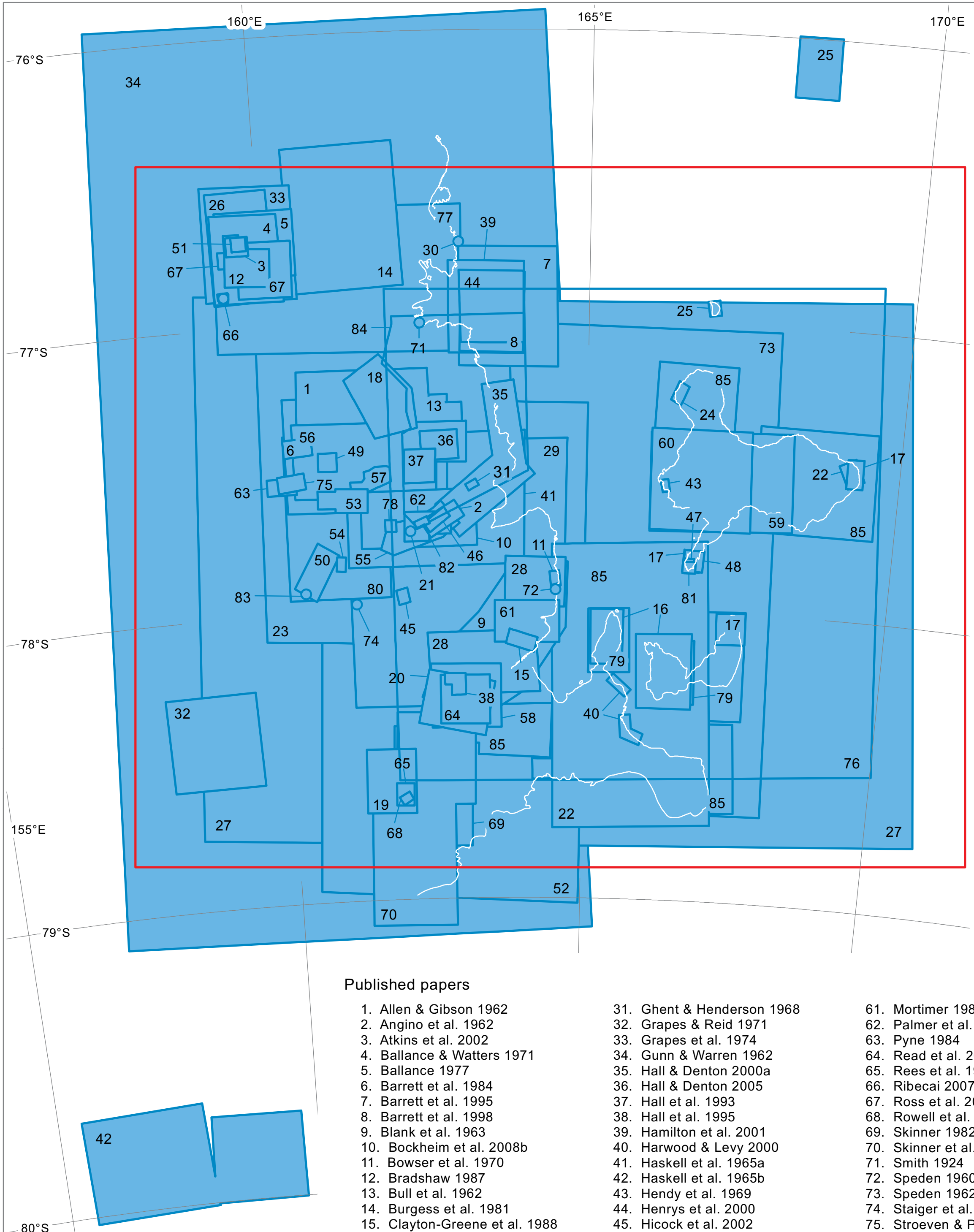
Detailed mapping and specialist studies, 1980–2010

Gunn, Warren, and their contemporaries and successors had, by about 1980, established the nature and distribution of the main rock types of southern Victoria Land. Since then, the emphasis of earth science research in the region has changed from reconnaissance studies to more detailed research intended to improve the understanding of specific units (e.g. the Paleozoic-Mesozoic Beacon Supergroup and the Miocene-Recent McMurdo Volcanic Group). The former emphasis on basic geological mapping was reduced, although specialist studies instigated by the Antarctic Coal Measures Study Group of Australia were later extended by New Zealand Geological Survey geologists and the results published as 1:50 000 maps covering 8000 km^2 of the Dry Valleys (e.g. McElroy & Rose 1987; Woolfe et al.1989; Fig. 3). The areas mapped in detail have perhaps the best rock exposures in the Transantarctic Mountains and the added benefit of being easily covered on foot, without the need for extensive helicopter or snowmobile support. In places the maps incorporated other NZARP work on the pre-Beacon granitoids and metasedimentary rocks (e.g. Findlay et al. 1984). Only the more recent of these maps give detailed information on the post-Ferrar Group (?Oligocene to Holocene) glacial geology (e.g. Pocknall et al. 1994; Isaac et al. 1996).

The metasedimentary and granitic rocks were the subject of much New Zealand research from the early 1980s. Detailed work began with expeditions under the Antarctic Division of the Department of Industrial and Scientific Research (DSIR), which included ongoing work by David Skinner and new mapping by Bob Findlay, Dave Craw and others (Skinner 1982, 1983; Findlay 1982; Findlay et al. 1984). In 1986 Dave Craw initiated research by the University of Otago Geology Department. Mapping and laboratory studies of the Neoproterozoic and Paleozoic rocks by students and their supervisors (e.g. Allibone 1992; Smillie 1992; Cox 1993; Allibone et al. 1993a,b; Walcott & Craw 1993; Worley & Cooper 1995; Simpson & Aslund 1996; Jones 1997a,b; Cook & Craw 2001, 2002; Read et al. 2002; Read 2010; Cooper et al. 2011) have been an important source of information for this map. Other specialist investigations of the geology of southern Victoria Land during this period included studies on the Ferrar Group dolerites and Mawson Formation (e.g. Morrison & Reay 1995; Elliot et al. 1999; McClintock & White 2002, 2006; Marsh 2004; Ross et al. 2008), the McMurdo Volcanic Group (e.g. Kyle 1981b, 1994; Kyle et al. 1992; LeMasurier et al. 1990; Martin et al. 2010), and continued work on the Beacon Supergroup by VUWAE (e.g. Pyne 1986; Arnot 1991; Wolfe 1991).

Antarctic glacial history and the great age of the Dry Valleys

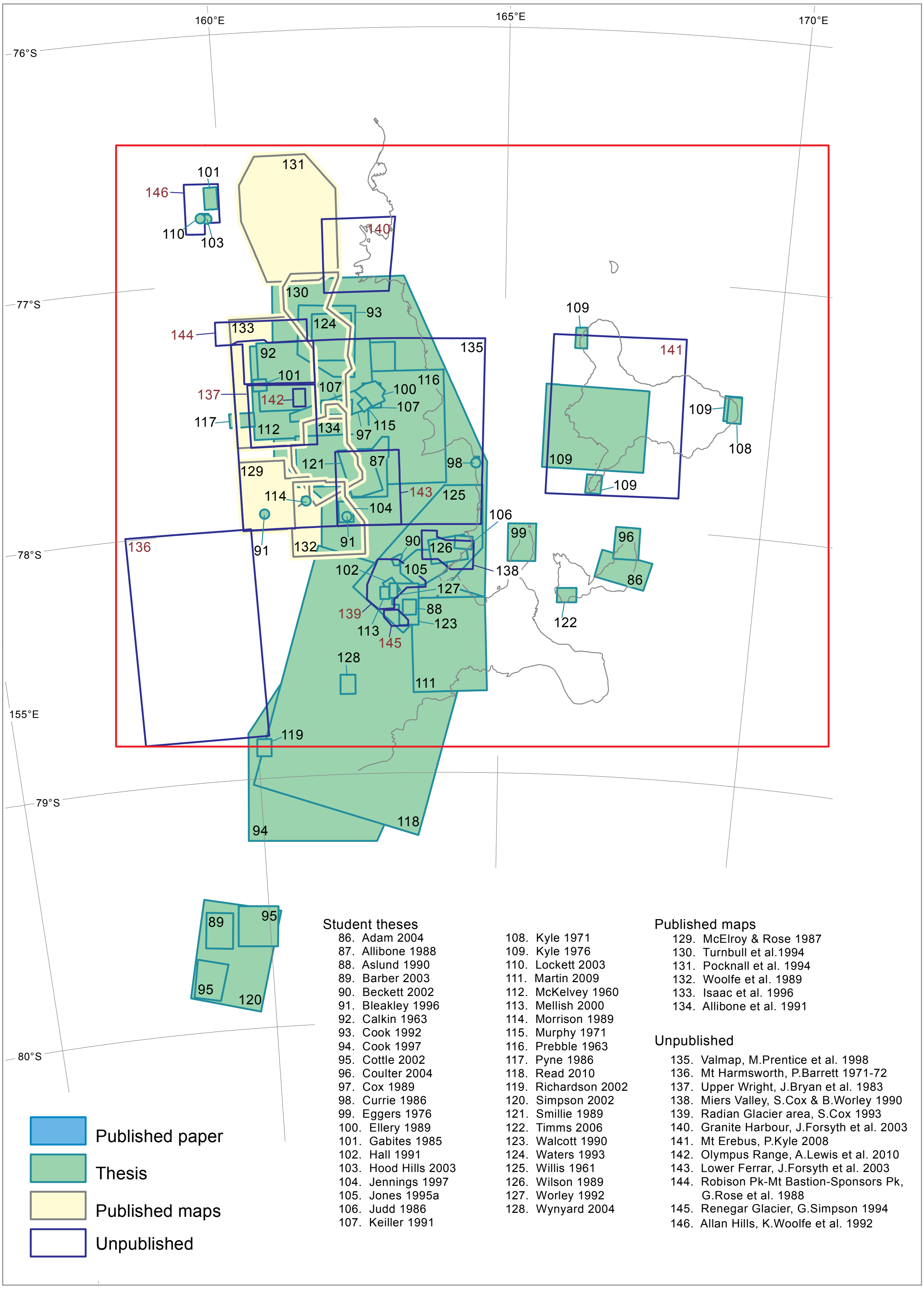
The Ross Ice Shelf, or "Great Icy Barrier", was first mapped by Ross in 1841 and 1842 (Ross 1847). Scott (1905) suggested that it had previously been more extensive in the past. Taylor (1922) thought the Antarctic Ice Sheet was likely to have originated in Miocene time and inferred that it was more extensive in the Pliocene than it is at the present day. Wright & Priestley (1922) noted Antarctic glaciation "apparently began there in Eocene or Oligocene time". However, up until the early 1960s, many believed that the glacial deposits of the McMurdo region were formed during the Quaternary period: "This writer believes that as yet there is no good evidence of Tertiary Antarctic glaciation" (Nichols 1964; see also Barrett 2009). Proof of pre-Quaternary glaciation in the McMurdo Sound area came when McMurdo Volcanic Group basalts overlain and underlain by glacial features were dated radiometrically at 2.8 Ma and 3.6 Ma (Armstrong et al. 1968; Denton et al. 1970). In 1972–1973, Deep Sea Drilling Project Leg 28 drillholes in the Ross Sea area found glacial marine debris as old as Late Oligocene (Hayes & Frakes 1975). Geomorphologists and soil scientists suggested there were Miocene moraines on land (Claridge & Campbell 1978) and possibly Tertiary cirque landforms (Selby & Wilson 1971; Wilson 1973). These results and the pioneering work on the surficial glacial and periglacial deposits which are so widespread in southern Victoria Land (Calkin 1963, 1964a,b; Campbell & Claridge 1978, among others), led to the recognition that the Dry Valleys are many millions of years old. More recent work (e.g. Marchant et al. 1993a,b, 1996; Sugden et al. 1995a,b; Summerfield et al. 1999; Denton & Sugden 2005; Bockheim 2010) suggests that



Published papers

1. Allen & Gibson 1962
2. Angino et al. 1962
3. Atkins et al. 2002
4. Ballance & Watters 1971
5. Ballance 1977
6. Barrett et al. 1984
7. Barrett et al. 1995
8. Barrett et al. 1998
9. Blank et al. 1963
10. Bockheim et al. 2008b
11. Bowser et al. 1970
12. Bradshaw 1987
13. Bull et al. 1962
14. Burgess et al. 1981
15. Clayton-Greene et al. 1988
16. Cole & Ewart 1968
17. Cole et al. 1971
18. Cook 1991
19. Cook 2007
20. Cottle & Cooper 2006a
21. Dahl & Palmer 1981
22. Denton & Marchant 2000
23. Denton et al. 1993
24. Dochat et al. 2000
25. Ellerman & Kyle 1990
26. Elliot & Hanson 2001
27. Ferrar 1907
28. Findlay 1978
29. Findlay 1982
30. Gardner et al. 2006
31. Ghent & Henderson 1968
32. Grapes & Reid 1971
33. Grapes et al. 1974
34. Gunn & Warren 1962
35. Hall & Denton 2000a
36. Hall & Denton 2005
37. Hall et al. 1993
38. Hall et al. 1995
39. Hamilton et al. 2001
40. Harwood & Levy 2000
41. Haskell et al. 1965a
42. Haskell et al. 1965b
43. Hendy et al. 1969
44. Henrys et al. 2000
45. Hicock et al. 2002
46. Higgins et al. 2000a
47. Kyle & Treves 1973
48. Kyle 1990b
49. Lewis et al. 2007
50. Linkletter et al. 1973
51. Lloyd-Davies et al. 2009
52. Lopatin 1972
53. Marchant et al. 1993a
54. Marchant et al. 1993b
55. McCraw 1962
56. McKelvey & Webb 1962
57. McLeod et al. 2008
58. Mellish et al. 2002
59. Moore & Kyle 1987
60. Moore & Kyle 1990
61. Mortimer 1981
62. Palmer et al. 1967
63. Pyne 1984
64. Read et al. 2002
65. Rees et al. 1989
66. Ribecai 2007
67. Ross et al. 2008
68. Rowell et al. 1993
69. Skinner 1982
70. Skinner et al. 1976
71. Smith 1924
72. Speden 1960
73. Speden 1962
74. Staiger et al. 2006
75. Stroeven & Prentice 1997
76. Stuiver et al. 1981
77. Sugden & Denton 2004
78. Swanger et al. 2010
79. Vella 1969
80. Webb 1963
81. Wellman 1964
82. Wilch et al. 1993
83. Wilson et al. 2002
84. Forsyth et al. 2002
85. Wright & Kyle 1990a-i

Figure 3 Major data sources used in compiling the southern Victoria Land map. Details for these sources are provided in the references. Unpublished maps are held in the map archives of GNS Science or in university libraries. The source map outlines and bibliographic references are also available as a part of the digital data set. The digital data set extends beyond the published map sheet (red rectangle).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78°S
79°S
80°S
155°E
Published paper
Thesis
Published maps
Unpublished
Student theses
86. Adam 2004
87. Allibone 1988
88. Aslund 1990
89. Barber 2003
90. Beckett 2002
91. Bleakley 1996
92. Calkin 1963
93. Cook 1992
94. Cook 1997
95. Cottle 2002
96. Coulter 2004
97. Cox 1989
98. Currie 1986
99. Eggers 1976
100. Ellery 1989
101. Gabites 1985
102. Hall 1991
103. Hood Hills 2003
104. Jennings 1997
105. Jones 1995a
106. Judd 1986
107. Keiller 1991
108. Kyle 1971
109. Kyle 1976
110. Lockett 2003
111. Martin 2009
112. McKelvey 1960
113. Mellish 2000
114. Morrison 1989
115. Murphy 1971
116. Prebble 1963
117. Pyne 1986
118. Read 2010
119. Richardson 2002
120. Simpson 2002
121. Smillie 1989
122. Timms 2006
123. Walcott 1990
124. Waters 1993
125. Willis 1961
126. Wilson 1989
127. Worley 1992
128. Wynyard 2004
Published maps
129. McElroy & Rose 1987
130. Turnbull et al.1994
131. Pocknall et al. 1994
132. Woolfe et al. 1989
133. Isaac et al. 1996
134. Allibone et al. 1991
Unpublished
135. Valmap, M.Prentice et al. 1998
136. Mt Harmsworth, P.Barrett 1971-72
137. Upper Wright, J.Bryan et al. 1983
138. Miers Valley, S.Cox & B.Worley 1990
139. Radian Glacier area, S.Cox 1993
140. Granite Harbour, J.Forsyth et al. 2003
141. Mt Erebus, P.Kyle 2008
142. Olympus Range, A.Lewis et al. 2010
143. Lower Ferrar, J.Forsyth et al. 2003
144. Robison Pk-Mt Bastion-Sponsors Pk, G.Rose et al. 1988
145. Renegar Glacier, G.Simpson 1994
146. Allan Hills, K.Woolfe et al. 1992

as the Transantarctic Mountains began to rise ~55 Ma ago (Fitzgerald 2002) a fluvial landscape developed; this was followed by wet-based glaciation from 34 to 14 Ma ago and subsequently by the largely dry-based glaciers found in the region today. Evidence for the persistent cold climate of the inland Dry Valleys comes from volcanic ash as old as 14 Ma, high surfaces older than 10 Ma demonstrated by cosmogenic dating, perched erosional surfaces and channel systems, and glacier ice and soils that have survived in upland areas. However, contrary opinions exist regarding some aspects (e.g. Ng et al. 2005; Sletten et al. 2007).

Interest in the surficial deposits, and what they can reveal of past climatic conditions, was partly the impetus behind the 1972–1974 Dry Valley Drilling Project (DVDP; McGinnis 1981) and subsequent offshore drilling (Barrett 2009). One of the key findings of the drilling has been that onshore glacial deposits in the valley floors date back to the Late Miocene, but offshore glacial deposits date back to Early Oligocene times. Offshore drilling programmes devoted to improving the record of glacial history and climate fluctuations have included MSSTS in 1979 (Barrett 1986); CIROS from 1984–1986 (Barrett 1989); and the Cape Roberts Project from 1997–1999 (Barrett et al. 1994), which recovered a series of drill cores through 1500 m of strata between 34 and 17 Ma old from beneath the western Ross Sea (Cape Roberts Science Team 1998a,b, 1999, 2000; Barrett 2007). In 2006 and 2007, a new Antarctic geological drilling programme (ANDRILL) recovered 1285 m of core (AND-1B) from beneath the McMurdo Ice Shelf (Naish et al. 2007a,b; 2008), and 1139 m of core (AND-2A) from beneath the sea ice of southern McMurdo Sound (Harwood et al. 2009). These cores record the detail of glacial and interglacial sedimentation over the last five million years (Naish et al. 2009) and the pattern of ice sheet and climate change over the last 20 million years (McKay et al. 2009; Fielding et al. 2011).

THE QMAP SERIES

This geological map of the Ross Island and Dry Valleys region of Antarctica (Fig. 1) has been completed as the final component of the QMAP (**Q**uarter-million **MAP**) series of New Zealand's Institute of Geological and Nuclear Sciences (GNS Science). Within the period 1994–2011, QMAP built a geographic information systems (GIS) database of New Zealand geology and published 21 full colour 1:250 000 geological maps which cover New Zealand, each with an explanatory monograph. The success of this series encouraged the QMAP team to apply the same methods to compile a similar digital database for that part of Antarctica where New Zealand earth scientists have made their major contribution i.e., the area between the Polar Plateau and the western coastline of McMurdo Sound.

Rock units are shown on this map primarily in terms of their age of deposition, eruption or intrusion, but also differentiated on rock type (lithology), either using colour variation or appropriate overprints. An exception is made for volcanic rocks—the Neogene to Recent McMurdo Volcanic Group rocks are coloured red, to indicate that they generally retain their volcanic landforms. Age subdivision is in terms of the international time scale (Gradstein et al. 2012); correlation between the geological time scale and absolute ages is given in the chart printed inside the front cover. This text summarises key features only and is not intended to be an exhaustive description of the rock units mapped, or their geological history. References cited in the text give more detailed information. A comprehensive list of adopted lithostratigraphic names, GIS database unit codes, map codes, reference localities and brief lithological descriptions is provided in the appendix.

The geographic information system

The QMAP series uses computer methods to store, manipulate and present topographic and geological information. The maps are drawn from data stored in a GIS, a database developed and maintained by GNS Science. Both ARC/INFO® and ArcGIS® software have been used to create the GIS, although the data are compatible with most other GIS software.

The 1:250 000 scale map was created from more detailed geological information plotted at 1:50 000 scale on topographic base maps. These maps have 50 m topographic contours and spatially corrected satellite photo imagery. Some of these more detailed geological maps are also available in digital form (e.g. VALMAP, Prentice et al. 1999; Forsyth et al. 2002). The detailed geology has been simplified for digitising, with line work smoothed and geological units amalgamated to a standard system based on age and lithology. All point data (such as dips and strikes) are stored in the GIS, but only representative structural observations are shown on the map. The GIS dataset covers a slightly wider area than the printed map, which had limitations due to maximum paper size. Procedures for map compilation, and details of data storage and manipulation techniques, are given by Rattenbury & Heron (1997).

Data sources

The map and text have been compiled from sources which include published maps and papers, the volumes of the Antarctic Research Series published by the American Geophysical Union, unpublished university theses, and digital data such as the New Zealand rock catalogue and geoanalytical database PETLAB. Much of the Dry Valleys area had been mapped at 1:50 000 in the period 1980–2005; additional field mapping in the 2008–2009 season filled some gaps and resolved some uncertainties. Mapping of the Neogene and recent "drift" deposits is a combination of previous work, outcrop studies, and interpretations made from aerial photographs and satellite imagery. Offshore geology has been taken from both regional-scale (>1:250 000) and local-scale (<1:200 000) publications (e.g. Barrett et al. 1995; Brancolini et al. 1995; Fielding et al. 2008a). The data sources used in map compilation are summarised in Figure 3.

About the map and its reliability

The map uses a Lambert Conformal Conic projection with standard parallels at 76˚40'S and 79˚20'S. It shows an interpretation of the geology of southern Victoria Land between 76˚30'S and 78˚45'S based on existing published and unpublished mapping, limited new mapping, drillholes, aerial photography, satellite imagery and geophysical information. Early work, including 1:50 000 maps of McElroy & Rose (1987), and Woolfe et al. (1989), was severely constrained by a lack of accurate topographic base maps. Studies prior to the mid-1990s were therefore re-plotted onto modern topographic maps using a combination of aerial photograph and satellite imagery interpretation, control from more recent geological work, local knowledge of these areas, or geo-referencing from well-defined topographic features such as glaciers, meltwater channels, ridge crests or mountain tops.

The scale of the map and cross-section has necessitated some generalisation of boundaries and omission of some features in the interests of clarity. For detailed investigation of the map, we recommend using the digital version of the data: pdf and raster versions are available and the vector data enables further analysis and exploration of the data attribute tables. However, enlarging the map beyond 1:50 000 scale is not recommended. A number of very thin units are depicted on the map but not on the cross-section. The cross-section also includes information from offshore seismic surveys projected onto the section line.

Topographic data used in the compilation of this map were created from the 1960s to 2000s by the USGS and Land Information New Zealand (LINZ). In places, locations were adjusted to the Landsat Image Mosaic of Antarctica (LIMA), which has 10 m pixels at ~50–100 m precision, created for the International Polar Year 2007–2008 by the USGS and the British Antarctic Survey. Ice-rock boundaries and blue ice shown on the map were drawn from LIMA imagery. Topographic contours, at 100 m intervals, have been manually adjusted to achieve continuity across dataset boundaries. Bathymetric contours are at 100 m intervals. Hydrographic data have been sourced from a variety of local and regional surveys, including the 14900 series maritime charts (LINZ, Crown Copyright Reserved), but are not intended for navigational purposes. Place names shown are from the New Zealand Gazetteer of Official Geographic Names, maintained by LINZ, as assigned by the New Zealand Geographic Names Board Ngā Pou Taunaha o Aotearoa and the United States Advisory Committee on Antarctic Names (US-ACAN). Although most countries do not explicitly recognise territorial sovereignty claims in Antarctica, most of the land within the map area lies within the Ross Dependency sector subject to New Zealand's territorial claim and administration, but west of 160° latitude is within the Australian Antarctic Territory.

REGIONAL SETTING

Physiography

The Antarctic continent comprises three major domains: the stable craton of East Antarctica; the Transantarctic Mountains; and the tectonically more active amalgamation of younger blocks which forms West Antarctica and the associated West Antarctic Rift System (Talarico & Kleinschmidt 2009). The Transantarctic Mountains extend across the continent for a distance of about 3800 km (Fig. 1), separating East and West Antarctica, and form a partial barrier to the thick continental ice sheet on East Antarctica. Mt Lister, at 4025 m, is the highest peak in the map area (Figs 4, 5).

Between latitudes 76°30'S and 78°45'S, the area covered by this geological map, the Transantarctic Mountains are 70 to 120 km wide and trend almost north-south. In the west, mountain summits project as nunataks through the ice at the margin of the Polar Plateau (e.g. Fig. 6; Mt Brooke in the Coombs Hills, 2630 m; Mt Dearborn in the Willett Range, 2300 m; Mt Crean in the Lashly Mountains, 2550 m). High peaks of the Transantarctic Mountains are generally close to the plateau margin (e.g. from north to south, Convoy Range 2463 m; Mt Bastion 2530 m; Shapeless Mountain 2739 m; Mt Feather 2985 m; Mt Harmsworth 2765 m). Farther east, the Royal Society Range forms an anomalously elevated block 70 km wide, where the crest is within 45 km of the Ross Sea shoreline (Figs 4, 5). Immediately east of the high peaks of Mt Lister (4025 m), Mt Rücker (3831 m) and Mt Huggins (3741 m), the escarpment facing the Ross Sea is 1600–2000 m high above the trough now occupied by the Blue Glacier.

Several large glaciers (e.g. the Mackay, Ferrar and Skelton), fed by ice flowing downward and outward from the East Antarctic Ice Sheet (otherwise termed the Polar Plateau), cross the Transantarctic Mountains in the map area to reach either the Ross Sea or the floating Ross Ice Shelf (Figs 6, 7). Other large glaciers (Koettlitz, Blue, Benson and Fry) are fed by névés east of the Transantarctic Mountains range crest. Some small glaciers fed entirely or in part by ice from the Polar Plateau (e.g. Webb, Upper Wright and Taylor) now terminate within ice-free valleys (e.g. Fig. 8), far from the coast. The Bowers, Wilson and Evans piedmont glaciers, typically 8 to 15 km wide, fringe the Ross Sea coastline.

Topographically, McMurdo Sound is dominated by Ross Island (Fig. 9) with the volcanoes of Mt Terror (3280 m), Mt Bird and Mt Erebus (3794 m) and in southern McMurdo Sound by the composite stratovolcanoes of Mt Morning (2723 m) and Mt Discovery (2681 m) and the 45 km-long peninsula of Minna Bluff. Erebus and Terror form the high points of Ross Island, which is connected by the McMurdo Ice Shelf to White Island, Black Island, Brown Peninsula and the Antarctic mainland. McMurdo Sound reaches bathymetric depths of 1000 m around Ross Island and prominent canyons are developed offshore from the Ferrar and Taylor valleys near Marble Point, and the Mackay Glacier at Granite Harbour (Fig. 4).

In the centre of the map area is the Dry Valleys region, at c. 2500 km^2 the largest ice-free area on the Antarctic continent (Chinn 1990). Though the Taylor Valley (Fig. 8) was discovered by members of Scott's 1901–1904 expedition, the full extent of the ice-free area (including the Victoria, Barwick, Balham, McKelvey and Wright valleys) was not appreciated until the 1950s, when aircraft flew over it. Valley floors are mainly bare, rocky ground (e.g. Fig. 7) as a result of the limited ice feed from the Polar Plateau and because evaporation and sublimation typically remove snow shortly after it falls. In some areas accumulations of snow, partly wind-blown, are sufficient to feed small alpine glaciers. The larger lakes and ponds on the valley floors are frozen (e.g. Lake Vida) or covered by permanent ice (e.g. lakes Fryxell, Bonney, Vanda and Vashka). Don Juan Pond in the upper Wright Valley and other smaller ponds are so saline that they do not freeze. The Dry Valleys have the climate of a hyper-arid polar desert, experiencing some of the largest seasonal temperature variations on earth, with summer maxima of 10ºC and winter minima of -60ºC (Doran et al. 2002a,b), caused by strong solar heating during the summer and radiative cooling during winter. Most precipitation occurs (as snow) during summer (Bromwich 1988). Present snow accumulation along the coast and on the piedmont glaciers appears to be driven by cyclonic systems in the Ross Sea that bring onshore winds from the south and east, which fluctuate with sea temperatures and opposing katabatic wind strength (Bertler et al. 2011). Where water is present, characteristic landforms have developed at various scales (Marchant & Head 2007). Landforms in the relatively warm coastal zone include solifluction lobes, ice-wedge polygons, mature gullies and raised (stranded) beaches. The inland zone hosts gelifluction lobes, sand-wedge polygons, desert pavements, and immature gullies. Landforms of the upland (coldest) zone include debris-covered glaciers and sublimation polygons. Landforms not in equilibrium with the local environment may constitute geomorphic evidence for climatic warming (Marchant & Head 2007).

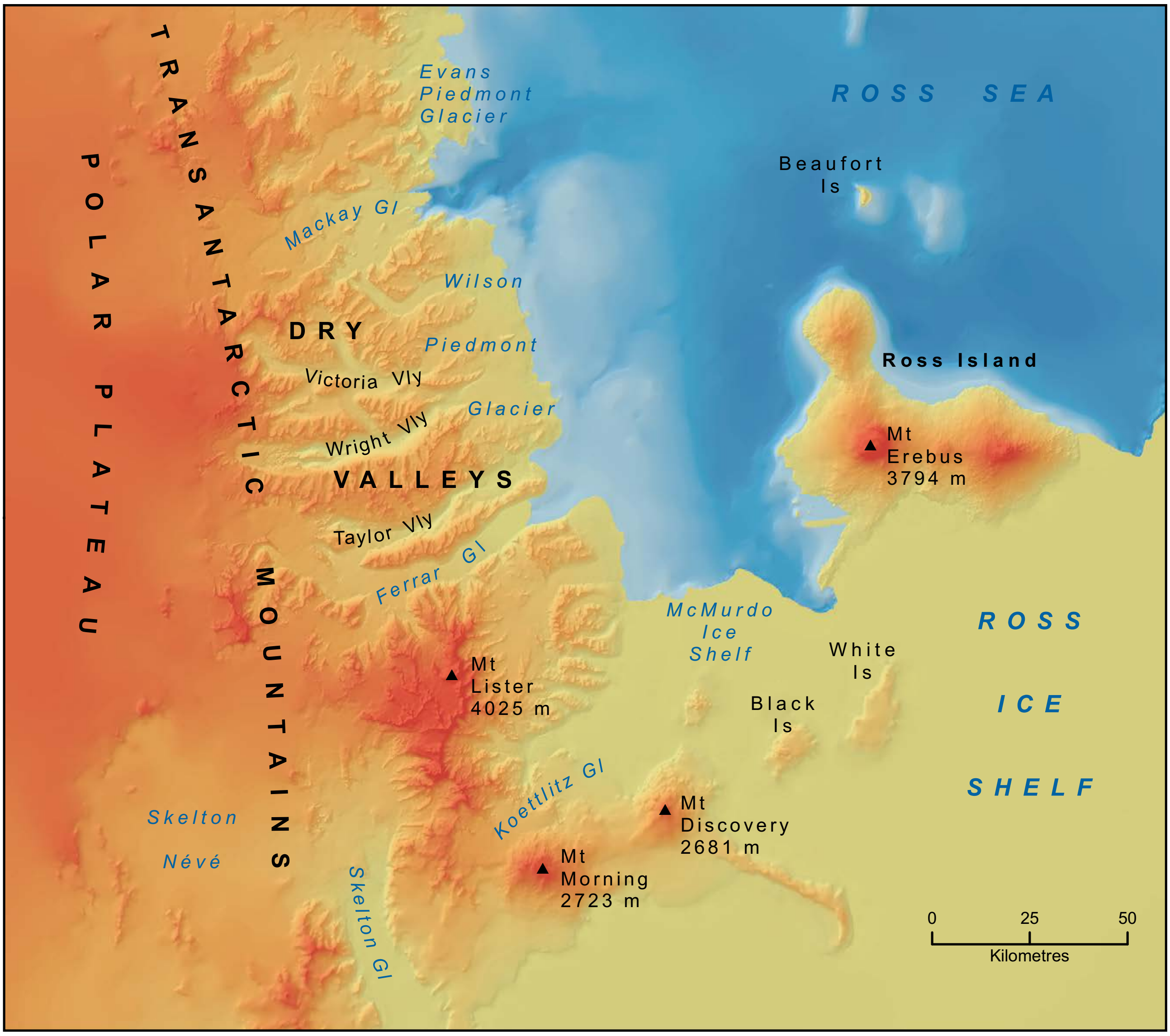


Figure 4 Digital elevation model, coloured according to elevation or bathymetric depth offshore (blue shades), showing the main physiographic features of the map area.

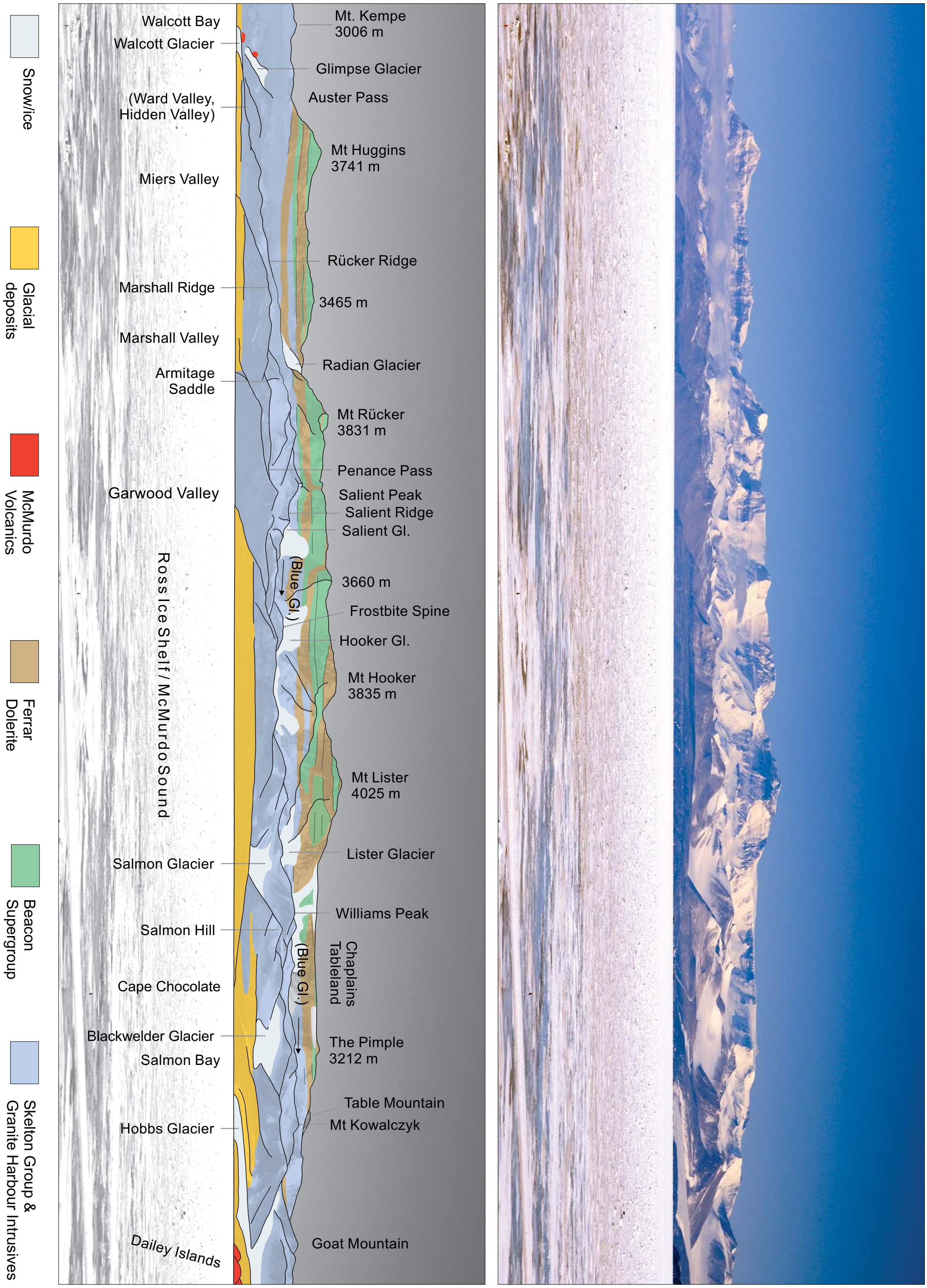


Figure 5 The Royal Society Range of the Transantarctic Mountains, viewed across the Ross Ice Shelf from Hut Point, near McMurdo Station (Photo: D.B. Townsend).

Figure 6 Physiography of East Antarctic Ice Sheet outlet glaciers. Top: Near the crest of the Transantarctic Mountains, ice in the Skelton Névé spills over cliffs of Ferrar Dolerite and Beacon Supergroup sandstone and into the Skelton Glacier (Photo: R. Jongens. Rock nunataks are c.250 m high). Bottom: The lower Skelton Glacier flows through the mountains to the coast, where it is 12 km across and merges into the Ross Ice Shelf (Photo: G.S. Wilson).

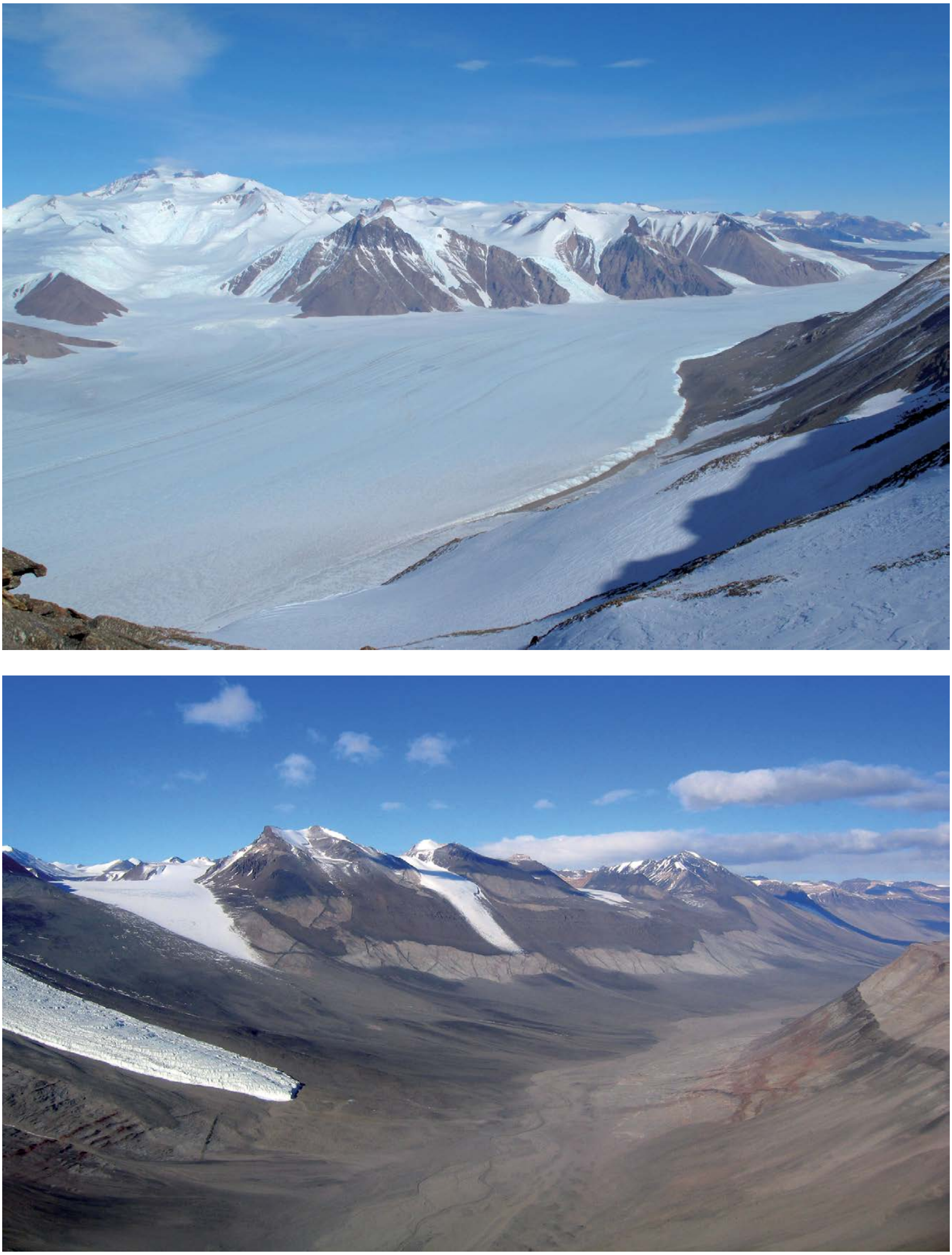


Figure 7 Physiography of valleys through the Transantarctic Mountains. Top: The Ferrar Glacier is an ice sheet outlet glacier, nourished by local alpine glaciers seen here flowing from the Royal Society Range. Bedrock beneath the ice of the lower Ferrar Glacier is below sea level. The glacier now fills a valley once occupied by a fjord (Photo: R. Jongens. The Ferrar Glacier is five kilometres across). Bottom: Local alpine glaciers flow from the Asgard Range into the Wright Valley and have left a series of moraines along the valley wall. A prominent loop moraine on the valley floor (foreground) was formed when the Ross Ice Sheet entered the valley from the coast. The Wright Valley, like the Ferrar, was also once occupied by a fjord and valley glacier, but is now almost completely dry (Photo: D. Haney/NSF collection. The Wright Valley is about three kilometres across).

Geological context

Southern Victoria Land lies between the Polar Plateau and the Victoria Land Basin, a major fault-bounded offshore sedimentary basin within the West Antarctic Rift System beneath the western Ross Sea. The West Antarctic Rift System dates from c. 85 Ma, when crustal extension between East and West Antarctica resulted in the break-up of this part of Gondwana (Lawver & Gahagan 1994). The Transantarctic Mountains mark the rift shoulder (Fitzgerald 2002); the boundary faults lie immediately offshore (Mortimer et al. 2002; Wilson et al. 2003; Henrys et al. 2007). The mountains were uplifted by as much as 6 km on the western side of the Victoria Land Basin between 55 and 30 Ma (Fitzgerald 1992, 1995; ten Brink et al. 1997), although slow uplift may have begun as early as the Late Cretaceous (Fitzgerald 2002). In southern Victoria Land the mountains form a largely coherent, gently westward-tilted block (Fig. 4). As a result of this uplift, tilting, and subsequent erosion, the oldest rocks of southern Victoria Land are now exposed close to the Ross Sea coast and rift margin, and the younger units of the Gondwana covering strata lie further inland toward the Polar Plateau. Thick sequences of Cenozoic marine sedimentary rocks are preserved in the extensional sedimentary basins in the western Ross Sea, seaward of the Transantarctic Mountains escarpment (Barrett et al. 1995; Fielding et al. 2008a), but not onshore.

The oldest rocks exposed in southern Victoria Land are metasedimentary rocks (schist, marble and gneiss) of the Skelton Group (Gunn & Warren 1962; Cook 1997; Cook & Craw 2001), deposited in a Neoproterozoic rift setting (Cook 2007). Radiometric dating of detrital zircon grains and conglomerate clasts indicates that Skelton Group rocks were deposited after 650 Ma (e.g. Wysoczanski & Allibone 2004; Cooper et al. 2011). The Skelton Group is strongly deformed and intruded by a wide variety of plutons, known collectively as the Granite Harbour Intrusive Complex (Gunn & Warren 1962). The oldest plutons are Neoproterozoic to Cambrian gabbros, diorites, A-type granites and nepheline syenites and carbonatites of the Koettlitz Glacier Alkaline Suite (557–542 Ma; Cooper et al. 1997; Read et al. 2002; Read 2010). Younger calc-alkalic to alkali-calcic granitoids, which form discrete petrogenetic suites, were intruded in Cambrian to Early Ordovician time (533–477 Ma; see Smillie 1992; Allibone et al. 1993a,b; Stump 1995; and Allibone & Wyzoczanski 2002 for summaries). The intrusives and their metasedimentary host rocks constitute the basement of the Transantarctic Mountains.

Episodic deformation and magmatism at the active paleo-Pacific continental margin of Gondwana continued at least until Early Ordovician time (the Ross Orogeny). A major but largely unrecorded tectonic event resulted in uplift of the Ross Orogen rocks by as much as 30 km, followed by deep erosion to form an almost flat landscape by

Figure 8 The Taylor Valley from Hjorth Hill, with New Harbour at left. Cold-based local alpine glaciers are flowing into the ice-free valley from the Kukri Hills (centre) and Asgard Range (right). Lake Fryxell can be seen beyond the spreading apron of the lower Commonwealth Glacier (middle right). The Royal Society Range forms the high mountains in the background. New Harbour now contains sea ice, but previously hosted thick grounded ice of the Ross Ice Shelf that flowed westwards into the Taylor Valley (Photo: D.B. Townsend. The Taylor Valley is about six kilometres across).

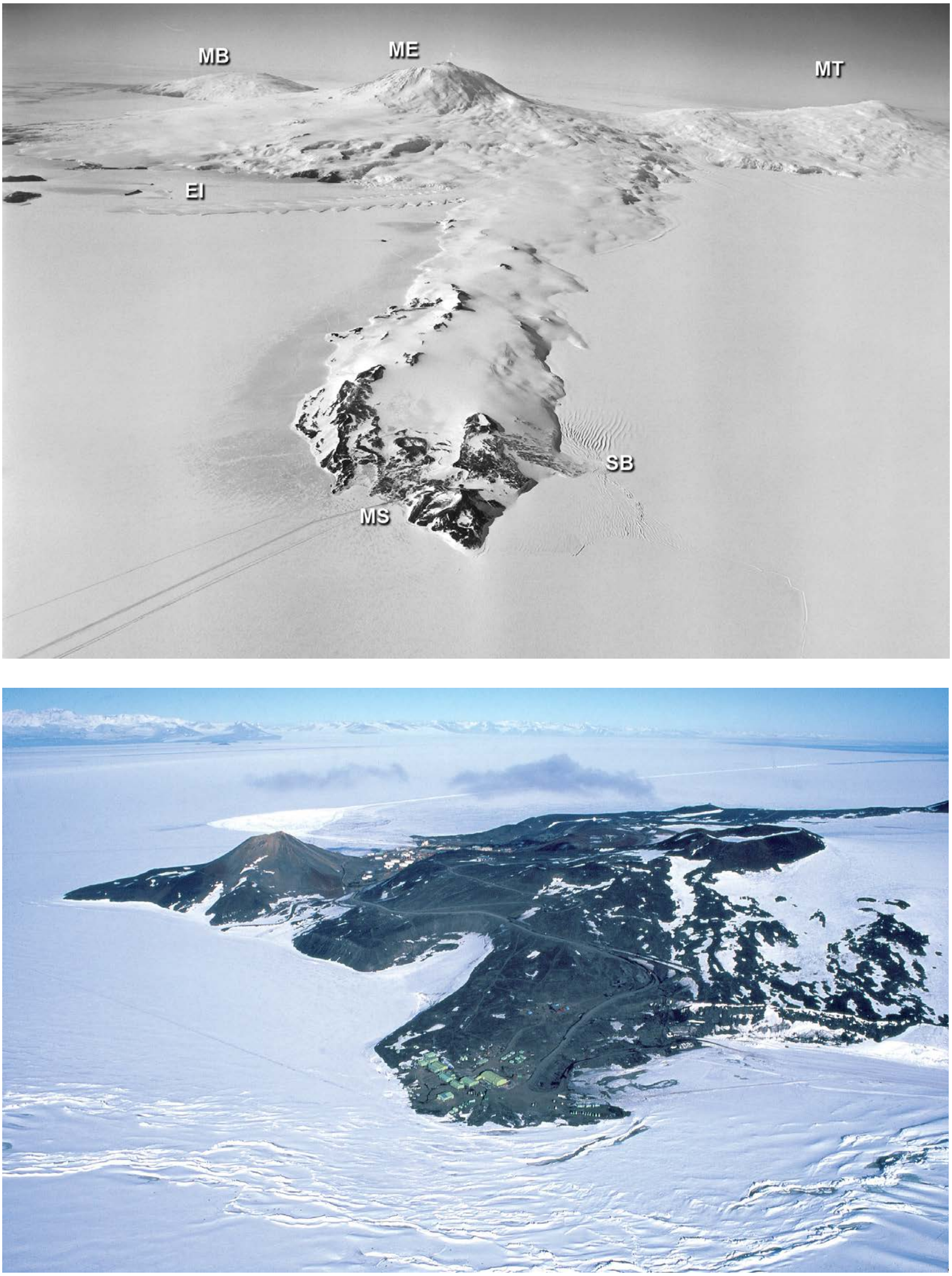


Figure 9 Physiography of Ross Island. Top: Historic aerial oblique photo illustrating the volcanoes of Ross Island—Mt Bird (MB), Mt Erebus (ME) and Mt Terror (MT). Scott Base (SB) and McMurdo Station (MS) are situated at the tip of Hut Point Peninsula (foreground). Roads across the sea ice can be seen in the foreground, and the floating Erebus Glacier ice tongue (EI) is in the middle distance (Photo: US Navy, TMA550 R0217, Nov 1959). Bottom: New Zealand's Scott Base (centre) is constructed on a lava flow near the distinctive volcanic cones of Crater Hill (302 m - right) and Observation Hill (226 m - left). Sea ice pressure ridges develop where the Ross Ice Shelf is deformed as it flows around Pram Point. The Transantarctic Mountains are visible in the far distance (Photo: N. Peat/Antarctica New Zealand collection).

Devonian time (c. 411 Ma). The resulting Kukri Erosion Surface (Woolfe & Barrett 1995; the Kukri Peneplain of Gunn & Warren 1962) can be traced the length of the Transantarctic Mountains (Isbell 1999). The overlying Beacon Supergroup, of Devonian to Triassic age, is an epicontinental sandstone-dominated sequence up to 2.5 km thick (Woolfe & Barrett 1995). The lower part (Taylor Group), known to be Devonian from fossil fish remains and palynomorphs, is truncated by the regionally extensive, glacially eroded Maya Erosion Surface, representing a period of non-deposition and/or erosion lasting for c. 86 to 109 million years. The Beacon rocks are little deformed and dip gently west, although in places they are cut by minor brittle faults and disrupted by younger intrusions.

Jurassic Ferrar Group dolerite sills are one of the more striking aspects of the Dry Valleys landscape; they form huge bluffs which overlook most valleys. Sills intrude the basement Ross Orogen rocks, the Kukri Erosion Surface and the Beacon Supergroup rocks. Several sills change laterally to upward-ramping dikes, and some have rafted large tracts of basement and/or Beacon Supergroup rocks, moving them for considerable distances. At and near the crest of the Transantarctic Mountains, Beacon rocks are locally overlain by extrusive equivalents of the Ferrar sills, namely the Kirkpatrick Basalt and volcanogenic sediments of the Mawson Formation.

The Cretaceous-Paleogene history of the region is relatively poorly constrained. There are no *in situ* outcrops of Paleogene sedimentary rock onshore, but Eocene and Oligocene erratic boulders are present in coastal moraines around McMurdo Sound (Stilwell & Feldmann 2000). Their fossils provide evidence for the temperate-warm conditions and coastal marine deposition that prevailed along the Transantarctic Mountains prior to ice sheet development. More continuous Late Eocene, Oligocene and Early Miocene sedimentary records are provided by the offshore MSSTS-1, CIROS-1, and CRP-2A and 3 drillholes (Barrett 2009), and other information on depositional history has been gleaned from seismic stratigraphy (Fielding et al. 2008a). Results from offshore drilling indicate that ice was present from about 34 Ma (Barrett 2009). Sediment was delivered to the offshore region by both rivers and glaciers while relatively warm conditions prevailed during the Middle Miocene climatic optimum (17.5–14.5 Ma), but a gradual change occurred from fluvial to glacial erosion and deposition in Late Miocene time (Haywood 2009).

The stability of Antarctic ice sheets during the Miocene and Pliocene has been the subject of vigorous debate for more than 20 years (e.g. Miller & Mabin 1998; Barrett 2013). Offshore drilling has intercepted units of diatomite that result from biologically active open water in McMurdo Sound, interlayered with terrigenous clastic units including ice-proximal diamictite (Fielding et al. 2011). These sediments record numerous cyclic fluctuations of the Ross Ice Shelf (and by inference the West Antarctic Ice Sheet) over the past 20 million years. During the same period, it appears that the East Antarctic Ice Sheet developed as a major and permanent feature (Marchant et al. 1996; Sugden et al. 1999). Hyper-arid, polar desert conditions became established around 14 Ma (Haywood et al. 2009). Water was present prior to this, with seasonally melting glaciers feeding alpine lakes that supported tundra communities (Lewis et al. 2008). Recent investigations of alpine lake sediments have discovered remarkable preservation of aquatic mosses, diatoms, ostracods and insects (Lewis et al. 2008). Meltwater landforms are inferred to have formed beneath the ice sheet as it overrode the mountains (Denton et al. 1984; Denton & Sugden 2005), incising channels and eroding bedrock features such as the Labyrinth in upper Wright Valley, and potentially releasing floods of fresh water from large subglacial lakes (Shaw & Healy 1977; Denton & Sugden 2005; Lewis et al. 2006). The transition to colder dry-based, alpine glacial regimes has been constrained to 13.9 Ma by dating of volcanic tephra that occur at 1200m elevation in the Olympus Range (Lewis et al. 2007). Despite global warming during the Pliocene, polar desert conditions appear to have persisted at high elevations in the Transantarctic Mountains (Denton et al. 1993). A landscape of remarkable antiquity, perhaps one of the oldest on earth (Schaefer et al. 1999), was frozen and preserved in the very dry, cold climate.

The Transantarctic Mountains now restrict the East Antarctic Ice Sheet, forming a topographic dam which in the area of this map is breached by only four major outlet glaciers (Skelton, Ferrar, Taylor and Mackay; Figs 6, 7). There is a marked contrast in the behaviour of the inland and coastal portions of this ice drainage system. At high elevations near the Polar Plateau, Ferrar and Taylor glaciers have shown <500 m variation in ice thickness in the past four million years (Brook et al. 1993; Staiger et al. 2006). At low elevations near the coast, ice thickness, glacier grounding and the position of the termini have varied considerably, in part due to interactions with dynamic fluctuations of the Ross Ice Sheet. During the Early Pliocene, for example, glaciers had retreated and open marine fjords occupied the lower Ferrar and Taylor valleys (Fielding et al. 2010; Ohneiser & Wilson 2012). During the Late Pliocene-Pleistocene, thick grounded ice in the Ross Sea Embayment flowed landwards as re-entrant glaciers into the valleys of the Transantarctic Mountains, which dammed the drainage and formed lakes. Major ice fluctuations from both the west and east are in many places now represented only by small moraine ridges, scattered boulders or thin veneers of till (Fig. 7). There has been considerable debate about their age, correlation, and the precise timing of inferred climatic events.

Basaltic and felsic Miocene to Holocene alkali volcanic rocks of the McMurdo Volcanic Group form the mountains east and south of McMurdo Sound (Erebus, Terror, Discovery and Morning), including Hut Point Peninsula (Fig. 9). Smaller cones and flow remnants are present in the hills and valleys west of McMurdo Sound and some deposits are intercalated with glacial units. The volcanic rocks are forming as a result of crustal thinning and resultant high heat flow along the margin of the Victoria Land Basin; they occur as far north as northern Victoria Land (Kyle 1990c; McIntosh & Kyle 1990).

The rocks and deposits of the Ross Island - Dry Valleys area are here subdivided and described in terms of six major units, differentiated on lithostratigraphy, age and tectonic history:

- Precambrian metasediments and lesser metavolcanics (Skelton Group)
- Late Precambrian – Early Ordovician granitoids and gneisses (Granite Harbour Intrusive Complex)
- Devonian – Triassic conglomerate, sandstone, siltstone and coal (Beacon Supergroup)
- Jurassic dolerite sills, breccia and basalt flows (Ferrar Group)
- Eocene – Holocene sedimentary rocks and sequences (mainly till and other fluvioglacial sediments)
- Miocene – Holocene volcanic rocks (McMurdo Volcanic Group).

PRECAMBRIAN

Skelton Group

Ferrar (1907) mapped the basement metamorphic rocks exposed along the Ross Sea coast between Granite Harbour and the Koettlitz Glacier as "Gneiss and Crystalline Limestone". These rocks, which are predominantly metamorphosed limestone, siltstone, sandstone, and conglomerate, were subsequently named Skelton Group by Gunn & Warren (1962), after the Skelton Glacier area where the metamorphic grade is typically greenschist facies. Higher grade rocks further north, in the eastern Dry Valleys, were named the Koettlitz Group by Grindley & Warren (1964), expanded from the Koettlitz Marble of Gunn & Warren (1962), and differentiated on the basis of higher (amphibolite facies) metamorphic grade. This nomenclature was generally followed by subsequent workers (e.g. Skinner 1982; Findlay et al. 1984; Allibone et al. 1991; Turnbull et al. 1994; Isaac et al. 1996, but cf. Lopatin 1972). Numerous formations have been established, more and less formally, within the Skelton Group (e.g. Allen & Gibson 1962; McKelvey & Webb 1962; Blank et al. 1963; Haskell et al. 1965a; Mortimer 1981; Findlay et al.1984), although other authors concentrated on petrology and structure (e.g. Williams et al. 1971). The name Salmon Marble was introduced for a distinctive map unit in the Blue Glacier area (Blank et al. 1963), and although possible correlatives have been mapped throughout the Dry Valleys area as far north as the upper Victoria Valley (Isaac et al. 1996), Salmon Marble is not differentiated from other marble bands on this map.

Detailed mapping in the Koettlitz Glacier region between Walcott Bay and the Foster Glacier by Cook (1997) and Cook & Craw (2001) identified structural and metamorphic discontinuities within the Skelton Group, with rocks of different metamorphic grades juxtaposed across ductile shear zones (Figs 10, 11; Cook & Craw 2001; 2002). This undermines the original basis for subdivision of the metasedimentary rocks into two groups and, following Cook & Craw (2001) and Wysoczanski & Allibone (2004), use of the term *Koettlitz Group* is abandoned; the basement rocks are here all included in an expanded **Skelton Group** (Fig. 12).

The Skelton Group rocks vary considerably in composition, with much interlayering at metre to decimetre scale within individual outcrops. Sedimentary structures and stratigraphy have for the most part been destroyed by deformation, and only a general indication of original lithologies is possible. Where possible, the map subdivides Skelton Group into informal lithologic units in which one particular rock type is predominant (Fig. 10). Given the lack of stratigraphic continuity and the obscuring effects of metamorphism and deformation, informal units were deemed to be more appropriate than using formations (e.g. Blank et al. 1963; Findlay et al. 1984). A number of marked changes within the Skelton Group occur near the Walcott Glacier, where the Frio Shear Zone has been mapped and is inferred to extend beneath the glacier (Cook 1997; Cook & Craw 2001). The Frio Shear Zone is only exposed near McConchie Ridge (162°49.98'E 78°08.69'S), where it is a subtle kilometre-wide zone of elevated strain (Beckett 2002) that locally separates rocks with distinct metamorphic histories. On the basis of new structural data, this map extends the Frio Shear Zone across Chancellor Ridge and eastwards beneath the Howchin Glacier (Fig. 11). Although its nature and location are not particularly well constrained, the shear zone serves as a useful reference for distinguishing different structural domains within the Skelton Group (e.g. Wysoczanski & Allibone 2004) and potentially also marks some significant changes in age and composition of granitoids (see below).

North of the Frio Shear Zone, the undifferentiated **Skelton Group** (**s**) is dominated by a lithologic association comprising interlayered quartzofeldspathic biotite (garnet) schist, felsic gneiss, and amphibolite. Minor muscovite-biotite-K-feldspar ± quartz pelitic schist, and rare thin marble and calc-silicate bands, are present locally (Findlay et al. 1984; Mortimer 1981; Allibone et al. 1991; Allibone 1992; Cox 1992; Turnbull et al. 1994; Isaac et al. 1996). Amphibolite comprises plagioclase-amphibole (mainly hornblende, cf. tremolite-actinolite) ± biotite. Associated calc-silicate gneisses are composed of diopsidic clinopyroxene with minor garnet, wollastonite, epidote and tremolite-actinolite. Weakly foliated felsic gneisses comprising plagioclase, K-feldspar, quartz, biotite ± muscovite and garnet are widespread. With decreasing feldspar content these grade into psammitic schist and gneiss, also containing variable amounts of garnet and generally more biotite. A minor component of tremolite-actinolite schist is also present (e.g. Findlay et al. 1984; Allibone 1988; Turnbull et al. 1994); it contains subordinate plagioclase, K-feldspar, biotite, and minor diopside. This lithology forms the matrix to metaconglomerate in some areas (Findlay et al. 1984). Distinctive massive to banded **marble** (**sm**), present in many areas, ranges from grey (due to disseminated graphite) at lower metamorphic grade, to creamy orange or white at amphibolite facies (Figs 10, 13). Calcite is the predominant mineral but in places marbles are dolomitic. Muscovite, diopside, tremolite-actinolite, pyrite, phlogopite and rare quartz occur as accessory minerals.

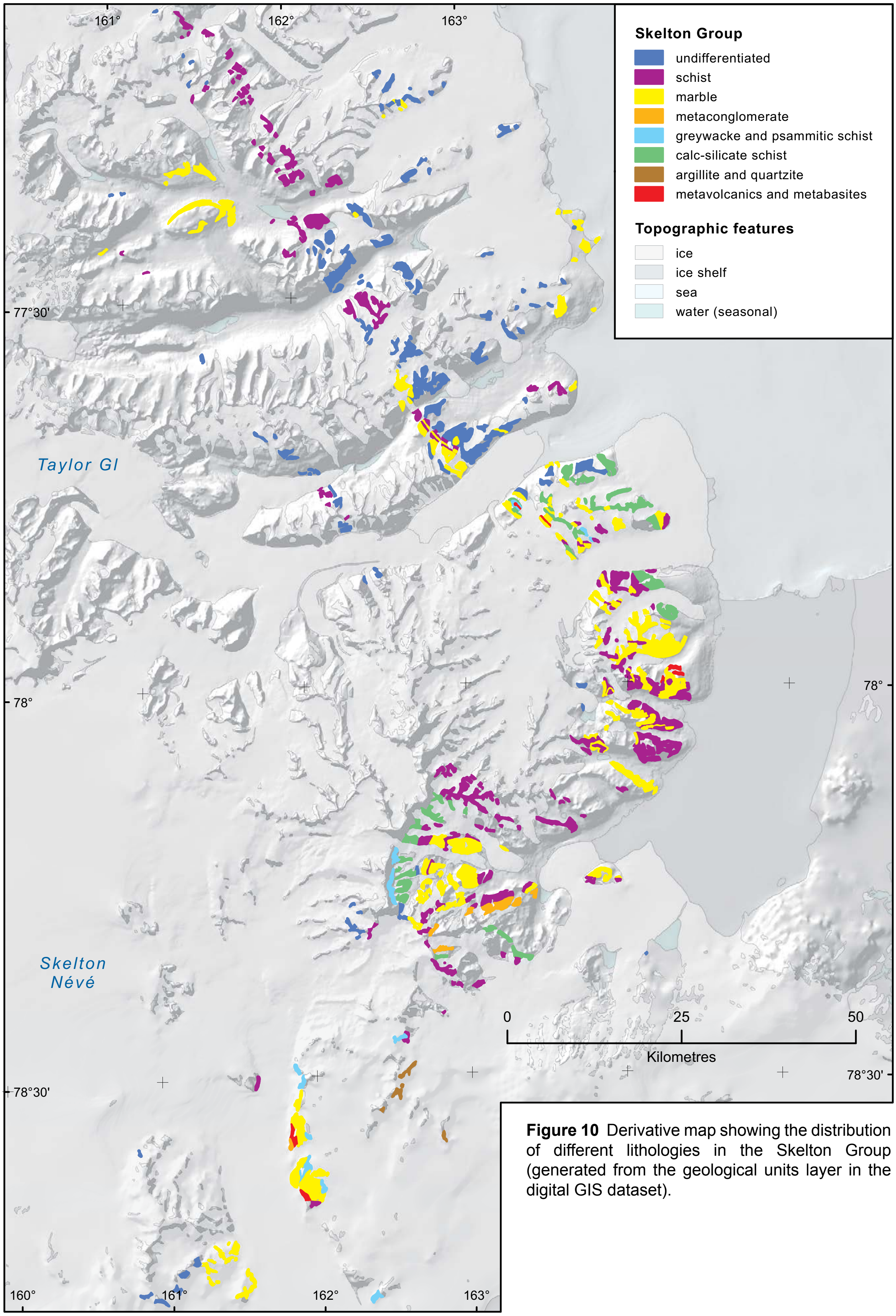


Figure 10 Derivative map showing the distribution of different lithologies in the Skelton Group (generated from the geological units layer in the digital GIS dataset).

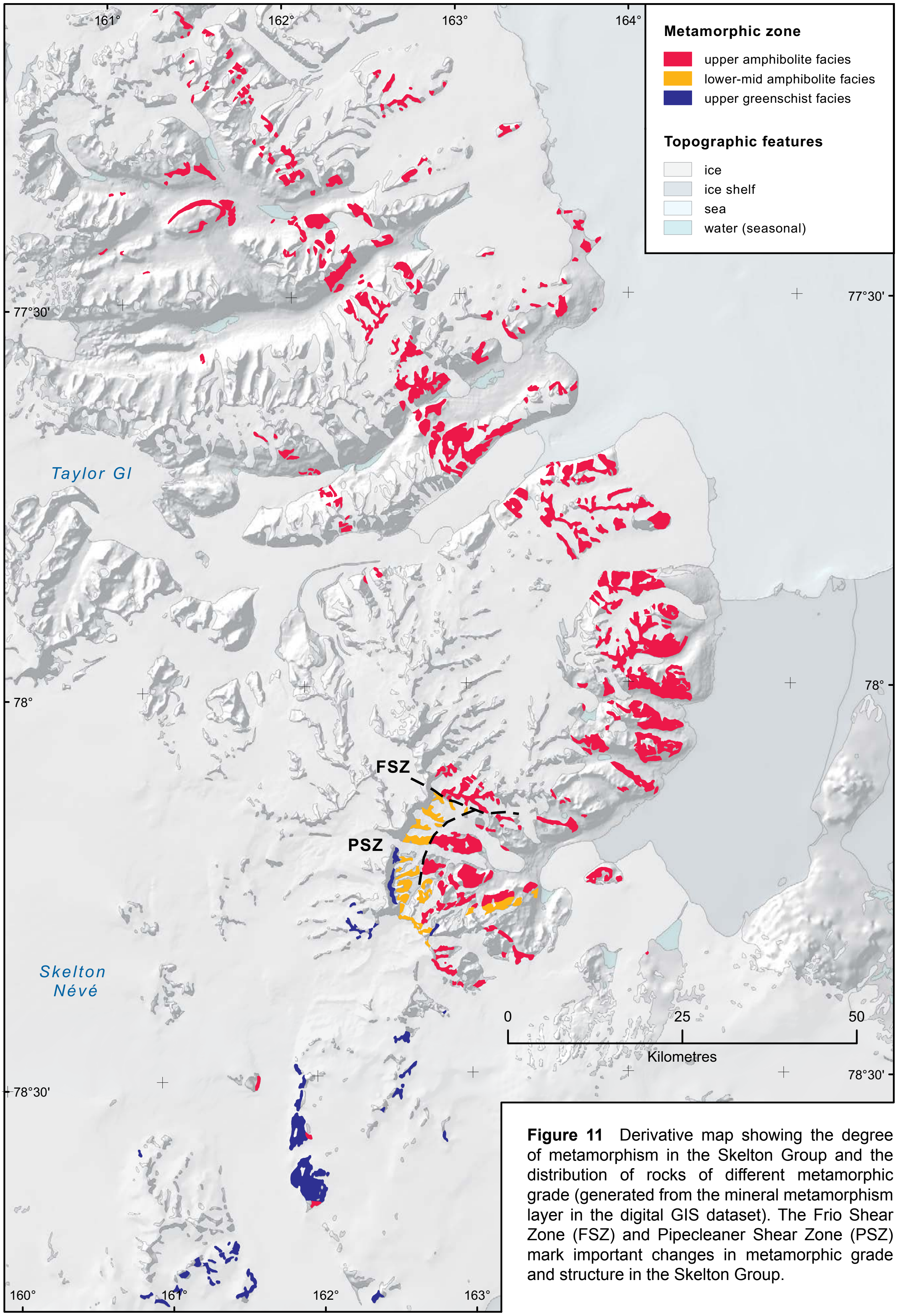


Figure 11 Derivative map showing the degree of metamorphism in the Skelton Group and the distribution of rocks of different metamorphic grade (generated from the mineral metamorphism layer in the digital GIS dataset). The Frio Shear Zone (FSZ) and Pipecleaner Shear Zone (PSZ) mark important changes in metamorphic grade and structure in the Skelton Group.

Marble is commonly interlayered, especially near contacts, with quartz-biotite schist, amphibolite, calc-silicate rocks, quartzofeldspathic gneiss and orthogneiss. Folding is common on all scales (e.g. Blank et al. 1963; Williams et al. 1971; Cox 1993). Locally, apparent thicknesses are as great as 3000 m.

Immediately south of the Frio Shear Zone, there is a structurally complex area between the Royal Society Range and the Koettlitz Glacier, where deformation of the Skelton Group has been very inhomogeneous (Walcott & Craw 1993). The five structurally distinct sub-blocks recognised by Cook (1997) and Cook & Craw (2001) are not of sufficient extent to be distinguished on this regional map. Where possible the boundaries between the sub-blocks have been depicted as shear zones or faults; however, despite the impression from Cook & Craw (2001) that boundaries are discrete and well defined, many are inferred beneath glaciers and, where exposed, they tend to be gradational features that are difficult to show with confidence. A band of relatively undeformed **greywacke** (**sg**) extends along the Royal Society Range between Mt Huggins and the Radian Glacier. The greywacke contains rounded detrital quartz and feldspar in a recrystallised epidote-actinolite-biotite-muscovite-chlorite ± graphite matrix (Cook & Craw 2001). Immediately to the east, the predominant rock type from Auster Pass to McConchie Ridge is a matrix-supported diopsidic **calc-silicate schist** (**sa**) with pebbly conglomeratic horizons containing quartz and quartzofeldspathic clasts in a matrix of diopside and actinolite. There are also pelitic metasediments nearby that include andalusite semischist, and garnet-biotite and kyanite-staurolite-garnet schists (mapped as **schist**; **ss**). The Pipecleaner Shear Zone, exposed at 162°39.68'E 78°14.45'S (Fig. 11), but not labelled on the map, separates the above rocks (Radian sub-block, Cook & Craw 2001) from an area dominated by white, coarsely crystalline, deformed **marble** (**sm**) (Rücker sub-block). A kilometre-scale discontinuous layer of biotite-garnet **schist** (**ss**) could be either an original lithologic variant, or tectonically emplaced (Cook 1997). Further southeast, Cook & Craw (2001) proposed three sub-blocks, each bounded by SW-NE to WSW-ENE oriented shear zones or faults. Skelton Group rocks between the Glimpse Glacier and Roaring Valley comprise **marble** (**sm**) between two units of biotite, amphibole, sillimanite and diopside **schist** (**ss**), all intruded

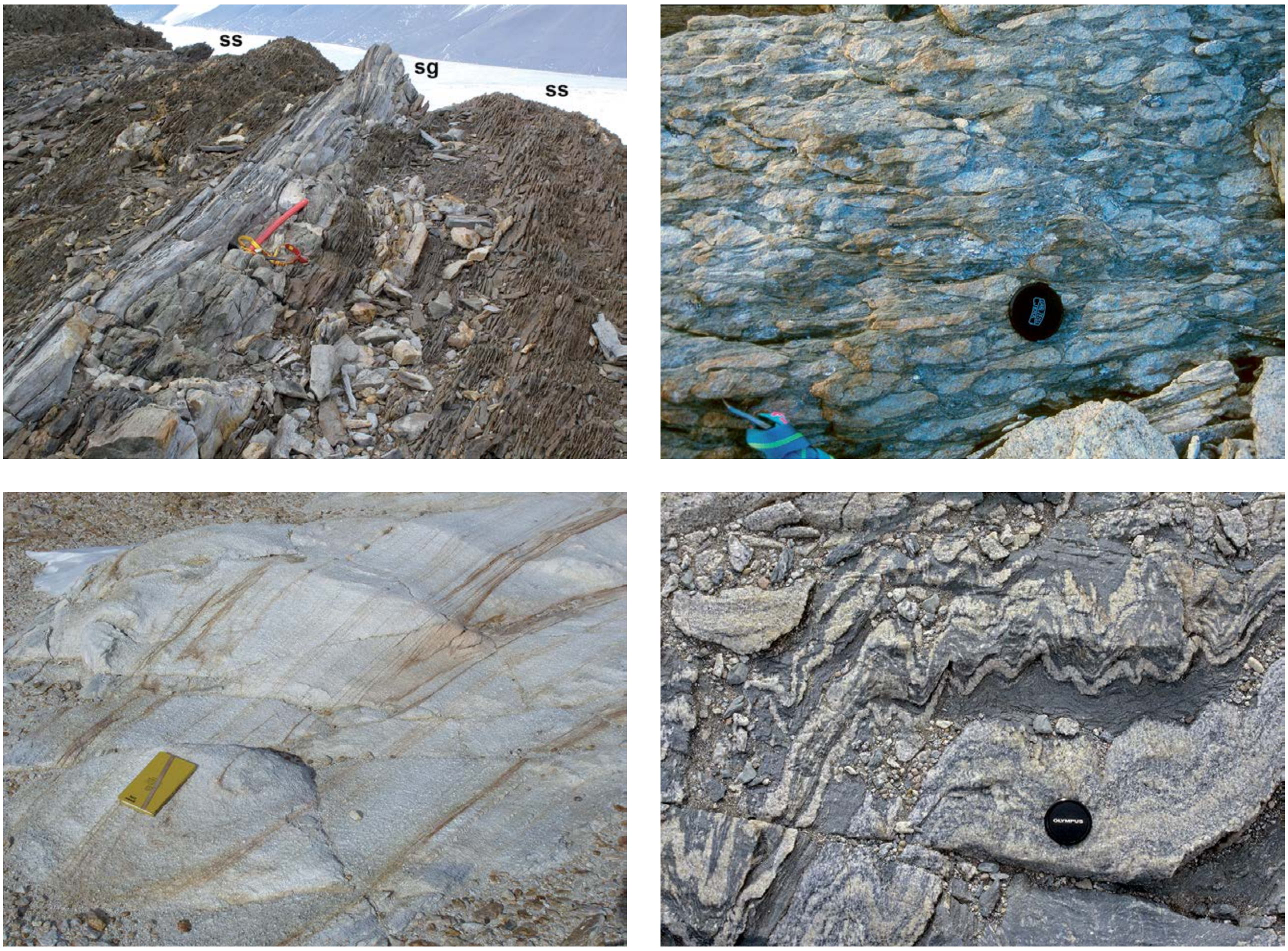


Figure 12 Examples of typical Skelton Group lithologies.
Top left: Psammitic schist (sg) interlayered with biotite schist (ss) in the eastern Kukri Hills (Photo R. Jongens. Ice axe is 65 cm long).
Top right: Metaconglomerate with deformed clasts in the St Johns Range (Photo I.M. Turnbull. Lens cap is 6 cm).
Bottom left: White marble near Salmon Valley with folds highlighted by orange-brown oxidised layers (Photo: S.C. Cox. Field book is 12 cm wide).
Bottom right: Migmatitic amphibole-bearing schist in the Wright Valley (Photo: S.C. Cox. Lens cap is 6 cm).

by syenite and gabbro bodies (Glee sub-block, Cook & Craw 2001). A shear zone separates them from adjacent metasediments between the head of the Kempe Glacier and the foot of the Dromedary Glacier (Kempe sub-block, Cook & Craw 2001), where a belt of (undifferentiated) greywacke, calc-silicate, marble, and biotite and amphibole **schist** (**ss**), plus diopsidic **metaconglomerate** (**sc**) have been intruded by Roaring Orthogneiss (see below). These rocks have undergone extensive alteration and annealing that is unique in southern Victoria Land (Cook 1997). Greywacke at Mt Kempe comprises 50–80% subangular to rounded, well-sorted quartz and feldspar grains in a fine-grained matrix of intergrown muscovite, chlorite and minor biotite. Metaconglomerate locally includes clasts of quartz, quartzofeldspathic metasediments, and granitoids. Skelton Group rocks in the Renegar Glacier area (Renegar sub-block, Cook & Craw 2001) are predominantly diopside ± amphibole **calc-silicate schist** (**sa**), with biotite-garnet and sillimanite schist, minor marble, and metabasite (mapped as **schist**; **ss**). There are also outcrops of **metaconglomerate** (**sc**) beside the Renegar Glacier containing clasts of quartzite and plagioclase-bearing igneous rocks in a biotite schist matrix (Simpson 1994). Two outcrops of metasediment and granitoid at Gandalf Ridge on Mt Morning, mapped as orthogneiss with interlayered Skelton Group (**gus**) due to their small size, are the most southeasterly exposure of Skelton Group rocks and place important constraints on the position of faults along the edge of the West Antarctic Rift System (Martin & Cooper 2010).

Metasediments between the upper Koettlitz and Skelton glaciers are generally less deformed and less recrystallised than those further north, hence primary features such as bedding and clastic textures are better preserved. Numerous structurally discrete units have been differentiated (Skinner et al. 1976; Cook 1997; Cook & Craw 2002). The differences in rock types, metamorphic grades, and structural reconstitution between these units preclude detailed correlation and they are not shown on this map. The major lithologies are marble, greywacke, metaconglomerate, calc-silicate, schist, argillite, and metavolcanics. West of the Skelton Glacier, on the eastern flank of the Worcester Range, limestone (**marble**, **sm**; Ant Hill Limestone of Gunn & Warren 1962) forms Ant Hill and bluffs to the north. Large areas of marble are also present east of the glacier from Hobnail Peak south to the Cocks Glacier. Fine-grained **greywacke** (**sg**) south of Red Dike Bluff (Teall Greywacke of Gunn & Warren 1962; Skinner 1982) is undeformed, with relict sedimentary structures; at Mt Tricouni it is of considerably higher grade and interbedded with marble (Gunn & Warren 1962).

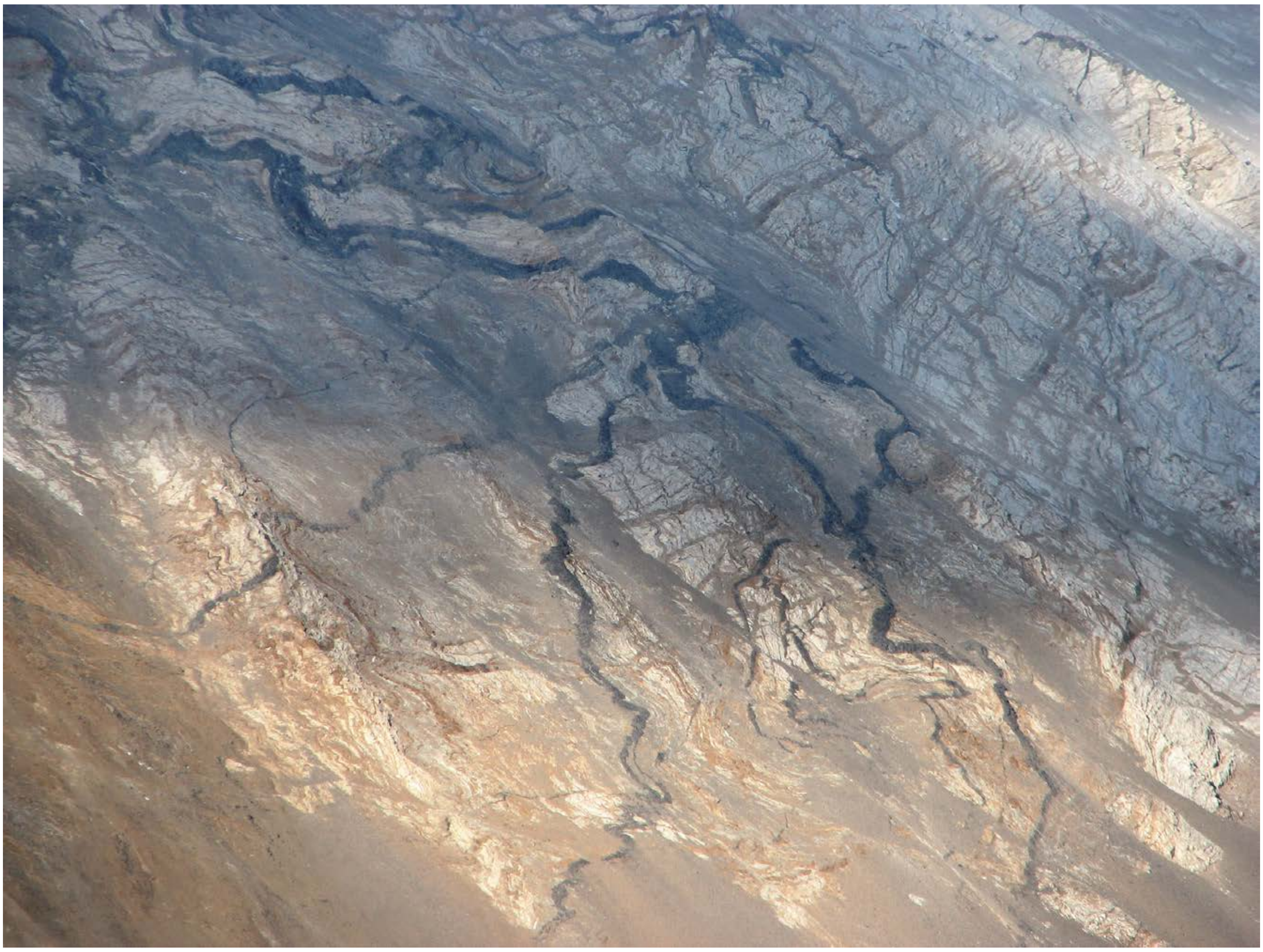


Figure 13 Large areas of deformed Skelton Group marble are exposed on the north wall of the Garwood Valley, where it is interlayered with schist (orange-brown, lower left) and cross-cut by mafic and granitic dikes. The dikes are also deformed, displaying variable degrees of folding or extension depending on their orientation, and locally contain gneissic textures (Photo: D. Strong. Hillside outcrop is around 300 m high).

Calcareous and quartzofeldspathic schist with metabasite at the Cocks Glacier (undifferentiated; **ss**) were named Cocks Formation by Skinner (1982), although this name was not used by Cook (1997) or Cook & Craw (2002).

Metaconglomerate (**sc**) containing rhyolite, basalt and trachyte clasts and interbedded with greywacke and marble occurs north of the Baronick Glacier (Baronick Formation of Cook 2007). Metamorphosed flows or sills of basalt, trachyte and syenite are interlayered with Baronick Formation metaconglomerate. In addition, Baronick Formation is intruded by sills of dolerite which are geochemically related to the adjacent Highway Suite of Cook (2007). This suite consists of intermingled gabbro and dolerite, comprising plagioclase, pyroxene and magnetite with deuteric amphibole, and secondary biotite, chlorite, calcite, epidote and sericite. These rocks are sheared, foliated and metamorphosed to greenschist facies, and were probably formed in a continental rift setting. The unusual alkaline volcanic-plutonic nature and distinctive geochemistry of the Baronick and Highway units makes them unique within the Skelton Group (Cook 2007). **Metavolcanics** (**sv**), including pillow basalts interlayered with basaltic flows and dikes, are exposed east of the Skelton Glacier between the Cocks and Baronick glaciers, surrounded by undifferentiated argillite, greywacke, marble and metaconglomerate. Calcareous **argillite** (**sr**) predominates in the upper Koettlitz Glacier/Mt Cocks region, where quartzite, minor calcareous sandstone, impure marble, and rare metavolcanics and volcaniclastic sandstone also occur (Skinner et al. 1976; Cocks Formation of Skinner 1983).

The regional variation in Skelton Group metamorphic grade is illustrated in Figure 11. North of the Frio Shear Zone, the metamorphic grade is entirely upper amphibolite facies, with significant migmatisation (Allibone & Norris 1992). Rare metamorphic pyroxene in rocks of the Taylor and Wright valleys indicates that incipient granulite facies metamorphism was reached locally (Williams et al. 1971; Allibone 1992; Cox 1992). Talarico et al. (2005) suggest that metamorphic assemblages between the Frio Shear Zone and Ferrar Glacier are the result of two phases of metamorphism, an earlier (pre-intrusion) medium-pressure event followed by lower pressure, higher temperature conditions associated with granitic intrusion. To the south of the Frio Shear Zone, metamorphic grade is more varied: predominantly upper greenschist facies, or lower and middle amphibolite facies, with minor upper amphibolite facies rocks (Walcott & Craw 1993; Cook 1997; Cook & Craw 2001; Wysoczanski & Allibone 2004).

The change in lithology and metamorphic facies across the Frio Shear Zone is also reflected in a change in structural style (Findlay et al. 1984; Cook & Craw 2001; Wysoczanski & Allibone 2004). To the north, foliation parallel to lithologic layering is isoclinally folded and refolded to give a north to northwest-trending structural grain which has partly been influenced by pluton emplacement. A younger non-penetrative northeast-trending fabric cuts the older structures. South of the shear zone, the structural grain is generally northeast-trending, with non-coaxial folding of foliation about variably trending axes. Earlier fabrics can be recognised and there appear to be a number of ductile shear zones (Cook & Craw 2001). No large shear zones have been recognised to the north of the Frio Shear Zone, although the rocks are highly strained. The north-south structural variation along the orogen could be spatially related to plutonism. Cox (1993) proposed that expansion of the regional-scale Bonney Pluton into a field of compression resulted in coaxial deformation of Skelton Group host rocks at the sides of the pluton, producing tight upright NW-trending folds and strong NW-SE extension, whereas non-coaxial deformation at the ends of the pluton resulted in complex folding, refolding and sheath folding in host rocks. Differences in Skelton Group metamorphism and migmatisation may therefore simply reflect different pressure-temperature-time paths experienced at different localities around the margins of the Bonney Pluton (Cox 1993). Although localised deformation is present immediately adjacent to smaller concordant plutons, these were probably of insufficient scale to develop buoyancy and influence Skelton Group structures further afield.

Skelton Group metasediments were deposited during a phase of rifting along the margin of the supercontinent Rodinia (Goodge et al. 1993, 2004a; Cook & Craw 2002; Goodge 2002; Cooper et al. 2011). Sedimentation took place on a continental margin or slope, and in shelf (platform) environments (Goodge et al. 2004b), with some smaller closed marginal marine basins (Cook 2007). It is possible that sedimentation patterns may have varied laterally due to structural segmentation. Various lines of evidence point to a Neoproterozoic depositional age for the Skelton Group, probably after 650 Ma. Deposition must be younger than the age of detrital zircons within the sediments. U-Pb ages of zircon grains are dominated by Mesoproterozoic populations, but include some younger Neoproterozoic grains, and anomalous Cambro-Ordovician ages that have been affected by Pb loss during metamorphism and/or granitoid intrusion (Wysoczanski & Allibone 2004; Goodge et al. 2004b; Cooper et al. 2011). North of the Frio Shear Zone, detrital zircon populations have a significantly larger component of Neoproterozoic zircons (Wysoczanski & Allibone 2004), and a quartzite from Hobbs Peak contains grains as young as 668 ± 19 Ma (Goodge et al. 2004b). Rb-Sr dating of impure marbles from the lower Wright and upper Victoria valleys returned a Neoproterozoic age (840 Ma; Adams & Whitla 1991). The timing of metamorphism is constrained by c. 505–480 Ma zircons in partially melted amphibolite facies sediments (Wysoczanski & Allibone 2004), which are consistent with ages derived from syntectonic plutons (e.g. Bonney Pluton c. 511–503 Ma), although metamorphic zircon rims as old as c. 550 Ma may indicate an earlier episode of high-grade metamorphism (Wysoczanski & Allibone 2004). To the south of the Frio Shear Zone, there are significant numbers of detrital zircons dated between 680 and 630 Ma in Skelton Group metasediments, and rhyolitic clasts in a metaconglomerate near the Baronick Glacier have zircon ages of c. 650 Ma (Cooper et al. 2011). Metamorphosed basaltic pillow lavas intercalcated with

Skelton Group metasediments near the Cocks Glacier gave an imprecise mantle separation age of 780–680 Ma (Rowell et al. 1993), although the extrusive age of the pillows is not known. These results suggest that the Skelton Group was deposited after 650 Ma, at least locally south of the Frio Shear Zone. Volcanic clasts in the metaconglomerate at the Baronick Glacier range from basanite to rhyolite, and are interpreted to reflect the initiation of extension-related volcanism associated with Rodinia fragmentation (Cooper et al. 2011). The oldest cross-cutting granitoids (Granite Harbour Intrusive Complex) constrain the minimum depositional age of the Skelton Group rocks, which must have been deposited before c. 557 Ma (Koettlitz Glacier Alkaline Province) south of the Frio Shear Zone, and 530–515 Ma (Dun Pluton) to the north (see below).

LATE PRECAMBRIAN TO ORDOVICIAN

Granite Harbour Intrusive Complex

In southern Victoria Land, numerous plutons intrude the Neoproterozoic Skelton Group metasedimentary rocks. These predominantly granitic rocks were first recorded in 1841, when granite clasts were dredged from the floor of the Ross Sea during James Clark Ross's expedition (Ross 1847). The early geologists mapping on land recognised numerous types of plutonic rock in southern Victoria Land, many as glacial erratic boulders (Prior 1907; Edgeworth David & Priestley 1909). Ferrar's (1907) subdivision of the granitoid rocks into "grey granite" and a younger "pink granite" was, many years later, amended by Gunn & Warren (1962) who described pre-, syn- and post-tectonic granites, a system that was largely adopted by later workers up until the 1980s. Various intrusive groups and some "plutons", such as "Irizar Granite" and "Larsen Granodiorite" were included within the regionally extensive **Granite Harbour Intrusive Complex** (Gunn & Warren 1962), which is synonymous with Granite Harbour Intrusives of Grindley & Warren (1964).

Most early attempts to differentiate and subdivide the granitoids relied on grouping together rocks with the same or similar appearance in hand specimen and thin section (e.g. "pink biotite granite"). However, detailed mapping in the Dry Valleys has shown that following this principle could (and did) result in discrete intrusions with different ages and field relationships being amalgamated into one unit. Conversely, some individual intrusions were shown to be so internally variable that under such a scheme they would probably have been placed into several different units. Recognition of these problems by Smillie (1989, 1992), Allibone et al. (1993a,b) and Cox & Allibone (1995), among others, led to the development of a pluton-based approach. Individual intrusions were mapped out in detail in the field, their field (intrusive) relationships determined and, ideally, petrographic data, geochemical analyses and radiometric ages obtained. Subsequently, plutons have been grouped into higher level, more interpretive petrogenetic suites based on geochemistry (e.g. Smillie 1992; Allibone et al. 1993a,b; Allibone & Wysoczanski 2002; Read et al. 2002), although there has been some debate over this approach (Cox & Allibone 1995). The pluton- and suite-based subdivision is followed here and the rocks are included in the Granite Harbour Intrusive Complex. Many, but not all, of these intrusives in the mapped area can be assigned to one of four petrogenetic suites (Fig.14):

- the predominantly mafic Koettlitz Glacier Alkaline Suite
- the Dry Valleys (DV) 1a Suite, dominated by hornblende-biotite granitoid rocks
- the Dry Valleys (DV) 1b Suite, dominated by biotite granitoid rocks
- the younger Dry Valleys (DV) 2 Suite, dominated by discordant granitoid plutons

In addition, numerous minor intrusive units and dikes are mapped, some not yet allocated to any petrogenetic suite.

The Koettlitz Glacier Alkaline Suite (Cooper et al. 1997; Read et al. 2002; Read 2010), present south of the Dry Valleys in the Royal Society Range, is the oldest. In contrast to younger suites, it includes significant amounts of gabbro and diorite, contains A-type granites, syenite and carbonatite, has alkaline chemistry, and is inferred to have been emplaced in an extensional tectonic environment (Read et al. 2002; Read 2010).

In contrast, the younger DV1a and DV1b suites are dominated by calc-alkaline, Cordilleran I-type granitoids that were emplaced in a convergent margin setting (Allibone et al. 1993a,b). The DV1a Suite is composed of hornblende-biotite quartz monzodiorite, granodiorite and granite plutons inferred to have developed during melting above a west-dipping subduction zone along the Antarctic craton margin (Allibone et al. 1993b). The DV1b Suite has relatively more evolved biotite granodiorite and granite plutons with distinctive adakitic chemistry, and may have been sourced from quartzofeldspathic sediments underplated beneath the continent during DV1a subduction or, possibly, terrane accretion (Allibone et al. 1993b). Both DV1a and DV1b suites include granitoids so deformed as to be termed orthogneisses, as well as unfoliated granitoids.

DV1a and DV1b plutons are cut by the DV2 Suite of Caledonian I-type rocks, which are generally undeformed and include alkali-calcic monzonite, quartz monzonite and granite plutons (Smillie 1992; Allibone et al. 1993b). This suite includes the mafic and felsic Vanda Dikes, with calc-alkaline to shoshonitic compositions, that occur both as isolated dikes and intense swarms. DV2 magmatism is interpreted as a response to uplift and extension following the cessation of subduction in the later stages of the Ross Orogeny (Smillie 1992; Allibone et al. 1993b). Several younger plutons that have identical field relations and relative ages to the DV2 Suite have geochemical characteristics that suggest melting of a variety of source rocks.

U-Pb dating of zircon, monazite and titanite has yielded crystallisation ages for plutons of all four suites, and has also given information on the age of inherited grains. Radiometric dating by Rb-Sr and K-Ar techniques

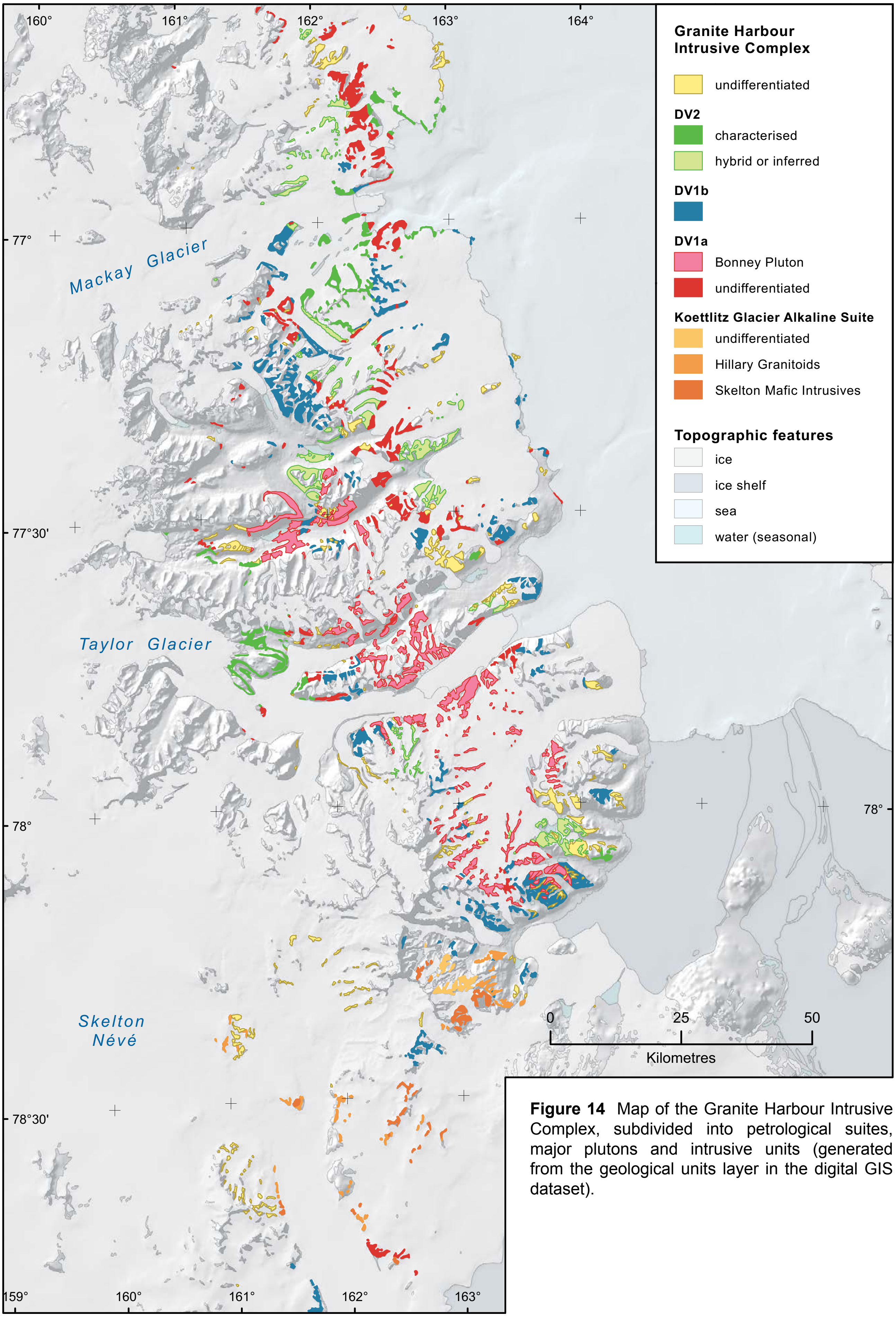


Figure 14 Map of the Granite Harbour Intrusive Complex, subdivided into petrological suites, major plutons and intrusive units (generated from the geological units layer in the digital GIS dataset).

gives ages of exhumation and cooling (as opposed to emplacement ages; Allibone & Wysoczanski 2002; Wysoczanski & Allibone 2004 and references therein). The Koettlitz Glacier Alkaline Suite has emplacement ages ranging from c. 557–542 Ma, with a number of younger ages now interpreted to reflect cooling or reheating (Rowell et al. 1993; Hall et al. 1995; Encarnacion & Grunow 1996; Cooper et al. 1997; Mellish et al. 2002; Read et al. 2002; Read 2010). The DV1a and DV1b suites were coeval, with DV1a peaking during syn-tectonic emplacement of Bonney Pluton (c. 511–503 Ma), coincident with regional deformation of the Skelton Group in the Dry Valleys area (Cox 1993), followed by a pulse of discordant post-tectonic DV1b plutons. DV1a crystallisation ages range between c. 517 and 495 Ma (Allibone et al. 1993a; Encarnacion & Grunow 1996; Hagen-Peter et al. 2011; Tulloch & Ramezani 2012). Volumetrically small foliated bodies within the DV1b Suite (the Calkin and Dun plutons) were emplaced at c. 516 Ma (Allibone & Wyzoczanski 2002; Tulloch & Ramezani 2012) prior to the major episode of deformation in the Dry Valleys area. In the southern part of the map area, the Hooper Intrusives have DV1b adakitic chemistry, but are mostly undeformed and include rocks dated from 533–511 Ma (Read 2010). The DV1b Suite ranges in age from 533 to 494 Ma, peaking towards the end of this period with intrusion of a number of relatively large discordant plutons (e.g. Valhalla Pluton).

DV2 pluton emplacement ages of c. 498–490 Ma, derived from U-Pb analysis of zircon by LA-MC-ICP-MS and the more precise CA-ID-TIMS methods, have recently been obtained but are yet to be formally published (Hagen-Peter et al. 2011; Tulloch & Ramezani 2012). They suggest that DV2 plutons post-date most emplacement ages of the DV1a and DV1b suites, consistent with observed field relations. Zircon U-Pb ages show that Vanda Dikes were emplaced within the interval 495–491 Ma (see below). Ages determined by Rb-Sr and K-Ar, some as young as 477 Ma, were all that was previously available to constrain the age of the DV2 Suite and Vanda Dikes (Angino et al. 1962; Jones & Faure 1967; Allibone et al. 1993a,b; Cox et al. 2000; Allibone & Wyzoczanski 2002); these ages almost certainly reflect cooling rather than intrusion.

Geobarometry indicates that the older DV1a and DV1b plutons were intruded at greater depths than younger DV2 bodies, with pressures ranging from >5 to <2 kbar over the duration of emplacement (Allibone et al. 1993b). No equivalent volcanic rocks are known from southern Victoria Land, although rhyolitic rocks preserved as clasts in a Beacon Supergroup conglomerate were linked to DV2 Suite granitoids by Wysoczanski et al. (2003). The Granite Harbour Intrusive Complex and its Skelton Group host rocks were exhumed by uplift and deep erosion in Ordovician to Silurian time (Calvert & Mortimer 2003), and planed off to produce the Kukri Erosion Surface.

The plutonic and meta-plutonic rock units are here described in general terms only, from oldest to youngest, as more detailed descriptions of the petrology, field relationships, geochemical analyses, and radiometric ages are given in the publications cited. Although named in published papers or conference abstracts, some plutonic units shown on the map have never been adequately defined (i.e. with nominated type localities and descriptions of their petrology, internal variability and field relationships). Additional information is given in Appendix 1.

Koettlitz Glacier Alkaline Suite

A diverse suite of predominantly mafic plutons with distinctive alkaline and A-type affinities, between the Koettlitz and Mulock glaciers, is termed the **Koettlitz Glacier Alkaline Suite**, renamed from the Koettlitz Glacier Alkaline Province of Read et al. (2002). It includes A-type granites (Read 2010), alkaline and sub-alkaline gabbros (Simpson & Aslund 1996; Mellish et al. 2002), and nepheline syenites and carbonatites (Hall et al. 1995; Worley & Cooper 1995; Worley et al. 1995; Cooper et al. 1997; Mellish et al. 2002; Read 2010). Rocks of the Koettlitz Glacier Alkaline Suite are not known north of the Frio Shear Zone (Read et al. 2002; Read 2010). The suite probably extends south beyond the area of the present map as far as the Darwin Glacier, where the Foggy Dog Granite and Mulock Granite have some A-type characteristics (Simpson 2002; Simpson & Cooper 2002; Cottle & Cooper 2006b).

The mafic **Glee Intrusives** (**gag**) comprise small plutons, stocks, and plugs of gabbro, monzonite, and granite that intrude Skelton Group metasediments between the Kempe and Pipecleaner glaciers (Aslund 1990; Read et al. 2002). The plutons are generally massive but orthoclase megacrysts may be flow-aligned. Gabbros are fine- to medium-grained with an assemblage of plagioclase-quartz-biotite-amphibole-orthoclase-clinopyroxene, and accessory ilmenite, titanite, apatite and zircon. The granitic bodies are coarse-grained orthoclase-quartz-plagioclase-biotite granites with accessory titanite, fluorite, amphibole, zircon, apatite and ilmenite. U-Pb dating of zircon and titanite from monzogabbro and monzonite yielded both concordant and discordant ages. Read (2010) interpreted parental magma to have formed at c. 558–550 Ma (upper intercept of discordant zircon ages) with a thermal event around 539 ± 4 to 534 ± 3 Ma recorded by titanite ages (cf. Read 2010).

Strongly foliated plutons, predominantly of **nepheline syenite** (**gas**) but including carbonatites and other alkaline rocks such as alkali-pyroxenite, intrude Skelton Group rocks on Dismal and Radian ridges. They include the Dismal Nepheline Syenite and the much smaller Radian Ridge Nepheline Syenite (Hall et al. 1995; Worley & Cooper 1995; Worley et al. 1995; Cooper et al. 1997; Mellish et al. 2002) (not differentiated on the map). These nepheline syenites consist of alkali feldspar-biotite-nepheline-calcite-fluorite assemblages with accessory apatite, magnetite and zircon. Dismal Nepheline Syenite ranges in composition from feldspathic ijolite to juvite, with layers of alkali pyroxenite. It is choked with rafts of marble and quartzite from the enclosing Skelton Group host. Rb-Sr dating indicates an age of 507 ± 21 Ma (Cooper et al. 1997). Radian Ridge Nepheline Syenite ranges from fine-grained to pegmatitic, with perthitic alkali feldspar megacrysts (Hall et al. 1995). The U-Pb SHRIMP age from zircons in the syenite is 531 ± 12 Ma. The Radian body is cut by a calcite-fluorite carbonatite dike; U-Pb SHRIMP dating of zircon in this dike gave an identical age of 531 ± 5.5 Ma (Hall et al. 1995).

Isolated outcrops of heterogeneous mafic plutonic rocks adjacent to the upper Skelton Glacier, described by Read (2010) as the Skelton Mafic Suite, are here renamed the **Skelton Mafic Intrusives** (**gam**; Fig. 15). This unit includes the Delta Diorite (named from Delta Bluff on the Skelton Glacier by Gunn & Warren (1962), but the name is now abandoned), but other mafic bodies they mapped as Delta Diorite further north are not included (see below). Gabbroic rocks between the Foster Glacier and Mt Cocks adjacent to the upper Koettlitz Glacier (Koettlitz gabbros of Read 2010), and mafic dikes at Cocks Glacier (Wynyard 2004) have been included in the Skelton Mafic Intrusives as they are broadly similar sub-alkaline gabbros, although Read (2010, p. 174) concluded the Koettlitz gabbros may be chemically distinct.

The Skelton Mafic Intrusives include gabbroic, dioritic and monzonitic intrusives of variable grain size, are typically unfoliated, and plutons often contain fine-grained mafic enclaves. Lithologies described by Read (2010) are fine-grained hornblende-plagioclase-biotite-titanite-ilmenite dolerite; medium- to coarse-grained diorite;

Figure 15 At Cocks Bluff, Skelton Glacier, a two-metre-thick dike of fine-grained Hillary Granitoid (orange, at top) cuts Skelton Mafic Intrusives that have been invaded and partially digested by Hillary Granitoid magma (light grey) (Photo: S.E. Read. Horizontal field of view is c. 3 m).

coarser orthopyroxene and hornblende gabbro and norite; and rare granodiorite. U-Pb dating of titanite from dolerite at Cocks Bluff gave an age of 547 ± 4 Ma, and of zircon from Delta Bluff, 548 ± 2 Ma (Read 2010).

The **Dromedary Mafic Complex** (Simpson & Aslund 1996) includes a wide range of lithologies, with a core of olivine gabbro, gabbro, norite and anorthosite and with minor pyroxenite, locally with cumulate layering (**gab**). It is surrounded by an equigranular, locally foliated diorite (**gad**) composed of plagioclase, brown biotite (unusually co-existing with clinopyroxene), quartz and K-feldspar, with accessory apatite, titanite, ilmenite, and magnetite. The gabbro-diorite contact is a complex intermingled intrusion zone, foliated parallel to the contact. Many of the lithologies within the Dromedary Mafic Complex are metamorphosed and the margin against Skelton Group is also foliated and strained. A discordant TIMS U-Pb age of 536 ± 10 Ma has been obtained from titanite and zircon (Mellish et al. 2002). The crystallisation age of the complex was re-interpreted by Read (2010) as around 557–546 Ma, based on a correlation with the mineralogically and geochemically similar subalkaline Panorama Pluton and Skelton Mafic Intrusives.

Panorama Pluton (**gap**) is a body of gabbro, diorite, monzodiorite and monzonite, together with stocks and sills, intruding Skelton Group metasediments near the Panorama Glacier. Two distinct groups of rocks within the main pluton (gabbro and gabbroic diorite, and monzodiorite to monzonite) are inferred to represent different but coeval melts (Mellish et al. 2002). The gabbros consist of plagioclase, amphibole, biotite and clinopyroxene with accessory rutile, ilmenite, titanite and, rarely, quartz. Actinolite is also present locally. The more monzonitic varieties also include K-feldspar. The pluton is generally undeformed, although the smaller bodies may be foliated parallel to the enclosing Skelton Group metasediments. A concordant TIMS U-Pb age from titanite of 535 ± 9 Ma (Mellish et al. 2002) was thought by Read (2010) to have been reset, and the crystallisation age re-interpreted as 557 ± 5 Ma.

Hillary Granitoids (**gaa**), re-named from the Hillary Suite of Read (2001, 2010), are granitoid intrusions extending from the Radian Glacier south to the Mulock Glacier. These are included in the Koettlitz Glacier Alkaline Suite on the basis of A-type chemistry and age (551–542 Ma; Fig. 15). They are mainly high silica alkaline granites with subordinate syenite, and form small intrusions adjacent to the Cocks and Foster glaciers, and between the Panorama and Kempe glaciers. Typically these granitoids are coarse-grained, comprising K-feldspar, quartz, plagioclase, and foliation-defining biotite which may be chloritised, with minor titanite, fluorite and allanite. Some granites near the Cocks and Kempe glaciers include hedenbergite, or rarely amphibole (Wynyard 2000, 2004; Read 2010). K-feldspar and plagioclase may be megacrystic. A marginal syenitic phase is present where the host rock is marble. Age determinations on numerous samples show that the Hillary Granitoids range from 551 ± 4 Ma to 542 ± 3 Ma (Read 2010).

The **Penny Hill Granite** (**gae**), exposed east of the Dromedary Glacier, is the most northerly of the Hillary Granitoids. It is a large intrusion of massive, medium- to coarse-grained, equigranular plagioclase-orthoclase-quartz-biotite granite transitional to granitic orthogneiss, with accessory titanite, apatite and zircon. It has a penetrative foliation defined by biotite, increasing toward the highly strained contact with the Dromedary Mafic Complex (Walcott & Craw 1993). Penny Hill Granite is texturally similar to granites present north of the Frio Shear Zone, but with A-type chemistry (Read et al. 2002). Several smaller intrusions with similar appearance and chemistry, such as the Kempe Granite (Read 2010), are present in the Royal Society Range (Hall 1991; Read et al. 2002) but few are large enough to show on a map of this scale. U-Pb dating of zircon from the Penny Hill Granite yields an age of 548 ± 4 Ma while titanite from the same sample is 517 ± 3 Ma. The pluton was probably emplaced at c. 548 Ma and reheated (during deformation) at 517 Ma (Read et al. 2002; Read 2010).

Near Mt Dromedary, north of the Renegar Glacier, the **Roaring Orthogneiss** (**gur**) is a composite unit which includes interlayered felsic, biotite- and muscovite-bearing orthogneisses, and mafic biotite-hornblende gneisses (Cook & Craw 2001). Rare biotite-muscovite quartzofeldspathic zones may be metasedimentary in origin. Igneous textures have been destroyed by pervasive annealing into a groundmass of microcline, plagioclase, quartz, and biotite with accessory muscovite, chlorite and titanite; garnet is abundant in some layers. The presence of metamorphic muscovite in granitic orthogneiss is unusual. Fine-grained and strongly foliated felsic orthogneiss occurs in the west of the body. The mafic orthogneisses consist of hornblende, plagioclase, biotite, and titanite; some layers are essentially mono-mineralic biotite and hornblende. Felsic units of the Roaring Orthogneiss have geochemistry closely resembling that of the Hillary Granitoids (Read 2010). TIMS U-Pb dating of zircons yielded an age of 553 ± 1 Ma, whereas LA-ICP-MS dating of further zircons from the same sample gave 546 ± 3 Ma for the felsic component (Read 2010).

Dry Valleys 1a Suite

DV1a Suite rocks are predominantly hornblende-biotite granitoids, with relatively low Rb, Sr, Na_20, K_2O and Al_2O_3 contents (Allibone et al. 1993). Typically, DV1a plutons are more deformed than DV1b and DV2 plutons and some DV1a rocks are strongly gneissic. Several discrete plutons are mapped, and smaller areas of DV1a orthogneisses have also been differentiated on the map face.

Figure 16 Outcrop photographs of Bonney Pluton granodiorite, highlighting some of the variation in lithology and texture caused by syntectonic emplacement of the pluton (Cox 1993). Top: Strongly foliated and lineated granodiorite near the margin of the pluton at Briggs Hills, with feldspar augen showing strong internal deformation (Photo: R. Jongens. Compass is 8 cm). Middle: Moderately foliated granodiorite at the margin of the pluton in the Kukri Hills, with weakly aligned K-feldspar megacrysts, hornblende and biotite (Photo: R. Jongens. Compass is 8 cm). Bottom: Orbicular granitoid from the centre of the pluton in the Taylor Valley, where compositional variation is flow-aligned but orbicules show no evidence of internal deformation. Orbicules are composed of concentric feldspar- and biotite+hornblende-rich compositional zones (Photo: I.M. Turnbull. Lens cap is 6 cm).

The **Bonney Pluton** (**grb**; Smillie 1992) is the largest DV1a pluton, mapped from the northern face of the Olympus Range south to the Blue Glacier (Fig. 16; Cox 1993). With a length of over 100 km and an area of more than 1000 km^2, the pluton accounts for 15% of basement rocks exposed in the map area. Bonney Pluton typifies DV1a lithologies, ranging in composition from granodiorite through quartz monzodiorite to monzodiorite (Allibone et al. 1991). Rocks commonly have well developed flow-aligned alkali feldspar megacrysts, mafic enclaves and hornblende in a matrix of plagioclase, alkali feldspar, biotite and quartz with accessory clinopyroxene, allanite, zircon, apatite, monazite, titanite and opaque minerals (Cox 1993). Locally there are megacryst swarms and zones with distinctive orbicular texture (Fig. 16; Palmer et al. 1967; Dahl & Palmer 1981; Smillie 1989; Allibone et al. 1993a). The margins of the pluton are commonly highly strained by post-crystallisation ductile-plastic flow (Fig. 16; Cox 1993). Marginal zones are also choked with rafts and xenoliths of the host Skelton Group and older orthogneisses (e.g. Cox 1989, 1993; Smillie 1989). High-precision U-Pb ages of 510.78 ± 0.56 Ma for the deformed marginal zone and 503.77 ± 0.37 Ma in the flow-foliated centre of the pluton have recently been obtained by CA-ID-TIMS analysis of zircon (Tulloch & Ramezani 2012), suggesting that emplacement and crystallisation may have occurred over several million years (see also Cox & Allibone 1991).

The **Cavendish Pluton** (**grv**) is exposed around the upper Ferrar Glacier and extensively at Cavendish Rocks; it was initially included in Bonney Pluton (Allibone et al. 1991) but is now recognised as a separate body. **Discovery Pluton** (**gri**) is a large DV1a intrusion that extends from the eastern Gonville & Caius Range south of Granite Harbour (Forsyth et al. 2002) north to Mt Arrowsmith north of Tiger Island (Forsyth et al. 2003; Forsyth 2010). The **Denton** (**grd**), **Evans** (**gre**), and **Wheeler** (**grw**) plutons are smaller bodies between the lower Wright Valley and the Cotton Glacier (Ellery 1989; Forsyth et al. 2002). All these plutons have a similar predominant mineralogy of plagioclase, hornblende, biotite, and distinctive large K-feldspar megacrysts. Compositionally they are mainly monzodiorites, quartz monzonites or granodiorites. These plutons also have well-developed flow foliation, defined by K-feldspar megacrysts, hornblende and biotite. Orbicular textures are another characteristic of several of these plutons (Gunn & Warren 1962 fig. 89). The relatively small **Armitage Pluton** (**gra**) is restricted to the area around and north of Armitage Saddle, south of the Blue Glacier (Jones 1995a, 1997a,b). Its mineralogy is similar to other DV1a plutons, but with more hornblende and biotite; it lacks megacrysts, is less deformed, and is compositionally a granite (Jones 1995a, 1997a). DV1a plutons typically contain mafic microgranite enclaves, elongated parallel to foliation, and interpreted as immiscible melt blebs (Smillie 1989; Allibone et al. 1993a). Xenoliths of Skelton Group metasediments are typically crowded along pluton margins, where megacrysts are commonly deformed into augen (Fig. 16), and together with schlieren and mafic banding may be deformed to give a swirly or chaotic appearance. The **Catspaw Pluton** (**grc**) is an elongate body of coarse-grained granite that extends from the Kukri Hills across the Taylor Glacier into the Asgard Range (Allibone et al. 1991). The Catspaw Pluton differs from megacrystic DV1a plutons in being texturally homogeneous and lacking flow-related segregation and foliation (Allibone et al. 1991, 1993a).

Unnamed and undifferentiated monzodioritic to granodioritic orthogneisses are commonly intercalated and coaxially deformed with their host Skelton Group metasediments. Foliation in these orthogneisses is parallel to that of the enclosing metasediments. **Hornblende biotite orthogneiss** (**guh**; Cox & Allibone 1991) forms an extensive pluton in the central St Johns Range (Turnbull et al. 1994), and smaller bodies within Skelton Group rocks in the Victoria Valley, eastern St Johns Range, and elsewhere in the Dry Valleys region. Only some of these bodies are large enough to show at this map scale. Hornblende biotite orthogneisses are typically medium- to coarse-grained, moderately to intensely foliated, and contain deformed alkali feldspar augen. Mineral assemblages are predominantly plagioclase-alkali feldspar-quartz-hornblende-biotite with accessory clinopyroxene, allanite, titanite, zircon, apatite and opaques. Deformed Skelton Group xenoliths, microgranite enclaves, and rare orbicules occur sporadically in most orthogneiss bodies. A small body of dioritic gneiss on Flint Ridge southeast of the Newall Glacier was named **Flint Pluton** (**guf**) by Forsyth et al. (2002). It resembles other hornblende biotite orthogneisses with a well developed gneissic structure, but contains augite, quartz and plagioclase megacrysts, and accessory titanite and allanite. Unusual clinopyroxene-rich mafic orthogneisses (not differentiated on the map) occur near Apocalypse Peaks and the northern side of the Insel Range (Isaac et al. 1996).

Other, smaller and un-named bodies of undeformed to weakly foliated **hornblende biotite granitoids** (**gr**) with DV1a characteristics are in places interlayered with younger DV1b biotite orthogneiss. Isolated outcrops of similar granitoid rocks underlie the Kukri Erosion Surface at Knobhead (Woolfe et al. 1989). At Moraine Bluff, **unfoliated granitoid** (**gro**) rocks are host to abundant mafic enclaves (Read 2010). The granitoid is medium-grained, hornblende-biotite granodiorite and monzogranite, comprising zoned and altered euhedral plagioclase, quartz, K-feldspar, biotite and hornblende with accessory zircon and allanite. Enclaves include hornblende monzodiorite, and hornblende–biotite diorite to quartz diorite with trace amounts of K-feldspar, titanite and allanite. The Moraine Bluff granitoids were correlated with the DV1a Suite by Read (2010) on the basis of geochemistry.

Dry Valleys 1b Suite

DV1b plutons are characteristically enriched in Na_2O, Al_2O_3 and Sr, and depleted in Y and Nb relative to DV1a rocks. Compositions are relatively restricted, ranging from granite to granodiorite. Foliation is variably developed (Figs 17, 18), and massive to weakly foliated biotite granitoids are more widespread than orthogneisses. Margins of these undeformed plutons are commonly choked with metasedimentary xenoliths, though mafic enclaves are uncommon.

The **Calkin Pluton** (**gc**) and **Dun Pluton** (**gd**) are the oldest of the DV1b Suite rocks in the Dry Valleys area (Allibone & Wysoczanski 2002). They are gneissic, with biotite defining a strong foliation parallel to, and folded with, the foliation in adjacent Skelton Group rocks. Hornblende is absent (in contrast to DV1a plutons). The Dun Pluton is a small quartz monzodiorite pluton exposed beside the lower Dun Glacier on the south side of the Kukri Hills (Allibone et al. 1991). It comprises medium-grained alkali feldspar, quartz and plagioclase with biotite and accessory clinopyroxene, zircon, allanite, calcite, apatite and opaques. A precise 515.16 ± 0.36 Ma zircon U-Pb age has been obtained by CA-ID-TIMS (Tulloch & Ramezani 2012). The nearby Calkin Pluton is exposed west of the Calkin Glacier on the northern flank of the Kukri Hills, and forms a band within deformed Skelton Group metasediments (Allibone et al. 1991). The Calkin Pluton is composed of fine- to medium-grained plagioclase, quartz, alkali feldspar and biotite with accessory zircon, allanite, apatite and magnetite. It has a 516 ± 10 Ma zircon U-Pb age from SHRIMP dating (Allibone & Wysoczanski 2002).

Chancellor Orthogneiss (**go**), a name once widely and loosely applied, has been restricted and redefined by Jones (1995a, 1997a) as a fine-grained, variably foliated, leucogranitic, biotite orthogneiss that occurs on Chancellor Ridge immediately north of the Frio Shear Zone and adjacent to the Howchin Glacier. It intrudes Skelton Group metasediments. Randomly oriented stocks and dikes of orthogneiss cut blocks of metasediment entrained within the pluton, especially on the margins (Jones 1997a). Chancellor Orthogneiss is strongly deformed, with a matrix of recrystallised quartz, biotite and feldspar wrapped around relict feldspars, which are commonly megacrystic (Fig. 17). Accessory minerals are titanite, apatite and garnet. Chancellor Orthogneiss has not been dated and the limited geochemical analyses are of samples that are silica-rich and strongly evolved (Jones 1997a). Although tentatively assigned to the DV1b Suite (Jones 1995a, 1997a), it is possible that Chancellor Orthogneiss is a correlative of the Hillary Granitoids and belongs to the Koettliz Glacier Alkaline Suite.

Small bodies of **biotite orthogneiss** (**gub**), some containing garnet, are intercalated with Skelton Group rocks in many areas, including the Garwood Valley (Blank et al. 1963; Portal Augen Gneiss of Mortimer 1981), the St Johns Range (Turnbull et al. 1994) and the Wilson Piedmont region (Forsyth et al. 2002); only the largest can be differentiated at 1:250 000 scale (Fig. 18). Few chemical

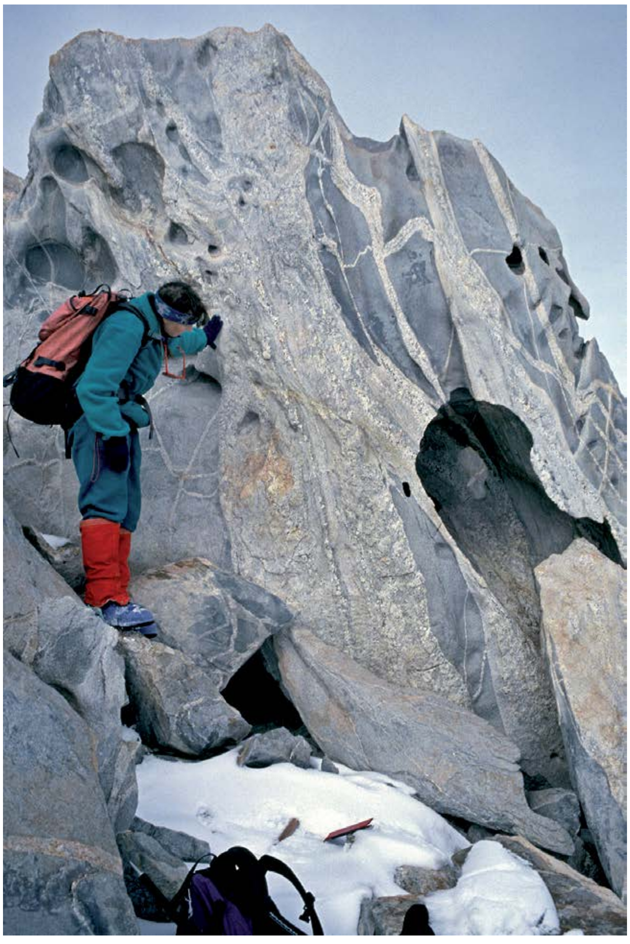


Figure 17 Examples of varying lithology and foliation development in DV1b Suite granitoids. Left: Primary lithological heterogeneity in weakly foliated Chancellor Orthogneiss at Chancellor Ridge, with felsic-rich aplitic melts separating biotite-rich zones (Photo: S.C. Cox). Right: Typical outcrop of Coleman Pluton, at Mount Coleman on the north side of the Taylor Valley, with a magmatic flow foliation defined by biotite-rich schlieren (Photo: I.M.Turnbull. Ice axe head is 22 cm across).

analyses are available for these rocks so inclusion in the DV1b Suite is tentative. Numerous small undeformed **biotite granitoid** plugs and dikes (**gf**), tentatively assigned to the DV1b Suite, are widespread and also form larger and more obviously discordant bodies.

Hedley Pluton (**gfh**), an unfoliated DV1b intrusion, is mapped from the Taylor Glacier through the western Kukri Hills to the Ferrar Glacier (Allibone et al. 1991), and probably extends across the Ferrar Glacier to the Zoller and Emmanuel glaciers at the northern end of the Royal Society Range (Forsyth et al. 2003; Forsyth 2010). Compositionally it ranges from granite to granodiorite, formed of medium-grained quartz, alkali feldspar and plagioclase with minor biotite and accessory apatite and allanite, zircon and opaques. Some flow alignment of biotite is evident on pluton margins, which are marked by zones of intrusion breccia up to two kilometres wide (Allibone et al. 1991). Orbicular texture occurs at Cathedral Rocks (Smillie 1989). A precise 499.26 ± 0.22 Ma zircon U-Pb age has been obtained by CA-ID-TIMS (Tulloch & Ramezani 2012).

The **Valhalla Pluton** (**gfv**) extends from the Valhalla Glacier in the Asgard Range across the Wright Valley to Bull Pass (Allibone et al. 1991; Turnbull et al. 1994). It consists of medium-grained granite to granodiorite with alkali feldspar, plagioclase and quartz, minor biotite, and accessory zircon, allanite, apatite and rare opaque phases. The pluton is elongate, but its intrusive style is discordant, involving stoping at its margins (Allibone et al. 1993a). U-Pb ages of 493.7 ± 4.1 Ma for zircon and 488 ± 2 Ma for monazite have been obtained for the pluton (Cox et al. 2000; Hagen-Peter et al. 2011), although it is cut by Vanda Dikes thought to be 495–491 Ma in age. The similar **St Johns** (**gfj**) and **Suess** (**gfs**) plutons are extensive intrusions which are mapped throughout much of the St Johns Range, and from Mt Suess to Sperm Bluff respectively (Turnbull et al. 1994). Both comprise medium-grained granite to granodiorite consisting of quartz, alkali feldspar, plagioclase and minor biotite with accessory allanite, zircon, apatite and opaques, and titanite in the Suess Pluton. Margins of both plutons are marked by stoped intrusion breccias. Poorly developed orbicular texture at Sperm Bluff (Turnbull et al. 1994) resembles that recorded from the Hedley Pluton (Smillie 1989).

The **Coleman Pluton** (**gfc**) is mapped only around Mt Coleman, northwest of New Harbour (Forsyth et al. 2002), where it intrudes Skelton Group metasediments and associated orthogneisses. The pluton is characterised by magmatic flow foliation, outlined by biotite-rich schlieren (Fig. 17). Compositionally it is a monzogranite, with alkali and plagioclase feldspar, up to 30% quartz, minor biotite and distinctive accessory garnet. In some areas the pluton is almost completely replaced by younger Vanda Dikes.

Figure 18 Well-foliated biotite orthogneiss outcrops at the eastern end of the Kukri Hills. The orthogneiss contains garnet in association with leucocratic feldspar- and quartz-rich patches.The chemistry of this rock has yet to be assessed, but it is inferred to belong to the DV1b Suite on the basis of its mineralogy and texture (Photo: S.C. Cox. Field book is 12 cm wide).

The **Hidden Granite** (**gfi;** Jones 1997a) is a biotite leucogranite cropping out between the Ward and Hidden valleys. Hidden Granite is chemically and petrographically similar to the nearby Chancellor Orthogneiss, but lacks foliation. It comprises quartz, plagioclase, alkali feldspar and biotite with accessory titanite, microcline, apatite and garnet. The pluton intrudes Bonney Pluton and Skelton Group metasediments as a discordant, irregular body that lacks distinct margins. Large areas of host rocks, cut by numerous Hidden Granite dikes, occur throughout the pluton. It is also cut by many, probably coeval, bodies of the Keyhole Mafic Intrusives (see below).

Small plutons and dikes with DV1b geochemical affinity form the Hooper Crags in the upper Koettlitz Glacier and have been named **Hooper Intrusives** (**gfo**) by Read (2010). Other smaller intrusions are mapped north and southeast of the Dromedary Glacier and in the lower Skelton Glacier. These bodies generally intrude Skelton Group metasediments, or in places older DV1a plutons, and have ages ranging from 533 to 511 Ma (Read 2010). They are predominantly granite to granodiorite, with some monzonite and quartz monzonite and minor diorite, and are mostly unfoliated. Granites are mostly medium-grained and composed of quartz, alkali feldspar, plagioclase and biotite, with accessory (but characteristic) clinopyroxene, titanite, opaques and rare calcite.

Other small intrusions correlated with the Hooper Intrusives include the **Radian Pluton** (**gfr**), a small, partially exposed but apparently concordant pluton exposed as a sliver within Skelton Group greywacke on the east face of Mt Huggins, south of the Radian Glacier (Cook & Craw 2001). Radian Pluton consists of unfoliated biotite granite, comprising quartz, altered plagioclase, and alkali feldspar, locally garnetiferous with rare hornblende and zircon, and containing mafic enclaves. Immediately south of the mapped area at the Kehle Glacier in the southern Worcester Range, the **Kehle Pluton** (**gfk** in digital dataset) is a small intrusion of medium-grained granodiorite (Richardson 2002), dated at 530 ± 8 Ma and correlated with the Hooper Intrusives by Read (2010).

Dry Valleys 2 Suite

DV2 Suite rocks are mainly undeformed, and range from granitic to quartz monzonitic in composition with higher K_2O, Rb, Pb and Zr contents than those of the DV1a and DV1b suites; they are depleted in MgO, CaO, V and Cr (Smillie 1992; Allibone et al. 1993a,b). Some are particularly enriched in Ba and light rare earth elements (La, Ce, Pr, Nd). The DV2 Suite includes most of the younger, generally discordant, biotite granitoid plutons and smaller dikes, sills and plugs of the Dry Valleys region. Most DV2 plutons have conspicuous enclaves of finer grained and more mafic rocks, and of felsic porphyry, which closely resembles the lithology of some Vanda Dikes.

The **Pearse** (**ggp**), **Nibelungen** (**ggn**), and **South Fork** (**ggx**) plutons underlie the western Asgard Range, from the Friis Hills above the western Taylor Valley, through the Nibelungen Valley to east of the Labyrinth in the upper Wright Valley (Fig. 19). They include granitic, monzonitic and quartz monzonitic rocks, often with considerable textural variation within individual plutons. Margins of these plutons are finer grained, and may be choked with enclaves to form intrusion breccias (e.g. Isaac et al. 1996). Mineralogically they comprise varying amounts of alkali feldspar (sometimes as megacrysts), plagioclase and subordinate quartz, with biotite and lesser hornblende as the main mafic phases. Accessory minerals include apatite, zircon, allanite, monazite, titanite and opaques. Alkali feldspar phenocrysts in the Nibelungen and South Fork plutons may be flow-aligned (Allibone et al. 1991; Isaac et al. 1996). The **Mt Falconer Pluton** (**ggf**) in the eastern Taylor Valley is a small quartz monzonite pluton, undeformed and strongly discordant to its host Skelton Group metasediments (Ghent & Henderson 1968). The medium- to coarse-grained quartz monzonite consists of K-feldspar, plagioclase, quartz, biotite and lesser hornblende, and accessory allanite, titanite, apatite, zircon and ilmenite (Ghent 1970). Its finer grained marginal zone is an intrusion breccia which hosts numerous oriented xenoliths of the adjacent dioritic country rock (Ghent & Henderson 1968). The Mt Falconer Pluton is correlated with the DV2 Suite by Forsyth et al. (2002) on the basis of age, discordant field relationships and lack of deformation.

Further south in the Dry Valleys region, the **Miers Granite** (**ggi**) is the most evolved pluton in the DV2 Suite. It forms an irregular, unfoliated, discordant intrusion with some outlying apophyses at the eastern end of Marshall Ridge, between the lower Miers and Marshall valleys (Mortimer 1981; Worley 1992). The intrusion consists of massive, coarse-grained syenite to syenogranite with abundant hornblende and K-feldspar phenocrysts, biotite, and rare mafic enclaves.

Two DV2 plutons are mapped around Granite Harbour. On the south side, the **Avalanche Bay Pluton** (**gga**) forms the cliffs between Avalanche Bay and Couloir Cliffs, with small outcrops in the eastern Gonville & Caius Range (Forsyth et al. 2002). A zircon U-Pb age of 498 ± 4 Ma has been obtained (Encarnacion & Grunow 1996). To the north, the **Lion Island Pluton** (**ggo**) is exposed around the southern margin of the Evans Piedmont Glacier, and between Lion and Tiger islands (Gunn & Warren 1962; Forsyth et al. 2003; Forsyth 2010). Avalanche Bay Pluton is an unfoliated, medium-grained quartz monzonite composed of quartz, plagioclase, K-feldspar, equal amounts of hornblende and biotite, and accessory zircon, allanite and magnetite (Forsyth et al. 2002). Lion Island Pluton is an unfoliated, medium- to coarse-grained, equigranular to slightly porphyritic granite comprising K-feldspar, plagioclase, quartz, biotite and subordinate hornblende, allanite, titanite, zircon and apatite (Graham & Palmer 1987; Forsyth et al. 2003). A precise zircon U-Pb age of 493.95 ± 0.17 Ma has been obtained for Lion Island Pluton by CA-ID-TIMS analysis (as 'Archer Pluton'; Tulloch & Ramezani 2012).

The **Gonville & Caius Pluton** (**ggc**) underlies most of the western Gonville & Caius Range south of Granite

Harbour (Gunn & Warren 1962; Forsyth et al. 2002), and extends north to the western Kar Plateau. Outcrops show characteristic mafic clots and microgranite and porphyritic inclusions in an otherwise homogeneous pink or grey, hornblende-biotite granite (Forsyth et al. 2002). The mineral assemblage is alkali feldspar, quartz and plagioclase, with accessory biotite, hornblende, zircon, apatite, titanite, allanite and magnetite, and secondary epidote. Zircon U-Pb ages of 495.9 ± 1.7 to 495.4 ± 2.2 Ma have recently been obtained for samples from the northern side of Mackay Glacier (Hagen-Peter et al. 2011).

Some of the younger, undeformed and discordant plutons have hybrid compositions which do not fall clearly within the DV1a, 1b or 2 suite classification (Allibone et al.1993b). The **Harker Pluton** (**ggh**) is one such hybrid body in the eastern St Johns Range between the Victoria Lower Glacier and Killer Ridge. It is a coarse-grained, homogeneous, equigranular or weakly porphyritic granite to syenogranite or monzogranite. The mineralogy is K-feldspar, plagioclase, and quartz with biotite as an accessory phase; other accessory minerals are hornblende, allanite, magnetite, zircon and apatite with secondary

Figure 19 DV2 Suite granitoids. Top: The South Fork Pluton forms light-coloured bluffs below the Ferrar Dolerite Peneplain Sill at the west end of the Dais, Wright Valley (Photo: P.J. Forsyth). Bottom left: Close view of South Fork Pluton granitoid containing a felsic porphyry enclave similar in composition to felsic Vanda Dikes (Photo: P.J. Forsyth. Hammer head is 17 cm long). Bottom right: Close view of relatively homogeneous area of quartz monzonite in the Mount Falconer Pluton, Taylor Valley, with small mafic clot (Photo: S.C. Cox. Visible part of ski pole is c. 7 cm high).

muscovite. Locally, the western margin of the pluton is pervasively intruded by quartz-feldspar pegmatites (Allibone et al. 1993a; Waters 1993; Turnbull et al. 1994; Forsyth et al. 2002). A zircon U-Pb age of 495.7 ± 2 Ma has been obtained for Harker Pluton (Hagen-Peter et al. 2011). Although its field relationships and age resemble those of DV2 plutons, geochemistry suggests a more complex petrogenesis. The adjacent **Swinford Pluton** (**ggf**) also has a hybrid geochemistry (Allibone et al. 1993b) and forms narrow bodies west of the Harker Pluton in the central St Johns Range, and east of it at the north end of Killer Ridge. It is a coarse-grained to megacrystic biotite granite to quartz monzonite, with occasional felsic enclaves. Swinford Pluton comprises alkali feldspar megacrysts in a matrix of plagioclase, quartz, K-feldspar and minor biotite, with accessory hornblende, zircon, apatite, allanite, titanite and opaque phases. The **Mount Perseverance Pluton** (**gge**) is a discrete body of pink granite that crops out at Mt Perseverance and on the southwest side of the Hunt Glacier (Gunn & Warren 1962). Mount Perseverance Pluton is inferred to belong to the DV2 suite, based on field relations and intrusive style, but only one geochemical sample has been analysed. A 502.1 ± 2.6 Ma zircon U-Pb age has recently been obtained (Hagen-Peter et al. 2011), which is slightly older than the c. 498–490 Ma ages typical of other DV2 plutons.

South of the St Johns Range, the **Orestes Pluton** (**ggt**) is a large biotite leucogranite intrusion which extends from the southern St Johns Range, across Lake Vida to near Bull Pass in the Olympus Range (Turnbull et al. 1994). Orestes Pluton has DV2 field relationships, and a young age, but DV1b geochemistry (Allibone et al. 1993b). Its northeasterly trend is discordant to the adjacent older Bonney and St Johns plutons. Orestes granite is composed of quartz, plagioclase, K-feldspar, minor biotite, and accessory apatite with traces of allanite, zircon, titanite, and opaques. Felsic porphyry enclaves are common. North of the St Johns Range, the **Gondola Pluton** (**ggg**) crops out entirely within, but intrudes, the Suess Pluton (see above) although the contact is cryptic (Turnbull et al. 1994). Gondola Pluton is a medium-grained, undeformed leucogranite consisting of K-feldspar, plagioclase and quartz with minor biotite, and accessory apatite, zircon and opaque minerals. The **Brownworth Pluton** (**ggb**) extends from the easternmost Asgard Range across the Wright Lower Glacier, through Doorly Spur to Blessing Bluff on the Wilson Piedmont Glacier (Ellery 1989; Forsyth et al. 2002). It is another undeformed, discordant DV2 intrusion of quartz monzonite, comprising K-feldspar, plagioclase, and quartz with minor biotite and hornblende and accessory titanite, allanite and zircon. Brownworth Pluton has distinctive and abundant K-feldspar megacrysts, and felsic porphyry enclaves. Zircon U-Pb ages of 496.5 ± 2 Ma and 493 ± 3 Ma have been obtained for the pluton (Hagen-Peter et al. 2011).

South of the Ferrar Glacier, two plutons are also tentatively assigned to the DV2 Suite. **Darkowski Pluton** (**ggd**) underlies the upper Darkowski and Bol glaciers and extends south into the Blue Glacier catchment. It is a massive, undeformed hornblende-biotite granite (Forsyth et al. 2003; Forsyth 2010), not yet described in detail but yielding a zircon U-Pb age of 493.8 ± 1.7 Ma (Hagen-Peter et al. 2011). The **Lama Pluton** (**ggy**) forms a discordant body intruding Skelton Group metasediments around the lower Joyce Glacier, Shangri La and Penance Pass north of the Miers Valley (Worley 1992; Simpson & Aslund 1996). It has a weak magmatic fabric, contains clinopyroxene, hornblende and biotite, and has distinct porphyritic and equigranular phases. Compositions range from monzodiorite and monzonite through quartz monzodiorite and quartz monzonite to monzogranite. Although it is atypically mafic, geochemically the Lama Pluton most closely matches the DV2 Suite, but with some DV1b characteristics (Worley 1992; Simpson & Aslund 1996).

Numerous smaller plutons, stocks, plugs, sills and related dikes whose geochemical affinities and ages are unknown have been tentatively assigned to the DV2 Suite. Only the largest of these bodies are mapped, as **undifferentiated granitoids** (**gg**).

Vanda Dikes

Basic, intermediate and acidic dikes which occur as both isolated intrusions and intense swarms throughout the Dry Valleys region are collectively mapped as the Vanda Dikes (Fig. 20; McKelvey & Webb 1962; Allibone et al. 1991; Keiller 1991; Wu & Berg 1992; Keiller & Allibone in Turnbull et al. 1994). The dikes range widely in composition, from leucogranite through lamprophyre to diorite. An older group is high-K calc-alkalic and ranges from monzodiorite to leucogranite. Younger dikes are shoshonitic, and include shoshonite, banakite, and granitoids (Keiller 1991). Geochemically the Vanda Dikes are part of the DV2 Suite (Allibone et al. 1993b). The different mineralogies, textures and compositions cannot be represented at this map scale and only mafic and felsic varieties are indicated, by different coloured symbols. Locally, dikes make up as much as 75% of the basement rocks (Keiller & Allibone in Turnbull et al. 1994) but this is atypical. Dike emplacement was more or less coeval with intrusion of DV2 plutons, and they commonly show mutually cross-cutting relationships, but the youngest dikes cut all other bodies. Enclaves lithologically equivalent to Vanda Dikes are common within some DV2 plutons (Allibone et al. 1993a; Fig. 19). The dikes typically dip steeply and the predominant strike is northeast-southwest; apart from minor brittle faulting they are undeformed. Individual dikes may be up to four metres wide and several kilometres long. Chilled margins are common. Both felsic and mafic varieties are normally porphyritic; felsic dikes usually cut mafic types but the opposite relationship also occurs. The mafic dikes near Mt Loke, in the southern Wright Valley, have an east-west strike, relatively shallow 30–40º dip, and may be slightly older than the main Vanda Dike swarms (Ellery 1989; Keiller 1991; Grunow & Encarnacion 2000). Small plugs and sills of **felsic porphyry** (**ge**), probably of Vanda Dikes affinity, have been recorded in the Friis Hills and at Solitary Rocks (Allibone et al. 1991), and in the eastern Asgard Range within the Brownworth Pluton (not mapped;

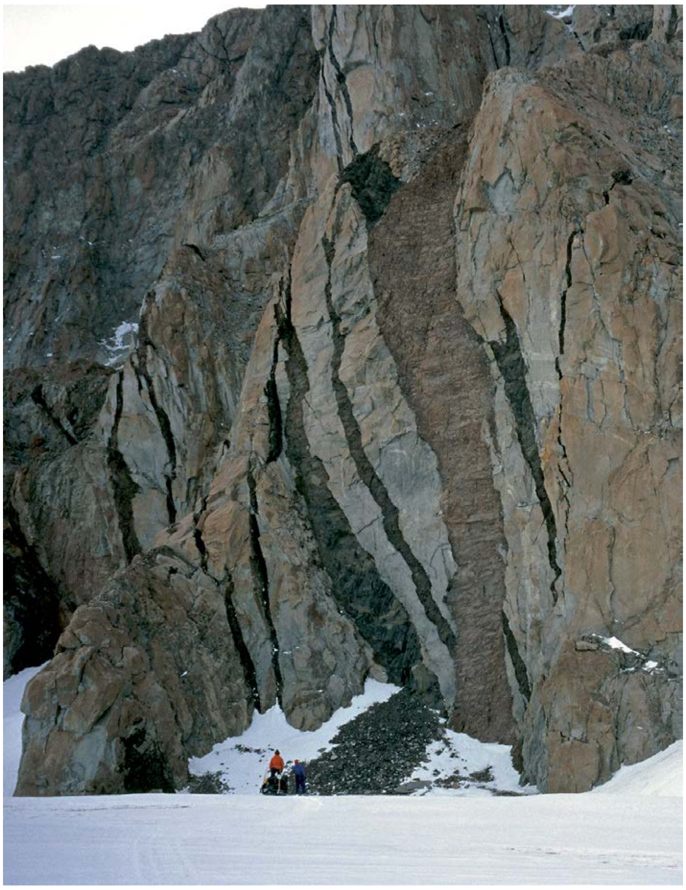
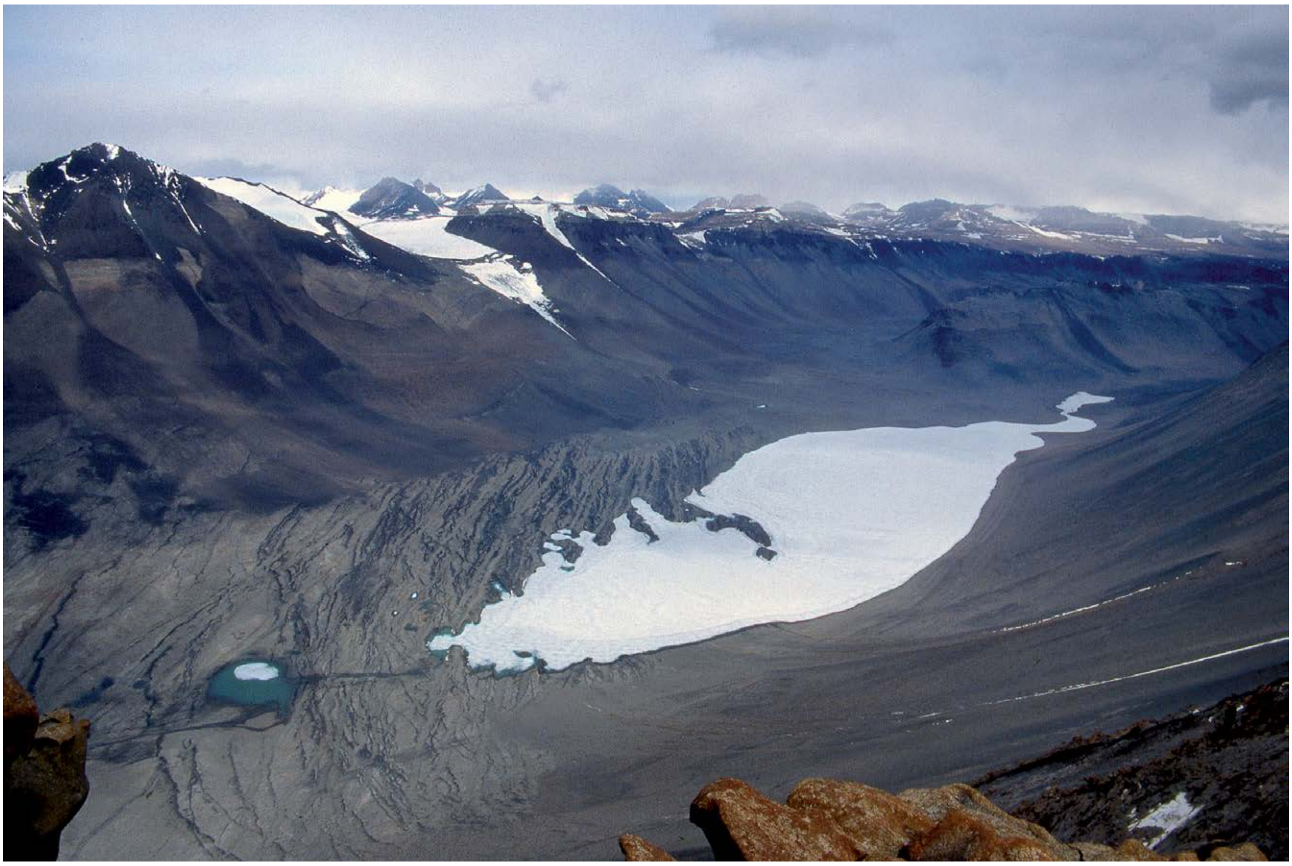


Figure 20 Vanda Dikes. Top: Mafic (black) and felsic porphyry (red-brown) dikes intrude granitoid of the Harker Pluton in the cliffs of Killer Ridge above the Miller Glacier (Photo: P.J. Forsyth. People in foreground provide scale). Bottom: Relatively erosion-resistant dikes form ridges and stripes across the floor of the Wright Valley beside Lake Vanda, where they have intruded the Bonney Pluton in a dense swarm (Photo: I.M. Turnbull).



Forsyth et al. 2002). Zircon U-Pb ages of 495–491 Ma have been obtained for Vanda Dikes and correlatives just to the north of the map area (Encarnacion & Grunow 1996; Rocchi et al. 2009; Bray et al. 2010).

Miscellaneous Granite Harbour Intrusive Complex rocks

Miscellaneous mafic rocks

Numerous small mafic intrusions, ranging from dikes to irregular bodies and small plugs up to two kilometres across, are mapped throughout southern Victoria Land (e.g. Turnbull et al. 1994; Cox et al. 2000; Forsyth et al. 2002). Some have been given formal pluton status. Few have been investigated in detail and their ages are constrained only by intrusive relationships; these mafic intrusions almost certainly include bodies of widely differing age. **Undifferentiated mafic intrusives** (**gm**) include discordant diorite plugs near Marble Point, Mt Newall and at Killer Ridge; these were mapped as Delta Diorite by Gunn & Warren (1962) but that name is now abandoned (see above, and Appendix). Forsyth et al. (2002) mapped additional dioritic intrusions around the Wilson Piedmont Glacier at King Pin and Hanson Ridge, and others occur in the lower Wright Valley (Ellery 1989; Keiller 1991), Mt Falconer (Ghent & Henderson 1968), Kukri Hills, Marshall Valley (Mortimer 1981) and along the western side of the Blue Glacier. Compositions of these mafic rocks range from hornblende-biotite quartz monzodiorite, through hornblende and hornblende-biotite diorite, to pyroxene-biotite-hornblende diorite. Forsyth et al. (2002) described megacrystic pyroxene gabbro forming a plug and dike on Staeffler Ridge, intruding Skelton Group metasediments. Slightly discordant hornblende-olivine-clinopyroxene diorite dikes, some containing hornblendite lenses, intrude Skelton Group on the St Johns Range (Turnbull et al. 1994). Dioritic to gabbroic dikes occur in the Clare Range and northern St Johns Range, the former unfoliated but the latter dismembered, foliated and folded within host Skelton Group metasediments (Turnbull et al. 1994). Together with mafic rocks on the Dais (Cox 1989; Isaac et al. 1994), they have been distinguished as **older mafic intrusives and orthogneiss** (**gum**).

Packard Pluton (**gmp**) is exposed beside the Packard Glacier in the southern St Johns Range, and in the eastern Olympus Range (Turnbull et al. 1994; Forsyth et al. 2002). It comprises undeformed gabbro and diorite to quartz diorite, with primary igneous layering preserved in several places. This pluton contains abundant hornblende and plagioclase, with minor quartz, biotite and pyroxene. Secondary alteration to chlorite, actinolite, muscovite, epidote and calcite is extensive. Coarse quartz-plagioclase-hornblende pegmatite is a distinctive minor lithology, as are rafts and xenoliths of the host Skelton Group. The Packard Pluton is cut by Vanda Dikes. The **Buddha Pluton** (**gmu**) is an irregular sill of variably porphyritic foid-bearing monzodiorite, diorite, monzonite and minor gabbro on the north side of the Miers Valley. The mineralogy is dominated by pyroxene, hornblende, biotite and plagioclase; textures range from porphyritic with mafic enclaves, to locally equigranular (Mortimer 1981; Worley 1992). The nearby **Keyhole Mafic Intrusives** (**gmk**) are a mixture of plugs, small sills and predominantly northeast-striking dikes, which intrude the Hidden Granite north and south of Hidden Valley, near the Adams Glacier. They include gabbro, diorite, and quartz monzodiorite and are locally mingled with Hidden Granite. The Keyhole intrusions have irregular and diffuse margins, are often choked with granite enclaves, and show no evidence of chilling; they are probably coeval with their host (Jones 1995a,b, 1997a).

These miscellaneous mafic intrusive units have not been dated radiometrically, but their intrusive relationships suggest that they are relatively young. Most of the undifferentiated mafic intrusives are much less foliated and deformed than the DV1a hornblende biotite orthogneisses (such as the Flint Pluton), previously described. Those cut by Vanda Dikes may be of DV1a or DV1b age.

Miscellaneous felsic rocks

There are many isolated outcrops in regions such as the northern Worcester Range, east of the Upper Staircase in the Skelton Névé, and north and south of the Fry Glacier, that remain unvisited by geologists. Most of these are inferred to be plutonic rocks, on the basis of their appearance in aerial photo and satellite imagery, from distant views, and from their elevation relative to the Kukri Erosion Surface. In the absence of other evidence they are mapped as **undifferentiated granitoid** (**g**) of unknown but pre-Silurian age. Small, fine-grained, equigranular to porphyritic granitoid plugs, sills and dikes that intrude Skelton Group metasediments and plutons of all suites, but with no known suite affinity of their own, are mapped as **unassigned late granitoid** (**gq**). Some of these intrusions can be shown to be slightly older, where they are cut by Vanda Dikes; these are grouped as **late granitoids** (**gl**). The largest area of such rocks comprises an intense swarm of granitic dikes in the Wright Valley that merges into a plug southeast of Bull Pass (Allibone et al. 1991; Turnbull et al. 1994). Other bodies follow the eastern margins of the St Johns and Wheeler plutons. All these granitoids range in composition from granodiorite to quartz monzonite and granite; hornblende-clinopyroxene granodiorite and monzonite occur in the central Taylor Valley. Granite and granodiorite are typically fine-grained, biotite-bearing, and lacking internal fabric. Locally, **quartz monzodiorite** (**gqz**) with quartz monzonite and monzonite forms slightly larger and mappable sills, such as around the Catspaw Glacier snout (Allibone et al. 1991). Hydrothermally altered quartz monzodiorite to granodiorite, mapped as undifferentiated granitoid (**g**), occurs near Knobhead (Woolfe et al. 1989).

KUKRI EROSION SURFACE

Cambrian to Ordovician Ross Orogeny deformation, intrusion and uplift at the margin of the East Antarctic craton was followed by a prolonged period of uplift, deep erosion, local dissection, weathering and planation. In southern Victoria Land, the basement of Skelton Group and

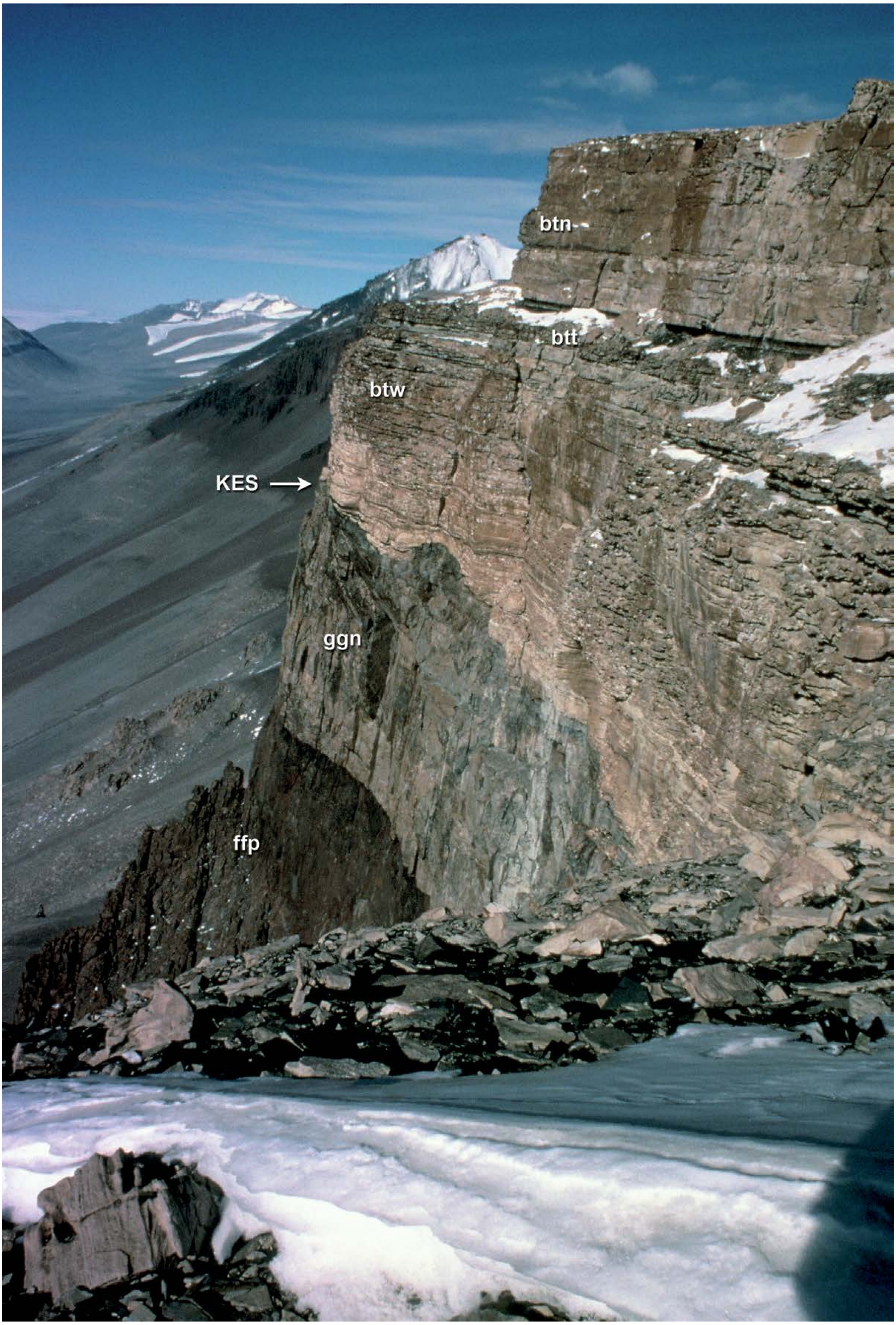


Figure 21 The Kukri Erosion Surface at the mouth of the Nibelungen Valley, Asgard Range. The basal formation of the Beacon Supergroup (Windy Gully Sandstone, btw) laps onto the irregular topography of Nibelungen Pluton granite (ggn, dark grey). Up to five metres of relief can be seen on the surface at this locality. Below the granite, the Ferrar Dolerite Peneplain Sill (ffp, dark brown) continues across the slopes into the far distance. Thick screes mantle the lower slopes, varying in composition according to source rocks being shed from gullies and cliffs above. The dark band on the ledge is Terra Cotta Siltstone (btt); the uppermost rocks are New Mountain Sandstone (btn) (Photo: P.J. Forsyth. The bluff is c. 200 m high).

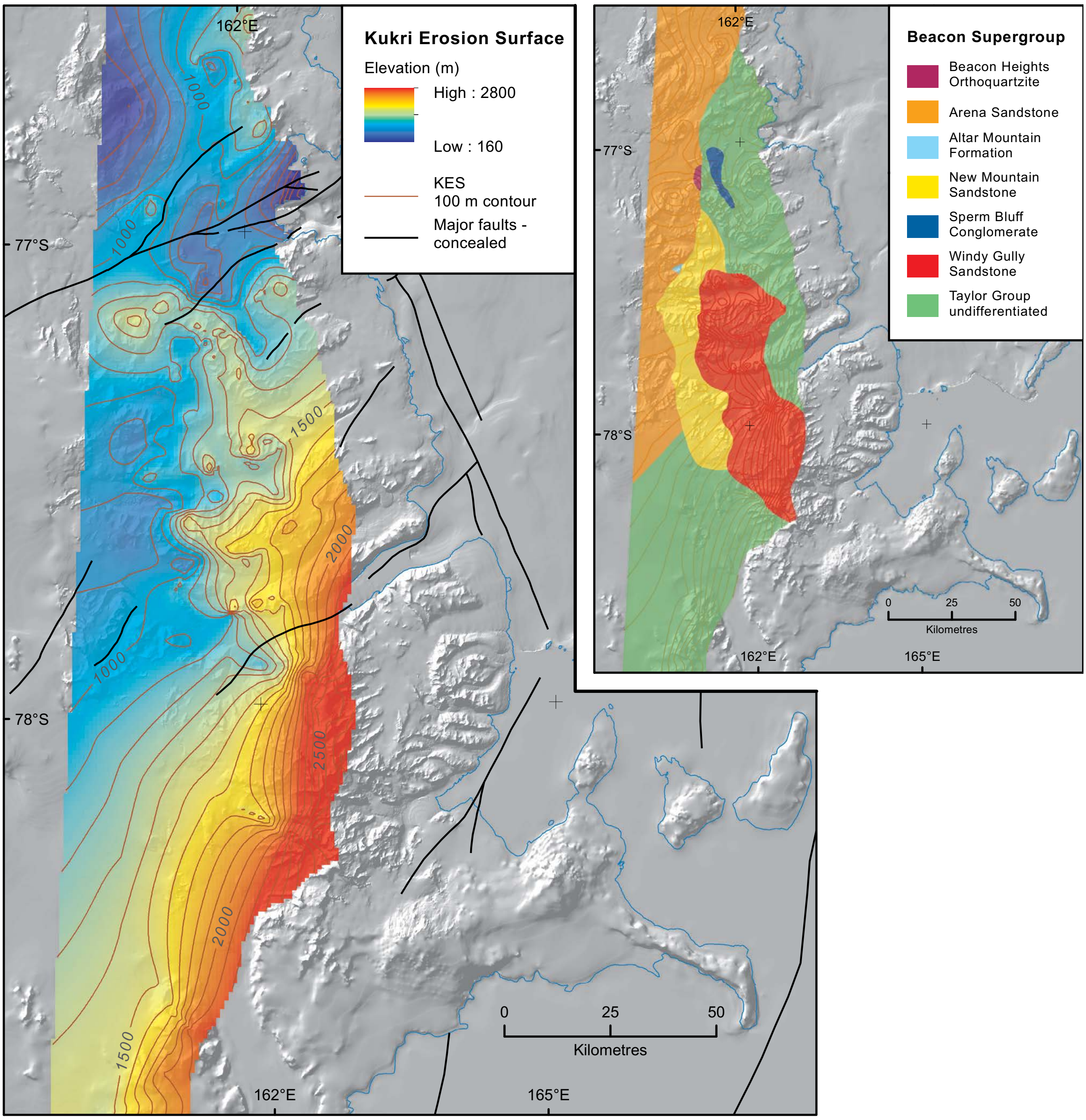


Figure 22 Map of the Kukri Erosion Surface, coloured according to elevation, with 100 m contours outlining its regional strike. Disrupted by Jurassic Ferrar Dolerite intrusions and Cenozoic uplift and minor faulting of the Transantarctic Mountains, the altitude of the surface varies between 200 m at the Mackay Glacier (north) and 2800 m in the Royal Society Range. The regional dip is between 2° and 4° west-northwest, but gradients locally reach ~30° over short distances due to local relief (paleo-valleys) on the surface. The background digital elevation model (grey) extends offshore and the coastline (blue line) is shown for reference. Inset map shows distribution of different basal sediments of the Beacon Supergroup immediately overlying the Kukri Erosion Surface.

Granite Harbour Intrusive Complex is now unconformably overlain by near-horizontal, sandstone-dominated covering strata; the contact is well exposed at many localities in the eastern Dry Valleys, though commonly complicated by the presence of a thick sill of younger dolerite (Fig. 21). This unconformity is known as the Kukri Erosion Surface (McKelvey et al. 1977; the Kukri Peneplain of Gunn & Warren 1962). It cuts across Late Cambrian - Early Ordovician granitoids and the sandstones above it are probably Early Devonian, hence it represents about 80 to 100 million years of time.

Between the Skelton and Fry glaciers the Kukri Erosion Surface is typically flat or gently undulating, though locally there is relief of tens of metres (e.g. Hamilton & Hayes 1963) and channels as deep as 77 m (Turnbull et al. 1994; Fig. 22). The significant northwestward onlap of lower Beacon Supergroup units onto the Kukri Erosion Surface shows that basement relief prevailed for much of the time represented. The extent and distribution of the lower Beacon Supergroup formations in the map area imply that the original paleoslope was towards the southeast, suggesting that the present northwest dip of the Kukri Erosion Surface results from tilting associated with uplift of the Transantarctic Mountains (Forsyth 1996). South of the map area, relief of hundreds of metres has been reported (Skinner 1965; Laird et al. 1971; Anderson 1979) and in the central Transantarctic Mountains the lower Beacon Supergroup may have been deposited within discrete basins on a surface with significant relief (Isbell 1999).

DEVONIAN TO TRIASSIC

Beacon Supergroup

The impressive sandstone-dominated outcrops of the Transantarctic Mountains were first seen at close quarters during the Discovery expedition's western journeys, when in 1903 Ferrar studied and named the Beacon Sandstone Formation in the area of the lower Taylor and upper Ferrar glaciers. Shackleton's party found similar rocks in their 1908 ascent of the Beardmore Glacier, 800 km to the south, proving that Beacon rocks are present over a large area. The full nature and extent of Beacon rocks in the area of this map were first determined and described by Gunn & Warren (1962) who recognised and described informal lithostratigraphic units, as did McKelvey & Webb (1959). By the early 1960s use of the term Beacon Group had become established (e.g. McKelvey 1961; Allen 1962); later it became the Beacon Supergroup (McKelvey 1970; McKelvey et al. 1970; Barrett et al. 1972).

The lower part of the Beacon Supergroup in southern Victoria Land is the Taylor Group (Harrington 1965), most complete in the area west of McMurdo Sound (Barrett 1971), where it ranges in age from Early to Late Devonian and is up to 1400 metres thick. Eight lithostratigraphic formations and one member have been differentiated on the map, based on the original work of Hamilton & Hayes (1963), Webb (1963), McElroy (1969, Table 1) and McKelvey et al. (1970); six of the type sections are in the Quartermain Mountains - Beacon Heights area (see Appendix 1). Lower Taylor Group units are absent in some places (Fig. 22), probably as a result of onlap over topographic "highs" (Bradshaw 1981; Plume 1982; Forsyth 1996; Isaac et al. 1996). More detailed descriptions of the grain size, sedimentary structures, trace fossils, and outcrop form are given in the publications cited below.

Taylor Group

South of the McKelvey Valley, the Kukri Erosion Surface is overlain by **Windy Gully Sandstone** (**btw**). A thin, discontinuous basal conglomerate, with clasts of angular to subrounded quartz and basement rocks, is succeeded by trough cross-bedded quartzose sandstone (Zeller et al. 1961; Plume 1978; McElroy & Rose 1987; Allibone at al. 1991). Windy Gully Sandstone crops out in the western Kukri Hills and in the eastern parts of the Asgard and Olympus ranges (Allibone et al. 1991; Turnbull et al. 1994; Isaac et al. 1996). Locally, the sandstones are intensely burrowed (Bradshaw 1981) and desiccation cracks and ripple marks are present in places. Windy Gully Sandstone is c. 30 m thick at the Windy Gully type section and up to 120 m thick in the Kukri Hills. The overlying **Terra Cotta Siltstone** (**btt**; Zeller et al. 1961; Plume 1978) comprises alternations of thinly bedded, fine-grained, pale sandstone with dark siltstone and claystone (Fig. 23). Sedimentary and biogenic structures include ripple marks, mud cracks and trace fossils (Bradshaw 1981). Terra Cotta Siltstone is up to 82 m thick at Mt Kempe, in the southern Royal Society Range (Plume 1978), and thins northward to disappear north of the McKelvey Valley (Isaac et al. 1996). Palynomorphs from the Terra Cotta Siltstone are of Early Devonian age (Kyle 1977a).

New Mountain Sandstone (**btn**; Hamilton & Hayes 1963; McElroy 1969) sharply and conformably overlies Terra Cotta Siltstone, or (locally) basement rocks (McKelvey et al. 1977; Plume 1978; Woolfe et al. 1989; Allibone et al. 1991; Turnbull et al. 1994; Isaac et al. 1996). At New Mountain, it comprises c. 100 m of medium- to coarse-grained sandstone, the upper part of which is characterised by large planar and trough cross-bed sets. It crops out extensively at Beacon Heights, and in the Asgard and Olympus ranges, and it may be present north of the Mackay Glacier in the Convoy Range (Pocknall et al. 1994). Near Knobhead it is up to 250 m thick, but only 32 m thick near Apocalypse Peaks, and it is absent at the head of the Balham Valley. A basal facies of breccia or conglomerate is present in places where New Mountain Sandstone directly overlies basement (as at Nickell Peak; Isaac et al. 1996). Sedimentary and biogenic structures include desiccation cracks in thin shale beds, and abundant trace fossils (Bradshaw 1981).

Figure 23 Taylor Group. Top: At Plane Table, Asgard Range, bluff-forming New Mountain Sandstone overlies slope-forming Terra Cotta Siltstone. A thin horizon of light-coloured Windy Gully sandstone forms the base of the sedimentary sequence. The Ferrar Dolerite Peneplain Sill (dark rocks at base) ramps up in the distance to form the slopes of Mount Odin (2066 m) (Photo: P.J. Forsyth). Bottom: Beacon Heights Orthoquartzite, intruded by thin sills of dolerite, forms cliffs that tower over the Arena Valley in the Quartermain Mountains. Black Face (right) is a thick intrusion of dolerite (Photo: M.J. Isaac).

Heimdall Erosion Surface

The Heimdall Erosion Surface, a disconformity between New Mountain Sandstone and overlying Altar Mountain Formation (McKelvey et al. 1970), is well exposed along the north flank of the Asgard Range for c. 25 km, and particularly well exposed in the Nibelungen Valley (Bradshaw 1981; Allibone et al. 1991). At Mt Jason and Mt Hercules it truncates New Mountain Sandstone cross-bed sets with up to a metre of relief (Turnbull et al. 1994); there is typically a marked change in grain size from fine- and medium-grained sandstone to granule and pebble conglomerate above the disconformity. Elsewhere (e.g. Beacon Heights; McElroy & Rose 1987) the disconformity is recognisable but not obvious. It is inferred to represent only a minor break in deposition. Where the lower Taylor Group units are absent the Kukri and Heimdall erosion surfaces are represented by a single unconformity, as between Altar Mountain Formation and Skelton Group marble, near the head of the Balham Valley (Isaac et al. 1996).

The Heimdall Erosion Surface is overlain by the **Altar Mountain Formation** (**bta**; McElroy 1969). More heterogeneous than units above and below, the main lithologies are planar and trough cross-bedded, quartzose sandstones, with subordinate siltstone and shale; overall the formation fines upward. A feldspathic sandstone or conglomerate at the base (**Odin Arkose Member**, **bto**) includes clasts of quartz and older Taylor Group lithologies (McKelvey et al. 1970; Allibone et al. 1991). Siliceous and ferruginous concretions are common, and sedimentary structures include ripple marks and desiccation cracks (Fig. 24). Altar Mountain Formation is 235 m thick near West Beacon (Barrett & Kohn 1971), and typically 130–200 m thick in the western and central Asgard and Olympus ranges, but has not been recognised in the eastern Olympus, St Johns, and eastern Clare ranges. The trace fossil assemblage is diverse and abundant (e.g. Bradshaw 1981; McElroy & Rose 1987; Woolfe et al. 1989; Woolfe 1990).

Typically the **Arena Sandstone** (**btr**) gradationally and conformably overlies Altar Mountain Formation, but locally it overlies basement rocks, as at Heaphy Spur in the Victoria Upper Glacier area (Isaac et al. 1996) and probably around the Greenville and Alatna valleys in the Convoy Range (Pocknall et al. 1994). It comprises planar and trough cross-bedded, medium- to fine-grained sandstones with intercalated siltstone and shale beds. Ripple marks are common and desiccation cracks are preserved in mudstone interbeds. A sequence of "coal measures" from the upper part of Arena Sandstone at Pivot Peak and Rotunda (Woolfe et al. 1989) was later shown to contain titaniferous ironstones, but no coal or carbonaceous shale (**Pivot Member**, differentiated in digital dataset but not on map; Woolfe et al. 1995). Arena Sandstone crops out widely in the central and western Transantarctic Mountains, with typical thicknesses of 150–250 m, and is up to 450 m thick at Knobhead (Woolfe et al. 1989). Many trace fossils have been described, including *Skolithos* and *Beaconites* (Fig. 25; Bradshaw 1981; Woolfe et al. 1989; Woolfe 1990; Allibone et al. 1991).

Beacon Heights Orthoquartzite (**btb**; Webb 1963) forms spectacular white to pale yellow cliffs (Fig. 23). Typically it overlies Arena Sandstone gradationally, but on the northern flank of the Clare Range it rests on basement rocks. It is particularly well exposed at Beacon Heights, the Asgard Range, the western Olympus Range peaks of Electra, Dido, Circe, Boreas and Aeolus, and at The Fortress and Parker Mesa, north of the Barwick Valley. At West Beacon, the Beacon Heights Orthoquartzite is 284 m thick (McElroy 1969; McElroy & Rose 1987). The lower part is medium-grained quartzose sandstone, parallel- and cross-bedded, with thin beds of shale and siltstone, grading upward into massive to well-bedded, white-weathering blocky sandstones. Dark mudstone interbeds are more common in the upper Beacon Heights Orthoquartzite; some preserve desiccation cracks and others are paleosols. The predominant lithology is well-sorted quartz sandstone with little feldspar (Korsch 1974). Lycopod stems from fallen blocks at West Beacon, Mt Fleming and Mt Electra indicate a Middle Devonian age (Harrington & Speden 1962; Plumstead 1964; McKelvey 1972). Trace fossils are less abundant than in underlying units (e.g. Bradshaw 1981; Woolfe et al. 1989).

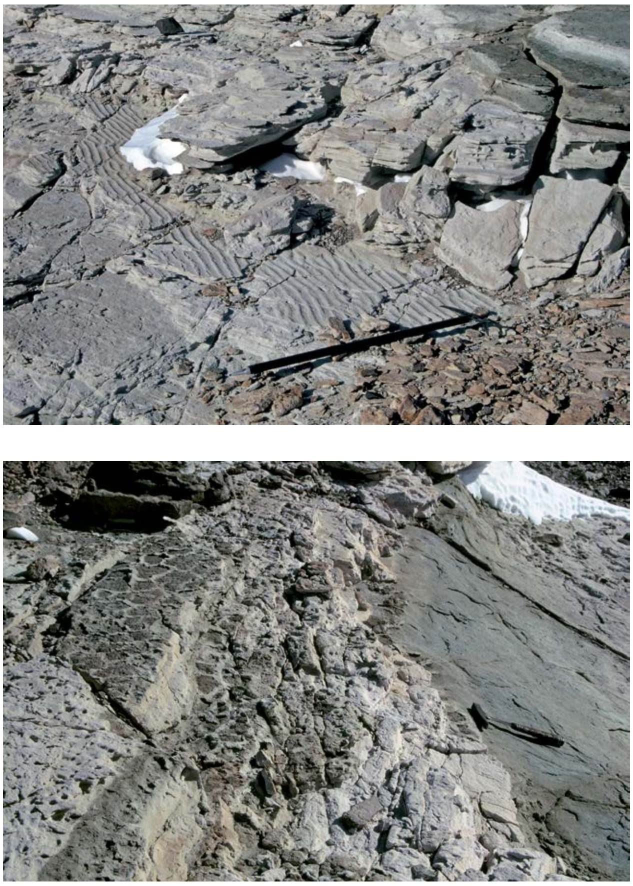


Figure 24 Sedimentary structures in Altar Mountain Formation in the Arena Valley, Quartermain Mountains. Fine-grained sandstone or siltstone at bed tops is commonly rippled (top) and in places shows mud-filled desiccation polygons (bottom) (Photos: M.J. Isaac. Ice axe is 80 cm long - top. Hammer is 32 cm long - bottom).

At Beacon Valley, the Beacon Heights Orthoquartzite is conformably and gradationally overlain by **Aztec Siltstone** (**btz**; Webb 1963; McKelvey et al. 1977), comprising trough cross-bedded and rippled sandstones with red and green mudstones. Desiccation cracks are common and highly oxidised paleosols are characterised by root traces, burrows, and calcareous nodules (McPherson 1978, 1979; Retallack et al. 1995). It is famous for nonmarine fossil fish remains, first collected from moraines of the lower Mackay Glacier by Debenham in 1911. Fish remains have also been collected from a boulder in moraine at Allan Hills (Gunn & Warren 1962) although no Aztec Siltstone outcrops are known in the area, the northernmost confirmed occurrence being at Shapeless Mountain (Plume 1978). The fossil material is typically preserved as white bone in a sandstone or siltstone matrix and the diverse fauna is of late Middle Devonian age (Young & Long 2005).

Subdivision of the Taylor Group has not been attempted in parts of the Royal Society Range and Polar Plateau areas where detailed investigations have yet to be carried out, and rocks there are mapped as undifferentiated Taylor Group (**bt**). In the eastern Olympus, St Johns, and eastern Clare ranges, subdivision of Taylor Group rocks into the lithostratigraphic units established at Beacon Heights has not been possible (Turnbull et al. 1994; Forsyth 1996). The areas of outcrop are small and the typical lithology of well-sorted quartzose sandstone is not distinctive; these undifferentiated Taylor Group rocks are shown with the label **bt**. In that area only one formation (**Sperm Bluff**



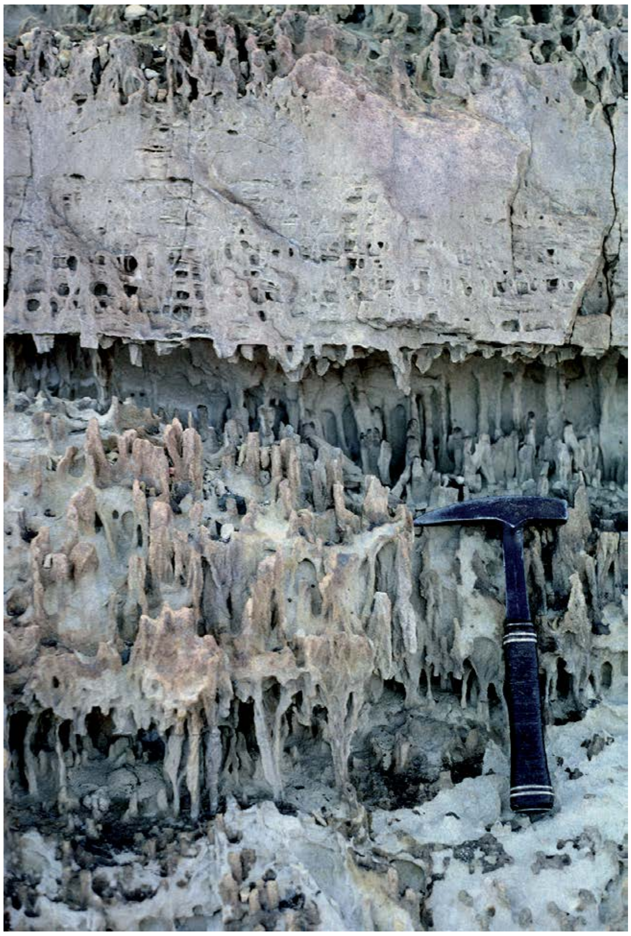



Figure 25 Trace fossils in the Taylor Group. Top left: *?Helminthopsis* (surface traces) and *Didymaulyponomos rowei* (burrows) in Altar Mountain Formation at Mount Hercules, Olympus Range (Photo: I.M.Turnbull. Ice axe is 70 cm long). Top right: Large burrows of *Beaconites barretti* in Arena Sandstone on Mount Carnes, Asgard Range, showing fine curved internal layers (Photo: I.M. Turnbull. Lens cap is 6 cm). Bottom left: Intense burrowing by *Heimdallia chatwini* in New Mountain Sandstone near Siegmund Peak, Olympus Range (Photo: P.J. Forsyth. Hammer is 35 cm long). Bottom right: Masses of perpendicular pipe-like *Skolithos linearis* burrows in Arena Sandstone west of Mount Electra, Olympus Range (Photo: S.W. Edbrooke. Hammer is 32 cm long).

Marine or nonmarine?

Although body fossils are absent from the Taylor Group, apart from the remains of nonmarine fishes in the Aztec Siltstone, trace fossils are both varied and abundant (Fig. 25). Bradshaw (1981) inferred from these that the lower formations comprise a marine transgressive sequence that progressively buried the irregular Kukri Erosion Surface. Plume (1978, 1982) analysed paleocurrents, sedimentary structures and carbon isotopes, and inferred deposition in braided river, lacustrine and aeolian environments. Wizevich (1997) interpreted New Mountain Sandstone as a deposit of mainly aeolian environments, with subordinate fluvial deposition as a result of episodic flooding. Woolfe (1990, 1993) considered that Taylor Group trace fossils are consistent with deposition in fluvial and lacustrine (non-marine) environments. Bradshaw & Harmsen (2007) supported a marine origin for those units with Skolithos *trace fossil burrows, in particular the Altar Mountain Formation, and inferred a prolonged and widespread marine incursion for an area between the Dry Valleys and the Darwin Glacier to the south.*

Lycopod plant remains and desiccation cracks in the Beacon Heights Orthoquartzite demonstrate intermittent subaerial exposure (Barrett 1971; Barrett & Webb 1973), and Barrett & Kohn (1975) concluded that it was deposited by low sinuosity braided streams. Aztec Siltstone, characterised by rootlet structures, abundant highly oxidised paleosols, red beds and fossil fish remains, was deposited on a broad alluvial plain crossed by shallow, meandering streams (McPherson 1978). Retallack (1997) inferred that some Aztec Siltstone paleosols were formed on a large alluvial plain comparable to the Indo-Gangetic Plain of northern India.

Bradshaw et al. (2010) have argued that deposition above the Kukri Erosion Surface records the initial marine flooding of a rocky shore platform, and that within the lower Taylor Group are three sequences of foreshore to shallow marine to estuarine deposits. The debate over nonmarine and marine deposition continues.

The ages from fossils suggest that the Taylor Group was probably deposited intermittently over a period of 6 to 31 million years and possibly longer. The lateral extent, consistency of the sedimentary facies, and mineralogical maturity indicate deposition in a stable, slowly subsiding cratonic basin, mainly or entirely on the broad floodplain of a large braided river system.

Conglomerate, **bts**; Turnbull et al. 1994) is differentiated; it consists mainly of clast-supported polymict pebble to cobble conglomerate and quartzose sandstone, massive or crudely stratified and locally channelled. The clast types include rhyolitic rocks not known to crop out in southern Victoria Land but possibly derived from eruptive equivalents of the DV2 Suite granitoids (Wysoczanski et al. 2003). *Heimdallia* burrows occur in profusion in sandstones near the top of the Sperm Bluff Conglomerate (Bradshaw & Harmsen 2007).

Maya and Pyramid erosion surfaces

Beacon Heights Orthoquartzite and Aztec Siltstone are truncated by the Maya Erosion Surface (Harrington 1965; McKelvey et al. 1977), a glacially eroded unconformity overlain by the Victoria Group, the lower units of which are Early Permian (e.g. Isbell & Cuneo 1996; Isbell et al. 2008). Woolfe (1994) concluded that following some early fluvial downcutting, advancing continental ice produced an extensive Maya Erosion Surface with gentle relief. The Metschel Tillite which overlies the unconformity is laterally discontinuous, either originally so or removed by subsequent erosion (Pyramid Erosion Surface), reflecting fluvial reworking of unconsolidated till during or after glacial retreat.

In many areas the Maya Erosion Surface is gently rolling (McKelvey et al. 1977; Isaac et al. 1996; Pocknall et al. 1994) but locally there are steep-sided valley walls cut into Aztec Siltstone. In places, the relief is at least 30 m and the valley infill comprises slumped and highly deformed Metschel Tillite (e.g. Kennar Valley, McKelvey et al. 1977). At Alligator Peak, Barrett (1972) reported 70 m of relief in a valley filled with fluvial sandstone. About 60 m of relief has been reported at Farnell Valley (McElroy & Rose 1987).

The Maya Erosion Surface represents a time gap of about 86 to 109 million years, equivalent to the Carboniferous period and possibly longer. Although it separates the geologically similar Taylor and Victoria groups, with little or no angular unconformity, it represents a time gap as long as, and perhaps longer than, that represented by the Kukri Erosion Surface.

Victoria Group

Above the Maya Erosion Surface, the Victoria Group rocks are a classic Gondwanan sequence, with basal glacial beds overlain by mainly fluviatile facies, which include coal measures with the characteristic *Glossopteris* and *Dicroidium* floras (e.g. Veevers 1988). Four laterally extensive lithostratigraphic formations are differentiated. The total thickness preserved is about 1000 m and the age range is Early Permian to Late Triassic. Victoria Group sections are commonly incomplete in that they are capped by Jurassic sills, lavas or volcanic breccia, or covered by the East Antarctic Ice Sheet. Undifferentiated Victoria Group rocks are shown with the label **vt**.

The patchy occurrence of products of the late Paleozoic glaciation in valleys in the Maya Erosion Surface was not recognised in southern Victoria Land until 1968, when

Figure 26 Metschel Tillite at the type locality, Mount Metschel in the Skelton Névé. The diamictite here contains acid plutonic, metamorphic and chert clasts that are dispersed through a fine-grained sandstone matrix (Photo: P.J. Barrett. Ice axe is 80 cm long).

glacial beds were found overlying the Aztec Siltstone at Mt Metschel (Fig. 26). The **Metschel Tillite** (**bvm**; McKelvey et al. 1970), typically a matrix-supported pebble-cobble diamictite, was subsequently found at a number of localities at the heads of the Dry Valleys, e.g. Beacon Heights (0–85 m thick, McElroy & Rose 1987), Mt Fleming and Shapeless Mountain (0–25 m thick, Pyne 1984; see also Barrett & Webb 1973) and as far north as Mt Razorback and Elkhorn Ridge, Convoy Range. At Kennar Valley, laminated graded sandstones and siltstones that fill Permian valleys are overlain by more typical diamictite facies (McKelvey et al. 1977). In places, as at Slump Mountain, Metschel Tillite is disrupted by folding and faulting attributed to subglacial deformation processes. Isbell et al. (2003, 2008) argued that equivalents of the Metschel Tillite were deposited in subglacial and glaciomarine and/or glaciolacustrine environments, and that it is unlikely a single ice sheet covered Antarctica continuously at any time during the Carboniferous and Permian. Equivalents of the Metschel Tillite elsewhere in Antarctica contain Early Permian palynomorphs (e.g. Kyle 1977b; Askin 1998; Isbell et al. 2008).

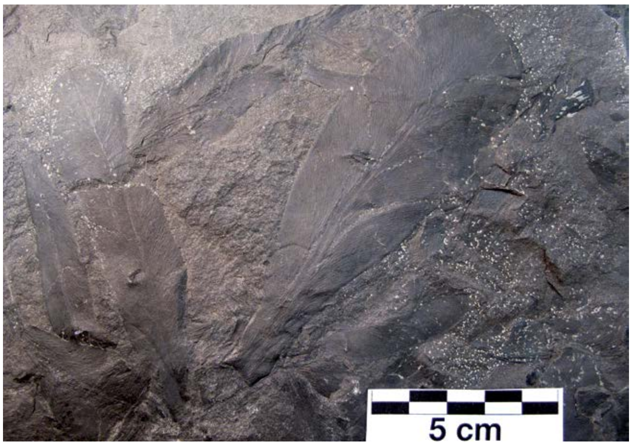
McElroy & Rose (1987) noted a marked lithologic contrast across the Pyramid Erosion Surface at Beacon Heights, but at Mt Crean the Metschel Tillite and overlying **Weller Coal Measures** (**bvw**; Webb 1963; McElroy 1969) appear to be conformable (Woolfe 1994), and a gradational contact has been observed at Mt Fleming (Isbell & Cuneo 1996). The Weller Coal Measures crop out along the crest of the Transantarctic Mountains for c. 230 km across the map area, from nunataks in the head of the Skelton Névé (e.g. Mt Metschel) to the easternmost known outcrops near Mt Douglas in the Convoy Range. They are 254 m thick at Mt Crean and at least 194 m thick at Robison Peak.

A basal unit comprises conglomeratic, arkosic, coarse-grained sandstone (Maya Arkose Member of McElroy 1969; not differentiated on map). Stacked, upward-fining cycles of sandstone are overlain by massive pebbly sandstone and trough cross-bedded sandstone, grading up into carbonaceous, fine-grained sandstone and siltstone, and commonly capped by carbonaceous mudstone, shale and coal. Plant fragments, leaves, rootlets, petrified logs and tree stumps are common; some upright stumps are in position of growth (Fig. 27; Francis et al. 1993; Isaac et al. 1996). In some areas the coals are apparently lenticular but elsewhere they are laterally persistent and change little in thickness over 1–2 km. Seam thicknesses and spacings strongly suggest that some seams can be correlated between Mt Bastion and Robison Peak, a distance of 17 km. Individual coals are at least 4.6 m thick and show cm-scale lithotype banding. Ash contents are typically between 8 and 36% and sulphur contents are low (mostly 0.1–0.9%; Arnot 1991; Isaac et al. 1996). The coals are heat-altered by adjacent dolerite intrusions, with an ASTM rank of low-volatile bituminous to semi-anthracite.

The Weller Coal Measures were deposited in alluvial plain, braided river, lacustrine and meandering river settings, with intermittent development of peat mires (Pyne 1983, 1986; Woolfe 1991; Isbell & Cuneo 1996). Pollen and spores were considered by some to be Early Permian (Kyle & Schopf 1982; Askin 1997; Isbell & Askin 1999) but others argue that the Weller Coal Measures - Feather Conglomerate contact may lie at the Permian-Triassic boundary (see below; Retallack 1999; Retallack et al. 1998, 2005, 2006).

The **Feather Conglomerate** (**bvf**; McElroy 1969) comprises granular and pebbly quartzofeldspathic sandstone, with lesser quartz pebble conglomerate, siltstone and mudstone. Sandstones are typically moderately to poorly sorted, with layers of rounded quartz pebbles and, occasionally, subangular granule- to pebble-sized clasts of feldspar. Much of the unit is in stacked upward-fining cycles of conglomerate and trough cross-bedded to horizontally bedded sandstone, capped by laminated siltstone and mudstone. Burrows are locally abundant, in places obliterating bedding. Sandstones lower in the Feather Conglomerate are separated by mudstone paleosols (Barrett & Fitzgerald 1985), with gammate soil structures and mottling in underlying sandstones (distinctive “Dolores” paleosols of Retallack et al. 2005). The sandstones in this interval have vertical burrows with all the characteristics of *Skolithos* (Fitzgerald & Barrett 1986), although previously *Skolithos* had been regarded as a marine environmental indicator. The striking change across the Weller Coal Measures - Feather Conglomerate contact

Figure 27 Fossil trees in the Weller Coal Measures are present as both upright stumps and drifted trunks, some with root systems still attached, along with *Glossopteris* leaves. Top: Tree stump at Mount Feather (Photo: P.J. Barrett. Staff divisions are 25 cm). Bottom right: Logs at Allan Hills (Photo: M.J. Arnot). Bottom left: Fossil leaves and stems of *Glossopteris* from Mount Feather (Photo: S.C. Cox).



What happened?

The reported occurrence of recumbent, petrified tree trunks "near the base of the Feather Conglomerate at Feather Bay" (Allan Hills; Francis et al. 1993) is anomalous. They may well be within Weller Coal Measures, for elsewhere in southern Victoria Land there is a striking contrast between highly carbonaceous, plant-bearing coal measures and the overlying Feather Conglomerate with no carbon or plant remains. The last known occurrences of Glossopteris *leaves and* Vertebraria *rootlets are at, or a few metres below, the Weller - Feather contact and the rocks record an abrupt change from a well-vegetated fluvial plain, with extensive and long-lived peat swamps, to fluvial environments in which vegetation was either absent or not preserved on burial.*

About 251 million years ago, an extinction event occurred in which over 90% of marine species and 70% of terrestrial vertebrate species became extinct—the most profound extinction event in the history of the planet. The consequent changes in fossil faunas are the basis for distinguishing the Permian period from the Triassic. Retallack et al. (2005, 2006) argued that, in the Transantarctic Mountains, the Permian-Triassic boundary is at the Weller Coal Measures - Feather Conglomerate contact (i.e. the horizon at which the vegetation seems to have disappeared).

The global extinction event at the end of the Permian period may have been triggered by the impact of a comet or asteroid (Retallack et al. 2005, 2006), and a possible impact crater of this age has been identified beneath the East Antarctic Ice Sheet of Wilkes Land, Antarctica by von Frese et al. (2006, 2009). An alternative explanation is that the global extinctions resulted from a drastic deterioration in global environments caused by eruption of the vast flood basalts of the Siberian Traps (Campbell et al. 1992; Payne et al. 2004; Black et al. 2012). The unfossiliferous and non-carbonaceous lower Feather Conglomerate was deposited during the Early Triassic period of ecological recovery.

is the disappearance of coals, rootlets and carbonaceous detritus. The contact is well exposed at Mt Bastion, where the topmost Weller coal is sharply overlain by non-carbonaceous sandstone, capped by a mudstone paleosol (Fig. 28). The Feather Conglomerate is well exposed at Portal Mountain, Mt Feather, Mt Bastion, Robison Peak and Allan Hills. It was deposited on an alluvial plain traversed by braided river systems, with no extensive peat mires and little vegetation.

The **Lashly Formation** (**bvl**; McElroy 1969) crops out intermittently at the crest of the Transantarctic Mountains and in nunataks west of the range crest (e.g. the Lashly Mountains, Mt Littlepage and Allan Hills). The lower contact is conformable over Feather Conglomerate, and Lashly outcrops are truncated by erosion, capped by Ferrar Dolerite, or unconformably overlain by Mawson Formation breccia. The thickness preserved is less than 260 m except at Mt Bastion, where an exceptional thickness of 524 m has been measured (Askin & Barrett 1971; Barrett & Webb 1973). The original type section at Mt Feather (Askin et al. 1973; McElroy & Rose 1987) covers only the lowermost 99 m.

Carbonaceous, micaceous, quartzofeldspathic and lithic sandstone and siltstone predominate, with lesser conglomerate, mudstone, breccia, and thin coal seams. Plant remains include leaves, rootlets, stems and tree stumps, with logs up to six metres long. Clasts are mainly quartz, with a minor component of metasedimentary rocks. Much of the formation comprises stacked, upward-fining cycles up to 15 m thick. Some upward-fining units are

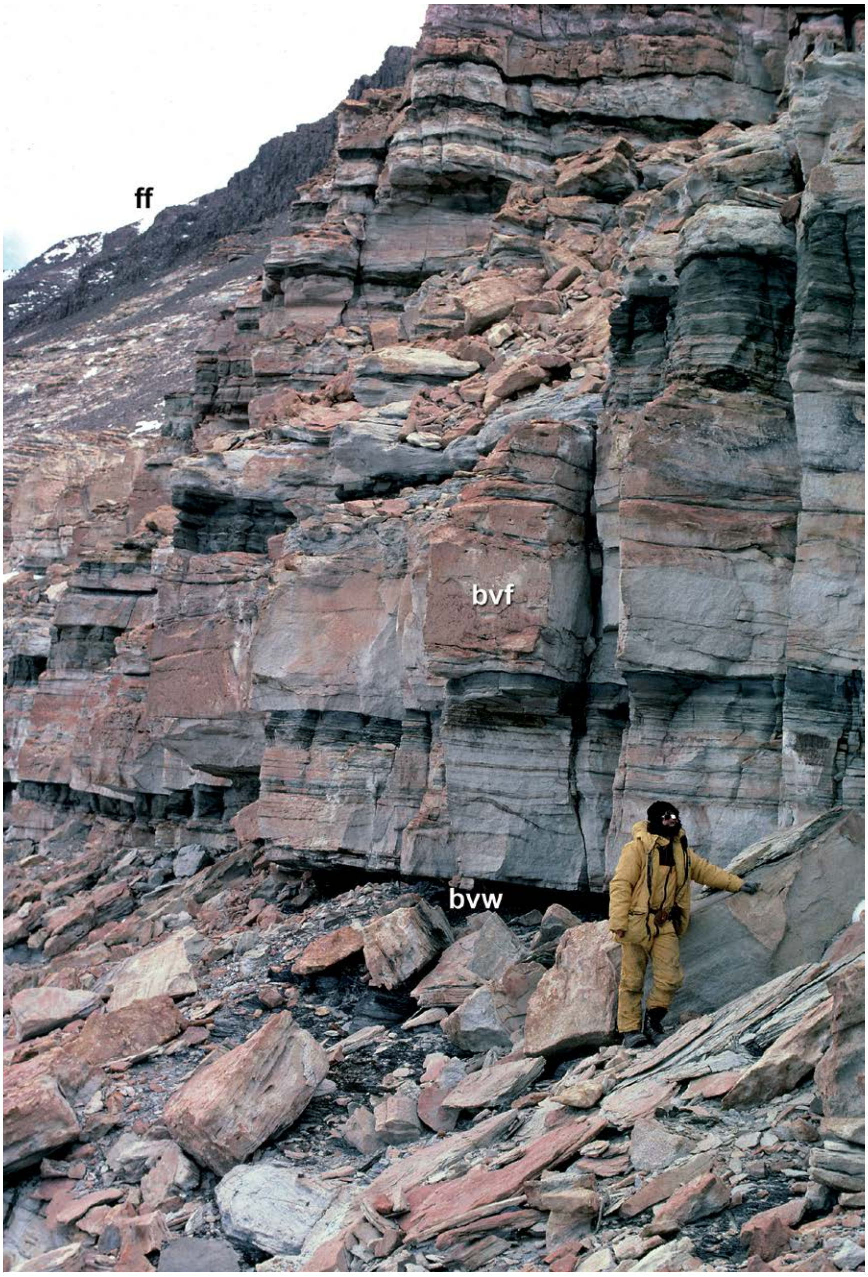


Figure 28 The Weller Coal Measures - Feather Conglomerate contact at Mount Bastion. The geologist is standing near the base of a 0.7 m thick seam of coal, partly obscured by fallen blocks, which is the highest seam of the Weller Coal Measures (bvw). The overlying Feather Conglomerate (bvf) consists of upward-fining trough cross-bedded sandstones, separated by non-carbonaceous mudstones and paleosols. A Ferrar Dolerite sill (ff) forms the cliffs at top left (Photo: M.J. Isaac).

capped by carbonaceous shale and thin coal seams (notably at Mt Bastion, Mt Dearborn and Mt Littlepage). Well-preserved plant macrofossils indicate that the lower Lashly Formation is Middle Triassic (229–246 Ma; Retallack & Alonso-Zarza 1998). The upper parts have yielded Late Triassic pollen and spores (Kyle 1977b; Kyle & Schopf 1982). The Lashly Formation was deposited in meandering to braided river and ephemeral lake environments, on a broad, well-vegetated alluvial plain (Barrett & Kohn 1975; Walker 1980; Woolfe 1991).

JURASSIC

Ferrar Group

The Ferrar large igneous province, emplaced in the Early Jurassic during the early stages of Gondwana break-up, occurs mainly in Antarctica but is also recognised in southeast Australia, New Zealand, and probably, South Africa (Mortimer et al. 1995; Leat 2008 and references therein). Though Kyle et al. (1981) and other authors have used the term Ferrar Supergroup, many recent publications (e.g. Morrison & Reay 1995; Fleming et al. 1997; Elliot et al. 2006; Elliot & Fleming 2008; Ross et al. 2008) refer to the Ferrar Group, as originally proposed by Grindley (1963), and that usage is followed here.

Ferrar rocks are exposed in a belt that extends for c. 3500 km along the Transantarctic Mountains, from the Weddell Sea to the Wilkes Land coast (Elliot & Fleming 2008). The outcrop belt is relatively narrow but the true extent is concealed by the East Antarctic Ice Sheet. Ferrar rocks are undoubtedly down-faulted beneath the southern Ross Sea but their extent is unknown. In southern Victoria Land the Ferrar province includes volcaniclastic rocks (Carapace Sandstone and Mawson Formation; Gunn & Warren 1962; Elliot 2000; McClintock 2001; Ballance & Watters 2002; Elliot et al. 2006; Ross et al. 2008), flood basalts (Kirkpatrick Basalt; Grindley 1963; Elliot et al. 1999), and the voluminous sills of the Ferrar Dolerite (Ferrar 1907; Gunn 1962a,b, 1963; Gunn & Warren 1962; Kyle et al. 1981; Marsh 2004; Boudreau & Simon 2007; Airoldi et al. 2011, 2012; Muirhead et al. 2012).

The Ferrar sills and their effusive equivalents were emplaced and erupted in a short period of magmatic activity over a few million years or less in late Early Jurassic time (Heimann et al. 1994; Fleming et al. 1997; Elliot et al. 1999; Riley & Knight 2001). Assigned ages vary depending on the method applied, differing between 183.6 ± 1.0 Ma using U-Pb methods (Encarnacion et al. 1996) and 179.4 ± 0.7 Ma by Ar-Ar (Fleming et al. 1999). Potentially more reliable zircon U-Pb ages by CA-TIMS have recently been reported at 182.7 to 182.2 ± 0.2 Ma (Fleming et al. 2011, unpublished). Ar-Ar dating of five individual Ferrar Dolerite sills gave consistent ages ranging from 177.2 to 176.2 Ma (Fleming et al. 1997). Heimann et al. (1994) dated Kirkpatrick Basalt from the central Transantarctic Mountains, southern Victoria Land and northern Victoria Land by Ar-Ar; all ages were in the range 176.8 to 176.4 Ma. Mawson Formation must be younger than Ferrar Dolerite because it includes clasts of dolerite (Faure & Mensing 2010). Gradational contacts between Ferrar Dolerite and Mawson Formation have been described at Shapeless Mountain (Korsch 1984), and a lenticular body of Mawson Formation breccia cuts across and intrudes Lashly Formation and Ferrar Dolerite at Mt Dearborn (Isaac et al. 1996).

Ferrar Dolerite

The spectacular sills of **Ferrar Dolerite** (**ff**) that form cliffs in the walls of the Dry Valleys and in the great escarpment of the Royal Society Range (Fig. 5) were obvious to the early geologists such as Ferrar (1907), for there is a striking colour contrast between the dark sills and the pale Beacon Supergroup sandstones and granites that they intrude. The dolerites were first studied in detail by Benson (1916), then in seminal studies by Gunn (1962a,b, 1963) and Hamilton (1965), and later by Kyle et al. (1981, 1983), Morrison & Reay (1995), Elliot et al. (1985) and Fleming et al. (1997, 1999).

Numerous Ferrar Dolerite sills, ranging from a few metres to over 400 metres thick, are widely distributed throughout southern Victoria Land and beyond (Fig. 29). The lower sills were initially mapped by Gunn & Warren (1962) and Gunn (1963), according to their position relative to the Kukri Erosion Surface, and termed the Basement Sill and Peneplain Sill. However, subsequent detailed mapping has shown that the **Basement Sill** (**ffb**) may rise to merge with or quench against higher sills, for example at the western end of the Kukri Hills (Allibone et al. 1991) and the south wall of the Wright Valley (Marsh 2004). It may also exchange positions with (Elliot & Fleming 2004) or ramp upward to become the Peneplain Sill (Turnbull et al. 1994). The Basement Sill emanates from the western Bull Pass area (Marsh 2004). The **Peneplain Sill** (**ffp**) is present at or close to the Kukri Erosion Surface almost everywhere the sill is exposed; thin, discontinuous slivers of Beacon Supergroup strata are commonly present beneath this sill, as in the Insel Range, the Olympus Range due north of Lake Vanda, and the upper Wright Valley. The Peneplain Sill is the host rock for the feature known as the Labyrinth (Fig. 30).

Other Ferrar Dolerite sills mapped in detail (e.g. Woolfe et al. 1989; Allibone et al. 1991; Turnbull et al. 1994; Isaac et al. 1996) have been distinguished in the accompanying digital dataset, but not on the geological map (Fig. 29). The **Asgard Sill** is a thick and extensive sill that forms the high plateau of the Asgard Range at, or close to, the Taylor Group - Victoria Group contact (i.e. the Maya Erosion Surface). It can be traced northwards and is correlated with dolerite at the same structural position in the Convoy Range. At Apocalypse Peaks the Asgard Sill is apparently merged with the Peneplain Sill, for in this area dolerite outcrops extend from c. 950 m above sea level to a height of about 2250 m. The complexity of sill geometry increases at structurally higher levels toward the west, particularly in the Quartermain Mountains, where the **unnamed upper sills** occur. Near Knobhead, dolerite crops out over a vertical

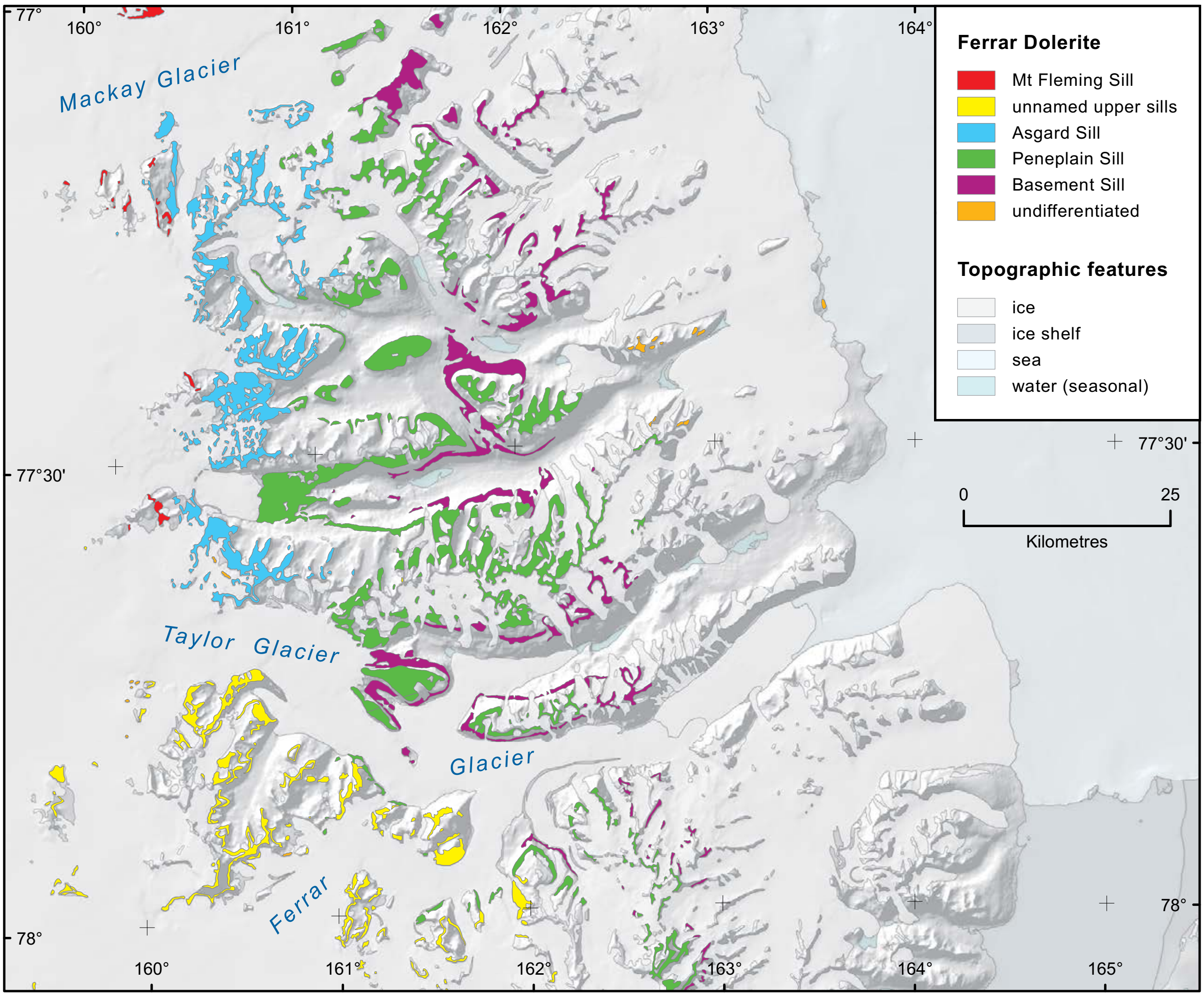


Figure 29 Ferrar Dolerite. Top: Unnamed upper sills of dolerite intrude Beacon Heights Orthoquartzite at Finger Mountain, beside the upper Taylor Glacier. Dolerite also forms thick, dark, screes at the base of the slope (Photo: K. Westerskov/ Hedgehog House). Bottom: Map showing the distribution of various Ferrar Dolerite sills between the Ferrar and MacKay glaciers, generated from the geological units layer in the digital GIS database.

range of 900 m, from the Ferrar Glacier to the summit of Mt Handsley (Woolfe et al. 1989). The **Mount Fleming Sill** lies along the margin of the Polar Plateau between Mt Fleming and Mt Littlepage (Pyne 1984). The structurally lowest known dolerite occurs beneath the Basement Sill on the coast at Kolich Point (Forsyth et al. 2002; Mortimer et al. 2002).

Dolerite intrusion can disrupt the stratigraphic succession, either through large-scale rafting or by sill lift of parts, or all, of the Beacon Supergroup sequence (McElroy & Rose 1987; Woolfe et al. 1989). In a rare example of demonstrable lateral rafting, granite has been emplaced above the lowermost Beacon units north of Lake Vanda (Turnbull et al. 1994).

Ferrar Dolerite sills typically show columnar jointing and in places enclose large bodies of the host rocks. Sills range from fine-grained, with chilled margins against adjacent rocks, to coarse-grained with doleritic to sub-ophitic texture. Minor granophyre and pegmatitic facies also occur. The Basement and Peneplain sills in the Wright Valley contain cumulate textures with orthopyroxenite-rich layers, and these pyroxenitic bands were also recognised in other sills by Gunn & Warren (1962) and Grapes & Reid (1971). At the Dais, in the upper Wright Valley, the lower sill forms a rhythmically layered intrusion of gabbronorite, leucogabbronorite and websterite (Marsh 2004; Bedard et al. 2007). In contrast, the Peneplain Sill at Solitary Rocks (Taylor Valley) is a uniform quartz tholeiite throughout, except for silicic segregations near the top (Marsh 1995). Thinner sills generally consist of sub-ophitic to intergranular augite-pigeonite-plagioclase dolerite with accessory iron oxides, and minor quartz, orthoclase, apatite and rare biotite. The granophyres and pegmatites are composed of quartz, sanidine, plagioclase, pyroxene, minor hornblende and biotite, abundant iron oxide, rare apatite and perhaps stilpnomelane (e.g. Gunn & Warren 1962; Morrison & Reay 1995). Geochemically the dolerites are tholeiitic with high initial $^{87}Sr/^{86}Sr$ ratios, and are probably mantle-derived (e.g. Kyle et al. 1981; Morrison & Reay 1995).

Some relatively small, cross-cutting dolerite plugs have been sources for sills in adjacent strata (Elliot & Fleming 2008). In places, sills thin and change orientation to become dikes; dolerite dikes are commonly seen cutting Beacon Supergroup strata (Fig. 31), and more rarely, cutting rocks of the Granite Harbour Intrusive Complex. Skew Peak is named from a thick Ferrar Dolerite dike or tilted sill which, near the summit, dips east at up to 30°. At Terra Cotta Mountain the Peneplain Sill is truncated and displaced by a dike 200–800 m wide; a swarm of thinner, more regular dikes intrudes Beacon Supergroup strata of the north face but apparently not the large cross-cutting dike to the

Figure 30 The Labyrinth, in the upper Wright Valley, has been carved into the columnar jointed Peneplain Sill. In the background, peaks of the Olympus Range (Electra, Circe, Dido and Boreas) are composed of erosion-resistant Beacon Heights Orthoquartzite, overlying less resistant Arena Sandstone and Altar Mountain Formation (Photo: P.J. Forsyth).

west, which may therefore be younger (Morrison & Reay 1995; Fig. 31). Typically, Ferrar dikes are one to several metres thick and laterally persistent, in sub-perpendicular sets which trend NW and ENE (Wilson 1992). A NNW-trending dike near Mt Fleming can be traced for about 4 km, and on the north flank of the Olympus Range a dike extends for 10 km.

Ferrar Dolerite sills have been used to estimate offset on known and inferred faults throughout southern Victoria Land (e.g. Fitzgerald 1992) but because the Basement Sill in places merges with the Peneplain Sill, caution must be exercised when using the sills as markers (Turnbull et al. 1994). Adjacent to large sills, rare examples of melted country rock forming dikes that re-inject Ferrar intrusions are documented (Hersum et al. 2007). Craw & Findlay (1984) and Craw et al. (1992) attribute hydrothermal veining in some Beacon Supergroup and Ferrar Group rocks to heat from Ferrar Dolerite intrusions, although other hydrothermal veins may have a different origin.

Mawson Formation

Breccia, sandstone, and siltstone with associated basaltic lavas discovered at Carapace Nunatak, Battlements Nunatak and Allan Hills by Gunn & Warren (1962) were thought to be a predominantly glacial facies of the Beacon Supergroup, and named Mawson Tillite. Later work established that the deposits are actually of volcanic origin, and a part of the Ferrar Group (Borns & Hall 1969). The mainly volcaniclastic rocks overlying Lashly Formation and other Beacon strata in the Coombs and Allan Hills were named **Mawson Formation** (**fm**) by Ballance & Watters (1971) and have since been extensively studied (e.g. Elliot 2000; White & McClintock 2001; Hood Hills & White 2002a,b; McClintock & White 2002, 2006; Reubi et al. 2005; Elliot et al. 2006; Lockett & White 2008; Ross et al. 2008). Both the lower and upper contacts with Lashly Formation and overlying Kirkpatrick Basalt are preserved at Coombs Hills, but in the Allan Hills Mawson Formation is the stratigraphically highest unit preserved (Elliot 2000;

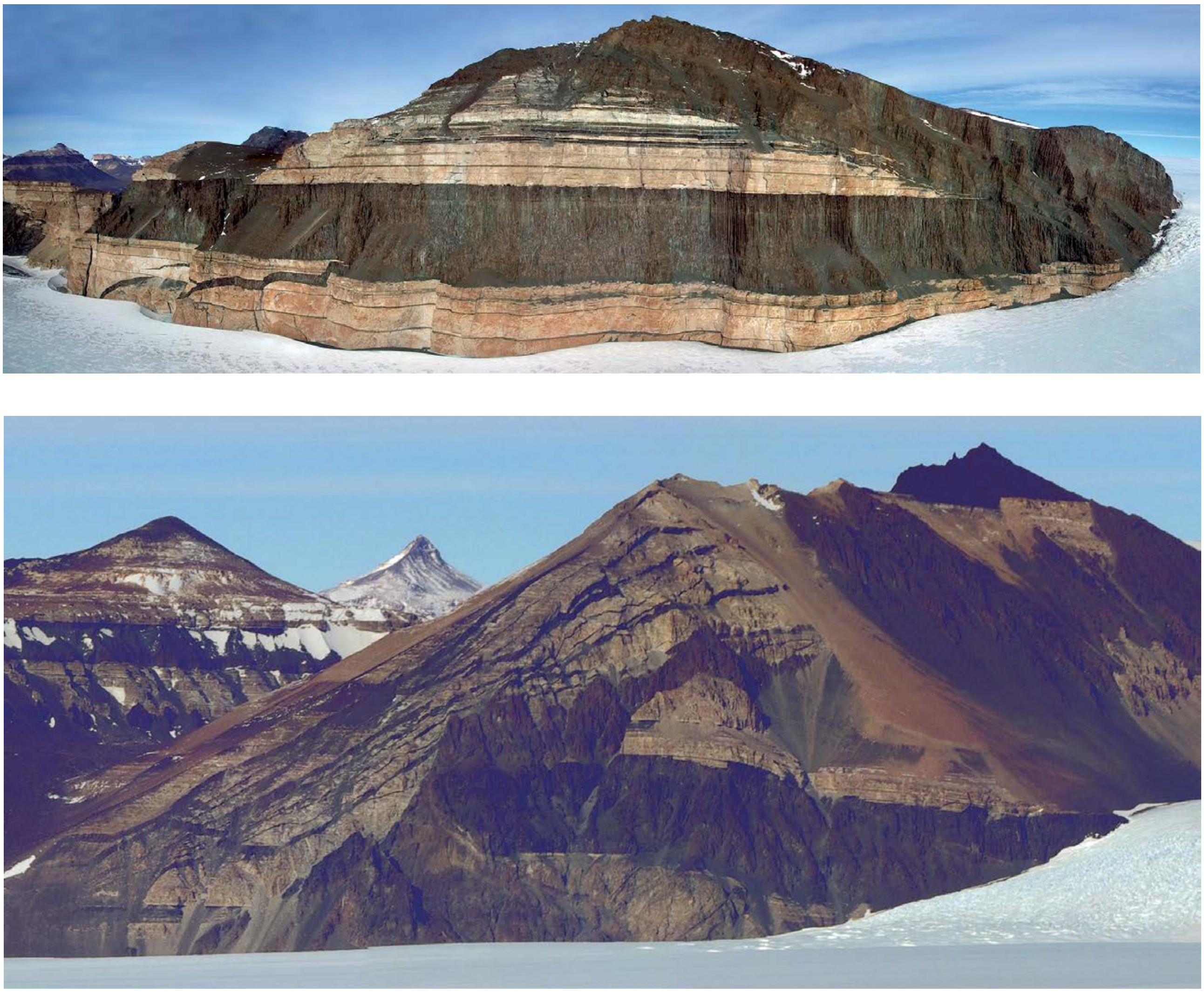


Figure 31 Sills and other forms of irregular Ferrar Dolerite intrusions. Top: The northeast side of Finger Mountain (c.1950 m). Bottom: Dikes and irregular sills in the north and west faces of Terra Cotta Mountain (c. 2050 m) (Photos: Z. Malolepszy).

Figure 32 Mawson Formation. Top left: Typical structureless, unsorted lapilli tuff containing fragments of glassy basalt and accretionary lapilli (pen is 15 cm long). Top right: Allan Hills debris avalanche deposit containing angular clasts of Beacon sandstone and carbonaceous shale (boot, highlighted, is 10 cm across). Bottom: Aerial view of light-coloured, sand-rich, Mawson Formation pyroclastics in Allan Hills. The outcrop has been cut by an unusually large, 12 m wide, clastic dike (mid-brown) which has, in turn, been cut by thin basaltic dikes in the foreground. Discontinuous dune-like patches of red-brown dolerite regolith overlie the Mawson bedrock surface (Horizontal field of view is c. 200 m) (Photos: J.D.L. White).

Ross 2005; Reubi et al. 2005; Ross et al. 2008). The total thickness is c. 400 m at both Coombs Hills (McClintock & White 2006) and Allan Hills (Elliot 2000; Ross et al. 2008).

McClintock & White (2006) and Ross et al. (2008) mapped two facies associations at Coombs Hills. The lower comprises massive, unsorted to poorly sorted lapilli tuff and breccia, commonly with abundant Beacon-derived clasts and rafts. The upper facies comprises generally finer grained, better sorted, layered volcaniclastics (Fig. 32). These facies are interpreted to represent an initial vent complex, up to five kilometres wide, overlain by pyroclastic deposits that retain evidence of their constructional landforms (Ross et al. 2008). At Allan Hills, the earlier deposits occupy a pre-existing topographic depression and include breccia composed almost entirely of Victoria Group sedimentary rocks, with scattered basaltic clasts and globules. Some sedimentary clasts are 'megablocks' up to 80 m across. This breccia is interpreted as a debris avalanche that slumped off a phreatomagmatic vent wall, entraining semi-plastic lava (Reubi et al. 2005). The overlying bedded lapilli tuffs and tuff breccias were probably deposited by lahars and pyroclastic flows, and in volcanic vent-complex infills (Reubi et al. 2005; Lockett & White 2008; Ross et al. 2008). The Mawson Formation is cut by large tuff-filled clastic dikes, which have possibly been elutriated from their host breccias by magmatic heat (Ross & White 2005). Mawson Formation is also cut by basalt dikes, many of which show evidence of intrusion or eruption into wet sediments (Fig. 32; McClintock & White 2006). Cementation by calcite and zeolites is pervasive (Ballance & Watters 2002).

A lenticular body of Mawson Formation breccia cuts across and intrudes Lashly Formation and Ferrar Dolerite at Mt Dearborn. At Shapeless Mountain and Mistake Peak, Mawson Formation breccias are intimately associated with both Ferrar Dolerite intrusions and Beacon Supergroup rocks (Korsch 1984); contacts between Mawson Formation and Beacon Supergroup are irregular and, commonly, steep. Mawson Formation lithologies include peperite; diamictites deposited from volcanic debris flows (lahars); volcanic breccia of Beacon clasts in a basaltic matrix that passes laterally into massive basalt; alloclastic breccia of

Beacon lithologies with minor hydrothermal veins;; pillow basalt; and stratified conglomerates and cross-bedded sandstone. Multiple and cross-cutting intrusive breccias indicate multiple eruption events. The Mawson Formation reaches a thickness of 123 m at Mistake Peak (Barrett & Webb 1973).

Carapace Sandstone

Lithic sandstone and conglomerate found by Gunn & Warren (1962) beneath basalt flows and hyaloclastite breccia at Carapace Nunatak, 15 km southwest of Coombs Hills, were originally considered to be a part of the Beacon Supergroup. Ballance & Watters (1971) showed that these consist of reworked Beacon and primary basaltic detritus, reassigned them to the Ferrar Group, and named the unit the **Carapace Sandstone** (**fc**). It is known only from Carapace Nunatak, and no base is seen. Massive silty sandstone is succeeded by well-bedded silty sandstone and polymict conglomerate, with abundant cross-bedding. Conglomerate clasts include granite, greywacke, locally derived sandstone and mudstone, coal, and basalt. Two samples of Carapace Sandstone examined petrographically are quartzose, with subordinate rock fragments and abundant zeolite cement. One contained shards of volcanic glass (Ballance & Watters 1971, 2002). The uppermost beds are silty sandstone and mudstone; thin beds of fossiliferous chert occur in the topmost eight metres. The Carapace Sandstone is at least 130 m thick and is conformably overlain by Kirkpatrick Basalt (Ballance & Watters 1971; Bradshaw 1987; Ross 2005).

Ostracods, conchostracans, insects, ferns and coniferous plant remains have been collected (e.g. Ballance & Watters 1971, 2002; Bradshaw 1987; Ball et al. 1979). Carapace Sandstone was thought to be Middle Jurassic, on the basis of plant fossils (Townrow 1967; Ball et al. 1979). The conchostracans were considered to be early Middle Jurassic (Yanbin 1994) and an Early Jurassic palynoflora has been recovered (Ribecai 2007). Given the short-lived nature of Ferrar large igneous province magmatism, a late Early Jurassic age is likely.

Kirkpatrick Basalt

Basalt lava flows and breccia at Carapace Nunatak first described by Gunn & Warren (1962) were studied in more detail by Ballance & Watters (1971) and included in the **Kirkpatrick Basalt** (**fk**; Grindley 1963; see also Bradshaw 1987; Ballance & Watters 2002). Columnar-jointed basalt overlying Carapace Sandstone is succeeded by 40 m of red, palagonitised hyaloclastite which includes both complete and fragmented basaltic pillows (Fig. 33), in turn overlain by flows of columnar-jointed basalt with an intercalated lens of Mawson Formation diamictite (Ballance & Watters 1971; Bradshaw 1987) and volcaniclastic intervals of tuff and lapilli tuff (Ross et al. 2008). Fossil ostracods, conchostracans, insects and plant remains have been collected from laminated siltstone rafts within the hyaloclastite. The flows overlying and underlying the hyaloclastite are 8–50 m thick, and range from coarse-grained dolerite to vesicular and nonvesicular basalt. Kirkpatrick Basalt is 164 m thick at Carapace Nunatak (Bradshaw 1987). In the Coombs Hills, Mawson Formation is capped by c. 250 m of Kirkpatrick Basalt lava flows, with at least two intercalations of diamictite up to 12 m thick. The lava sequence that forms the summit of Mt Brooke includes a ten-metre-thick interval of vesicular basaltic pillow lava (Bradshaw 1987). Kirkpatrick Basalt flows intercalated with volcaniclastics are also present at Battlements Nunatak (Gunn & Warren 1962; Borns & Hall 1969; Grapes et al. 1974), in the extreme northwest corner of the map area.

Figure 33 The Kirkpatrick Basalt at Carapace Nunatak includes a distinctive sequence of red, palagonitised hyaloclastite breccia with fragmented basaltic pillows (left), locally grading into thick pillow lavas with minor amounts of inter-pillow material (right). Pillows are up to three metres in diameter with thick (4 cm) dark glassy rims, and some have large vesicles now filled with secondary minerals. The pillow lavas were interpreted by Ross (2005) as having been emplaced in a temporary lake. The sequence is locally overlain by several hundred metres of columnar jointed basalt in three major flows (Photos: O. Reubi).

EOCENE TO HOLOCENE SEDIMENTS

Surficial sediments cover much of the landscape of the Dry Valleys, blanketing lower mountain slopes and filling the valley floors. Although landforms are well preserved, the internal structure and content of the deposits are generally only exposed where there has been sufficient meltwater to cut into the sediments. Mapping of these deposits is therefore based primarily on the morphology of landforms developed on the sediments, supplemented with lithologic information from scattered exposures, or from a few drill cores and hand-dug pits.

Early geologists recognised that in many places ice cover had been greater than at present (Scott 1905; Edgeworth David & Priestley 1914; Wright & Priestley 1922). Subsequent detailed mapping of glacial deposits and landforms (e.g. Blank et al. 1963; Calkin 1971; Linkletter et al. 1973) provided evidence for multiple phases of glaciation, and began to outline the distribution of deposits and define past ice limits (e.g. Péwé 1960; Bull et al. 1962; Calkin 1963, 1964a,b; Calkin et al. 1970; Denton et al. 1970; Nichols 1971; Calkin & Bull 1972). Regional reconstruction of the ice sheets and understanding their fluctuations then became a focus, particularly with attempts to understand the relative timing of changes in the margins of the East Antarctic Ice Sheet and the West Antarctic Ice Sheet, as well as changes in alpine glaciers (Stuiver et al. 1981; Denton et al. 1984; Clayton-Greene et al. 1988; Clapperton & Sugden 1990; Denton & Marchant 2000; Fig. 34). A major debate as to whether the East Antarctic Ice Sheet had collapsed as recently as the Pliocene was initiated by Webb et al. (1984), and pervaded the scientific literature for decades (Clapperton & Sugden 1990; Webb & Harwood 1991; Barrett et al. 1992; Denton et al. 1993; Sugden et al. 1993; Stroeven & Prentice 1997; Miller & Mabin 1998; Denton & Marchant 2000). Central to the debate was the mode of emplacement of Pliocene marine diatoms enclosed in Sirius Group, thought by Webb et al. (1984) to have been eroded from interior marine basins, but by others to be atmospheric contaminants. Contrary evidence supporting relative stability of the East Antarctic

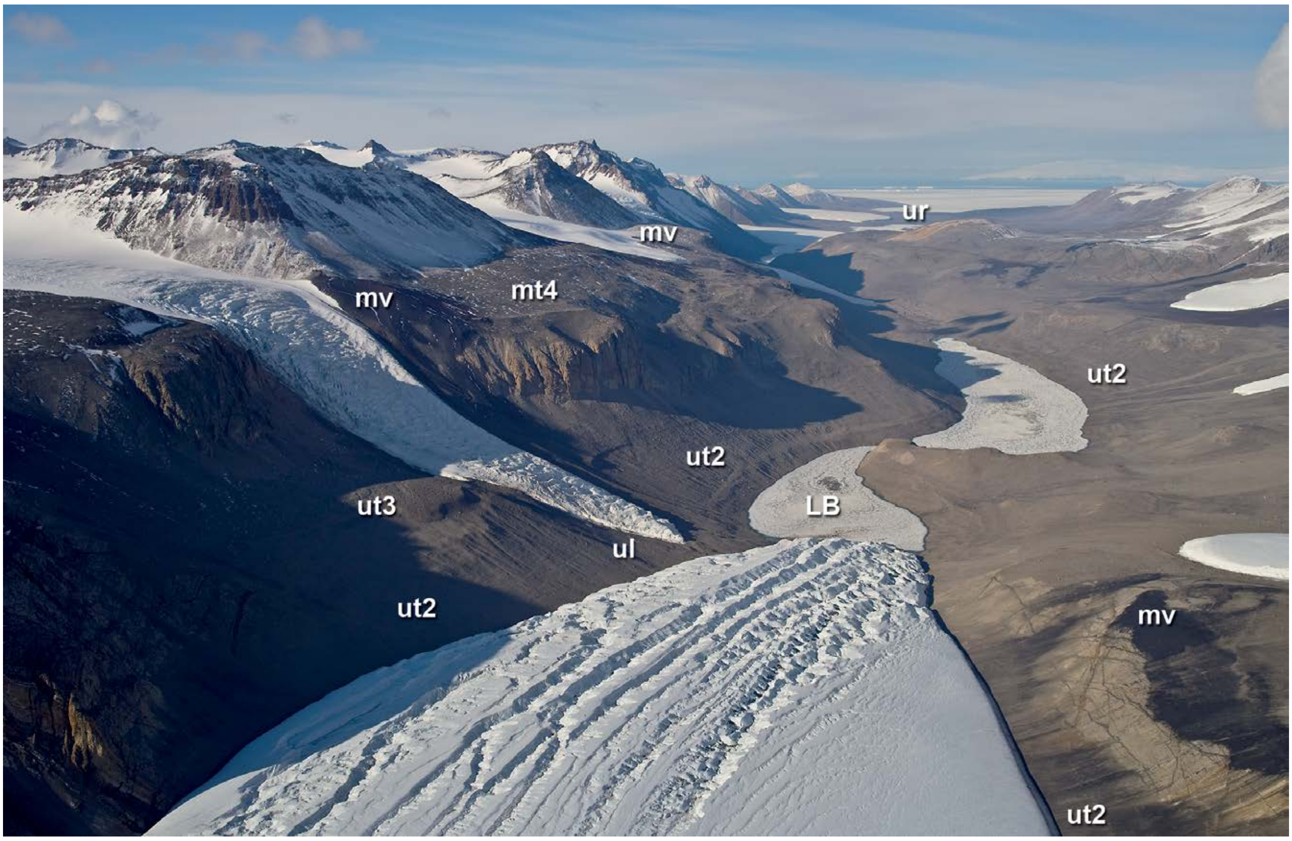


Figure 34 The Taylor Valley is a critical locality for deciphering the relative histories of the East Antarctic Ice Sheet, local alpine glaciers and the Ross Ice Sheet. McMurdo Volcanic Group (mv) centres on the platform high above the valley are interlayered with Taylor 4 Drift (mt4 – Thomson Drift). Pliocene ages obtained for these volcanics confirmed the considerable age of the Dry Valleys glacial deposits and landscape (Armstrong et al. 1968; Wilch et al. 1993). At lower elevations, and more recently, thickened Taylor ice has left near-continuous sheets of Taylor 3 (ut3) and Taylor 2 (ut2) drifts along the valley walls above the present position of the glacier. The terminus of the Taylor Glacier (foreground) and the level of Lake Bonney (LB) are highly responsive to thickening and thinning of the East Antarctic Ice Sheet. The Rhone Glacier (left) has advanced into the valley and deposited local glacial tills with prominent moraine ridges (ul) across Taylor 2 & 3 drifts. Cross-cutting relationships such as these form the basis of a debate as to whether or not the behaviour of local alpine glaciers is synchronous with ice sheet behaviour. At the far end of the valley, asynchronous incursion of the grounded Ross Ice Shelf into the valley has left lake deposits and tills (ur) that indirectly record expansion of the West Antarctic Ice Sheet (Photo: A. Apse).

Ice Sheet came from the antiquity of volcanic ash and rock surfaces at high elevations in the Dry Valleys, indicating that these landscapes had remained unmodified since the Middle Miocene (Marchant et al. 1993a,b, 1996; Sugden et al. 1995a; Summerfield et al. 1999; Staiger et al. 2006). Subsequently, ash-bearing moraines in the Olympus Range (Lewis et al. 2007, 2008) have been found to record the transition from warmer wet-based to cold dry-based ice about 14 million years ago, supporting the view that the East Antarctic Ice Sheet became stable at about this time apart from periods of relatively minor retreat around its margins. Drill core records from McMurdo Sound show that the Ross Embayment has been periodically ice-free in Pliocene and Early Pleistocene times (Naish et al. 2009), but this is consistent with a persistent East Antarctic Ice Sheet and a high thermal gradient across the Transantarctic Mountains, as DeConto et al. (2012) show in their modelling of the Ross Ice Shelf collapse during the Early Quaternary (MIS 31 period). Barrett (2013) has reviewed the history of the debate and the reasons for its slow resolution. An important issue is that much of the grounded Ross Ice Sheet (or floating Ross Ice Shelf) is nourished locally by outlet glaciers draining the East Antarctic Ice Sheet (e.g. Kellogg et al. 1996; Denton & Hughes 2000) so that the sedimentary record sampled by drilling may only partially reflect behaviour of the West Antarctic Ice Sheet (e.g. Wilson 2000; Naish et al. 2008; Talarico et al. 2012).

This map covers the largest ice-free area of Antarctica, where there is a unique geological record of the evolution of three major glacial systems: valley outlet and spill-over glaciers that drain the East Antarctic Ice Sheet; the Ross Ice Sheet; and local alpine glaciers of the Transantarctic Mountains (Fig. 34). Fluctuations of these systems do not appear to be synchronous. During the Middle Miocene, the East Antarctic Ice Sheet evolved from a dynamic and temperate state (Naish et al. 2001) to its present sluggish and mainly cold-based state. During this thermal transformation, there were large-scale ice-sheet expansions when grounded (and erosive) ice extended well out onto the Ross Sea continental shelf (Denton et al. 1984; Clapperton & Sugden 1990; Anderson & Bartek 1992; Bart et al. 2000). Reconstructed ice surface profiles, based on mapping and dating of drift sheets, suggest that at this time large outlet glaciers from the Polar Plateau thickened by as much as 1000 m although the plateau ice barely thickened at all (Denton et al. 1989). East Antarctic Ice Sheet outlet glaciers did not, however, extend through the Wright and Victoria valleys during the Quaternary. Alpine glaciers terminating in the Dry Valleys also appear to have retreated during glacial maxima when they became starved of accumulation, then re-advanced during warmer intervals of the Quaternary (Denton et al. 1989). In their absence, grounded ice sheets in the Ross Embayment entered McMurdo Sound from the southeast, penetrating westwards into the ice-free valleys and damming the valley mouths to form large lakes (Hall & Denton 1994; Hall et al. 2000, 2010). Proglacial lake-ice conveyor systems transported drift westward from Ross Ice Sheet glacial lobes into the ice-free valleys (Hendy et al. 2000).

As a direct consequence of these ice flow patterns, older Miocene-Pliocene deposits and landscapes have been preserved in the Dry Valleys, whereas in coastal regions and on the volcanic islands the glacial deposits are almost entirely Quaternary in age. It has been suggested that grounding and thickening of the ice shelf must have been in response to reduced temperature, precipitation, and sea level, since there is such a large difference in behaviour of the continental and marine portions of the ice drainage system (Denton et al. 1989). Discrepancies between ice sheet reconstructions (e.g. Stuiver et al. 1981; cf. Wilson 2000) highlight the need to improve chronology and reassess glacial deposits in the region before the contribution of the Ross Ice Sheet to global sea-level changes can be determined with confidence.

In many instances the imprint of glaciers on the ice-free Dry Valleys landscape is subtle. Glaciers have more commonly reshaped existing deposits, recycled material, eroded new surfaces, or left scattered boulder trains, rather than leaving behind extensive areas of new deposits (Fig. 35). Till formations probably represent many major events, with local advances and retreats controlled by local fluctuations in snow cover and precipitation, sea level and ice-sheet grounding, as much as by direct temperature fluctuations (Clayton-Greene et al. 1988; Hall & Denton 2002; Fountain et al. 2010). In view of the limited opportunity for dating the deposits, or for making robust correlations across the region, this map does not subdivide Antarctic events into specific glacial and interglacial stages as used in temperate latitudes, for example in the rest of the QMAP series in New Zealand. Also, the record in one valley may differ from that in another, because glaciers are variably sensitive to local climatic patterns (Bertler et al. 2011; Markle et al. 2012). Instead, this map shows surficial sediments differentiated on the basis of their environment of formation and inferred age. Formational names have been adopted where deposits are clearly defined, well described, and of sufficient regional scale or importance. Some new names have been used and are defined in Appendix 1. The legend discriminates between deposits pertaining to the ice sheets (East Antarctic Ice Sheet and Ross Ice Sheet) and piedmont glaciers, valley outlet glaciers, and local alpine glaciers. The legend also distinguishes between deposits of warmer wet-based glaciers, and those deposited by dry-based cold glaciers (see text box), but the distinction is highly generalised and will contain anomalies when examined in detail. Some simplification of deposit source and type has been inevitable in this regional map classification. We suspect that many of the formations depicted on the map (e.g. Taylor 4 Drift, Ross Sea 1, undifferentiated till etc.) represent a considerable range in age, and span a number of climatic events.

The term diamicton has been used to describe non-lithified, poorly sorted sediment with a wide range of particle sizes, whereas a diamictite is the lithified equivalent. The general term drift is used to describe all sedimentary material (clay, silt, sand, gravel, boulders) transported by a glacier and deposited directly by or from the ice, or by running

Figure 35 The passage and melting of ice does not always leave continuous tills, so can be more difficult to represent on geological maps of deposits than on geomorphological maps. Top: A lone erratic boulder of Ferrar Dolerite sits on a glacially smoothed surface of Suess Pluton granitoid on Gondola Ridge. Striations and plucking indicate the flow direction (left to right) of thickened Mackay Glacier ice (Photo: I.M. Turnbull. Boulder is c. 50 cm tall). Bottom: Ferrar Dolerite boulders and cobbles scattered discontinuously across a Lashly Formation pavement at Mount Littlepage, Willett Range, are 'transparent' remnants of wind-deflated Jotunheim Till, but are still not continuous enough to be shown on this regional-scale geological map (Photo: M.J. Isaac. Largest clasts are c. 40 cm across).

Figure 36 Examples of wind erosion and weathering. Top left: A cavernously weathered granite erratic (60 cm long), with dolerite erratics behind, on volcanic-rich till at Chancellor Ridge (Photo: D.B. Townsend). Top right: Wind-sculpted and polished dolerite ventifact on granite- and basalt-rich till, Taylor Valley (Photo: R. Jongens. Ventifact is 15 cm tall). Bottom: A cavernously weathered granite erratic (c. 50 cm tall) near Bull Pass is much less erosion-resistant than nearby dolerite erratics, and has been almost entirely eroded away (Photo: D. Haney/NSF collection).

Figure 37 Fields of wind-shaped features are common in the Dry Valleys. This boulder of orthogneiss at Chancellor Ridge exemplifies the irregular shapes that are formed (Photo: S.C. Cox. Boulder is about 1.5 m tall).

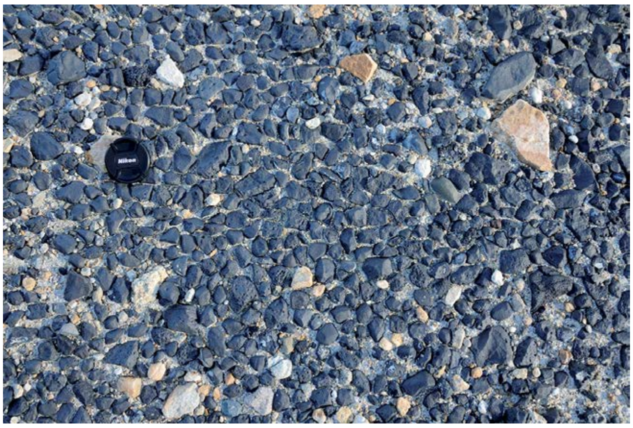


Figure 38 Most of the glacial deposits in the map area have been subjected to some degree of deflation by the Antarctic winds. The upper surfaces of the deposits are armoured with lags of pebbles and cobbles. Top left: A ventifacted pavement of Beacon sandstone (Photo: M.J. Isaac. Lens cap is 6 cm across). Top right: An armoured surface on Ross Sea Drift, with ventifacted, polished McMurdo Volcanic Group pebbles (Photo: D.B. Townsend. Lens cap is 6 cm across). Bottom: Beneath its armoured surface, this seemingly volcanic-rich Ross Sea Drift is rich in quartz sand, and strikingly different in colour (Photo: S.C. Cox. Boot for scale).

Cold dry-based *vs* warmer wet-based glaciers

Glaciers in the Dry Valleys are currently cold and dry-based, but evidence from landforms, sedimentary deposits and erosional features suggests that the glacial regime was quite different in earlier times. Tills deposited prior to c. 14 Ma tend to be matrix-supported and contain rounded and striated clasts, suggesting deposition by wet-based glaciers, which are typically more dynamic and fast-moving. The continent began to cool and ice sheets expanded during the Middle Miocene, resulting first in alpine glaciers at higher elevations becoming dry-based, eventually followed by the valley and piedmont glaciers. Unlike wet-based glaciers, which entrain debris by regelation (melting and freezing under pressure) and slide across bedrock surfaces, dry-based glaciers flow only by internal deformation. The rate of erosion beneath a dry-based alpine glacier is usually much less (potentially by several orders of magnitude) than for wet-based alpine glaciers (Hall et al. 1997). Dry-based glaciers ride across their frozen base, entrain and recycle clasts, or produce poorly sorted tills and surface meltwater channels, but they are also capable of preserving underlying landforms and deposits leaving little trace of their presence or passage across the landscape (Atkins et al. 2002; Atkins & Dickinson 2007; Bockheim 2010). Many low-elevation glaciers currently present in southern Victoria Land are entirely frozen to their beds and do not produce subglacial meltwater, but during summer do produce supraglacial meltwater, which flows off the glacier and modifies adjacent landforms (Atkins & Dickinson 2007). Interpretation of glacial lithofacies is often contentious, and the distinction between wet- and dry-based tills is not always clear-cut.

water emanating from a glacier. Drift includes unstratified material that forms moraines, and stratified deposits that form outwash plains, eskers, kames, varves and fluvioglacial sediments. Till is applied specifically to predominantly unstratified drift, generally unconsolidated, deposited directly by and underneath a glacier without subsequent reworking by meltwater, and consisting of a heterogeneous mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape. Useful criteria for differentiating deposits of different ages or sources include the prevalence of surficial boulders and degree of cavernous weathering (Figs 36, 37; Calkin & Cailleux 1962), lithological content, and radiocarbon or exposure-age dating. Boulder and pebble lags are commonly developed on the surface of tills, as winds strip away fine-grained material, with variable degrees of desert polish and ventifaction (shaping by wind erosion) of pebbles left behind (Fig. 38).

Older ice sheet and outlet glacier deposits

Sirius Group (**mis**) is a collective name for eroded remnants of glacigenic sequences found throughout the Transantarctic Mountains (Mercer 1972; McKelvey et al. 1991). In southern Victoria Land patchy deposits crop out near the edge of the Polar Plateau at Allan Hills, in the Willett Range, at Shapeless Mountain, Mt Fleming, Mt Feather and Table Mountain (Barrett & Powell 1982; Brady & McKelvey 1983; Stroeven & Prentice 1997; Hicock et al. 2002, 2003; Wilson et al. 2002). The deposits comprise highly weathered semi-lithified diamictons or lodgement tills, with some fluvioglacial and glaciolacustrine interbeds of sand, conglomerate and pebbly silt. Clasts of locally sourced dolerite and resistant Beacon Supergroup quartzites are faceted and oriented. At Mt Feather (Fig. 39), deposits distinguished in the dataset as **Mt Feather Diamicton** locally reach 40 m in thickness and contain several disconformity-bounded units (Wilson et al. 2002). The paleoclimatic significance of the Sirius Group has been the focus of intensive debate because of reported Pliocene marine diatoms (as noted above, p. 53), but it is now generally accepted that Sirius Group represents deposits of multiple glaciations within different wet-based ice sheet drainage systems, and contains diatoms that were recycled by atmospheric transport (Wilson et al. 2002; McKay et al. 2008, Barrett 2013). Although minimum depositional ages have been inferred from exposure-age dating (many >5 Ma; Brook et al. 1993, 1995b; Ivy-Ochs et al. 1995; Bruno et al. 1997; Schaefer et al. 1999), as well as the numerous dated ash deposits found on or in cracks in glacial deposits, the absolute ages of individual formations remain unknown.

Remnants of older wet-based glacial deposits are also found in the Dry Valleys. **Insel Drift** (**mii**) occurs in the Barwick Valley and on the Insel Range as scattered small patches of diamicton, and as a more extensive deposit in the McKelvey Valley (Calkin 1971). The latter is composed of very weathered, uniformly silty and loose till with few upstanding resistant boulders, no surviving morainal topography, and no frost-wedge polygons. It is distinguished from other older ice sheet deposits by an abundance of granitoid clasts. Insel Drift has been covered by solifluction sheets and extensively modified. Inferred to be derived from Polar Plateau ice (Calkin 1971), Insel Drift may be a lower-elevation correlative of the Sirius Formation. It is locally overlain by **Bull 2-3 Drift** (**mib**) which forms extensive deposits in the McKelvey, Balham, and Barwick valleys and at Bull Pass (Appendix 1; Turnbull et al. 1994; Isaac et al. 1996). This highly weathered, poorly sorted, very silty, bouldery till resembles Insel Drift but has more variable morphology. It contains exotic boulders which exhibit extreme cavernous weathering, and many boulders on the surface of the deposit have been reduced to ground level. Although the Bull 2-3 Drift surface is modified and masked by solifluction, there are still some well-defined moraine ridges that indicate deposition by ice that flowed either from the Wright Valley through Bull Pass, or in the opposite direction from the Victoria Upper and Webb glaciers. It has been correlated with Peleus Till in the Wright Valley on this basis (Turnbull et al. 1994), and interpreted as being related to expansion of the East Antarctic Ice Sheet. No correlative deposits have been found in the upper McKelvey and Balham valleys.

Figure 39 Top: A thin veneer of Sirius Group diamicton (foreground), lying unconformably on Lashly Formation and Ferrar Dolerite, is exposed on the shoulder of Mt Feather at 2500 m in the Transantarctic Mountains. Bottom: At this locality, semi-lithified diamicton that was deposited beneath wet-based ice contains well-rounded and polished clasts, mostly of quartz (Photos: G.S. Wilson. Lens cap is 6 cm across).

Peleus Till (**mie**) blankets the floor of the Wright Valley up to an elevation of about 1150 m (Prentice 1985; Hall et al. 1997). Its upper surface lacks morainic or other glacial landforms, and has been extensively deflated to leave a lag of gravel and scattered large blocks. At Prospect Mesa, below Bull Pass, Peleus Till comprises very poorly sorted, bouldery gravel to pebbly silt and sand, up to six metres thick. It is massive and unstratified, in places weathered to pale yellow or yellowish brown, and contains Pliocene marine diatoms and unidentified shell fragments that may have been reworked from underlying sediment (Prentice et al. 1993). Clasts within the till are predominantly dolerite, granite and metasediments, with rarer dike lithologies and Beacon sandstone, and are rounded and striated. Peleus Till lacks McMurdo Volcanic Group clasts, which are common in younger tills nearby. It is interpreted as a basal till deposited beneath ice flowing east from the Polar Plateau down the Wright Valley, but its age is unclear. At the Bartley Glacier, Peleus Till is overlain by colluvium and older local glacier till, indicating that it is at least Early Pliocene in age. At Prospect Mesa, Peleus Till overlies Prospect Formation and is thought to have been locally remobilised by debris flows that have complicated stratigraphic relationships and age interpretation (Prentice et al. 1993; Hall et al. 1997). Peleus Till may be as old as Miocene (Hall et al. 1997) and potentially a correlative of Asgard Till found at higher elevations around the Wright Valley, but deposited by wet-based ice in the centre of the valley where ice was thick enough to reach pressure melting point (Hall et al. 1993).

Local alpine and valley glacier deposits

Discontinuous local alpine glacier tills of Miocene-Pliocene age are preserved in the Quartermain Mountains, and in the Olympus and Asgard ranges. They are poorly sorted, with striated and smoothed ('glacially moulded', Marchant et al. 1993a,b) clasts that can be correlated directly with local bedrock outcrops, and are thought to have been deposited from local wet-based glacier ice. Relative ages have been assigned on the basis of stratigraphic relationships with overlying oxidised colluvium and volcanic ash (Marchant et al. 1993a,b; see also Wilson 1995). **Circe Till** (**mlc**) is a Middle Miocene deposit found high in the Olympus Range (Lewis et al. 2007), comprising a compact, lower silt-rich diamicton (lodgement till) and an upper stratified ablation till with sand and gravel lenses. It rests on a striated bedrock pavement and is locally overlain by weathered colluvium interbedded with 13.9 Ma ash. Clasts, predominantly of Beacon sandstone and Ferrar dolerite, have been striated, moulded and aligned by northeastward flow of local wet-based ice. **Sessrumnir Till** (**mls**) is an unsorted, unstratified and unconsolidated sandy diamicton, found locally in hanging valleys in the Asgard Range. It contains numerous striated and moulded clasts of dolerite and some siltstone, with underlying bedrock striae indicating deposition from northward-flowing ice, prior to deposition of overlying Koenig Colluvium and 15.2 Ma ash (Marchant et al. 1993a). **Inland Forts Till** (**mlf**) is an isolated, silt-rich, unconsolidated diamicton mapped on the Taylor Glacier side of the Asgard Range (Marchant et al. 1993a). It is a structureless and massive deposit, containing faceted and striated clasts predominantly of Beacon Supergroup sandstone, with minor dolerite. The morphology of underlying bedrock steps and bedrock striations suggests deposition from southward-flowing ice, prior to deposition of a volcanic ash dated at 13.5 Ma. **Altar Till** (**mla**) in the upper Arena Valley, Quartermain Mountains, is a silt-rich and highly oxidised diamicton containing near-horizontal layers of medium- to coarse-grained gravel within a sandy matrix (Marchant et al. 1993b). Clasts are predominantly dolerite, moulded and striated, and set in a matrix of disaggregated Beacon Supergroup sedimentary rocks. The till is distinguished from others nearby, such as Quartermain Till (see below), by a lack of granite erratics. It is thought to have been deposited by local ice, although the underlying bedrock surface is not exposed and flow direction is unconfirmed.

Other older tills are either not entirely derived from local source rocks, or were deposited by variably dry- or wet-based ice, depending on their elevation and/or the thickness of ice that was close to pressure melting point. **Asgard Till** (**mia**) is a silt-rich and unconsolidated diamicton, containing granite erratics and striated sandstone and dolerite clasts, deposited in hanging valleys in the Asgard Range. The till has complex internal stratigraphy and its clasts include granodiorite and Feather Conglomerate which are not known to crop out locally. Frost-wedge cracks contain 13.6 Ma ash (Marchant et al. 1993a), which constrains the minimum depositional age of the till (see also Wilson 1995). Asgard Till may have been deposited beneath ice lobes spilling southward from an outlet glacier that filled the Wright Valley. Preservation of ventifact pavements and sand wedges beneath Asgard Till at elevations above 1500 m was presented as evidence that ice tongues above this elevation were probably dry-based, whereas the wet-based glacial conditions required to produce striated and moulded clasts occurred below 1500 m (Marchant et al. 1993a). Similar drifts in the McKelvey and Barwick valleys and on the Dais, mostly at elevations <1300 m, have also been interpreted as being deposited by valley glaciers and mapped as Asgard Till (Fig. 40; Isaac et al. 1996).

Jotunheim Till (**mij**) is an unconsolidated and structureless, dolerite-rich diamicton distributed in elongate tongues down valley floors in the Asgard Range, locally overlying Asgard Till with a sharp planar contact (Marchant et al. 1993a). Restricted almost entirely to elevations above 1400 m, correlative tills occur in the Olympus and Willett ranges (Isaac et al. 1996). Jotunheim Till lacks both exotic lithologies and striated clasts. Sand wedges in Jotunheim Till contain 10.5 Ma ash (Marchant et al. 1993a). Occurrences of Jotunheim tills locally have thin feathered edges and commonly lie down-valley from colluvium, dolerite bedrock and/or rock glaciers. These tills are interpreted to represent reworking of deposits, either by local glaciers or possibly beneath a northeast-flowing over-riding ice sheet that was close to pressure melting point. **Nibelungen Till** (**min**), a small, discontinuous deposit in the Asgard Range, contains clasts of granite and sandstone derived from local bedrock (Marchant et al. 1993a). It cuts through Sessrumnir Till and overlies colluvium and bedrock pavements, and is possibly also derived from an over-riding ice sheet. **Brawhm Till** (**mih**) is a poorly sorted, unoxidised, gravel-rich diamicton derived locally from reworked dolerite-rich colluvium at the head of Arena Valley (Marchant et al. 1993b). Occurring only as small outcrops, Brawhm Till marks the overflow of wet-based ice across Arena Saddle. Although Nibelungen and Brawhm tills are very small in volume and extent, their outcrops are shown because of their importance for constraining local glacial history.

Taylor Valley glacial deposits are particularly important for understanding past climate variations, as the glacier and the position of its terminus appear particularly sensitive to ice mass balance variations. The Taylor Glacier flows directly from a small dome at the edge of the East Antarctic Ice Sheet, which is primarily controlled by moisture supply to the Antarctic interior; snow accumulation in this area appears to increase during interglacial periods (Denton et al. 1989). Multiple sets of tills with prominent moraines have been mapped in the central Taylor Valley, in the Arena and Pearse valleys and in other ice-free areas along the margin of the Taylor Glacier. **Quartermain Till** (**mtq**) comprises granite-bearing, dolerite-rich diamictons that form elongate tongues and isolated patches in Arena Valley (Marchant et al. 1993b). There is an absence of striated or moulded clasts, but some show desert polish. The till was deposited in two stratigraphic intervals by dry-based Miocene-Pliocene lobes of the Taylor Glacier flowing into Arena Valley. **Arena Till** (**mlr**) is a sandstone-rich diamicton in Arena Valley, locally overlain by Quartermain 1 till and locally overlying erosional remnants of Quartermain 2 till. Arena Till has complex internal stratigraphy, with well-sorted sandy gravels interbedded with massive silty diamicton, locally folded and containing flame structures at contacts between fine sand and silt layers. Arena Till is also interpreted as Miocene in age, based on stratigraphic relationships with dated ash deposits in the valley (Marchant et al. 1993b). Clasts are predominantly locally derived Altar Mountain Sandstone, striated and rounded by wet-based glacial action. Underlying bedrock striations indicate that Arena Till was deposited from ice flowing down-valley, then exposed for a period sufficient to form a desert pavement before being overridden by dry-based Taylor Glacier ice that deposited Quartermain 1 till (Marchant et al. 1993b). **Slump Mountain Diamicton** (**mlu**) is a silt-rich, unconsolidated, massive diamicton with clasts dominated by dolerite, which mantles an extensive area on the floor of the central Arena Valley. Its origin is poorly understood, but it may be coeval with Arena Till.

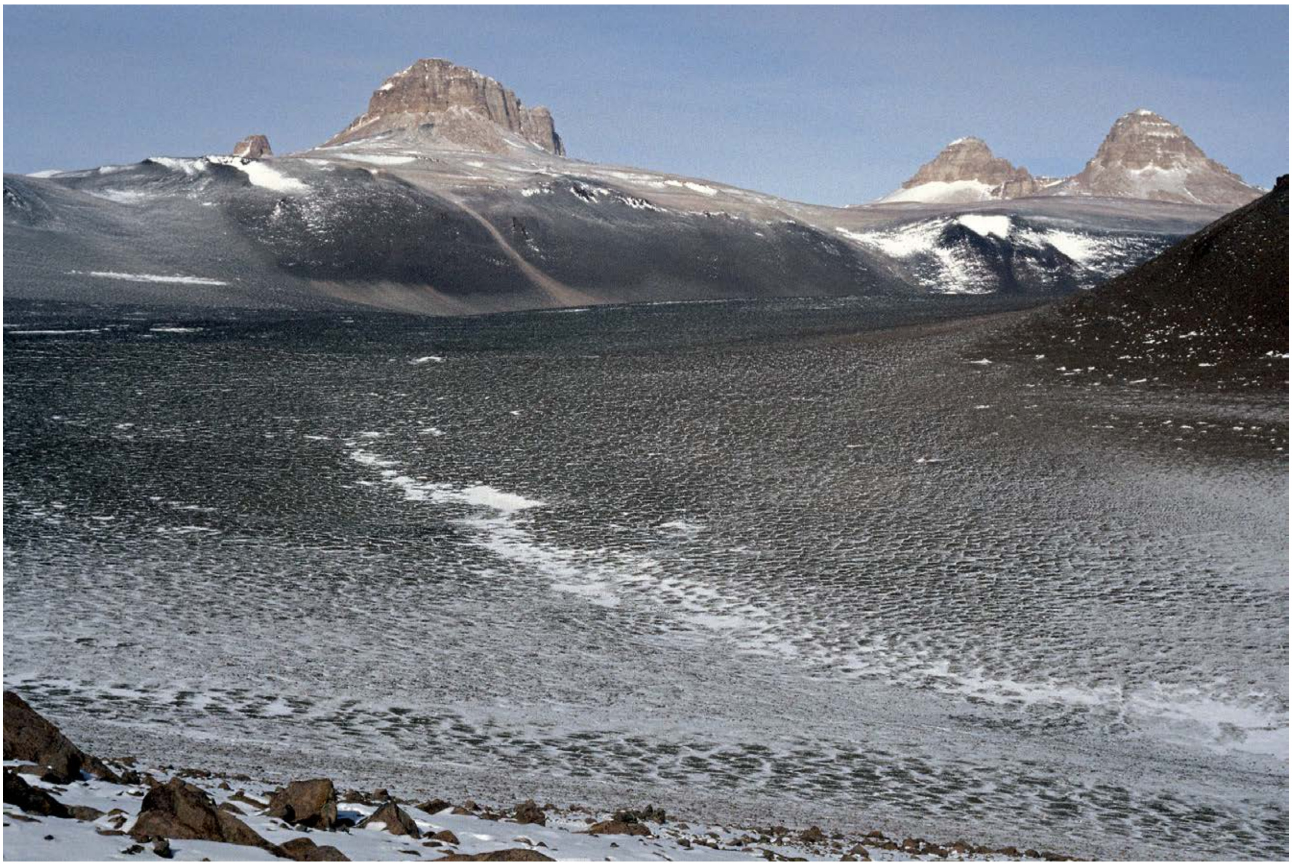


Figure 40 Dolerite-rich Asgard Till (mia) covers the floor of the McKelvey Valley, and is strongly patterned by snow lying in cracks between polygons about ten metres across. Dating of ash preserved in frost wedge cracks has placed constraints on the age of deposits and glacial evolution. Massifs of the Olympus Range (from left, Boreas, Dido and Circe) are composed of erosion-resistant Beacon Heights Orthoquartzite. They rise above a platform of less resistant Arena Sandstone, Altar Mountain Formation and the Ferrar Dolerite Peneplain Sill (Photo: S.W. Edbrooke).

Taylor 4 Drift (**mt4**) is the innermost part of a well preserved sequence of tills, with at least 29 distinct and nearly intact moraine ridges, formed by southward incursions of the Taylor Glacier into Arena Valley that were less extensive than that which formed the Quartermain tills (Denton et al. 1989; Marchant et al.1993b). Taylor 4 Drift rests on relict soil horizons and delicate desert pavements in Arena Valley, suggesting deposition from dry-based ice, and in Beacon Valley it overlies ice that may be the oldest preserved on earth (Sugden et al. 1995b). Taylor 4 Drift is composed of angular, unweathered gravel- to cobble-sized clasts of Beacon Supergroup sandstone, Ferrar Dolerite and exotic granite (Marchant et al. 1993b, 1994). Dating by ^{3}He and ^{10}Be cosmogenic methods shows that it is at least 400 ka old, and potentially older than 2.1 Ma (Brook et al. 1993), but younger than underlying Quartermain Till and 7.4 Ma ash (Marchant et al. 1993a). Deposits of similar age are not as clearly defined in the central Taylor Valley as in the Quartermain Mountains. A deposit known as **Thomson Drift** (Wilch et al. 1993), occurring at 900–1100 m elevation on the platform between the Rhone and Matterhorn glaciers, marks the maximum known thickening of Taylor Glacier ice (Fig. 34). This till has an age constrained, by intercalated volcanic rocks, to 2.7–3.0 Ma and is included in Taylor 4 Drift (following Bockheim et al. 2008), together with a small patch of till at a similar elevation on the north side of the Kukri Hills. An older diamicton, not shown on the map, was found beneath small McMurdo volcanic centres dated at 3.5 Ma (Wilch et al. 1993). **Taylor 3 Drift** (**ut3**) is more extensive in the central Taylor Valley, forming near-continuous tills along the valley walls about 100–200 m above the present elevation of the glacier, cross-cut by local alpine glacier tills (Fig. 34). In Arena Valley it was deposited on a desert pavement with preserved *in situ* ventifacts (Marchant et al. 1993b). Unlike Taylor 4 Drift, it is not prominent in Beacon Valley and not extensive enough in Arena Valley to be shown as a separate unit on this map. Cosmogenic dating suggests that Taylor 3 Drift is Middle Pleistocene in age (Brook et al.1993; Bockheim et al. 2008).

Taylor 2 Drift (**ut2**; Denton et al. 1970; Bockheim et al. 2008) forms a nearly continuous sheet on the floor and sides of the central Taylor and Pearse valleys and includes deposits referred to as **Bonney Drift** in some studies (e.g. Higgins et al. 1996, 2000a,b). In the central Taylor Valley, Taylor 2 Drift is composed of sand- and silt-rich tills and associated glaciolacustrine and fluvioglacial sediments. The drift forms multiple sets of hummocky moraines on the valley floor, but more subdued features on the valley walls where it is locally modified by downslope movement (Higgins et al. 2000a; Swanger et al. 2010). A coarse-grained lag on the moraine surface, including cavernously weathered granite boulders, could be either the result of till deflation or a distinct younger depositional unit (Higgins et al. 2000a). Taylor 2 Drift is interpreted as a combination of waterlaid and melt-out tills that were deposited following the penultimate down-valley advance of the Taylor Glacier into an extensive proglacial lake. Thin-bedded algal carbonates in lacustrine sediments yield U-Th ages of 70 to 130 ka (Higgins et al. 2000b), indicating that Taylor Glacier expansion occurred during the penultimate global 'interglacial' period (MIS 5 period, 70–120 ka). Concurrent expansion of valley wall alpine glaciers is indicated by the merging of their lateral moraines with Taylor 2 Drift at its upper limit (Higgins et al. 2000a). Smaller fluctuations in ice extent occurred at the head of the Taylor Glacier, where 15 moraine ridges in Arena Valley are constrained by cosmogenic dating to the Late Pleistocene (Brook et al. 1993; Marchant et al. 1994). The area of Taylor 2 Drift in Arena Valley is too small to be clearly depicted on a regional map, and has been included within the undifferentiated local till unit (ul). The larger area of Taylor 2 Drift at the mouth of Beacon Valley has been shown.

Once the valley and ice-sheet glaciers had retreated, a history of local glacier deposition was recorded in the more northern Dry Valleys. Following deposition of Peleus Till, considerably less extensive ice left **Wright Upper 3 Drift** (**mlw**), which forms kame moraines and eskers, in the north and south forks of the Wright Valley (Calkin et al. 1970). The drift comprises unconsolidated sandy diamicton, which locally incorporates Peleus Till. Although a Pliocene age has been inferred, the deposits await precise dating (Bockheim & McLeod 2008). **Bull 1 Drift** (**mlb**) is a highly weathered, very silty, bouldery till in the Barwick and Victoria valleys that contains clasts predominantly of dolerite, but also Beacon sandstone (Turnbull et al. 1994). It resembles the older Bull 2-3 Drift in composition and lithology, but has been distinguished because moraine ridges indicate deposition or reworking from expanded local ice, rather than ice flowing through Bull Pass. Nearby **Vida Drift** (**mlv**) is a younger equivalent, with distinct morainic topography and well preserved terminal moraine ridges derived from expansion and retreat of the Webb, Victoria Upper and Clark glaciers. Surface boulders are cavernously weathered and polygonal ground is well developed. Vida Drift and Bull 1 Drift are undated but thought to be Early Pleistocene and Pliocene (possibly Miocene), respectively, from the degree of weathering and relative geographic positions in valleys.

Younger local tills situated closer to the Webb and Victoria Upper glaciers are mapped as **Victoria Drift** (**ulv**) following Kelly et al. (2002), and distinguished from very sandy tills beside the Victoria Lower Glacier mapped as **Packard Drift** (**ulp**). Both of these deposits were included within the same unit by Calkin (1971). Whilst the composition and degree of weathering is similar at either end of the valley, Victoria and Packard drifts pertain to very different glacial systems that may not have advanced or retreated simultaneously (Borns 1982): the Victoria Lower Glacier is a distributary lobe of the Wilson Piedmont Glacier, whereas the Victoria Upper Glacier has a smaller névé in the Clare Range. The Victoria Valley is separated from the coast and the Ross Sea by a 670 m high bedrock ridge beneath the ice of the Wilson Piedmont Glacier (Calkin 1974a). A paucity of basalt clasts in Packard Drift (Calkin 1971), compared to deposits in the eastern Wright Valley (Hall & Denton 2005), supports the idea that the thickened Ross Ice Sheet was blocked from entering the Victoria Valley by this ridge (Calkin 1974a, cf. Turnbull et al. 1994). Packard Drift is dominated by locally derived clasts of dolerite and granite (Calkin 1971), so is inferred to have been deposited by advance(s) of the Victoria Lower Glacier. Victoria Drift consists of poorly sorted, bouldery sand that forms hummocky moraines and ridges, locally derived from the Victoria Upper Glacier. Near the Victoria Upper Lake it has either been locally reworked by meltwater into bedded, sandy gravel alluvium and deltas, or is glaciolacustrine in origin (Kelly et al. 2002). Late Quaternary ages on entrained algae vary from 11 ka to >45 ka (^{14}C yrs B.P.) without systematic spatial order. Based on the number of moraine ridges and scale of the deposits, Victoria Drift may have had a protracted evolution that started during the Middle Pleistocene.

Two generations of undated drift lie at elevations of 600–1000 m and 400–600 m above the Miller and Cotton glaciers, mapped as **Miller 2 Drift** (**ul2**) and **Miller 1 Drift** (**ul1**), respectively. Clasts in the deposits are predominantly dolerite, but also include metasediment, marble, Beacon sandstone and locally derived granitic material. Small areas of till on Pegtop Mountain and Gondola Ridge, above the Mackay Glacier, have been correlated with Miller 2 Drift on the basis of their composition and elevation. Moraine ridges, particularly well developed in Wheeler Valley, indicate that Miller Glacier ice once flowed westward into hanging valleys of the St Johns and Clare ranges. The Miller Glacier area has one of the more complex ice-flow patterns in southern Victoria Land, where multiple sources of ice merge and have probably flowed in different directions in the past. Whether the Miller 2 and Miller 1 drifts were deposited by thickened Wilson Piedmont Glacier ice, the Mackay Glacier, or possibly even incursions of the Ross Ice Sheet (Turnbull et al. 1994) has yet to be determined. **Convoy 2 Drift** (**ui2**) and **Convoy 1 Drift** (**ui1**) are a similar pair of undated glacial deposits left by two (or more) generations of ice flowing west, but at much higher elevations of 1100–1300 m and 800–1100 m, respectively, in the Convoy Range (Calkin 1964b). Notable for containing granite and gneiss boulder erratics, which were thought to be exotic by previous authors, it has been suggested that these drifts were deposited by incursion of the Ross Ice Sheet (Pocknall et al. 1994). Granitoid bedrock does, however, crop out locally at Wildwind Glacier and Greenville Valley, and derivation from the Ross Ice Sheet would require a substantial uplift that is not supported by the local position of the Kukri Erosion Surface (see Fig. 22) or by rates of beach deposit exhumation along the coast (Hall & Denton 2002; Hall et al. 2004). The Convoy 2 and Convoy 1 drifts are here interpreted as the result of ice thickening and development of a piedmont glacier or dome in the Benson-Fry-Towle glacier area. They post-date local glacial tills deposited by plateau ice that overflowed the Ferrar Dolerite escarpment into valley heads from the west, but their age is otherwise poorly understood (Calkin 1964b). In places in Alatna Valley, Convoy 1 Drift is little more than a veneer of cavernously weathered boulders scattered over Convoy 2 Drift, but elsewhere both Convoy 2 and Convoy 1 drifts are thick, unstratified deposits outlined by distinct lateral and terminal moraines. In the Towle Valley, some Convoy 1 Drift is ice-cored and extensively modified by downslope creep (Pocknall et al. 1994).

Younger ice sheet, piedmont and undifferentiated glacial deposits

Undifferentiated ice sheet margin till (**ui**) has been mapped at high elevations near the Polar Plateau, at the margins of large snowfields such as the Skelton Névé, and along outlet glaciers such as the Mackay and Ferrar. These till deposits are generally unweathered to slightly weathered and comprise angular boulders and sand, derived mainly from dolerite, but commonly also containing clasts of Beacon sedimentary rocks. Those adjacent to the Polar Plateau may contain meteorites (Faure & Mensing 2010). At lower elevations ice sheet margin tills also include boulders and clasts derived from the Skelton Group and Granite Harbour Intrusive Complex. Many are actively forming from dry-based ice, have ice cores and morainic forms, and merge laterally into areas mapped as supraglacial till. Others have sequences of moraines representing protracted periods of deposition. This undifferentiated material includes Middle-Late Pleistocene tills and moraine ridges deposited by a lobe of the Ferrar Glacier in Vernier Valley (Staiger et al. 2006), and by the Taylor Glacier in Arena Valley (Denton et al. 1989; Marchant et al. 1993b). Undifferentiated tills at these localities form part of a Pliocene-Pleistocene sequence that has been important for constraining the progressive reduction of ice surface elevation of the Ferrar and Taylor glaciers (Brook et al.1993; Staiger et al. 2006), and modelling behaviour of outlet glaciers draining the East Antarctic Ice Sheet (Kavanaugh et al. 2009a,b; Golledge & Levy 2011).

Wilson Drift (**uw**; Hall & Denton 2000a) is an ice sheet margin deposit beside the Wilson Piedmont Glacier. It occurs as thin discontinuous drift along the coast from Cape Bernacchi to Spike Cape, but is not preserved on ice-free areas further north as these were all below the marine limit prior to 6.5 ka (Hall & Denton 1999). Wilson Drift is a loose, coarse-grained sandy till that shows little weathering. Cavernously weathered boulders are rare. It contains numerous ventifacts and stained, carbonate-coated clasts of local gneiss, granite, schist, marble and dolerite. It also contains rare red and black basalt of unknown source. Wilson Drift is distinguished from nearby Ross Sea Drift (see below) by a lack of anorthoclase phonolite ('kenyte') and reworked shells, corals or other marine organisms (Hall & Denton 2000a). Wilson Drift has an irregular contact with Ross Sea Drift, marked by lobate moraines near Hjorth Hill and Cape Bernacchi, thought to reflect contemporaneous Late Pleistocene deposition. The Wilson Piedmont Glacier is interpreted to have thickened along its eastern margin during the Last Glacial Maximum, when it advanced eastward and southward over the Scott Coast

Figure 41 The floor of the upper Beacon Valley, in the Quartermain Mountains, is covered by ice-cored local glacial till. Ice buried beneath tills and volcanic ash in the valley is thought to have survived since the Miocene; it may be >8.1 million years old (Sugden et al. 1995b). The tills here are composed of local bedrock lithologies, including Ferrar Dolerite (the dark cliffs are sills), Victoria Group sandstone and mudstone (Weller Coal Measures – grey outcrops) and Taylor Group sandstone (Beacon Heights Orthoquartzite – light yellow outcrops) (Photo: K. Westerskov/Hedgehog House).

to merge with the landward-flowing Ross Ice Shelf, but showed little advance into the Dry Valleys (Hall & Denton 2002). During the mid-Holocene the glacier retreated to a position less extensive than at present, exposing scarce deposits of Wilson Drift, and has subsequently advanced and retreated to a lesser extent (Hall & Denton 2002).

Scattered deposits of **older undifferentiated till** (**mt**) in the Transantarctic Mountains are of uncertain origin, but are clearly weathered, have modified landforms, or have stratigraphic relationships that suggest an older Pliocene-Miocene age. Several such deposits are mapped in the Allan and Coombs hills and the Convoy Range, reflecting the lack of detailed investigations of glacial deposits in these areas. **Older undifferentiated local glacier till** (**ml**) has also been mapped in the Coombs Hills, Beacon Valley and Asgard Range, principally according to its degree of modification and weathering, and proximity to glaciers and other nearby tills. The floor of the upper Beacon Valley (Fig. 41) is covered by a locally derived, dolerite-rich till, with irregular relief suggesting that it is ice-cored (Linkletter et al. 1973), by possibly some of the oldest ice on earth (Sugden et al. 1995b; Schaefer et al. 2000; Ng et al. 2005; Kowalewski et al. 2012). The Alpine 3 and 4 tills (Hall et al. 1993), which were deposited by Late Pliocene glaciers ancestral to those which still flow from the Asgard Range into the Wright Valley (Fig. 42), and the Middle Miocene Dido Drift in the Olympus Range (Lewis et al. 2007), are collectively mapped as older undifferentiated local glacier till. Radiometric dating of entrained basalt clasts and underlying Hart Ash indicates that Alpine 3 tills must be younger than c. 3.7–3.5 Ma (Hall et al. 1993), but pre-date Ross Ice Sheet incursion and deposition of drift deposits on the floor of the Wright Valley (Hall & Denton 2005). Some older local glacier tills (ml) may have been mapped as undifferentiated local glacier tills (ul), and *vice versa*, because their age or origin is unknown, or they are of insufficient scale or continuity to be shown individually on a regional map.

Undifferentiated till (**ut**) has been mapped where the origin and age of the deposits are unknown, although landforms or degree of weathering suggest a relatively young Quaternary age. **Undifferentiated local glacier till** (**ul**) deposits are thought to be relatively young on the basis of proximity to local glaciers, presence of prominent moraine ridges, and/or a lack of modification (Fig. 43). Undifferentiated tills are mapped on the volcanoes of Ross, White and Black islands, Mt Discovery and Minna Bluff, at elevations above Ross Sea 1 Drift. These include some deposits at c. 400–700 m elevation at Cape Crozier and Mt Discovery, although it is possible the tills there could be Ross Sea 1 or 2 drift, local glacier till, or even colluvium. Deposits in the lower Victoria Valley, at the eastern edge of Lake Vida, comprise

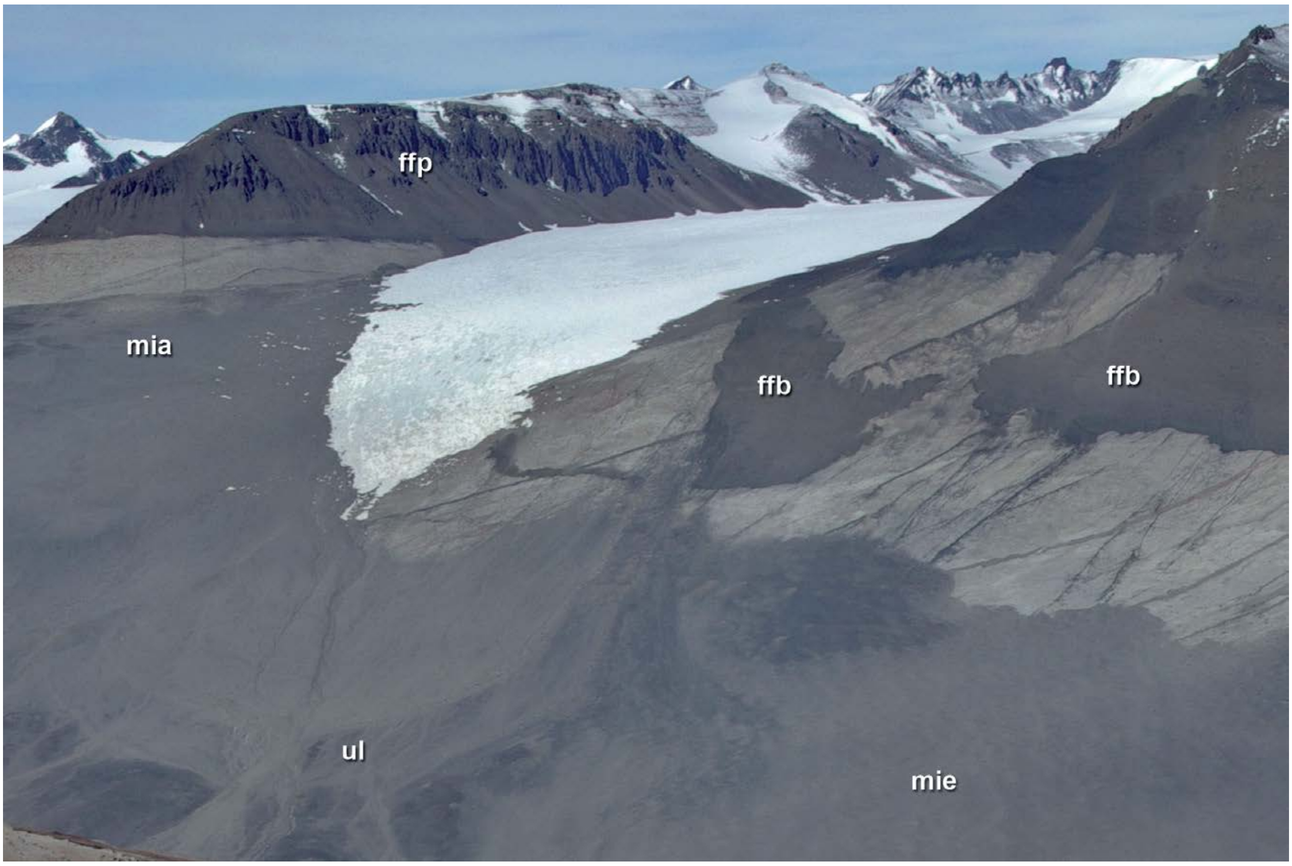


Figure 42 Local glacial till (ul) with prominent arcuate moraine ridges (Alpine 2 till of Hall et al. 1993) marks the former extent of the Conrow Glacier, which advanced from the Asgard Range across older valley glacier tills in the Wright Valley (Asgard Till - mia; Peleus Till - mie). The Ferrar Dolerite Basement Sill (ffb) intrudes the light-coloured Valhalla Pluton, abruptly stopping at this locality and stepping up to merge with the Peneplain Sill (ffp) (Photo: Z. Malolepszy).

Figure 43 A small alluvial fan and delta are presently developing where meltwater runoff from the Koettlitz Glacier enters Trough Lake. The ice-covered lake (foreground) develops a meltwater moat around its margin during late summer. Differential melting transports englacial till as rock debris southwards across the lake some distance from the Koettlitz Glacier ice and the prominent dark ground moraine immediately adjacent to the glacier. On the slopes beside the glacier, a kame terrace and moraine ridges, mapped as undifferentiated local glacier till, show that similar processes occurred when levels of the Koettlitz Glacier ice were much higher. Thick colluvium mantles the slopes of The Bulwark (right), where orthogneiss (light pink) and McMurdo Volcanics (dark brown) form the bedrock. Heald Island (far distance) consists of Skelton Group marble and schist with small eruptive centres of McMurdo Volcanics and, in places, a thin covering of till (Photo: D.B. Townsend).

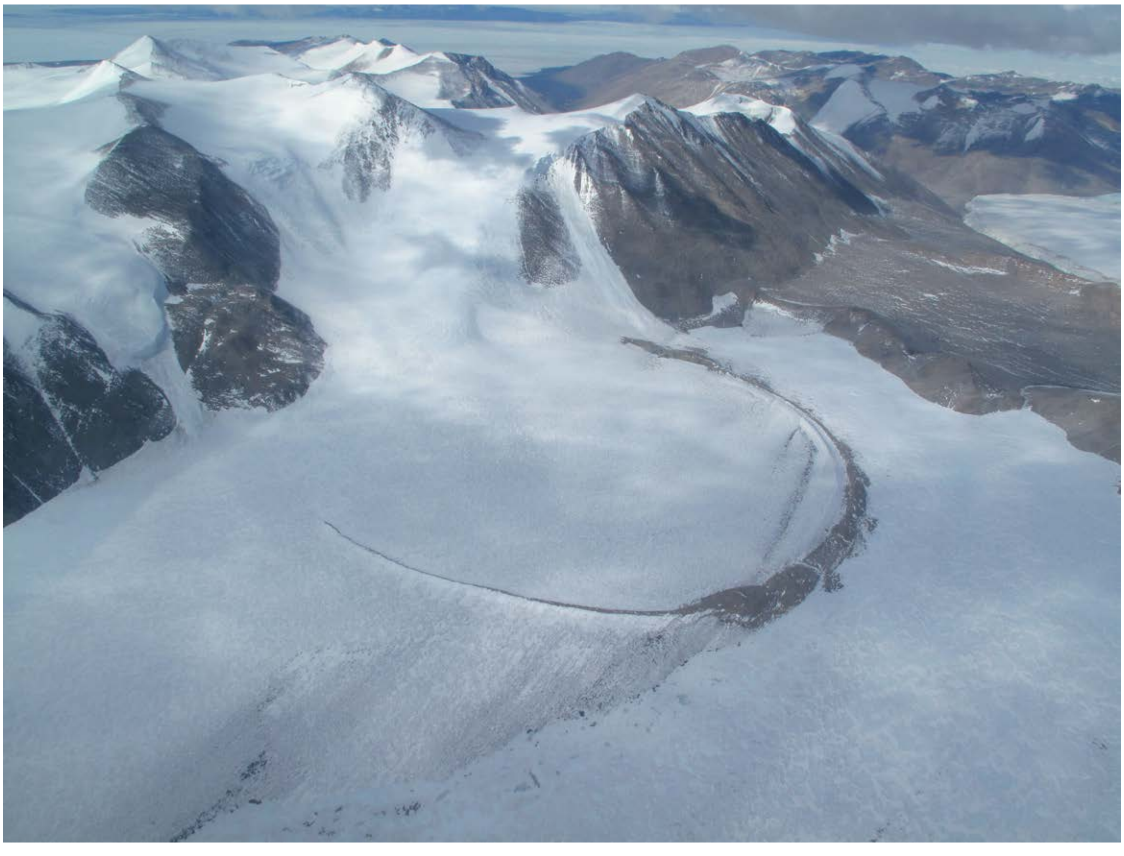


Figure 44 The eastern Blue Glacier névé and the foothills of the Royal Society Range. A loop of supraglacial till marks the limit of ice that flows west from a small local glacier near Williams Peak into the Blue Glacier. Strong winds have spread the till across the ice. The bare ground between this ice and the Joyce Glacier (far right) is covered in undifferentiated till and colluvium (Photo: R. Jongens).

poorly sorted, bouldery sand with clasts of dolerite, granite, and rare scoriaceous olivine basalt (Calkin 1964a; Borns 1978, 1982). The age and origin of these deposits is unclear. Alpine 1 and Alpine 2 tills in the Wright Valley (Hall et al. 1993) have been mapped collectively as undifferentiated local glacier till (ul). Many are ice-cored and there is not always a clear distinction between such tills, rock glaciers, or places where thin veneers of **supraglacial till** (**us**) cover active glacial ice (Fig. 44).

Areas of supraglacial till located high on the Polar Plateau margin are known to contain meteorites, cosmic dust, and other extraterrestrial particles that have fallen on the East Antarctic Ice Sheet, then been transported and concentrated at the bare ice surfaces of the ablation zone where flow of ice is deflected upward by subglacial bedrock barriers (Whillans & Cassidy 1983; Score & Lindstrom 1990). A large number of well-preserved meteorites have been collected from the ablating ice sheet west of Allan Hills (Cassidy 2003). These meteorites have terrestrial ages ranging widely from <100 000 years to 2.2 ± 0.4 Ma, exceptionally old compared with meteorites elsewhere in the world (Faure & Mensing 2010). Others have been collected from the Odell and Mackay glaciers, Mt DeWitt, Mt Crean, Mt Baldr and even Purgatory Peak (from the Wilson Piedmont Glacier). Retrieved specimens are predominantly fragments from the asteroid belt between Mars and Jupiter, but rarely include rocks ejected from the Moon (Faure & Mensing 2010 and references therein).

Ross Ice Sheet deposits

At times in the Plio-Pleistocene, grounded ice of the Ross Ice Sheet, fed from the West Antarctic Ice Sheet and/or local trunk glaciers, has extended to fill McMurdo Sound and flowed as re-entrant glaciers into the valleys of the Transantarctic Mountains (Fig. 45). 'Ross Ice' deposits of Pliocene to Middle Pleistocene age are preserved in the Wright and Taylor valleys, where lateral moraines on the valley walls and arcuate terminal moraines indicate previous ice limits. These deposits are weathered, modified, and of limited spatial extent (Fig. 46). Widespread and extensive Late Pleistocene to Holocene drift sheets mantle the coastline of McMurdo Sound and the lower slopes of Minna Bluff, Brown Peninsula, Black Island and, locally, Ross Island. At times, grounded ice dammed proglacial lakes in ice-free valleys that opened to McMurdo Sound, and left prominent moraine ridges on coastal headlands (Fig. 45). These drifts are conspicuous in the Transantarctic Mountains landscape because of their abundance of dark McMurdo Volcanic Group clasts. The advance of westward-flowing re-entrant ice marked a different style of glaciation in the Dry Valleys, and had a much greater impact on the landscape than that of the alpine glaciers. The moraines deposited by the re-entrant lobes rest on top of or beneath alpine moraines, implying that these ice lobes fluctuated out of phase with alpine glaciers. Improved and more widespread dating of deposits is needed to better define grounded ice thickness in the Ross Sea, the timing of ice advance/retreat, and its potential contribution to sea-level change (e.g. Denton et al. 1989; Hall & Denton 1999). Although the mouth of the Wright Valley is currently blocked by the Wilson Piedmont Glacier, the valley extends beneath the glacier where bedrock reaches only 100 m above sea level (Calkin 1974a). The Ross Ice Sheet has crossed this threshold, and has left eight drift sheets and distinct moraines now preserved along the floor of the eastern Wright Valley (Fig. 46). The oldest deposits are included together in **Ross Sea 4 Drift** (**mr4**), following the name (but not necessarily the definition) introduced by Denton et al. (1970, 1971; see Appendix 1). They are moderately to highly weathered, poorly sorted, bouldery sandy tills modified by gelifluction. In the Wright Valley they are locally distinguished as the Loop, Valkyrie and Wright drifts (Hall & Denton 2005). Tills underlying McMurdo Volcanic Group lava flows in Walcott Bay are mapped provisionally as Ross Sea 4 Drift and shown as outcrops on the map.

Loop Drift (**mrl**) in the central Wright Valley is a loose, unstratified, highly weathered, coarse-sand diamicton with clasts of local lithologies that are commonly stained, ventifacted and striated (Hall & Denton 2005). Unlike other Ross Ice Sheet deposits, basalt clasts have not been recognised in Loop Drift. It forms prominent lateral moraines and an 80 m high terminal moraine adjacent to the Goodspeed Glacier. This moraine is significantly larger, and derived from ice with a lower surface slope, than other Ross Ice Sheet deposits in the valley (Hall & Denton 2005). The exact age of Loop Drift is unknown, but it is thought to be Pliocene or older on the basis of stratigraphic position and degree of surface weathering. It was subsequently overridden and covered by younger Ross Sea drifts. Patches of a highly weathered drift containing basalt clasts between the Bartley and Conrow glaciers have been distinguished as **Valkyrie Drift** (**mrv**; Hall & Denton 2005). The drift post-dates older local alpine glacier till (ml, Alpine 4) in front of the Conrow Glacier. **Wright Drift** (**mrw**) is an unstratified, highly weathered, coarse-grained diamicton with angular clasts that are commonly stained and display ventifaction, but are not striated. Clasts include local dolerite, gneiss and granite, and basalt erratics. Boulders have been weathered to ground level. Wright Drift is exposed as a continuous sheet on the south wall of the Wright Valley. It is represented by scattered boulders on the north side of the valley, except opposite the Bartley Glacier, where it thickens and forms a series of arcuate lateral moraines which contain cores of reworked Peleus Till and lacustrine silts. Wright Drift overlies and is therefore younger than the 3.9 Ma Hart Ash.

Ross Sea 3 Drift (**ur3**) as shown on this map includes the Onyx, Trilogy and Loke drifts in the Wright Valley (Hall & Denton 2005), and an elevated drift deposit at 250–400 m near Andrews Ridge in the lower Taylor Valley. **Onyx Drift** is exposed on the inland side of Loop Drift. It is a highly weathered, salt-rich, coarse-sand diamicton that is typically massive. Clasts, which include basalt, are stained, ventifacted and polished, but not striated. Surficial boulders are shattered and cavernously weathered. The deposit forms at least five distinct lateral moraines on the south wall of the Wright Valley, two on the north wall, and a hummocky terminal moraine on the valley floor.

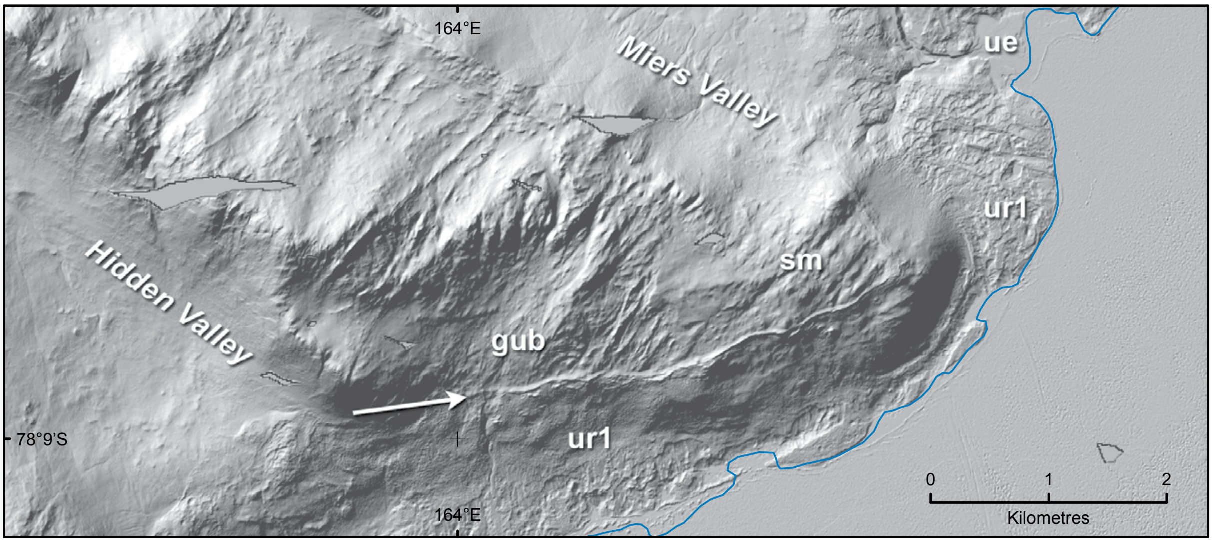


Figure 45 Ross Sea Drift. Top: Aerial oblique view of ice-cored, dark, volcanic-rich tongues of Ross Sea Drift in the mouths of the Hidden (HV), Miers (MV), Marshall (MA) and Garwood (GV) valleys. Prominent moraine ridges across the headlands at 250 m mark the uppermost ice-limit (arrows). Lacustrine deposits in these valleys were formed where meltwater was dammed against the thickened ice (Photo: US Navy, TMA 337 L0090, Dec 1956). Bottom: Details of the moraine ridge and Ross Sea Drift around the headland south of Miers Valley are shown in this shaded LIDAR digital elevation model. In places the foliation of Skelton Group marble (sm) and biotite orthogneiss (gub) basement rock can be seen through the thin veneer of ur1 till. A delta (ue) is presently developing where a meltwater stream carries alluvium to the coast.

A Pliocene or early Quaternary age is suggested for Onyx Drift by contact relationships with nearby tills: it overlies the Loop Drift and older undifferentiated local glacial till (Alpine 3 & 4), but is crosscut by local glacial till ('Alpine 2') at the Hart Glacier. **Trilogy Drift** is a very similar deposit, but exposed closer to the coast than Onyx Drift. It is a moderately to highly weathered, sandy diamicton with stained and ventifacted clasts that include basalt (Hall & Denton 2005). Surficial boulders are pitted and cavernously weathered, and many have been weathered to ground level. Trilogy Drift forms numerous lateral moraines that descend up-valley on both the north and south walls of the Wright Valley, locally including reworked Loop Drift material. In places, Trilogy Drift is stratified and sorted, with soft-sediment deformation features showing deposition associated with water. It also forms indistinct and irregular terminal moraines on the valley floor, which include tilted blocks of Peleus Till and alluvium, possibly indicating a thrust moraine where it entered a proglacial lake. Based on its weathering, Hall & Denton (2005) suggest an early to mid-Quaternary age. **Loke Drift** forms a sheet on the floor of the Wright Valley, with numerous channels, kettles and depressions, and a hummocky terminal moraine about three kilometres up-valley from Lake Brownworth. It is a moderately weathered, sandy diamicton with some stratified sand and gravel, and local patches of buried ice. Clasts are stained and ventifacted, many with carbonate crusts, and include rare basalt erratics. Surficial boulders are cavernously weathered or weathered to ground level. The exact age is unknown, but thought to be mid-Quaternary (Hall & Denton 2005).

Ross Sea 2 Drift (**ur2**) covers extensive areas of the Taylor and lower Wright valleys, and is present in the Royal Society Range foothills between the Blue Glacier and Walcott Bay as a series of deposits at 300–600 m elevation. Compared with the younger Ross Sea 1 Drift, the surface morphology of these deposits is more subdued, the surface clasts are more weathered, they are less continuous, and are generally not ice-cored. They commonly contain stratified sediments and/or are associated with lake sediments, which are distinguished separately (uk2, see below). Boulders

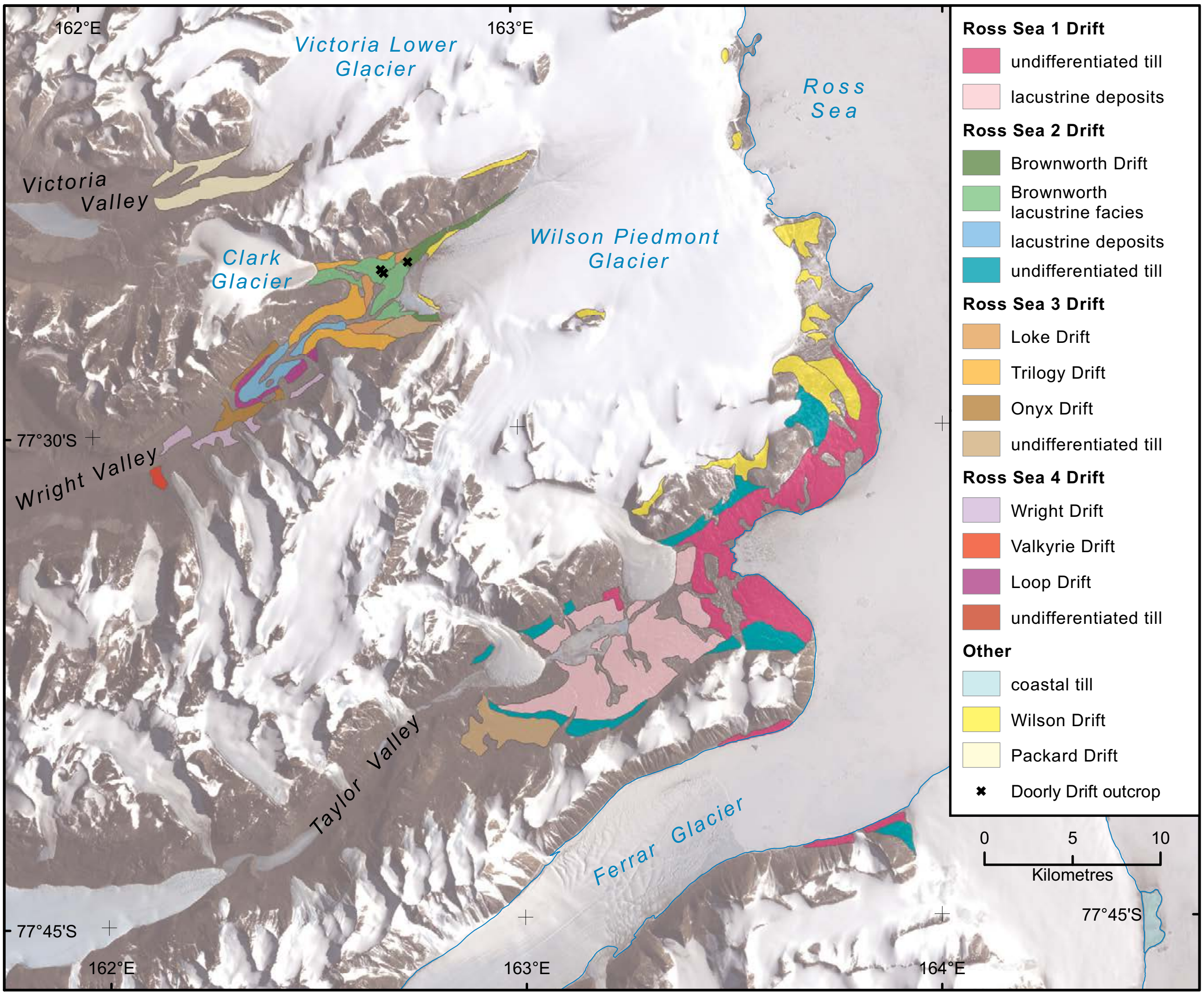


Figure 46 Map of Ross Sea Drift deposits in the Wright and Taylor valleys. The deposits comprise both till and lacustrine facies, formed when grounded ice of the Ross Ice Sheet filled McMurdo Sound and flowed landwards as re-entrant glaciers into the valleys, locally forming lakes where drainage in the valleys was blocked. The Packard, Doorly and Wilson drifts were deposited from an expansion of the Wilson Piedmont Glacier. The figure is coloured using the geological units layer in the digital GIS dataset, overlain on the Landsat Image Mosaic of Antarctica (LIMA).

are cavernously weathered and ventifacted. In the Wright Valley, the unit includes tills mapped as **Brownworth Drift** (Hall & Denton 2005). Ross Sea 2 Drift forms lateral moraines on the valley walls and extensive sheets with hummocky topography across the lower Wright Valley, as well as deposits in the adjacent Clark Valley. Tills are coarse-sand diamictons with numerous boulders, predominantly of local granite, many of which are slightly rounded and have a water-worn appearance. Clasts of basalt are rare. The lacustrine facies contains buried ice and rare flakes of ancient algae. Radiocarbon dating suggests that the drift is beyond the age datable by this method, i.e. >40 ka. Ross Sea 2 Drift marks the last advance of the Ross Ice Sheet into the Wright Valley, as overlying lacustrine deposits (Doorly Drift) are basalt-free and appear to be locally derived from Wilson Piedmont Glacier ice. A series of buried Ross Sea Drift 2 tills and lacustrine sediments in the Marshall Valley, locally referred to as **Marshall Drift**, have *in situ* gypsum and algal carbonate that yield U-Th ages of 130 to 180 ka. These ages provide the principal evidence that Ross Sea 2 Drift formed during a global 'glacial' MIS 6 period (Dagel 1984; Judd 1986; Hendy et al. 1979; Hendy 2000).

The younger **Ross Sea 1 Drift** (**ur1**) forms a near-continuous drift sheet that mantles the eastern slopes and coastal valley mouths south from Marble Point (Fig. 45). It also occurs as extensive deposits on Brown Peninsula, Black Island and Minna Bluff, but is more localised on Ross and White islands (Stuiver et al. 1981; Denton et al. 1989). It is commonly bordered by well-defined moraine ridges that are analogous to those currently forming at the edge of the ice shelf. The uppermost moraine of Ross Sea 1 Drift varies in elevation, from 250–300 m along the western side of McMurdo Sound, to 400–500 m on the volcanic islands. Ross Sea 1 Drift extends furthest inland in the Taylor Valley, reaching as far as the Canada Glacier. Convex up-valley threshold moraines and ice-contact embankments are prominent features in the Taylor, Miers and Hidden valleys (Fig. 45). There is no sharp upper boundary to Ross Sea 1 Drift on Ross Island, but it has been mapped up to 590 m above sea level near Cape Bird (Dochat et al. 2000). At Cape Crozier, tills up to c. 400 m above sea level are shown as Ross Sea Drift (cf. up to 710 m of Cole et al. 1971; Denton & Marchant 2000), but higher tills have been assigned to the undifferentiated tills unit (ut) because of uncertainty as to their origin. Locally, tills mapped as Ross Sea 1 Drift have been subdivided on the map and in the digital dataset, with the position of internal contacts defined by changes in till composition or colour, the position of prominent moraine ridges, or other variations in landform (e.g. Blank et al. 1963).

Ross Sea 1 Drift is composed of loose till, waterlaid diamicton, glaciolacustrine silt, stratified sand, and interbedded silt, sand and gravel (Stuiver et al. 1981; Hall et al. 2000). These deposits are unweathered to slightly weathered and commonly ice-cored. Lacustrine and deltaic units have been locally distinguished as **Ross Sea 1 Drift lacustrine deposits** (**uk1**) or **deltaic deposits** (**ue**) where these facies are known to be extensive, but in many places they are hidden beneath surface lags of cobbles and boulders. The drift surface is commonly marked with kettles, eskers and/or sinuous bands of erratics. Cavernous weathering of surface boulders is rare. Tills are matrix-supported and contain carbonate-coated clasts ranging from gravel to boulders several metres in diameter. Waterlaid diamicton shows stratification and numerous glaciotectonic features, including internal faulting, folding and dewatering structures (Fig. 47). Clasts of McMurdo Volcanic Group are present in all Ross Sea 1 Drift sediments. In places the cobble-sized clasts are almost entirely of basalt, but typically the larger clasts and boulders are of granite, granodiorite, dolerite, sandstone, and schist. Erratics of granite boulders and Scallop Hill Formation occur on the volcanic islands and stand out prominently in basalt-dominated tills. The drift also contains preserved algae and abundant reworked marine microfossils and macrofossils. Mirabilite (Fig. 48), a sodium sulphate formed by freeze concentration and evaporation of supraglacial and periglacial meltwater ponds (Bowser et al. 1970; Lovett 2011), is common in drift on the west coast of McMurdo Sound. Here the drift also contains clasts of anorthoclase-phyric phonolite, often referred to as kenyte—a name originally given by Smith (1954) but now abandoned. Plagioclase-phyric intermediate lavas which are common in the McMurdo Sound area have been mistakenly identified as "kenyte" and this has caused some confusion. The presence of phonolite has been used to argue for ice sheet flow from east to west across McMurdo Sound (Denton & Marchant 2000), as the only known local source of anorthoclase phonolite is from Mt Erebus on Ross Island. An alternative view is that ice may have flowed northwards through McMurdo Sound in a series of discrete ice sheet lobes (Wilson 2000; Glasser et al. 2006; Timms 2006).

The Ross Sea 1 Drift sheet is in contact with local alpine glaciers and their moraines near the Hobbs, Walcott, Commonwealth and Canada glaciers. Ice-cored, mirabilite-rich Ross Sea 1 Drift has been deformed by the advance of the Hobbs Glacier, and its internal layering is now subvertical near the glacier snout (Fig. 48). Elsewhere, the cliffed terminus of the Hobbs Glacier rests directly on deltaic deposits that post-date Ross Sea 1 Drift, and small alpine glaciers flowing off Minna Bluff deform young coastal tills (Wilson 2000). Such relationships have been presented as evidence that the Ross Ice Sheet advances out of phase with local alpine glaciers (Stuiver et al. 1981), but in phase with the Wilson Piedmont Glacier (Hall & Denton 2000a, 2002). Attempts to derive a chronology for Ross Sea 1 Drift have used a wide variety of materials and methods (e.g. Hendy et al. 1979; Stuiver et al. 1981; Clayton-Greene 1986; Esser et al. 1994; Brook et al. 1995a; Dochat et al. 2000; Hall & Denton 2000b), summarised by Denton & Marchant (2000). The latest grounding of the ice sheet in McMurdo Sound occurred at about 27 ka, the ice sheet remained during the Last Glacial Maximum, then began to lower during the mid- to late Holocene with final unloading of grounded ice at c. 7.8 ka (Conway et al. 1999; Kellogg et al. 1996; Hall et al. 2004). Some areas mapped as Ross Sea 1 Drift may include tills older than 27 ka, particularly if the contrasting view of Wilson (2000) is correct that recycling of material has been widespread and the deposits reflect complicated interaction of local ice sheet lobes flowing northwards through McMurdo Sound (Glasser et al. 2006; Timms 2006). A number of undated yet well-defined moraine ridges and internal contacts shown on the map could be used to subdivide Ross Sea 1 Drift between Walcott Bay and the Blue Glacier (e.g. Blank et al. 1963); these were possibly formed by local fluctuations in ice level caused by interaction of grounded sea ice with the Koettlitz Glacier.

Coastal tills (**ur**) containing well-preserved macrofossils are actively forming along the margins of the Koettlitz Glacier, the McMurdo Ice Shelf and the Ross Ice Shelf (Blank et al. 1963; Currie 1986; Vella 1969; Wilson 2000). These tills are ice-cored and matrix-poor, with armoured surfaces caused by wind deflation during meltout. Clasts are dominated by McMurdo Volcanic Group lithologies, but include dolerite, schist, granite, and Beacon sedimentary rocks. The larger boulders are typically of granite, but

Figure 47 Ross Sea Drift lacustrine deposits (uk1) in the lower Taylor valley. Top: Exposures in Commonwealth Stream display rippled, laminated, silt horizons and sand-silt interbeds containing chaotic soft-sediment deformation structures. Bottom: An ice-cored exposure near the snout of the Commonwealth Glacier, with laminated silt and pebble and cobble dropstones. This ice is likely to be at least 10 000 years old (Hall et al. 2000b) (Photos: S.C. Cox. Walking pole is 90 cm long).

Figure 48 Top: Near the snout of the Hobbs Glacier, near-vertical layers of ice, silt, pebbly diamictite and mirabilite in Ross Sea 1 Drift have been tilted by the advance of the glacier. Complex internal folds, particularly noticeable in mirabilite and ice in the right side of the photograph, are within the formation and pre-date tilting (Photo: D.B. Townsend). Bottom: Detailed view of fresh mirabilite (sodium sulphate) crystals, exposed beneath a white surficial weathering layer, from a two-metre-thick evaporite deposit outcrop near Cape Chocolate (Photo: S.C. Cox. Hammer head is 17 cm across).

include fossiliferous Eocene erratics (see p. 78, Marine deposits exposed onshore). The coastal tills record the most recent stages of Holocene deglaciation, Ross Ice Sheet thinning, and retreat of the ice margin from coastal areas. **Supraglacial till** (**us**) covers much of the ice shelf between Black Island and Brown Peninsula (Kellogg et al. 1990; Kellogg et al. 1991a,b, 1996). Its distribution does not reflect current ice sheet flow patterns, but rather the extent of three distinct former lobes of grounded ice in McMurdo Sound (Wilson 2000), and it records the retreat of the ice shelf grounding line. The supraglacial till has been transported from the sea floor, through the ice to the ice shelf surface, by processes of basal freezing and surface ablation (Debenham 1919; Glasser et al. 2006). Supraglacial tills in the ice near Minna Bluff reflect upwarping of layers within the ice shelf to a 45° NNE dip (Wilson 2000; Fig. 49).

Lake and delta deposits

Miocene lake deposits (**mk**) crop out on the northern side of the Olympus Range, where small meltwater lakes were impounded behind recessional moraines (Lewis et al. 2008). The lacustrine deposits consist of unconsolidated, horizontally stratified silt, sand, diatomite and peat, and contain exceptionally well-preserved fossils including ostracods, insects, palynomorphs, mosses and diatoms.

Figure 49 Historic aerial oblique photo view looking east along Minna Bluff, showing a relatively continuous ridge of coastal till (ur). On and in the Ross Ice Shelf to the north, supraglacial tills (us) are composed of material entrained from the sea floor by basal adfreezing and exposed by surface ablation. Strata within the ice shelf are now upwarped to a 45° angle. Minna Bluff peninsula is composed of overlapping volcanic centres. Small alpine glaciers flowing off Minna Bluff deform young coastal tills, recycle older drift and have deposited local till (ul). Eocene sedimentary erratics are found both in coastal till (ur) and, less commonly, recycled within local tills (ul). Large areas of Ross Sea Drift (ur1) are exposed at the eastern end of the peninsula (Photo: US Navy, TMA 352 L0030, Dec 1957).

The beds interfinger with fluvial sand, gravel and wet-based till, which are overlain by sublimation tills from dry-based alpine glaciers. A volcanic ash dated at 14.1 Ma has been found within one deposit (Lewis et al. 2008). The fossil assemblage represents a mountain tundra community that is an important onshore record of climatic conditions immediately prior to Middle Miocene cooling.

Numerous lakes and ponds are present in the Dry Valleys region and on the flanks of volcanoes in McMurdo Sound (Hendy 2000). The majority have water that is frozen for most of the year, if not permanently, but some contain brines that do not freeze. Prolonged periods of cyclic melting and evaporation have concentrated dissolved salts in the lakes and evaporite salts around their margins. Some salt deposits are sufficiently thick to be mapped as individual **evaporite** (**uv**) outcrops; mirabilite is notably common in Ross Sea Drift (Fig. 48; Edgeworth David & Priestley 1909; Bowser et al. 1970; Lovett 2011). Lake-water convection and differential ablation can transport ice and its entrained material across proglacial lakes, eventually leaving a variety of lacustrine facies and landforms that include arcuate ridges at the lake margins, thin diamicton veneers that may include locally exotic material, hummocky mounds and ridges, or isolated dropstones (Hendy et al. 2000).

Undifferentiated lacustrine deposits (**uk**) include stratified silt and fine sand, coarser unstratified lacustrine diamicton, and pebbly beach deposits where tills and colluvium around lake shores have been reworked by wave action. Strand line benches, particularly well developed at Lake Vanda up to 52 m above the present lake surface (Fig. 50), show that lake levels have been considerably higher in the past. Lakes have fluctuated throughout the late Quaternary, due to either variations in evaporation-precipitation associated with local climate change, or glacial fluctuations resulting in changes to meltwater and drainage (Hendy 2000). Patches of lacustrine **Doorly Drift** in the lower Wright Valley, mapped as **uk** outcrops, include clasts of local lithologies but not McMurdo Volcanic Group. These deposits provide evidence that an extensive proglacial lake was developed in front of the Wright Lower Glacier during the Late Pleistocene, with the Wilson Piedmont Glacier blocking the mouth of the Wright Valley (Hall & Denton 2005).

Large lakes were once present where drainage of the Dry Valleys was blocked by grounded glacial ice or ice-cored moraines entering the valleys from McMurdo Sound. Particularly extensive **Ross Sea lacustrine deposits** (**uk1, uk2**) have been left across the floors of the Taylor and

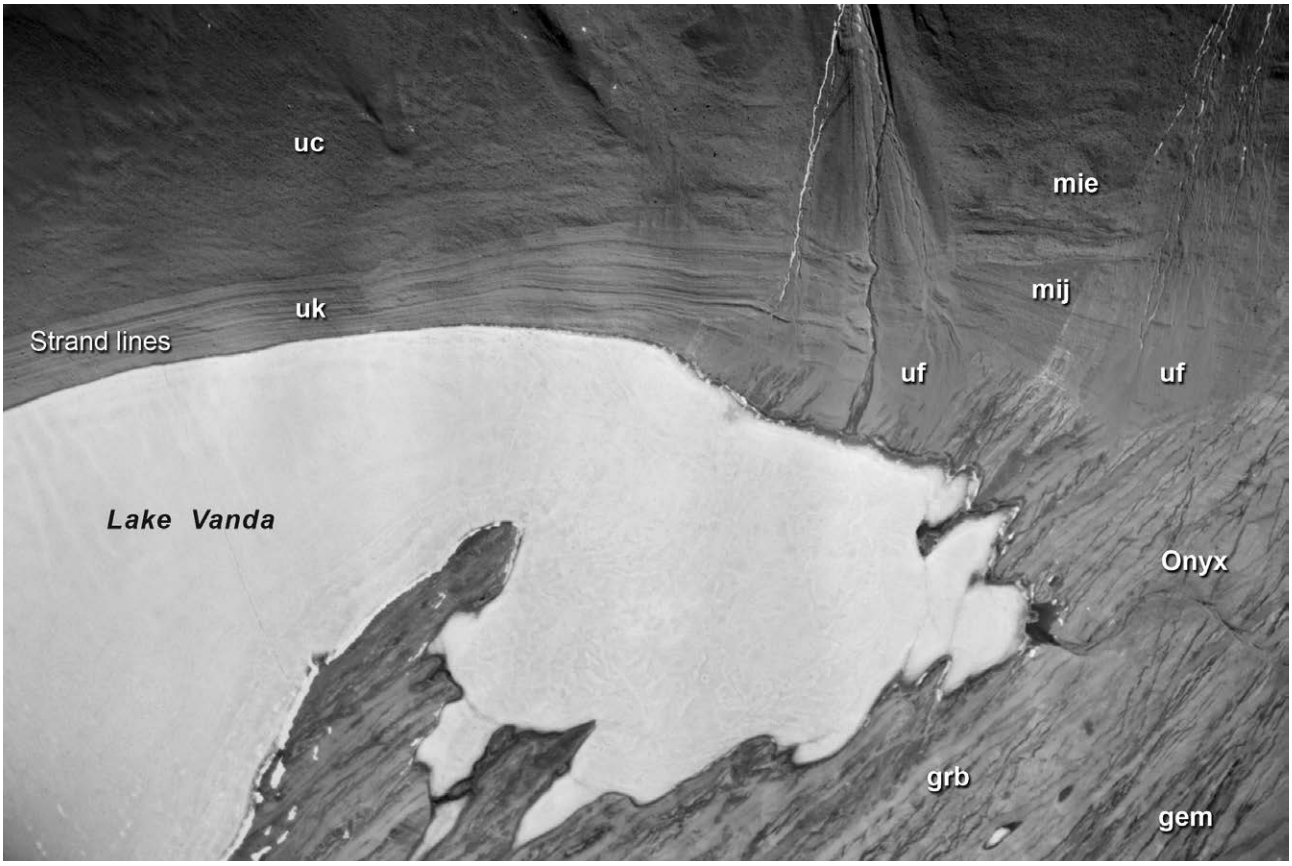


Figure 50 Strand lines around the shores of Lake Vanda in the Wright Valley show that it was much larger in previous times. Lake beach and lacustrine deposits (uk) have been formed from reworked Jotunheim (mij) and Peleus (mie) tills. Alluvial fans (uf) and solifluction lobes in colluvium (uc) have formed on the valley walls. During late summer the Onyx River, the largest river in Antarctica, brings fresh water into the hypersaline, ice-covered lake. Basement rocks exposed across the valley floor in the foreground comprise light-coloured Bonney Pluton (grb) cut by dark mafic Vanda Dikes (gem) (Vertical aerial photo: US Navy, TMA 1313 V0084, Jan 1964).

Figure 51 Trough Lake is a proglacial lake formed where drainage is dammed by a lobe of the Koettlitz Glacier flowing into Walcott Bay. Floating ice forms a conveyor system that carries rock debris in arcuate bands across the lake and leaves it as discontinuous deposits where the ice melts – usually some distance from the glacier face (Hendy et al. 2000). Such ice lake conveyors are thought to be responsible for scattered dropstones, mounds, lateral ridges and benches, and cross-valley and longitudinal ridges found throughout the Dry Valleys. Proglacial lakes developed when the Ross Ice Sheet thickened and flowed westward into the valleys. The slopes in the photograph on the far side of the Koettlitz Glacier are mantled by volcanic-rich Ross Sea Drift, with a series of moraines marking former, much higher, levels of ice (Photo: D.B. Townsend).

Wright valleys associated with tills of Ross Sea 1 and 2 drifts, but there are scattered outcrops suggesting that lakes may also have been present in many other valleys, on Brown Peninsula, and at Walcott Bay. These are recorded both as outcrops and mapped units, the former recorded in the digital dataset in greater detail than has been depicted on the map. The Ross Sea lacustrine deposits are weakly to moderately lithified, composed of stratified sand, silt or clay with sporadic dropped pebbles, cobbles and boulders, and algal mat horizons. Ripples, flame structures and chaotic soft-sediment deformation textures are common. These deposits are interpreted to have formed from interlocked glacial-and-lake-ice systems that acted as conveyor belts to transport both fine and coarse sediment from glacial lobes westward into the ice-free valleys on rafts of lake ice (Clayton-Greene et al. 1988; Hall et al. 2001). Processes presently occurring at Trough Lake are a modern analogue (Fig. 51; Hendy et al. 2000). Fine-grained lacustrine facies are for the most part poorly exposed and/or preserved, hidden beneath coarser lacustrine drift or beneath surfaces armoured by cobble and boulder lags.

Lake deposits locally entrain algal flakes and mats that can be dated by radiocarbon methods, or have concentrations of evaporites that can be dated by uranium series methods. Dating generally yields ages of either 190–130 ka or c. 24–6 ka, indicating that the grounded Ross Ice Sheet plugged the mouths of the valleys during the Middle Pleistocene and Late Pleistocene-Holocene (Clayton-Greene et al. 1988; Denton et al. 1989; Hall & Denton 2000b; Hall et al. 2001; Kelly et al. 2002). Whether the deposits are related to large, continuous bodies of water, or localised meltwater ponds, is controversial (Hall et al. 2002; Kelly et al. 2002; Bockheim & McLeod 2006; Atkins & Dickinson 2007). The presence of large glacial lakes would necessitate a considerable, and as yet unexplained, change in the water balance within the Dry Valleys (see Clayton-Greene et al. 1988; Hall et al. 2001, 2010). The Ross Sea lacustrine deposits are rich in McMurdo Volcanic Group lithologies, which have been carried up-valley well beyond the maximum extent of the grounded ice.

Deltaic deposits (**ue**) along the coast from Marble Point to Walcott Bay and on Brown Peninsula (Speden 1960; Hall & Denton 2002) are mapped at elevations up to 300 m above sea level, although only those below c. 20 m are marine. These deposits of sand, laminated silt and subordinate gravel were formed where meltwater streams carried alluvium into water ponded along the margins of the Koettlitz Glacier or Ross Ice Sheet, many at a time when the ice was considerably thicker than at present (Fig. 43). Some contain fossils including a free-swimming marine scallop (*Adamussium colbecki*), pieces of freshwater *Nostoc* sp. algae and starfish remains (Hall & Denton 2000a). Deltas have also formed where meltwater entered lakes in the Dry Valleys (Calkin 1964a), and deposits have been used to argue that these lakes were much more extensive than at present (Hall et al. 2001, 2002; Hall & Denton 2005). Where unmodified, deltaic deposits are flat-topped with steeply sloped fronts; modified landforms can only be distinguished from alluvial fans by the presence of stratified waterlaid silts or macrofossils. Deltaic deposits commonly lie buried beneath surface lags and cannot always be readily identified. Some fan units shown as deltaic on the map are therefore interpretive and may be in part alluvial.

Colluvium, scree, fans, alluvium and aeolian deposits

Colluvium and scree (talus) (**uc**) mantles most slopes in the Dry Valleys and many surfaces of volcanoes around McMurdo Sound (Fig. 52). The deposits range from clast-supported angular boulders with little matrix, to subrounded cobbles in a sandy matrix, forming a thin veneer over basement rocks and in places covering till and other surficial deposits. Clasts commonly bear desert polish and ventifact facets. Valley floor deposits are typically polymict, but they tend to become more monomict higher on the hill slopes closer to their source. Dolerite commonly forms clast-supported scree that is vertically graded with coarser material at the base, whereas basement rocks and Beacon sandstone typically form sandy scree that may be cemented by ice or clay. Solifluction and gelifluction have modified large areas of colluvium, scree and till deposits. Patterned ground, where surficial deposits are dissected into polygons by interconnected troughs or cracks (Fig. 40), has been developed extensively by freeze/thaw action and ice wedges; different types are characteristic of the coastal, inland and upland climatic zones (Marchant & Head 2007). Patterned ground is particularly well developed on surfaces near retreating snow or ice fronts, and is least developed or absent on very old surfaces. Although not differentiated on this map due to its widespread occurrence, patterned ground is shown on several of the source maps (e.g. Woolfe et al 1989; Allibone et al. 1991; Pocknall et al. 1994; Turnbull et al 1994; Isaac et al 1996). **Older colluvium** (**mc**) occurs in ice-free valleys of the Quartermain Mountains, western Asgard Range, and Coombs Hills (Marchant et al.1993a,b). It includes the Koenig and Monastery colluvium units of Marchant et al. (1993a,b). Older colluvium consists of highly weathered, poorly sorted diamicton, locally bright orange, composed predominantly of ventifacted cobbles in a sandy matrix. Older colluvium is up to a few metres thick, developed on the surfaces of old tills, but is discordant with, or truncated by, present surface topography. Its age is inferred from degree of modification and/or stratigraphic relationships with nearby tills and topography.

Strong winds transport loose surficial material, sandblast stones and outcrops, produce ventifacts and desert polish, and winnow deposits to leave armoured lag surfaces in the hyper-arid Antarctic landscape. **Dune sand and other aeolian deposits** (**ud**) have been mapped in the Victoria Valley, where there is an extensive belt of dunes and sand sheets covering about 4 km^2 near Lake Vida (Calkin 1974b). Individual dunes are up to 15 m high and 1 km long and comprise loose, well-sorted, fine to medium sand, with medium to coarse sand and granules in interdune hollows. The dunes are capable of moving at rates of 20 cm/day (Calkin 1964a; Selby et al. 1974). Surface bed forms and climbing ripples show the predominant wind directions. Snow has become interlayered with sand and turned to ice within the dunes, and frozen internal dune structures may provide paleoclimate information. Victoria Valley dunes are blown and shaped by prevailing easterlies during the summer, and reworked by stronger but less frequent katabatic winds from the west (Speirs et al. 2008). Smaller drifts of wind-blown sand are mapped in the Wright and upper Taylor valleys, but there are many other deposits in the Dry Valleys too small to be individually distinguished from underlying colluvium or till. Aeolian transport in close proximity to ice-free areas tends to be dominated by movement of sand, whereas sites on ice-covered lakes and glaciers are dominated by transport of silt and clay (Lancaster 2002). Northward transport of fine-grained sediment from the McMurdo volcanoes and supraglacial till on the ice shelf contributes significantly to sedimentation in the Ross Sea (Atkins & Dunbar 2009).

Meltwater streams and rivers are intermittently active in most of the Dry Valleys for a short period in summer. **Alluvium** (**ua**) is present as gravel ribbons along the active stream channels, the most extensive being along the Onyx River in the Wright Valley (Fig. 50). The deposits range from well-sorted gritty sand to poorly sorted coarse gravels, and are frozen during all but the warmest periods of the day. Alluvium is associated with both aggradational and degradational terrace surfaces, depending on local changes in base levels caused by shifting glaciers and changing lake levels. Alluvial and colluvial **fan deposits** (**uf**) are present on the sides of volcanoes and valleys, typically beneath gullies or meltwater drainage channels (Fig. 50). Gelifluction debris lobes and debris flow deposits are included within fan deposits. Fan and alluvium deposits may grade into deltaic deposits where meltwater streams have entered lakes and the Ross Sea. Surficial deposits of unclear origin, or inferred from aerial photographs or satellite imagery, have been mapped as **undifferentiated cover** (**u**).

Coastal deposits

Deposits of **lithified grit and diamictite** (**mw**) have been found around the margins of the Koettlitz Glacier. At Gandalf Ridge, on the northern flank of Mt Morning, a chaotic lithified deposit of matrix-supported volcanic and sedimentary blocks is intruded by younger McMurdo Volcanic Group dikes and crosscut by north-south trending faults (Martin & Cooper 2010). The deposit occurs around 300 m above sea-level. Nearby outcrops of granitoid rocks suggest that the sediments either rest unconformably on basement, or are very close to this unconformity. Individual blocks (up to four metres in diameter) of bedded volcaniclastic sandstone and more common mugearite are randomly oriented. The deposit has been interpreted as an olistostrome (Martin & Cooper 2010), although earlier

Figure 52 Colluvium and scree are present throughout the Dry Valleys, mantling most moderate to steep slopes. These screes in the south branch of the upper Wright Valley show compositional variation where different rock types feed talus onto the slopes (granite - pink, dolerite - dark brown or black, schist and orthogneiss - grey). A local rock glacier till that occupies the floor of the valley, to the left of Don Juan Pond, also shows some compositional variation reflecting the distribution of different rock types above. Don Juan Pond contains saturated calcium chloride brine that does not freeze, even in winter (Photo: A. Apse).

work described it as a mud or maar volcano, or diamictite (Muncy 1979; Kyle & Muncy 1989). An Early Miocene age of deposition is constrained by a dated mugearite block within the deposit at 18.7 ± 0.3 Ma, and the emplacement of a cross-cutting felsic dike at 17.6 ± 0.6 Ma (Martin & Cooper 2010).

On the west side of Walcott Bay, the Howchin Glacier meltwater channel exposes indurated volcaniclastic grit interlayered with diamictite in a series of outcrops between 100 and 300 m elevation (Fig. 53). These grits are found as channel deposits up to 3 m thick, with 1–10 cm eastward-prograding ripples and foresets, surrounded by diamictite that contains thrust and internal deformation textures indicating deposition by grounded ice. At one locality the grits are overlain by McMurdo Volcanic Group flows. The flows have yet to be dated, but have reversed magnetic polarity (therefore >781 ka) and are expected to be similar in age to nearby cinder cones and flows that range from 14 to 0.3 Ma (Wright & Kyle 1990h). Although as yet poorly understood, the deposits are of importance as potential correlatives of Miocene glaciomarine sedimentary cycles in the AND-1B drillhole (Naish et al. 2008), now uplifted and exposed onshore.

Beach and stranded marine deposits (ub) occur discontinuously along the west side of McMurdo Sound from Cape Ross to Granite Harbour (Butler 1999; Hall et al. 2004). Sea ice thrust features are prominent on south-facing beaches, which receive small waves from a relatively restricted fetch, whereas north-facing beaches have a greater degree of rounded material caused by larger storm waves and a greater marine influence (Butler 2001). Modern beaches not formed by storms consist of gently sloping sandy benches within about a metre of sea level. Scattered remains of seals, skuas, gastropods, starfish and scallops (*Adamussium colbecki*) are common. Storm benches with pavements of sorted cobbles and boulders, or wave-washed bedrock, can be found up to about four metres above sea level.

Stranded beach deposits, situated well above the present one-metre tidal range, have also been recognised along the west side of McMurdo Sound (Edgeworth David & Priestley

Figure 53 Meltwater from alpine glaciers around Walcott Bay has cut channels through Ross Sea 1 Drift, exposing vertical sections (up to 5 m) through older lithified grits and diamictites, and interlayered McMurdo Volcanic Group rocks. Top left: Indurated volcaniclastic grits in the stream below the Howchin Glacier. Top right: Grit containing pebble- to boulder-sized clasts of granitoid, schistose and volcanic rocks has been baked by an overlying basaltic flow in the same stream. Bottom left: Grey unconsolidated diamictite (Ross Sea 1 Drift) overlies pale yellow massive diamictite, which overlies a McMurdo Volcanic Group flow and orange sandy diamictite. Stream section below the Walcott Glacier. Bottom right: The indurated pale yellow diamictite is matrix-supported and contains granite and basalt pebbles (Photos: S.C. Cox and D.B. Townsend. Visible part of walking pole in bottom right photo is 35 cm long).

1909; Priestley 1922; Nichols 1968; Hall et al. 2004) and at Cape Bird (Dochat et al. 2000). The most elevated are 34 m above sea level at Cape Ross but the marine limit appears to decrease in elevation southwards to about eight metres at Granite Harbour (Hall & Denton 2000a; Gardner et al. 2006). Beach deposits range from sandy, gravelly diamicton to large boulders, with most comprising clast-supported cobbles and boulders. Stranded beaches also contain *A. colbecki* shells, kelp, penguin remains and guano, seal and elephant seal remains, and some buried ice (Nichols 1968; Hall et al. 2004). The deposits appear have been formed during two or more time intervals (Gardner et al. 2006). Raised beach ridges terminate against the Wilson Piedmont Glacier at Kolich Point, Spike Cape and Cape Roberts and appear to extend beneath the ice, suggesting late Holocene advance of piedmont ice since beach formation (Nichols 1968; Hall & Denton 2002). Shells and elephant seal remains and penguin guano have yielded Holocene conventional radiocarbon ages as old as 7140 ^{14}C yr B.P. (Baroni & Orombelli 1994; Hall et al. 2004), but DNA analysis of penguin bones suggests that the uppermost deposits may pre-date the Holocene (Gardner et al. 2006). The stranded beach deposits help to constrain relative sea level curves and rates of isostatic and/or tectonic uplift, and the timing of deglaciation and grounded ice retreat in McMurdo Sound (Conway et al. 1999; Denton & Marchant 2000; Hall et al. 2004). Deposit emergence probably followed retreat of the Ross Ice Sheet grounding line in the middle to late Holocene, driven by unloading after about 6.5 ka (Hall & Denton 1999). The north-to-south tilt of the marine limit is not straightforward to interpret; it may have been influenced by unknown contributions of the Wilson Piedmont or Mackay glaciers, or a difference in ice-shelf calving front and grounding line positions in McMurdo Sound (Stuiver et al. 1981; Colhoun et al. 1992; Denton & Marchant 2000).

Marine deposits exposed onshore

Glacial erratic boulders of Eocene, Oligocene, Miocene and Pliocene sediments are found in coastal moraines around southern McMurdo Sound and at Cape Crozier (Harwood & Levy 2000). **Eocene erratics** (mapped as **oe** outcrops) contain a rich suite of fossil floras and faunas including marine and terrestrial palynomorphs, diatoms, edidians, marine vertebrates and invertebrates, terrestrial plants and bird remains, which date from Middle to Late Eocene, ~43–34Ma (Stilwell & Feldmann 2000). Eocene erratics are interpreted as relicts of fan deltas formed in a coastal setting in front of the rising Transantarctic Mountains, and now lying in sub-glacial basins beneath the Ross Ice Shelf such as the Discovery Deep (Fitzgerald 1992; Paulsen et al. 2011), although their exact provenance is not known. Significantly, no Eocene erratics of diamictite or mudstone with dropstones have been found. The erratic boulders provide an important window on the temperate-warm environment when "Greenhouse Earth" conditions prevailed prior to ice sheet development. Miocene diamictite and mudstone have been found at Minna Bluff (Harwood & Levy 2000) but have not been distinguished on the map.

The **Jason Glaciomarine Diamicton** (**mtj**; Prentice 1985; Prentice et al. 1993) crops out in the Wright Valley and was intercepted beneath Lake Vanda in the DVDP-4 drillhole. Comprising weathered coarse silt to fine sand, with scattered cobbles and pebbles and coarse sand interbeds, the diamicton has been subjected to shearing and soft-sediment deformation. It contains marine diatoms and unidentified shell fragments, the latter returning a 9 ± 1.5 Ma Sr isotope age (Prentice et al. 1993). Other small outcrops of glaciomarine diamicton that occur in the Wright Valley (including the Onyx Pond Diamicton and Heimdall Glaciomarine Diamicton; Turnbull et al. 1994) have been included in **mtj**, but may be of distinctly different age (Prentice et al. 1993). **Prospect Formation** (**mp**) has been mapped only at Prospect Mesa, below Bull Pass in the Wright Valley, where there are small outcrops of brownish grey sandy gravel and pale yellow pebbly mud (Fig. 54) that were deposited as subaqueous sediment flows into a marine fjord (Vucetich & Topping 1972; Webb 1972, 1974). The fauna includes benthic foraminifera, sponge spicules, diatoms, and the distinctive pectinid bivalve *Chlamys tuftsensis* (Turner 1967; Buckeridge 1989). Prospect Formation includes the **Pecten Gravels Member** (not distinguished on map face) interbedded within the glaciomarine diamicton. The age of the formation is c. 3–2.5 Ma based on diatoms, although ^{87}Sr/^{86}Sr ratios from shell carbonate suggest an age of 5.5 ± 0.4 Ma (Prentice et al. 1993). Although of limited lateral extent and thickness (<6–7 m thick), the formation is significant as an indicator that conditions in the latest Miocene to Early Pliocene were

Figure 54 Fossiliferous Pecten Gravels Member of the Prospect Formation at Prospect Mesa, Wright Valley (Photo: I.M. Turnbull. Hammer head is 18 cm across).

Climate History

Over the past 30 years several drilling projects have successfully recovered core from locations across the McMurdo Sound region, including the Dry Valleys (Barrett 2009). Compared with outcrop geology, drilling provides more continuous geological records of lithology, fossils, isotopes and magnetostratigraphy, from which climate records can be derived. Outcrop geology contributes a geographical context and spatial extent that is missing from drilling records. A combined history of ice sheet response to global climate variability can be derived by combining observations from various drillholes and surface deposits (e.g. Levy et al. 2012).

The onset of glaciation is not well constrained, but from the presence of lonestones in the CIROS-1 drill core it is known that glaciers, although not necessarily ice sheets, were locally present at sea level by Late Eocene time. CIROS-1 and CRP cores show that during the Oligocene and Early Miocene the Victoria Land coast was characterised by piedmont glaciers fed from an early East Antarctic Ice Sheet, depositing glacial debris offshore during glacial periods and braided outwash plains on land during interglacial times (Naish et al. 2001; Barrett 2007). Fragmentary records of these times, when the mountains were lower, have also been found on land as the high-elevation Sirius Group and other deposits (e.g. Hicock et al. 2003; Lewis et al. 2007, 2011). Contemporaneous palynomorphs from drill cores suggest that a low-diversity scrubby vegetation, including Nothofagus *and conifers, persisted locally under cool conditions (summer temperatures of 4° to 12°C) through the Oligocene and Early Miocene (Prebble et al. 2006; Francis et al. 2009; Ashworth & Lewis 2011).* Nothofagus *leaves have also been found in drill cores from both Early Oligocene (CRP-3; Cantrill 2001) and Early Miocene (CIROS-1; Hill 1989) intervals.*

A mid-Miocene "climatic optimum" is suggested at ~17–15 Ma from the deep sea isotope record (Holbourn et al. 2007), but the ANDRILL-2A core from 20 to 15 Ma suggests periods of more or less ice with superimposed oscillation of the ice margin at Milankovitch frequencies (Fielding et al. 2011). Geochemical proxies indicate summer temperatures around 7°C (Feakins et al. 2012). The core shows a brief period of unusual warmth at 15.7 Ma (Warny et al. 2009). On-land studies report evidence of subglacial meltwater and erosive outburst floods scouring channel landforms and producing scablands between ~14 and 12 Ma (Denton & Sugden 2005; Lewis et al. 2006). Local alpine glaciers deposited wet-based glacial tills, and tundra communities inhabited the mountains until ~14 Ma, when glaciers close to the ice margin became dry-based (Denton et al. 1993; Marchant et al. 1993a,b; Lewis et al. 2008). This change coincides with the dramatic deep-sea oxygen isotope shift at 13.6 Ma indicating cooling and/or ice growth (Shevenell et al. 2004), and was followed by a period of significant ice sheet expansion (Haywood et al. 2009).

The latest Miocene to earliest Pliocene (~10–4.8 Ma) was generally characterised by a climate that was warmer than present, with wet-based outlet glaciers delivering sediment-laden meltwater plumes into the Ross Sea, similar to current sedimentation off the coast of East Greenland (McKay et al. 2009). Glacial/interglacial cycles at ~40 ka intervals continued to generate advance and retreat of the ice in McMurdo Sound, although earlier uplift of the Transantarctic Mountains had caused the outlet glaciers to withdraw from the Dry Valleys for extensive periods, creating fjords within them (Levy et al. 2012).

The Early Pliocene (4.8–3.5 Ma) included a period of warmth when the glaciers rarely advanced into McMurdo Sound. Outlet glaciers, such as the Mackay to the north and the Skelton to the south, are thought to have been wet-based and fast-flowing. During Pliocene interglacials, rates of erosion and supply of detritus into the Ross Sea diminished, and increased deposition of diatomites is observed in the AND-1B drill core (McKay et al. 2012). Early Pliocene moraines indicate that alpine glaciers were much more extensive than at present, but dry-based. Glacial/interglacial cycles continued during the Late Pliocene to Early Pleistocene (3.5–1.5 Ma), when the outlet glaciers became colder with reduced melt water, low elevation terrestrial environments became more arid, and cold dry-based alpine glaciers deposited sand-rich glacial drifts.

During the Early Pleistocene (1.5 Ma) the duration of interglacial cycles decreased and the climate cooled as it became less sensitive to obliquity modulation of incoming solar radiation. A semi-permanent fringe of land-fast sea ice persisted through most interglacial periods and the Ross Ice Sheet became a relatively constant feature. By about 800 ka the present style of climate variability was established, in which the ice sheets respond to 100 ka eccentricity-paced climate variability (McKay et al. 2012). The onshore glacial setting changed from a predominance of valley or outlet glaciers, to a predominance of invasions of ice by an expanded and thickened Ross Ice Sheet, which may in part have been triggered by falling sea level. Grounded lobes of the Ross Ice Sheet have entered the Dry Valleys on at least eight occasions, damming the valleys to produce large lake systems. The complex interfingering of the outlet and alpine glaciers with the Ross Ice Sheet reflects differing response of these glacial systems to local precipitation and global climate change, but is still not fully understood.

warmer than at present, with a fjord occupying the Wright Valley (Webb 1972). Debate continues regarding the degree of soft-sediment slumping, age, and paleoclimatic significance of the Prospect Formation (Hall et al. 1993, 1997; Prentice et al. 1993; Jonkers 1998; Prentice & Krusic 2005; Levy et al. 2012). Early Pliocene fjord sediments have also been recovered from the DVDP-10 and DVDP-11 drillholes in the Taylor Valley (Fielding et al. 2010; Ohneiser & Wilson 2012), and from CIROS-2 offshore from the Ferrar Glacier (see **opl** on cross section, and Offshore geology below).

In contrast to the restricted marine macrofauna of the Prospect Formation in the Wright Valley, much more richly macrofossiliferous sediments occur around the shores of McMurdo Sound, both as *in situ* deposits and as glacial erratics (Harwood & Levy 2000). Some of the more significant **Pliocene-Pleistocene deposits and erratics** (**op**) are shown on the map as outcrops and include the **Scallop Hill Formation** (**ops**) of Late Pliocene age, although these may not be *in situ* (Speden 1962; Leckie & Webb 1982). The much younger Taylor Formation, of probable Holocene age (Buckeridge 1989; Speden 1962), comprises unconsolidated marine sediments that include both shallow and deep (>220 m) water facies. These sediments have probably been incorporated from the floor of McMurdo Sound into the Ross Ice Sheet then carried to the surface by ablation. Taylor Formation erratics have not been mapped.

Offshore geology

Apart from some scattered erratic boulders, there is no terrestrial geological record in southern Victoria Land from Early Jurassic, when Ferrar magmatism ended, to Early Miocene, when the first eruptions of the McMurdo Volcanic Group began. About 150 million years of history are missing, during which ice sheets developed and the Transantarctic Mountains were uplifted. The lack of onshore strata reflects the prevalence of major erosional episodes and large expanses of ice. In contrast, widespread deposition offshore has resulted in a more complete geological record, which includes effects of ice sheet oscillations and associated oceanic variations, and formation of the Victoria Land Basin and associated rift-related volcanism.

A geophysical survey of the Victoria Land Basin (Fig. 55) in 1984 suggested that it contained up to 14 km of sediments of Cretaceous and younger age (Cooper et al. 1987b). Further

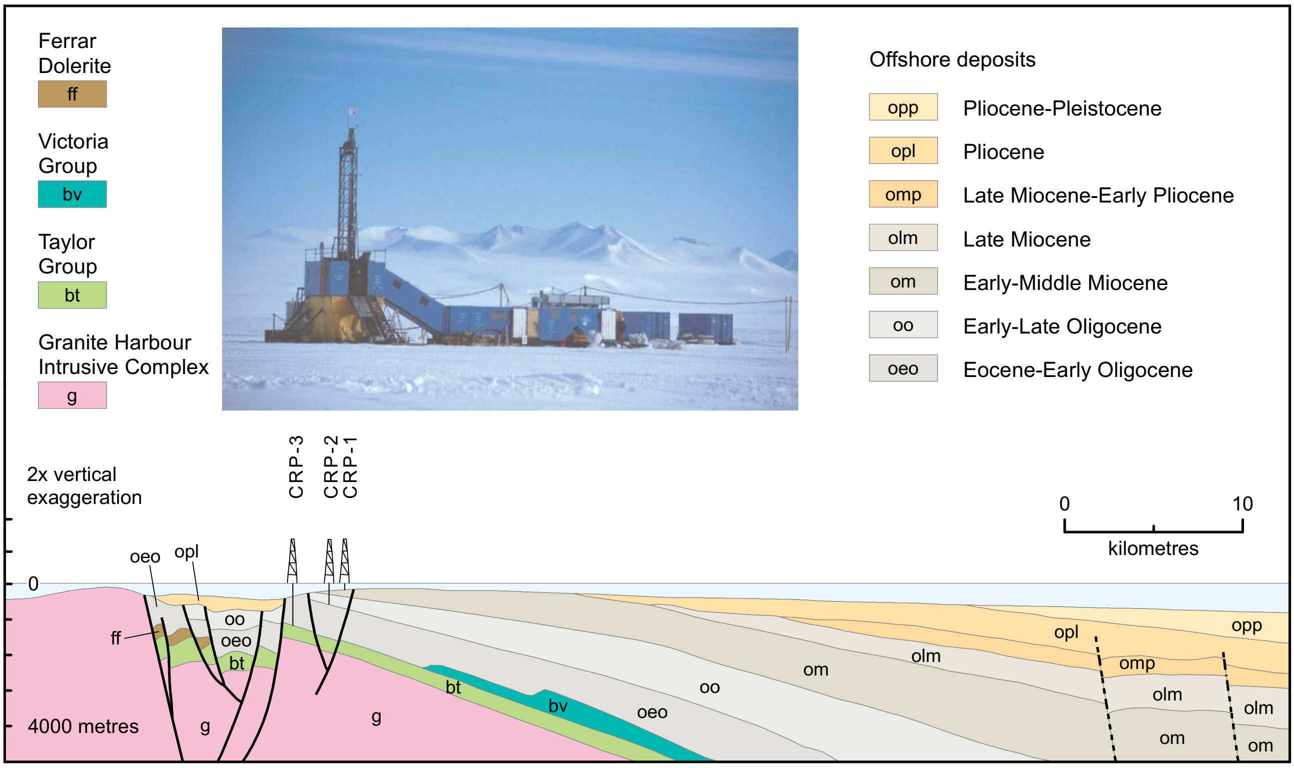


Figure 55 During the austral summers of 1997–1999, the Cape Roberts Project drilled at three sites for a composite Cenozoic section of ~1500 m on the western margin of the Victoria Land Basin. Situated ten kilometres offshore, above a local basement high and bathymetric ridge, CRP-3 (pictured) drilled 942 m below the sea floor (water depth 305 m) through a sequence of predominantly Early Oligocene sediment, and reached Beacon Supergroup strata (Photo: P.J. Barrett). The CRP-2 and CRP-1 drillholes, situated further offshore, sampled progressively younger parts of the sequence. Together the drillholes provide a record of 46 unconformity-bound, Oligocene to Early Miocene glaciomarine cycles (Barrett 2007). The cross-section in a west-east direction offshore from Cape Roberts, with vertical exaggeration x2, shows a local graben structure associated with normal fault rifting along the coast, the position of the drillholes, and the seaward-thickening wedge of Cenozoic strata accumulated in the Victoria Land Basin (after Cooper et al. 1987b; Cape Roberts Science Team 1998a; Fielding et al. 2008a).

surveys have confirmed the thickness and revealed details of the basin geometry (Fielding et al. 2008b), but drilling close to the margin indicates that the oldest Cenozoic unit there is a Late Eocene conglomerate resting on Devonian Taylor Group sandstone (Barrett 2007). Basin evolution, inferred from seismic stratigraphy and drilling, is described below in terms of five key intervals identified by Fielding et al. (2008b):

- Eocene-Early Oligocene (Early rift)
- Early Oligocene-Early Miocene (Main rift)
- Early-Middle Miocene (Passive thermal subsidence)
- Late Miocene-Early Pliocene (Renewed rifting – lower Terror Rift)
- Pliocene-Pleistocene (Continued rifting – upper Terror Rift)

The offshore sequence is shown on the geological cross-section, and in Figure 55.

Eocene-Early Oligocene (Early rift)

The oldest offshore sedimentary sequence imaged by seismic surveys in McMurdo Sound is an **Eocene-Early Oligocene sequence** (**oeo**) that is deeply buried and for the most part poorly known. It approaches the sea floor towards the western margin of McMurdo Sound, where parts of the sequence have been intercepted by CIROS-1, the lower part of CRP-2A and the CRP-3 drillholes (Fig. 55). Basal conglomerate and breccia-dominated intervals are overlain by cyclic marine sandstone-mudstone sedimentary successions of Eocene to Early Oligocene age (c. 36–29 Ma), with diamictite appearing in the cycles at ~ 33 Ma. The oldest sediments intercepted by drilling are Late Eocene (CIROS 1; Barrett 1989; Wilson et al. 1998), though Cooper et al. (1987a,b) speculated that older strata might be found in other parts of the western Ross Sea and mid-late Eocene erratics are well known around the shores of southern McMurdo Sound (Wilson 2000). Lonestones in the oldest drill cores indicate that glaciers, although not necessarily continental ice-sheets, were calving at sea level by Late Eocene time. Events between the initiation of Transantarctic Mountains denudation at c. 55 Ma and the onset of Antarctic continent-wide glaciation at ~34 Ma, more evident from deep sea records and Prydz Bay than coastal Victoria Land, are not yet understood.

Early-Late Oligocene (Main rift)

A regionally extensive offshore **Early-Late Oligocene sequence** (**oo**) thickens significantly through the centre of McMurdo Sound and contains clinoform geometries that suggest deposition associated with west-to-east offshore progradation. This sequence is deeply buried, except in the west of McMurdo Sound; where intercepted by drilling (MSSTS-1, CIROS-1, CRP-2A), it ranges in age from 29 to 23 Ma. It is interpreted as the main rift interval of the Victoria Land Basin (Fielding et al. 2008a) and comprises well-developed cycles of diamictite, mudstone, stratified sandstone and siltstone, typical of nearshore sedimentation with glacioeustatic sea level changes. Deformational textures show that ice was locally grounded above the drill sites.

Early-Middle Miocene (Passive thermal subsidence)

A continuous sheet-like **Early-Middle Miocene sequence** (**om**) is visible in seismic data throughout McMurdo Sound and has been sampled in a number of drillholes (including CRP-1, CRP-2, MSSTS-1, AND-1B and AND-2A; Fig. 55). Lithologies are diverse, with diamictite interlayered with mudstone containing ice-rafted debris, sandstone and conglomerate. Seismic reflectors within and at the top of the sequence appear to correlate with disconformities recorded from the drillholes. The sequence is thought to be Early to Middle Miocene in age (23–c. 13 Ma; Fielding et al. 2008b; Naish et al. 2008) on the basis of radiometric, biostratigraphic and magnetostratigraphic age control. Seismic data show channelling and clinoform sets with variable directions of progradation. Sediment cycles at 10–20 m thick are condensed, incomplete and commonly top-truncated. The sequence has been interpreted to represent deposition on a marine shelf, influenced by glacial advance-retreat cycles and ice that was locally grounded. Ice margin oscillations were at orbital frequencies (Naish et al. 2001), concomitant with sea level fall and rise (Dunbar et al. 2008). Sediment supply kept the Victoria Land Basin close to sea level as it underwent passive thermal subsidence (Fielding et al. 2008a).

Late Miocene-Early Pliocene (Renewed rifting)

A **Late Miocene sequence** (**olm**) in McMurdo Sound, defined by seismic data, contains parallel reflections suggesting a relatively homoclinal sedimentary package that underlies a major basin-wide angular unconformity (Fielding et al. 2008a). The sequence is thickest near Ross Island. It was intersected by AND-1B, where it comprises several hundred metres of Late Miocene diamictite-mudstone and sandstone-conglomerate-mudstone cycles (13–c. 7.6 Ma; Naish et al. 2008). The facies changes are interpreted to represent phases of ice-sheet growth across the drill site, then retreat and open marine deposition during renewed rifting activity in the Victoria Land Basin (lower "Terror Rift"; Fielding et al. 2008a). The top of the sequence is thought to represent the effects of tectonic uplift along the western margin of the basin.

A **Late Miocene-Early Pliocene sequence** (**omp**), also defined by seismic data, contains regionally onlapping high-amplitude reflections on the western side of McMurdo Sound and conformable reflections in the east. The unit tapers to the east, and thickens to several hundred metres close to Ross Island. Here the sequence was intersected by AND-1B and comprises Late Miocene lapilli tuff, a lava flow, and volcanic sandstone and mudstone thought to be proximal turbidites from a nearby active volcanic centre, overlain by Early Pliocene diamictite/diatomite sedimentary cycles. Rocks from the volcanic centre at White Island have been identified at this stratigraphic level (Fielding at al. 2008a). Biostratigraphic dating of samples from the CIROS-1 and MSSTS-1 drillholes indicates that the regional reflector taken as the top of this sequence is of Early Pliocene (4.6–4.0 Ma) age. Late Miocene-Early

Pliocene units intercepted in DVDP-10 and DVDP-11 record terrestrial glacial-interglacial cycles occurring near the McMurdo Sound coast, with diamictites passing up into diverse interbedded mudstone, sandstone, conglomerate and minor diatomite (Fielding et al. 2010).

Pliocene-Pleistocene (Continued rifting)

The offshore **Pliocene sequence** (**opl**) is another prominent eastward-thickening interval in McMurdo Sound. Characterised by large-scale clinoform sets, its internal geometry suggests progradation of a thick terrigenous clastic succession, possibly via deltas, into standing water (Fielding et al. 2008a). In AND-1B, the sequence includes several diatomite-dominated intervals, including a 76 m thick diatomite that indicates an extended period of high-productivity open water in this area (Naish et al. 2007a). The Pliocene sequence includes the oldest units intercepted in CIROS-2, where granitic gneiss is overlain by sandy mudstone containing a rich diatom flora that indicates open water at the mouth of the Ferrar valley at c. 4.7-4.4 Ma, in turn overlain by a lodgement till diamictite derived from the Ross Ice Sheet (Barrett & Hambrey 1992; Sandroni & Talarico 2006). Units beneath the Taylor Valley, intercepted by DVDP-10, 11 and 12, are mainly diamictons with minor interbedded conglomerate, sandstone and laminated muds (Fielding et al. 2010). Foraminiferal assemblages reflect relatively deep water deposition, requiring that the sediments have been uplifted (Levy et al. 2012).

A **Pliocene-Pleistocene sequence** (**opp**) overlies the oldest stratigraphic horizon that can be related to flexural loading by the Ross Island volcano, and incorporates the youngest sediments offshore up to the sea floor. The sequence is thickest around Ross Island and is locally very thin on the western side of McMurdo Sound, where it truncates older sediments. The base of the sequence is aged c. 3.5 Ma and coincides with a significant change to colder climatic conditions (Levy et al. 2012). AND-1B intercepted Late Pliocene-Early Pleistocene diamictite-diatomite sedimentary cycles, with a transition to volcaniclastic mudstone and sandstone in the upper part of the sequence. A similar transition occurs in CIROS-2, and may reflect aeolian sedimentation similar to that occurring on the McMurdo Ice Shelf today (Atkins & Dunbar 2009). Erosional relief on the modern sea floor, such as the valleys offshore from the Mackay and Ferrar glaciers, appears to have been cut into, and therefore post-dates, much of this Pliocene-Pleistocene sequence (Fielding et al. 2008a).

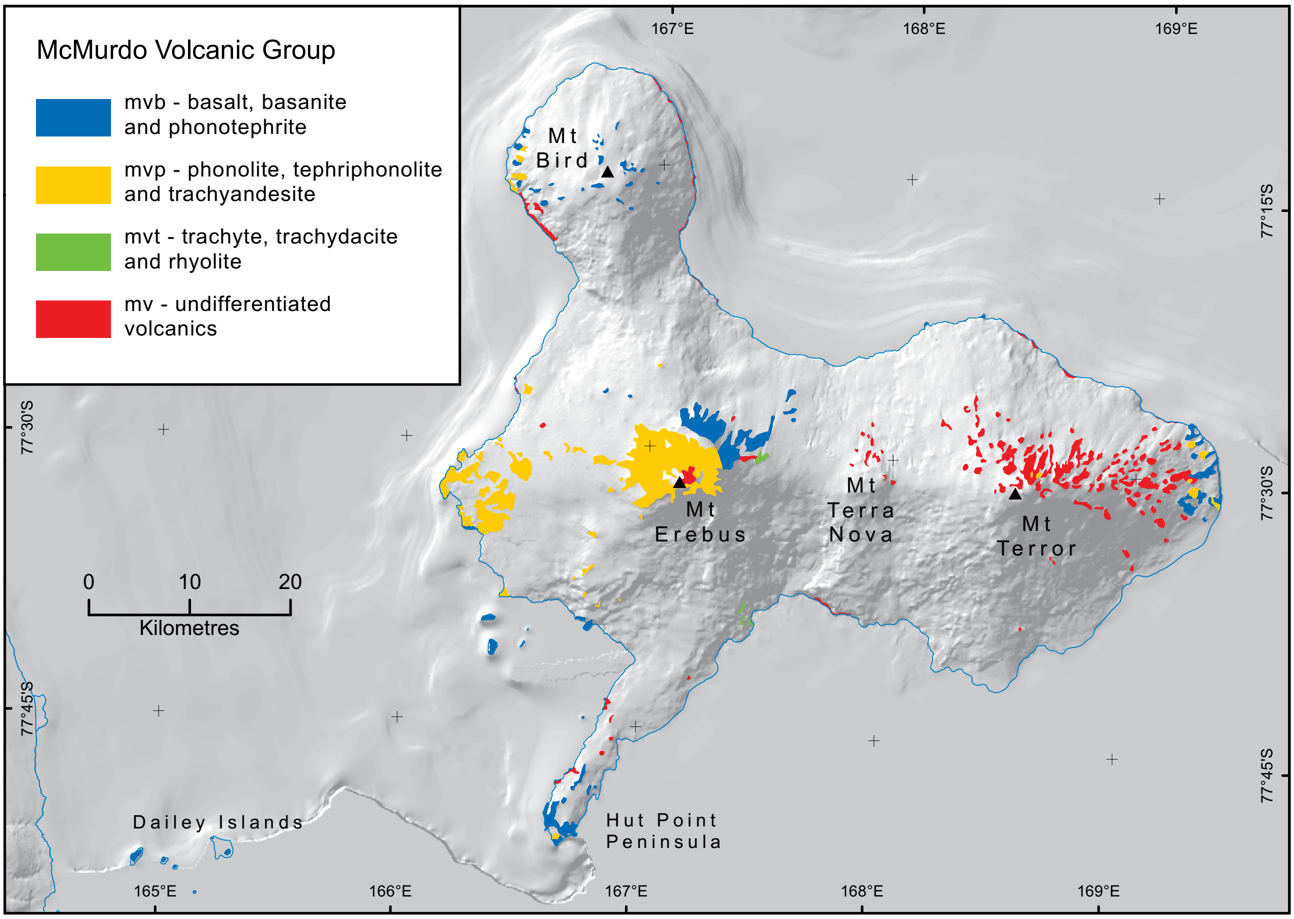
MIOCENE TO HOLOCENE VOLCANIC ROCKS

McMurdo Volcanic Group

Large and small Cenozoic volcanoes composed of mainly alkaline basaltic rocks are exposed along the flanks of the West Antarctic Rift System from the Adare Peninsula of northern Victoria Land to the Bellingshausen Sea (LeMasurier 1990). In southern Victoria Land these include the large volcanoes of Mt Bird, Mt Terror, Mt Terra Nova and Mt Erebus, which form Ross Island, and Mt Discovery and Mt Morning and the 45 km long Minna Bluff, which dominate southern McMurdo Sound. Many small volcanoes are present further west in the eastern foothills of the Royal Society Range and in the Taylor and Wright valleys. The Cenozoic volcanic rocks of the Ross Sea area in or adjacent to the Transantarctic Mountains were formally named the McMurdo Volcanic Group by Kyle (1990a), following Harrington (1958a); the Cenozoic volcanoes of the map area are a part of the Erebus volcanic province (Kyle & Cole 1974; Kyle 1990a).

Field studies have described McMurdo Volcanic Group rocks in relatively simple terms based on their composition, for example as dark mafic 'basalts' or lighter felsic 'trachytes', with modifiers according to their phenocryst content (for example, olivine basalt; e.g. Cole & Ewart 1968; Cole et al. 1971). This map relies upon previous work, and adopts a similarly simple lithological classification, subdividing flows, dikes, scoria cones, agglomerates and pyroclastics of the McMurdo Volcanic Group into units of ultrabasic to basic, intermediate, and acid composition: **mvb** – basalt, basanite and phonotephrite; **mvp** – phonolite, tephriphonolite and trachyandesite; **mvt** – trachyte, trachydacite and rhyolite. Small, but scientifically important, occurrences of distal ash are significant chronological markers and are shown as outcrops. **Undifferentiated McMurdo Volcanic Group** (**mv**) is mapped in areas where lithology has yet to be distinguished, or in places with complex compositional variation (Fig. 56). Volcanic rocks can also be named and classified more specifically using the relationship between combined alkali content (Na_2O + K_2O) and silica content (Fig. 57; after Le Bas et al. 1986). In this classification, McMurdo Volcanic Group lavas fall mostly in the basanite, phonotephrite, tephriphonolite, phonolite, or trachyte-rhyolite fields. The major volcanic centres cannot be distinguished compositionally, but a number of evolutionary trends or 'lineages' have been distinguished within each centre (e.g. Kyle 1990a; Kyle et al. 1992; Martin et al. 2010). 'DVDP' and 'Erebus' lineages are recognised on Ross Island based upon the presence or absence of kaersutite, respectively, which reflects varying water content of the magmas (Kyle 1981a; Kyle et al. 1992). Most of the McMurdo Volcanic Group has strongly alkaline compositions, but a distinctive mildly alkaline phase has been recognised at Mt Morning (Martin 2009) and Minna Bluff (Wright-Grassham 1987). It has been suggested that trachytic peralkaline rocks dominated volcanism from about 24 to about 11 Ma. Greater volumes of rock have been preserved in the last 11 million years and these have been almost exclusively basanitic to phonolitic (Kyle 1990a; Martin et al. 2010). The map depicts the predominant lithology at any one place, which is commonly the youngest overlying material at each volcanic centre.

McMurdo Volcanic Group rocks are locally rich in xenoliths, which include a variety of upper mantle-derived ultramafic nodules as well as supracrustal granulites (Fig. 58; Kyle et al. 1987; Gamble et al. 1988; Cox et al. 2000). Mineralogical and geochemical analyses of



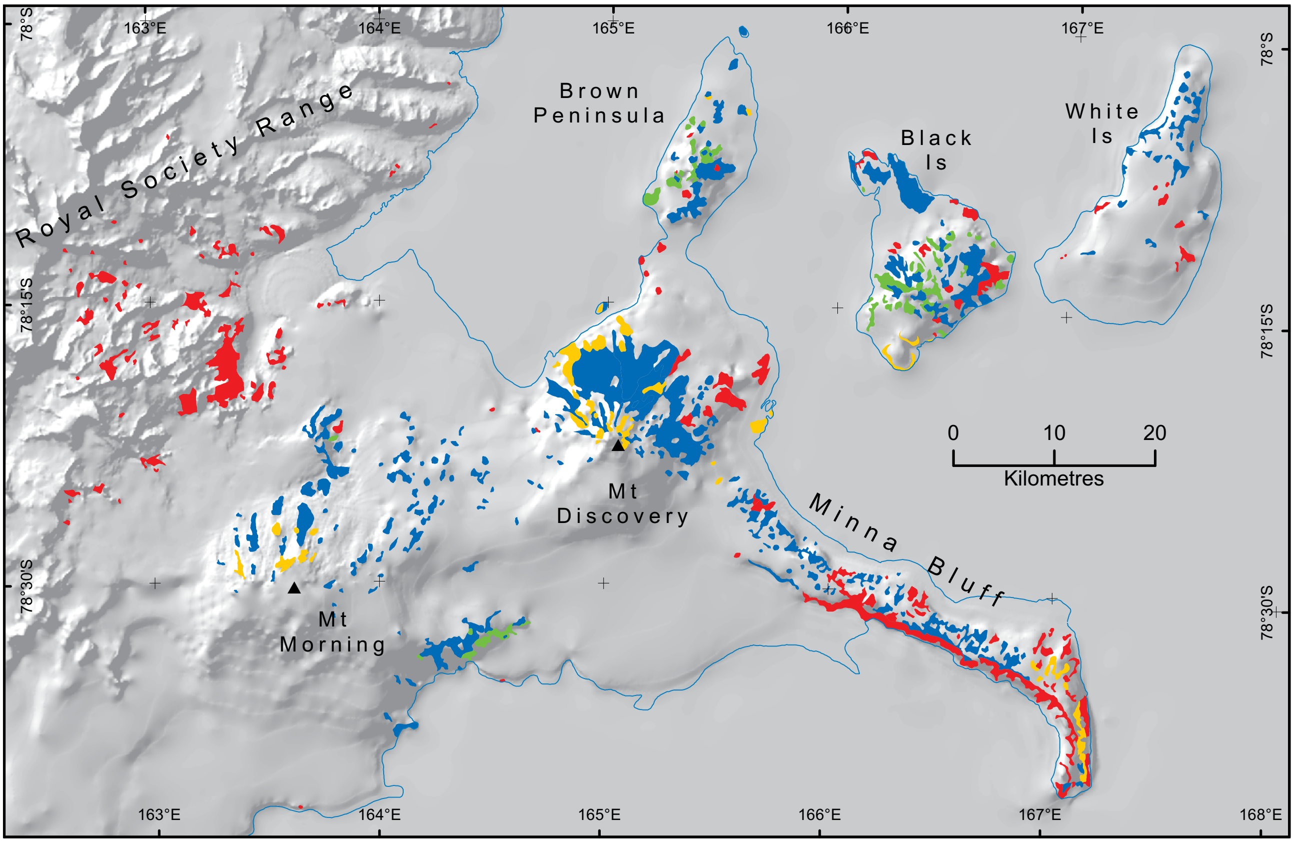


Figure 56 Derivative maps of the main volcanic centres in McMurdo Sound showing the distribution of different lithologies. Both maps were generated from the geological units layer in the digital GIS dataset.

granulite xenoliths indicate that the lower crust beneath the Transantarctic Mountains is significantly different in composition from that under the Ross Sea (Kalamarides et al. 1987).

The major volcanoes of Ross Island

Ross Island covers 2460 km², only a small part of which is ice-free. It comprises three major overlapping and abutting volcanoes, the largest of which is the active Mt Erebus (back cover). The only other active volcano in the McMurdo Volcanic Group is Mt Melbourne, in northern Victoria Land.

Mt Erebus, a polygenetic stratovolcano, is a broad shield surmounted by at least two cones (Esser et al. 2004; Kelly et al. 2008b). Older basanite and phonotephrite lavas that crop out in the remains of the initial cone at Fang Ridge and elsewhere on the flanks are overlain by voluminous flows of phonolitic lavas, commonly with abundant large phenocrysts of anorthoclase feldspar (Esser et al. 2004). Anorthoclase megacrysts are as large as 10 cm in length and may form 30% of the rock by volume (Kyle 1977; Dunbar et al. 1994).

The lower slopes of Mt Erebus dip relatively gently at 7° to 15° but above 2000 m the flanks dip at 30° to 40°. A plateau in the region of the summit is interpreted as a caldera filled with phonolite lavas (Fig. 59). The steep-sided summit cone has formed around the active vent of Main Crater, an elliptical pit up to 600 m across and over 100 m deep, and the inactive Side Crater. Within Main Crater is Inner Crater, a near circular pit 250 m in diameter and 100 m deep containing a lake of molten phonolite lava (Fig. 60; Kelly et al. 2008a), the site of frequent Strombolian eruptions (Giggenbach et al. 1973; Aster et al. 2003). Although high-temperature activity is restricted to the northern half of Inner Crater, towers of ice up to 15 m high are present in the summit plateau area, where escaping geothermal vapours are condensing and freezing (Lyon & Giggenbach 1974;

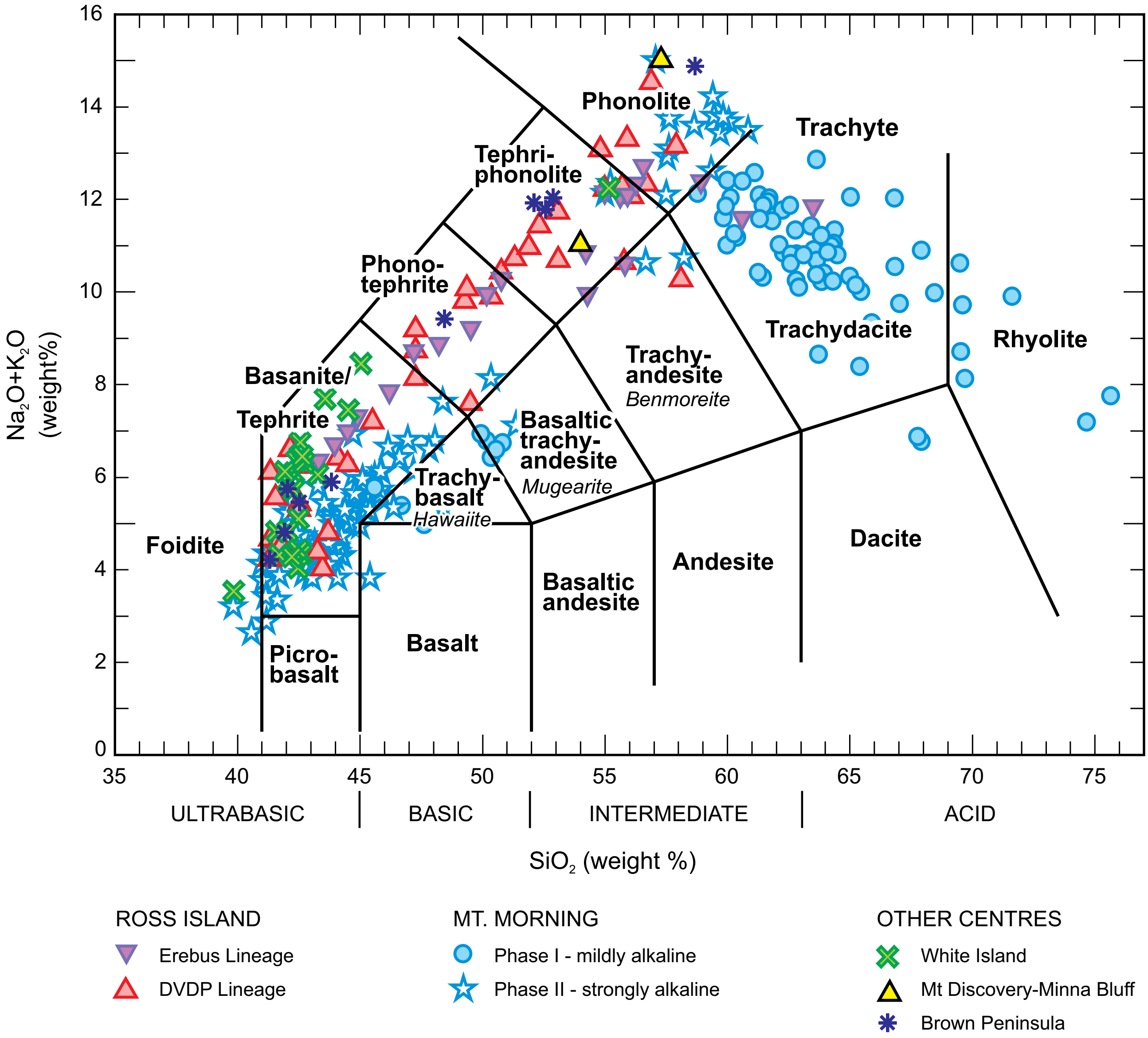
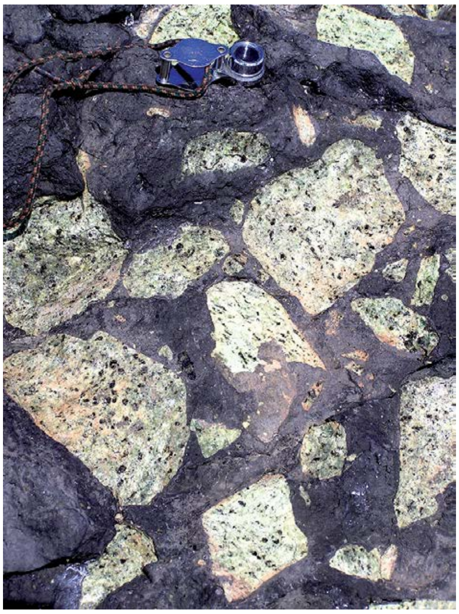


Figure 57 Compositional variation of McMurdo Volcanic Group, separated into Ross Island, Mount Morning and other volcanic centres, on the combined alkali vs silica compositional diagram (after Le Bas et al. 1986). Data sources: Cooper et al. (2007); Kyle et al. (1981, 1992); Martin (2009); McGinnis (1981); Wright-Grassham (1987).



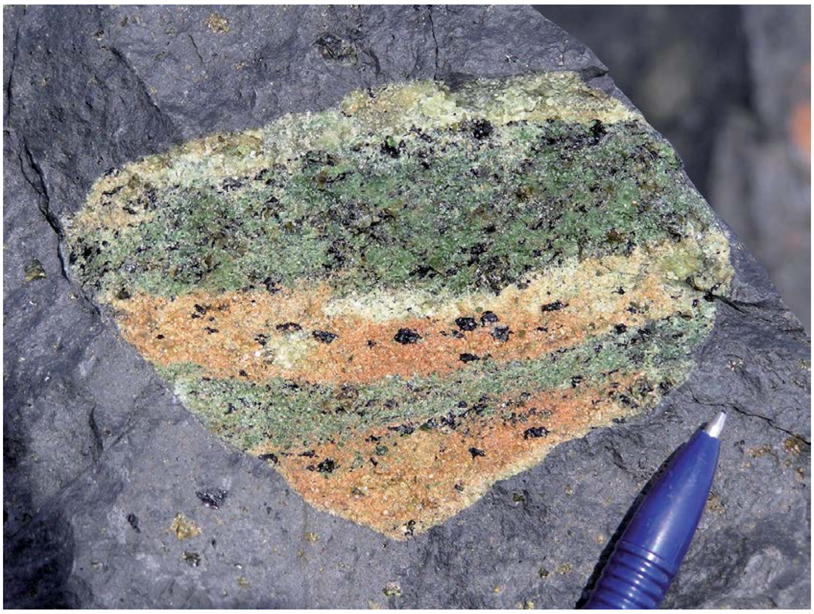


Figure 58 Upper mantle-derived xenoliths in a basanite dike, northern slopes of Mount Morning. Left: Angular peridotite nodules. Right: Metasomatised nodule with green clinopyroxene-rich layers replacing olivine. Large brown porphyroblasts in orange bands are orthopyroxene (Photos: A.F. Cooper. Hand lens is 5 cm long. Pen is c. 1 cm across).

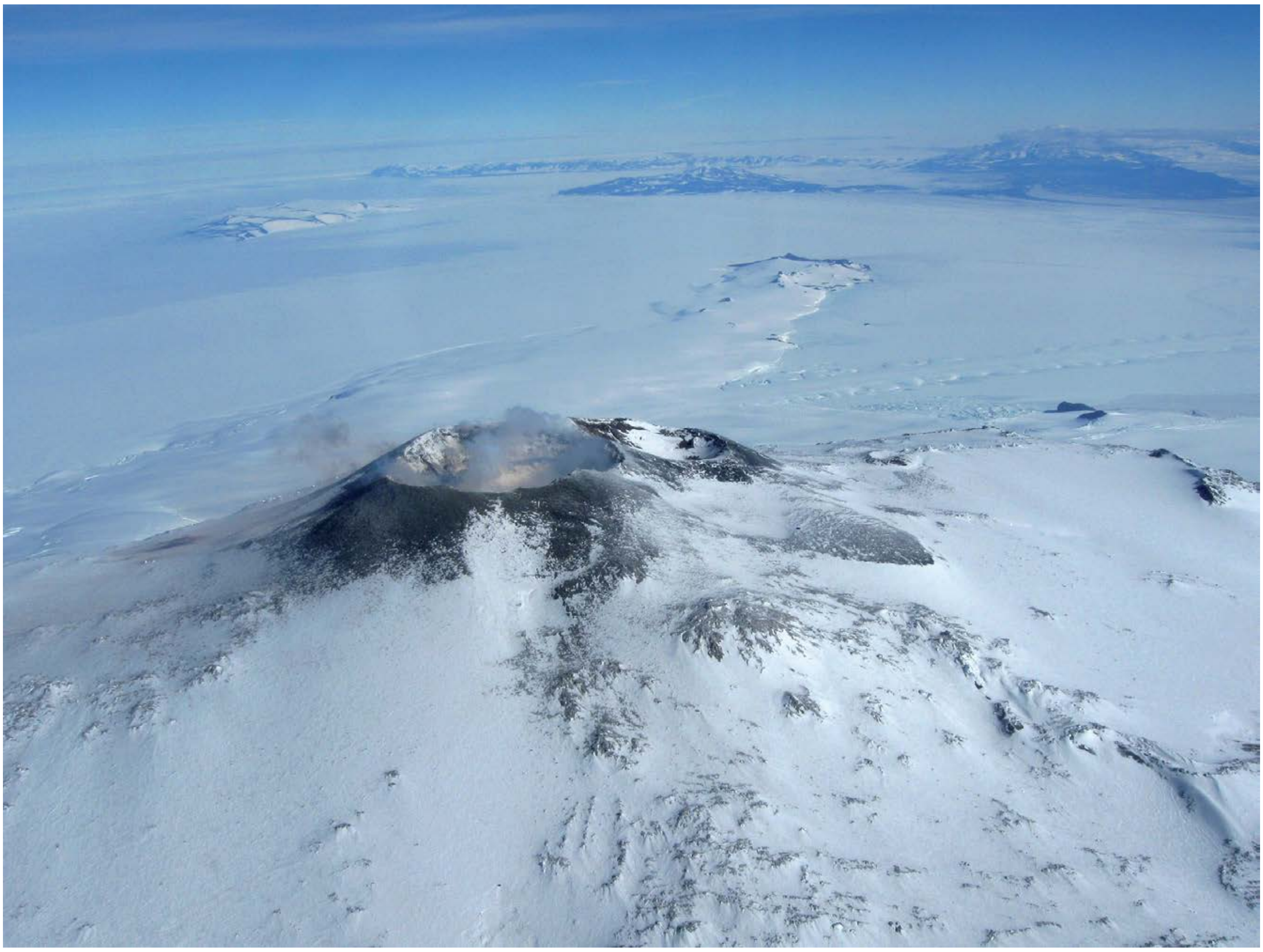


Figure 59 Aerial view of Mount Erebus (3794 m). Hut Point Peninsula juts out into southern McMurdo Sound (upper centre). Barely visible, extending at an angle to the right, is the Erebus Glacier ice tongue which floats out into McMurdo Sound and is surrounded by annual sea ice. In the distance, from left to right, are White Island, Minna Bluff, Black Island and Mount Discovery (Photo: N. Powell, National Science Foundation, Jan 2009).

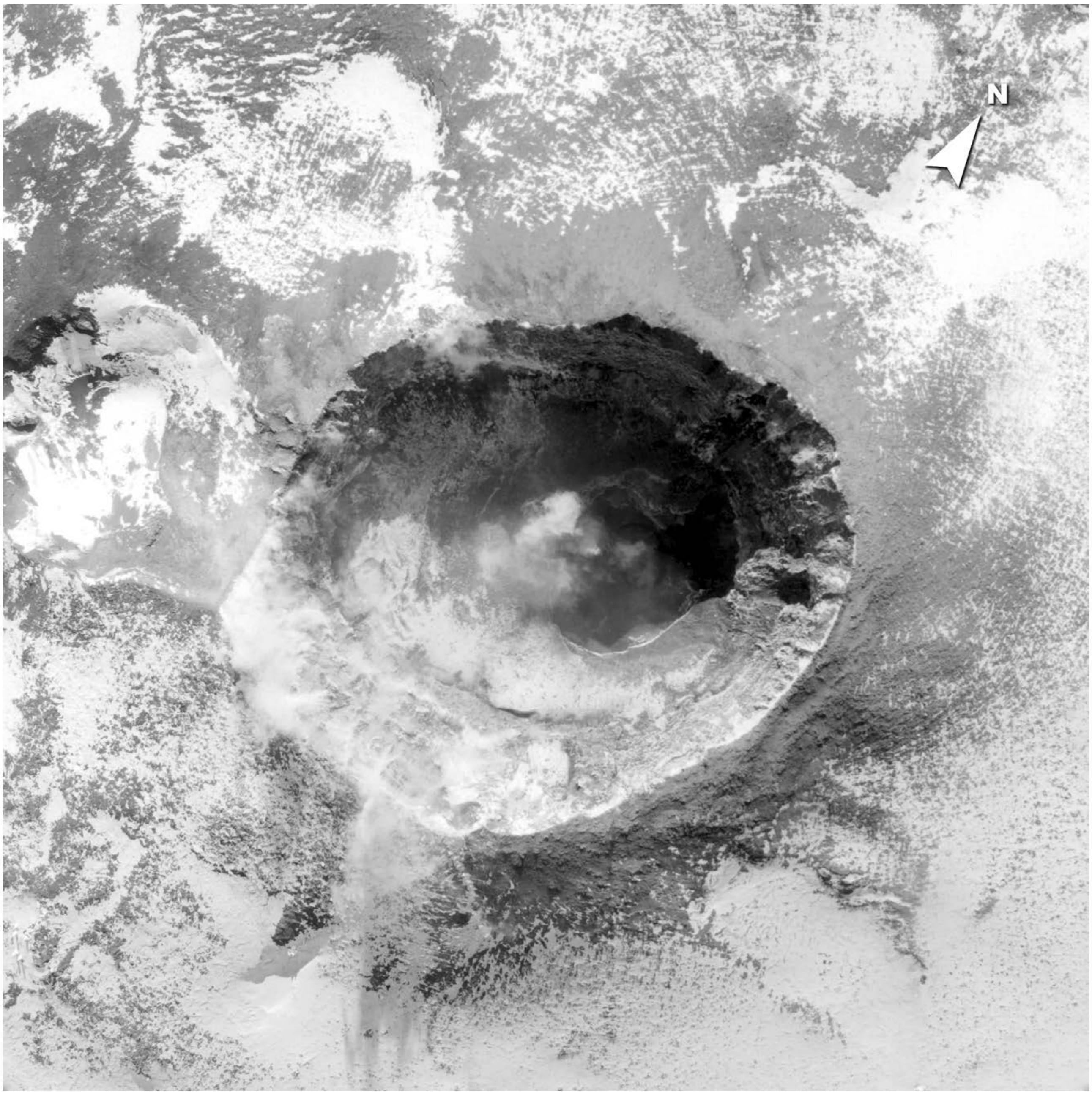


Figure 60 Mount Erebus. Top: Vertical aerial photograph of the summit area. A convecting anorthoclase phonolite lava lake is situated on the north side of Main Crater, which degasses in frequent small Strombolian eruptions. Main Crater is about 600 m across and 100 m deep, with a nearly flat floor. A series of flows capped by a pyroclastic breccia can be seen in the steep crater walls. Partially decomposed lava bombs and anorthoclase crystals are scattered around Main Crater. The smaller inactive Side Crater is visible to the west of Main Crater (Photo: US Navy, TMA 2508 V0144, Jan 1983). Bottom: Detailed view of the lava lake (Photo: C. Brian Smith/Hedgehog House).

Curtis & Kyle 2011). Areas of warm ground are present in the floor and rim of Main and Side craters, and on the northwest and southwest flanks up to 1.7 km from the main vent (Lyon & Giggenbach 1974).

The history of Erebus volcano has been described by Esser et al. (2004). Initial activity probably involved extrusion of lavas at the floor of the Ross Sea, and Ar-Ar dating has shown the shield-building phase of eruptions occurred between 1.3 and 1 million years ago. The first cone-building phase was punctuated by a catastrophic collapse or subsidence event, which destroyed the summit of the proto-Erebus volcano and formed a large escarpment on the upper flank of the volcano, now represented by Fang Ridge. The collapse or subsidence post-dates the youngest Fang Ridge lavas (718 ka) and is inferred to have happened about 700 000 years ago. Smaller vents such as at Abbott Peak (531 ka), Turks Head (378 ka), and the Dellbridge Islands (539 ka), were active on the flanks and at the margins during the cone-building phase. The youngest phase of cone-building activity started about 250 000 years ago. Large volumes of anorthoclase-phyric tephriphonolite lavas have issued from vents at the summit and on the upper flanks. Mapping, Ar-Ar and Cl-cosmogenic ages of lava flows from the summit show that there have been two caldera collapse events, followed by lava infilling (Harpel et al. 2004; Kelly et al. 2008b).

Ross Island has one of the world's few known occurrences of anorthoclase-phyric phonolite, which closely resembles kenyte from the East African volcanoes Kenya and Kilimanjaro. The phonolite has exceptionally large rhomb-shaped phenocrysts of anorthoclase, and forms relatively young (90–32 ka; Esser et al. 1994) lava flows between Cape Royds and Cape Barne, as well as all lavas, the lava lake and recent ejecta at the Mt Erebus summit. It has been argued that feldspar-phyric erratics in the Ross Sea Drift of the Transantarctic Mountains, loosely referred to in the past as kenyte, were derived from Ross Island and can therefore constrain the flow of ice across McMurdo Sound (Kyle 1981b; Stuiver et al. 1981; Denton & Marchant 2000; but see p. 70, Ross Sea 1 Drift).

Northern Ross Island is formed by the large shield volcano of Mt Bird, the main cone of which comprises flows of Early Pliocene basanite lava, K-Ar dated at 4.6–3.8 Ma (Wright & Kyle 1990a). Eruptions at parasitic vents have formed cones and domes of basanite and phonolite. At least ten basaltic flows 1–8 m thick are well exposed in cliffs south of Cape Bird, and agglomerate and tuff occur locally. Well-bedded bright red basaltic scoria forms the small cone of Cinder Hill (Cole & Ewart 1968). Basaltic and phonolitic lavas from the Cape Bird area yield K-Ar ages in the range 3.7–3.0 Ma (Armstrong 1978). Eastern Ross Island is formed by the large basaltic shield volcano of Mt Terror, only a small part of which has been mapped geologically. Parasitic basaltic and phonolitic cones and domes are present on the flanks. Early Pleistocene Ar-Ar ages of 1.45–1.33 Ma (Lawrence et al. 2009) and K-Ar ages of 1.75–0.8 Ma (Armstrong 1978; Wright & Kyle 1990b) are reported from Cape Crozier. Mt Terra Nova is a mainly basaltic parasitic vent situated halfway between the high peaks of Terror and Erebus (Wright & Kyle 1990b).

Beaufort Island

Beaufort Island, 95 km ENE of Cape Roberts and 22 km north of Cape Bird, Ross Island, is the eroded and glaciated remnant of a tephrite and phonotephrite stratovolcano; the interlayered lavas, breccias and tuffs have been intruded by many dikes (Harrington 1958b; Ellerman & Kyle 1990).

Volcanic landforms of Hut Point Peninsula

Hut Point Peninsula extends SSW 25 km from the south flank of Mt Erebus and is typically 4–6 km wide, broader in the north. The peninsula comprises a series of coalesced, predominantly basaltic volcanic cones and lava flows, mainly covered by snow and ice except in the south. Intercalated basanite, tephriphonolite and phonotephrite lavas and pyroclastics intersected by the DVDP-1 and 2 drillholes in the vicinity of McMurdo Station have K-Ar ages in the range 1.34–1.16 Ma (Kyle 1981a,c). The drill site is stratigraphically overlain by the endogenous kaersutite phonolite dome of Observation Hill (1.18 Ma). Nearby Crater Hill has a summit crater 250 m long and 100 m across, elongated NNW-SSE. The northern flanks of Crater Hill are ice-covered, but basanite lava flows exposed at the surface radiate south and east from the summit area; they are crossed by the road between Scott Base and McMurdo Station. A basanite lava flow extending from a vent near the southern crater rim flows 1.4 km southeast to form Pram Point, on which Scott Base is built (Wellman 1964; Kyle 1990b).

Castle Rock is a steep-sided remnant tuff cone of basanite hyaloclastite formed by subaqueous eruption. A K-Ar date of 1.18 Ma has been determined on a feeder dike (Kyle 1981a, 1990b). Hills and slopes north of McMurdo Station are formed of young basanite lava flows and scoria cones; there are well preserved craters at Twin Crater and northern Arrival Heights (Wellman 1964; Kyle 1990b). K-Ar ages of 0.57 Ma and 0.43 Ma have been determined (Armstrong 1978). Ar-Ar ages for Hut Point Peninsula show that the youngest eruptions from Crater Hill and nearby vents were at 0.33 Ma, and 0.65 Ma at Breached Cone north of Scott Base (Lawrence et al. 2009).

Brown Peninsula, Black Island and White Island

The area south of the McMurdo Ice Shelf is dominated by the huge conical stratovolcano of Mt Discovery, but the glaciated and eroded inactive volcanoes of Brown Peninsula, Black Island and White Island are also prominent (Figs 56, 59). The first two are mainly ice-free and the latter mainly covered by snow and ice. Magnetic anomalies extending under the McMurdo Ice Shelf for 5–10 km southeast and northeast of Black Island and west of White Island show that lava flows continue beneath the ice shelf, and that the volcanic massifs are significantly larger than indicated by the present coastline (Wilson et al. 2007).

Brown Peninsula is formed of overlapping and abutting centres that have erupted basanitic, phonolitic and trachytic lavas. Trachyte flows cover much of the centre of the peninsula, radiating outward from several centres, and trachyte also forms small domes (Cole & Ewart 1968; Wright & Kyle 1990c). Fractional crystallisation appears to be the predominant process controlling the evolution of lavas, which have been erupted in three basaltic to phonolitic eruptive cycles (Kyle et al. 1979). The most extensive exposures of volcanic rock are about the high point of Mt Wise, a scoria cone with a crater almost a kilometre in diameter. Three K-Ar ages determined on basanite and trachyte flows from this area are in the range 2.25 to 2.1 Ma, suggesting that activity was short-lived (Armstrong 1978). The youngest flow at Rainbow Ridge (a trachyte) has been dated at 2.7 Ma (Armstrong 1978; Kyle et al. 1979). Small cones of basaltic scoria are present north and south of Mt Wise, at Frame Ridge, and in the area of Tuff Bluff. Outcrops of tuff are present south of Mt Wise, at Tuff Bluff, and near the northern tip of Brown Peninsula (Cole & Ewart 1968). The Dailey Islands, 15 km north of Brown Peninsula, comprise small, partly eroded cones of Middle Pleistocene basanite (Tauxe et al. 2004).

Cole & Ewart (1968) mapped intercalated basalt, trachybasalt and trachyte in the area of Mt Melania, in northern Black Island. Numerous domes, plugs and flows of trachyte are present in central Black Island and many flows radiate outward from the highest point (Mt Aurora). Isolated scoriaceous cones overlie the older trachytes. Radiometric dating indicates that Black Island erupted in the Late Miocene and Pliocene: a 10.9 Ma K-Ar age was determined for basalt from northern Black Island (Armstrong 1978); Ar-Ar ages of 9.02 and 7.26 Ma were reported for lavas at Mt Ochre by Lawrence et al. (2009); K-Ar ages of 3.8 Ma and 3.35 Ma have been obtained from trachyte and basalt collected east of Mt Aurora (Armstrong 1978); and an Ar-Ar age range of 1.8–1.7 Ma was obtained for phonolite at the southern tip of the island (Timms 2006). Black Island volcanic rocks have been severely modified by glacial erosion.

Cooper et al. (2007) have given a detailed account of the geology of White Island; they mapped 22 individual craters, the largest of which are close to the high points of Mt Heine and Mt Nipha. In the south, outcrop is limited to relatively small areas about a kilometre across. Vesicular basanite lavas are present at Mt Henderson and Mt Nesos, and at Camp Crater basanite lava includes abundant xenoliths of peridotite, wehrlite, gabbro, granulite and anorthoclasite. Pillow lava occurs at Mt Hayward. Bedded lapilli tuff and breccia form Mt Nipha and Isolation Point, in the southeast, and at Precision Point there are agglutinated spatter deposits of scoria and lava fragments, including lava bombs. The extensive exposures about and north of Mt Heine are of basanite lava flows, spatter breccias and lapilli tuffs. One K-Ar age of 0.17 Ma has been determined (Kyle 1981a) but Ar-Ar radiometric ages on basanites are significantly older (5.04–2.11 Ma; Cooper et al. 2007) and a U-Pb age on zircon in an anorthoclasite nodule extends the history of White Island magmatism back into the Late Miocene (7.65 ± 0.69 Ma; Cooper et al. 2007). Early volcanic activity is inferred to have been submarine and perhaps subglacial. The tuffs and lapilli tuffs could have been formed by volcanic eruptions through englacial lakes or in marine settings. Basanite lavas, scoria and spatter that form the shield volcano of northern White Island were erupted subaerially.

Minna Bluff

The narrow peninsula of Minna Bluff extends about 44 km ESE from the flank of Mt Discovery out into the Ross Ice Shelf, then trends south for a further 13 km (Fig. 49). The crest of its single ridge is in several places more than 1000 m high. The peninsula comprises many overlapping volcanic centres of Middle to Late Miocene age and more than 50 partially eroded subaerial domes and cinder cones have been identified (Wilch et al. 2008). Older phonolites and tephriphonolites are succeeded by volumetrically predominant basanite and phonotephrite (Wright & Kyle 1990d). In the lower part of the east-facing cliffs of "Minna Hook", intercalated subaerial lava and breccia, and thin subaqueous pillow lava and hyaloclastite, include undulating unconformities mantled with glacial and fluvial sediments. Higher in the section and in the southwest-facing cliffs are subaerial lavas, breccias and vent complexes. Ar-Ar ages indicate two closely spaced episodes of eruption (11.86–11.20 Ma and 10.5–8.18 Ma; Fargo et al. 2008).

Mount Discovery and Mount Morning

The two large composite volcanoes close to the margin of the Antarctic continent southwest from Ross Island are Mt Discovery and Mt Morning. Mt Discovery is prominent in the view from Hut Point but the more distant Mt Morning is obscured behind Brown Peninsula. Both volcanoes have large areas on their northern flanks which are free of snow and ice.

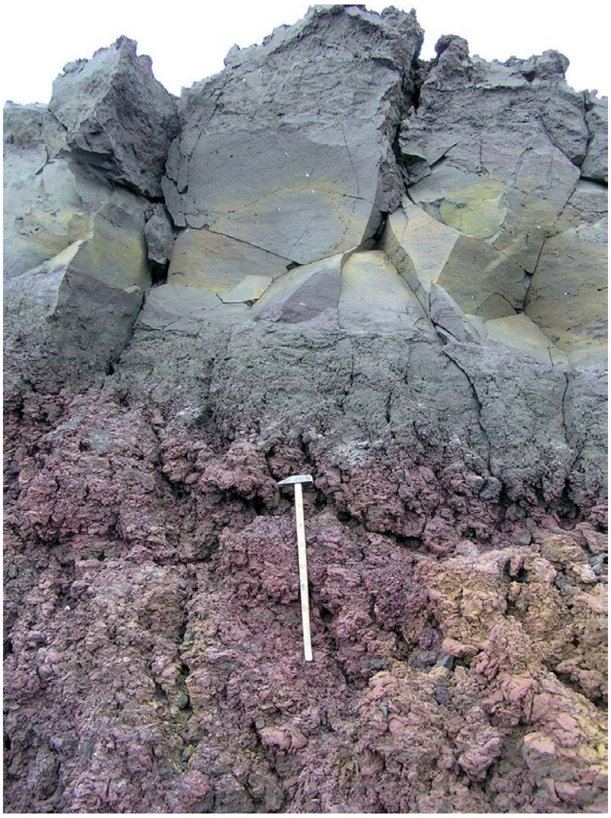
At sea level, Mt Discovery is 20 to 27 km across, elongate northeast-southwest. Relatively gentle lower slopes are surmounted by a dome-like mass, the sides of which slope at about 35°. In the summit area, interlayered lava flows of trachyandesite (benmoreite), lahar deposits and volcaniclastic sediments are capped by a series of 20–100 m thick phonolite flows, erupted from the summit and from domes to the north (Wright-Grassham 1987; Wright & Kyle 1990e). Younger basanite and phonotephrite from numerous small vents mantle the lower slopes. The vents are characterised by scoria cones, agglutinates, volcanic bombs, and lava flows 3–10 m thick, which extend up to several kilometres from their sources. Eleven vents extend from the summit in a NNE-SSW alignment. K-Ar ages indicate that the central Mt Discovery volcano was active in latest Miocene to Early Pliocene time (5.3 Ma, Armstrong 1978; Wright-Grassham 1987) and that eruptions from later vents are at least as young as 1.87 Ma (Wright-Grassham 1987).

Mt Morning is a polygenetic shield volcano 30–35 km across, irregular in outline at the base and more symmetrical above about 2000 m. A northwest-southeast elongate, 5 km by 4 km summit caldera is filled with snow and ice (Wright-Grassham 1987; Wright & Kyle 1990g; Paulsen & Wilson 2009). 186 vents have been identified, most of which are basaltic cinder cones; vent alignments are mainly southwest-northeast (Paulsen & Wilson 2009). Martin et al. (2010) identified two phases of volcanism. Rocks from the earlier phase are exposed in only three areas at the periphery of the volcano; elsewhere they are mantled by the younger eruptives, snow, and ice. Phase I eruptions were mainly subaerial but include rare pillow lava, diamictite and intrusive dike complexes, which were mainly trachytic in composition, with minor rhyolite and basanite (Fig. 61). The overlying Phase II rocks are subaerial basanitic lava flows, cinder cones and other pyroclastic deposits of picrobasalt, basalt, basanite, tephrite and trachybasalt, with lesser phonolite (Fig. 62; Martin et al. 2010). K-Ar and Ar-Ar ages (Martin et al. 2010 and references therein) from Phase I rocks are in the range 18.7–11.4 Ma and for Phase II rocks 6.13–0.07 Ma. Nine dated samples are of Middle to Late Pleistocene age (<0.78 Ma), but although there is no evidence for Holocene activity (Wright & Kyle 1990f), Mt Morning may not be extinct. Based on high heat flow (LeMasurier & Wade 1968) and the timing of eruptions, Martin et al. (2010) argue that the volcano should be considered dormant.

Volcanoes of the Wright and Taylor valleys

Several Pliocene basanite scoria cones are present around the Bartley, Meserve and Goodspeed glaciers, in the eastern Wright Valley, although most are too small to show on a map of this scale. Eight K-Ar ages are in the range 4.3–2.6 Ma (Armstrong 1978; Wright & Kyle 1990i). About 30 Pliocene and Pleistocene scoria cones and mounds up to 60 m high and 250 m across are present on the flanks and floor of Taylor Valley, around the Taylor Glacier snout and Lake Bonney, and on the Kukri Hills (Fig. 34; Haskell et al. 1965a; Wright & Kyle 1990i; Allibone et al. 1991). They are formed of bedded and welded spatter deposits, blocks, bombs and scoria. Some cones produced thin (1.5–10 m) blocky flows of basanite lava. Other flows originated from fissure vents (Allibone et al. 1991). K-Ar and Ar-Ar ages on Taylor Valley basanites are in the range 4.8–1.5 Ma (Armstrong 1978; Wright & Kyle 1990i; Wilch et al. 1993).

Figure 61 Intrusive dike complex in Mount Morning Phase 1 intrusives at Mason Spur on the southeast side of Mount Morning. Basanite dikes invade trachytic and rhyolitic flows and pyroclastic sediments (Photo: A.F. Cooper. Person for scale).



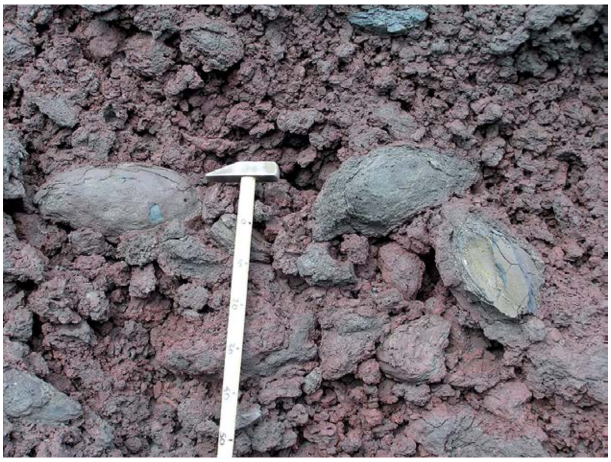


Figure 62 Phase 2 rocks on the northern slopes of Mount Morning. Top left: Cross-section through a pahoehoe flow (Photo: A.P. Martin. Hammers are 80 cm long). Top right: Basanite flow, or possibly welded pyroclastic deposit, above airfall scoria. Bottom left: Local unconformity between two sets of bedded pyroclastic deposits on the margin of a cinder cone. Bottom right: Spindle bombs and spatter (Photos: A.F. Cooper. Hammer is 80 cm long).

Volcanoes in the foothills of the Royal Society Range

Over 50 volcanic vents have erupted basanite lava and scoria in the eastern foothills of the Royal Society Range (Fig. 63; Blank et al. 1963; Wright 1980; Wright & Kyle 1990h). The most extensive area covers about 15 km^2 to the south of Walcott Bay and east of Mt Dromedary. Lavas from Chancellor Ridge, near The Pyramid and from east of the Howchin Glacier are as old as Middle Miocene, with Ar-Ar ages of 13.4–12.6 Ma (Lawrence et al. 2009) and K-Ar ages of 14.2 Ma and 13.5 Ma (Armstrong 1978; also Wright & Kyle 1990h). There are also seven lavas dated as Late Miocene-Pliocene, but by far the majority of vents were active in the Early and Late Pleistocene (Lawrence et al. 2009). Volcanic activity in the Royal Society Range foothills overlapped with that in the Taylor and Wright valleys, where eruptions were mainly in the Late Pliocene and Early Pleistocene. The youngest dated lavas in the Royal Society Range foothills are from basalt domes in Pyramid Valley (K-Ar ages 0.22–0.08 Ma; Armstrong 1978) and flows beside the Walcott Glacier (Ar-Ar ages 0.41–0.26 Ma; Lawrence et al. 2009).

Those vents which are little modified or unmodified by glacial erosion are typically surmounted by cones 10–300 m high with preserved craters, some breached by lava flows. Flows that extend beyond the cones are typically 3–10 m thick and most are less than 4 km long; none extend more than 10 km (Wright & Kyle 1990h). Some eruptions have been onto or underneath glacial ice, as shown by development of pillow lava and hyaloclastite (Wright 1980). There have been multiple eruptions at some sites (e.g. Foster Crater, on the north flank of the Foster Glacier).

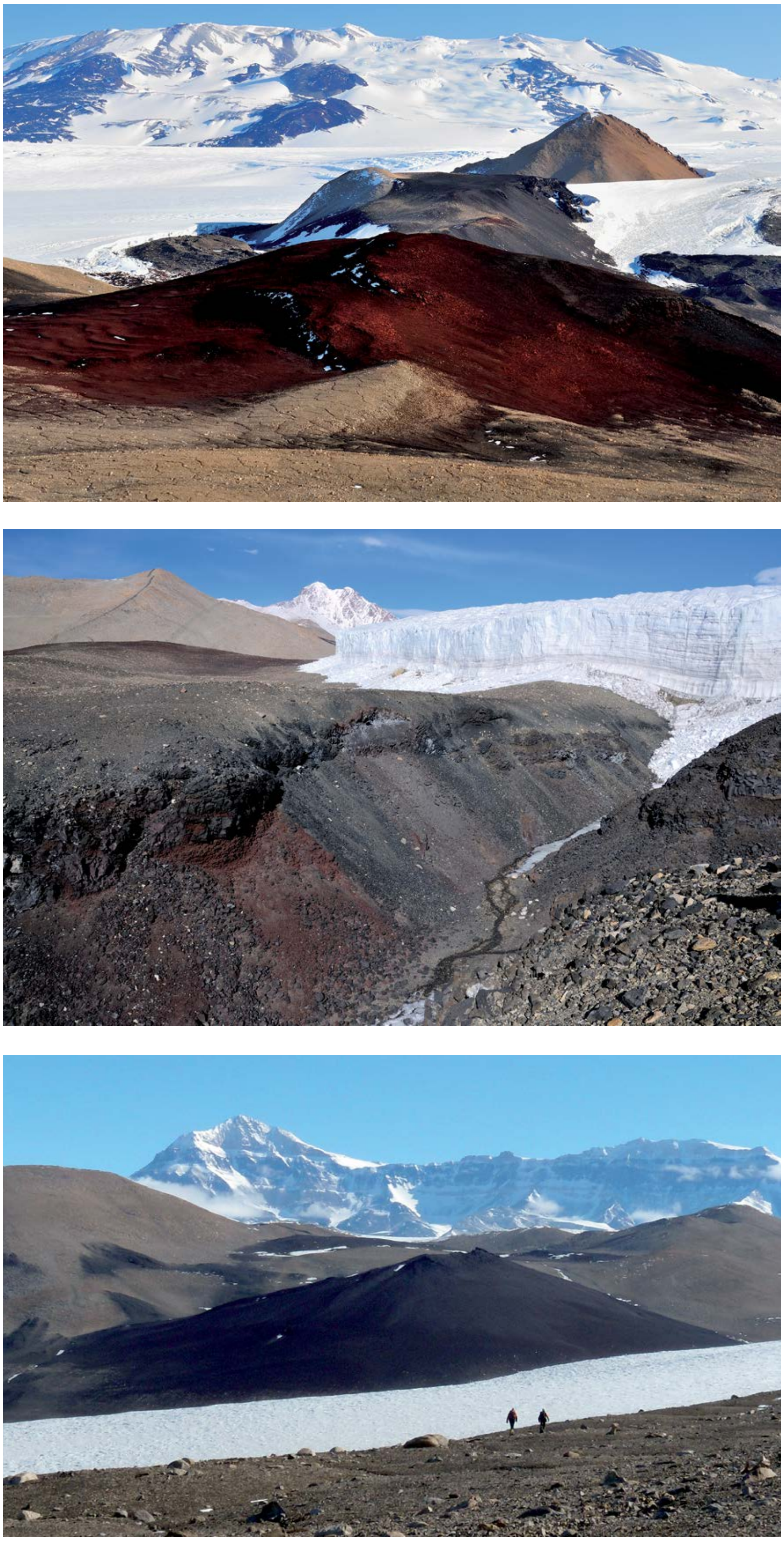


Figure 63 There are over 50 McMurdo Volcanic Group centres in the foothills of the Royal Society Range, ranging in size from small scoria mounds to larger cones (up to 300 m high) of intercalated scoria, agglutinate, bombs and lava flows, mostly Pleistocene in age (Wright & Kyle 1990h; Lawrence et al. 2009). Top: A red scoria cone 700 m wide has erupted over patterned till on The Bulwark (foreground) and lava flows are present along the ridge to Pyramid (middle right), but these are dwarfed by the Mt Morning volcano (background). Middle: At least five separate flows are exposed in a stream section below the Walcott Glacier. Ice now flows down the c. 50 m deep valley occupied previously by lava. Bottom: An Early Pleistocene (2.6 Ma) cone a kilometre wide and 150 m high sits beside eroded vents on Chancellor Ridge, the most distant of which was active in the Middle Miocene (13.4 Ma). Mount Huggins (3741 m) is the high summit in the background (Photos: D.B. Townsend).

Distal volcanic ash layers

Numerous slightly weathered or unweathered volcanic ash fall deposits, generally less than a metre thick, have been identified in the surficial sediments of the Dry Valleys. Their chemical composition and grain size distribution suggest that the most likely sources are the numerous volcanoes of the Erebus volcanic province (Hall et al. 1993; Marchant et al. 1996; Lewis et al. 2007, 2008). The ash layers, dated by K-Ar or Ar-Ar techniques, range in age from 15.5 Ma to 3.9 Ma. **Hart Ash** (**mvh**) in the Wright Valley (Hall et al. 1993) and **Arena Valley Ash** (**mva**) in the Quartermain Mountains (Marchant et al. 1993b, 1996) are Pliocene, whereas the other **ash deposits** (**mvo**) found in the Quartermain Mountains and the Asgard and Olympus ranges are Miocene (Marchant et al. 1993a,b, 1996; Lewis et al. 2007). These latter deposits include *in situ* deposits, redeposited debris flows, disseminated ash in tills and colluvium, or ash that was deposited in water. An unusually thick (>1 m) ash unit in Ward Valley is still under investigation (Fig. 64). Tephra and debris layers are also present in glacier ice (Keys et al. 1977; Harpel et al. 2008) and in the Ross Ice Shelf (Wilson 2000). The dated layers of volcanic ash provide minimum ages for the surfaces they overlie and are fundamental in glacial reconstruction and paleoclimate interpretation (Marchant et al. 1996; Lewis et al. 2007, 2008). Distal ash layers in the Dry Valleys provide evidence that cold desert conditions have prevailed at high elevations since the Middle Miocene.

Drillhole AND-1B, the first of the ANDRILL project, was sited on the Ross Ice Shelf to core the sub-glacial, glaciomarine and marine sediments that had accumulated around Ross Island due to flexural loading and downwarping of the crust by the volcano. The 1285 m sedimentary section drilled comprised ~58 depositional cycles and also included tephras, a volcaniclastic sandstone 173 m thick, and a basaltic lava flow. Ar-Ar ages of the volcanic and volcaniclastic rocks are in the range 13.57–1.10 Ma (Naish et al. 2007a,b; McKay et al. 2009). Further north in McMurdo Sound, the CRP-2A drillhole offshore from Cape Roberts intercepted a series of tephra layers and volcanic clasts, the oldest of which are a clast at 24.98 ± 0.03 Ma and a tephra layer dated at 24.22 ± 0.03 Ma (McIntosh 2000). The former represents the oldest evidence of McMurdo Volcanic Group volcanism in southern Victoria Land.

Figure 64 An undated ash deposit in Ward Valley is composed of small vesicular glass spherules and dark volcanic rock fragments. The spherules have tephriphonolitic chemistry and low density; they would have initially floated in water, sinking once saturated. The deposit occurs inland of a grounded ice moraine correlated with Ross Sea Drift 1, and possibly represents a lacustrine accumulation of ash in an ice-dammed lake (Photos: S.C. Cox. Knife (top) is 9 cm long).

AVAILABILITY OF QMAP DATA

The geological map accompanying this book is derived from information stored in the QMAP geographic information system (GIS) database maintained by GNS Science, and from other GIS-compatible digital databases. The data shown on the map are a subset of the available information, and the GIS dataset covers a slightly wider area than the printed map, which had limitations due to maximum paper size. Customised single-factor and multi-factor maps can be generated from the GIS and integrated with other data sets to produce, for example, maps showing glacial deposits in relation to biota. Data can be presented for user-defined specific areas, for irregular areas such as glacial catchment regions, or in the form of strip maps showing information within a specified distance of linear features such as the coastline. The information can be made available at any required scale, bearing in mind the scale of data capture and the generalisation involved in digitising. Maps produced at a scale greater than 1:50 000 will generally not show accurate, detailed geological information. The QMAP series maps are available in GIS vector and raster digital forms using standard data interchange formats. More information and the digital vector GIS files are available through www.gns.cri.nz/qmap and the WMS/WFS GIS server at map.gns.cri.nz/geology.

For new or additional information, for prints of this map at other scales, for selected data or combinations of data sets or for derivative or single-factor maps based on QMAP data, please contact:

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REFERENCES

Ackert RP 1990. Surficial geology and geomorphology of the western Asgard Range, Antarctica: implications for late Tertiary glacial history. Unpublished MSc thesis, University of Maine, Orono.

Adam LJ 2004. The geology of southern White Island, Antarctica. Unpublished BSc (Hons) thesis, University of Otago, Dunedin.

Adams CJ, Whitla PF 1991. Precambrian ancestry of the Asgard Formation (Skelton Group): Rb-Sr age of basement metamorphic rocks in the Dry Valley region, Antarctica. Abstract. In: Thomson MRA, Crame JA, Thomson JW eds. Geological evolution of Antarctica. Proceedings of the Fifth International Symposium on Antarctic Earth Sciences, Robinson College, Cambridge, 23-28 August 1987. Pp. 129-135.

Airoldi G, Muirhead JD, White JDL, Rowland JV 2011. Emplacement of magma at shallow depth and development of local vents: insights from field relationships at Allan Hills (South Victoria Land, East Antarctica). Antarctic Science 23(2): 281-296.

Airoldi G, Muirhead JD, Zanella E, White JDL 2012. Emplacement process of Ferrar Dolerite sheets at Allan Hills (South Victoria Land, Antarctica) inferred from magnetic fabric. Geophysical Journal International 188: 1046-1060.

Allen AD 1962. Geological investigations in Southern Victoria Land, Antarctica. Part 7, Formations of the Beacon Group in the Victoria Valley Region. New Zealand Journal of Geology and Geophysics 5: 278-294.

Allen AD, Gibson GW 1962. Geological investigations in Southern Victoria Land, Antarctica. Part 6, outline of the geology of the Victoria Valley region. New Zealand Journal of Geology and Geophysics 5: 234-242.

Allibone AH 1988. Koettlitz Group metasediments and intercalated orthogneisses from the mid Taylor Valley and Ferrar Glacier regions. Unpublished MSc thesis, University of Otago, Dunedin.

Allibone AH 1992. Low pressure/high temperature metamorphism of Koettlitz Group schists, Taylor Valley and upper Ferrar Glacier area, South Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 35: 115-127.

Allibone AH, Cox SC, Graham IJ, Smillie RW, Johnstone RD, Ellery SG, Palmer K 1993a. Granitoids of the Dry Valleys area, southern Victoria Land, Antarctica: plutons, field relationships, and isotopic dating. New Zealand Journal of Geology and Geophysics 36: 281-297.

Allibone AH, Cox SC, Smillie RW 1993b. Granitoids of the Dry Valleys area, southern Victoria Land: geochemistry and evolution along the early Paleozoic Antarctic Craton margin. New Zealand Journal of Geology and Geophysics 36: 299-316.

Allibone AH, Forsyth PJ, Sewell RJ, Turnbull IM, Bradshaw MA 1991. Geology of the Thundergut area, Southern Victoria Land, Antarctica. New Zealand Geological Survey 1:50 000 miscellaneous geological map 21. Lower Hutt, DSIR Geology & Geophysics. 1 sheet + 59 p.

Allibone AH, Norris RJ 1992. Migmatite development in Koettlitz Group metasediments, Taylor Valley, Antarctica. Journal of Metamorphic Geology 10: 589-600.

Allibone A, Wysoczanski R 2002. Initiation of magmatism during the Cambrian-Ordovician Ross orogeny in southern Victoria Land, Antarctica. Geological Society of America Bulletin 114: 1007-1018.

Anderson JM 1979. The geology of the Taylor Group, Beacon Supergroup, Byrd Glacier area, Antarctica. New Zealand Antarctic Record 2: 6-11.

Anderson JR, Bartek LR 1992. Cenozoic glacial history of the Ross Sea revealed by intermediate resolution seismic reflection data combined with drill site information. In: Kennett JP, Warnke DA eds. The Antarctic Paleoenvironment: A perspective on Global Change Part 1. Antarctic Research Series 56. Washington DC, American Geophysical Union. Pp 231-263.

Angino EE, Turner MD, Zeller EJ 1962. Reconnaissance geology of Lower Taylor Valley, Victoria Land, Antarctica. Geological Society of America Bulletin 73: 1553-1562.

Armstrong RL 1978. K-Ar dating: Late Cenozoic McMurdo Volcanic Group and dry valley glacial history, Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 21: 685-698.

Armstrong RL, Hamilton WB, Denton GH 1968. Glaciation in Taylor Valley, Antarctica, older than 2.7 million years. Science 159: 187-189.

Arnot MJ 1991. C/S geochemistry of Beacon Supergroup rocks, from Southern Victoria Land and the Ohio Range, Transantarctic Mountains, Antarctica. Unpublished MSc thesis, Victoria University of Wellington, Wellington.

Ashworth AC, Lewis AR 2011. The Early Miocene paleoclimate of the McMurdo Dry Valleys region of Antarctica. Abstract. Eleventh International Symposium on Antarctic Earth Sciences, Edinburgh, Scotland, 10-15 July 2011. p. 31.

Askin RA 1997. Permian palynomorphs from southern Victoria Land, Antarctica. Antarctic Journal of the United States 30: 47-48.

Askin RA 1998. Floral trends in the high latitudes: Palynological evidence from the Transantarctic Mountains. Journal of African Earth Sciences 27: 12-13.

Askin RA, Bamford DA, Bright DV, Chinn AN 1973. Mt Feather [stratigraphic section]. In: Barrett PJ and Webb PN ed. Stratigraphic sections of the Beacon Supergroup (Devonian and older (?) to Jurassic) in south Victoria Land. Antarctic Data Series 3. Wellington, Victoria University of Wellington. Pp. 97-103.

Askin RA, Barrett PJ 1971. Tabular Mountain [stratigraphic section] In: Barrett PJ ed. Stratigraphic sections of the Beacon Supergroup (Devonian and older? to Jurassic) in south Victoria Land. Antarctic Data Series 2. Wellington, Victoria University of Wellington. Pp. 64-66.

Aslund T 1990. Metamorphism and magmatism of mafic intrusives at Dromedary massif, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Aster R, Mah S, Kyle P, McIntosh W, Dunbar N, Johnson J 2003. Very long period oscillations of Mount Erebus volcano. Journal of Geophysical Research 108, B11: 2522 doi:10 .1029/2002JB002101.

Atkins CB, Barrett PJ, Hicock SR 2002. Cold glaciers erode and deposit: evidence from Allan Hills, Antarctica. Geology 30: 659-662.

Atkins CB, Dickinson WW 2007. Landscape modification by meltwater channels at margins of cold-based glaciers, Dry Valleys, Antarctica. Boreas 36: 47-55 doi:10.1080/03009480600827306.

Atkins CB, Dunbar GB 2009. Aeolian sediment flux from sea ice into southern McMurdo Sound, Antarctica. Global and Planetary Change 69: 133-141.

Ball HW, Borns HW, Hall BA, Brooks HK, Carpenter FM, Delevoryas T 1979. Biota, age, and significance of lake deposits, Carapace Nunatak, Victoria Land, Antarctica. In: Lasker B, Rao CSR ed. Fourth International Gondwana Symposium, Calcutta. Delhi, Hindustan Publishing Corporation. Pp. 166-175.

Ballance PF 1977. The Beacon Supergroup in the Allan Hills, central Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 20: 1003-1016.

Ballance PF, Watters WA 1971. The Mawson diamictite and the Carapace Sandstone, formations of the Ferrar Group at Allan Hills and Carapace Nunatak, Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 14: 512-527.

Ballance PF, Watters WA 2002. Hydrothermal alteration, contact metamorphism, and authigenesis in Ferrar Supergroup and Beacon Supergroup rocks, Carapace Nunatak, Allan Hills, and Coombs Hills, Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 45: 71-84.

Barber AJW 2003. The Neoproterozoic-early Paleozoic evolution of the Ross Orogeny in the Reeves Bluffs area, southern Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Baroni C, Orombelli G 1994. Abandoned penguin rookeries as Holocene paleoclimatic indicators in Antarctica. Geology 22: 23-26.

Barrett PJ ed. 1971. Stratigraphic sections of the Beacon Supergroup (Devonian and older? to Jurassic) in south Victoria Land. Antarctic Data Series 2. Wellington, Victoria University of Wellington. 88 p.

Barrett PJ 1972. Late Paleozoic glacial valley at Alligator Peak, Southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 15: 262-268.

Barrett PJ ed. 1986. Antarctic Cenozoic history from the MSSTS-1 drillhole, McMurdo Sound. DSIR Bulletin 237. Wellington, Department of Scientific and Industrial Research. 174 p.

Barrett PJ ed. 1989. Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound. DSIR Bulletin 245. Wellington, Department of Scientific and Industrial Research. 254 p.

Barrett PJ 2007. Cenozoic climate and sea level history from glacimarine strata off the Victoria Land coast, Cape Roberts Project, Antarctica. In: Hambrey MJ, Christoffersen P, Glasser NF, Hubbart B eds. Glacial Processes and Products. International Association of Sedimentologists Special Publication 39: 259-287.

Barrett PJ 2009. A history of Antarctic Cenozoic glaciation - View from the margin. In: Florindo F, Siegert M eds. Antarctic Climate Evolution. Developments in Earth & Environmental Sciences 8. Elsevier. Pp. 33-83.

Barrett PJ 2013. Resolving views on Antarctic Neogene glacial history - the Sirius debate. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 104(1).

Barrett PJ, Adams CJ, McIntosh WC, Swisher CC, Wilson GS 1992. Geochronological evidence supporting Antarctic deglaciation three million years ago. Nature 359: 816-818.

Barrett PJ, Davey FJ, Cita MB, Tessensohn F, Thomson MRA, Webb PN 1994. Coring for Antarctic tectonic and climatic history - the Cape Roberts Project. Terra Antartica 1(2): 473-474.

Barrett PJ, Fielding C, Wise SW, Cape Roberts Science Team 1998. Initial report on CRP-1, Cape Roberts Project, Antarctica. Terra Antartica 5(1): 1-187.

Barrett PJ, Fitzgerald PG 1985. Deposition of the Lower Feather Conglomerate, a Permian braided river deposit in South Victoria Land, Antarctica, with notes on the regional paleogeography. Sedimentary Geology 45: 189-208.

Barrett PJ, Grindley GW, Webb PN 1972. The Beacon Supergroup of east Antarctica. In: Adie RJ ed. Antarctic Geology and Geophysics. Oslo, Universitetsforlaget. Pp. 319-332.

Barrett PJ, Hambrey MJ 1992. Plio-Pleistocene sedimentation in Ferrar Fiord, Antarctica. Sedimentology 39: 109-123.

Barrett PJ, Henrys SA, Bartek LR, Brancolini G, Busetti M, Davey FJ, Hannah MJ, Pyne AR 1995. Geology of the margin of the Victoria Land basin off Cape Roberts, southwest Ross Sea. In: Cooper AK, Barker PF, Brancolini G eds. Geology and seismic stratigraphy of the Antarctic margin. Washington DC, American Geophysical Union. Pp. 183-207.

Barrett PJ, Kohn BP 1971. Beacon Heights [stratigraphic sections]. In: Barrett PJ ed. Stratigraphic sections of the Beacon Supergroup (Devonian and older? to Jurassic) in south Victoria Land. Antarctic Data Series 2. Wellington, Victoria University of Wellington. Pp. 67-73.

Barrett PJ, Kohn BP 1975. Changing sediment transport directions from Devonian to Triassic in the Beacon Supergroup of south Victoria Land, Antarctica. In: Campbell KSW ed. Gondwana Geology. Third International Gondwana Symposium, Canberra, 1973. Canberra, Australia, ANU Press. Pp. 15-35.

Barrett PJ, McKelvey BC 1981. Permian tillites of south Victoria Land, Antarctica. In: Hambrey, MJ ed. Earth's pre-Pleistocene glacial record. Cambridge, UK, Cambridge University Press. Pp. 233-236.

Barrett PJ, Powell RD 1982. Middle Cenozoic glacial beds at Table Mountain, Southern Victoria Land. In: Craddock C ed. Antarctic Geoscience. Madison, University of Wisconsin Press. Pp. 1058-1068.

Barrett PJ, Stoffers P, Glasby GP, Plueger WL 1984. Texture, mineralogy and composition of four sediment cores from Granite Harbour and New Harbour, southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 27: 477-485.

Barrett PJ, Webb PN ed. 1973. Stratigraphic sections of the Beacon Supergroup (Devonian and older (?) to Jurassic) in south Victoria Land. Antarctic Data Series 3. Wellington, Victoria University of Wellington. 165 p.

Bart PJ, Anderson JB, Trincardi F, Shipp SS 2000. Seismic data from the Northern Basin, Ross Sea, record extreme expansions of the East Antarctic Ice Sheet during the late Neogene. Marine Geology 166: 31-50.

Beckett SA 2002. The Frio Peak area, upper Walcott Glacier region, southern Victoria Land, Antarctica: a detailed study of rocks comprising Frio Shear Zone. Unpublished MSc thesis, University of Otago, Dunedin.

Bedard JHJ, Marsh BD, Hersum TG, Naslund HR, Mukasa SB 2007. Large-scale mechanical redistribution of orthopyroxene and plagioclase in the basement sill, Ferrar Dolerites, McMurdo dry valleys, Antarctica: petrological, mineral-chemical and field evidence for channelized movement of crystals and melt. Journal of Petrology 48: 2289-2326.

Benson WN 1916. Report on the Petrology of the Dolerites collected by the British Antarctic Expedition, 1907-1909. Reports of the British Antarctic Expedition, 1907-1909 Geology: 153-160.

Bertler NAN, Mayewski PA, Carter L 2011. Cold conditions in Antarctica during the Little Ice Age - Implications for abrupt climate change mechanisms. Earth and Planetary Science Letters 308(1-2): 41-51.

Black BA, Elkins-Tanton LT, Rowe MC, Peate IU 2012. Magnitude and consequences of volatile release from the Siberian Traps. Earth and Planetary Science Letters 317-318: 363-373.

Blank HR, Cooper RA, Wheeler RH, Willis IAG 1963. Geology of the Koettlitz - Blue Glacier region, Southern Victoria Land, Antarctica. Transactions of the Royal Society of New Zealand (Geology) 2: 79-100.

Bleakley N 1996. Geology of the Sirius Group at Mount Feather and Table Mountain, South Victoria Land, Antarctica. Unpublished MSc thesis, Victoria University of Wellington, Wellington.

Bockheim JG 2010. Soil preservation and ventifact recycling from dry-based glaciers in Antarctica. Antarctic Science 22: 409-417.

Bockheim J, McLeod M 2006. Soil formation in Wright Valley, Antarctica since the late Neogene. Geoderma 137: 109-116.

Bockheim J, McLeod M 2008. Early Pliocene expansion of the East Antarctic ice sheet, upper Wright Valley, Antarctica. Geografiska Annaler 90A: 187-199.

Bockheim JG, Prentice ML, McLeod M 2008. Distribution of glacial deposits, soils, and permafrost in Taylor Valley, Antarctica. Arctic, Antarctic, and alpine research 40(2): 279-286.

Borns HW 1978. Ross Sea glaciations: Events in Lower Victoria Valley. Antarctic Journal of the United States 13(4): 43-55.

Borns HW 1982. Ross Sea glaciations: Events in the Lower Victoria Valley. Antarctic Journal of the United States 17(5): 52-53.

Borns HW, Hall BA 1969. Mawson Tillite in Antarctica: preliminary report of a volcanic deposit of Jurassic age. Science 166: 870-872.

Boudreau A, Simon A 2007. Crystallization and degassing in the Basement Sill, McMurdo Dry Valleys, Antarctica. Journal of Petrology 48: 1369-1386.

Bowser CJ, Rafter TA, Black RF 1970. Geochemical evidence for the origin of mirabilite deposits near Hobbs Glacier, Victoria Land, Antarctica. Mineralogical Society of America Special Paper 3: 261-272.

Bradshaw MA 1981. Paleoenvironmental interpretations and systematics of Devonian trace fossils from the Taylor Group (lower Beacon Supergroup), Antarctica. New Zealand Journal of Geology and Geophysics 24: 615-652.

Bradshaw MA 1987. Additional field interpretation of the Jurassic sequence at Carapace Nunatak and Coombs Hills, south Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 30: 37-49.

Bradshaw MA, Bradshaw J, Bassett K, Savage J, Gilmer G, O'Toole T 2010. Beacon sediments revisited: New insights into the early development of the Devonian sedimentary basin across the SVL sector of Gondwana (Abstract). Programme and abstracts of the Annual Antarctic Conference 2010, University of Canterbury, 5-7 July. Christchurch, Antarctica New Zealand. p. 35.

Bradshaw MA, Harmsen FJ 2007. The paleoenvironmental significance of trace fossils in Devonian sediments (Taylor Group), Darwin Mountains to the Dry Valleys, southern Victoria Land. In: Cooper A, Raymond C et al. eds. Antarctica: A keystone in a changing world. 10th International Symposium on Antarctic Earth Sciences 2007, University of California, Santa Barbara. USGS Open File Report. Extended Abstract 133, 5 p.

Brady HT, McKelvey BC 1979. The interpretation of a Tertiary tillite at Mount Feather, southern Victoria Land, Antarctica. Journal of Glaciology 22: 189-193.

Brady HT, McKelvey BC 1983. Some aspects of the Cenozoic glaciation of southern Victoria Land. Journal of Glaciology 29: 343-349.

Brancolini G, Cooper AK, Coren F 1995. Seismic facies and glacial history in the western Ross Sea (Antarctica). In: Cooper AK, Barker PF, Brancolini G eds. Geology and seismic stratigraphy of the Antarctic margin. Antarctic Research Series 68. Washington DC, American Geophysical Union. Pp. 209-233.

Bray B, Harpp KS, Geist D, Garcia MO, Swarr GJ 2010. Origin of the Vanda Dike Swarm, Dry Valleys, Antarctica. Abstract #V33B-2362. American Geophysical Union Fall Meeting 2010, San Francisco.

Bromwich DH 1988. Snowfall in high southern latitudes. Reviews of Geophysics 26(1): 149-168.

Brook EJ, Brown ET, Kurz MD, Ackert RP, Raisbeck GM, Yiou F 1995b. Constraints on age, erosion, and uplift of Neogene glacial deposits in the Transantarctic Mountains determined from in-situ cosmogenic ^{10}Be and ^{26}Al. Geology 23: 1063-1066.

Brook EJ, Kurz MD, Ackert RP, Denton GH, Brown ET, Raisbeck GM, Yiou F 1993. Chronology of Taylor Glacier advances in Arena Valley, Antarctica, using in-situ cosmogenic ^{3}He and ^{10}Be. Quaternary Research 39: 11-23.

Brook EJ, Kurz MD, Ackert RP, Raisbeck GM, Yiou F 1995a. Cosmogenic nuclide exposure ages and glacial history of late Quaternary Ross Sea drift in McMurdo Sound, Antarctica. Earth and Planetary Science Letters 131: 41-56.

Bruno LA, Bauer H, Graf T, Schlüchter C, Signer P, Wieler R 1997. Dating of Sirius Group tillites in the Antarctic Dry Valleys with cosmogenic ^{3}He and ^{21}Ne. Earth and Planetary Science Letters 147: 37-54.

Buckeridge JS 1989. Marine invertebrates from late Cainozoic deposits in the McMurdo Sound region, Antarctica. Journal of the Royal Society of New Zealand 19: 333-342.

Bull C 2009. Innocents in the Dry Valleys: An account of the Victoria University of Wellington Antarctic Expedition 1958-1959. Wellington, Victoria University Press. 267 p.

Bull C, McKelvey BC, Webb PN 1962. Quaternary glaciations in southern Victoria Land, Antarctica. Journal of Glaciology 4: 63-78.

Burgess CJ, Palmer A, Anderson JM 1981. The geology of the Fry Glacier area, south Victoria Land, Antarctica, with particular reference to the Taylor Group. New Zealand Journal of Geology and Geophysics 24: 373-388.

Butler ERT 1999. Process environments on modern and raised beaches in McMurdo Sound, Antarctica. Marine Geology 162: 105-120.

Butler ERT 2001. Beaches in McMurdo Sound, Antarctica. Unpublished PhD thesis, Victoria University of Wellington, Wellington.

Calkin PE 1963. Geomorphology and glacial geology of the Victoria Valley system, Southern Victoria Land, Antarctica. Unpublished PhD thesis, Ohio State University.

Calkin PE 1964a. Geomorphology and glacial geology of the Victoria Valley system, southern Victoria Land, Antarctica. Report of the Institute of Polar Studies, Ohio State University No.10. 66 p.

Calkin PE 1964b. Glacial geology of the Mount Gran Area, Southern Victoria Land, Antarctica. Geological Society of America Bulletin 75: 1031-1036.

Calkin PE 1971. Glacial geology of the Victoria Valley system, southern Victoria Land, Antarctica. In: Crary AP ed. Antarctic snow and ice studies II. Antarctic Research Series 16. Washington DC, American Geophysical Union. Pp. 363-412.

Calkin PE 1974a. Subglacial geomorphology surrounding the ice-free valleys of southern Victoria Land, Antarctica. Journal of Glaciology 13(69): 415-429.

Calkin PE 1974b. The sand dunes of Victoria Valley, Antarctica. Geographical Review 1974: 189-216.

Calkin PE, Behling RE, Bull C 1970. Glacial history of Wright Valley, southern Victoria Land, Antarctica. Antarctic Journal of the United States 5(1): 22-27.

Calkin PE, Bull C 1972. Interaction of the East Antarctic Ice Sheet, Alpine Glaciations and Sea-level in Wright valley Area, Southern Victoria Land. In: Adie RJ ed. Antarctic Geology and Geophysics. Oslo, Universitetsforlaget. Pp. 435-440.

Calkin PE, Cailleux A 1962. A quantitative study of cavernous weathering (taffonis) and its application to glacial chronology in Victoria Valley, Antarctica. Annals of Geomorphology 6: 317-324.

Calvert AT, Mortimer N 2003. Thermal History of Transantarctic Mountains K-feldspars, Southern Victoria Land. Terra Antartica 10(1): 3-15.

Campbell IB, Claridge GGC 1978. Soils and Late Cenozoic history of the Upper Wright Valley area, Antarctica. New Zealand Journal of Geology and Geophysics 21(5): 635-644.

Campbell IH, Czamanske GK, Fedorenko VA, Hill RI, Stepanov V 1992. Synchronism of the Siberian Traps and the Permian-Triassic boundary. Science 258: 1760-1763.

Cantrill DJ 2001. Early Oligocene Nothofagus from CRP-3, Antarctica: implications for the vegetation history. Terra Antartica 8(4): 401-406.

Cape Roberts Science Team 1998a. Summary of results from CRP-1, Cape Roberts Project, Antarctica. Terra Antartica 5(1): 125-187.

Cape Roberts Science Team 1998b. Background to CRP-1, Cape Roberts Project, Antarctica. Terra Antartica 5(1): 1-30.

Cape Roberts Science Team 1999. Studies from the Cape Roberts Project, Ross Sea, Antarctica: initial report on CRP-2/2A. Terra Antartica 6(1/2): 1-173.

Cape Roberts Science Team 2000. Studies from Cape Roberts Project, Ross Sea, Antarctica. Initial report on CRP-3. Terra Antartica 7(1/2): 1-209.

Cassidy WA 2003. Meteorites, ice, and Antarctica. Cambridge, UK, Cambridge University Press. 350 p.

Chinn TJ 1990. The Dry Valleys. In: Hatherton T ed. Antarctica: the Ross Sea Region. Wellington, N.Z., DSIR Publishing. Pp. 137-153.

Clapperton CM, Sugden DE 1990. Late Cenozoic glacial history of the Ross Embayment, Antarctica. Quaternary Science Reviews 9: 253-272.

Claridge GGC, Campbell IB 1978. Moraines of probable Miocene age, Dry Valleys, Antarctica. New Zealand Antarctic Record 1: 1-5.

Clayton-Greene JM 1986. Proglacial sedimentation of Late Wisconsin age in Miers Valley, Antarctica. Unpublished MSc thesis, University of Waikato, Hamilton.

Clayton-Greene JM, Hendy CH, Hogg AG 1988. Chronology of a Wisconsin age proglacial lake in the Miers Valley, Antarctica. New Zealand Journal of Geology and Geophysics 31: 353-361.

Cole JW, Ewart A 1968. Contributions to the geology of the Black Island, Brown Peninsula, and Cape Bird areas, McMurdo Sound, Antarctica. New Zealand Journal of Geology and Geophysics 1: 793-828.

Cole JW, Kyle PR, Neall VE 1971. Contributions to Quaternary geology of Cape Crozier, White Island and Hut Point Peninsula, McMurdo Sound Region, Antarctica. New Zealand Journal of Geology and Geophysics 14: 528-546.

Colhoun EA, Mabin MCG, Adamson DA, Kirk RM 1992. Antarctic ice volume and contribution to sea-level fall at 20,000 yr BP from raised beaches. Nature 358: 316-319.

Conway H, Hall BL, Denton GH, Gades AM, Waddington ED 1999. Past and future grounding-line retreat in the West Antarctic Ice Sheet. Science 286: 280-283.

Cook YA 1991. Deformation in the St Johns Range, Southern Victoria Land. New Zealand Antarctic Record 11(1): 19-35.

Cook YA 1992. Physical and chemical processes associated with deformation, South Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Cook YA 1997. The Skelton Group and the Ross Orogeny. Late Neoproterozoic to Early Ordovician Evolution of South Victoria Land, Antarctica. Unpublished PhD thesis, University of Otago, Dunedin.

Cook YA 2007. Precambrian rift-related magmatism and sedimentation, south Victoria Land, Antarctica. Antarctic Science 19(4): 471.

Cook YA, Craw D 2001. Amalgamation of disparate crustal fragments in the Walcott Bay-Foster Glacier area, South Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 44(3): 403-416.

Cook YA, Craw D 2002. Neoproterozoic structural slices in the Ross Orogen, Skelton Glacier area, South Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 45(1): 133-143.

Cooper AF, Adam LJ, Coulter RF, Eby GN, McIntosh WC 2007. Geology, geochronology and geochemistry of a basanitic volcano, White Island, Ross Sea, Antarctica. Journal of Volcanology and Geothermal Research 165: 189-216.

Cooper AF, Maas R, Scott JM, Barber AJW 2011. Dating of volcanism and sedimentation in the Skelton Group, Transantarctic Mountains: Implications for the Rodinia-Gondwana transition in southern Victoria Land, Antarctica. Geological Society of America Bulletin 123: 681-702.

Cooper AF, Worley BA, Armstrong RA, Price RC 1997. Syn-orogenic alkaline and carbonatite magmatism in the Transantarctic Mountains of South Victoria Land, Antarctica. In: Ricci CA ed. The Antarctic Region: Geological evolution and processes. Siena, Terra Antartica Publication. Pp. 245-252.

Cooper AK, Davey FJ, Behrendt JC 1987b. Seismic stratigraphy and structure of the Victoria land basin, western Ross Sea, Antarctica. In: Cooper AK, Davey FJ eds. The Antarctic Continental Margin: Geology and Geophysics of the Western Ross Sea. Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources. Earth Sciences Series, 5B. Pp. 27-65.

Cooper AK, Davey FJ, Hinz K 1987a. Crustal extension and origin of sedimentary basins beneath the Ross Sea and Ross Ice Shelf, Antarctica. In: Thomson MRA, Crame JA, Thomson JW eds. Geological Evolution of Antarctica. Cambridge, UK, Cambridge University Press. Pp. 285-291.

Cottle JM 2002. A study of Ross Orogeny magmatism in the Carlyon Glacier region, southern Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Cottle JM, Cooper AF 2006a. The Fontaine Pluton: An early Ross Orogeny calc-alkaline gabbro from southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 49: 177-189.

Cottle JM, Cooper AF 2006b. Geology, geochemistry, and geochronology of an A-type granite in the Mulock Glacier area, southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 49: 191-202.

Coulter RF 2004. Geology of northern White Island, Antarctica. Unpublished PG Dip Sci thesis, University of Otago, Dunedin.

Cox SC 1987. Origin of Olympus granite-gneiss. New Zealand Antarctic Record 8(1): 42-47.

Cox SC 1989. Gneiss geology: a structural perspective of foliated granitoids and their host rocks in the Wright Valley, south Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Cox SC 1992. Garnet-biotite geothermometry of Koettlitz Group metasediments, Wright Valley, South Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 35: 29-40.

Cox SC 1993. Inter-related plutonism and deformation in South Victoria Land, Antarctica. Geological Magazine 130: 1-14.

Cox SC, Allibone AH 1991. Petrogenesis of orthogneisses in the Dry Valleys region, South Victoria Land. Antarctic Science 3: 405-417.

Cox SC, Allibone AH 1995. Naming of igneous and metamorphic rock units in Antarctica: recommendation by the SCAR Working Group on Geology: discussion. Antarctic Science 7: 303-306.

Cox SC, Parkinson DL, Allibone AH, Cooper AF 2000. Isotopic character of Cambro-Ordovician plutonism, southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 43: 501-520.

Craddock C, Adie RJ, Carryer SJ, Ford AB, Gair HS, Grindley GW, Kizaki K, Lackey LL, Laird MG, Laudon TS, McGregor VR, McLeod IR, Mirsky A, Neethling DC, Nichols RL, Otway PM, Quilty PG, Roots EF, Schmidt DL, Sturm A, Tatsumi T, Trail DS, Van Autenboer T, Wade FA, Warren, G 1970. Geologic Maps of Antarctica. Antarctic Map Folio Series 12. New York, American Geographical Society.

Craw D, Findlay RH 1984. Hydrothermal alteration of Lower Ordovician granitoids and Devonian Beacon Sandstone at Taylor Glacier, McMurdo Sound, Antarctica. New Zealand Journal of Geology and Geophysics 27: 465-475.

Craw D, Morrison AD, Walcott CR 1992. Fluid inclusion evidence for widespread shallow hydrothermal activity in South Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 35(1): 21-28.

Currie PJ 1986. The structure and origin of the Strand Moraines, Antarctica. Unpublished BSc (Hons) thesis, Victoria University of Wellington, Wellington.

Curtis A, Kyle PR 2011. Geothermal point sources identified in a fumarolic ice cave on Erebus volcano, Antarctica using fiber optic distributed temperature sensing. Geophysical Research Letters 38: L16802 doi:10.1029/2011GL048272.

Dagel MA 1984. Stratigraphy and chronology of Stage 6 and 2 glacial deposits, Marshall Valley, Antarctica. Unpublished MSc thesis, University of Maine, Orono.

Dahl PS, Palmer DF 1981. Field study of orbicular rocks in Taylor Valley, southern Victoria Land. Antarctic Journal of the United States 1981 Review 16(5): 47-49.

Debenham F 1919. A new mode of transport by ice. Quarterly Journal of the Geological Society of London 75: 51-76.

DeConto RM, Pollard D, Kowalewski D 2012. Modeling Antarctic ice sheet and climate variations during Marine Isotope Stage 31. Global and Planetary Change 88-89: 45-52.

Denton GH, Armstrong RL, Stuiver M 1970. Late Cenozoic Glaciation in Antarctica: The Record in the McMurdo Sound Region. Antarctic Journal of the United States 5(1): 15-21.

Denton GH, Armstrong RL, Stuiver M 1971. The Late Cenozoic glacial history of Antarctica. In: Turekian KK ed. The late Cenozoic glacial ages. New Haven and London, Yale University Press. Pp. 267-306.

Denton GH, Bockheim JG, Wilson SC, Stuiver M 1989. Late Wisconsin and early Holocene glacial history, inner Ross Embayment, Antarctica. Quaternary Research 31: 151-182.

Denton GH, Hughes TJ 2000. Reconstruction of the Ross Ice drainage system, Antarctica, at the Last Glacial Maximum. Geografiska Annaler 82A: 143-166.

Denton GH, Marchant DR 2000. The geologic basis for a reconstruction of a grounded ice sheet in McMurdo Sound, Antarctica, at the Last Glacial Maximum. Geografiska Annaler 82A: 167-211.

Denton GH, Prentice ML, Kellogg DE, Kellogg TB 1984. Late Tertiary history of the Antarctic ice sheet: evidence from the Dry Valleys. Geology 12: 263-267.

Denton GH, Sugden DE 2005. Meltwater features that suggest Miocene ice-sheet overriding of the Transantarctic Mountains in Victoria Land, Antarctica. Geografiska Annaler 87: 67-85.

Denton GH, Sugden DE, Marchant DR, Hall BL, Wilch TI 1993. East Antarctic Ice Sheet sensitivity to Pliocene climatic change from a Dry Valleys perspective. Geografiska Annaler 75A: 155-204.

Dochat TM, Marchant DR, Denton GH 2000. Glacial geology of Cape Bird, Ross Island, Antarctica. Geografiska Annaler 82A: 237-247.

Doran PT, McKay CP, Clow GD, Dana GL, Fountain AG, Nylen T, Lyons WB 2002a: Valley floor climate observations from the McMurdo dry valleys. Antarctica, 1986-2000. Journal of Geophysical Research 107(D24): 4772-4784 doi:10.1029/2001JD002045.

Doran PT, Priscu JC, Lyons WB, Walsh JE, Fountain AG, McKnight DM, Moorhead DL, Virginia RA, Wall DH, Clow GD, Fritsen CH, McKay CP, Parsons AN 2002b: Antarctic climate cooling and terrestrial ecosystem response. Nature 415: 517-520.

Dunbar NW, Cashman KV, Dupre R 1994. Crystallization processes of anorthoclase phenocrysts in the Mount Erebus magmatic system: Evidence from crystal composition, crystal size distributions and volatile contents of melt inclusions. In: Kyle PR ed. Volcanological and Environmental Studies of Mt. Erebus, Antarctica. Antarctic Research Series 66. Washington DC, American Geophysical Union. Pp. 129-146.

Dunbar GB, Naish TR, Barrett PJ, Fielding CR, Powell RD 2008. Constraining the amplitude of late Oligocene bathymetric changes in western Ross Sea during orbitally-induced oscillations in the East Antarctic Ice Sheet: (1) implications for glacimarine sequence stratigraphic models. Palaeogeography, Palaeoclimatology, Palaeoecology 260: 50-65.

Edgeworth David TW, Priestley RE 1909. Geological Observations in Antarctica by the British Antarctic Expedition, 1907-1909. In: Shackleton EH. The Heart of the Antarctic. London, William Heinemann. Appendix II, Pp. 268-307.

Edgeworth David TW, Priestley RE 1914. Glaciology, Physiography, Stratigraphy and Tectonic Geology of South Victoria Land. Reports of British Antarctic Expedition 1907-09, Geology 1. London, William Heinemann. Pp. 1-319.

Eggers AJ 1976. The Scallop Hill Formation, Brown Peninsula, McMurdo Sound, Antarctica. Unpublished BSc (Hons) thesis, Victoria University of Wellington, Wellington.

Ellerman PJ, Kyle PR 1990. A.14. Beaufort Island. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 94-96.

Ellery SC 1989. Lower Wright geology. Unpublished MSc thesis, University of Otago, Dunedin.

Elliot DH 2000. Stratigraphy of Jurassic pyroclastic rocks in the Transantarctic Mountains, Antarctica. Journal of African Earth Sciences 31: 77-89.

Elliot DH, Fleck RJ, Sutter JF 1985. Potassium-argon age determinations of Ferrar Group rocks, central Transantarctic Mountains. In: Turner MD, Splettstoesser JE eds. Geology of the Central Transantarctic Mountains. Antarctic Research Series 36. Washington DC, American Geophysical Union. Pp. 197-224.

Elliot DH, Fleming TH 2004. Occurrence and dispersal of magmas in the Jurassic Ferrar Large Igneous Province, Antarctica. Gondwana Research 7: 223-237.

Elliot DH, Fleming TH 2008. Physical volcanology and geological relationships of the Jurassic Large Igneous Province, Antarctica. Journal of Volcanological and Geothermal Research 172: 20-37.

Elliot DH, Fleming TH, Kyle PR, Foland KA 1999. Long-distance transport of magmas in the Jurassic Ferrar Large Igneous Province, Antarctica. Earth and Planetary Science Letters 167: 89-104.

Elliot DH, Fortner EH, Grimes CB 2006. Mawson breccias intrude Beacon strata at Allan Hills, south Victoria Land: regional implications. In: Futterer DK, Damaske D, Kleinschmidt G, Miller H, Tessensohn F eds. Antarctica – Contributions to Global Earth Sciences. Potsdam, Springer. Pp. 291-298.

Elliot DH, Hanson RE 2001. Origin of widespread, exceptionally thick basaltic phreatomagmatic tuff breccia in the Middle Jurassic Prebble and Mawson Formations, Antarctica. Journal of Volcanological and Geothermal Research 111: 183-201.

Encarnacion J, Fleming TH, Elliot DH, Eales HV 1996. Synchronous emplacement of Ferrar and Karoo dolerites and the early breakup of Gondwana. Geology 24: 535-538.

Encarnacion J, Grunow A 1996. Changing magmatic and tectonic styles along the paleo-Pacific margin of Gondwana and the onset of early Paleozoic magmatism in Antarctica. Tectonics 15: 1325-1341.

Esser R, Heizler M, Kyle P, McIntosh WC 1994. $^{40}Ar/^{39}Ar$ dating of Mount Erebus, Ross Island, Antarctica. Antarctic Journal of the United States 29(5): 14-15.

Esser RP, Kyle PR, McIntosh WC 2004. $^{40}Ar/^{39}Ar$ dating of the eruptive history of Mount Erebus, Antarctica: volcano evolution. Bulletin of Volcanology 66: 671-686.

Fargo A, McIntosh WC, Dunbar NW, Wilch TI 2008. $^{40}Ar/^{39}Ar$ geochronology of Minna Bluff, Antarctica: Timing of Mid Miocene glacial erosion events within the Ross Embayment. Abstract #V13C-2127. American Geophysical Union Fall Meeting 2008, San Francisco.

Faure G, Mensing TM 2010. The Transantarctic Mountains. Dordrecht, Springer. 804 p.

Feakins SJ, Warny S, Lee J 2012. Hydrologic cycling over Antarctica during the middle Miocene warming. Nature Geoscience 5: 557-560.

Ferrar HT 1907. Report on the field geology of the region explored during the (Discovery) Antarctic Expedition, 1901-1904. Natural History Reports of the National Antarctic Expedition 1901-1904: Geology 1(1). London, The British Museum. Pp. 1-100.

Ferrar HT 1925. The geological history of the Ross Dependency. New Zealand Journal of Science and Technology 7: 354-361.

Fielding CR, Atkins CB, Bassett KN, Browne GH, Dunbar GB, Field BD, Frank TD, Krissek LA, Panter KS, Passchier S, Pekar SF, Sandroni S, Talarico F and the ANDRILL-SMS Science Team 2008b. Sedimentology and stratigraphy of the AND-2A core, ANDRILL Southern McMurdo Sound Project, Antarctica. Terra Antartica 15(1): 77-112.

Fielding CR, Browne GH, Field B, Florindo F, Harwood DM, Krissek LA, Levy RH, Panter KS, Passchier S, Pekar SF 2011. Sequence stratigraphy of the ANDRILL AND-2A drillcore, Antarctica: A long-term, ice-proximal record of Early to Mid-Miocene climate, sea-level and glacial dynamism. Palaeogeography, Palaeoclimatology, Palaeoecology 305: 337-351 doi:10.1016/j.palaeo.2011.03.026.

Fielding CR, Harwood DM, Winter DM, Francis JE 2010. Neogene stratigraphy of Taylor Valley, Transantarctic Mountains, Antarctica: Evidence for climate dynamism and a vegetated Early Pliocene coastline of McMurdo Sound. Global and Planetary Change 96-97: 97-104 doi:10.1016/j.gloplacha.2010.09.003.

Fielding CR, Whittaker J, Henrys SA, Wilson TJ, Naish TR 2008a. Seismic facies and stratigraphy of the Cenozoic succession in McMurdo Sound, Antarctica: implications for tectonic, climatic and glacial history. Palaeogeography, Palaeoclimatology, Palaeoecology 260: 8-29 doi:10.1016/j.palaeo.2007.08.016.

Findlay RH 1978. Provisional report on the geology of the region between the Renegar and Blue Glaciers, Antarctica. New Zealand Antarctic Record 1: 39-44.

Findlay RH 1982. Basement Geology of the McMurdo Sound Region, Antarctica. Unpublished report to the Ross Dependency Research Commission. Housed in the library of Antarctica New Zealand, Christchurch. 50 p.

Findlay RH 1985. The Granite Harbour Intrusive Complex in McMurdo Sound; progress and problems. New Zealand Antarctic Record 6: 10-12.

Findlay RH, Skinner DNB, Craw D 1984. Lithostratigraphy and structure of the Koettlitz Group, McMurdo Sound, Antarctica. New Zealand Journal of Geology and Geophysics 27: 513-536.

Fitzgerald PG 1992. The Transantarctic Mountains of southern Victoria Land: the application of apatite fission track analysis to a rift shoulder uplift. Tectonics 11(3): 634-662.

Fitzgerald PG 1995. Cretaceous and Cenozoic exhumation of the Transantarctic Mountains: evidence from the Kukri Hills of southern Victoria Land compared to fission track data from gneiss at DSDP Site 270. Abstract. Seventh International Symposium on Antarctic Earth Sciences, Siena, Italy, 10-15 September 1995. p. 133.

Fitzgerald PG 2002. Tectonics and landscape evolution of the Antarctic plate since the breakup of Gondwana, with an emphasis on the West Antarctic Rift System and the Transantarctic Mountains. In: Gamble JA, Skinner DNB, Henrys SA eds. Antarctica at the close of a millennium. Proceedings of the 8th International Symposium on Antarctic Earth Sciences. Royal Society of New Zealand Bulletin 35: 453-470.

Fitzgerald PG, Barrett PJ 1986. *Skolithos* in a Permian braided river deposit, southern Victoria Land, Antarctica. Paleogeography, Paleoclimatology, Paleoecology 52: 237-247.

Fleming TH, Elliot DH, Burgess S, Shea E, Bowring S 2011. High-precision U-Pb geochronology of the Ferrar Large Igneous Province. Abstract. Eleventh International Symposium on Antarctic Earth Sciences, Edinburgh, Scotland, 10-15 July 2011. p. 78.

Fleming TH, Foland KA, Elliot DH 1999. Apophyllite $^{40}Ar/^{39}Ar$ and Rb-Sr geochronology: potential utility and application to the timing of secondary mineralization of the Kirkpatrick Basalt, Antarctica. Journal of Geophysical Research. Solid Earth 104: 20081-20095.

Fleming TH, Heimann A, Foland KA, Elliot DH 1997. $^{40}Ar/^{39}Ar$ geochronology of Ferrar Dolerite sills from the Transantarctic Mountains, Antarctica: Implications for the age and origin of the Ferrar magmatic province. Geological Society of America Bulletin 109: 533-546.

Forsyth PJ 1996. Comment on “Constraining the Devonian to Triassic Evolution of the Ross Sea Sector” by K.J. Woolfe and P.J. Barrett (1995). Terra Antartica 3(1): 55-56.

Forsyth PJ 2010. Revision of Faultless Expedition ‘Immediate Science Report’ K101 Tectonic History of the Trans-Antarctic Mountains. Techfile report ANT/571, held in the Dunedin Office, GNS Science. 2 p.

Forsyth PJ, Mortimer N, Turnbull IM 2002. Plutonic rocks from the Cape Roberts hinterland: Wilson Piedmont Glacier, Southern Victoria Land, Antarctica. Terra Antartica 9(2): 57-72.

Forsyth PJ, Rattenbury MS, Tulloch AJ, Spencer J 2003. Immediate Science Report to Antarctica New Zealand: K101 Tectonic History of the Transantarctic Mountains. Techfile report ANT/081, held in the Dunedin Office, GNS Science. 13 p.

Fountain AG, Nylen TH, Monaghan A, Basagic HJ, Bromwich D 2010. Snow in the McMurdo Dry Valleys, Antarctica. International Journal of Climatology 30: 633-642.

Francis JE, Marenssi S, Levy R, Hambrey M, Thorn VC, Mohr B, Brinkhuis H, Warnarr J, Zachos J, Bohaty S, DeConto R 2009. From Greenhouse to Icehouse – The Eocene/Oligocene in Antarctica. In: Florindo F, Siegert M eds. Antarctic climate evolution. Developments in Earth & Environmental Sciences 8. Amsterdam, Elsevier. Pp. 311-372.

Francis JE, Woolfe KJ, Arnot MJ, Barrett PJ 1993. Permian forests of Allan Hills, Antarctica: the palaeoclimate of Gondwanan high latitudes. Special Papers in Palaeontology 49: 75-83.

Gabites HI 1985. Triassic paleoecology of the Lashly Formation, Transantarctic Mountains, Antarctica. Unpublished MSc thesis, Victoria University of Wellington, Wellington.

Gamble JA, McGibbon F, Kyle PR, Menzies MA, Kirsch I 1988. Metasomatised xenoliths from Foster crater, Antarctica: Implications for lithospheric structure and processes beneath the Transantarctic Mountain front. In: Menzies MA, Cox KG eds. Oceanic and continental lithosphere: similarities and differences. Journal of Petrology Special Issue. Oxford University Press. Pp. 109-138.

Gardner N, Hall B, Wehmiller J 2006. Pre-Holocene raised beaches at Cape Ross, Southern Victoria Land, Antarctica. Marine Geology 229: 273-284 doi:10.1016/j.margeo.2006.01.006.

Ghent ED 1970. Chemistry and mineralogy of the Mt Falconer pluton and associated rocks, lower Taylor Valley, south Victoria Land, Antarctica. Transactions of the Royal Society of New Zealand (Earth sciences) 8(9): 117-132.

Ghent ED, Henderson RA 1968. Geology of the Mt Falconer pluton, Lower Taylor Valley, South Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 11: 851-880.

Giggenbach WF, Kyle PR, Lyon GL 1973. Present volcanic activity on Mount Erebus, Ross Island, Antarctica. Geology 1: 135-136.

Glasser N, Goodsell B, Copland L, Lawson W 2006. Debris characteristics and ice-shelf dynamics in the ablation region of the McMurdo Ice Shelf, Antarctica. Journal of Glaciology 52: 223-234.

Golledge NR, Levy RH 2011. Geometry and dynamics of an East Antarctic Ice Sheet outlet glacier, under past and present climates. Journal of Geophysical Research 116: 3025-3038.

Goodge JW 2002. From Rodinia to Gondwana: supercontinent evolution in the Transantarctic Mountains. In: Gamble JA, Skinner DNB, Henrys SA eds. Antarctica at the close of a millennium. Proceedings of the 8th International Symposium on Antarctic Earth Sciences. Royal Society of New Zealand Bulletin 35: 61-74.

Goodge JW, Myrow P, Phillips D, Fanning CM, Williams IS 2004b. Siliciclastic record of rapid denudation in response to convergent-margin orogenesis, Ross Orogen, Antarctica. Geological Society of America Special Paper 378: 105-126.

Goodge JW, Walker NW, Hansen VL 1993. Neoproterozoic - Cambrian basement-involved orogenesis within the Antarctic margin of Gondwana. Geology 21: 37-40.

Goodge JW, Williams IS, Myrow P 2004a. Provenance of Neoproterozoic and lower Paleozoic siliciclastic rocks of the central Ross orogen, Antarctica: detrital record of rift-, passive-, and active-margin sedimentation. Geological Society of America Bulletin 116(9/10): 1253-1279.

Gradstein FM, Ogg JG, Schmitz M, Ogg G 2012. The Geological Time Scale 2012. Elsevier.

Graham IJ, Palmer K 1987. New precise Rb-Sr mineral and whole-rock dates for I-type granitoids from Granite Harbour, south Victoria Land, Antarctica. New Zealand Antarctic Record 8(1): 72-80.

Grapes RH, Reid DL 1971. Rhythmic layering and multiple intrusion in the Ferrar Dolerite of south Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 14: 600-604.

Grapes RH, Reid DL, McPherson JG 1974. Shallow dolerite intrusion and phreatic eruption in the Allan Hills region, Antarctica. New Zealand Journal of Geology and Geophysics 17(3): 563-577.

Grindley GW 1963. The geology of the Queen Alexandra Range, Beardmore Glacier, Ross Dependency, Antarctica, with notes on the correlation of Gondwana sequences. New Zealand Journal of Geology and Geophysics 6: 307-347.

Grindley GW, Warren G 1964. Stratigraphic nomenclature and correlation in the western Ross Sea region. In: Adie RJ ed. Antarctic Geology. Amsterdam, North Holland Publishing Company. Pp. 314-333.

Grunow AM, Encarnacion JP 2000. Cambro-Ordovician palaeomagnetic and geochronologic data from southern Victoria Land, Antarctica: revision of the Gondwana apparent polar wander path. Geophysical Journal International 141: 391-400.

Gunn BM 1962a. Differentiation in Ferrar Dolerites, Antarctica. Unpublished PhD thesis, University of Otago, Dunedin.

Gunn BM 1962b. Differentiation in Ferrar Dolerites, Antarctica. New Zealand Journal of Geology and Geophysics 5: 820-863.

Gunn BM 1963. Layered intrusions in the Ferrar Dolerites, Antarctica. Mineralogical Society of America Special Paper 1: 124-133.

Gunn BM, Warren G 1962. Geology of Victoria Land between the Mawson and Mulock Glaciers, Antarctica. New Zealand Geological Survey Bulletin 71. Wellington, Department of Scientific and Industrial Research. 157 p.

Hagen-Peter GA, Cottle J, Tulloch A 2011. Exploring the petrochronology of subduction-related magmatism in the Ross Orogen: a case study from the Dry Valleys, southern Victoria Land, Antarctica. GSA Annual Meeting in Minneapolis (9-12 October 2011). Geological Society of America Abstracts with Programs 43(5): 46.

Hall BL, Baroni C, Denton GH 2004. Holocene relative sea-level history of the southern Victoria Land coast, Antarctica. Global and Planetary Change 42: 241-263.

Hall BL, Denton GH 1994. Late Wisconsin/Holocene history of the Wilson Piedmont Glacier. Antarctic Journal of the United States 29(5): 20-22.

Hall BL, Denton GH 1999. New relative sea-level curves for the southern Scott Coast, Antarctica: evidence for Holocene deglaciation of the western Ross Sea. Journal of Quaternary Science 14(7): 641-650.

Hall BL, Denton GH 2000a. Extent and chronology of the Ross Sea Ice Sheet and the Wilson Piedmont Glacier along the Scott Coast at and since the Last Glacial Maximum. Geografiska Annaler 82A: 337-363.

Hall BL, Denton GH 2000b. Radiocarbon chronology of Ross Sea Drift, eastern Taylor Valley, Antarctica: Evidence for a grounded ice sheet in the Ross Sea at the Last Glacial Maximum. Geografiska Annaler 82A: 305-335.

Hall BL, Denton GH 2002. Holocene history of the Wilson Piedmont Glacier along the southern Scott Coast, Antarctica. Holocene 12: 619-627.

Hall BL, Denton GH 2005. Surficial geology and geomorphology of eastern and central Wright Valley, Antarctica. Geomorphology 64: 25-65.

Hall BL, Denton, GH, Fountain A, Hendy CH, Henderson G 2010. Antarctic lakes suggest millennial reorganizations of Southern Hemisphere atmospheric and oceanic circulation. Proceedings of the National Academy of Sciences of the United States of America 107: 21355-21359.

Hall BL, Denton GH, Hendy CH 2000. Evidence from Taylor Valley for a grounded ice sheet in the Ross Sea, Antarctica. Geografiska Annaler 82A: 275-303.

Hall BL, Denton GH, Hendy CH 2002. Glacial Lake Victoria, a high-level Antarctic lake inferred from lacustrine deposits in Victoria Valley. Journal of Quaternary Science 17: 697-706.

Hall BL, Denton GH, Lux DR, Bockheim JG 1993. Late Tertiary Antarctic paleoclimate and ice-sheet dynamics inferred from surficial deposits in Wright Valley. Vega Symposium (1993: Stockholm, Sweden). Pp. 239-267.

Hall BL, Denton GH, Lux DR, Schlüchter C 1997. Pliocene paleoenvironment and Antarctic ice sheet behaviour: evidence from Wright Valley. Journal of Geology 105(3): 285-294.

Hall BL, Denton GH, Overturf B 2001. Glacial Lake Wright, a high-level Antarctic lake during the LGM and early Holocene. Antarctic Science 13: 53-60.

Hall CE 1991. Petrology and geochemistry of alkaline and granitoid intrusions, Pipecleaner Glacier region, southern Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Hall CE, Cooper AF, Parkinson DL 1995. Early Cambrian carbonatite in Antarctica. Journal of the Geological Society (London) 152: 721-728.

Hamilton RJ, Luyendyk BP, Sorlien CC, Bartek LR 2001. Cenozoic tectonics of the Cape Roberts rift basin and Transantarctic Mountains front, Southwestern Ross Sea, Antarctica. Tectonics 20: 325-342.

Hamilton W 1965. Diabase sheets of the Taylor Glacier region, Victoria Land, Antarctica. United States Geological Survey Professional Paper 456B: 1-71.

Hamilton WB, Hayes PT 1960. Geology of Taylor Valley: Taylor Dry Valleys region, South Victoria Land, Antarctica. United States Geological Survey Professional Paper 400B: 376-378.

Hamilton W, Hayes PT 1963. Type section of the Beacon Sandstone of Antarctica. United States Geological Survey Professional Paper 456A: 1-18.

Harpel CJ, Kyle PR, Esser RP, McIntosh WC, Caldwell DA 2004. $^{40}Ar/^{39}Ar$ dating of the eruptive history of Mount Erebus, Antarctica: Summit flows, tephra, and caldera collapse. Bulletin of Volcanology 66: 687-702.

Harpel CJ, Kyle PR, Dunbar NW 2008. Englacial tephrostratigraphy of Erebus volcano, Antarctica. Journal of Volcanology and Geothermal Research 177: 549-568.

Harrington HJ 1958a. Nomenclature of units in the Ross Sea region, Antarctica. Nature (London) 182: 290-291.

Harrington HJ 1958b. Beaufort Island, Remnant of a Quaternary Volcano in the Ross Sea, Antarctica. New Zealand Journal of Geology and Geophysics 1: 595-603.

Harrington HJ 1965. Geology and morphology of Antarctica. In: Van Oye P, Van Mieghen J eds. Biogeography and ecology in Antarctica. The Hague, Junk. Pp. 1-71.

Harrington HJ, Speden IG 1962. Section through the Beacon sandstone at Beacon Height West, Antarctica. New Zealand Journal of Geology and Geophysics 5: 707-717.

Harwood D, Florindo F, Talarico F, Levy RH eds. 2009. Studies from the ANDRILL Southern McMurdo Sound Project, Antarctica—Initial Science Report on AND-2A. Terra Antartica 15(1/2).

Harwood DM, Levy RH 2000. The McMurdo erratics: introduction and overview. In Stilwell JD, Feldman RM eds. Paleobiology and paleoenvironments of Eocene rocks, McMurdo Sound, east Antarctica. Antarctic Research Series 76. Washington DC, American Geophysical Union. Pp. 1-18.

Haskell TR, Kennett JP, Prebble MW, Smith G, Willis IAG 1965a. The geology of the middle and lower Taylor Valley of South Victoria Land, Antarctica. Transactions of the Royal Society of New Zealand 2: 169-186.

Haskell TR, Kennett JP, Prebble MW 1965b. Geology of the Brown Hills and Darwin Mountains, Southern Victoria Land, Antarctica. Transactions of the Royal Society of New Zealand 2: 231-248.

Hayes DE, Frakes LA eds. 1975. Initial reports of the Deep Sea Drilling Project Leg 28. Washington DC., US Government Printing Office. 1019 p.

Haywood AM, Smellie JL, Ashworth AC, Cantrill DJ, Florindo F, Hambrey MJ, Hill D, Hillenbrand C-D, Hunter SJ, Larter RD, Lear CH, Passchier S, van der Wal R. 2009. Middle Miocene to Pliocene history of Antarctica and the Southern Ocean. In: Florindo F, Siegert M eds. Antarctic climate evolution. Developments in Earth & Environmental Sciences 8. 1st ed. Amsterdam, Elsevier. Pp. 401-463.

Heimann A, Fleming TH, Elliot DH, Foland KA 1994. A short interval of Jurassic continental flood basalt volcanism in Antarctica as demonstrated by $^{40}Ar/^{39}Ar$ geochronology. Earth and Planetary Science Letters 121: 19-41.

Hendy CH 2000. Late Quaternary lakes in the McMurdo Sound region of Antarctica. Geografiska Annaler 82A(2-3): 411-432.

Hendy CH, Healy TR, Rayner EM, Shaw J, Wilson AT 1979. Late Pleistocene glacial chronology of the Taylor Valley, Antarctica and the global climate. Quaternary Research 11: 172-184.

Hendy CH, Neall VE, Wilson AT 1969. Recent marine deposits from Cape Barne, McMurdo Sound, Antarctica. New Zealand Journal of Geology and Geophysics 12: 707-712.

Hendy CH, Sadler AJ, Denton GH, Hall BL 2000. Proglacial lake-ice conveyors: a new mechanism for deposition of drift in polar environments. Geografiska Annaler 82A: 249-270.

Henrys SA, Buecker CJ, Bartek LR, Bannister SC, Niessen F, Wonik T 2000. Correlation of seismic reflectors with CRP 2/2A, Victoria Land Basin, Antarctica. Terra Antartica 7(3): 221-230.

Henrys SA, Wilson TJ, Whittaker JM, Fielding CR, Hall JM, Naish T 2007. Tectonic history of mid-Miocene to present southern Victoria Land Basin, inferred from seismic stratigraphy in McMurdo Sound, Antarctica. In: Cooper A, Raymond C et al. eds. Antarctica: A keystone in a changing world. 10th International Symposium on Antarctic Earth Sciences 2007, University of California, Santa Barbara. USGS Open-File Report 2007-1047. Short Research Paper 049, 4 p.

Hersum TG, Marsh BD, Simon AC 2007. Contact Partial Melting of Granitic Country Rock, Melt Segregation, and Re-injection as Dikes into Ferrar Dolerite Sills, McMurdo Dry Valleys, Antarctica. Journal of Petrology 48: 2125-2148.

Hicock SR, Barrett PJ, Holme PJ 2003. Fragment of an ancient outlet glacier system near the top of the Transantarctic Mountains. Geology 31: 821-824.

Hicock SR, Goff JR, Dickinson WW 2002. Macroscopic and mesoscopic analysis of outcrop and core, Sirius Group, Table Mountain, Dry Valleys, Antarctica. In: Gamble JA, Skinner DNB, Henrys SA eds. Antarctica at the close of a millennium. Proceedings of the 8th International Symposium on Antarctic Earth Sciences. Royal Society of New Zealand Bulletin 35: 319-325.

Higgins SM, Denton GH, Hendy CH 1996. U/Th geochronology and glacial geomorphology of Bonney Drift, central Taylor Valley, Antarctica: evidence for interglacial expansions of the East Antarctic ice sheet (EAIS) during the last 400 kyr. Eos 77 (46: supplement): F57.

Higgins SM, Denton GH, Hendy CH 2000a. Glacial geomorphology of Bonney Drift, Taylor Valley, Antarctica. Geografiska Annaler 82A: 365-389.

Higgins SM, Denton GH, Hendy CH 2000b. Geochronology of Bonney Drift, Taylor Valley, Antarctica: Evidence for interglacial expansions of Taylor Glacier. Geografiska Annaler 82A: 391-432.

Hill RS 1989. Fossil leaf. In: Barrett PJ ed. Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound. DSIR Bulletin 245: 143-144.

Hood Hills SB 2003. Vent structures preserved in the Mawson Formation, a phreatomagmatic complex in the Allan Hills, south Victoria Land. Unpublished MSc thesis, University of Otago, Dunedin.

Hood Hills SB, White JDL 2002a. Characteristics and interpretation of vent structures preserved in the Mawson Formation, Allan Hills, Southern Victoria Land, Antarctica. Eos 83 (22: supplement): WP111.

Hood Hills SB, White JDL 2002b. Mawson Formation vent characteristics, Allan Hills, Southern Victoria Land, Antarctica. In: Grenfell H ed. GSNZ Annual Conference, 2nd-5th December 2002, Whangarei, Northland: programme & abstracts. Geological Society of New Zealand Miscellaneous Publication 112A: 28.

Holbourn A, Kuhnt W, Schulz M, Flores J-A, Andersen N 2007. Orbitally-paced climate evolution during the Middle Miocene "Monterey" carbon-isotope excursion. Earth and Planetary Science Letters 261: 534-550.

Isaac MJ, Chinn TJ, Edbrooke SW, Forsyth PJ 1996. Geology of the Olympus Range Area, Southern Victoria Land, Antarctica. Institute of Geological and Nuclear Science 1:50 000 geological map 20. Lower Hutt, Institute of Geological & Nuclear Sciences. 1 sheet + 60 p.

Isbell JL 1999. The Kukri Erosion Surface; a reassessment of its relationship to rocks of the Beacon Supergroup in the central Transantarctic mountains, Antarctica. Antarctic Science 11: 228-238.

Isbell JL, Askin RA 1999. Search for evidence of impact at the Permian-Triassic boundary in Antarctica and Australia: Comment. Geology 27: 859.

Isbell JL, Cuneo NR 1996. Depositional framework of Permian coal-bearing strata, Southern Victoria Land, Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 125: 217-238.

Isbell JL, Koch ZJ, Szablewski GN, Lenaker PA 2008. Permian glacigenic deposits in the Transantarctic Mountains, Antarctica. In: Fielding CR, Frank TD, Isbell JL eds. Resolving the Late Paleozoic Ice Age in Time and Space. Geological Society of America Special Paper 441. Pp. 59-70.

Isbell JL, Lenaker PA, Askin RA, Miller MF, Babcock LE 2003. Re-evaluation of the timing and extent of Late Paleozoic glaciation in Gondwana: role of the Transantarctic Mountains. Geology 31: 977-980.

Ivy-Ochs S, Schlüchter C, Kubik PW, Dittrich-Hannen B, Beer J 1995. Minimum ^{10}Be exposure ages of early Pliocene for the Table Mountain plateau and the Sirius Group at Mount Fleming, Dry Valleys, Antarctica. Geology 23: 1007-1010.

Jennings I 1997. Sedimentology of the Sirius Group at Table Mountain, Antarctica. Unpublished BSc (Hons) thesis, Victoria University of Wellington, Wellington.

Jones LM, Faure G 1967. Age of the Vanda porphyry dikes in the Wright Valley, southern Victoria Land, Antarctica. Earth and Planetary Science Letters 3: 321-324.

Jones SA 1995a. Structural evolution of northern Walcott Bay, South Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Jones SA 1995b. Igneous structure associated with coeval mafic and felsic magmatism, south Victoria Land, Antarctica. Seventh International Symposium on Antarctic Earth Sciences, Siena, Italy, 10-15 September 1995. p. 216.

Jones SA 1997a. Contrasting structural styles during polyphase granitoid intrusion, South Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 40: 237-251.

Jones SA 1997b. Structural Inheritance from Crustal Anisotropy, South Victoria Land, Antarctica. In: Ricci CA ed. The Antarctic Region: Geological evolution and processes. Siena, Terra Antartica Publication. Pp. 571-576.

Jonkers HA 1998. Stratigraphy of Antarctic Late Cenozoic pectinid-bearing deposits. Antarctic Science 10: 161-170.

Judd FM 1986. The chronology of the Ross Sea II Glaciation, an Antarctic glaciation of Illinoian age. Unpublished MSc thesis, University of Waikato, Hamilton.

Kalamarides RI, Berg JH, Hank RA 1987: Lateral isotopic discontinuity in the lower crust: An example from Antarctica. Science 237: 1192-1195.

Kavanaugh JL, Cuffey KM, Morse DL, Bliss AK, Aciego SM 2009a. Dynamics and mass balance of Taylor Glacier, Antarctica: 3. State of mass balance. Journal of Geophysical Research. F04012. Earth Surface 114(F04) doi:10.1029/2009JF001331.

Kavanaugh JL, Cuffey KM, Morse DL, Conway H, Rignot E 2009b. Dynamics and mass balance of Taylor Glacier, Antarctica: 1. Geometry and surface velocities. Journal of Geophysical Research. F04010. Earth Surface 114(F04) doi:10.1029/2009JF001309.

Keiller IG 1991. Wright dikes: a geochemical study of dike-forming rock types within the Wright Valley, Southern Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Kellogg TB, Hughes T, Kellogg DE 1996. Late Pleistocene interactions of the East and West Antarctic ice-flow regimes: evidence from the McMurdo Ice Shelf. Journal of Glaciology 42: 486-500.

Kellogg DE, Kellogg TB 1996. Diatoms in South Pole ice: implications for eolian contamination of Sirius Group deposits. Geology 24: 115-118.

Kellogg TB, Kellogg DE, Stuiver M 1990. Late Quaternary history of the southwestern Ross Sea: evidence from debris bands on the McMurdo Ice Shelf, Antarctica. In: Elliot DH ed. Contributions to Antarctic Research. Antarctic Research Series 50. Washington DC, American Geophysical Union. Pp. 25-56.

Kellogg TB, Kellogg DE, Stuiver M 1991a. Oxygen isotope data from the McMurdo Ice Shelf, Antarctica; implications for debris band formation and glacial history. Antarctic Journal of the United States 26(5): 73-76.

Kellogg TB, Kellogg DE, Stuiver M 1991b. Radiocarbon dates from the McMurdo Ice Shelf, Antarctica; implications for debris band formation and glacial history. Antarctic Journal of the United States 26(5): 77-79.

Kelly MA, Denton GH, Hall BL 2002. Late Cenozoic paleoenvironment in southern Victoria Land, Antarctica, based on a polar glaciolacustrine deposit in western Victoria Valley. Geological Society of America Bulletin 114: 605-618.

Kelly PJ, Dunbar NW, Kyle PR, McIntosh WC 2008b. Refinement of the late Quaternary geologic history of Erebus volcano, Antarctica using $^{40}Ar/^{39}Ar$ and ^{36}Cl age determinations. Journal of Volcanology and Geothermal Research 177: 569-577.

Kelly PJ, Kyle PR, Dunbar NW, Sims KWW 2008a. Geochemistry and mineralogy of the phonolite lava lake, Erebus volcano, Antarctica: 1972-2004 and comparison with older lavas. Journal of Volcanology and Geothermal Research 177: 589-605.

Keys JR, Anderton PW, Kyle PR 1977. Tephra and debris layers in the Skelton Neve and Kempe Glacier, south Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 20: 971-1002.

Korsch RJ 1974. Petrographic comparison of the Taylor and Victoria Groups (Devonian to Triassic) in south Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 17: 523-541.

Korsch RJ 1984. The structure of Shapeless Mountain, Antarctica, and its relation to Jurassic igneous activity. New Zealand Journal of Geology and Geophysics 27(4): 487-504.

Kowalewski DE, Marchant DR, Head JW, Jackson DW 2012. A 2D model for characterising first-order variability in sublimation of buried glacier ice, Antarctica: Assessing the influence of polygon troughs, desert pavements and shallow subsurface salts. Permafrost and Periglacial Processes 23: 1-14.

Kyle PR 1971. The geology and geochemistry of Cape Crozier, Ross Island, Antarctica. Unpublished BSc (Hons) thesis, Victoria University of Wellington, Wellington.

Kyle PR 1976. Geology, mineralogy and geochemistry of the Late Cenozoic McMurdo Volcanic Group, Victoria Land, Antarctica. Unpublished PhD thesis, Victoria University of Wellington.

Kyle PR 1977. Mineralogy and glass chemistry of recent volcanic ejecta from Mt Erebus, Ross Island, Antarctica. New Zealand Journal of Geology and Geophysics 20(6): 1123-1146.

Kyle PR 1981a. Mineralogy and geochemistry of a basanite to phonolite sequence at Hut Point Peninsula, Antarctica, based on core from Dry Valley Drilling Project drillholes 1, 2 and 3. Journal of Petrology 22: 451-500.

Kyle PR 1981b. Glacial history of the McMurdo Sound area as indicated by the distribution and nature of McMurdo Volcanic Group rocks. Antarctic Research Series 33. Washington DC, American Geophysical Union. Pp. 403- 412.

Kyle PR 1981c. The geological history of Hut Point Peninsula as indicated by Dry Valley Drilling Project holes 1, 2 and 3. Antarctic Research Series 33. Washington DC, American Geophysical Union. Pp. 427-445.

Kyle PR 1990a. Erebus Volcanic Province: Summary. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 81-88.

Kyle PR 1990b. A.18. Hut Point Peninsula. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 109-112.

Kyle PR 1990c. Melbourne Volcanic Province: Summary. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 48-52.

Kyle PR ed. 1994. Volcanological and environmental studies of Mount Erebus, Antarctica. Antarctic Research Series 66. Washington DC, American Geophysical Union. 162 p.

Kyle PR, Adams J, Rankin PC 1979. Geology and petrology of the McMurdo Volcanic Group at Rainbow Ridge, Brown Peninsula, Antarctica. Geological Society of America Bulletin 90: 676-688.

Kyle PR, Cole JW 1974. Structural control of volcanism in the McMurdo Volcanic Group, Antarctica. Bulletin of Volcanology 38: 16-25.

Kyle PR, Elliot DH, Sutter JF 1981. Jurassic Ferrar Supergroup tholeiites from the Transantarctic Mountains, Antarctica, and their relationship to the initial fragmentation of Gondwana. In: Cresswell MM, Vella P eds. Gondwana Five: selected papers and abstracts of papers presented at the Fifth International Gondwana Symposium, Wellington. Rotterdam, A.A. Balkema. Pp. 283-287.

Kyle PR, Moore JA, Thirlwall MF 1992. Petrologic evolution of anorthoclase phonolite lavas at Mount Erebus, Ross Island, Antarctica. Journal of Petrology 33: 849-875.

Kyle PR, Muncy HL 1989. Geology and geochronology of McMurdo Volcanic Group rocks in the vicinity of Lake Morning, McMurdo Sound, Antarctica. Antarctic Science 1: 345-350.

Kyle PR, Sutter JF, McIntosh WC, Cherry E, Noltimier G 1983. $^{40}Ar/^{39}Ar$ age spectra and paleomagnetic measurements of Ferrar Supergroup samples from the Transantarctic Mountains, Antarctica. Abstract. In: Oliver RL, James PR, Jago JB eds. Antarctic Earth Science. Canberra, Australian Academy of Science. p. 242.

Kyle PR, Treves SB 1973. Review of the geology of Hut Point Peninsula, Ross Island, Antarctica. Dry Valley Drilling Project Bulletin 2: 1-10.

Kyle PR, Wright AC, Kirsch I 1987. Ultramafic xenoliths in the late Cenozoic McMurdo Volcanic Group, Western Ross Sea embayment, Antarctica. In: Nixon P ed. Mantle Xenoliths. New York, John Wiley. Pp. 287-293.

Kyle RA 1977a. Devonian palynomorphs from the basal Beacon Supergroup of south Victoria Land, Antarctica: note. New Zealand Journal of Geology and Geophysics 20: 1147-1150.

Kyle RA 1977b. Palynostratigraphy of the Victoria Group of south Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 20: 1081-1102.

Kyle RA, Schopf JM 1982. Permian and Triassic palynostratigraphy of the Victoria Group, Transantarctic Mountains. In: Craddock C ed. Antarctic Geoscience. Madison, University of Wisconsin Press. Pp. 649-659.

Laird MG, Mansergh GD, Chappell JMA 1971. Geology of the central Nimrod Glacier area, Antarctica. New Zealand Journal of Geology and Geophysics 14: 427-68.

Lancaster N 2002. Flux of eolian sediment in the McMurdo dry valleys, Antarctica: a preliminary assessment. Arctic, Antarctic, and Alpine Research 34: 318-318-323.

Lawrence KP, Tauxe L, Staudigel H, Constable, CG, Koppers A, McIntosh WC, Johnson CL 2009. Paleomagnetic field properties at high southern latitude. Geochemistry Geophysics Geosystems 10: Q01005 doi:10.1029/2008GC002072.

Lawver LA, Gahagan LM 1994. Constraints on Timing of Extension in the Ross Sea Region. Terra Antartica 1(3): 545-552.

Leat PT 2008. On the long-distance transport of Ferrar magmas. Geological Society of London Special Publication 302: 45-61.

Le Bas M, Le Maitre MJ, Streckeisen A, Zanettin B 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology 27: 745-750.

Leckie RM, Webb PN 1982. Scallop Hill Formation and associated Pliocene marine deposits of southern McMurdo Sound. Antarctic Journal of the United States 17(5): 54-56.

LeMasurier WE 1990. Overview. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 1-17.

LeMasurier WE, Thomson JW, Baker PE, Kyle PR, Rowley PD, Smellie JL, Verwoerd WJ 1990. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. 487 p.

LeMasurier WE, Wade AF 1968. Fumarolic activity in Marie Byrd Land, Antarctica. Science 162(3851): 352.

Levy R, Cody R, Crampton J, Fielding C, Golledge N, Harwood D, Henrys S, McKay R, Naish T, Ohneiser C, Wilson GS, Wilson TA, Winter D 2012. Late Neogene climate and glacial history of the Southern Victoria Land coast from integrated drill core, seismic and outcrop data. Global and Planetary Change 80-81: 61-84.

Lewis AR, Ashworth AC, Lepper K, Willenbring JK, Hemming SR 2011. Neogene ice-marginal climate from terrestrial records in the Transantarctic Mountains. Abstract. Eleventh International Symposium on Antarctic Earth Sciences, Edinburgh, Scotland, 10-15 July 2011. p. 30.

Lewis AR, Marchant DR, Ashworth AC, Hedenaes L, Hemming SR, Johnson JV, Leng MJ, Machlus ML, Newton AE, Raine JI, Willenbring JK, Williams M, Wolfe AP 2008. Mid-Miocene cooling and the extinction of tundra in continental Antarctica. Proceedings of the National Academy of Sciences of the United States of America 105(31): 10676-10680 doi:10.1073/pnas.0802501105.

Lewis AR, Marchant DR, Ashworth AC, Hemming SR, Machlus ML 2007. Major middle Miocene global climate change: Evidence from East Antarctica and the Transantarctic Mountains. Geological Society of America Bulletin 115 (11/12): 1449-1461.

Lewis AR, Marchant DR, Kowalewski DE, Baldwin SL, Webb LE 2006. The age and origin of the Labyrinth, western Dry Valleys, Antarctica: evidence for extensive Middle Miocene subglacial floods and freshwater discharge to the Southern Ocean. Geology 34: 513-516.

Linkletter G, Bockheim J, Ugolini FC 1973. Soils and glacial deposits in the Beacon Valley, southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 16: 90-108.

Lloyd-Davies MT, Atkins CB, van der Meer JJM, Barrett PJ, Hicock SR 2009. Evidence for cold-based glacial activity in the Allan Hills, Antarctica. Quaternary Science Reviews: 1-14 doi:10.1016/j.quascirev.2009.08.002.

Lockett GM 2003 Landslide and debris flow deposits at the margin of a large vent complex, Mawson Formation, Allan Hills, southern Victoria Land. Unpublished MSc thesis, University of Otago, Dunedin.

Lockett GM, White JDL 2008. Coal-fragment rank and contact relationships of debris avalanche and primary pyroclastic deposits in the Mawson Formation, Ferrar LIP, Allan Hills, Antarctica. Journal of Volcanology and Geothermal Research 172(1/2): 61-74 doi:10.1016/j.jvolgeores.2006.02.017.

Lopatin BG 1972. Basement complex of the McMurdo “oasis”, southern Victoria Land. In: Adie RJ ed. Antarctic Geology and Geophysics. Oslo, Universitetsforlaget. Pp. 287- 292.

Lovett AP 2011. Origin, formation and deformation of mirabilite deposits: Hobbs Glacier region, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Lyon GL, Giggenbach WF 1974. Geothermal activity in Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 17: 511-521.

Marchant DR, Denton GH, Bockheim JG, Wilson SC, Kerr AR 1994. Quaternary changes in level of the upper Taylor Glacier, Antarctica: implications for paleoclimate and East Antarctic ice sheet dynamics. Boreas 23: 29-43.

Marchant DR, Denton GH, Sugden DE, Swisher CC 1993a. Miocene glacial stratigraphy and landscape evolution of the western Asgard Range, Antarctica. Vega Symposium (1993: Stockholm, Sweden). Pp. 303-330.

Marchant DR, Denton GH, Swisher CC 1993b. Miocene-Pliocene-Pleistocene glacial history of Arena Valley, Quartermain Mountains, Antarctica. Vega Symposium (1993: Stockholm, Sweden). Pp. 269-302.

Marchant DR, Denton GH, Swisher CC, Potter N 1996. Late Cenozoic Antarctic paleoclimate reconstructed from volcanic ashes in the Dry Valleys region of southern Victoria Land. Geological Society of America Bulletin 108: 181-194.

Marchant DR, Head JW 2007. Antarctic dry valleys: Microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars. Icarus 192(1): 187-222.

Markle BR, Bertler NAN, Sinclair KE, Sneed SB 2012. Synoptic variability in the Ross Sea region, Antarctica, as seen from back-trajectory modeling and ice core analysis. Journal of Geophysical Research. D. Atmospheres 117(D2).

Marsh BD 1995. Solidification fronts and magmatic evolution. Mineralogical Magazine 60: 5-40.

Marsh BD 2004. A magmatic mush column Rosetta Stone: the McMurdo Dry Valleys of Antarctica. Eos 85 (47: supplement): 497-508 doi:10.1029/2004EO470001.

Martin AP 2009. Mt. Morning, Antarctica: Geochemistry, geochronology, petrology, volcanology, and oxygen fugacity of the rifted Antarctic lithosphere. Unpublished PhD thesis, University of Otago, Dunedin.

Martin AP, Cooper AF 2010. Post 3.9 Ma fault activity within the West Antarctic rift system: onshore evidence from Gandalf Ridge, Mount Morning eruptive centre, southern Victoria Land, Antarctica. Antarctic Science 22: 513-521.

Martin AP, Cooper AF, Dunlap WJ 2010. Geochronology of Mount Morning, Antarctica: two-phase evolution of a long-lived trachyte-basanite-phonolite eruptive center. Bulletin of Volcanology 72: 357-371.

McClintock MK 2001. Phreatomagmatism at Coombs Hills, Antarctica: Magma-water super-volcanism in a wet, failed rift. Unpublished MSc thesis, University of Otago, Dunedin.

McClintock MK, White JDL 2002. Granulation of weak rock as a precursor to peperite formation: coal peperite, Coombs Hills, Antarctica. Journal of Volcanology and Geothermal Research 114: 205-217.

McClintock M, White JDL 2006. Large phreatomagmatic vent complex at Coombs Hills, Antarctica: Wet, explosive initiation of flood basalt volcanism in the Ferrar-Karoo LIP. Bulletin of Volcanology 68: 215-239.

McCraw JD 1962. Volcanic detritus in Taylor Valley, Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 5: 740-745.

McElroy CT 1969. Comparative lithostratigraphy of Gondwana sequences, eastern Australia and Antarctica. In: Amos AJ ed. Gondwana Stratigraphy. Paris, UNESCO. Pp. 441-466.

McElroy CT, Rose G 1987. Geology of Beacon Heights, Southern Victoria Land, Antarctica. New Zealand Geological Survey 1:50 000 miscellaneous series map 15. Wellington, Department of Scientific and Industrial Research. 1 sheet + 47 p.

McGinnis LD ed. 1981. Dry Valley Drilling Project. Antarctic Research Series 33. Washington DC, American Geophysical Union. 465 p.

McIntosh WC 2000. $^{40}Ar/^{39}Ar$ geochronology of tephra and volcanic clasts in CRP-2A, Victoria Land Basin, Antarctica. Terra Antartica 7(4): 621-630.

McIntosh WC, Kyle PR 1990. Hallett Volcanic Province: Summary. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 26-51.

McKay RM, Barrett PJ, Harper MA, Hannah MJ 2008. Atmospheric transport and concentration of diatoms in surficial and glacial sediments of the Allan Hills, Transantarctic Mountains. Palaeogeography, Palaeoclimatology, Palaeoecology 260: 168-183.

McKay R, Browne G, Carter L, Cowan E, Dunbar G, Krissek L, Naish T, Powell R, Reed J, Talarico F, Wilch T 2009. The stratigraphic signature of the late Cenozoic Antarctic ice sheets in the Ross Embayment. Geological Society of America Bulletin 121: 1537-1561.

McKay R, Naish T, Powell R, Barrett P, Talarico F, Kyle P, Monien D, Kuhn G, Jackolski C, Williams T 2012. Pleistocene variability of Antarctic Ice Sheet extent in the Ross Embayment. Quaternary Science Reviews 34: 93-112.

McKelvey BC 1960. Geological investigations in south Victoria land, Antarctica. Unpublished MSc thesis, Victoria University of Wellington, Wellington.

McKelvey BC 1961. Geological reconnaissance in Victoria Land, Antarctica. Nature (London) 189(4764): 545-547.

McKelvey BC 1970. Recent discoveries of Devonian fish in Antarctica. Polar Record 15: 216-217.

McKelvey BC 1972. Stratigraphy of the Beacon Supergroup between the Olympus and Boomerang ranges, Victoria Land. In: Adie RJ ed. Antarctic Geology and Geophysics. Oslo, Universitetsforlaget. Pp. 345-352.

McKelvey BC, Webb PN 1959. Geological investigations in south Victoria Land, Antarctica. Part 2: Geology of the Upper Taylor Glacier region. New Zealand Journal of Geology and Geophysics 2: 718 -728.

McKelvey BC, Webb PN 1962. Geological investigations in southern Victoria Land, Antarctica. Part 3, Geology of Wright Valley. New Zealand Journal of Geology and Geophysics 5: 143-162.

McKelvey BC, Webb PN, Gorton MP, Kohn BP 1970. Stratigraphy of the Beacon Supergroup between the Olympus and Boomerang ranges, south Victoria Land, Antarctica. Nature (London) 227: 1126-1128.

McKelvey BC, Webb PN, Harwood DM, Mabin MCG 1991. The Dominion Range Sirius Group: a record of the Late Pliocene-Early Pleistocene Beardmore Glacier. In: Thompson MRA, Crame JA, Thompson JW eds., Geological Evolution of Antarctica. Cambridge, UK, Cambridge University Press. Pp. 675-682.

McKelvey BC, Webb PN, Kohn BP 1977. Stratigraphy of the Taylor and lower Victoria Groups (Beacon Supergroup) between the Mackay Glacier and Boomerang Range, Antarctica. New Zealand Journal of Geology and Geophysics 20: 813-863.

McLeod M, Bockheim JG, Balks MR 2008. Glacial geomorphology, soil development and permafrost features in central-upper Wright Valley, Antarctica. Geoderma 144: 93-103.

McPherson JG 1978. Stratigraphy and sedimentology of the Upper Devonian Aztec Siltstone, southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 21: 667-683.

McPherson JG 1979. Calcrete (caliche) palaeosols in fluvial redbeds of the Aztec Siltstone (Upper Devonian), southern Victoria Land, Antarctica. Sedimentary Geology 22: 267-285.

Mellish SD 2000. Panorama geology, Antarctica: a study of the mafic, undersaturated and granitic alkaline Ross Orogeny magmatism from Panorama Ridge, southern Victoria Land. Unpublished MSc thesis, University of Otago, Dunedin.

Mellish SD, Cooper AF, Walker NW 2002. Panorama Pluton: a composite gabbro-monzodiorite early Ross Orogeny intrusion in southern Victoria Land, Antarctica. In: Gamble JA, Skinner DNB, Henrys SA eds. Antarctica at the close of a millennium. Proceedings of the 8th International Symposium on Antarctic Earth Sciences. Royal Society of New Zealand Bulletin 35: 129-141.

Mercer JH 1972. Some observations on the glacial geology of the Beardmore Glacier area. In: Adie RJ ed. Antarctic Geology and Geophysics. Oslo, Universitetsforlaget. Pp. 427-433.

Miller MF, Mabin MCG 1998. Antarctic Neogene landscapes: in the refrigerator or in the deep freeze? GSA Today 8(4): 1-8.

Moore JA, Kyle PR 1987. Volcanic geology of Mount Erebus, Ross Island, Antarctica. Proceedings of the National Institute of Polar Research Symposium on Antarctic Geoscience 1: 48-65.

Moore JA, Kyle PR 1990. A.17. Mount Erebus. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 103-108.

Morrison AD 1989. Ferrar Dolerite intrusions, Terra Cotta Mountain, Southern Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Morrison AD, Reay A 1995. Geochemistry of Ferrar Dolerite sills and dikes at Terra Cotta Mountain, south Victoria Land, Antarctica. Antarctic Science 7: 73-85.

Mortimer G 1981. Provisional report on the geology of the basement complex between the Salmon and Miers Valleys, McMurdo Sound, Antarctica. New Zealand Antarctic Record 3: 1-8.

Mortimer N, Forsyth PJ, Turnbull IM 2002. Reassessment of faults in the Wilson Piedmont Glacier area: implications for age and style of Transantarctic Mountains uplift. In: Gamble JA, Skinner DNB, Henrys SA eds. Antarctica at the close of a millennium. Proceedings of the 8th International Symposium on Antarctic Earth Sciences. Royal Society of New Zealand Bulletin 35: 207-213.

Mortimer N, Parkinson D, Raine JI, Adams CJ, Oliver PJ, Palmer K 1995. Ferrar magmatic province rocks discovered in New Zealand: implications for Mesozoic Gondwana geology. Geology 23: 185-188.

Muirhead JD, Airoldi G, Rowland JV, White JDL 2012. Interconnected sills and inclined sheet intrusions control shallow magma transport in the Ferrar large igneous province, Antarctica. Geological Society of America Bulletin 124: 162-180.

Muncy HL 1979. Geologic history and petrogenesis of alkaline volcanic rocks, Mount Morning, Antarctica. Unpublished MSc thesis, Ohio State University, Columbus.

Murphy DJ 1971. The petrology and deformation of the basement complex, Wright Valley, Antarctica, with special reference to the origin of augen gneisses. Unpublished PhD thesis, University of Wyoming, Laramie.

Murrell B 1973. Cenozoic stratigraphy in Lower Taylor Valley, Antarctica. New Zealand Journal of Geology and Geophysics 16: 225-242.

Naish TR, Powell RD, Barrett PJ, Levy RH, Henrys SA, Wilson GS, Krissek LA, Niessen F, Pompilio M, Ross J, Scherer R, Talarico F, Pyne A, ANDRILL-MIS science team 2008. Late Cenozoic climate history of the Ross embayment from the AND-1B drill hole: culmination of three decades of Antarctic margin drilling. In: Cooper A, Raymond C et al. eds. Antarctica: A keystone in a changing world. 10th International Symposium on Antarctic Earth Sciences 2007, University of California, Santa Barbara. USGS Open-File Report 2007-1047. Keynote paper KP07, 11 p.

Naish TR, Powell RD, Levy RH eds. 2007b. Studies from the ANDRILL, McMurdo Ice Shelf Project, Antarctica—Initial Science Report on AND-1B. Terra Antartica 14(3).

Naish TR, Powell RD, Levy RH, Florindo F, Harwood D, Kuhn G, Niessen F, Talarico F, Wilson G 2007a. A record of Antarctic climate and ice sheet history recovered. Eos, Transactions, American Geophysical Union 88: 557-558.

Naish TR, Powell R, Levy RH, Wilson G, Scherer R, Talarico F, Krissek L, Niessen F, Pompilio M, Wilson T, Carter L, DeConto R, Huybers P, McKay R, Pollard D, Ross J, Winter D, Browne GH, Cody R, Crampton JS, Graham IJ, Hansaraj D, Henrys SA, Raine JI, Strong CP 2009. Obliquity-paced Pliocene West Antarctic ice sheet oscillations. Nature 458(7236): 322-328 doi:10.1038/nature07867.

Naish TR, Woolfe KJ, Barrett PJ, Wilson GS, Atkins C, Bohaty SM, Buecker CJ, Claps M, Davey FJ, Dunbar GB and others 2001. Orbitally induced oscillations in the East Antarctic ice sheet at the Oligocene/Miocene boundary. Nature 413(6857): 719-723.

Ng F, Hallet B, Sletten RS, Stone JO 2005. Fast-growing till over ancient ice in Beacon Valley, Antarctica. Geology 33: 121-124.

Nichols RL 1961. Multiple glaciation in the Wright Valley, McMurdo Sound, Antarctica. Abstract of symposium papers. Tenth Pacific Science Congress, Honolulu, The Pacific Science Association. p. 317.

Nichols RL 1964. Present status of Antarctic glacial geology. In: Adie RJ ed. Antarctic Geology. Amsterdam, North Holland Publishing Company. Pp. 123-137.

Nichols RL 1968. Coastal geomorphology, McMurdo Sound, Antarctica. Journal of Glaciology 7(51): 449-478.

Nichols RL 1971. Glacial geology of the Wright Valley, Antarctica. In: Quam LO ed. Research in the Antarctic. A symposium presented at the Dallas meeting of the American Association for the Advancement of Science, December, 1968. Washington DC, American Association for the Advancement of Science. Pp. 293-340.

Ohneiser C, Wilson GS 2012. Revised magnetostratigraphic chronologies for New Harbour drill cores, southern Victoria Land, Antarctica. Global and Planetary Change 82-83: 12-24 doi:10.1016/j.gloplacha.2011.11.007.

Palmer DF, Bradley J, Prebble WM 1967. Orbicular granodiorite from the Taylor Valley, south Victoria Land, Antarctica. Geological Society of America Bulletin 78: 1423-1428.

Paulsen T, Encarnacion J, Valencia VA, Roti Roti JM, Rasoazanamparany C 2011. Detrital U-Pb zircon analysis of an Eocene McMurdo Erratic sandstone, McMurdo Sound, Antarctica. New Zealand Journal of Geology and Geophysics 54: 353-360.

Paulsen TS, Wilson TJ 2009. Structure and age of volcanic fissures on Mount Morning: a new constraint on Neogene to contemporary stress in the West Antarctic Rift, southern Victoria Land, Antarctica. Geological Society of America Bulletin 121: 1071-1088.

Payne JL, Lehrmann, DJ, Wei J, Orchard MJ, Schrag DP, Knoll AH 2004. Large perturbations of the carbon cycle during recovery from the end-Permian extinction. Science 305: 506-509.

Péwé TL 1960. Multiple Glaciation in the McMurdo Sound Region, Antarctica: A Progress Report. Journal of Geology 68: 498-514.

Plume RW 1978. A revision of the existing stratigraphy of the New Mountain Sandstone (Beacon Supergroup), south Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 21: 167-173.

Plume RW 1982. Sedimentology and paleocurrent analysis of the basal part of the Beacon Supergroup (Devonian [and older?] to Triassic) in south Victoria Land, Antarctica. In: Craddock C ed. Antarctic Geoscience. Madison, University of Wisconsin Press. Pp. 571-580.

Plumstead EP 1964. Paleobotany of Antarctica. In: Adie RJ ed. Antarctic Geology. Amsterdam, North Holland Publishing Company. Pp. 637-654.

Pocknall DT, Chinn T, Sykes RO, Skinner DNB 1994: Geology of the Convoy Range area, southern Victoria Land, Antarctica. Institute of Geological & Nuclear Sciences 1:50 000 geological map 11. Lower Hutt, Institute of Geological & Nuclear Sciences. 1 sheet + 36 p.

Prebble JG, Raine JI, Barrett PJ, Hannah MJ 2006. Vegetation and climate from two Oligocene glacioeustatic sedimentary cycles (31 and 24 Ma) cored by the Cape Roberts Project. Palaeogeography, Palaeoclimatology, Palaeoecology 231: 101-109.

Prebble WM 1963. Lamprophyre, microgranite, and porphyry dykes of the Taylor Valley region, Southern Victoria Land, Antarctica. Unpublished BSc (Hons) thesis, Victoria University of Wellington, Wellington.

Prentice ML 1985. Peleus glaciation of Wright Valley, Antarctica. South African Journal of Science 81: 241-243.

Prentice ML, Bockheim JG, Wilson SC, Burckle LH, Hodell DA, Schlüchter C, Kellogg DE 1993. Late Neogene Antarctic Glacial History: Evidence from Central Wright Valley. Antarctic Research Series 60. Washington DC, American Geophysical Union. Pp. 207-250.

Prentice ML, Krusic AG 2005. Early Pliocene alpine glaciation in Antarctica: Terrestrial versus tidewater glaciers in Wright Valley. Geografiska Annaler 87(A): 87-109.

Prentice M, Mullins J, Thomas J-C, Isaac M, Smith S, Chinn TJ, Bockheim J, Campbell I, Turnbull I, Claridge G and others 1999. VALMAP: A GIS for Physical Features in the McMurdo Dry Valleys, Antarctica (abstract). In: Skinner DNB ed. 8th International Symposium of Antarctic Earth Sciences, Wellington, 1999. p. 250.

Priestley RE 1909. Scientific results of the Western Journey. In: Shackleton EH. The Heart of the Antarctic. London, William Heinemann. Appendix III, Pp. 315-330.

Priestley RE 1922. Geological climates of the Antarctic. In: Wright CSP, Priestley RE eds. British Antarctic (Terra Nova) Expedition 1910-1913. London, Harrison and Sons. Pp. 418-447.

Prior GT 1907. Report on the rock specimens collected during the “Discovery” Antarctic Expedition, 1901-4. Natural History (Geology) Vol. 1. London, The British Museum. Pp. 101-160.

Pyne AR 1983. Deposition of the Weller Coal Measures (Permian) in south Victoria Land. (Abstract). In: Oliver RL, James PR, Jago JB eds. Antarctic Earth Science. Canberra, Australian Academy of Science. p. 227.

Pyne AR 1984. Geology of the Mt Fleming area, south Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 27(4): 505-512.

Pyne AR 1986. Sedimentology of Weller Coal Measures at Mount Fleming, Antarctica. Unpublished MSc thesis, Victoria University of Wellington, Wellington.

Rattenbury MS, Heron DW 1997. Revised procedures and specifications for the QMAP GIS. Institute of Geological & Nuclear Sciences Science Report. 52 p.

Read SE 2001. Hillary Granitoids of the Koettlitz Glacier Alkaline Province, Antarctica. In: GSNZ Annual Conference, 27-29th November 2001, Hamilton: programme & abstracts. Geological Society of New Zealand Miscellaneous Publication 110A: 131.

Read SE 2010. Koettlitz Glacier Alkaline Province: Late Neoproterozoic extensional magmatism in southern Victoria Land, Antarctica. Unpublished PhD thesis, University of Otago, Dunedin.

Read SE, Cooper AF, Walker NW 2002. Geochemistry and U-Pb geochronology of the Neoproterozoic-Cambrian Koettlitz Glacier Alkaline Province, Royal Society Range, Transantarctic Mountains, Antarctica. In: Gamble JA, Skinner DNB, Henrys SA eds. Antarctica at the close of a millennium. Proceedings of the 8th International Symposium on Antarctic Earth Sciences. Royal Society of New Zealand Bulletin 35: 143-151.

Rees MN, Duebendorfer EM, Rowell J 1989. The Skelton Group, southern Victoria Land. Antarctic Journal of the United States 1989 Review 24(5): 21-24.

Retallack GJ 1997. Early forest soils and their role in Devonian global change. Science 276(5312): 583-585.

Retallack GJ 1999. Search for evidence of impact at the Permian-Triassic boundary in Antarctica and Australia: Reply. Geology 27: 860.

Retallack GJ, Alonso-Zarza AM 1998. Middle Triassic paleosols and paleoclimate of Antarctica. Journal of Sedimentary Research 68(1): 169-184.

Retallack GJ, Jahren AJ, Sheldon ND, Chakrabarti R, Metzger CA, Smith RMH 2005. The Permian-Triassic boundary in Antarctica. Antarctic Science 17: 241-258.

Retallack GJ, Metzger CA, Greaver T, Jahren AJ, Smith RMH, Sheldon ND 2006. Middle - Late Permian mass extinction on land. Geological Society of America Bulletin 118: 1398-1411.

Retallack GJ, Robinson SE, Krull ES 1995. Middle Devonian paleosols and vegetation of the Lashly Mountains, Antarctica. Antarctic Journal of the United States 30: 62-65.

Reubi O, Ross P-S, White JDL 2005. Debris avalanche deposits associated with large igneous province volcanism: An example from the Mawson Formation, central Allan Hills, Antarctica. Geological Society of America Bulletin 117: 1615-1628.

Ribecai C 2007. Early Jurassic miospores from Ferrar Group of Carapace Nunatak, South Victoria Land, Antarctica. Review of Paleobotany and Palynology 144: 3-12.

Richardson CD 2002. Geology of west Worcester Hills, southern Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Riley TR, Knight KB 2001. Age of pre-break-up Gondwana magmatism: a review. Antarctic Science 13: 99-110.

Rocchi S, Di Vincenzo G, Ghezzo C, Nardini I 2009. Granite lamprophyre connection in the latest stages of the early Paleozoic Ross Orogeny (Victoria Land, Antarctica). Geological Society of America Bulletin 121: 801-819.

Ross JC 1847. A voyage of discovery and research in the southern and Antarctic regions during the years 1839-43. London, John Murray. 2 volumes.

Ross P-S 2005. Volcanology of the Mawson Formation at Coombs and Allan Hills, South Victoria Land, Antarctica. Unpublished PhD thesis, University of Otago, Dunedin.

Ross P-S, White JDL, McClintock M 2008. Geological evolution of the Coombs-Allan Hills area, Ferrar large igneous province, Antarctica: Debris avalanches, mafic pyroclastic density currents, phreatocauldrons. Journal of Volcanology and Geothermal Research 172: 38-60.

Rowell AJ, Rees EM, Duebendorfer ET, Wallin ET, van Schmus WR, Smith IE 1993. An active Neoproterozoic margin; evidence from the Skelton Glacier area, Transantarctic Mountains. Journal of the Geological Society of London 150: 677-682.

Salvador A 1994 International stratigraphic guide: a guide to stratigraphic classification, terminology, and procedure. International Subcommission on Stratigraphic Classification, International Union of Geological Sciences. 2nd edition. 214 p.

Sandroni S, Talarico F 2006. Clasts from CIROS-2 core, New Harbour, Antarctica: implications for ice flow in the McMurdo Sound during Pliocene-Pleistocene time. Palaeogeography, Palaeoclimatology, Palaeoecology 231: 215-232.

Schaefer JM, Baur H, Denton GH, Ivy-Ochs S, Marchant DR, Schlüchter C, Wieler R 2000. The oldest ice on Earth in Beacon Valley, Antarctica; new evidence from surface exposure dating. Earth and Planetary Science Letters 179: 91-99.

Schaefer JM, Ivy-Ochs S, Wieler R, Leya I, Baur H, Denton GH, Schlüchter C 1999. Cosmogenic noble gas studies in the oldest landscape on earth: surface exposure ages of the Dry Valleys, Antarctica. Earth and Planetary Science Letters 167: 215-226.

Score R. Lindstrom MM 1990. Guide to the U.S. collection of Antarctic meteorites 1976-1988. Antarctic Meteorite Newsletter 13(1). Johnson Space Centre, Houston, Texas. 135 p.

Scott RF 1905. The Voyage of the Discovery. London, Smith, Elder and Co. 2 volumes.

Selby MJ, Rains RB, Palmer RWP 1974. Eolian deposits of the ice-free Victoria Valley, southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 17: 543-562.

Selby MJ, Wilson AT 1971. Possible Tertiary age for some Antarctic cirques. Nature 229: 623-624.

Seward AC 1914. Antarctic fossil plants. Natural History Report of the British Antarctic (Terra Nova) Expedition 1910: Geology 1(1). London, The British Museum. 49 p.

Shaw J, Healy TR 1977. Formation of the Labyrinth, Wright Valley, Antarctica. New Zealand Journal of Geology and Geophysics 20: 933-947.

Shaw J, Healy TR 1980. Morphology of the Onyx River system, McMurdo Sound region, Antarctica. New Zealand Journal of Geology and Geophysics 23: 223-238.

Shevenell A, Kennett JP, Lea DW 2004. Middle Miocene Southern Ocean cooling and Antarctic cryosphere expansion. Science 305: 1766-1770.

Simpson AL 2002. Felsic magmatism in the Darwin Glacier region, southern Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Simpson AL, Cooper AF 2002. Short note: geochemistry of the Darwin Glacier region granitoids, southern Victoria Land. Antarctic Science 14: 425-426.

Simpson G 1994. Fluids and metamorphism of the Koettlitz Group. Unpublished MSc thesis, University of Otago, Dunedin.

Simpson G, Aslund T 1996. Diorite and gabbro of the Dromedary mafic complex, South Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 39: 403-414.

Skinner DNB 1965. Petrographic criteria of the rock units between the Byrd and Starshot Glaciers, South Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 8: 292-303.

Skinner DNB 1982. Stratigraphy and structure of low-grade metasedimentary rocks of the Skelton Group, southern Victoria Land: does Teall greywacke really exist? In: Craddock C ed. Antarctic Geoscience. Madison, University of Wisconsin Press. Pp. 555-563.

Skinner DNB 1983. The granites of two orogenies of southern Victoria Land. In: Oliver PB, James PR, Jago JB eds. Antarctic Earth Science. Canberra, Australian Academy of Science. Pp. 160-163.

Skinner DNB, Waterhouse BC, Brehaut G, Sullivan K 1976. NZ Geological Survey Expedition 1975-76 Skelton-Koettlitz Glaciers. New Zealand Geological Survey report DS 58. 51 p.

Sletten RS, Mann DH, McIntosh WC, Dunbar NW, Prentice ML, Dickinson W, Stone JO 2007. Possible redeposition of volcanic ashes in the Dry Valleys by glacier transport. In: Cooper A, Raymond C et al. eds. Antarctica: A keystone in a changing world. 10th International Symposium on Antarctic Earth Sciences 2007, University of California, Santa Barbara. USGS Open-File Report 2007-1047. Extended Abstract 158, 4 p.

Smillie RW 1989. Granite Harbour Intrusives, Taylor Valley and Ferrar Glacier region, Southern Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Smillie RW 1992. Suite subdivision and petrological evolution of granitoids from the Taylor Valley and Ferrar Glacier region, south Victoria Land. Antarctic Science 4: 71-87.

Smith WC 1924. The plutonic and hypabyssal rocks of South Victoria Land. Natural History Reports of the British Antarctic (Terra Nova) Expedition 1910: Geology 1(6). London, The British Museum. Pp. 167-227.

Smith WC 1954. The volcanic rocks of the Ross Archipelago. Natural History Reports of the British Antarctic (Terra Nova) Expedition 1910: Geology 2(1). London, The British Museum. Pp. 1-107.

Smith WC, Debenham F 1921. The metamorphic rocks of the McMurdo Sound region: Natural History Reports of the British Antarctic (Terra Nova) Expedition 1910: Geology 1(5a). London, The British Museum. Pp. 131-144.

Speden IG 1960. Post-glacial terraces near Cape Chocolate, McMurdo Sound, Antarctica. New Zealand Journal of Geology and Geophysics 3(2): 203-217.

Speden IG 1962. Fossiliferous Quaternary marine deposits in the McMurdo Sound region, Antarctica. New Zealand Journal of Geology and Geophysics 5: 746-774.

Speirs JC, McGowan HA, Neil DT 2008. Polar Eolian Sand Transport: Grain Characteristics Determined by an Automated Scanning Electron Microscope (QEMSCAN®). Arctic, Antarctic, and Alpine Research 40: 731-743.

Staiger JW, Marchant DR, Schaefer JM, Oberholzer P, Johnson JV, Lewis AR, Swanger KM 2006. Plio-Pleistocene history of Ferrar Glacier, Antarctica: implications for climate and ice sheet stability. Earth and Planetary Science Letters 243: 489-503 doi:10.1016/j/epsl.2006.01.037.

Stilwell JD, Feldmann RM eds. 2000. Paleobiology and paleoenvironments of Eocene rocks, McMurdo Sound, east Antarctica. Antarctic Research Series 76. Washington DC, American Geophysical Union. 372 p.

Stroeven AP, Prentice ML 1997. A case for Sirius Group glaciation at Mount Fleming, South Victoria Land, Antarctica: a case against Pliocene East Antarctic Ice Sheet reduction. Geological Society of America Bulletin 109(7): 825-840.

Stuiver M, Denton GH, Hughes TJ, Fastook JL 1981. History of the marine ice sheet in West Antarctica during the Last Glaciation: a working hypothesis. In: Denton GH, Hughes TJ eds. The last of the great ice sheets. New York, John Wiley and Sons. Pp. 319-436.

Stump E 1995. The Ross Orogen of the Transantarctic Mountains. Cambridge, UK, Cambridge University Press. 248 p.

Stump E, Gehrels G, Talarico F, Carosi R 2007. Constraints from detrital zircon geochronology on the early deformation of the Ross orogen, Transantarctic Mountains, Antarctica. In: Cooper A, Raymond C et al. eds. Antarctica: A keystone in a changing world. 10th International Symposium on Antarctic Earth Sciences 2007, University of California, Santa Barbara. USGS Open-File Report 2007-1047. Extended Abstract 166, 3 p.

Sugden D, Denton G 2004. Cenozoic landscape evolution of the Convoy Range to Mackay Glacier area, Transantarctic Mountains: onshore to offshore synthesis. Geological Society of America Bulletin 116: 840-857.

Sugden DE, Denton GH, Marchant DR 1995a. Landscape evolution of the Dry Valleys, Transantarctic Mountains: tectonic implications. Journal of Geophysical Research 100: 9949-9967.

Sugden DE, Marchant DR, Denton GH 1993. The case for a stable east Antarctic Ice Sheet: the background. Geografiska Annaler 75A: 151-154.

Sugden DE, Marchant DR, Potter N, Souchez RA, Denton GH, Swisher CC, Tison J-L 1995b. Preservation of Miocene glacier ice in East Antarctica. Nature (London) 376(6539): 412-414.

Sugden DE, Summerfield MA, Denton GH, Wilch TI, McIntosh WC, Marchant DR, Rutford RH 1999. Landscape development in the Royal Society Range, southern Victoria Land, Antarctica: stability since the mid-Miocene. Geomorphology 28: 181-200.

Summerfield MA, Sugden DE, Denton GH, Marchant DR, Cockburn HAP, Stuart FM 1999. Cosmogenic isotope data support previous evidence of extremely low rates of denudation in the Dry Valleys region, southern Victoria Land, Antarctica. Geological Society of London Special Publications 162: 255-267.

Swanger KM, Marchant DR, Kowalewski DE, Head JW 2010. Viscous flow lobes in central Taylor Valley, Antarctica: Origin as remnant buried glacial ice. Geomorphology 120: 174-185.

Talarico FM, Findlay RH, Rastelli N 2005. Metamorphic evolution of the Koettlitz Group in the Koettlitz-Ferrar Glaciers Region (Southern Victoria Land, Antarctica). Terra Antartica 12(1): 3-23.

Talarico FM, Kleinschmidt G 2009. The Antarctic continent in Gondwanaland: a tectonic review and potential research targets for future investigations. In: Florindo F, Segert M eds. Antarctic Climate Evolution. Amsterdam, Elsevier. Pp. 257-308.

Talarico FM, McKay RM, Powell RD, Sandroni S, Naish T 2012. Late Cenozoic oscillations of Antarctic ice sheets revealed by provenance of basement clasts and grain detrital modes in ANDRILL core AND-1B. Global and Planetary Change 96-97: 23-40 doi:10.1016/j.gloplacha.2009.12.002.

Tauxe L, Luskin C, Selkin PA, Gans P, Calvert A 2004. Paleomagnetism and $^{40}Ar/^{39}Ar$ ages from volcanics extruded during the Matuyama and Brunhes chrons near McMurdo Sound, Antarctica. Geochemistry, Geophysics, Geosystems 5: Q006H12 doi:10.1029/2003GC000656.

Taylor TG 1913. Map of the region traversed on the western journeys. In: Huxley L ed. Scott's Last Expedition. Volume 2. London, Smith, Elder & Co.

Taylor TG 1922. The physiography of McMurdo Sound and Granite Harbour region. London, Harrison and Sons. 246 p.

ten Brink US, Hackney RI, Bannister S, Stern TA, Makovsky Y 1997. Uplift of the Transantarctic Mountains and the bedrock beneath the East Antarctic ice sheet. Journal of Geophysical Research 102: 27603-27621.

Timms CJ 2006. Reconstruction of a Grounded Ice Sheet in McMurdo Sound - Evidence from Southern Black Island, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Tingey RJ 1982. International lexicon of Antarctic stratigraphic names. Canberra, Australia Bureau of Mineral Resources, Geology and Geophysics. 356 p.

Townrow JA 1967. Fossil plants from Allan and Carapace Nunataks, and from the Upper Mill and Shackleton Glaciers, Antarctica. New Zealand Journal of Geology and Geophysics 10: 456-473.

Tulloch AJ, Ramezani J 2012. Immediate Report: High-precision U-Pb zircon ages of 5 plutons from 3 GHI suites. Techfile report ANT/594, held in the Dunedin Office, GNS Science. 2 p.

Turnbull IM, Allibone AH, Forsyth PJ, Heron DW 1994. Geology of the Bull Pass-St Johns Range area, southern Victoria Land, Antarctica. Institute of Geological and Nuclear Sciences 1:50 000 geological map 14. Lower Hutt, Institute of Geological & Nuclear Sciences. 1 sheet + 52 p.

Turner RD 1967. A new species of fossil *Chlamys* from Wright Valley, McMurdo Sound, Antarctica. New Zealand Journal of Geology and Geophysics 10: 446-454.

Veevers JJ 1988. Gondwana facies started when Gondwanaland merged in Pangea. Geology 16: 732-734.

Veevers JJ, Belousova EA, Saeed A, Sircombe K, Cooper AF, Reas SE 2006. Pan-Gondwanaland detrital zircons from Australia analysed for Hf-isotopes and trace elements reflect an ice-covered Antarctic provenance of 700-500 Ma age, T-DM of 2.0-1.0 Ga, and alkaline affinity. Earth Science Reviews 76: 135-176.

Vella P 1969. Surficial geological sequence, Black Island and Brown Peninsula, McMurdo Sound, Antarctica. New Zealand Journal of Geology and Geophysics 12: 761-770.

von Frese RR, Potts LV, Wells SB, Gaya-Piqué LR, Golynsky AV, Hernandez O, Kim J, Kim H, Hwang J 2006. Permian-Triassic Mascon in Antarctica (Abstract). Eos Transactions, AGU, 87(36: supplement): T41A-08.

von Frese RRB, Potts LV, Wells SB, Leftwich TE, Kim HR, Kim JW, Golynsky AV, Hernandez O, Gaya-Piqué LR 2009. GRACE gravity evidence for an impact basin in Wilkes Land, Antarctica. Geochemistry, Geophysics, Geosystems 10: Q02014 doi:10.1029/2008GC002149.

Vucetich CG, Topping WW 1972. A fiord origin for the Pecten deposits, Wright Valley, Antarctica. New Zealand Journal of Geology and Geophysics 15: 660-673.

Walcott RC 1990. Koettlitz Group Structure. Unpublished MSc thesis, University of Otago, Dunedin.

Walcott CR, Craw D 1993. Post-emplacement deformation of plutons and their metasedimentary host, Mt Dromedary area, southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 36: 487-496.

Walker BC 1980. The petrology of the Triassic strata at Horseshoe Mountain, south Victoria Land, Antarctica. Unpublished BSc (Hons) thesis, Victoria University of Wellington, Wellington.

Warny S, Askin RA, Hannah MJ, Mohr BAR, Raine JI, Harwood DM, Florindo F, SMS Science Team, Naish TR, Browne GH, Field BD 2009. Palynomorphs from a sediment core reveal a sudden remarkably warm Antarctica during the Middle Miocene. Geology 37: 955-958 doi:10.1130/G30139A.1.

Warren G 1970. Sheet 14 Geology of the Terra Nova Bay-McMurdo Sound Area Victoria Land. In Craddock C ed. Antarctic Map Folio Series 12. New York, American Geographical Society.

Waterhouse BC, Barrett PJ 1975. Lexicon of Antarctic stratigraphic names introduced by members of New Zealand expeditions. Unpublished volume, held in the library of GNS Science, Dunedin. 279 p.

Waters AS 1993. The Swinford and Harker Plutons: a study in late-orogenic magmatism in southern Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Webb P-N 1963. Geological investigations in southern Victoria Land, Antarctica. Part 4 - Beacon Group of the Wright Valley and Taylor Glacier region. New Zealand Journal of Geology and Geophysics 6: 361-387.

Webb P-N 1972. Wright Fiord, Pliocene marine invasion of an Antarctic dry valley. Antarctic Journal of the United States 7: 227-234.

Webb P-N 1974. Micropaleontology, paleoecology, and correlation of the Pecten gravels, Wright Valley, Antarctica, and description of *Trochoelphidiella onyxi* n. gen., n. sp. Journal of Foraminiferal Research 4: 184-199.

Webb P-N, Harwood DM 1991. Late Cenozoic glacial history of the Ross Embayment, Antarctica. Quaternary Science Reviews 10: 215-223.

Webb P-N, Harwood DM, McKelvey BC, Mercer JH, Stott LD 1984. Cenozoic marine sedimentation and ice-volume variation on the East Antarctic craton. Geology 12: 287-291.

Webb P-N, McKelvey BC 1959. Geological investigations in South Victoria Land, Antarctica: Part 1 - Geology of Victoria Dry Valley. New Zealand Journal of Geology and Geophysics 2: 120-136.

Wegner C, Craddock W 1972. Lexicon of Antarctic stratigraphic names introduced by members of United States expeditions. Washington, Committee on Polar Research, National Research Council. 129 p.

Wellman HW 1964. Later geological history of Hut Point Peninsula, Antarctica. Transactions of the Royal Society of New Zealand (Geology) 2(10): 147-154.

Whillans IM, Cassidy WA 1983. Catch a falling star: Meteorites and old ice. Science 222: 55-57.

White JDL, McClintock MK 2001. Immense vent complex marks flood-basalt eruption in a wet, failed rift: Coombs Hills, Antarctica. Geology 29: 935-938.

Wilch TI, Denton GH, Lux DR, McIntosh WC 1993. Limited Pliocene glacier extent and surface uplift in middle Taylor Valley, Antarctica. Vega Symposium (1993: Stockholm, Sweden). Pp. 331-351.

Wilch TI, McIntosh WC, Panter KS, Dunbar NW, Smellie JL, Fargo A, Scanlan M, Zimmerer MJ, Ross J, Bosket ME 2008. Volcanic and glacial geology of the Miocene Minna Bluff Volcanic Complex, Antarctica. Abstract #V11F-06. American Geophysical Union Fall Meeting 2008, San Francisco.

Williams PF, Hobbs BE, Vernon RH, Anderson DE 1971. The structural and metamorphic geology of basement rocks in the McMurdo Sound area, Antarctica. Journal of the Geological Society of Australia 18: 127-142.

Willis IAG 1961. Quaternary volcanics of the Koettlitz-Blue Glacier region, southern Victoria Land, Antarctica. Unpublished BSc (Hons) thesis, Victoria University of Wellington, Wellington.

Wilson AT 1973. The great antiquity of some Antarctic landforms - evidence for an Eocene temperate glaciation in the McMurdo region. In: van Zinderen Bakker EM ed. Paleoecology of Africa and the surrounding islands and Antarctica. SCAR Conference on Quaternary Studies, Canberra, Australia, 1972. Pp. 23-35.

Wilson GS 1989. Sedimentary facies and processes, and Quaternary history of the Miers Valley, South Victoria Land, Antarctica. Unpublished BSc (Hons) thesis, Victoria University of Wellington, Wellington.

Wilson GS 1995. The Neogene East Antarctic Ice Sheet: a dynamic or stable feature? Quaternary Science Reviews 14: 101-123.

Wilson GS 2000. Glacial geology and origin of fossiliferous-erratic-bearing moraines, southern McMurdo Sound, Antarctica: an alternative ice sheet hypothesis. In Stilwell JD, Feldman RM eds. Paleobiology and paleoenvironments of Eocene rocks, McMurdo Sound, east Antarctica. Antarctic Research Series 76. Washington DC, American Geophysical Union. Pp. 19-37.

Wilson GS, Barron JA, Ashworth AC, Askin RA, Carter JA, Curren MG, Dalhuisen DH, Friedmann EI, Fyodorov-Davidov DG, Gilichinsky DA, Harper MA, Harwood DM, Hiemstra JF, Janecek TR, Licht KJ, Ostroumov VE, Powell RD, Rivkina EM, Rose SA, Stroeven AP, Stroeven P, van der Meer JJM, Wizevich MC 2002. The Mount Feather Diamicton of the Sirius Group: an accumulation of indicators of Neogene Antarctic glacial and climatic history. Palaeogeography, Palaeoclimatology, Palaeoecology 182: 117-131.

Wilson GS, Damaske D, Moller HD, Tinto K, Jordan T 2007. The geological evolution of southern McMurdo Sound - New evidence from a high-resolution aeromagnetic survey. Geophysical Journal International 170(1): 93.

Wilson GS, Roberts AP, Verosub KL, Florindo F, Sagnotti L 1998. Magnetobiostratigraphic chronology of the Eocene-Oligocene transition in the CIROS-1 core, Victoria Land margin, Antarctica: implications for Antarctic glacial history. Geological Society of America Bulletin 110: 35-47.

Wilson TJ 1992. Mesozoic and Cenozoic kinematic evolution of the Transantarctic Mountains. In: Yoshida Y ed. Recent Progress in Antarctic Earth Science. Tokyo, Terrapub. Pp. 303-314.

Wilson TJ, Henrys SA, Barrett P, Hannah M, Fielding C, Jarrard R, Paulsen T 2003. New rift history for the southwestern Ross Sea, Antarctica. In: Futterer DK, Miller H eds. Antarctic contributions to global earth science. 9th International Symposium on Antarctic Earth Sciences 2003. Potsdam, University of Potsdam and Alfred-Wegener Institute for Polar and Marine Research. p. 347.

Wizevich MC 1997. Fluvial-eolian deposits in the Devonian New Mountain Sandstone, Table Mountain, southern Victoria Land, Antarctica: sedimentary architecture, genesis and stratigraphic evolution. In: Ricci CA ed. The Antarctic Region: Geological evolution and processes. Siena, Terra Antartica Publication. Pp. 933-944.

Woolfe KJ 1990. Trace fossils as paleoenvironmental indicators in the Taylor Group (Devonian) of Antarctica. Paleogeography, Paleoclimatology, Paleoecology 80: 301-310.

Woolfe KJ 1991. History of the Ross Sea sector of Antarctica as recorded by the Beacon Supergroup in Southern Victoria Land and the Darwin Mountains. Unpublished PhD thesis, Victoria University of Wellington, Wellington.

Woolfe KJ 1993. Devonian depositional environments in the Darwin Mountains: marine or non-marine? Antarctic Science 5(2): 211-220.

Woolfe KJ 1994. Cycles of erosion and deposition during the Permo-Carboniferous glaciation in the Transantarctic Mountains. Antarctic Science 6: 93-104.

Woolfe KJ, Arnot MJ, Bradley GM 1995. Jurassic titaniferous ironstone in a Devonian host: Pivot Coal Measures expunged. Antarctic Science 7(3): 293-301.

Woolfe KJ, Barrett PJ 1995. Constraining the Devonian to Triassic tectonic evolution of the Ross Sea sector. Terra Antartica 2(1): 7-21.

Woolfe KJ, Kirk PA, Sherwood AM 1989. Geology of the Knobhead area, southern Victoria Land, Antarctica. New Zealand Geological Survey 1:50 000 miscellaneous series map 19. Wellington, New Zealand, Wellington, New Zealand, Department of Scientific and Industrial Research. 1 sheet + 39 p.

Worley BA 1992. Dismal geology: a study of magmatic and subsolidus processes in a carbonated alkaline intrusion, Southern Victoria Land, Antarctica. Unpublished MSc thesis, University of Otago, Dunedin.

Worley BA, Cooper AF 1995. Mineralogy of the Dismal Nepheline Syenite, southern Victoria Land, Antarctica. Lithos 35: 109-128.

Worley BA, Cooper AF, Hall CE 1995. Petrogenesis of carbonate-bearing nepheline syenites and carbonatites from southern Victoria Land, Antarctica: origin of carbon and the effects of calcite-graphite equilibrium. Lithos 35: 183-199.

Wright AC 1980. Landforms of McMurdo Volcanic Group, southern foothills of Royal Society Range, Antarctica. New Zealand Journal of Geology and Geophysics 23: 605-613.

Wright AC, Kyle PR 1990a. A.15. Mount Bird. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 97-98.

Wright AC, Kyle PR 1990b. A.16. Mount Terror. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 99-102.

Wright AC, Kyle PR 1990c. A.19. White Island, Black Island and Brown Peninsula. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 113-116.

Wright AC, Kyle PR 1990d. A.20. Minna Bluff. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 117-119.

Wright AC, Kyle PR 1990e. A.21. Mount Discovery. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 120-123.

Wright AC, Kyle PR 1990f. A.22. Mount Morning. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 124-127.

Wright AC, Kyle PR 1990g. A.23. Mason Spur. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 128-133.

Wright AC, Kyle PR 1990h. A.24. Royal Society Range. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 131-133.

Wright AC, Kyle PR 1990i. A.25. Taylor and Wright valleys. In: LeMasurier WE, Thomson JW et al. eds. Volcanoes of the Antarctic Plate and Southern Oceans. Antarctic Research Series 48. Washington DC, American Geophysical Union. Pp. 134-135.

Wright CS, Priestley RE 1922. Glaciology. British Antarctic (Terra Nova) Expedition 1910-1913. London, Harrison and Sons. 581 p.

Wright-Grassham AC 1987. Volcanic geology, mineralogy, and petrogenesis of the Discovery Volcanic Subprovince, Southern Victoria Land, Antarctica. Unpublished PhD thesis, New Mexico Institute of Mining and Technology, Socorro.

Wu B, Berg JH 1992. Early Paleozoic lamprophyre dikes of southern Victoria Land: geology, petrology and geochemistry. In: Yoshida Y ed. Recent progress in Antarctic Earth Science. Tokyo, Terrapub. Pp. 257-264.

Wynyard MJ 2000. Geochemistry of a quartz syenite-quartz monzonite-granite fractionation series emplaced during the Ross Orogeny, South Victoria Land, Antarctica. Geological Society of New Zealand and New Zealand Geophysical Society Joint Conference 2000, Victoria University of Wellington. Geological Society of New Zealand Miscellaneous Publication 108A: 173.

Wynyard MJ 2004. Geology of the Cocks Glacier area, Antarctica: A study of neo-Proterozoic metamorphism, deformation and magmatism during the Ross Orogeny in South Victoria Land. Unpublished MSc thesis, University of Otago, Dunedin.

Wysoczanski RJ, Allibone AH 2004. Age, correlation, and provenance of the Neoproterozoic Skelton Group, Antarctica: Grenville age detritus on the margin of East Antarctica. Journal of Geology 112: 401-416.

Wysoczanski RJ, Forsyth PJ, Woolfe KJ 2003. Zircon dating and provenance of rhyolitic clasts in Beacon Conglomerate, Southern Victoria Land, Antarctica. Terra Antartica 10(2): 67-80.

Yanbin S 1994. Jurassic conchostracans from Carapace Nunatak, southern Victoria Land, Antarctica. Antarctic Science 6(1): 105-113.

Young GC, Long JA 2005. Phyllolepid placoderm fish remains from the Devonian Aztec Siltstone, southern Victoria Land, Antarctica. Antarctic Science 17: 387-408.

Zeller EJ, Angino EE, Turner MD 1961. Basal sedimentary section at Windy Gully, Taylor Glacier, Victoria Land, Antarctica. Geological Society of America Bulletin 72: 781-786.

Lexicon of units adopted for the southern Victoria Land geological map

Where possible, only formally published stratigraphic names have been used for geological units shown on this map (Wegner & Craddock 1972; Waterhouse & Barrett 1975; Tingey 1982). However, some units have previously only been named in theses or informal literature, or have been named but not described at all. Their lack of appropriate definition means that such units would be omitted from any formal international lexicon of stratigraphic nomenclature (see Tingey 1982 p.314). In order to rationalise the nomenclature used for this map, the names, definitions and descriptions of existing, formalised, and new rock units are given in this appendix, together with the alpha-numeric codes for the map units in the GIS dataset, and the three-letter text labels used on the map face and in this text (formalised **names** and **text labels** are shown in **bold**). Areas which are only inferred to be of a certain rock type can be identified in the GIS database by the "?" attached to the unit code. New and previously informal name headings are shown by *italics*. Where no type areas or sections were given in the original definitions, reference areas are nominated for units, based on our field knowledge. Approximate geographic coordinates (latitude and longitude) are given for reference and type areas, where appropriate. The appendix is subdivided at group level, and is generally ordered within each group from younger to older (broadly following the layout of the map legend).

Unit definitions follow established lithostratigraphic nomenclatural procedures as outlined by Salvador (1994), modified for plutonic rocks following arguments presented by Cox & Allibone (1995). Intrusive rocks are generally mapped as plutons, intrusive bodies which may comprise a variety of rocks with different compositions and textures. However, all rocks within a single pluton have field relationships that suggest they are derived from a single or several closely related batches of magma. In some places, while it would have been preferable only to use specific compositional names (e.g. Buddha Diorite) for plutons, detailed mapping shows these units to be quite inhomogeneous and the names have been modified (e.g. Buddha Pluton). The nomination of type areas rather than single outcrops for many plutonic and fluvioglacial units also reflects their variable internal character. At the highest level, plutonic rocks are grouped into petrogenetic suites (cf. Smillie 1992; Allibone et al. 1993b; Read 2010). Radiometric ages given are the most recently published; several as yet unpublished ages have also been provided by A.J. Tulloch & J. Ramezani, S.E. Read and G. Hagen-Peter.

Note that for many units, there are no useful, specific or appropriate geographic names near the reference or type areas, and these units are named from a general area rather than a discrete place – e.g. Nibelungen Valley. Many other lithologic units shown on the map and described in the text are not formally named (e.g. biotite orthogneiss; scree; fan gravels; supraglacial till), and no definitions are given for these, but their map face and text labels, GIS database unit codes, and brief descriptions are included here for completeness. These informal units are indicated by underlining. Some units described in this appendix are in the digital dataset, but have not been displayed on the map.

CONTENTS OF APPENDIX 1

SKELTON GROUP

SKELTON GROUP (s, s?; **s, s?**)
Previous usage or definition: Gunn & Warren (1962), redefined by Cook & Craw (2001) to include and supersede the Koettlitz Group of Grindley & Warren (1964). Formation names of Blank et al. (1963), Gunn & Warren (1962), McKelvey & Webb (1962), Skinner (1982), Findlay et al. (1984) have not been applied.
Name: from the Skelton Glacier.
Reference area: none given.
Description: interlayered schist, psammitic schist, felsic gneiss, tremolite-actinolite schist, and minor marble, calc-silicate and conglomerate; with or without intercalated orthogneiss. Includes unvisited areas inferred to be metasediment (**s?**).
Age: sedimentation post-dates detrital zircon ages of 691, 684 and 649 Ma (Stump et al. 2007) and 634 to 615 Ma (Cooper et al. 2011). Intercalated rhyolites are 650 ± 4 to 648 ± 3.2 Ma (zircon LA-ICP-MS; Cooper et al. 2011). Sedimentation is constrained by the oldest known intrusions, 551 Ma (Rowell et al. 1993) in the south and 535 Ma (Allibone & Wysoczanski 2002) in the north. Metamorphism occurred at c. 550 Ma, and between 505–480 Ma (detrital zircon by SHRIMP; Wysoczanski & Allibone 2004).

marble (sm, sm?; **sm**)
Previous usage or definition: n/a
Name: n/a
Reference area: n/a
Description: white, rusty weathering, coarsely crystalline marble with minor grey discontinuous bands: impure grey black and white marble; schist or metabasite inclusions. Includes limestone in the Skelton Glacier area.
Age: c. 650 Ma, pre-dates 550 Ma (see above).

schist (ss, ss?; **ss**)
Previous usage or definition: n/a
Name: n/a
Reference area: n/a
Description: biotite schist and semi-schist commonly with epidote or garnet, locally migmatitic; interlayered with minor marble, conglomerate, gneiss, metabasite, or argillite.
Age: c. 650 Ma, pre-dates 550 Ma (see above).

calc-silicate schist (sa, **sa**)
Previous usage or definition: n/a
Name: n/a
Reference area: n/a
Description: calc-silicate schist, diopside-biotite schist, amphibole schist, pebbly conglomerate schist; interlayered with metagreywacke, metabasite and minor conglomerate.
Age: c. 650 Ma, pre-dates 550 Ma (see above).

metaconglomerate (sc; **sc**)
Previous usage or definition: n/a. Includes Baronick Formation of Cook (2007).
Name: n/a
Reference area: n/a
Description: metaconglomerate or conglomeratic schist, commonly interlayered with greywacke, marble, metavolcanics, or schist. May be transposed, recrystallised and/or locally migmatised. Baronick Formation (*not shown separately on map face*) has abundant igneous clasts and interbedded layers of basalt, trachyte and quartz syenite.
Age: c. 650 Ma, pre-dates 550 Ma (see above).

greywacke and psammitic schist (sg; **sg**)
Previous usage or definition: n/a
Name: n/a
Reference area: n/a
Description: meta-greywacke and meta-sandstone, interlayered with psammitic schist, subordinate argillite, calc-silicate, metavolcanics or mafic schist.
Age: c. 650 Ma, pre-dates 550 Ma (see above).

metavolcanics and metabasites (sv; **sv**)
Previous usage or definition: n/a. Includes Highway Suite of Cook (2007).
Name: n/a
Type area: n/a
Description: meta-igneous amphibolite and metabasite rocks with subordinate argillite, greywacke and marble; locally includes metamorphosed pillow basalts. Highway Suite (*not shown separately on map face*) is sheared and foliated gabbro and dolerite.
Age: c. 650 Ma, pre-dates 550 Ma (see above).

argillite and quartzite (sr; **sr**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: equigranular epidote argillite interlayered with metagreywacke; locally interlayered with quartzite, biotite and amphibole semischist, and meta-tuff and muscovite schist.
Age: c. 650 Ma, pre-dates 550 Ma (see above).

GRANITE HARBOUR INTRUSIVE COMPLEX

Previous usage or definition: Gunn & Warren (1962); synonymous with Granite Harbour Intrusives (Grindley & Warren 1964; Allibone et al. 1993a, b; Cooper et al. 2011).
Name: from Granite Harbour.
Reference area: Granite Harbour, where several granite plutons are well exposed; note that the complex includes a much wider variety of rocks throughout South Victoria Land (see below).
Description: variably deformed to undeformed suites of calc-alkalic, alkalic, and alkali-calcic plutonic rocks intruding Skelton Group metasedimentary rocks in southern Victoria Land (*subdivided into individual plutons or intrusive bodies, dike swarms, or informal lithological units on the map face*). A number of previously named lithology-based units within the Granite Harbour Intrusive Complex have been abandoned (see Smillie 1992; Allibone et al. 1993a,b; Cox & Allibone 1991) including: Larsen Granodiorite, Irizar Granite, Delta Diorite, Gauss Granodiorite, Skelton Granodiorite, Taylor Pluton (Gunn

& Warren 1962); Victoria Intrusives, Wright Intrusives, Vida Granite, Theseus Granodiorite, Loke Microdiorite, Dais Granite and Olympus Granite Gneiss (Allen & Gibson 1962; McKelvey & Webb 1959, 1962); Murray Granite, Crags Granite, Renegar Mafic Gneiss, Portal Augen Gneiss (Skinner 1983); Victoria Intrusive Group, Larsen Intrusive Group, Briggs Hills phase, Kukri Hills Group (Findlay 1982, 1985).
Age: Neoproterozoic-?Ordovician.

Unassigned younger plutonic rocks

undifferentiated granitoids (g, g?; **g**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: undifferentiated plutonic rocks, including gabbro, diorite, granodiorite and granite; may be foliated and gneissic.
Age: unknown, but early Paleozoic.

unassigned late granitoids (gq; **gq**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: hornblende-biotite-alkali feldspar quartz monzonite to granite forming small stocks, plugs, dikes and sills; locally porphyritic. Cross-cut all other intrusions including Vanda Dikes.
Age: inferred to post-date Vanda Dikes (of age 495-491 Ma), based on cross-cutting relationships.

late quartz monzodiorite (gqz; **gqz**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: fine- to medium-grained homogeneous quartz monzodiorite and granodiorite cutting Orestes and Packard plutons in the St Johns Range.
Age: cross-cuts Orestes Pluton, so may be younger than 490 Ma (or 486 ± 14 Ma cooling age).

late granitoids (ggr; ggm; ggk; **gl**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: fine-grained to porphyritic dikes stocks and plugs of biotite granodiorite (ggr), hornblende-biotite quartz monzodiorite (ggm), and hornblende-clinopyroxene granodiorite (ggk) in the central Taylor Valley, cut by Vanda Dikes; *differentiated in digital database but not on the map face.*
Age: cross-cut by Vanda Dikes, so older than 495-491 Ma.

undifferentiated mafic intrusives (gm; **gm**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: small plugs, sills and dikes of massive to variably foliated diorite, quartz monzodiorite, quartz diorite and minor gabbro.
Age: unknown, but inferred Cambrian - Early Ordovician.

Keyhole Mafic Intrusives (gmk; **gmk**)
Previous usage or definition: modified from Keyhole Mafic Suite (Jones 1995a, 1997a,b).
Name: from Keyhole Lake, Hidden Valley area.
Reference area: southeast of Keyhole Lake (163°45.55'E, 78°08.12'S).
Description: irregular plugs dikes and sills of gabbro, diorite, and quartz monzodiorite; locally mingled with Hidden Granite. High-K, alkali-calcic chemistry.
Age: Cambrian. Intrusive relationships suggest coeval with Hidden Granite.

Buddha Pluton (gmu; **gmu**)
Previous usage or definition: modified from Buddha Diorite of Mortimer (1981), following Worley (1992).
Name: from Buddha Lake, eastern Blue Glacier area.
Reference area: north wall of Miers Valley (163°57.28'E, 78°04.96'S).
Description: sill-like body of foid-bearing monzodiorite to monzonite with diorite and minor gabbro; porphyritic with mafic enclaves; locally equigranular.
Age: Cambrian-?Early Ordovician. Field relations suggest it is coeval with Lama Pluton.

Packard Pluton (gmp; **gmp**)
Previous usage or definition: Turnbull et al. (1994).
Name: from the Packard Glacier, southern St Johns Range.
Reference area: western side of the Packard Glacier (162°09.46'E, 77°21.63'S).
Description: Inhomogeneous hornblende biotite clinopyroxene gabbro and diorite; locally with cumulate layering and abundant xenoliths.
Age: constrained only by intrusive relationships (cross-cuts foliation, and intruded by Vanda Dikes and Orestes Pluton).

DRY VALLEYS 2 SUITE
Previous usage or definition: petrogenetic suite of plutonic rocks, introduced by Smillie (1992), modified by Allibone et al. (1993b). Includes younger discordant granitoids with hybrid geochemical characteristics, or yet to be characterised, which are inferred to belong to the suite on the basis of intrusive relationships, lithology or outcrop characteristics.
Name: from the Dry Valleys region of South Victoria Land.
Type area: n/a
Description: undeformed alkali-calcic monzonite, quartz monzonite, and granite plutons, enriched in K, Rb, Zr, and light Rare Earth elements and depleted in Na and Ca (*not shown separately on map face, but see Fig. 14*).
Age: Cambrian-?Ordovician.

late DV2 granitoids (gg, gg?; **gg**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: late-stage granitoids, typically unfoliated homogeneous and massive with pegmatites and enclaves; postdate Vanda Dikes. Alkali-calcic chemistry.

Age: Late Cambrian-Early Ordovician. Younger than Vanda Dikes (495-491 Ma).

Darkowski Pluton (ggd; **ggd**)
Previous usage or definition: new unit, following Forsyth (2003).
Name: from the Darkowski Glacier on the south side of the lower Ferrar Glacier.
Reference area: bluffs on the western side of the middle Darkowski Glacier (162°24.76'E, 77°52.92'S).
Description: massive and undeformed hornblende-biotite granite.
Age: 493.8 ± 1.7 Ma U-Pb zircon (Hagen-Peter et al. 2011 unpublished LA-MC-ICP-MS ages).

Lama Pluton (ggy; **ggy**)
Previous usage or definition: not formally named; see Worley (1992) and Simpson & Aslund (1996).
Name: from Mt Lama, Miers Valley.
Reference area: in Shangri-la, north of Mt Lama (163°41.57'E, 78°03.74'S).
Description: discordant clinopyroxene-hornblende-biotite granitoid with distinct equigranular and porphyritic phases, and a weak magmatic fabric.
Age: Late Cambrian-Early Ordovician from discordant (post-tectonic) intrusive relationships and DV2 chemistry.

Lama Pluton mafic hybrid phase (ggyh; **ggy**)
Previous usage or definition: not formally named; see Worley (1992).
Name: from Mt Lama, Miers Valley.
Reference area: slopes east of Penance Pass (163°53.58'E, 78°04.45'S) and south of Buddha Lake (163°45.65'E, 78°03.27'S).
Description: irregular zones rich in mafic enclaves within Lama Pluton. *Distinguished in digital dataset but not on map face.*
Age: as for Lama Pluton. Youngest phase of the pluton.

Gondola Pluton (ggg; **ggg**)
Previous usage or definition: Turnbull et al. (1994).
Name: from Gondola Ridge, Mackay Glacier.
Reference area: eastern end of Gondola Ridge (161°58.19'E, 77°00.30'S).
Description: medium-grained undeformed leucogranite pluton intruding Suess Pluton.
Age: intrudes and is surrounded by Suess Pluton, so < 500 Ma.

Gonville & Caius Pluton (ggc; **ggc**)
Previous usage or definition: Forsyth et al. (2002) after Gunn & Warren (1962). Provisional DV1a correlation (Forsyth et al. 2002) no longer supported.
Name: from the Gonville & Caius Range.
Reference area: ridge east of the Crisp Glacier, Gonville & Caius Range (162°10.36'E, 77°10.61'S).
Description: massive homogeneous fine- to coarse-grained hornblende biotite granite to granodiorite.
Age: 495.9 ± 1.7 Ma, 495.7 ± 2 Ma and 495.4 ± 2.2 Ma U-Pb zircon (Hagen-Peter et al. 2011 unpublished LA-MC-ICP MS ages).

Orestes Pluton (ggt; **ggt**)
Previous usage or definition: Turnbull et al. (1994); see also Allibone et al. (1993a,b).
Name: from the Orestes Valley near Bull Pass.
Reference area: slopes of Orestes Valley (161°53.38'E, 77°27.77'S).
Description: massive, homogeneous, coarse-grained, equigranular, biotite leucogranite with microgranitoid enclaves. Hybrid chemistry.
Age: inferred 498-490 Ma. 486 ± 14 Ma Rb-Sr (Stuckless & Ericksen 1975) – probably records cooling; see also 480-450 Ma discordant U-Pb (Vocke & Hanson 1981)

Harker Pluton (ggh; **ggh**)
Previous usage or definition: Waters (1993); Turnbull et al. (1994); extended by Forsyth et al. (2002).
Name: from Mt Harker, eastern St Johns Range.
Reference area: bluffs of Mt Harker (162°04.79'E, 77°17.60'S).
Description: massive, homogeneous, medium- to coarse-grained equigranular biotite syenogranite; graphic pegmatite veins locally abundant. Hybrid chemistry.
Age: 495.7 ± 2 Ma U-Pb zircon (Hagen-Peter et al. 2011 unpublished LA-MC-ICP-MS ages) (477 ± 7 Ma by Rb-Sr; Allibone et al. 1993a – probably records cooling).

Swinford Pluton (ggs; **ggs**)
Previous usage or definition: Waters (1993); Allibone et al. (1993a,b; 1994); see also Forsyth et al. (2002).
Name: from Mt Swinford, central St Johns Range.
Reference area: from Mt Swinford northwest to the Ringer Glacier (161°54.13'E, 77°15.60'S).
Description: massive homogeneous coarse-grained granite and quartz monzonite with alkali feldspar megacrysts: minor biotite and accessory hornblende. Hybrid chemistry.
Age: intruded by Harker Pluton, so older than 495.7 ± 2 Ma; intrudes Skelton Group and Wheeler Pluton.

Brownworth Pluton (ggb; **ggb**)
Previous usage or definition: Forsyth et al. (2002), after Ellery (1989).
Name: from Lake Brownworth, lower Wright Valley.
Reference area: Doorly Spur, Wright Lower Glacier (161°46.44'E, 77°23.53'S).
Description: massive to weakly foliated, megacrystic, biotite hornblende quartz monzonite.
Age: 496.5 ± 2 Ma and 493 ± 1.4 Ma U-Pb zircon (Hagen-Peter et al. 2011 unpublished LA-MC-ICP-MS ages). Post-dates Vanda Dikes.

Nibelungen Pluton (ggn; **ggn**)
Previous usage or definition: Allibone et al. (1991).
Name: from the Nibelungen Valley, Asgard Range.
Reference area: western side of the northern Nibelungen Valley (161°19.76'E, 77°36.68'S).
Description: flow-foliated and altered medium- to coarse-grained biotite alkali-feldspar porphyritic quartz monzonite
Age: 498-490 Ma by correlation with other plutons.

South Fork Pluton (ggx; **ggx**)
Previous usage or definition: Isaac et al. (1996).
Name: from the South Fork of upper Wright Valley.
Reference area: western side of Dais col (161°03.12'E, 77°33.03'S).
Description: massive coarse-grained equigranular hornblende biotite granite: finer grained quartz monzonite on margins.
Age: 498-490 Ma, by correlation with other plutons.

Pearse Pluton (ggp; **ggp**)
Previous usage or definition: Allibone et al. (1991).
Name: from Pearse Valley.
Reference area: slopes of the Friis Hills south of Lake House (161°25.23'E, 77°42.78'S).
Description: texturally variable, weakly alkali-feldspar porphyritic, hornblende biotite granite to quartz monzonite with numerous felsic porphyry enclaves.
Age: 498-490 Ma by correlation with Brownworth and other plutons.

Avalanche Bay Pluton (gga; **gga**)
Previous usage or definition: Graham & Palmer (1987); Forsyth et al. (2002).
Name: from Avalanche Bay, Granite Harbour.
Type area: Couloir Cliffs at Avalanche Bay (162°49.28'E, 77°00.76'S).
Description: massive, medium-grained, variably megacrystic, quartz monzodiorite with abundant metasedimentary rafts near contacts.
Age: 498 ± 4 Ma U-Pb zircon (Encarnacion & Grunow 1996); cf. less reliable 459 ± 4 or 452 ± 6 Ma Rb-Sr ages (Allibone et al. 1993a).

Mt Falconer Pluton (ggf; **ggf**)
Previous usage or definition: Ghent & Henderson (1968); Ghent (1970).
Name: from Mt Falconer, lower Taylor Valley.
Reference area: summit ridge of Mt Falconer (163°07.86'E, 77°34.77'S).
Description: medium- to coarse-grained, hornblende biotite quartz monzonite; locally contains intrusion breccia with metasediment and diorite rafts in quartz monzodiorite.
Age: inferred 498-490 Ma with 461-451 Ma cooling, K-Ar biotite (McDougall & Ghent 1970).

Lion Island Pluton (ggo; **ggo**)
Previous usage or definition: Gunn & Warren (1962). Referred to informally as the Cape Archer Pluton (Forsyth et al. 2003; Forsyth 2010).
Name: from Lion Island, north of Granite Harbour.
Reference area: bluffs on the northeastern side of Lion Island (162°35.16'E, 76°50.97'S).
Description: unfoliated, medium- to coarse-grained, equigranular hornblende biotite granite with drusy cavities.
Age: 493.95 ± 0.17 Ma U-Pb zircon (Tulloch & Ramezani 2012 CA-ID-TIMS age as 'Archer Pluton'); 498.4 ± 1.5 Ma U-Pb zircon (Hagen-Peter et al. 2011 unpublished LA-MC-ICP-MS age).

Mount Perseverance Pluton (gge; **gge**)
Previous usage or definition: Gunn & Warren (1962).
Name: from Mt Perseverance, east of Benson Glacier.
Reference area: Mt Perseverance (162°10.24'E, 76°47.78'S).
Description: unfoliated, medium-grained, inequigranular granite.
Age: 502.1 ± 2.6 Ma U-Pb zircon (Hagen-Peter et al. 2011 unpublished LA-MC-ICP-MS age).

Miers Granite (ggi; **ggi**)
Previous usage or definition: informally named by Mortimer (1981); used by Worley (1992).
Name: from the Miers Valley.
Reference area: eastern end of Marshall Ridge, north of the lower Miers Valley (162°35.16'E, 76°50.97'S).
Description: irregular unfoliated pluton of hornblende-biotite syenite-syenogranite with abundant K-feldspar phenocrysts and rare mafic enclaves.
Age: inferred 498-490 Ma, from discordant 'post-tectonic' intrusive relationships.

<u>felsic porphyry plugs</u> (gep; **ge**)
Previous usage or definition: Allibone et al. 1991.
Name: n/a
Reference area: n/a
Description: isolated hornblende-biotite-alkali feldspar porphyritic felsic plugs at Solitary Rocks, Friis Hills and Wright Valley.
Age: inferred 498-490 Ma, from discordant 'post-tectonic' intrusive relationships.

Vanda Dikes (gef, gem; **not labelled**)
Previous usage or definition: after McKelvey & Webb (1962); Keiller (1991); Turnbull et al. (1994). Also known informally as Vanda dikes or the Vanda Dike Swarm.
Name: from Lake Vanda, Wright Valley.
Reference area: south side of Wright Valley at the eastern end of Lake Vanda (161°42.06'E, 77°31.97'S).
Description: field subdivision of <u>felsic</u> hornblende-biotite-alkali feldspar porphyritic plugs and dikes (gef); and <u>mafic</u> hornblende biotite microdiorite, micromonzodiorite and monzonite dikes (gem).
Age: inferred range 495-491 Ma based on U-Pb zircon 484 ± 7 Ma (Encarnacion & Grunow 1996); 494 ± 3 U-Pb zircon (Rocchi et al. 2009); and unpublished 495 to 491 ± 0.3 Ma U-Pb zircon ages by CA-TIMS (Bray et al. 2010).

DRY VALLEYS 1B SUITE
Previous usage or definition: petrogenetic suite of plutonic rocks, introduced by Smillie (1992), modified by Allibone et al. (1993b).
Name: from the Dry Valleys region of South Victoria Land.
Type area: n/a
Description: variably deformed calc-alkalic biotite quartz monzodiorite, granodiorite, and granite plutons with distinctive Sr, Na, and Al enrichment and Y and Nb depletion (*not shown separately on map face, but see Fig. 14*).
Age: Cambrian.

DV1b biotite granitoids (gf; **gf**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: irregular plugs and dikes of massive, homogeneous, medium-grained equigranular biotite granite and granodiorite, rarely flow-foliated; high Sr low Y adakitic chemistry.
Age: inferred 515-485 Ma, from intrusive relationships.

Hedley Pluton (gfh; **gfh**)
Previous usage or definition: Allibone et al. (1991).
Name: from the Hedley Glacier, western Kukri Hills.
Reference area: confluence of the Hedley with the Ferrar Glacier (162°07.17'E, 77°49.05'S).
Description: massive, homogeneous, medium-grained equigranular biotite granite and granodiorite.
Age: 499.26 ± 0.22 U-Pb zircon (Tulloch & Ramezani 2012 CA-ID-TIMS age).

Hidden Granite (gfi; **gfi**)
Previous usage or definition: Jones (1995a, 1997a,b).
Name: from Hidden Valley, south of Miers Valley.
Reference area: ridges west of Hidden Valley (163°40.36'E, 78°08.75'S).
Description: massive, homogeneous, fine- to medium-grained equigranular biotite garnet leucocratic granite and granodiorite; forming dikes and irregular bodies.
Age: between 495-491 Ma (cut by Vanda Dikes) and 511-503 Ma (intrudes Bonney Pluton) (cf. Jones 1997a). Coeval with Keyhole Mafic Intrusives.

Suess Pluton (gfs; **gfs**)
Previous usage or definition: Turnbull et al. (1994).
Name: from Mt Suess, Gondola Ridge.
Reference area: northwestern slopes of Gondola Ridge (161°41.53'E, 77°01.45'S).
Description: homogeneous to flow-foliated, medium-grained equigranular biotite granite to granodiorite; locally orbicular; intrusion breccia at western margin.
Age: 501 ± 7 Ma K-Ar (C.J. Adams *pers. comm. in* Turnbull et al. 1994).

St Johns Pluton (gfj; **gfj**)
Previous usage or definition: Turnbull et al. (1994).
Name: from the St Johns Range.
Reference area: head of the Willis Glacier, central St Johns Range (161°53.53'E, 77°18.38'S).
Description: weakly foliated, homogeneous, medium-grained equigranular biotite granite to granodiorite.
Age: 490 ± 14 Ma Rb-Sr (Allibone et al. 1993a).

Valhalla Pluton (gfv; **gfv**)
Previous usage or definition: Allibone et al. (1991).
Name: from the Valhalla Glacier, Wright Valley.
Reference area: below the snout of the Valhalla Glacier (161°59.98'E, 77°32.66'S).
Description: homogeneous, medium-grained equigranular biotite granite to granodiorite.
Age: 493.7 ± 4.1 Ma U-Pb zircon (Hagen-Peter et al. 2011 unpublished LA-MC-ICP-MS age); 488 ± 2 Ma U-Pb monazite (Cox et al. 2000).

Coleman Pluton (gfc; **gfc**)
Previous usage or definition: Forsyth et al. (2002).
Name: from Mt Coleman, southern Wilson Piedmont Glacier.
Type area: Mt Coleman (163°23.94'E, 77°32.43'S).
Description: flow-banded, fine- to medium-grained monzogranite to granite; minor pegmatite.
Age: between 509 Ma (intrudes Flint Pluton) and 495-491 Ma (cut by Vanda Dikes) (Forsyth et al. 2002).

biotite orthogneiss (gub; **gub**)
Previous usage or definition: n/a
Name: n/a
Reference area: n/a
Description: weakly to moderately foliated biotite orthogneiss of granitic composition; as large bodies or intercalated with Skelton Group schist and marble.
Age: probably 539-510 Ma, from intrusive and deformational relationships (Allibone & Wysoczanski 2002).

Dun Pluton (gud; **gd**)
Previous usage or definition: Allibone et al. (1991).
Name: from the Dun Glacier, southern Kukri Hills.
Reference area: eastern side of the Dun Glacier (162°13.36'E, 77°48.24'S).
Description: strongly foliated biotite quartz monzodiorite orthogneiss; non-migmatitic.
Age: 515.16 ± 0.36 U-Pb zircon (Tulloch & Ramezani 2012 CA-ID-TIMS age) compared with less reliable 531 ± 10 Ma U-Pb zircon age by SHRIMP (Allibone & Wysoczanski 2002).

Calkin Pluton (gua; **gc**)
Previous usage or definition: Allibone et al. (1991).
Name: from the Calkin Glacier, northern Kukri Hills.
Reference area: ridges between ice tongues 3 km west of Calkin Glacier (162°09.57'E, 77°46.29'S).
Description: strongly foliated migmatitic biotite granite orthogneiss concordantly interlayered with Skelton Group metasediments.
Age: 516 ± 10 Ma U-Pb zircon by SHRIMP (Allibone & Wysoczanski 2002).

Chancellor Orthogneiss (guo; **go**)
Previous usage or definition: Gunn & Warren (1962), redefined by Jones (1997a).
Name: from Chancellor Lakes, north of the Walcott Glacier.
Reference area: Chancellor Lakes (163°17.48'E, 78°12.78'S).
Description: variably foliated, fine- to medium-grained biotite orthogneiss with schist xenoliths, schlieren, and garnet in leucocratic patches and pegmatites.
Age: poorly constrained; between 520 and 490 Ma (Jones 1997a).

Hooper Intrusives (gfo; **gfo**)
Previous usage or definition: new name, from Read (2010).
Name: from Hooper Crags in the upper Koettlitz Glacier.
Reference area: Hooper Crags (162°42.13'E, 78°24.92'S).
Description: undifferentiated discordant plutons and dikes of medium-grained biotite granite with lesser granodiorite, quartz monzonite, and diorite; mostly non-foliated; distinctive high Sr low Y adakitic chemistry.
Age: variable 533 ± 3 Ma, 524 ± 4 Ma, 520 ± 4 Ma and 511 ± 3 Ma ages by LA-ICP-MS (Read 2010).

Radian Pluton (gfr; **gfr**)
Previous usage or definition: Cook & Craw (2001) after Cook (1997) (*not* the Radian Nepheline Syenite of Worley & Cooper 1995).
Name: from the Radian Glacier, southern Royal Society Range.
Reference area: northwest of Radian Ridge (161°31.11'E, 78°13.93'S).
Description: small, elongate, zoned pluton of unfoliated biotite granite, locally garnetiferous with rare hornblende; contains mafic enclaves; high Sr low Y adakitic chemistry.
Age: 515 ± 4 Ma U-Pb zircon by LA-ICP-MS (Read 2010).

Kehle Pluton (gfk; *in digital dataset but not within map area*)
Previous usage or definition: new name, from Richardson (2002); reinterpreted by Read (2010) to include rocks mapped as 'Harvey Pluton' by Richardson (2002).
Name: from the Kehle Glacier, a branch of the Mulock Glacier.
Reference area: from peak on northwest side of the Kehle Glacier (160°12.87'E, 78°53.30'S).
Description: unfoliated homogeneous medium-grained biotite granodiorite and granite; high Sr low Y adakitic chemistry. Cut by late-stage quartz-rich dikes.
Age: 530 ± 8 Ma zircon LA-ICP-MS age in Richardson (2002); reinterpreted by Read (2010).

DRY VALLEYS 1A SUITE
Previous usage or definition: petrogenetic suite of plutonic rocks, introduced by Smillie (1992), modified by Allibone et al. (1993b).
Name: from the Dry Valleys region of South Victoria Land.
Type area: n/a
Description: variably deformed calc-alkalic quartz monzodiorite and granodiorite plutons similar to I-type Cordilleran-style, igneous rocks of convergent-margin settings (*not shown separately on map face, but see Fig. 14*).
Age: Cambrian.

<u>DV1a hornblende-biotite granitoids</u> (gr, gr?; **gr**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: variably foliated or flow-banded and segregated hornblende biotite granitoid; typically megacrystic with mafic enclaves. LoSY calc-alkaline chemistry.
Age: 517-495 Ma, but possibly as old as 530 Ma, based on lithologic correlation (cf. Allibone & Wysoczanki 2002).

Bonney Pluton (grb, grb?; **grb**)
Previous usage or definition: Smillie (1989, 1992); adopted by Allibone et al. (1991); Cox (1993). Previously applied terms Larsen Granodiorite (Gunn & Warren 1962) and Olympus Granite Gneiss (McKelvey & Webb 1964; Cox 1987; Cox & Allibone 1991) are no longer used.
Name: After Lake Bonney, Taylor Valley.
Type area: Bonney Riegel (162°21.43'E, 77°43.12'S).
Description: unfoliated to strongly foliated, coarse-grained hornblende biotite alkali-feldspar megacrystic diorite to monzodiorite and granodiorite; local mafic enclaves and orbicules.
Age: 510.78 ± 0.56 Ma U-Pb zircon in deformed marginal phase and 503.77 ± 0.37 Ma in the unfoliated centre of pluton (Tulloch & Ramezani 2012 CA-ID-TIMS age); compared with 507.4 ± 3.8 Ma U-Pb zircon (Hagen-Peter et al. 2011 unpublished LA-MC-ICP MS age); 505 ± 2 Ma U-Pb zircon (Encarnacion & Grunow 1996); and less reliable discordant 506 ± 4 Ma U-Pb zircon (Cox et al. 2000); 499 ± 6 Ma U-Pb zircon by SHRIMP (Allibone & Wysoczanski 2002); or 493 ± 17 Ma and 479 ± 15 Ma Rb-Sr ages (Allibone et al. 1993a).

Catspaw Pluton (grc; **grc**)
Previous usage or definition: Allibone et al. (1991).
Name: after the Catspaw Glacier, Taylor Valley.
Reference area: around the Catspaw Glacier snout (161°45.45'E, 77°43.04'S).
Description: massive homogeneous coarse-grained equigranular biotite hornblende granite.
Age: 503-495 Ma, from intrusive relationships (pre-dates Vanda Dikes and intrudes Bonney Pluton).

Armitage Pluton (gra; **gra**)
Previous usage or definition: Jones (1995a; 1997a,b).
Name: from Armitage Saddle, upper Blue Glacier.
Reference area: Armitage Saddle (163°23.16'E, 77°08.76'S).
Description: weakly foliated fine- to medium-grained hornblende biotite granodiorite.
Age: 511-503 Ma from mutually cross-cutting relationships that indicate intrusion took place during Bonney Pluton crystallisation (Jones 1997a).

Wheeler Pluton (grw; **grw**)
Previous usage or definition: Turnbull et al. (1994).
Name: from the Wheeler Valley, northern St Johns Range.
Reference area: southwestern side of Queer Mountain (161°42.41'E, 77°08.80'S).
Description: variably foliated coarse-grained hornblende biotite alkali-feldspar megacrystic diorite to granodiorite; margins banded and segregated.
Age: 511-503 Ma, based on lithologic correlation with Bonney Pluton (Allibone et al. 1993a).

Cavendish Pluton (grv; **grv**)
Previous usage or definition: Allibone et al. (1993a).
Name: from Cavendish Rocks, Ferrar Glacier.
Reference area: Cavendish Rocks (161°25.33'E, 77°49.92'S).

Description: variably foliated hornblende biotite alkali-feldspar megacrystic granodiorite, quartz monzodiorite and quartz diorite.
Age: 511-503 Ma, based on lithologic correlation with Bonney Pluton (Allibone et al. 1993a).

Discovery Pluton (gri; **gri**)
Previous usage or definition: Forsyth et al. (2002).
Name: from Discovery Bluff, Granite Harbour.
Type area: Discovery Bluff (162°37.42'E, 77°00.40'S).
Description: variably foliated coarse-grained hornblende biotite alkali-feldspar megacrystic granodiorite, quartz monzodiorite and quartz diorite.
Age: from 510 ± 2.8 to 502 ± 2.7 and 499.6 ± 3.5 Ma U-Pb zircon (Hagen-Peter et al. 2011 unpublished LA-MC-ICP MS ages).

Denton Pluton (grd; **grd**)
Previous usage or definition: Allibone et al. 1993a,b; after Ellery 1989; see also Forsyth et al. (2002).
Name: from the Denton Glacier, lower Wright Valley.
Reference area: western side of the Denton Glacier (162°22.91'E, 77°26.63'S).
Description: variably foliated coarse-grained hornblende biotite alkali-feldspar megacrystic granodiorite, quartz monzodiorite and quartz diorite.
Age: 517.2 ± 4 Ma U-Pb zircon (Hagen-Peter et al. 2011 unpublished LA-MC-ICP MS age).

Evans Pluton (gre; **gre**)
Previous usage or definition: Forsyth et al. (2002).
Name: from Mt Evans, eastern St Johns Range.
Reference area: southern ridge of Mt Evans (162°31.14'E, 77°15.88'S).
Description: variably foliated coarse-grained hornblende biotite alkali-feldspar megacrystic granodiorite, quartz monzodiorite and quartz diorite.
Age: 511-503 Ma, based on lithologic correlation with Bonney Pluton (Forsyth et al. 2002).

undifferentiated DV1a granitoids (gro, gro?; **gro**)
Previous usage or definition: n/a; includes granitoid referred to as Moraine Bluff Suite by Read (2010).
Name: n/a
Type area: n/a
Description: medium-grained hornblende biotite granodiorite, monzodiorite and diorite; contains mafic enclaves and calc-silicate xenoliths.
Age: unconstrained but on the basis of lithologic correlation may post-date Skelton Mafic Intrusives and Hillary Granitoids, so is probably younger than 551-546 Ma (Read 2010).

hornblende biotite orthogneiss (guh; **guh**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: weakly to strongly foliated hornblende biotite orthogneiss of dioritic quartz monzonitic to granitic composition.
Age: 530-500 Ma, based on lithologic correlation with Bonney Pluton (cf. Allibone & Wysoczanki 2002).

Flint Pluton (guf; **guf**)
Previous usage or definition: Forsyth et al. (1992).
Name: from Flint Ridge, north of the Commonwealth Glacier.
Reference area: Flint Ridge (163°02.37'E, 77°31.59'S).
Description: strongly foliated coarse-grained hornblende diorite gneiss.
Age: 509.1 ± 1.8 Ma U-Pb zircon (Hagen-Peter et al. 2011 unpublished LA-MC-ICP-MS ages).

KOETTLITZ GLACIER ALKALINE SUITE
Previous usage or definition: petrogenetic suite of plutonic rocks, introduced by Read et al. (2002) as Koettlitz Glacier Alkaline Province (see also Cooper et al. 1997; Read 2010), here modified to Koettlitz Glacier Alkaline Suite. Note that the name Koettlitz Group (for metasedimentary rocks) has been abandoned (Cook & Craw 2001).
Name: from the Koettlitz Glacier region of South Victoria Land.
Reference area: Koettlitz Glacier to Skelton Glacier.
Description: alkalic gabbro, diorite, syenite, monzonite, and A-type granite intrusions (*not shown separately on map face, but see Fig. 14*).
Age: Neoproterozoic-Cambrian.

Glee Intrusives (gag; **gag**)
Previous usage or definition: Read et al. (2002) after Aslund (1990).
Name: from the Glee Glacier, south of the Walcott Glacier.
Reference area: ridge south of the Glee Glacier (162°50.71'E, 78°17.22'S).
Description: biotite-, amphibole- or pyroxene-bearing gabbro, quartz monzonite and nepheline syenite; mostly non-foliated but locally mylonitised; Ti-, Fe- and K-rich with some A-type characteristics.
Age: discordant zircon fractions have upper intercept ages of 553 ± 5 and 550 ± 5 Ma interpreted to be parental magma age (U-Pb zircon TIMS by Read 2010). Concordant titanite fractions have concordia ages 538 ± 2 Ma and 534 ± 1 Ma, interpreted be post-magmatic cooling ages (cf. Read et al. 2002).

nepheline syenite (gas; **gas**)
Previous usage or definition: n/a
Name: n/a
Reference area: Dismal Ridge (162°50.50'E, 78°16.46'S).
Description: small plutons and plugs of nepheline syenite with interstitial calcite, alkali pyroxenite cumulate layering and carbonatite dikes. Includes **Dismal Syenite** and **Radian Ridge Syenite** (Worley & Cooper 1995; Worley et al. 1995; Cooper et al. 1997) *which are not distinguished on map face.*
Age: age of intrusion (cf. inheritance or reheating) remains unclear. Dating includes: 531 ± 12 Ma U-Pb zircon by SHRIMP for Radian Ridge Syenite (Cooper et al. 1997), which is cross-cut by undeformed carbonatite with 531 ± 5.5 Ma U-Pb zircon (Hall et al.1995). Other zircons at

Radian Ridge ranged from 567 to 507 Ma (Veevers et al. 2006), including four from the carbonatite concordant at 533 ± 13 Ma and one at 567 ± 12 Ma, and from nepheline syenite 545 ± 12 Ma and 507 ± 12 Ma. Dismal Syenite gave a 507 ± 21 Ma whole-rock Rb-Sr isochron (Cooper et al. 1997).

Roaring Orthogneiss (gur; **gur**)
Previous usage or definition: Cook & Craw (2001) - without definition; after Cook (1997).
Name: from Roaring Valley, south of Walcott Glacier.
Reference area: east ridge of Mt Dromedary, above the Dromedary Glacier (163°01.96'E, 78°18.38'S).
Description: inhomogeneous interlayered felsic garnet muscovite orthogneiss and mafic hornblende biotite orthogneiss interlayered with and including rafts of amphibolitic schist. Note that some felsic orthogneiss within this unit appears to have A-type chemistry and may be a deformed portion of the Hillary Granitoids (Read 2010).
Age: 546 ± 3 Ma zircon LA-ICP-MS (Read 2010); discordant TIMS zircon.

Skelton Mafic Intrusives (gam, gam?; **gam**)
Previous usage or definition: Formalised after Read (2010 - as Skelton Mafic Suite). Term Delta Diorite (Gunn & Warren 1962) no longer used.
Name: from the Skelton Glacier (note that the name Skelton is also applied to adjacent metasedimentary rocks).
Reference area: Delta Bluff on the western side of the Skelton Glacier (161°23.79'E, 78°40.82'S).
Description: heterogeneous gabbroic, dioritic and monzonitic intrusives of variable grain size, typically unfoliated; adjacent to the Skelton Glacier; often with finer grained mafic enclaves or intrusions.
Age: 548 ± 2 Ma to 547 ± 4 Ma; U-Pb titanite and zircon by TIMS (Read 2010).

Panorama Pluton (gap; **gap**)
Previous usage or definition: Mellish et al. (2002), after Cook (1997).
Name: from the Panorama Glacier, southern Royal Society Range.
Reference area: northwest side of the upper Panorama Glacier (162°38.17'E, 78°17.16'S).
Description: stock and sill-like bodies of gabbro, monzodiorite, diorite and monzonite.
Age: 557 ± 5 Ma; discordant U-Pb titanite and zircon by TIMS (535 ± 9 Ma Mellish et al. 2002) reinterpreted by Read (2010).

Dromedary Mafic Complex (gab, gad; **gab, gad**)
Previous usage or definition: Simpson & Aslund (1996) after Aslund (1990); formalised by Mellish et al. (2002); includes Dromedary Metagabbro of Walcott & Craw (1993).
Name: from Mt Dromedary.
Reference area: ridges adjacent to the central Renegar Glacier, south of Mt Dromedary (163°6.26'E, 78°20.09'S).
Description: inhomogeneous medium- to coarse-grained gabbro, anorthosite, norite and pyroxenite with local cumulate textures (**gab**); and homogeneous equigranular pyroxene-biotite-bearing diorite (**gad**) containing granitoid dikes and metasediment rafts.
Age: interpreted to be c. 557-546 Ma. Discordant U-Pb titanite and zircon by TIMS (536 ± 10 Ma; Mellish et al. 2002) reinterpreted by Read (2010).

Hillary Granitoids (gaa, gaa?; **gaa**)
Previous usage or definition: Formalised after Read (2010) (as Hillary Suite); includes Harmsworth Pluton of Gunn & Warren (1962).
Name: from the Hillary Coast.
Reference area: none given; a composite from the included (informal) units.
Description: includes several plutons (Kempe granite; Cocks granitoids; north Foster granite; Read 2010) of high silica A-type biotite granite and subordinate syenite, typically K-feldspar megacrystic, variably foliated, and locally amphibole-bearing granite (*not differentiated on the map face*).
Age: various ages from 551 ± 4 Ma to 542 ± 3 Ma (Read 2010, and others).

Penny Hill Granite (gae; **gae**)
Previous usage or definition: Read et al. (2002), after Aslund (1990) and Walcott (1990).
Name: from an informally named hill east of Penny Lake, Roaring Valley.
Reference area: hills east of Roaring Valley (163°18.19'E, 78°15.89'S).
Description: white to pink, equigranular, medium- to coarse-grained, foliated biotite granite. A-type chemistry.
Age: 548 ± 4 Ma U-Pb zircon by ICP-MS (Read 2010); cf. interpreted 517 ± 4 Ma titanite U-Pb age by TIMS (Read et al. 2002).

Unassigned older plutonic rocks

older mafic intrusives and orthogneiss (gmm; **gum**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: undifferentiated variably foliated dioritic and gabbroic orthogneiss, dominated by hornblende-plagioclase-clinopyroxene-biotite gneiss.
Age: probably 539-510 Ma, from intrusive and deformational relationships.

undifferentiated orthogneiss (gu; **gu**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: mappable bodies of undifferentiated dioritic to granitic orthogneiss interlayered with Skelton Group and other orthogneisses.
Age: probably 539-510 Ma, from intrusive and deformational relationships.

orthogneiss interlayered with Skelton Group (gus; **gus**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: undifferentiated dioritic to granitic orthogneiss interlayered with Skelton Group and other orthogneisses, generally indistinguishable at map scale.
Age: probably 539-510 Ma, from intrusive and deformational relationships.

BEACON SUPERGROUP

BEACON SUPERGROUP (undifferentiated; b; **b**)
Previous usage or definition: Beacon Sandstone (Group) of Harrington (1958) and Gunn & Warren (1962); McKelvey et al. (1970); Barrett et al. (1972).
Name: Named by Ferrar, after prominent hills named Beacon Heights.
Type area: originally Beacon Heights; now composite of constituent groups and formations. Thickness in southern Victoria Land at least 2300 m.
Description: undifferentiated quartzose sandstone, conglomerate and siltstone; minor titaniferous ironstone and coal.
Age: Devonian to Triassic, from paleontology (e.g., macrofossil plant remains, fish and palynology).

VICTORIA GROUP (undifferentiated; bv, bv?; **bv**)
Previous usage or definition: Harrington (1965).
Name: from Victoria Valley, one of the larger dry valleys.
Type area: composite of constituent groups and formations.
Description: quartzose and feldspathic sandstone and siltstone; conglomerate; minor mudstone, carbonaceous shale and coal.
Age: Permian to Triassic, from paleontology (e.g., macrofossil plant remains and palynology).

Lashly Formation (bvl; **bvl**)
Previous usage or definition: McElroy (1969); Askin et al. (1973); McElroy & Rose (1987).
Name: from Lashly Glacier and the Lashly Mountains.
Type section: southeast of Mt Feather (160°23.07'E, 77°57.65'S).
Description: light greenish-grey and dark grey coarse- to fine-grained sandstone and mudstone; minor conglomerate; coal seams up to at least 0.8 m thick.
Age: Middle to Late Triassic, on plant macrofossils and palynology.

Feather Conglomerate (bvf; **bvf**)
Previous usage or definition: McElroy (1969); Askin et al. (1973); McElroy & Rose (1987).
Name: from Mt Feather.
Type section: southeast of Mt Feather (160°23.46'E, 77°57.76'S). Thickness 183 m at type section, ranging locally from 150-215 m.
Description: white to light grey coarse-grained sandstone and conglomerate: intercalated green-brown mudstones, some of which are paleosols.
Age: inferred Early Triassic; from age of plant fossils.

Weller Coal Measures (bvw; **bvw**)
Previous usage or definition: Webb (1963); Askin et al. (1973); McElroy & Rose (1987).
Name: from Mt Weller.
Type Section: east of Mt Feather (160°25.33'E, 77°57.31'S). Thickness 222 m at type section.
Description: white to medium grey coarse- to fine-grained sandstone and mudstone; minor conglomerate and breccia; coal seams up to 4.4 m thick.
Age: Early Permian, from plant macrofossils; possibly Late Permian.

Pyramid Erosion Surface
Previous usage or definition: McKelvey et al. (1970).
Name: from Pyramid Mountain, Quartermain Mountains.
Reference area: well exposed at Slump Mountain, Aztec Mountain, Mt Feather, Mt Fleming and Shapeless Mountain (Isaac et al. 1996).
Description: regional disconformity separating glacial deposits of the Metschel Tillite from the overlying fluvial Weller Coal Measures. Converges with or cuts the older Maya Erosion Surface and can be problematic to distinguish from the Maya Erosion Surface where the intervening Metschel Tillite has been removed. Generally a planar surface with less than 2 m local relief that is persistent beyond southern Victoria Land. Maximum ~2300 m elevation in the map area at Mt Crean (Lashly Mountains), and minimum elevation ~1100 m from the Mackay Glacier north. Orientation and elevation are affected by intrusion of Ferrar Dolerite sills.
Age: Early Permian.

Metschel Tillite (bvm; **bvm**)
Previous usage or definition: McKelvey et al. (1970).
Name: from Mt Metschel, Skelton Névé.
Type locality: southern face of Mt Metschel at eastern end, Skelton Névé (158°59.56'E, 78°17.04'S).
Description: conglomerate, diamictite, pebbly quartzose sandstone and silty sandstone.
Age: correlative units elsewhere in Antarctica have Early Permian palynomorphs.

Maya Erosion Surface
Previous usage or definition: Harrington (1965).
Name: from Maya Mountain, Quartermain Range.
Reference area: Kennar Valley, Quartermain Range; also Boomerang Range.
Description: glacially eroded regional unconformity which truncates the Taylor Group; typically a rolling surface with less than 2 m relief, but locally with up to 80 m relief (McKelvey et al. 1977; Barrett & McKelvey 1981). Overlain by Metschel Tillite; only locally preserved remnants survive, in part eroded by younger Pyramid Erosion Surface.
Age: represents a time-gap of about 86 to 109 million years. No record of Carboniferous rocks; erosion probably earliest Permian (McKelvey et al. 1977; Barrett & McKelvey 1981).

TAYLOR GROUP (bt, bt?; **bt**)
Previous usage or definition: Harrington (1965).
Name: from the Taylor Valley.
Type area: composite from constituent formations.
Description: pale grey to brown quartzose sandstone, planar to trough cross bedded; minor black siltstone, conglomerate and breccia.
Age: Early to Middle Devonian, from palynology and fish fossils.

Aztec Siltstone (btz; **btz**)
Previous usage or definition: Webb (1963); McElroy & Rose (1987).
Name: from Aztec Mountain.
Type section: eastern flank of Aztec Mountain (160°34.20'E, 77°48.08'S). Thickness 40 m, but reaching 120 m in Warren Range (Barrett & Kohn 1971).
Description: white to yellow-grey medium- to very fine-grained sandstone, green-grey to red-grey siltstone and mudstone; locally abundant fossil fish.
Age: Late Middle Devonian; abundant fish fauna; plant microfossils near the top.

Beacon Heights Orthoquartzite (btb, btb?; **btb**)
Previous usage or definition: Webb (1963); McKelvey et al. (1977); McElroy & Rose (1987).
Name: from Beacon Heights.
Type section: northwest ridge of West Beacon (160°49.16'E, 77°49.15'S) – but see McElroy & Rose (1987).
Description: hard cliff-forming white to light grey coarse- to medium-grained highly quartzose sandstone; minor olive green to brown mudstone.
Age: Middle Devonian based on lycopod stems (plant macrofossils) – see Plumstead (1964), McKelvey et al. (1977).

Pivot Member of **Arena Sandstone** (btrp; **btr**)
Previous usage or definition: Woolfe et al. (1989), but see Woolfe et al. (1995).
Name: from Pivot Peak, south of the Ferrar Glacier.
Type section: north ridge of Ugolini Peak, Rotunda massif (161°30.77'E, 78°00.46'S).
Description: cliff- or steep slope-forming, colour-banded, planar-bedded grit and sandstone interlayered with maroon shale; dark titaniferous ironstones were formerly and erroneously taken to be carbonaceous shale and thin coal; diverse ichnofauna. *Distinguished in digital dataset but not on map*.
Age: Early to Middle Devonian; inferred from ages of enclosing units.

Arena Sandstone (btr; **btr**)
Previous usage or definition: McElroy (1969); McElroy & Rose (1987).
Name: from Arena Valley.
Type section: western Arena Valley (160°48.81'E, 77°52.26'S). Thickness 385 m, but more typically c. 200 m.
Description: slope-forming light brown, yellow and grey medium-grained sandstone; cross bedding and intense burrowing common; Fe speckling.
Age: Early to Middle Devonian age inferred from ages of enclosing units.

Odin Arkose Member of **Altar Mountain Formation** (bto; **bto**)
Previous usage or definition: Proposed as a formation by Webb (1963); reduced to member status by McKelvey et al. (1970, 1972).
Name: from Mt Odin, Asgard Range.
Type section: Mt Odin, Asgard Range (161°42.08'E, 77°34.68'S). Thickness c. 30 m.
Description: quartz pebble conglomerate and pebbly sandstone, commonly sub-arkosic, overlying Heimdall Erosion Surface; intercalated green, purple and red siltstones and shales.
Age: Early to Middle Devonian; inferred from ages of enclosing units.

Altar Mountain Formation (bta; **bta**)
Previous usage or definition: McElroy (1969); McKelvey et al. (1977); McElroy & Rose (1987). Includes Ashtray Sandstone Member (McElroy 1969) *which is not distinguished on map face.*
Name: from Altar Mountain.
Type section: Ashtray Basin in Arena Valley, northeast of Altar Mountain (160°59.71'E, 77°52.81'S). Thickness 230 m at type section.
Description: white to grey planar and trough cross-bedded granule conglomerate and medium-grained sandstone; basal conglomerate and pebbly sandstone.
Age: Early to Middle Devonian; inferred from ages of enclosing units.

Heimdall Erosion Surface
Previous usage or definition: McKelvey et al. (1970); Plume (1978).
Name: from Heimdall Glacier, Asgard Range.
Reference area: well exposed in Nibelungen Valley (Allibone et al. 1991) and Olympus Range (Isaac et al. 1996; Turnbull et al. 1994).
Description: locally erosive disconformity between New Mountain Sandstone and overlying Altar Mountain Formation; well exposed on northern side of Asgard Range (particularly Nibelungen Valley) and Olympus Range; coincides with Kukri Erosion Surface at Sponsors Peak (upper Victoria Valley); recognisable but not obvious south of Ferrar Glacier; yet to be recognised south of Table Mountain. Regional dip varies from 2° to 4° west.
Age: Early to Middle Devonian.

New Mountain Sandstone (btn; **btn**)
Previous usage or definition: Hamilton & Hayes (1963); McElroy (1969); McKelvey et al. (1977); Plume (1978).
Name: from New Mountain.
Type section: eastern spur of New Mountain (161°12.01'E; 77°52.10'S). Thickness c.100 m at type locality, but elsewhere up to 250 m.
Description: white to light brown coarse- to medium-grained sandstone with minor conglomerate and siltstone; large scale planar cross bedding.

Age: Early to Middle Devonian; inferred from ages of enclosing units.

Terra Cotta Siltstone (btt; **btt**)
Previous usage or definition: Zeller et al. (1961); Kyle (1977a); Plume (1978).
Name: from Terra Cotta Mountain.
Type section: eastern spur of New Mountain (161°14.44'E, 77°51.60'S).
Description: purple, dark brown, green or black laminated siltstone; minor interbeds of medium- to fine-grained sandstone.
Age: Early Devonian, from palynomorphs (Kyle 1977a).

Windy Gully Sandstone (btw; **btw**)
Previous usage or definition: Zeller et al. (1961); Plume (1978).
Name: from Windy Gully.
Type section: eastern spur of New Mountain (161°15.81'E, 77°51.91'S). Thickness at type section is 36 m.
Description: cream to pale brown coarse- to medium-grained sandstone; planar and trough cross beds on cm-dm scale; basal pebble conglomerate and rare breccia.
Age: inferred Early Devonian; based on age of microflora in Terra Cotta Siltstone.

Sperm Bluff Conglomerate (bts; **bts**)
Previous usage or definition: Turnbull et al. (1994).
Name: from Sperm Bluff, Cotton Glacier.
Type section: west face of Mt Suess (161°40.06'E, 77°02.34'S).
Description: clast-supported polymict pebble to boulder conglomerate, minor breccia-conglomerate; interbedded with pebbly quartzose sandstone.
Age: inferred Early Devonian and possibly younger.

Kukri Erosion Surface
Previous usage or definition: McKelvey et al. (1977); Kukri Peneplain of Gunn & Warren (1964).
Name: from Kukri Hills between Taylor and Ferrar glaciers.
Reference area: first recognised and described from Kukri Hills (Debenham 1921).
Description: regionally extensive angular unconformity and erosional contact between basement (Granite Harbour Intrusive Complex or Skelton Group) and overlying Devonian to Triassic Beacon Supergroup strata; local relief of up to about 80 m and gradients reaching c. 30°; regional dip between 2° and 4° WNW; elevation in the map area varies between c. 200 m at Mackay Glacier and c. 2800 m in the Royal Society Range (Mt Kempe); disrupted by Jurassic Ferrar Dolerite intrusions and Cenozoic uplift and minor faulting of Transantarctic Mountains.
Age: represents about 39 to 57 million years of Ordovician-Early Devonian time.

FERRAR GROUP

Previous usage or definition: Grindley (1963) and others; also known as Ferrar Supergroup (Kyle 1981).
Name: from Ferrar Glacier.
Type area: none given; composite from constituent units.
Description: undifferentiated massive and layered dolerite intrusives, mainly sills, with volcanic and volcaniclastic units (see below).
Age: latest Early Jurassic.

Ferrar Dolerite (undifferentiated ff, ff?; **ff**)
Previous usage or definition: Gunn & Warren (1962); also known as Ferrar Supergroup (Kyle 1981).
Name: from Ferrar Glacier.
Type area: sills in the Ferrar and Taylor valleys (Gunn & Warren 1962).
Description: undifferentiated massive and layered sills of dolerite up to 500 m thick, and minor dolerite dikes and bosses. Includes several named sills (see below).
Age: latest Early Jurassic. 182.7 to 182.2 ± 0.2 Ma U-Pb zircon (Fleming et al. 2011 unpublished by CA-TIMS ages). 176 ± 1.8 Ma by Ar-Ar dating (Fleming et al. 1999) may depend on the age assigned to the standard used to monitor the neutron flux during irradiation of samples.

Mt Fleming Sill (fff; **ff**)
Previous usage or definition: Marsh (2004); after Pyne (1984).
Name: from Mt Fleming.
Reference area: no type area given. Exposed on eastern slopes of Mt Fleming (160°11.83'E, 77°32.75'S).
Description: massive sill of dolerite up to 50 m thick intruded along the Weller Coal Measures - Feather Conglomerate contact. *Distinguished in digital dataset, but not on map face.*
Age: latest Early Jurassic.

Unnamed upper sill (ffu; **ff**)
Previous usage or definition: n/a
Name: n/a.
Reference area: n/a.
Description: massive and layered sills of dolerite up to 500 m thick; dolerite dikes and bosses. *Distinguished in digital dataset, but not on map face.*
Age: latest Early Jurassic.

Asgard Sill (ffa; **ff**)
Previous usage or definition: Isaac et al. (1996); also Marsh (2004) and Bedard et al. (2007).
Name: from the western Asgard Range.
Reference area: no type area given. Well exposed in the cliffs of Mt Freya (160°50.58'E, 77°35.93'S).
Description: dolerite sill up to 250 m thick, intruded at or slightly below the contact between Taylor and Victoria groups. *Distinguished in digital dataset, but not on map face.*
Age: latest Early Jurassic.

Peneplain Sill (ffp; **ffp**)
Previous usage or definition: Gunn & Warren (1962).
Name: from its proximity to the Kukri Erosion Surface (peneplain).
Reference area: no type area given. Well exposed in cliffs around the upper Wright Valley (161°12.80'E, 77°34.94'S and 161°05.23'E, 77°31.38'S).

Description: massive and layered sill of dolerite up to 350 m thick, locally containing cumulate textures with orthopyroxenite-rich layers; generally intruded along the Kukri Erosion Surface.
Age: latest Early Jurassic.

Basement Sill (ffb, ffb?; **ffb**)
Previous usage or definition: Gunn & Warren (1962); redescribed by Bedard et al. (2007).
Name: from its typical location within basement rocks.
Reference area: no type area given. Well exposed on the Dais (161°24.23'E, 77°33.08'S) and at Bull Pass (161°56.92'E, 77°30.22'S) in the Wright Valley.
Description: dolerite sill, often differentially layered, up to 400 m thick, within plutonic rocks and generally beneath the Kukri Erosion Surface. This sill may rise to follow the Kukri Erosion Surface.
Age: latest Early Jurassic. Sill in Pearse Valley returned a 183.8 ± 1.6 Ma U-Pb age (Encarnacion et al. 1996); 176 ± 0.7 Ma Ar-Ar age (Fleming et al. 1997) cf. reported 183-182 Ma ages for U-Pb zircon by CA-TIMS (Fleming et al. 2011, unpublished).

Kirkpatrick Basalt (fk; **fk**)
Previous usage or definition: Grindley (1963); Ballance & Watters (1971).
Name: from Mt Kirkpatrick, in the Beardmore Glacier area.
Type area: Blizzard Peak, Marshall Mountains, in the Beardmore Glacier area (164°25.5'E, 84°38.3'S) (Grindley 1963).
Description: tholeiitic basalt pillow lavas, lava flows and hyaloclastic basalt breccia: rare thin tuffaceous and sedimentary interbeds.
Age: latest Early Jurassic. 176.4 ± 0.5 Ma Ar-Ar age (Fleming et al. 1997). See also 176.8 to 176.4 Ma range for basalt in central Transantarctic Mountains, southern Victoria Land and northern Victoria Land (Heimann et al. 1994).

Carapace Sandstone (fc, fc?; **fc**)
Previous usage or definition: Ballance & Watters (1971).
Name: from Carapace Nunatak, at the head of the Mackay Glacier.
Type section: Carapace Nunatak (159°25.88'E, 76°53.60'S). Thickness at least 120 m.
Description: lithic lacustrine sandstone and conglomerate with some volcanic detritus, minor silty horizons.
Age: Early Jurassic to early Middle Jurassic on plant fossils, conchostracans and palynology. Probably latest Early Jurassic from correlation and known age of Ferrar Dolerite.

Mawson Formation (fm, fm?; **fm**)
Previous usage or definition: originally Mawson Tillite within Beacon Supergroup (Gunn & Warren 1962) but recognised as part of Ferrar Group by Borns & Hall (1969) and Ballance & Watters (1971).
Name: from the Mawson Glacier.
Type area: ridge which forms southern half of Allan Hills, McKay Glacier area (159°34.30'E, 76°42.30'S).
Description: volcanic and sedimentary breccia, diamictite, conglomerate, sandstone and minor basalt.
Age: latest Early Jurassic, based on paleontology of Carapace Sandstone and Ar-Ar dating of Ferrar Dolerite.

EOCENE TO HOLOCENE SEDIMENTS

unknown (unk; **?**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: area known to be exposed rocks or cover deposits, the exact nature of which is unknown.
Age: unknown.

undifferentiated cover (u; **u**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: undifferentiated cover materials, potentially including scree, colluvial, glacial, alluvial, aeolian, beach, delta, or lacustrine deposits.
Age: uncertain.

undifferentiated till (ut, ut?; **ut**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: undifferentiated till in moraines of uncertain origin, and cover deposits inferred to be till.
Age: uncertain. Suspected Quaternary age (cf. older undifferentiated till) based on landforms or degree of weathering.

supraglacial till (uts, uts_ice; **us**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: surficial till on top of glacial ice and snow: may include some young active or mobile ice-cored till. *Supra-glacial till on the Ross Ice Shelf is distinguished in the digital dataset by the unit code uts_ice.*
Age: uncertain. Actively forming or deforming.

undifferentiated local glacier till (ul; ul?; **ul**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: locally derived till in moraines and rock glaciers; variably weathered; usually associated with present-day alpine glaciers. *As mapped includes Alpine 1 and Alpine 2 tills in lower Wright Valley/Asgard Range (Calkin* et al.*1970; Hall* et al. *1993; Hall & Denton 2005) and Alpine A and Alpine B tills in Quartermain Mountains (Marchant* et al. *1993b).*
Age: uncertain. Suspected Quaternary age based on proximity to local glaciers, prominent moraine ridges and/or lack of modification.

undifferentiated ice sheet margin till (ui; **ui**)
Previous usage or definition: n/a
Name: n/a

Type area: n/a
Description: till in moraines on margins of ice sheets, large snowfields or large glaciers occupying the major valleys; commonly degraded and covered by scree. Multiple advances not always differentiated.
Age: uncertain.

colluvium and scree (uc, uc?; **uc**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: angular material forming talus slopes, loose glacial material, scree and polygonal ground.
Age: uncertain. Quaternary and potentially older.

alluvium (ua; **ua**)
Previous usage or definition: n/a, but see Shaw & Healy (1980); Turnbull et al. (1994).
Name: n/a
Type area: n/a
Description: loose sand and gravel deposited in stream beds and alluvial terraces by summer meltwater streams.
Age: uncertain Quaternary. Holocene and potentially older.

fan deposits (uf; **uf**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: gravel and fanglomerate deposited on alluvial fans by summer meltwater streams. May include some colluvial fans and gelifluction debris lobes.
Age: uncertain Quaternary. Holocene and potentially older.

beach and stranded marine deposits (ub; **ub**)
Previous usage or definition: Priestley (1922), Nichols (1968), Hall & Denton (2000), Gardner et al. (2006).
Name: n/a
Reference area: examples on west side of McMurdo Sound from Cape Ross to Granite Harbour.
Description: unconsolidated sandy, gravelly diamicton and boulders associated with Ross Sea beaches; rounded cobbles and wave-washed bedrock. May be fossiliferous.
Age: Quaternary. Radiocarbon ages are mid-Holocene but DNA analysis of penguin bones suggests some beaches may pre-date the Holocene.

dune sand and other aeolian deposits (ud; **ud**)
Previous usage or definition: Calkin (1964a), Selby et al. (1974), Turnbull et al. (1994).
Name: n/a
Reference area: good examples near Lake Vida, lower Victoria Valley.
Description: fine- to medium-grained sand and silt reworked by wind into isolated dunes or dune fields; interdune gravelly lag deposits; loess. Includes both active and frozen bedforms.
Age: Quaternary.

undifferentiated lacustrine deposits (uk, uk?; **uk**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: poorly consolidated sand, silt and mud deposited in lakes; locally interbedded with evaporites and algal limestone; may contain gypsum, aragonite, calcite, halite, or other salts. Typically with deflated and armoured pebbly surfaces. Interbedded with diamictite (till). Includes elevated pebbly deposits where tills and colluvium have been reworked into lake benches and strandlines.
Age: uncertain Quaternary.

deltaic deposits (ue; **ue**)
Previous usage or definition: Speden (1960), Hall & Denton (2005), Hall et al. (2000, 2002).
Name: n/a
Type area: n/a
Description: poorly consolidated gravel, sand and silt forming deltas along the Ross Sea coastal margin or beside lakes. May contain marine fossils or algal mats.
Age: uncertain Quaternary. Algal mats in Victoria Valley are 19.8-8.9 ka (Hall et al. 2002). Radiocarbon ages of blue-green algae from lacustrine deltas on Hjorth Hill range from 13.7-10.4 ka ^{14}C yrs (Hall & Denton 2000a). Other radiocarbon ages indicate a grounded Ross Ice Sheet blocked the mouth of Taylor Valley and formed an ice-dammed lake between 23.8 - 8.3 ka ^{14}C yrs (Hall & Denton 2000b), within which deltaic deposits were formed.

coastal till (uir; **ur**)
Previous usage or definition: n/a
Name: n/a
Reference area: beside Ross Ice Shelf at Minna Bluff (Wilson 2000) (165°49.85'E, 78°25.82'S).
Description: slightly to moderately weathered, matrix-poor, loose bouldery sandy till, waterlaid diamicton, glaciolacustrine silt, stratified sand, and interbedded silt/sand/gravel sediments, locally with evaporite. May be ice-cored and/or deflated. Typically rich in McMurdo Volcanic Group clasts, locally including anorthoclase phonolite (referred to by some glaciologists as 'kenyte') and plagioclase-bearing tephriphonolite and phonotephrite. Deposited by incursion of the Ross Ice Sheet and contains marine fossils.
Age: probably Holocene.

evaporite deposits (uv; **X uv** outcrops only)
Previous usage or definition: Bowser et al. (1970), Clayton-Greene et al. (1988), Lovett (2011).
Name: n/a
Reference area: near the Hobbs Glacier terminus (164°28.2'E, 77°54.6'S).
Description: accumulations of evaporite salts and carbonate, such as gypsum, aragonite, halite or mirabilite; of sufficient size or importance to be individually shown on the map.
Age: uncertain Quaternary.

Victoria Drift (ulv; **ulv**)
Previous usage or definition: informally named by Kelly et al. (2002), equivalent to part of Packard Drift of Calkin (1964a), as modified by Turnbull et al. (1994).
Name: from the Victoria Valley.
Reference area: Victoria Valley, adjacent to Victoria Upper Lake (161°38'E, 77°20'S).

Description: poorly sorted, very bouldery sandy till in the Barwick and Victoria valleys: slight cavernous weathering of clasts; patterned ground on surface. Includes some alluvial, deltaic and lacustrine deposits.
Age: uncertain Middle to Late Pleistocene. Entrained algal sample ages are from 11 ka to >40 ka, but a more extended range is inferred.

Packard Drift (ulp; **ulp**)
Previous usage or definition: equivalent to part of Packard Drift of Calkin (1964a), being that adjacent to Packard Glacier, but not including drift in upper Victoria Valley (see Victoria Drift). Equivalent to the Ross Sea II Drift of Turnbull et al. (1994), but not accepting their proposed modification.
Name: from the Victoria Valley.
Reference area: Victoria Valley, adjacent to Packard Glacier (162°16.5'E, 77°21.9'S).
Description: loose, slightly weathered, very sandy till in lower Victoria Valley; clasts mostly locally derived dolerite and granite; slight cavernous weathering of boulders and wind erosion of clasts; patterned ground on surface; includes some bedded sand and silt.
Age: uncertain Middle to Late Pleistocene. Deposited by an advance(s) of Victoria Lower Glacier. Potentially equivalent in age to Victoria Drift and/or Doorly Drift (Wright Valley). The source of rare scoriaceous olivine basalt clasts (Borns 1978, 1982) has yet to be conclusively determined, but could provide evidence that the deposit was derived from the Ross Ice Sheet rather than the Wilson Piedmont-Victoria Lower glaciers.

Wilson Drift (uiw1; **uw**)
Previous usage or definition: informally named by Hall & Denton (2000a).
Name: from the Wilson Piedmont Glacier.
Reference area: coastal region from Cape Bernacchi to Cape Dunlop (163°39.84'E, 77°24.13'S).
Description: loose, slightly to moderately weathered bouldery sandy till at margin of Wilson Piedmont Glacier.
Age: Quaternary of probable 27-6 ka age.

Doorly Drift (ukw1; **X uk** outcrop only)
Previous usage or definition: informally named by Hall & Denton (2005).
Name: from Mt Doorly.
Reference area: below Mt Doorly on the north wall of the lower Wright Valley (162°41.25'E, 77°25.13'S).
Description: slightly weathered patches of well sorted sand and gravel; locally stratified with some reverse grading; contains algae and ice. Boulders mantle the surface but are not present within the deposit.
Age: Late Pleistocene. Radiocarbon ages of 20.6-18.7 ka ^{14}C yrs BP (Hall & Denton 2005). Deposition in a proglacial lake by Wilson Piedmont Glacier (Hall & Denton 2005).

Ross Sea 1 Drift (uir1; **ur1**)
Previous usage or definition: informal definition by Stuiver et al. (1981) after Denton et al. (1970). Includes deposits referred to as Kenyte Moraine (Vella 1969) and Canada Formation (Murrell 1973).
Name: from Ross Sea and pertaining to the Ross Ice Sheet.
Reference area: lower Taylor Valley, in particular Commonwealth Stream (163°27.17'E, 77°33.86'S).
Description: slightly to moderately weathered loose bouldery sandy till, waterlaid diamicton, glaciolacustrine silt, stratified sand, and interbedded silt/sand/gravel sediments. Locally with evaporite, typically rich in McMurdo Volcanic Group clasts, locally including a distinctive anorthoclase phonolite (referred to by some glaciologists as 'kenyte'). Deposited by onland incursion of the Ross Ice Sheet.
Age: Quaternary, of probable 27-6 ka age. Radiocarbon ages indicate a lobe of grounded Ross Ice Sheet blocked the mouth of Taylor Valley and formed an ice-dammed lake between 23.8-8.3 ka ^{14}C yrs (Hall & Denton 2000b).

<u>Ross Sea 1 lacustrine deposits </u>(ukr1; **uk1**)
Previous usage or definition: a facies within Ross Sea 1 Drift, not previously mapped. Described by Hall et al. (2000). See also Murrell (1973).
Name: from Ross Sea.
Reference area: exposed sections in Commonwealth Stream, Taylor Valley (163°27.17'E, 77°33.86'S).
Description: Loose lacustrine sand, silt and mud with interbedded till; commonly contain gypsum, aragonite, calcite, mirabilite or other evaporite minerals. Surfaces deflated and pebble-armoured.
Age: Quaternary, of probable 27-6 ka age.

Ross Sea 2 Drift (uir2, uir2?; **ur2**)
Previous usage or definition: informally named by Denton et al. 1970. Sometimes referred to as Marshall Drift (Denton et al. 1989).
Name: from Ross Sea and pertaining to the Ross Ice Sheet.
Reference area: below Mt Doorly on the north wall of the Wright Valley (162°46.06'E, 77°24.70'S).
Description: slightly to moderately weathered bouldery sandy till; interbedded lacustrine mud, sand, basalt clasts. Deposited by onland incursion of the Ross Ice Sheet. *As mapped includes deposits mapped as Marshall, and Brownworth (uir2b) drifts (Judd 1986; Denton* et al. *1989; Hall & Denton 2005).*
Age: Middle to Late Pleistocene. Probable 180-130 ka age indicated by U-Th and exposure age dating.

<u>Ross Sea 2 lacustrine deposits</u> (ukr2; **uk2**)
Previous usage or definition: a facies within Ross Sea 2 Drift; not previously distinguished.
Name: from Ross Sea.
Reference area: Wright Valley, north side of Lake Brownworth (162°43.13'E, 77°25.29'S).
Description: loose lacustrine sand, silt and mud; with interbedded till. Commonly contains gypsum, aragonite, calcite, mirabilite or other evaporite minerals. Surfaces deflated and pebble-armoured.
Age: Middle to Late Pleistocene.

<u>Bonney Drift</u> - see Taylor 2 Drift.

Marshall Drift - see Ross Sea 2 Drift.

Brownworth Drift (uir2b; **ur2**)
Previous usage or definition: Hall & Denton (2005).
Name: from Lake Brownworth, eastern Wright Valley.
Reference area: below Mt Doorly on the north wall of the Wright Valley (162°46.06'E, 77°24.70'S).
Description: poorly sorted bouldery sandy till, containing stained and ventifacted clasts including basalt, and some buried ice. Forms lateral moraines on valley walls. Deposited by onland incursion of Ross Sea ice. *Included in Ross Sea 2 Drift.*
Age: uncertain Middle to Late Pleistocene. Older than 19 ka delta and 49 ka ^{14}C yrs BP sediments and beyond the age of radiocarbon dating. Possibly deposited during penultimate glaciation.

Brownworth lacustrine deposits (ukr2b; **uk2**)
Previous usage or definition: a facies within the Brownworth Drift (Hall & Denton 2005); not previously mapped.
Name: as for Brownworth Drift.
Reference area: Wright Valley, north side of Lake Brownworth (162°43.13'E, 77°25.29'S).
Description: well-sorted horizontally stratified lake sediments of silt, sand and gravel capped by boulders: contains stained and ventifacted clasts including basalt and some buried ice: forms a thin veneer on Wright Valley floor. Deposited in a lake dammed against the Ross Ice Sheet, distal to Brownworth Drift moraines. *Mapped within Ross Sea 2 lacustrine deposits.*
Age: uncertain Middle to Late Pleistocene. Older than 19 ka delta and 49 ka sediments. Possibly deposited during penultimate glaciation (Q6).

Ross Sea 3 Drift (uir3; **ur3**)
Previous usage or definition: informally named by Denton et al. (1970).
Name: from Ross Sea and pertaining to the Ross Ice Sheet.
Reference area: as for Trilogy Drift - on the north wall of Wright Valley (162°32.90'E, 77°26.39'S).
Description: poorly sorted, moderately to highly weathered bouldery sandy diamicton with some stratified waterlaid sediments. Clasts stained, ventifacted - basalt common. *As mapped includes Loke, Onyx and Trilogy drifts.*
Age: not well constrained. Moderate to strong surface weathering. Inferred Early to Middle Pleistocene.

Loke Drift (uir3l; **ur3**)
Previous usage or definition: Hall & Denton (2005).
Name: from Mt Loke, in the eastern Asgard Range
Reference area: floor and lower walls of eastern Wright Valley (162°39.01'E, 77°26.89'S).
Description: sandy moderately weathered diamicton with stratified sand and gravel deposited in areas with kettles; clasts stained and ventifacted. Some boulders and buried ice; rare basalt. Forms lateral moraines on walls of Wright Valley. Deposited by onland incursion of the Ross Ice Sheet. *Mapped as Ross Sea 3 Drift.*
Age: not well constrained. Possibly mid-Quaternary.

Trilogy Drift (uir3t; **ur3**)
Previous usage or definition: Hall & Denton (2005).
Name: from an informal name for the Trilogy (third) glaciation in Wright Valley (Nichols 1961).
Reference area: on the north wall of Wright Valley (162°32.90'E, 77°26.39'S).
Description: moderately to highly weathered bouldery sandy diamicton with some waterlaid sediments. Clasts stained, ventifacted. Basalt common, including a distinctive lithology. *Mapped as Ross Sea 3 Drift.*
Age: not well constrained. Moderate to strong surface weathering. Inferred early to mid-Quaternary.

Onyx Drift (uir3x; **ur3**)
Previous usage or definition: Hall & Denton (2005).
Name: from the Onyx River, Wright Valley.
Reference area: Wright Valley, at the base of Mt Loke (161°22.2'E, 77°29.4'S).
Description: highly weathered salt-rich massive coarse sand diamicton. Clasts stained ventifacted and polished, but lack striation, basalt common. *Mapped as Ross Sea 3 Drift.*
Age: not well constrained. Overlies Alpine and Loop drifts. Contains 3.3 Ma clasts. Inferred early-Quaternary.

Taylor 2 Drift (uit2; **ut2**)
Previous usage or definition: informally named by Denton et al. (1970, 1989), synonymous with Bonney Drift (Higgins et al. 2000a,b; Hall et al. 2000).
Name: from the Taylor Valley.
Reference area: near Lake Bonney, central Taylor Valley (162°31.74'E, 77°41.58'S).
Description: poorly sorted, bouldery sandy till, locally matrix-rich and waterlaid. Includes both glaciolacustrine and glaciofluvial sediment. Deposited as near-continuous sheets in central Taylor Valley.
Age: Middle to Late Pleistocene. U/Th ages of 130-70 ka suggest deposition from Taylor Glacier during penultimate global interglacial period.

Taylor 3 Drift (uit3; **ut3**)
Previous usage or definition: informally named by Denton et al. (1970, 1989).
Name: from the Taylor Valley.
Reference area: Pearse Valley (161°29.98'E, 77°42.05'S).
Description: poorly sorted bouldery sandy till, slightly weathered and modified. Deposited as near-continuous tills 100-200 m above Taylor Glacier.
Age: Middle Pleistocene from cosmogenic dating (Brook et al. 1993; Bockheim et al. 2008).

Taylor 4 Drift (mit4; **mt4**)
Previous usage or definition: informally named by Denton et al. (1970, 1989), who also distinguished Taylor 4a (younger) and Taylor 4b (older) deposits. *As mapped includes Thomson Drift of Wilch* et al. *(1993).*
Name: from the Taylor Valley.
Reference area: in Arena Valley, beside Taylor Glacier (160°59.47'E, 77°50.00'S).

Description: poorly sorted bouldery sandy silty till, slightly to moderately weathered. Modified by gelifluction at higher elevations. Exposed in Beacon and Arena valleys, and as a series of discontinuous deposits at relatively high elevations in central Taylor Valley.
Age: Late Pliocene-Middle Pleistocene. Constrained by 1.6-3.5 Ma Ar-Ar ages of McMurdo Volcanic Group flows and ash (Wilch et al. 1993; Marchant et al. 1993b) and exposure age dating (Brook et al. 1993).

Thomson Drift - see Taylor 4 Drift.

Convoy 1 Drift (uic1; **ui1**)
Previous usage or definition: new unit; previously described as Alatna Valley B2 till (Calkin 1964b) or Ross Sea I till (Pocknall et al. 1994).
Name: from the Convoy Range.
Reference area: Convoy Range, at 800-1100 m elevation in Towle and Northwind valleys (160°55.64'E, 76°43.55'S).
Description: poorly sorted, bouldery sandy till containing dolerite and erratic granitoid boulders. Basalt absent. Locally ice-cored and modified by downslope creep. Deposited by ice lobes flowing toward the west.
Age: undated. Inferred Middle to Late Pleistocene.

Convoy 2 Drift (uic2; **ui2**)
Previous usage or definition: new unit; previously described as Alatna Valley B1 till (Calkin 1964b) or Ross Sea II till (Pocknall et al. 1994).
Name: from the Convoy Range.
Reference area: Convoy Range, at 1100-1300 m elevation in Towle and Northwind valleys (160°48.80'E, 76°44.40'S).
Description: poorly sorted, bouldery sandy till containing dolerite and erratic granitoid boulders. Basalt absent. Deposited by ice lobes flowing toward the west.
Age: undated. Post-dates local glacier tills from lobes of overriding plateau ice. Inferred Pliocene- Pleistocene.

Miller 1 Drift (uim1; **ul1**)
Previous usage or definition: new unit; previously mapped as Ross Sea Drift (Turnbull et al. 1994).
Name: from Miller Glacier.
Reference area: Clare Range, northwest side of Cotton Glacier (161°32.3'E, 77°7.1'S).
Description: poorly sorted, bouldery sandy till, deflated and slightly weathered, containing dolerite, Beacon sandstone, local granitoid and metasedimentary clasts. Deposited by Miller ice lobes flowing toward the west.
Age: undated. Inferred Middle to Late Pleistocene, of possible 24-10 ka age.

Miller 2 Drift (uim2; **ul2**)
Previous usage or definition: new unit; previously mapped as Ross Sea Drift (Turnbull et al. 1994).
Name: from Miller Glacier.
Reference area: mouth of Wheeler Valley (161°47.19'E, 77°10.88'S).
Description: poorly sorted, bouldery sandy till. Deflated and weathered. Contains dolerite, Beacon sandstone, local granitoid and metasedimentary clasts, including porphyritic felsic debris in Wheeler Valley. Deposited by Miller ice lobes flowing toward the west.
Age: undated. Inferred Pliocene- Pleistocene.

<u>older colluvium</u> (mc mck mcm; **mc**)
Previous usage or definition: *As mapped includes Koenig Colluvium (mck) of Marchant* et al. *(1993a) and Monastery Colluvium (mcm) of Marchant* et al. *(1993b).*
Name: n/a
Reference areas: Koenig Valley (160°50.39'E, 77°35.50'S) and upper Arena Valley (160°48.02'E, 77°52.87'S).
Description: undifferentiated angular material forming talus slopes, loose glacial material, scree and polygonal ground. Surfaces modified and degraded.
Age: poorly constrained, inferred from degree of modification or nearby stratigraphic relationships.

Koenig Colluvium (mck; **mc**)
Previous usage or definition: Marchant et al. (1993a); see also Isaac et al. (1996).
Name: from the Koenig Valley, Asgard Range.
Reference area: northeastern flank of the Koenig Valley (160°50.39'E, 77°35.50'S).
Description: highly weathered poorly sorted bright orange diamicton of ventifacts in a sandy matrix, on valley floors in Asgard Range. *Not distinguished on map face.*
Age: ?Early to Middle Miocene. Pre-dates Asgard Till and 15.2 Ma ash.

Monastery Colluvium (mcm; **mc**)
Previous usage or definition: Marchant et al. (1993b).
Name: from Monastery Nunatak, Quartermain Range.
Reference area: north flank of Altar Mountain and at base of Arena Valley walls (160°48.02'E, 77°52.87'S).
Description: highly weathered poorly sorted bright orange diamicton of ventifacts in a sandy matrix in central Arena Valley. *Not distinguished on map face.*
Age: Early to Middle Miocene. Post-dates Altar Till. Overlain by 11.3 Ma ash.

<u>older undifferentiated till</u> (mt; **mt**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: undifferentiated moderately weathered to highly weathered bouldery sandy till with modified surfaces and uncertain origin.
Age: uncertain. Stratigraphic relationships and weathering suggest Miocene-Pliocene age.

<u>older undifferentiated local glacier till</u> (ml; **ml**)
Previous usage or definition: *As mapped includes Alpine 3 and Alpine 4 tills (Hall* et al. *1993) and Dido Drift (Lewis* et al. *2007).*
Name: n/a
Type area: n/a
Description: undifferentiated moderately weathered to highly weathered bouldery sandy till, with modified surfaces. Inferred to be derived from a local glacier source.
Age: uncertain. Stratigraphic relationships and weathering suggest Miocene-Pliocene age.

Ross Sea 4 Drift (mir4; **X mr4** outcrop only)
Previous usage or definition: informally named by Denton et al. (1970).
Name: from Ross Sea and pertaining to the Ross Ice Sheet.
Reference area: as for Loop Drift - below Goodspeed Glacier in Wright Valley (162°21.89'E, 77°29.07'S).
Description: moderately to highly weathered, poorly sorted, bouldery sandy till: modified by gelifluction. *Locally differentiated in Wright Valley as Valkyrie (mirv), Wright (mirw), and Loop (mirl) drifts*.
Age: not well constrained. Moderately to highly weathered surface. Inferred Pliocene or Early Pleistocene, although possibly Miocene (Hall & Denton 2005).

Valkyrie Drift (mirv; **mrv**)
Previous usage or definition: Hall & Denton (2005).
Name: from Mt Valkyrie, Asgard Range.
Reference area: south side of Wright Valley between Bartley and Conrow glaciers (162°09.26'E, 77°31.38'S).
Description: highly weathered, loose, unstratified, coarse sand diamicton. Angular clasts of local lithologies and basalt are stained and ventifacted. Only reworked clasts striated. Highly weathered surface, soils contain salt. Deposited by onland incursion of the Ross Ice Sheet.
Age: poorly constrained, inferred Pliocene. Overlies older local glacial till beside Conrow Glacier.

Wright Drift (mirw; **mrw**)
Previous usage or definition: Hall & Denton (2005).
Name: from Wright Valley.
Reference area: east-central Wright Valley (162°18.67'E, 77°30.04'S).
Description: highly weathered, loose, unstratified, coarse sand diamicton. Angular clasts of local lithologies and basalt are stained and ventifacted. Only reworked clasts striated. Highly weathered surface, soils contain salt. Deposited by onland incursion of the Ross Ice Sheet.
Age: poorly constrained, inferred Pliocene. Contains 3.4 Ma basalt clasts and reworked Peleus Till.

Loop Drift (mirl; **mrl**)
Previous usage or definition: Hall & Denton (2005).
Name: from an informal name for the Loop Moraine and interpreted glaciation (Nichols 1961).
Reference area: small hummock below Goodspeed Glacier in Wright Valley (162°21.89'E, 77°29.07'S).
Description: highly weathered, loose, unstratified, coarse-sand diamicton. Clasts stained and ventifacted, some striated. Clasts of local lithologies, with rare basalt on surface. Deposited by onland incursion of the Ross Ice Sheet, overlain by other drifts.
Age: inferred Pliocene or Miocene age.

Vida Drift (mlv; **mlv**)
Previous usage or definition: Calkin (1964a), modified by Turnbull et al. (1994).
Name: from Lake Vida, Victoria Valley.
Reference area: central Victoria Valley, northeast of the Insel Range (161°40.58'E, 77°21.58'S).
Description: moderately weathered, poorly sorted, bouldery sandy till in Barwick and Victoria valleys. Moraines moderately well preserved. Cavernous weathering of clasts; patterned ground developed.
Age: undated. Inferred Early Pleistocene age.

<u>Wright Upper 3 Drift</u> (mlw; **mlw**)
Previous usage or definition: informal name; from Calkin et al. (1970); adopted by Bockheim & McLeod (2008).
Name: from Upper Wright Glacier.
Reference area: western Wright Valley, north and south forks (161°12.24'E, 77°31.96'S).
Description: undifferentiated moderately to highly weathered bouldery sandy till in western Wright Valley.
Age: undated. Inferred Pliocene age.

Bull 1 Drift (mlb; **mlb**)
Previous usage or definition: Calkin (1964a, 1971); subdivided into two units by Turnbull et al. (1994) and Isaac et al. (1996). This youngest unit is treated separately because it was deposited by a different (local) glacier regime.
Name: after Bull Pass in the Olympus Range.
Reference area: lower McKelvey Valley, southeast of the Insel Range (161°37.44'E, 77°24.76'S).
Description: highly weathered, very silty, bouldery till containing clasts of predominantly dolerite, forming moraines in Balham and Victoria valleys and Bull Pass. Locally modified by gelifluction. Deposited from expanded local glaciers.
Age: undated. Inferred Pliocene age, potentially a correlative of Alpine 3 and 4 glacial events.

Quartermain Till (mtq; **mtq**)
Previous usage or definition: Marchant et al. (1993b); originally separated into Quartermain 1 and 2 tills.
Name: from the Quartermain Mountains.
Reference areas: valley wall and floor of lower Arena Valley (Quartermain 2) (160°59.65'E, 77°50.94'S).; floor of east-central Arena Valley (Quartermain 1) (160°57.35'E, 77°51.46'S).
Description: granite-bearing diamicton in Arena Valley with dolerite and sandstone clasts. Angular clasts, without striation or moulding, show desert polish. Deposited from dry-based Taylor Glacier ice flowing up-valley, interfingered with locally derived Arena Till.
Age: Miocene-Pliocene. Relative ages constrained locally by 11.3 and 7.4 Ma ash deposits (Marchant et al. 1993b).

Jotunheim Till (mij; **mij**)
Previous usage or definition: Marchant et al. (1993a); see also Isaac et al. (1996).
Name: from the Jotunheim Valley, Asgard Range.
Reference area: northern slopes of St Pauls Mountain, upper Jotunheim Valley (161° 12.84'E 77° 38.03'S).
Description: unconsolidated and unstructured dolerite gravel-rich diamicton deposited at high elevations.
Age: Middle-Late Miocene. Sand wedges in till contain 10.5 Ma ash; overlies Sessrumnir and Asgard tills (Marchant et al. 1993a).

Asgard Till (mia; **mia**)
Previous usage or definition: Marchant et al. (1993a) after Ackert (1990). See also Isaac et al. (1996).
Name: from the Asgard Range.
Reference area: at the mouth of the Sessrumnir Valley (160° 56.11'E 77° 35.65'S).
Description: silt-rich unconsolidated diamicton with complex internal stratigraphy, containing locally exotic clasts of granite, striated sandstone and dolerite. Deposited from valley glacier overflowing into cirques in Asgard and Olympus ranges. Interpreted to be cold-based above ~1500 m (Marchant et al. 1993a).
Age: ?Early to Middle Miocene. Sand wedge deposit truncating the till contains 13.6 Ma ash (Marchant et al. 1993a).

Brawhm Till (mih; **X mih** outcrops only)
Previous usage or definition: Marchant et al. (1993b).
Name: from Brawhm Pass, Quartermain Mountains.
Reference area: Arena Saddle, west of Altar Mountain, Quartermain Mountains (160°46.40'E, 77°53.14'S).
Description: poorly sorted, unweathered dolerite gravel-rich till derived from reworked colluvium. Deposited by wet-based ice flowing across Arena Saddle.
Age: Middle-Late Miocene age inferred from local stratigraphic relationships (Marchant et al. 1993b).

Nibelungen Till (min; **X min** outcrops only)
Previous usage or definition: Marchant et al. (1993a). See also Isaac et al. (1996).
Name: from the Nibelungen Valley, Asgard Range.
Reference area: on the floor of Nibelungen Valley (160°54.94'E, 77°36.03'S).
Description: loose unstratified gravelly clast-supported till in Nibelungen Valley, containing angular sandstone and granite clasts.
Age: Middle Miocene. Sand wedges in till contain 13.6 Ma ash (Marchant et al. 1993a).

Slump Mountain Diamicton (mlu; **mlu**)
Previous usage or definition: Marchant et al. (1993b).
Name: from Slump Mountain, Quartermain Mountains.
Reference area: on the floor of central Arena Valley (160° 55.94'E 77° 51.83'S).
Description: silt-rich unconsolidated massive diamicton with clasts of dolerite in matrix of disaggregated sandstone.
Age: Middle Miocene age inferred from local stratigraphic relationships with colluvium and nearby 11.3 Ma ash deposit (Marchant et al. 1993b).

Arena Till (mlr; **mlr**)
Previous usage or definition: Marchant et al. (1993b).
Name: from Arena Valley, Quartermain Mountains.
Reference area: on the floor of Arena Valley (160°57.32'E, 77°50.75'S).
Description: massive silt-rich diamicton with well-sorted sandy gravel interbeds, locally folded or cross-cut by flame structures. Clasts of predominantly local sandstone are striated and rounded.
Age: Middle Miocene age inferred from local stratigraphic relationships with colluvium and nearby 11.3 Ma ash deposit (Marchant et al. 1993b).

Inland Forts Till (mlf; **mlf**)
Previous usage or definition: Marchant et al. (1993a) after Ackert (1990). See also Isaac et al. (1996).
Name: from the Inland Forts, Asgard Range.
Reference area: on valley floors south of the Inland Forts, above Taylor Glacier.
Description: loose, unstratified, silty massive till. Includes striated and faceted clasts of local sandstone and minor dolerite. Deposited by a wet-based local alpine glacier. Pre-dates stringer of 13.5 Ma ash.
Age: ?Early-Middle Miocene.

Sessrumnir Till (mls; **mls**)
Previous usage or definition: Marchant et al. (1993a). See also Isaac et al. (1996).
Name: from the Sessrumnir Valley, western Asgard Range.
Reference area: Sessrumnir Valley (160°55.33'E, 77°36.22'S).
Description: unsorted, unstratified and unconsolidated sandy glacial diamicton in valleys of the Asgard Range. Includes striated and faceted clasts of siltstone and dolerite. Deposited by wet-based local alpine glaciers.
Age: ?Early-Middle Miocene. Pre-dates sand wedge in overlying Koenig Colluvium that contains 15.2 Ma ash.

Circe Till (mlc; **mlc**)
Previous usage or definition: Lewis et al. (2007).
Name: from Mt Circe, Olympus Range.
Reference area: Kellogg Valley, Olympus Range (161°10.55'E, 77°28.48'S)
Description: weathered compact silt-rich diamicton and stratified ablation till, containing sand and gravel lenses. Clasts of sandstone and dolerite.
Age: ?Early-Middle Miocene. Pre-dates overlying colluvium interbedded with 13.9 Ma ash.

Altar Till (mla; **mla**)
Previous usage or definition: Marchant et al. (1993b).
Name: from Altar Mountain, Quartermain Mountains.
Reference area: the northeastern flank of Altar Mountain (160°53.23'E, 77°52.50'S).
Description: highly weathered loose silt-rich till, includes striated clasts of dolerite and siltstone but lacks granite. Origin not clearly understood, but thought to be transported beneath wet-based ice.
Age: ?Early-Middle Miocene age inferred from local stratigraphic relationships with colluvium and nearby 11.3 Ma ash deposit (Marchant et al. 1993b).

Bull 2-3 Drift (mib; **mib**)
Previous usage or definition: Calkin (1964a, 1971); modified by Turnbull et al. (1994). The subdivision of Isaac et al. (1996) is followed here, using an amalgamated Bull 2-3 Drift unit that recognises a third older moraine.
Name: from Bull Pass.
Reference areas: northern approaches to Bull Pass (161°40.62'E, 77°27.33'S -Bull Drift II); central McKelvey

Valley (161°12.02'E, 77°26.46'S - Bull Drift III).
Description: highly weathered poorly sorted very silty bouldery till. Contains exotic boulders that are cavernously weathered. Surfaces modified, but remnant moraine topography indicates deposition from ice that flowed through Bull Pass. *Bull Drift II and III phases are not distinguished in this dataset and map.*
Age: poorly constrained, inferred Pliocene or Miocene age. Potentially a correlative of Peleus Till (Turnbull et al. 1994).

Peleus Till (mie; **mie**)
Previous usage or definition: Prentice (1985); see also Turnbull et al. (1994).
Name: from Mt Peleus in the Olympus Range.
Type area: floor of central Wright Valley (161°52.79'E, 77°31.23'S).
Description: highly weathered, very poorly sorted, bouldery to sandy silt-rich valley glacier till. Deflated and modified upper surface. Contains rounded and striated clasts.
Age: ?Middle Miocene - Pliocene. At Prospect Mesa it overlies Prospect Formation but is potentially remobilised, and near Bartley Glacier is overlain by a local alpine till that pre-dates 3.9 Ma (Hall et al. 1993). Contains Pliocene diatoms and shells, but these may be reworked.

Insel Drift (mii; **mii**)
Previous usage or definition: Calkin (1964a); modified by Isaac et al. (1996).
Name: from the Insel Range.
Reference area: floor of the central McKelvey Valley, south of the western Insel Range (161°21.32'E, 77°26.30'S).
Description: very weathered, unsorted, unstratified, silty and loose diamicton with abundant granitoid clasts. Surface modified and no moraine topography preserved.
Age: ?Middle Miocene. Tentative correlation with Sirius Formation; overlain by Bull Drift.

SIRIUS GROUP (undifferentiated; mis; **mis**)
Previous usage or definition: McKelvey et al. (1991) after Mercer (1972); but see Wilson et al. (2002) and Barrett (2013). *Includes the Mount Feather Diamicton (Wilson* et al. *2002)*.
Name: Mt Sirius in the Beardmore Glacier area, central Transantarctic Mountains.
Type section: Dominion Range. Section composite from the constituent Mt Mills and Meyer Desert formations (McKelvey et al. 1991). Note that discrete Sirius Group units in southern Victoria Land (e.g. Brady & McKelvey 1979; Barrett & Powell 1982; Stroeven & Prentice 1997; Hicock et al. 2002, 2003) may be quite different to the stratified Sirius Group formations in the Beardmore Glacier and Reedy Glacier regions (see Wilson et al. 2002).
Description: weathered unsorted semi-lithified diamicton with some fluvioglacial and glaciolacustrine interbeds of sand. Found at high elevations. May represent multiple geologic events and contain exotic microflora.
Age: contentious; probably represents a range of Miocene-Pliocene aged deposits, possibly some even Oligocene or Quaternary. Local exposure ages imply depositional ages of >5 Ma (Brook et al. 1993, 1995b; Ivy-Ochs et al. 1995; Bruno et al. 1997), with some minimum exposure ages as much as 10 Ma (Schaefer et al. 1999), but units contain Pliocene diatoms (probably exotic).

Mt Feather Diamicton (misf; **mis**)
Previous usage or definition: Brady & McKelvey (1979), Wilson et al. (2002).
Name: from Mt Feather.
Type area: Mt Feather (160°25.92'E, 77°55.92'S).
Description: weathered, unsorted, semi-lithified diamicton with locally derived clasts. May contain exotic microflora. *Distinguished in digital database, but shown as undifferentiated Sirius Group on map.*
Age: Miocene; contentious. Contains diatoms *Anomoeoneis costata* and *Stephanodiscus sp*.

<u>lithified grit and diamictite</u> (mw; **mw**)
Previous usage or definition: n/a
Name: n/a
Reference area: Walcott Bay.
Description: well-indurated gritty marine sandstone. Veined by zeolite and/or calcite. Interlayered with diamictite.
Age: Miocene-?Pliocene or ?Pleistocene. Constrained at Gandalf Ridge to between 18.7 ± 0.3 and 17.0 ± 0.6 Ma (Martin & Cooper 2010).

Scallop Hill Formation (osh; **X ops** outcrop only)
Previous usage or definition: Speden (1962).
Name: from Scallop Hill, Black Island.
Type locality: west side of Scallop Hill, east corner of Black Island (166°44.11'E, 77°12.04'S), overlying irregular surface cut in trachyte. Note that some occurrences in Speden (1962) are erratics, and there has been debate as to how extensive the deposits are at the type locality and whether or not they represent an *in situ* occurrence (Leckie & Webb 1982).
Description: cemented tuffaceous sandstones, grits and conglomerates. Fossiliferous, containing the extinct *Chlamys (Zygochlamys) anderssoni*.
Age: Late Pliocene.

Prospect Formation (mtp; **mp**)
Previous usage or definition: Turnbull et al. (1994) after Vucetich & Topping (1972). Includes Pecten Gravels Member (Nichols 1971; Webb 1972) and Prospect Mesa lower waterlaid diamicton and Prospect Mesa gravel (Prentice et al. 1993).
Name: from Prospect Mesa in lower Wright Valley.
Type area: 6 km east from Lake Vanda, below Bull Pass (161°54.82'E, 77°31.20'S).
Description: weathered, poorly sorted, pebbly sandy silt, to very poorly sorted pebbly mud with rare dropped boulders. Includes fossiliferous sandy gravel and pebbly mud of the Pecten Gravels Member.
Age: Late Miocene to Early Pliocene. 5.5 ± 0.4 Ma Sr-isotope age from shells. Diatom assemblage in Pecten Gravel Member and Peleus Till is 3.0-2.5 Ma (Prentice et al. 1993).

Pecten Gravels Member - see **Prospect Formation**

Jason Glaciomarine Diamicton (mtj; **mj**)
Previous usage or definition: informally named by Turnbull et al. (1994); after Denton et al. (1984) and Prentice et al. (1993).
Name: from Mt Jason in the Olympus Range.
Reference area: discontinuous outcrops up to 220 m in Wright Valley, particularly along the northern shores of Lake Vanda below Mt Jason (161°40.20'E, 77°31.12'S). Intercepted beneath Lake Vanda by DVDP-4 drillhole.
Description: weathered, coarse silt to fine sand with scattered cobbles, pebbles and shell fragments. Shearing and soft sediment deformation.
Age: Middle to Late Miocene. Marine diatom assemblage and 9 ± 1.5 Ma Sr-isotope age from unidentified shell fragments (Prentice et al. 1993).

Miocene lake deposits (mk; **X mk** outcrops only)
Previous usage or definition: n/a
Name: n/a
Reference area: northern slopes of Mt Boreas, Olympus Range (161°10.29'E, 77°28.42'S).
Description: very thin deposits of horizontally stratified silt, sand, diatomite and moss peat: locally dammed behind tills and/or buried by fine-grained alluvial fan sediments.
Age: ?Early to Middle Miocene. Ar-Ar age on ash layer 14.07 ± 0.05 Ma. Fossil pollen, beetles, mosses, diatoms and ostracods (Lewis et al. 2008).

Eocene glacial erratics (oee; **X oe** outcrops only)
Previous usage or definition: possible local onshore equivalents of Eocene-Early Oligocene sequence (oeo); also referred to as McMurdo Erratics (Harwood & Levy 2000).
Name: n/a
Reference area: around the shorelines east of Brown Peninsula, near Minna Bluff and Mt Discovery.
Description: erratics of cemented stratified fossiliferous quartz sandstone, sandy mudstone, and conglomerate in coastal moraines. Contain a rich suite of fossil floras and faunas including marine and terrestrial palynomorphs, diatoms, edidians, marine vertebrates and invertebrates, terrestrial plant remains and bird bones.
Age: Middle to Late Eocene (Stilwell & Feldmann 2000). Note that younger erratics are also present.

Offshore deposits

Pliocene-Pleistocene sequence (o1.3; **opp**)
Shown on cross-section only.
Previous usage or definition: part V1 of Cooper et al. (1987b), RSU4 of Brancolini et al. (1995); Rj-Rk of Fielding et al. (2008a). See also Levy et al. (2012).
Name: n/a
Type area: n/a. Offshore – intercepted in AND-1B and CIROS-2 drillholes.
Description: diamictite and diatomite sedimentary cycles, with volcaniclastic mudstone and sandstone.
Age: Pliocene to Pleistocene. Rj reflector at base ~3.5 Ma, but poorly constrained (Levy et al. 2012).

Pliocene-Pleistocene deposits and erratics (ose; **X op** outcrops only)
Previous usage or definition: Local onshore equivalents of Pliocene-Pleistocene sequence (opp); sometimes referred to as McMurdo Erratics (Harwood & Levy 2000).
Name: n/a
Reference area: n/a.
Description: outcrops and erratics of cemented well-bedded fossiliferous, tuffaceous sandstone, grit and conglomerate. *Includes Scallop Hill Formation (osh;* ***X ops*** *outcrop).*
Age: Pliocene - Pleistocene.

Pliocene sequence (o1.2; **opl**)
Shown on cross-section only.
Previous usage or definition: part V1 of Cooper et al. (1987b), RSU2-1 of Brancolini et al. (1995); Ri-Rj of Fielding et al. (2008a). See also Levy et al. (2012).
Name: n/a
Type area: n/a. Offshore – intercepted in AND-1B and CIROS-2 drillholes.
Description: diamictite and diatomite sedimentary cycles, sandstone and conglomerate forming a terrigenous clastic succession with large clinoforms.
Age: Pliocene. Base in CIROS-2 ~4.7-4.4 Ma (Levy et al. 2012). Upper Rj reflector age poorly constrained: ~2 Ma estimated from flexural loading.

Late Miocene-Early Pliocene sequence (o1.1; **omp**)
Shown on cross-section only.
Previous usage or definition: part V1 of Cooper et al. (1987b), RSU4 of Brancolini et al. (1995); Rh-Ri of Fielding et al. (2008a).
Name: n/a
Type area: n/a. Offshore – intercepted in AND-1B, CIROS-1 and MSSTS-1 drillholes.
Description: volcaniclastic sandstone, mudstone, tuff, interbedded with diamictite-diatomite cycles.
Age: Late Miocene-Early Pliocene. The upper limit = Ri reflector ~4.6-4 Ma in CIROS-1 and MSSTS-1 drillholes.

Late Miocene sequence (o2; **olm**)
Shown on cross-section only.
Previous usage or definition: approximates V2 of Cooper et al. (1987b); RSS3 of Brancolini et al. (1995); Rg-Rh of Fielding et al. (2008a).
Name: n/a
Type area: n/a. Offshore – intercepted by AND-1B drillhole.
Description: diamictite and mudstone, sandstone-conglomerate-mudstone cycles. Homoclinal.
Age: Late Miocene.

Early-Middle Miocene sequence (o3; **om**)
Shown on cross-section only.
Previous usage or definition: approximates V3 of Cooper et al. (1987b); part RSS2 of Brancolini et al. (1995); Re-Rg of Fielding et al. (2008a).
Name: n/a

Type area: n/a. Offshore – intercepted in CRP-1, CRP-2, MSTS-1, AND1B and AND-2A drillholes.
Description: Interbedded diamictite and mudstone with rare ice-rafted clasts, sandstone and conglomerate. Channelling, clinoforms, and top-truncated cycles. Age: Early to Middle Miocene.

Early-Late Oligocene sequence (o4; **oo**)
Shown on cross-section only.
Previous usage or definition: approximates V4 of Cooper et al. (1987b); part RSS1of Brancolini et al. (1995); Rc-Re of Fielding et al. (2008a).
Name: n/a
Type area: n/a. Offshore – intercepted in MSTS-1, CIROS-1, CRP-2A drillholes.
Description: bedded diamictite and mudstone, stratified sandstone and siltstone. Clinoforms prograding offshore. Age: Early to Late Oligocene.

Eocene-Early Oligocene sequence (o5; **oeo**)
Shown on cross-section only.
Previous usage or definition: approximates V5 of Cooper et al. (1987b); part RSS1 of Brancolini et al. (1995); Ra-Rc of Fielding et al. (2008a).
Name: n/a
Type area: n/a
Description: basal conglomerate and breccia intervals overlain by cyclic marine sandstone-mudstone, and diamictite. Age: Eocene to Early Oligocene, but may include strata older than Eocene.

McMURDO VOLCANIC GROUP

MCMURDO VOLCANIC GROUP (mv, mv?; **mv**)
Previous usage or definition: Kyle (1990a) after Harrington (1958a).
Name: from McMurdo Sound.
Type area: none available; composite of constituent units.
Description: undifferentiated lava flows, dikes, scoria cones, agglomerates and other pyroclastics. Compositions include basalt, basanite, trachybasalt, phonotephrite, tephriphonolite, trachyandesite, phonolite, trachyte and some rhyolite.
Age: Miocene to Holocene. K-Ar and Ar-Ar whole rock.

basalt, basanite and phonotephrite (mvb, mvb?; **mvb**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: basalt, basanite, trachybasalt and phonotephrite; including hawaiite, olivine-augite basalt, plagioclase basalt, hornblende basalt; forming lava flows, dikes, scoria cones and pyroclastic deposits.
Age: Miocene to Holocene. K-Ar and Ar-Ar whole rock.

phonolite, tephriphonolite and trachyandesite (mvp; **mvp**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: phonolite, tephriphonolite and trachyandesite; including mugearite and benmoreite; forming intermediate composition lava flows, dikes, scoria cones, and pyroclastic deposits.
Age: Miocene to Holocene. K-Ar and Ar-Ar whole rock.

trachyte, trachydacite and rhyolite (mvt; **mvt**)
Previous usage or definition: n/a
Name: n/a
Type area: n/a
Description: trachyte and rhyolite; forming acid composition flows, dikes, scoria cones, and pyroclastic deposits.
Age: Miocene to Holocene. K-Ar and Ar-Ar whole rock.

Hart Ash (mvh; **X mvh** outcrops only)
Previous usage or definition: Hall et al. (1993).
Name: from Hart Glacier, Wright Valley.
Type locality: near the snout of Hart Glacier (162°22.26'E, 77°29.75'S).
Description: fine-grained glass-rich white ash in Wright Valley, up to 1m thick.
Age: Pliocene. 3.9 ± 0.3 Ma K-Ar age of glass within ash.

Arena Valley Ash (mva; **X mva** outcrops only)
Previous usage or definition: Marchant et al. (1993b, 1996).
Name: from Arena Valley, Quartermain Mountains.
Type locality: central Arena Valley (160°50.58'E, 77°51.72'S).
Description: white, phonolitic ash containing euhedral crystals of anorthoclase, aegerine, sub-calcic augite, and magnetite. Unweathered with <2.5% clay, 25 cm thick, resting on *in situ* ventifact pavement in west-central Arena Valley.
Age: Pliocene. 4.33 ± 0.07 Ma Ar-Ar age from anorthoclase.

ash deposits (mvo; **X mvo** outcrops only)
Previous usage or definition: Marchant et al. (1993ab, 1996); Lewis et al. (2006, 2007).
Name: n/a
Type area: n/a
Description: fine-grained glass shards and/or ash deposits. May be continuous *in situ* deposits, redeposited as ash-avalanche deposits, disseminated ash in tills and colluvium, or having signs of deposition in water. *Includes Mount Thundergut Ash, Koenig Valley Ash, Nibelungen Valley Ash, Beacon Valley Ash, Arena Valley ash-avalanche deposits (Marchant* et al. *1996), and ash in the Labyrinth and Olympus Range (Lewis* et al. *2006, 2007).*
Age: Miocene. Ar-Ar ages.

This map illustrates the geology of Ross Island and the Dry Valleys region of southern Victoria Land, Antarctica. The map replaces a 1:250 000 map published in 1962. Geological information has been obtained from published and unpublished mapping by researchers from GNS Science, New Zealand universities and the United States Antarctic Program. All geological data are held in a Geographic Information System, available in digital format on request. The accompanying illustrated text summarises the geology, landforms, and paleoclimate history of the area, as well as previous geological exploration.

The region is crossed by a major rift basin, the uplifted shoulder of which forms the Transantarctic Mountains escarpment. Large stratovolcanoes associated with the rift are present on Ross Island and on the mainland nearby. In the Transantarctic Mountains, Neoproterozoic and Paleozoic granitoids and their metasedimentary host rocks are overlain by a thick sequence of sedimentary rocks of the Beacon Supergroup, intruded by Ferrar Group dolerite sills. These rocks are exposed in spectacular outcrops of the ice-free Dry Valleys, the mountain range crest, and the nunataks that project through the ice of the Polar Plateau. The Eocene to Holocene deposits in the Dry Valleys and beneath the Ross Sea preserve a record of ice sheet and glacier fluctuations, from which the history of climate change can be inferred.

New Zealand's Scott Base on Ross Island is situated on a McMurdo Volcanic Group lava flow that forms Pram Point. Mount Erebus (3794 m), steaming in the background, is a composite stratovolcano and is the southernmost active volcano in the world.

Photo: C. Monteath/Hedgehog House.

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