Gondwana Research 80 (2020) 50–122

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

GR focus review

Geological and tectonic evolution of the Transantarctic Mountains, from ancient craton to recent enigma

John W. Goodge

Department of Earth and Environmental Sciences, University of Minnesota, Duluth, MN 55812, USA

ARTICLE INFO

Article history:
Received 27 May 2019
Received in revised form 3 November 2019
Accepted 17 November 2019
Available online 27 November 2019

Handling Editor: M. Santosh

Keywords:
Antarctica
Intraplate mountains
Orogeny
Tectonics
Supercontinents

ABSTRACT

The Transantarctic Mountains (TAM) are one of Earth's great mountain belts and are a fundamental physiographic feature of Antarctica. They are continental-scale, traverse a wide range of latitudes, have high relief, contain a significant proportion of exposed rock on the continent, and represent a major arc of environmental and geological transition. Although the modern physiography is largely of Cenozoic origin, this major feature has persisted for hundreds of millions of years since the Neoproterozoic to the modern. Its mere existence as the planet's longest intraplate mountain belt at the transition between a thick stable craton in East Antarctica and a large extensional province in West Antarctica is a continuing enigma. The early and more cryptic tectonic evolution of the TAM includes Mesoarchean and Paleoproterozoic crust formation as part of the Columbia supercontinent, followed by Neoproterozoic rift separation from Laurentia during breakup of Rodinia. Development of an Andean-style Gondwana convergent margin resulted in a long-lived Ross orogenic cycle from the late Neoproterozoic to the early Paleozoic, succeeded by crustal stabilization and widespread denudation during early Gondwana time, and intra-cratonic and foreland-basin sedimentation during late Paleozoic and early Mesozoic development of Pangea. Voluminous mafic volcanism, sill emplacement, and layered igneous intrusion are a primary signature of hotspot-influenced Jurassic extension during Gondwana breakup. The most recent phase of TAM evolution involved tectonic uplift and exhumation related to Cenozoic extension at the inboard edge of the West Antarctic Rift System, accompanied by Neogene to modern glaciation and volcanism related to the McMurdo alkaline volcanic province. Despite the remote location and relative inaccessibility of the TAM, its underlying varied and diachronous geology provides important clues for reconstructing past supercontinents and influences the modern flow patterns of both ice and atmospheric circulation, signifying that the TAM have both continental and global importance through time.

Contents

E-mail address: jgoodge@d.umn.edu.

https://doi.org/10.1016/j.gr.2019.11.001
1342-937X/

1. Introduction

The modern continent of Antarctica resembles Africa from a tectonic perspective, in that both continents are centered within a larger plate and generally surrounded by continental shelves, passive margins and oceanic lithosphere. Antarctica differs in one important aspect — the presence of a long, high-standing intraplate mountain belt that separates the continent into eastern and western elements (Fig. 1). The Transantarctic Mountains (TAM) divide ancient ~200 km-thick cratonic lithosphere of East Antarctica from thinned crust and warm upper mantle of an extensional province referred to as the West Antarctic Rift System (WARS). Uplift of the modern TAM occurred mostly in the late Mesozoic and early Cenozoic, overlapping in part with extension in the WARS, which is thought to signify a genetic relationship between the two. Origins of the modern TAM are controversial, however, in part due to its coincidence with older crustal structures. For example, the TAM can be traced along a reconstructed Neoproterozoic rift margin of cratonic East Antarctica, and the basement roots of the TAM are a product of a late Precambrian and early Paleozoic Andean-type orogenic system, suggesting a significant role of mechanical inheritance in the development of younger structures within this modern intraplate mountain belt. Rocks exposed within the TAM range in age from over 3 billion years to the modern, and they record contrasting tectonic regimes during that time period related to continental rifting, convergent-margin orogenesis, intracratonic and foreland basin deposition, mantle upwelling, and rift-shoulder uplift. Despite its enigmatic recent origins, therefore, geological features of the TAM record a long history of events representing a sequence of tectonic interactions between cratonic East Antarctica and a variety of other tectonic elements over time.

Not only do the TAM reflect a long and complex tectonic history within Antarctica, they contain rock assemblages that help to complete a global picture of supercontinent evolution and inter-cratonic interaction. Owing to the high elevations of the TAM, some of the oldest crust within East Antarctica is exposed where the ice sheet thins along the inland mountain flanks. This ancient crystalline basement near Nimrod Glacier is a rare window into the East Antarctic craton and correlates with similar cratonic rocks of the Mawson Continent extending across Adélie Land into southern Australia (Harley et al., 2013; Goodge and Fanning, 2016), together representing a key piece within the Proterozoic supercontinents of Columbia and Rodinia. The Neoproterozoic breakup of Rodinia and separation of East Antarctica from western Laurentia, first postulated by Moores (1991) and Dalziel (1991), was confirmed by diagnostic age and isotopic signatures in sedimentary and glacial materials (Goodge et al., 2004b, 2008, 2017) and is recorded in rift-margin volcanics exposed in southern Victoria Land and near Nimrod Glacier (Goodge et al., 2002; Cooper et al., 2011). Underlying much of the TAM is the Ross orogenic belt, a latest Neoproterozoic and early Paleozoic foldbelt that formed along an active, convergent plate margin of Gondwana and that is correlated with the broader Terra Australis orogen extending into present-day Australia and South America (see Cawood, 2005). In addition to marginal-basin sedimentary deposits, metamorphic assemblages, and structures, the convergent plate-boundary setting of the Ross Orogen produced a volumetrically large continental-margin magmatic arc constructed mostly within older Proterozoic to early Paleozoic crust and represented by a prolific calc-alkaline granitoid batholith along most of the range (e.g., Borg et al., 1987, 1990). Ross convergence also produced distinctive features such as ultra-high pressure eclogites in northern Victoria Land (see Godard and Palmeri, 2013) and structures indicative of oblique convergence and transpression (Goodge et al., 1993a). Late Paleozoic and early Mesozoic sedimentary and volcanic successions in the Beacon Supergroup contain famous late Paleozoic and early Mesozoic fossil assemblages that provide important insight into the paleoenvironments of the high-latitude parts of Gondwana and Pangea (e.g., Barrett, 1991; Collinson et al., 1986, 1994; Isbell et al., 2008; Bradshaw, 2013), and they record development of a renewed active margin during coevolution of areas presently found in the Ellsworth Mountains, Marie Byrd Land, and greater Zealandia (including Campbell Plateau, Challenger Plateau, Lord Howe Rise, New Zealand, and Thurston Island; Mortimer et al., 2017), followed by the geodynamic pulse of a mantle plume and its thermal imprint as recorded by widespread Ferrar magmatism during the breakup of Gondwana (see Elliot and Fleming, 2004). During Cenozoic time, when Antarctica became further isolated

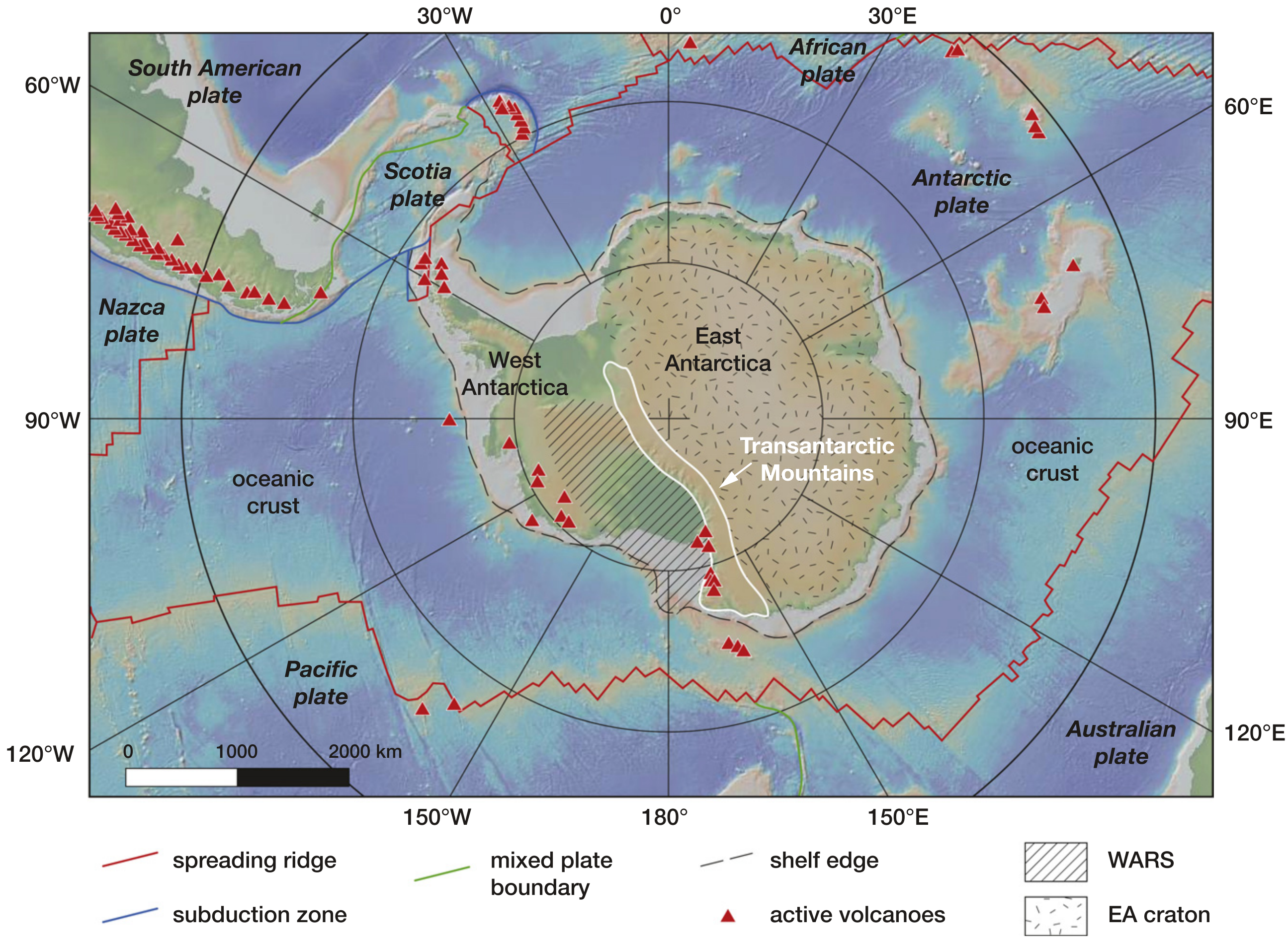


Fig. 1. Tectonic map of the Antarctic plate, showing bounding spreading ridges and subduction zones. Continental Antarctica extends to the shelf edge. Thick cratonic crust and lithosphere of East Antarctica (dashed pattern) and extensional West Antarctic rift system (WARS, diagonal ruling) are transected by the intraplate Transantarctic Mountains. Base from GeoMapApp (http://www.geomapapp.org).

tectonically and geographically from other continents, the TAM have been witness to a complex interplay of tectonic uplift, denudation, glaciation, and volcanism, creating a varied and inter-connected landscape that records Oligocene and younger evolution of the East Antarctic ice sheet. Thus, despite the challenges imposed by geographic remoteness and generous cover of ice and snow, the TAM provide both a rich geologic history for a significant part of Antarctica over a period exceeding 3 billion years, and important connections to now distant partners in the supercontinent cycle (Fig. 2). This contribution attempts to summarize our current understanding of the geological and tectonic evolution of the TAM and provide context for future study.

This paper summarizes the main geologic features of the TAM, including the geology of the Pensacola Mountains (Fig. 3), that help to inform and constrain the tectonic history. My goal is not to provide a complete discussion of every phase of tectonic development, but rather to draw out key aspects of the underlying geology, highlight important research problems, and provide literature references that can point a reader to primary data and analysis. I hope to develop as complete a picture as possible based on geologic features of the extant mountain belt, so only occasional reference is made to other regions in Antarctica and elsewhere; for comparison, the reader is referred to the literature discussing other areas. Also, while geophysical data are indeed relevant to the structure and tectonic evolution of the TAM, the principal focus remains on the geology. I have worked in and briefly visited areas in northern Victoria Land, southern Victoria Land and the southern TAM, but my main experience is in geological study of the central TAM between the Byrd and Shackleton glaciers. Thus, many of the examples provided borrow from my personal experience in the central part of the mountain belt. These are representative of the geology described in other areas, but they are not intended to provide a comprehensive treatment of geology along the entire belt. I highlight here findings of many other workers, and I take responsibility for any omissions and errors in interpretation. Detailed summaries of geologic features and relationships exposed along the length of the TAM are also provided by Stump (1995) and Faure and Mensing (2011). Geologic mapping is currently being updated through an international effort coordinated by the Scientific Committee on Antarctic Research, which will provide a seamless geological map of Antarctica in an electronic format at a scale of 1:250,000, including higher spatial resolution in the TAM where chronostratigraphy and lithostratigraphy allow (Cox et al., 2019). Elliot (2013) gave a concise synopsis of the geological and tectonic evolution, with an emphasis on the Mesozoic history. The Ellsworth Mountains and Shackleton Range, not discussed here, are geographically separate yet contain Precambrian, Paleozoic and Mesozoic rocks that correlate with TAM geology.

2. Physiographic setting and geological background

2.1. Physiography

The Transantarctic Mountains extend over 3200 km from the Oates Coast and northern Victoria Land areas of the Australian-New Zealand sector in Antarctica, to the Pensacola Mountains near the eastern Ronne Ice Shelf at the Weddell Sea (Fig. 3). Physiographically they

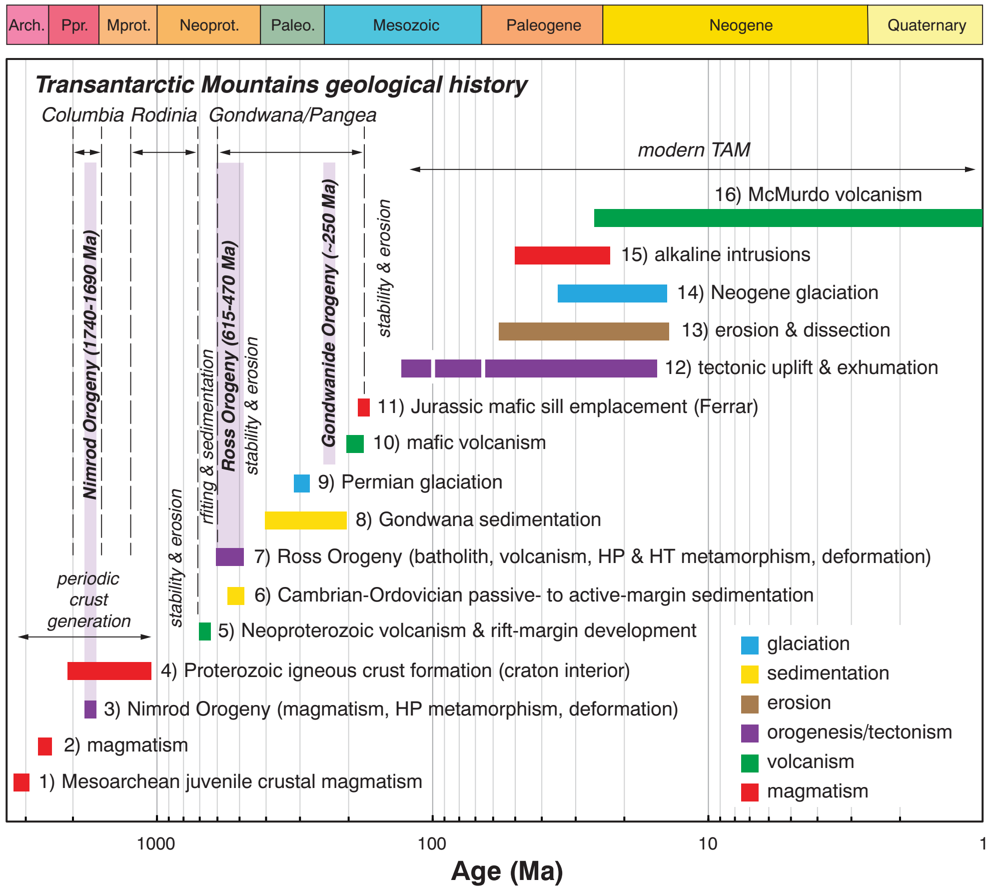


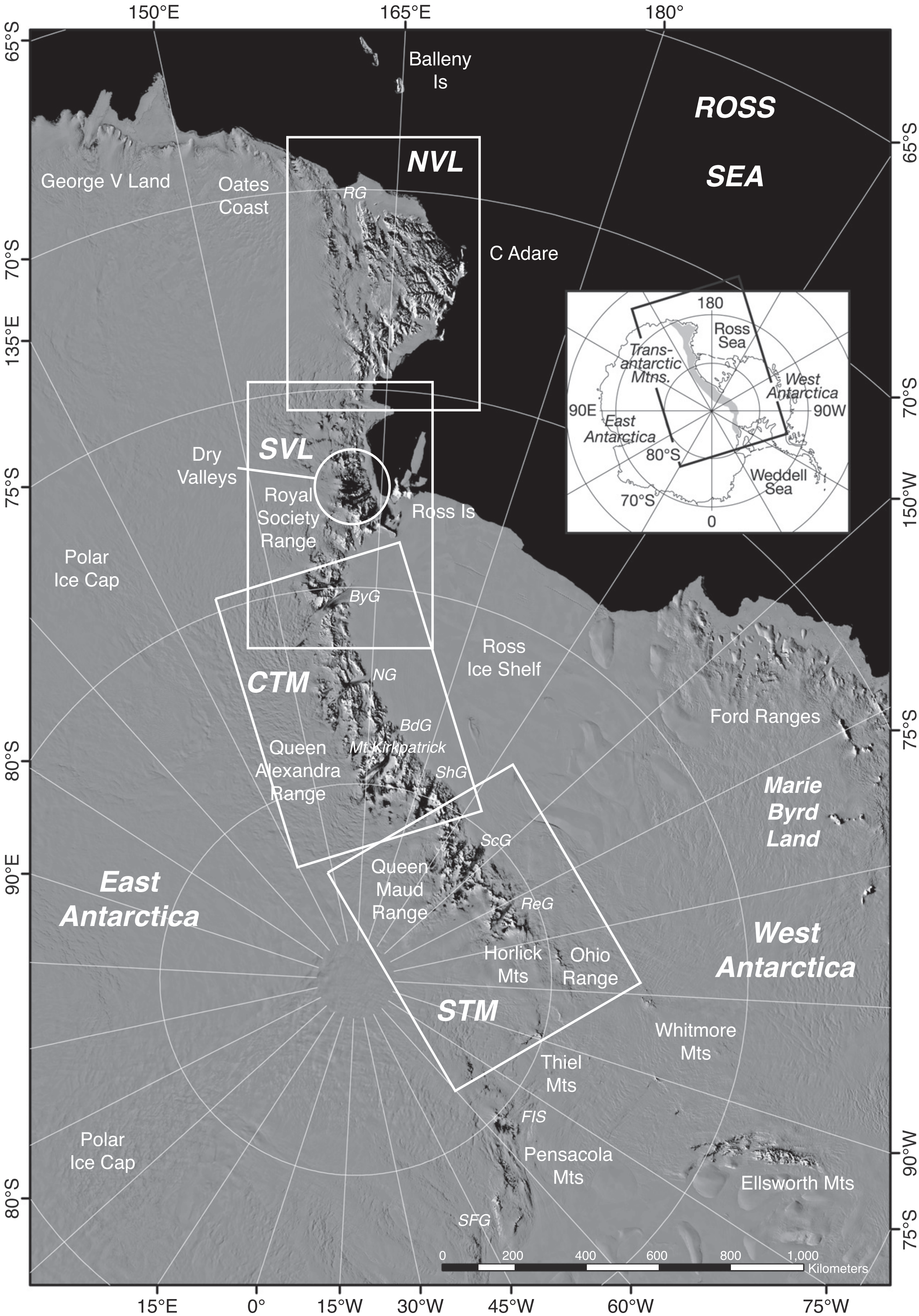
Fig. 2. Timeline showing major geologic and tectonic events during development of the Transantarctic Mountains (TAM). In its entirety, the geologic evolution of the TAM extends from about 3.1 Ga to today, a remarkable period of semi-continuous geological activity. Note that timeline is displayed with a log scale in order to conserve space, which means that older events are highly generalized. See text for discussion of each major event and sources. Periods of relative stability and erosion indicated by major gaps in the rock record and/or recognized unconformities. Association with extant supercontinents Columbia, Rodinia and Gondwana/Pangea shown for reference. Geologic time scale shown for reference at top to emphasize time compression; colors of geologic periods do not correspond to colors used for geologic events. Arch, Archean; Ppr, Paleoproterozoic; Mprot, Mesoproterozoic; Neoprot, Neoproterozoic; Paleo, Paleozoic.

represent a major divide between East and West Antarctica, rising to elevations of >4500 m (>14,000 ft) directly from sea level along the Ross Sea coastline. As discussed below, the TAM are a youthful tectonic feature, expressed by its sharp glacial topography rising above the polar ice cap (Fig. 4), yet they are underlain by remnants of both an older mountain belt that rivaled the modern Andes and the ancient continent of East Antarctica. To the west (in this paper, geographic coordinates will refer to local north, approximately along the 165°E meridian), the TAM are flanked by igneous and metamorphic rocks of the Precambrian East Antarctic craton, although these rocks are mostly ice-covered and known from scattered coastal outcrops and geophysical surveys. Eastward, along the margin of the Ross Sea and in Marie Byrd Land, the TAM are bounded by heterogeneous crust of West Antarctica, composed primarily of Paleozoic and Mesozoic sedimentary and igneous rocks, as well as Cenozoic volcanics. Present-day topographic expression in the TAM is related to geologically recent extension along the Ross Sea margin, yet rocks exposed in the range reflect a protracted history of continental rifting, mountain building, and renewed crustal extension between late Precambrian and Mesozoic time.

As a nearly continuous physiographic barrier between East and West Antarctica (Fig. 3), the modern TAM rise from near sea level at the Ross Sea and Ross Ice Shelf, to elevations typically reaching 2500–4000 m. The highest point in the main range is Mt. Kirkpatrick (4528 m), near Beardmore Glacier in the Queen Alexandra Range. Given that many parts of the TAM are <200 km wide, the local relief in many areas is extraordinary. On the western 'backside' of the TAM, ice of the polar ice cap laps across the mountains at elevations in excess of 2500 m, rising to over 3500 m elevation in the central domes. The TAM thus form a buttress blocking the lateral flow of ice outward toward the Ross Sea. This high-standing East Antarctic ice sheet drains through individual outlet glaciers into the Ross Sea (Figs. 3, 5), many of which have intermediate grounding lines and velocities up to several meters per day. Byrd Glacier, among the fastest in Antarctica, flows at ~825 m/yr at the grounding line (Stearns et al., 2008).

The TAM represent a major divide or transition zone manifested by observable gradients in all major systems from the solid-earth to the atmosphere (Elliot et al., 2007). Significant variations are recognized both along and across the range, including lithosphere structure and evolution between Precambrian and Mesozoic time; secular change in Paleozoic to Mesozoic climate and biota; uplift and erosion history, and its influence on ice-sheet development; surface processes and environments; climate and weather systems on timescales from Neogene to present-day; glacial history and present-day dynamics of the East and West Antarctic ice sheets; and gradients in modern biodiversity and

Fig. 3. Moderate resolution imaging spectroradiometer (MODIS) satellite image of Transantarctic Mountains region of Antarctica (Haran et al., 2005, 2014), showing major geographic features. Illumination from southwest (lower left in this view). Boxes indicate areas covered in detailed figures (CTM, central Transantarctic Mountains; NVL, northern Victoria Land; STM, southern Transantarctic Mountains; SVL, southern Victoria Land). Major outlet glaciers include: ByG, Byrd; BdG, Beardmore; FIS, Foundation Ice Stream; NG, Nimrod; ScG, Scott; ShG, Shackleton; ReG, Reedy; RG, Rennick; SFG, Support Force.


150°E
165°E
180°
65°S
70°S
135°E
75°S
80°S
90°E
80°S
65°S
70°S
150°W
75°S
90°W
75°S
15°E
0°
15°W
30°W
45°W
60°W
75°W
Balleny Is
ROSS SEA
NVL
RG
George V Land
Oates Coast
C Adare
SVL
Dry Valleys
Royal Society Range
Ross Is
Polar Ice Cap
ByG
CTM
NG
Ross Ice Shelf
BdG
Mt Kirkpatrick
ShG
Queen Alexandra Range
Ford Ranges
Marie Byrd Land
ScG
Queen Maud Range
ReG
East Antarctica
Horlick Mts
Ohio Range
West Antarctica
STM
Whitmore Mts
Thiel Mts
FIS
Polar Ice Cap
Pensacola Mts
Ellsworth Mts
SFG
0 200 400 600 800 1,000 Kilometers
180
Ross Sea
Trans-antarctic Mtns.
West Antarctica
90E
90W
East Antarctica
80°S
Weddell Sea
70°S
0

biogeochemical processes. The TAM thus provide a natural laboratory in which to examine natural variations with respect to tectonic regime, geological materials, latitude, elevation, climate, ice-sheet characteristics and the interdependencies between them.

Katabatic-type polar winds ablate relatively stagnant ice dammed against the mountain buttress, leaving behind a lag of rocky debris, including numerous meteorites (Whillans and Cassidy, 1983; Harvey, 2003) and glacially-eroded rock clasts from the continental interior (e.g., Goodge et al., 2008, 2010, 2017). Modern and recent climate patterns are controlled in part by the balance of ice present in the major ice sheets to either side of the mountain belt. Although the modern alpine features of the TAM reflect ongoing glacial erosion, some parts of the belt, particularly in the ice-free Dry Valleys of southern Victoria Land (Figs. 6, 7), contain glacial deposits and landscape surfaces that suggest polar desert conditions extending back at least 17 million years ago (Sugden and Denton, 2004). Ongoing research addresses whether the East Antarctic ice sheet has existed continuously at the edge of the TAM since Miocene time, or whether glaciation was episodic.

2.2. Geological exploration

Sailing expeditions crossing from the southern Pacific Ocean first sighted the high peaks of Antarctic mountains in the mid-19th century, and the region was named Victoria Land by the British Ross expedition in 1841. A later British expedition led by Borchgrevink in 1899 made landings between northern Victoria Land and Ross Island, sampling volcanic rocks in the region. The first geological studies to penetrate inland in the TAM were achieved by members of the early polar exploration parties, including the British Antarctic Expeditions of 1901, 1907 and 1910. Historically significant overland traverses completed in Victoria Land and onto the polar plateau determined the position of the southern geomagnetic pole, by the Australian Mawson expedition in 1909, and went in search of routes across the TAM to the South Pole, pioneered by Shackleton in 1908. On their fateful return from the South Pole in early 1912, Scott's polar party collected rock specimens along Beardmore Glacier. Geologists accompanying US and Australian expeditions in the 1920s and 1930s did periodic scientific reconnaissance. In 1929, as part of Byrd's first Antarctic expedition, American geologist Gould made a reconnaissance exploration of the Queen Maud Mountains and was able to correlate sedimentary strata at Mount Fridtjof Nansen with those on other continents (Gould, 1931). Comprehensive surveying, geological mapping, and study of rock exposures began in earnest with activities of the International Geophysical Year, begun in 1957. Combined geographic surveying and geologic mapping were conducted primarily by New Zealand and American field parties through the 1960s and 1970s, then by German expeditions beginning in the 1980s. Active geological research in the TAM today is sponsored primarily by the national programs of Germany, Italy, New Zealand, South Korea, the United Kingdom, and the United States.

2.3. Mineral resources

No mineral deposits of economic value are known in the TAM. Large volumes of early Paleozoic and Jurassic igneous rocks underlie the mountain belt, including granites of continental-margin volcanic-arc affinity and gabbros found in mafic layered intrusions, such as the Dufek Massif in the northern Pensacola Mountains (Fig. 3; Ford, 1976). Similar occurrences of igneous rocks host important economic mineral deposits in other parts of the world (for example, copper and platinum-group elements), but no indications of such mineralization are known here. An occurrence of native gold associated with silver, arsenopyrite and an iron-arsenic compound was identified in veins associated with faults of northern Victoria Land (Crispini et al., 2007, 2009); this mineralization may be Devonian in age and is restricted to faults within rocks of the Bowers terrane. Thin coal seams in Gondwana strata of the Beacon Supergroup are of low rank, making them of greater interest for paleoclimate reconstructions than as a potential economic mineral resource.

Fig. 4. View to the northwest (local coordinates) across the central Transantarctic Mountains in the vicinity of the Queen Alexandra Range. View is across Lennox-King Glacier (left foreground) and the Holland Range, with the sharp high peak of Mt. Markham in the right distance, and low cliff faces of the Geologists Range on the far horizon in front of the polar ice cap. Rocks underlying the mountain range here include mainly Cambrian-Ordovician siliciclastic sedimentary rocks of the upper Byrd Group, capped by flat-lying strata of the Beacon Supergroup.

3. Stratigraphy and geological evolution

3.1. General geologic setting

The TAM occupy not only a physiographic crossroads, but they stand astride the boundaries between three major tectonic provinces (Fig. 8), the Precambrian craton, Ross Orogenic belt, and West Antarctic Rift System. Inboard of the TAM, buried beneath the polar ice cap, is the Neoproterozoic rift margin of East Antarctica (Goodge and Finn, 2010). It is inferred from the pattern of ice-penetrating geophysical signatures and from exposures of Precambrian basement in the Miller and Geologists ranges near Nimrod Glacier. As discussed below, geophysical transects across the TAM help to define the position of the Neoproterozoic rift margin between the South Pole and the coast of George V Land (Fig. 8), which is probably offset along left-lateral transfer faults in a stepwise pattern. All of the areas to the east of this rift boundary represent either outboard East Antarctic geology stranded as cryptic crustal fragments or are younger than the age of rifting. Some rocks, such as the Mesoarchean to Paleoproterozoic Nimrod Complex in the central TAM (Goodge and Fanning, 2016), represent the only known continental basement of East Antarctica exposed between George V Land and the Shackleton Range. The main spine of the TAM is underlain by deformed rocks and a granitoid batholith of the early Paleozoic Ross Orogen (Fig. 9), whose structures trend generally parallel to the modern range. Although the upper levels of the orogen were removed by erosion as of middle Paleozoic time, geophysical data show that present-day crustal thickness is about 5–10 km greater beneath the TAM than an average thickness of about 35–40 km beneath the adjacent East Antarctic shield (Lawrence et al., 2006a; Chaput et al., 2014; Hansen et al., 2016; Heeszel et al., 2016). Thus, the roots of the modern mountain belt consist of an already thickened early Paleozoic orogen. Immediately outboard of the TAM, along the steep TAM front, are the main faults bordering the West Antarctic Rift System (Fig. 8). Within the TAM itself are a series of steeply-dipping normal faults that accommodate displacement leading to uplift of the TAM, but the main fault system along the western segment of the rift province lies beneath the western edge of the Ross Ice Shelf and Ross Sea. The relationship of

Fig. 5. View to the south down Skelton Glacier in southern Victoria Land, showing tributary glaciers joining the main flow toward the Ross Ice Shelf (background). Main rock types exposed in the cliff faces to the left are dark metasedimentary rocks of the Skelton Group (foreground; see Cook and Craw, 2002) and light-colored granitic plutons of the Granite Harbour Intrusive suite (background).

the TAM to Neogene uplift and opening of the West Antarctic Rift System is discussed separately below.

Geologically, the TAM divide cratonic East Antarctica from younger provinces in West Antarctica (Dalziel, 1992), marking a fundamental boundary that extends for >3200 km along about one third of the East Antarctic cratonic margin between northern Victoria Land and the Pensacola Mountains (Figs. 1, 3). There are hints of East Antarctic and/or Ross Orogen basement in present-day West Antarctica and underlying the Ross Sea, including Ross Orogen-age metamorphic rocks in basement of the Mt. Murphy volcano in Marie Byrd Land, a 545 Ma metarhyolite dredged from the Iselin Bank in the northern Ross Sea, derital zircon populations in sedimentary rocks of Marie Byrd Land with Ross Orogen affinity, and geophysical evidence of extended TAM-type crust in the western Ross Sea (Ford and Barrett, 1975; Pankhurst et al., 1998; Mukasa and Dalziel, 2000; Mortimer et al., 2011; Yakymchuk et al., 2015; Tinto et al., 2019). These disparate clues indicate that extended or fragmented cratonic basement may partially underlie areas east of the TAM, yet the mountain range remains a significant tectonic boundary in terms of elevation, relief, crustal thickness, and position at the edge of the East Antarctic craton. High elevations in the TAM expose a Devonian and younger Gondwana succession (Beacon Supergroup and Ferrar Group tholeiitic igneous rocks), underlain mainly by early Paleozoic Ross Orogen basement (Fig. 9; Stump, 1995; Goodge, 2002, 2007b). Deformed Neoproterozoic and lower Paleozoic supracrustal rocks and a continental-margin plutonic belt (Granite Harbour series) are widespread, yet cratonic Precambrian basement is virtually absent. Uplift of the TAM rift shoulder is related to Cretaceous-Paleogene development of the West Antarctic Rift System that resulted in lithospheric extension, crustal thinning and widening of the Ross Sea basin. Mechanisms of uplift are debated, but include mechanical flexure (Stern and ten Brink, 1989; ten Brink et al., 1997; Yamasaki et al., 2008; Wannamaker et al., 2017), thermal buoyancy (LeMasurier and Rex, 1991; Rocholl et al., 1995), and collapse of a West Antarctic plateau leaving a low-density, buoyant lithosphere root (Studinger et al., 2004, 2006; Huerta and Harry, 2007; Bialas et al., 2007). Within the TAM, extension was accommodated along steep, range-parallel normal faults (Barrett, 1965; Laird et al., 1971), although there is evidence for Cenozoic dextral transtension (Wilson, 1995; Rossetti et al., 2006).

The general distribution of Precambrian through Neogene rock units within the TAM is shown in Fig. 9. Its highly varied geology makes up a number of different geotectonic features, including: (1) a Neoproterozoic rift margin that is associated with breakup of the Rodinia supercontinent; (2) an active, Andean-type Gondwana margin formed by subduction of paleo-Pacific ocean lithosphere beneath East Antarctica and leading to development of the Ross Orogen; (3) a Gondwana overlap assemblage, spanning sedimentation from Devonian to Triassic time; (4) the Ferrar magmatic province, part of a widespread Jurassic system involving eruption of continental basalts and emplacement of thick sills along an unusually linear belt; and (5) an enigmatic Neogene volcanic and uplift history that is related to development of the West Antarctic Rift System. Here I discuss the main aspects of the Archean to Neogene geological evolution in chronological order beginning with the Precambrian crystalline basement and ending with the young glacial deposits.

3.2. Precambrian basement

The TAM sit astride the eastern limit of Precambrian crust in East Antarctica (Figs. 8, 9; Roland, 1991; Goodge and Finn, 2010). The composite East Antarctic shield contains some of Earth's oldest crustal rocks and has a long-lived tectonic association with other East Gondwana cratons in Australia, India, and southern Africa during supercontinent evolution (Tingey, 1991; Fitzsimons, 2003; Harley and Kelly, 2007; Boger, 2011; Harley et al., 2013). In addition to its juvenile ancestry dating to 3.8–3.0 Ga, East Antarctica shares orogenic ties with other now-distant continental pieces thought to reflect Paleoproterozoic (~1.9–1.6 Ga), Mesoproterozoic (~1.2–0.9 Ga), and Pan-African (~0.6–0.5 Ga) crustal assembly. Recent advances in our understanding of the ages, kinematics and continuity of these orogenic belts within and adjacent to East Antarctica (Fitzsimons, 2000, 2003; Boger and Miller, 2004; Jacobs et al., 2003a, 2003b; Goodge et al., 2008, 2017; Boger, 2011; Harley et al., 2013) is helping to clarify periodic stages in the assembly of the late Mesoproterozoic Rodinia and late Neoproterozoic-early Paleozoic Gondwana supercontinents, in which East Antarctica played a critical role. However, because of the polar ice cap and remote access in East Antarctica, it is difficult to extrapolate isolated outcrop data across the continent for tectonic reconstruction and testing of crustal assembly hypotheses. Indeed, the only area in the entire TAM where bona fide Precambrian crystalline basement rocks are exposed is in the central region near Nimrod Glacier (Figs. 8, 9, 10, 11). There, the presence of Precambrian basement underlying the TAM is affirmed by rare exposures within the mountain belt and geophysical imaging of rocks beneath the adjacent polar ice cap. Similar crystalline basement terrain is exposed in Terre Adélie and the Shackleton Range (Peucat et al., 1999; Ménot et al., 1999; Will et al., 2009; Goodge and Fanning, 2016).

Archean and Proterozoic basement in the central TAM is comprised by the Nimrod Complex and Argosy Schist (formerly Nimrod Group as a single unit; Goodge and Fanning, 2016), mapped in the Miller and Geologists ranges (Figs. 10, 12, 13). Despite the effects of younger metamorphism and deformation during the Ross Orogeny (about 500 Ma), these high-grade metamorphic and igneous rocks record a rich Precambrian geologic history of the East Antarctic craton that spans 2.5 billion years of Archean to early Paleozoic time (Fig. 14; Borg et al., 1990; Goodge and Fanning, 1999, 2002, 2016; Goodge et al., 2001). Recognized events include primary Mesoarchean magmatism between 3150 and 3000 Ma, crustal stabilization and metamorphism between 2955 and 2900 Ma, partial melting at ~2500 Ma, deep-crustal metamorphism and magmatism between 1730 and 1700 Ma (Nimrod Orogeny), and basement reactivation involving high-grade metamorphism, magmatism and penetrative deformation during the Ross Orogeny between 540 and 515 Ma.

Metaigneous and metasedimentary lithologies in the Miller and Geologists ranges include upper-amphibolite to lower-granulite facies interlayered pelitic schist, micaceous quartzite, amphibolite, banded quartzofeldspathic to mafic gneiss, homogeneous (garnet-)biotite-hornblende gneiss, granitic to gabbroic orthogneiss, calc-silicate gneiss and marble, migmatite, and relict eclogite (Figs. 15A-D; Grindley et al.,

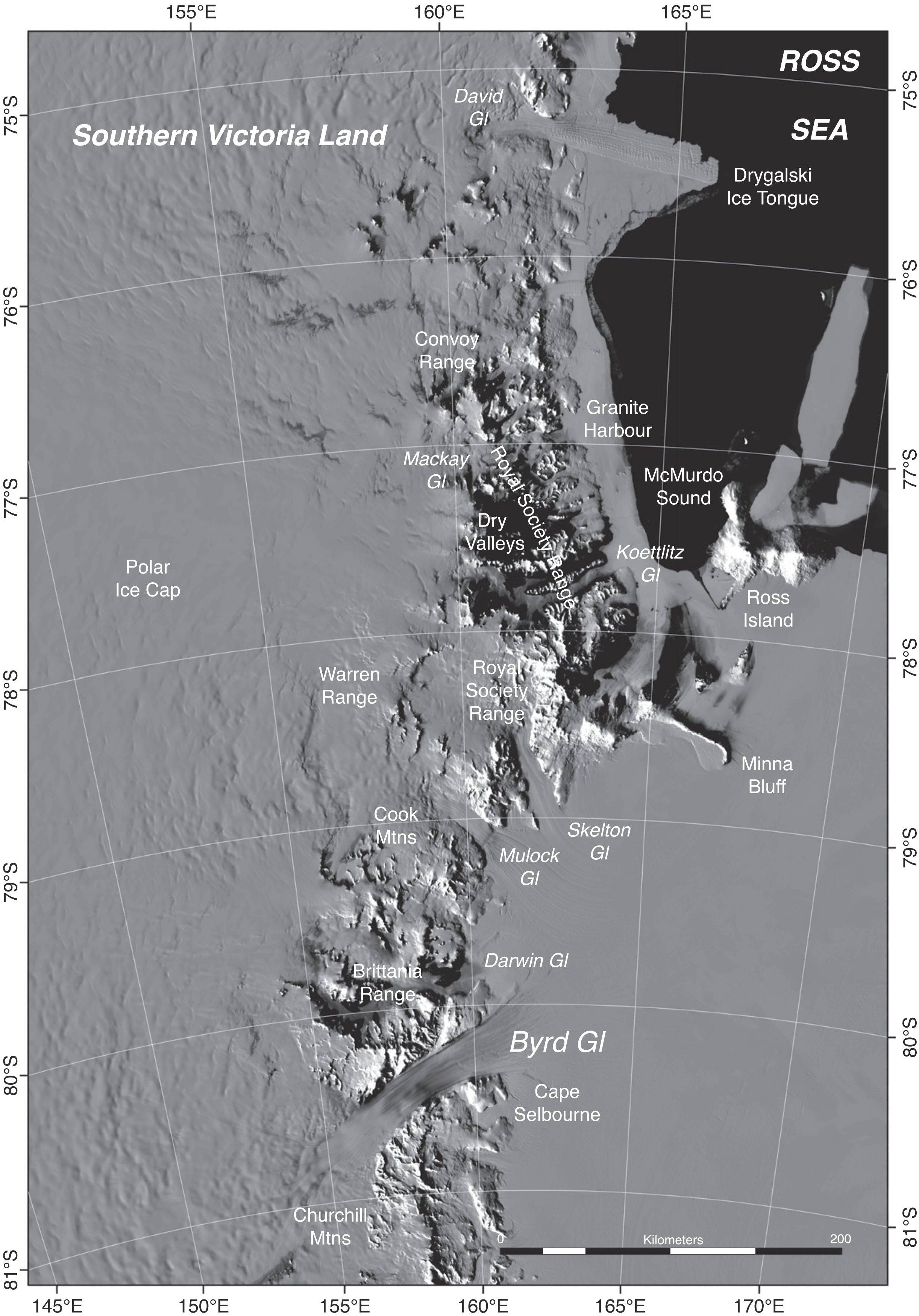


Fig. 6. MODIS image of southern Victoria Land and McMurdo Sound area, showing major geographic features.

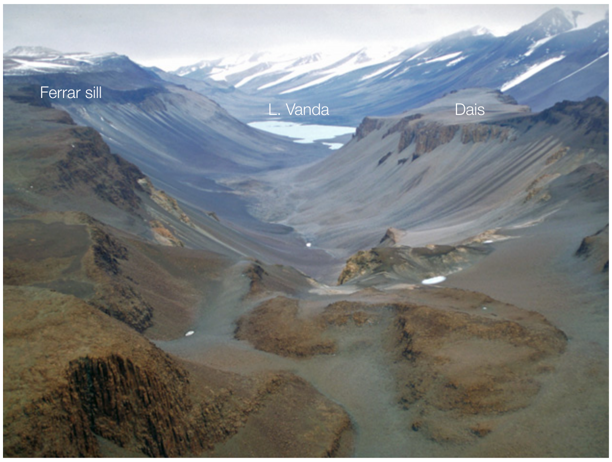


Fig. 7. View looking east along Wright Valley, one of the main group of Dry Valleys in southern Victoria Land. Dark-colored rocks in cliff faces and foreground are sills of the Ferrar Group dolerite within basement and subhorizontal Beacon strata. Rocks in the lower foreground form a feature called the Labyrinth, thought to be carved by subglacial meltwater discharge (Lewis et al., 2006). Lake Vanda in middle distance.

1964; Grindley, 1972; Goodge et al., 1991, 1993a; Peacock and Goodge, 1995). These are now divided into metaigneous layered gneisses and orthogneisses of the Nimrod Complex and metasedimentary units of the Argosy Schist (Goodge and Fanning, 2016). Within the Nimrod Complex, the oldest layered gneisses represent magmatic Mesoarchean crust formed between ~3150 and 3050 Ma from juvenile mantle melts. Magmatism at ~3100 Ma was followed closely by high-temperature metamorphism at 2955–2900 Ma, likely caused by high advective heat transfer and/or thermal insulation of newly stabilized crust. Metaigneous units with ages of ~2500 Ma indicate a late Neoarchean period of anatexis and/or magmatism, although the geologic context for these events is uncertain. Following Archean magmagenesis, deep-crustal granulite- to eclogite-facies metamorphism affected rocks of the Nimrod Complex (Goodge and Fanning, 1999; Goodge et al., 2001). Eclogites occur as detached blocks within layered gneisses and have mineralogical characteristics of lower-crustal eclogites (Grindley, 1972; Goodge et al., 1992; Peacock and Goodge, 1995). Zircon ages of ~1.7 Ga from gneisses, eclogites and orthogneiss units define a period of Paleoproterozoic activity ascribed to the (redefined) Nimrod Orogeny (Goodge et al., 2001; Goodge and Fanning, 2016) that may have played an early role in assembly of East Gondwana cratons. The Argosy Schist consists of interlayered mica schist, quartzite, amphibolite, and calc-silicate schist; siliciclastic protoliths have detrital zircon age components limiting the age of deposition to between 2000 and 900 Ma.

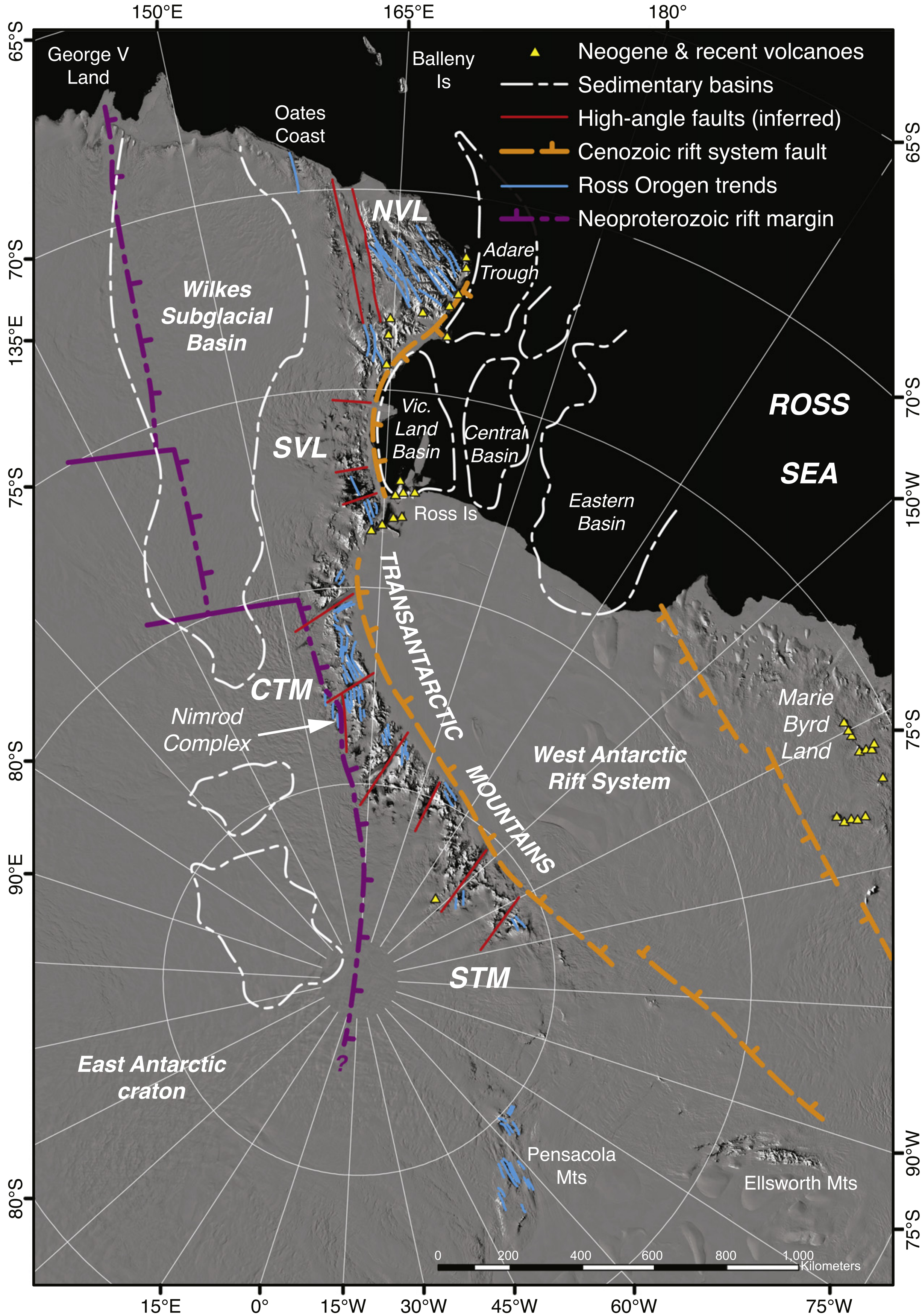
The Nimrod and Argosy assemblages also show a strong thermomechanical imprint by the Ross Orogeny (Goodge et al., 1991; Goodge and Dallmeyer, 1992, 1996; Goodge et al., 1993a, 1993b; Goodge, 2007a), reflecting basement reactivation during Ross time. Medium- to high-*P*/*T* kyanite-zone metamorphic mineral assemblages are widespread within both the Nimrod and Argosy assemblages, indicating exposure of relatively deep crustal levels in this part of the Ross Orogen (Grindley, 1972; Goodge et al., 1992; Goodge, 2007a). In addition, the metamorphic tectonites are intruded by a compositionally diverse suite of early Paleozoic igneous rocks characterized by variable development of solid-state deformation fabrics (Figs. 16A-C; Goodge et al., 1993b, 2012). They include diorite, tonalite, granodiorite, granite, aplite and pegmatite lithologies, emplaced as plutons, wide sheets, sills and dikes. It can be difficult to distinguish these younger intrusive units in the field from older units of the Nimrod Complex, but zircon fractions from different units have yielded U—Pb ages ranging mainly from about 545–485 Ma (Goodge et al., 1993b, 2012). These compositionally variable granitoids are related to the broader Granite Harbour intrusive series, discussed separately below. The variations in fabric development relative to the tectonites they intrude indicate progressively weakening Ross tectonism during this interval in the Early Cambrian.

3.3. Neoproterozoic rift-margin successions

Metasedimentary and volcanic rocks thought to comprise rift-margin deposits along the paleo-Pacific margin of East Antarctica are exposed in northern Victoria Land (Priestley Formation and Rennick Schist in the Wilson Group), southern Victoria Land (Skelton Group), central and southern TAM (Beardmore Group), and Pensacola Mountains (Patuxent and Hannah Ridge formations). These successions in Antarctica likely correlate in a general way with rift-margin sedimentary and volcanic rocks in southeast Australia (Crawford et al., 1997, 2003; Preiss, 2000). The Antarctic rocks are variably metamorphosed and deformed, and in many cases, due to sparse age data, their actual depositional age remains uncertain. They consist mainly of siliceous quartzites, slates, paragneisses, impure marbles and calc-silicate schists, and mica schists (see Laird, 1991). In northern Victoria Land and near Terra Nova Bay, in particular, they are metamorphosed to high grade, locally producing migmatites. Generally, their protoliths consist of graywackes, shales, sandstones and impure limestones of marine origin. In several areas there is good preservation of sedimentary structures (e.g., Beardmore Group; Myrow et al., 2002b), and the presence of acritarchs is known from the Berg Group (Iltchenko, 1972), but by and large their primary features are strongly modified and an absence of biostratigraphic control makes a definable stratigraphy all but impossible.

In northern Victoria Land, rocks thought to represent Precambrian (pre-Ross Orogen) basement are included in the Wilson terrane (Figs. 17, 18). This composite tectonic unit is made up of metasedimentary rocks generally included in the Wilson Group that host ubiquitous felsic igneous rocks, but additional units have been defined west of Rennick Glacier and in the area of Terra Nova Bay (Rennick Schist, Berg Group, Priestley Formation, Morozumi Schist). These latter units occur in geographically distinct areas and are of uncertain correlation. Here, I will refer to this assemblage generally as Wilson Group. The Wilson assemblage consists of micaceous paragneiss, mica schist, psammitic schist, quartzite, marble and local migmatite (Ravich et al., 1965; Gair et al., 1969; Sturm and Carryer, 1970; Stump, 1995; Henjes-Kunst and Schüssler, 2003; Estrada et al., 2016). The other units are mainly metamorphosed siliciclastic rocks (including greywacke, psammite, and argillite protoliths) with minor calcareous units. Notable among them is the Priestley Formation, which includes metamorphosed shales, argillites, graywackes and limestones showing highly variable metamorphic grade (Skinner, 1983). In other cases, such as in the Berg Group, metamorphism is of a sufficiently low grade that primary sedimentary structures indicating turbidite sediment deposition are preserved (Stump, 1995). These rocks also contain acritarch microfossils indicating a Neoproterozoic (Riphean) age (Iltchenko, 1972). Metamorphic rocks in the Lanterman and Salamander ranges are also probably correlative with the Wilson Group (Talarico et al., 1998). Regional metamorphism is variable from greenschist to granulite facies, and in many areas these rocks are intimately mixed with granitoids and migmatites of the Granite Harbour batholith (Babcock et al., 1986; Schüssler et al., 1999, 2004). Despite variable and locally high-grade metamorphism, available geochronologic evidence shows that the Wilson terrane does not represent primary Archean or Paleoproterozoic crust of the East Antarctic shield (westward, the first such rocks occur in the Terre Adélie craton of Wilkes Land), but rather is a composite metasedimentary assemblage of latest Neoproterozoic to Cambrian age. Here I discuss the older assemblage and will return to the Cambrian components in the next section.

Due to pervasive Ross Orogen metamorphism, U—Pb zircon geochronology provides the most reliable constraints on depositional age of the Wilson siliciclastic units. Recent U—Pb detrital zircon



Neogene & recent volcanoes
Sedimentary basins
High-angle faults (inferred)
Cenozoic rift system fault
Ross Orogen trends
Neoproterozoic rift margin
George V Land
Oates Coast
Balleny Is
NVL
Adare Trough
Wilkes Subglacial Basin
SVL
Vic. Land Basin
Central Basin
Eastern Basin
Ross Is
ROSS SEA
CTM
Nimrod Complex
TRANSANTARCTIC MOUNTAINS
West Antarctic Rift System
Marie Byrd Land
STM
East Antarctic craton
Pensacola Mts
Ellsworth Mts
150°E
165°E
180°
65°S
70°S
135°E
75°S
80°S
90°E
150°W
90°W
15°E
0°
15°W
30°W
45°W
60°W
75°W
0 200 400 600 800 1,000
Kilometers

geochronology from inboard metasedimentary samples reveals that protoliths to the Priestley Formation and Rennick Schist are dominated by Mesoproterozoic ('Grenvillian') sources with minor older cratonic components (Estrada et al., 2016; Paulsen et al., 2016). These samples also show evidence of Ross Orogen-age metamorphism overprinting older Mesoproterozoic detrital zircon ages. Priestley Formation samples contain zircons as young as about 592–598 Ma, indicating possible deposition up to ~600 Ma (Estrada et al., 2016). Some samples of Rennick Schist have maximum depositional ages of ~1100 Ma (Paulsen et al., 2016), indicating a probable Neoproterozoic stratigraphic age and cratonic provenance distinguished from other petrographically similar samples. Sr- and Nd-isotope compositions of S-type Granite Harbour intrusions within the Wilson assemblage indicate derivation by melting of pre-existing continental crust (Borg et al., 1987), which likely reflects a cratonic sedimentary source of detritus. The geochemical and isotopic compositions of Preistley Formation samples likewise indicate that Wilson material was derived from a crustal source with an average early Paleoproterozoic formation age (Henjes-Kunst and Schüssler, 2003). Other units within the Wilson metamorphics show Ross Orogen sources and have maximum depositional ages of 525–560 Ma, indicating a Cambrian or younger stratigraphic age. These rocks should actually be considered correlative with early Paleozoic active-margin successions in the central and southern TAM, discussed below. Thus, some of the inboard units of the Wilson terrane (Priestley and Rennick units) can be considered likely Neoproterozoic rift-margin deposits, possibly equivalent to the Beardmore and Skelton groups farther south, whereas most of the assemblage is actually Cambrian or younger.

Metasedimentary rocks in southern Victoria Land include the Skelton (and formerly Koettlitz) groups (Gunn and Warren, 1962; Findlay et al., 1984; Stump, 1995; Cook and Craw, 2001, 2002), but a lack of fossils as well as regional metamorphism, deformation, and granite intrusion obscure their age and stratigraphic relationships. The Skelton Group is dominated by greenschist to upper-amphibolite facies calc-silicate schist, marble, and amphibolite, with minor mafic, quartzofeldspathic and pelitic rocks. These siliciclastic and calcareous rocks are thought to represent late Neoproterozoic and early Paleozoic continental-margin deposits (Laird, 1991) and therefore correlate generally with rocks of the Beardmore and/or lower Byrd groups. A minimum age of ~550 Ma, bracketed by crosscutting plutons, indicates that the rocks are indeed Precambrian (Rowell et al., 1993; Encarnación and Grunow, 1996; Read and Cooper, 1999). Detrital zircon age distributions in the Skelton and Koettlitz groups show a preponderance of Grenville-age zircons relative to Paleoproterozoic and Archean components, and a lack of Ross-age detrital grains appears to confirm a Neoproterozoic depositional age (Wysoczanski and Allibone, 2004; Goodge et al., 2004b). Similarity between their age patterns and those from Goldie and basal Shackleton sandstones farther south, and the calcareous nature of the associated Koettlitz units, suggest that the Skelton and Koettlitz units may record platform deposition in the latest Neoproterozoic.

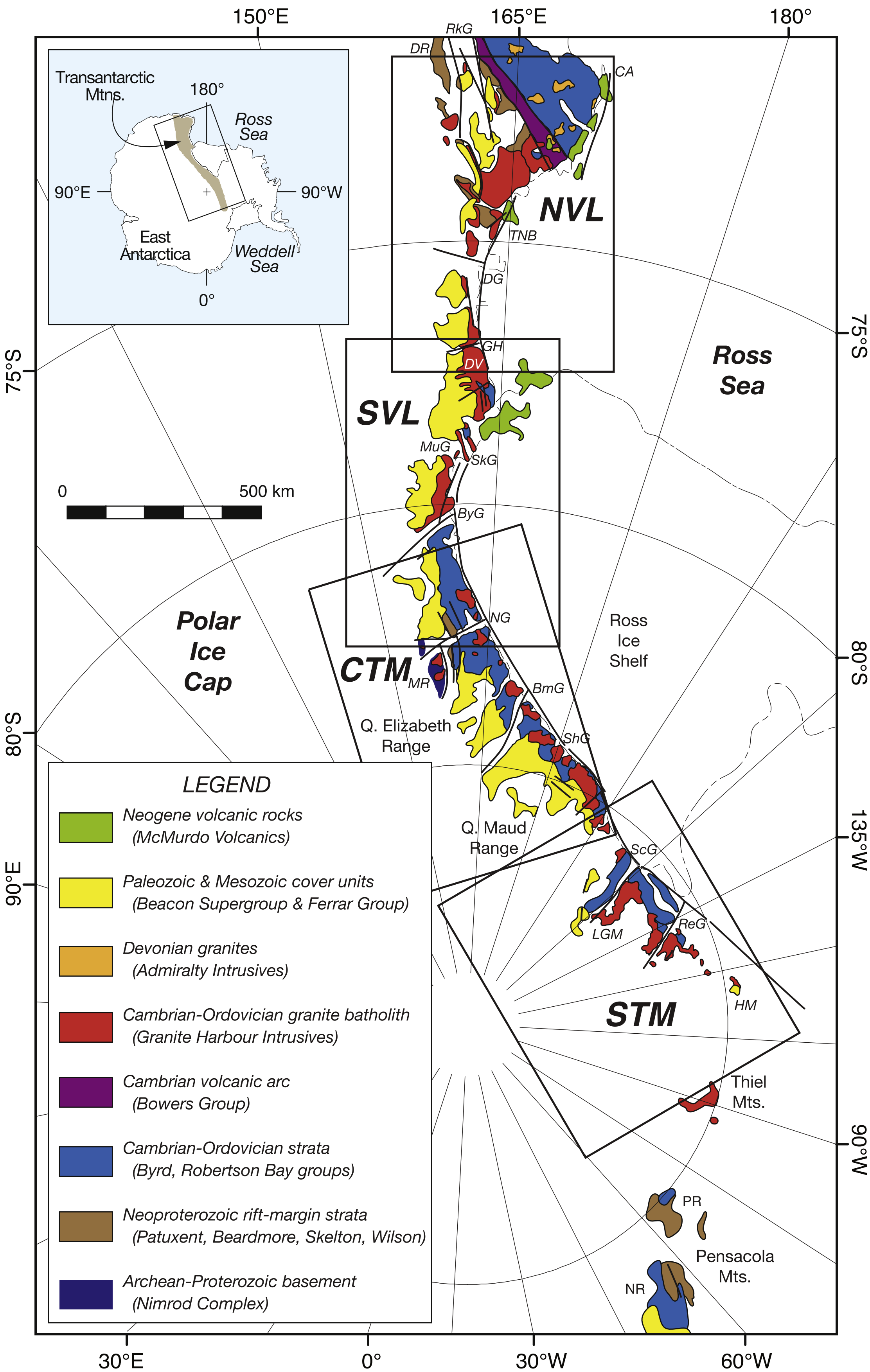
In the Skelton Glacier area, the Baronick Formation consists of low-grade metasedimentary rocks that preserve primary features (Cook, 2007). This unit includes interlayered coarse clastic sediments, conglomerate, and tuffaceous volcanic to subvolcanic layers. Clasts in the conglomerates are mainly volcanic, ranging from trachyte to basalt and minor comendite, but also include marble. Igneous layers parallel to bedding in the Baronick unit include quartz syenite, trachyte, basalt and basaltic tuff; geochemically they represent a bimodal association of alkaline basalt and trachyte which resemble igneous rocks formed in intraplate settings associated with continental rifts and mantle plumes (Cook, 2007). Further work on conglomeratic clasts of the Baronick Formation showed that the basaltic types are mildly alkalic and resemble ocean-island basalts, compatible with eruption in a continental-margin rift environment (Cooper et al., 2011). Rhyolite clasts from this section gave U—Pb zircon ages of ~650 Ma (Cooper et al., 2011), indicating that they were erupted and re-deposited as conglomeratic material in the same general timeframe as the Beardmore Group farther south. The similarity of detrital zircon age signatures in Skelton Group sandstones with those of the Beardmore Group (Goodge et al., 2002, 2004b; Wysoczanski and Allibone, 2004; Cooper et al., 2011), as well as the similar ages of bimodal volcanism in the Skelton and Nimrod glacier areas, indicates that their deposition is related to extension and rifting during supercontinental breakup of Rodinia.

In the central TAM, the Beardmore Group is a thick assemblage of non-fossiliferous sandstone, shale, carbonate, diamictite, and minor volcanic rocks (Gunn and Walcott, 1962; Laird et al., 1971; Laird, 1981, 1991; Stump, 1982, 1995). It was originally mapped from Byrd Glacier to south of Beardmore Glacier (Fig. 10) and divided into the Cobham and Goldie formations (Fig. 19). Little is known about the sedimentology of the Cobham Formation as a result of contact metamorphism, but it is quartz rich at its base and carbonate rich near its top, suggesting inner continental-shelf sedimentation (Laird et al., 1971). The Goldie Formation is a siliciclastic succession composed predominantly of quartzofeldspathic sandstone and shale, with minor calcareous sandstone and matrix-supported conglomerates (Grindley, 1963; Laird et al., 1971; Stump et al., 1988; Goodge et al., 2002, 2004b). Regional low-grade metamorphism and deformation have transformed the Goldie assemblage to interlayered quartzites and slates (Fig. 20). The presence of tabular-bedded sandstone with cross-bedding, ripple lamination, and graded bedding led previous workers (e.g., Laird et al., 1971) to suggest that the Goldie represents deep-water turbidites. More recent work shows, instead, that most, if not all, Goldie rocks contain abundant large-scale hummocky cross-stratification, parallel lamination, and quasi-planar stratification, indicating that they were deposited in a shallow marine setting above storm wave base (Myrow et al., 2002a; Goodge et al., 2004b).

Early workers regarded the group as a Neoproterozoic siliciclastic succession representing rift- or passive-margin deposits of the East Antarctic margin, but its depositional relationships with underlying and overlying units are controversial. The Beardmore Group is younger than crystalline basement of the East Antarctic craton (represented by the Mesoarchean and Paleoproterozoic Nimrod Complex to the west), and a Neoproterozoic depositional age is widely inferred because of a lack of fossils and a putative unconformable relationship with the Lower Cambrian Byrd Group (Laird et al., 1971; Stump, 1995). Others have questioned this relationship on the basis of field relationships and structural features (Rowell et al., 1986; Goodge, 1997; Goodge et al., 1999); rather, all sub-Byrd contacts observed in the Nimrod Glacier area are recognized as faults, including those earlier interpreted as unconformities, leaving uncertain the stratigraphic and age relationships of the Beardmore Group. However, a U—Pb zircon age of 668 ± 1 Ma for basalt and gabbro interlayered with Goldie sandstone (Goodge et al., 2002) indicates that mafic magmatism, and by inference the Goldie deposits themselves, are indeed Neoproterozoic in age.

Detrital zircon provenance signatures have led to a complete revision of Neoproterozoic to Ordovician stratigraphic relationships in the central TAM (Fig. 19). Rocks mapped originally as Goldie Formation over a wide area of the central TAM are lithologically similar (Grindley

Fig. 8. Tectonic map of the TAM and surrounding areas. Base is same as in Fig. 3. Neoproterozoic rift margin boundary is inferred from magnetic, gravity and seismic geophysical data (Goodge and Finn, 2010), and marks the Ross margin of the Precambrian East Antarctic shield. Neogene faults bounding the West Antarctic Rift System (WARS; from Wilson, 1999; Studinger et al., 2006) also form the TAM front. High-angle faults inferred to underlie the major TAM outlet glaciers are related to movement on the TAM frontal fault system, but they may also be locally reactivated from Neoproterozoic transfer faults. Sedimentary basins in the Ross Sea area are related to opening of the WARS, but the origin of the interior basins such as the Wilkes Subglacial Basin are enigmatic. Neogene and recent volcanoes in the TAM and Marie Byrd Land are related to extension in the WARS, including the active systems on Ross Island.


150°E
165°E
180°
RkG
DR
CA
Transantarctic
Mtns.
180°
Ross
Sea
90°E
90°W
East
Antarctica
Weddell
Sea
0°
NVL
TNB
DG
GH
DV
75°S
Ross
Sea
SVL
MuG
SkG
0
500 km
ByG
Polar
Ice
Cap
NG
CTM
MR
Ross
Ice
Shelf
80°S
BmG
Q. Elizabeth
Range
ShG
LEGEND
Neogene volcanic rocks
(McMurdo Volcanics)
Paleozoic & Mesozoic cover units
(Beacon Supergroup & Ferrar Group)
Devonian granites
(Admiralty Intrusives)
Cambrian-Ordovician granite batholith
(Granite Harbour Intrusives)
Cambrian volcanic arc
(Bowers Group)
Cambrian-Ordovician strata
(Byrd, Robertson Bay groups)
Neoproterozoic rift-margin strata
(Patuxent, Beardmore, Skelton, Wilson)
Archean-Proterozoic basement
(Nimrod Complex)
Q. Maud
Range
ScG
135°W
90°E
LGM
ReG
HM
STM
Thiel
Mts.
90°W
PR
Pensacola
Mts.
NR
30°E
0°
30°W
60°W

and Laird, 1969; Laird et al., 1971), yet detrital-zircon geochronology indicates that only a small proportion of these exposures contain Neoproterozoic and older age components from cratonic sources (these are the 'inboard' type of Goodge et al., 2002). These rocks, plus the Cobham Formation, comprise the redefined Beardmore Group (Fig. 19; Myrow et al., 2002b), which is thus restricted to rocks in the eastern Cobham Range and Cotton Plateau areas of upper Nimrod Glacier (Figs. 10, 12). Most of the rocks previously mapped in this region as Goldie Formation contain Cambrian and older zircons indicative of Ross Orogen sources; they were thus reassigned to the Starshot Formation of the upper Byrd Group (see below). Sediment compositions and detrital zircon age distributions indicate that the Beardmore Group consists of moderately mature, multicycle sediments derived from mixed sources dominated by 2.8, 1.8–1.6 and 1.1 Ga crust (Goodge et al., 2004b). Lithofacies of the Goldie Formation, its sediment composition, and association with mafic volcanic rocks indicate that these Neoproterozoic deposits formed in shallow water across a rifted cratonic margin during early extensional and later passive-margin tectonic phases. The detrital signatures in these sandstones mainly indicate a simple, two-component source consisting of Archean and Paleoproterozoic–Mesoproterozoic cratonic provinces.

Siliciclastic and volcanic rocks in the Pensacola Mountains were long thought to represent deposition and volcanic eruption within a Neoproterozoic basin at the margin of East Antarctica (Fig. 21; Schmidt et al., 1964, 1965; Schmidt and Ford, 1969; Storey et al., 1992, 1996; Curtis et al., 2004). These rocks, including the Patuxent and Nelson formations, are strongly deformed by Ross Orogen deformation. As discussed in the next section, however, all stratigraphic units in the Pensacola Mountains are now considered to be part of a latest Neoproterozoic and lower Paleozoic succession that records a transition from passive to active margin deposition (Millar and Storey, 1995; Van Schmus et al., 1997; Rowell et al., 2001; Goodge et al., 2004b).

3.4. Early Paleozoic successions (passive margin, active margin, arc rocks)

During the Cambrian and Ordovician periods, the TAM were located in a stable equatorial to southerly tropical paleogeographic position spanning 0–30°S latitude (Grunow and Encarnación, 2000; Torsvik and Cocks, 2017). Lower Paleozoic strata deposited along the continuously active convergent plate margin of Gondwana occur throughout the TAM and display the principal evidence of Ross Orogen contractional deformation. Lower Cambrian platform-type strata are restricted to the central and southern TAM, whereas Middle Cambrian arc-volcanic and arc-derived strata, as well as a poorly dated siliciclastic assemblage, are unique to northern Victoria Land. A widespread record of Middle Cambrian syn-orogenic, molasse-basin deposition is recognized in the central TAM and southern Victoria Land, overturning long-held ideas about the distribution of Neoproterozoic strata on the rift margin of East Antarctica. Here, I will summarize these successions by region, from north to south.

3.4.1. Northern Victoria Land

The geology of northern Victoria Land is dominated by three tectonic assemblages that developed largely during the Ross Orogeny — the Wilson, Bowers, and Robertson Bay terranes — consisting mostly of sedimentary and volcanic material of early Paleozoic age and volumetrically significant arc-type intrusions. As discussed above, many of the rocks assigned to the Wilson terrane are actually Cambrian in age (detrital zircon and muscovite ages indicating deposition <550–525 Ma; Henjes-Kunst and Schüssler, 2003; Henjes-Kunst et al., 2004; Di Vincenzo et al., 2014; Paulsen et al., 2016) and have a combined cratonic and early Ross Orogen provenance. The detrital zircon provenance data illustrate that, rather than representing reworked Precambrian crust, much of the Wilson terrane consists of Cambrian syn-orogenic clastic deposits sourced from, and metamorphosed during, the Ross Orogeny. As such, these rocks can be correlated with Starshot Formation of the central TAM and equivalent strata (see below). The Wilson units also have strong Grenvillian and older cratonic signatures that nonetheless indicate an autochthonous relationship with respect to East Antarctic crust. Detrital muscovite data from the Wilson terrane bear a resemblance to turbidites in the Kanmantoo Group of eastern Australia (Di Vincenzo et al., 2014), further indicating an autochthonous relationship at the Neoproterozoic-Cambrian transition.

Unique to the TAM, other lower Paleozoic strata in northern Victoria Land consist of volcanic, volcaniclastic and siliciclastic rocks of an oceanic arc and/or active plate-margin setting. They include two principal assemblages, the Bowers and Robertson Bay terranes, separated from each other and the inboard Wilson terrane by major faults. Reference to these terranes as tectonic units follows established literature, but they are represented by stratigraphic units of the Bowers Supergroup and Robertson Bay Group. The Bowers is divided, from lowermost units upward, into the Sledgers, Mariner and Leap Year groups (Laird et al., 1982; Wodzicki and Robert Jr, 1986; Stump, 1995). These rocks are only weakly metamorphosed, preserve sedimentary features, and contain a variety of fossils. The Sledgers unit includes a distinctive (lower?) conglomerate unit (Husky Conglomerate) that contains variably-deformed, dark- and light-colored clasts of amphibolite and quartzite (Fig. 22A, B). A similar unit in the northeast part of the Lanterman Range is mapped as Lanterman Conglomerate (Fig. 22C), but it is of uncertain affinity to the Husky. The Sledgers unit is dominated, however, by a thick sequence of volcanic and volcaniclastic material (Glasgow Volcanics and overlying Molar Formation). The former consists of volcanic breccias, debris flows, pillow basalts, and tuffaceous sediment thought to represent deposition in a marine, subaqueous volcanic setting (Gibson et al., 1984; Jordan et al., 1984; Rocchi et al., 2003a). These rocks range in composition from basalt to andesite but include rocks of rhyolitic composition. A K—Ar age on hornblende of 521 Ma from a cumulate gabbroic unit that intrudes the Sledgers indicates a Neoproterozoic or Early Cambrian age (Kreuzer et al., 1987). The Molar Formation consists of weakly metamorphosed, interbedded sandstone, greywacke, shale, siltstone and conglomerate (Fig. 22D). Conglomerate clasts include volcanic rocks, limestone, quartzite, granite and schist (Wodzicki et al., 1982), and a Middle Cambrian depositional age is suggested from trilobites within the limestone clasts (Cooper et al., 1983). If the Molar and Glasgow units are depositionally related, this would strengthen the idea that the Glasgow volcanics are Cambrian and not Neoproterozoic in age.

Late Cambrian(?) marine strata of the Mariner Group consist of fossiliferous limestones and mudstones interbedded with fine-grained sandstones and lenses of conglomerate, limestone, and tuffaceous material (Laird and Bradshaw, 1983). Mud cracks and trace fossils indicate an intertidal, partly subaerial depositional setting (Andrews and Laird, 1976; Laird and Bradshaw, 1983), and fossils indicate a late Middle to late Late Cambrian depositional age (Cooper et al., 1982). The Mariner sediments were likely deposited in shallow-water, near-shore settings ranging from intertidal to lagoonal. Together, rocks of the Sledgers and Mariner groups are interpreted to represent an oceanic arc or back-arc assemblage with associated basin fill deposited in deep- to shallow-water marine conditions of an active-margin slope setting (Weaver et al., 1984; Kleinschmidt and Tessensohn, 1987; Laird et al., 1982; Rocchi et al., 2003a, 2011; Tessensohn and Henjes-Kunst, 2005; Federico et al., 2009).

Fig. 9. Simplified map of the major geologic units underlying the TAM (after American Geographical Society geologic folio maps, 1969; Goodge, 2007a, and sources therein). Boxes indicate areas covered in detailed figures (as in Fig. 3). BmG, Beardmore Glacier; ByG, Byrd Glacier; CA, Cape Adare; DG, Davis Glacier; DR, Daniels Range; DV, Dry Valleys; GH, Granite Harbour; HM, Horlick Mountains; LGM, La Gorce Mountains; MR, Miller Range; MuG, Mulock Glacier; NG, Nimrod Glacier; NR, Neptune Range; PR, Patuxent Range; ReG, Reedy Glacier; ScG, Scott Glacier; ShG, Shackleton Glacier; SkG, Skelton Glacier; TNB, Terra Nova Bay.

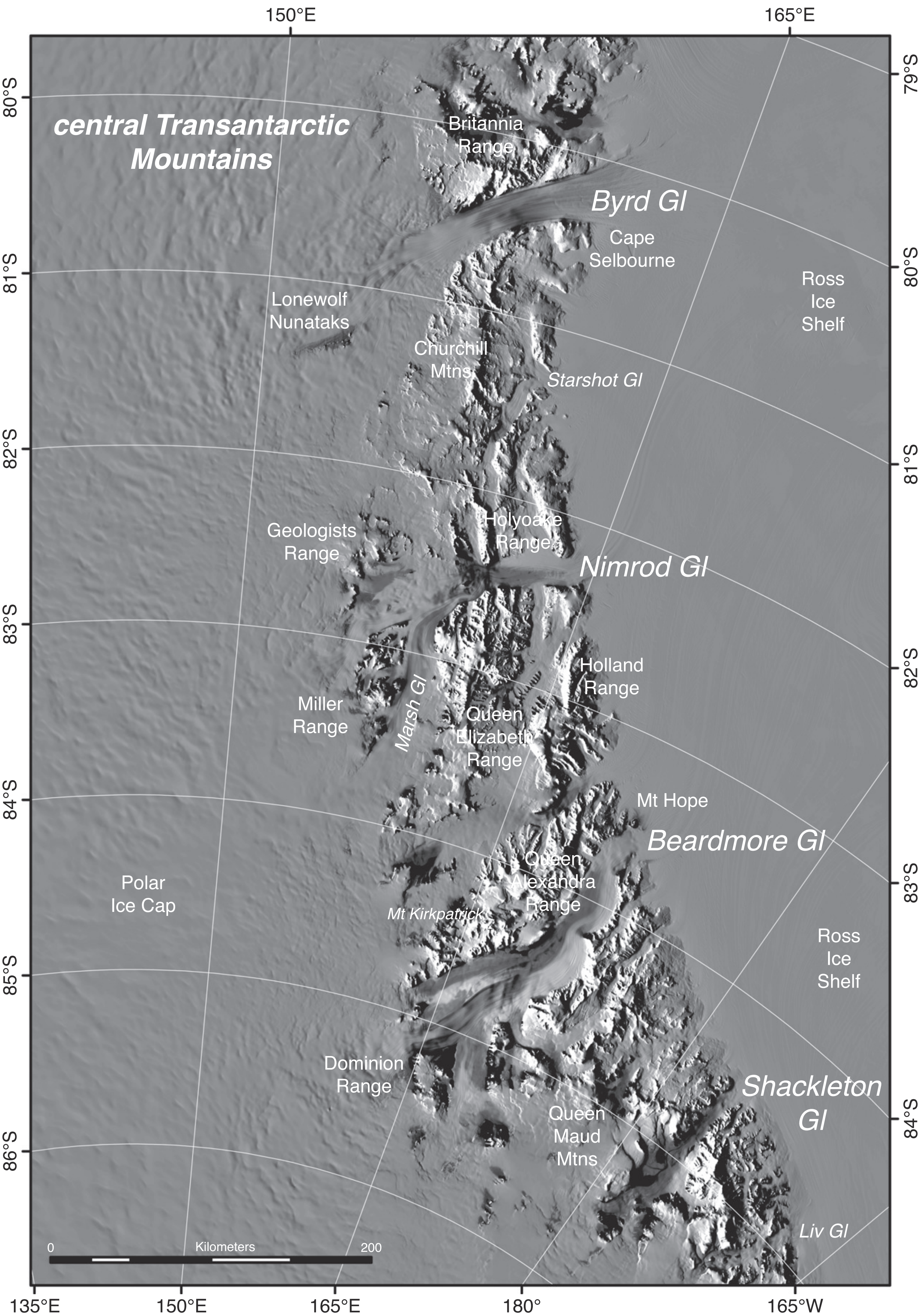


Fig. 10. MODIS image of the central TAM area, showing major geographic features.

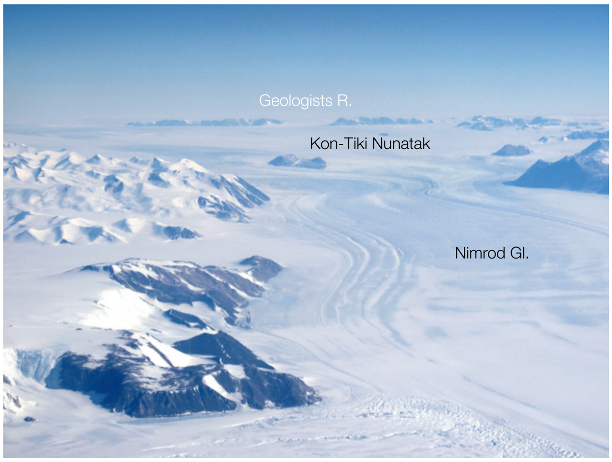


Fig. 11. Aerial view looking west up Nimrod Glacier. Campbell Hills in foreground are exposures of Cambrian-Ordovician Starshot Formation siliciclastic rocks, intruded by granites of the Granite Harbour Intrusives. Lower Cambrian rocks of the Byrd Group exposed in the middle distance, including at the prominent escarpment of Cambrian Bluff on the right (north); Neoproterozoic rift-margin strata of the Beardmore Group are exposed at Kon-Tiki Nunatak in the middle of Nimrod Glacier. Distant cliff faces in the background are Precambrian rocks of the Nimrod Complex in the Geologists Range.

A thick sequence of molasse-type shallow marine to coarse fluvial siliciclastic rocks (Leap Year Group) forms the top of the Bowers succession. Rocks of the Leap Year Group consist primarily of coarse sandstones and polymict conglomerates deposited in a fluvial setting (Laird and Bradshaw, 1983; Wodzicki and Robert Jr, 1986). Clast compositions in the conglomerates suggest deposition proximal to exposed volcanic and plutonic sources. U—Pb ages of detrital zircons in samples from the Bowers Supergroup (including Leap Year, Sledgers, and Mariner units) indicate a uniform provenance, with dominantly Ross Orogen and Mesoproterozoic cratonic sources. A maximum depositional age of about 480–490 Ma for Leap Year Group sandstones is consistent with a Late Cambrian to Early Ordovician depositional age, whereas Molar and Mariner units are most likely Cambrian in age (Estrada et al., 2016; Paulsen et al., 2016). Di Vincenzo et al. (2014) noted that samples from the Bowers and Robertson Bay terranes yield indistinguishable detrital muscovite age patterns that indicate a common primary Ross Orogen source like those found in the Lachlan belt of eastern Australia.

A relatively monotonous succession of Upper Cambrian to Lower Ordovician siliciclastic rocks comprising the Robertson Bay Group is exposed in the eastern part of NVL (Fig. 18). The group is a seemingly simple succession of siliciclastic rocks having uncertain internal stratigraphy, age and provenance. These rocks consist mostly of greywacke, sandstone, argillite and shale, with local minor conglomerate. As in the Bowers Supergroup, they were weakly metamorphosed (up to greenschist facies, but mostly lower grade; Buggisch and Kleinschmidt, 1991) and they are characteristically deformed into upright folds (Kleinschmidt, 1981, 1983, 1992). Because these rocks are mostly nonfossiliferous graywackes and shales with few marker beds, their thickness is difficult to determine, but they cover a large geographic region and are likely to be several thousand meters thick. The Robertson Bay units were likely deposited as turbiditic fans in a deep-marine setting, but their sedimentary provenance is poorly known. Sediment characteristics and clast compositions are consistent with erosion of igneous and metamorphic continental crust. Conodonts in a limestone from Handler Ridge indicate a Late Cambrian to Early Ordovician depositional age (Burrett and Findlay, 1984; Buggisch and Repetski, 1987). U—Pb ages of detrital zircons in samples from the Robertson Bay Group indicate a dominantly Ross-orogen and Mesoproterozoic cratonic provenance and a maximum depositional age of about 465–490 Ma (Estrada et al., 2016; Paulsen et al., 2016), consistent with an Early Ordovician depositional age. Geochemical and isotopic compositions indicate a shield-type source, but there is no direct evidence for an island-arc source component (Henjes-Kunst and Schüssler, 2003). Although an Ordovician deposition age is indicated by both fossils and detrital mineral ages, apparent discrepancy between deposition and metamorphic ages leaves the origin of this assemblage uncertain, as well as its relation to the Ross Orogeny. Some consider the Robertson Bay to be correlative with the Ordovician-Devonian Lachlan Fold Belt because of its similarities with the Swanson Formation in Marie Byrd Land, the Greenland Group of New Zealand, and the Stawell Zone of Australia (Bradshaw et al., 1983; Bradshaw, 2007). If the Robertson Bay assemblage is indeed as young as Devonian, then its involvement in the Ross Orogeny is substantially in doubt.

3.4.2. Southern Victoria Land

Because of the regional metamorphic grade and intimate relationship with granitic melts and anatectites, there is no clear evidence of late Neoproterozoic to early Paleozoic sedimentary rocks in southern Victoria Land corresponding to those elsewhere in the TAM. As noted above, Skelton Group metasedimentary rocks have detrital zircon ages indicating deposition as old as about 1050–950 Ma. Wysoczanski and Allibone (2004) concluded that the Skelton rocks are likely correlative with Beardmore Group and Adelaidean successions, and they proposed a depositional age greater than ~600 Ma. Detrital zircons from the Hobbs Formation of the Koettlitz Group are ~670 Ma and older, likewise indicating a Neoproterozoic depositional age concurrent with rift-stage volcanism (Goodge et al., 2004b). Although volcanic sources are not exposed, rhyolitic volcanic clasts with compositions similar to Dry Valleys granitoids are known from Beacon Supergroup (Taylor Group) conglomerates at Sperm Bluff (Wysoczanski et al., 2003). These clasts give zircon U—Pb ages ranging from about 497–482 Ma, documenting Late Cambrian and Early Ordovician felsic volcanism in southern Victoria Land.

3.4.3. Central TAM

The central TAM preserve the best record of Lower Cambrian platform carbonate deposition. The Lower Cambrian Shackleton Limestone crops out between Beardmore and Byrd Glaciers (Fig. 12); its most complete exposures are in the Holyoake Range (Rowell et al., 1988b; Rees et al., 1989; Rowell and Rees, 1989, 1991) where Laird (1963) designated a type locality. The Shackleton Limestone is a thick carbonate deposit with a lower unit of unfossiliferous interbedded quartzite and carbonate. In several localities, the Shackleton was mapped as resting on rocks of the Goldie Formation, leading Laird (1963) to interpret the contact as an unconformity over Neoproterozoic turbidites. However, at Panorama Point on the western slopes of Cotton Plateau, the contact shows structural evidence for fault displacement (Goodge et al., 1999), including angular discordance, a mineral-elongation lineation and stretched pebbles, asymmetric folds, asymmetric microstructures, and mineralization indicating a structural relationship. The contact is also faulted at other localities (Rowell et al., 1986; Rees et al., 1989; Palmer and Rowell, 1995; Myrow et al., 2002b). From a detailed section measured at Cotton Plateau, the basal member of the Shackleton consists of interbedded white- to cream-weathering, vitreous, quartz sandstone and brown-weathering, white, fine-grained dolomitic grainstone (Myrow et al., 2002b). The percentage of carbonate increases up section, and the sandstone component eventually disappears as the section shifts into a thick, massive boundstone unit containing meter-scale, mixed siliciclastic-carbonate cycles indicative of shallow-water deposition. These cycles are thought to record upward-deepening and an upward decrease in sandstone from cycle to cycle and eventual stratigraphic transition into a carbonate platform representing transgression and establishment of a long-standing carbonate ramp. Formation thickness is difficult to assess because of strong deformation (Rowell and Rees, 1991), and estimates of 1000–2000 m (e.g., Burgess and Lammerink, 1979) are not well constrained.

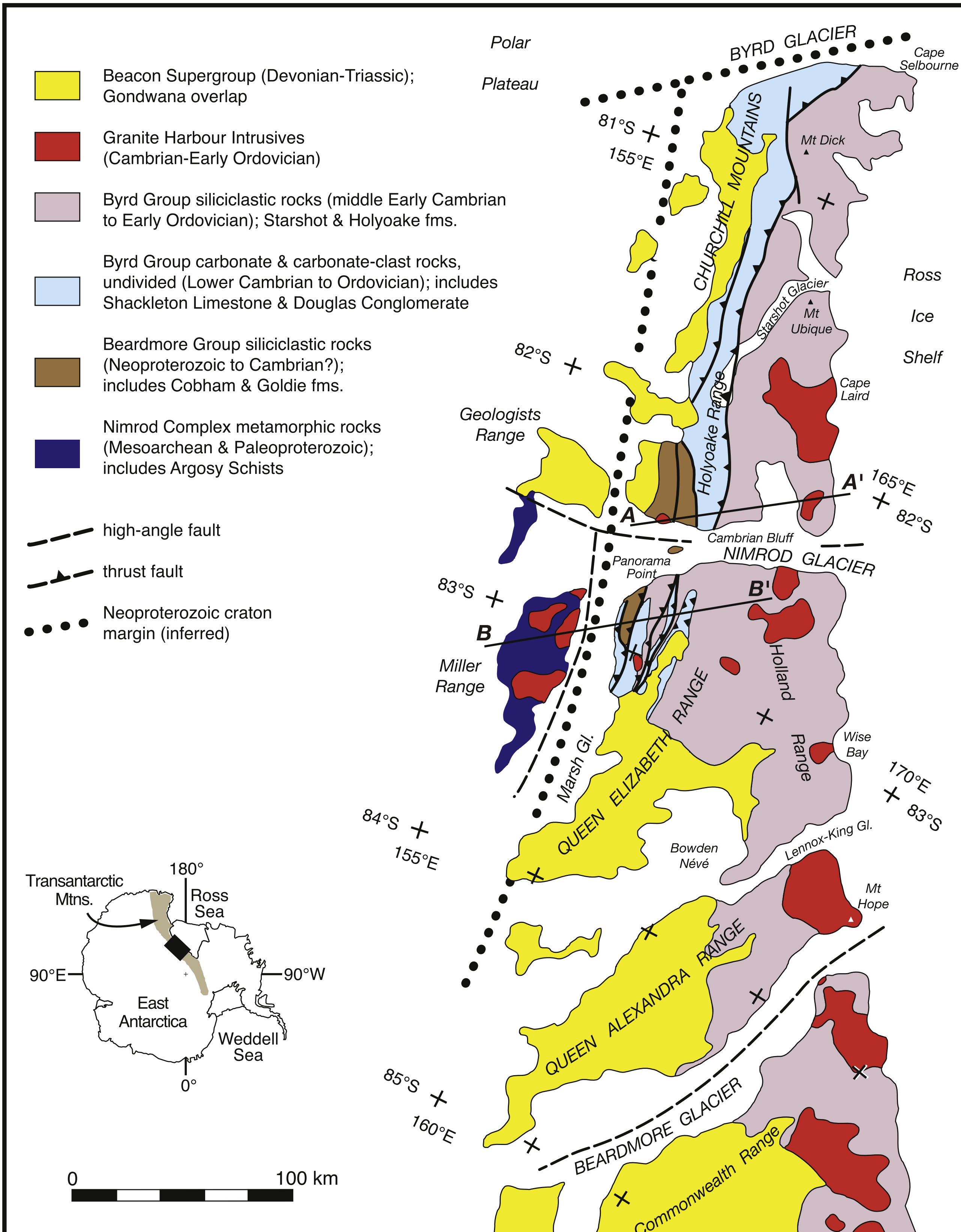


Fig. 12. General geology of the central Transantarctic Mountains between Byrd and Beardmore glaciers (after Goodge et al., 2004a). Stratigraphic assignment of Neoproterozoic and lower Paleozoic units follows Myrow et al. (2002b) and Goodge et al. (2002). Structure sections along profile lines A-A′ and B-B′ are shown in Fig. 43.

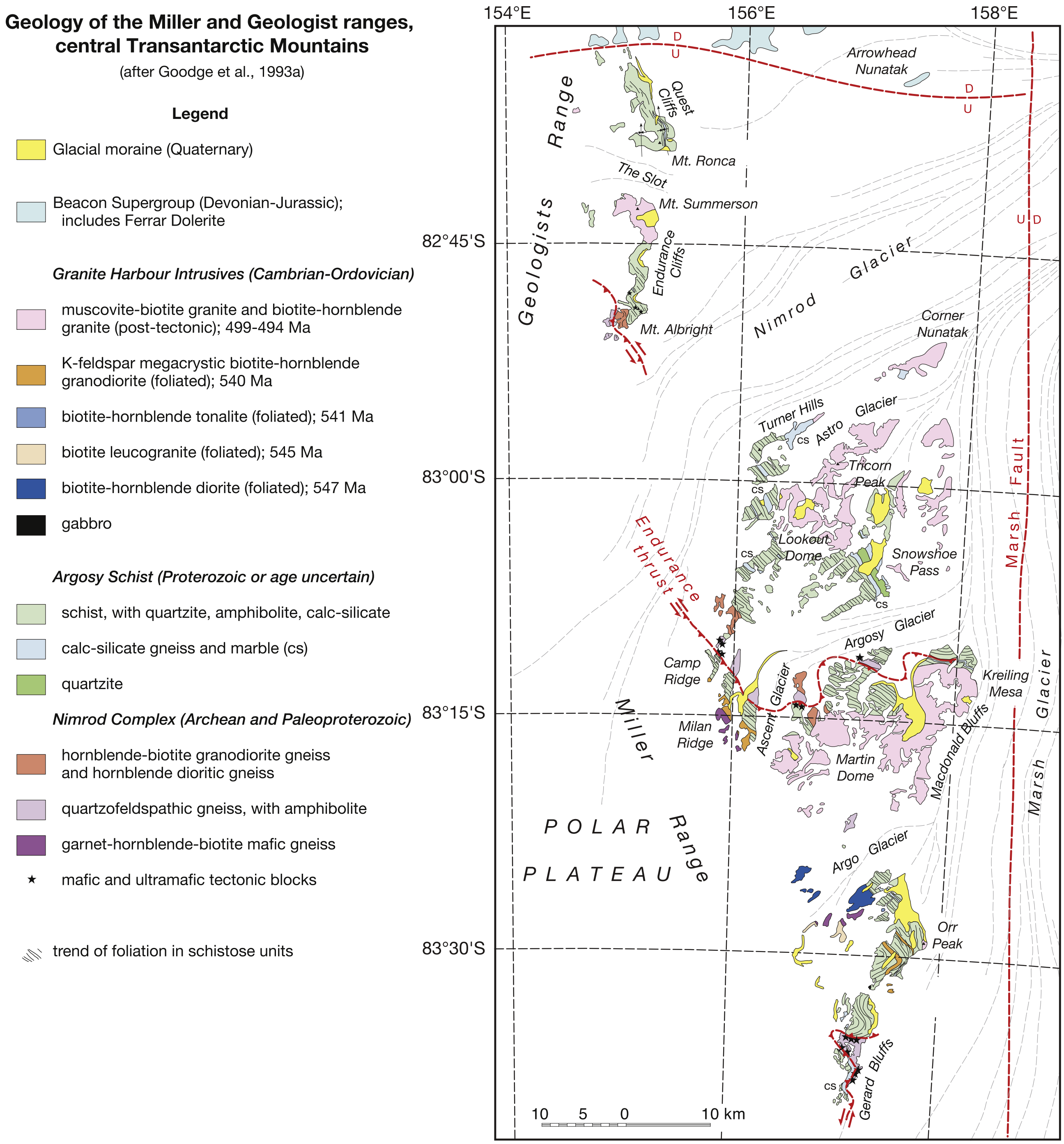


Fig. 13. Geologic map of the Miller and Geologists ranges, showing distribution of Nimrod Complex, associated rocks of the Argosy Schist unit, and igneous rocks of the Granite Harbour Intrusive suite. After Goodge et al. (1993a) and Goodge and Fanning (2016).

As summarized by Myrow et al. (2002b), archaeocyathan-bearing rocks from the Shackleton Limestone were collected during Ernest Shackleton's ill-fated 1908–1909 expedition, but extensive study did not begin on this formation until much later (e.g., Laird et al., 1971; Rees et al., 1989). The archaeocyathans indicate a Botomian (Russian system, Cambrian Series 2) depositional age for at least part of the formation (Debrenne and Kruse, 1986). Trilobite fauna described by Rowell et al. (1988a) and Palmer and Rowell (1995) confirmed a Botomian age but suggested that some deposits are Atdabanian and that younger parts were possibly deposited in the Toyonian. Nearly all of the trilobites have close affinities with Chinese forms of the Tsanglangpuan Stage, which largely overlaps the Botomian Stage. Carbonate units in the Queen Maud Mountains that are considered equivalents of the Shackleton Limestone also contain Botomian and possible Atdabanian trilobites and archaeocyathans (Rowell et al., 1997).

Detailed reconstruction of paleoenvironments and depositional history of the Shackleton Limestone is hampered by locally severe deformation and numerous fault contacts. The depositional setting of the formation in the Byrd-Nimrod region was first interpreted as a simple ramp with intertidal facies passing laterally into a high-energy oolitic shoal complex containing many individual archaeocyathan bioherms (Rees et al., 1989); no basinal facies were reported. Deposits of the oolitic shoal facies are laterally extensive and commonly include small

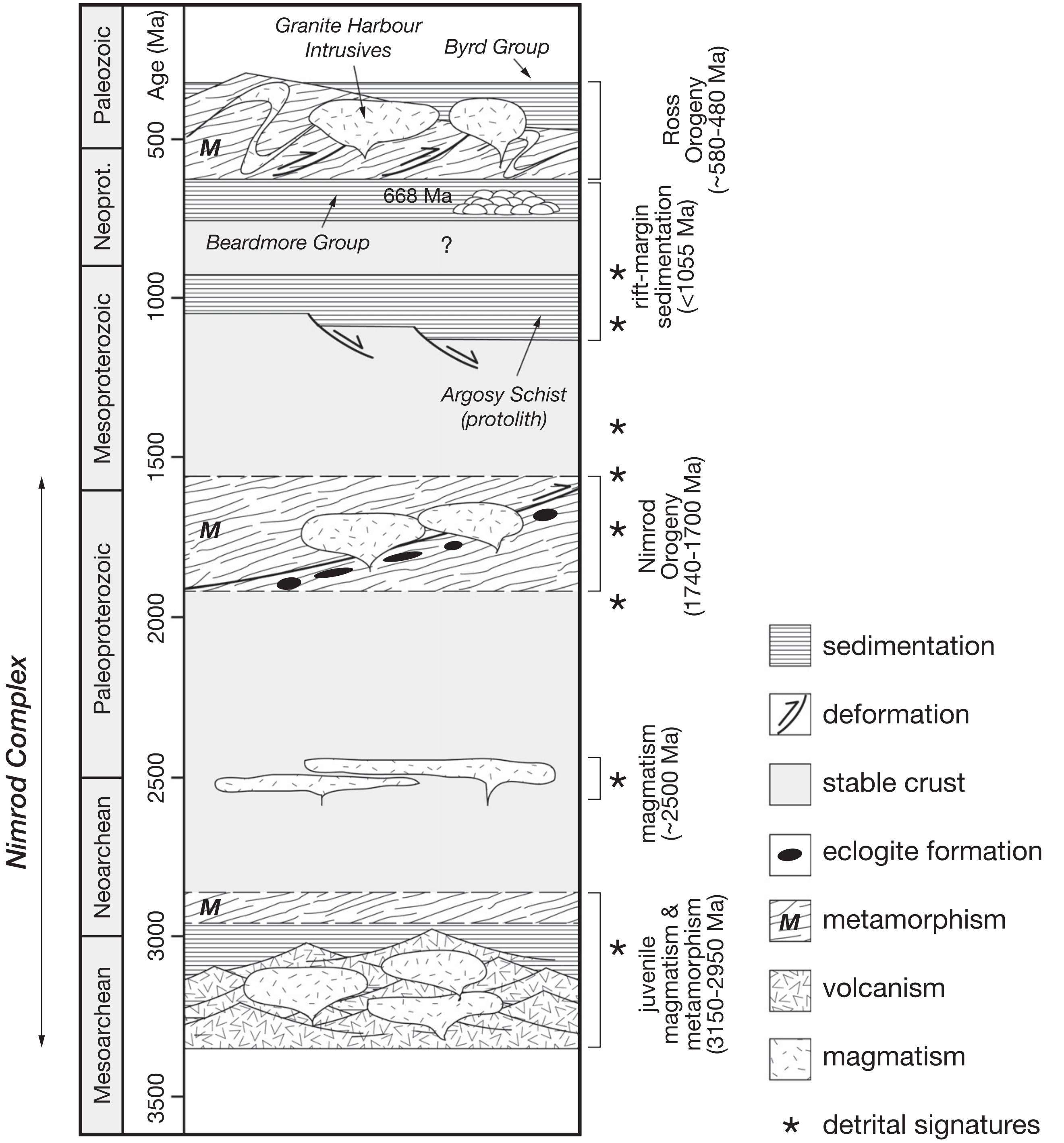


Fig. 14. Schematic geologic history of the Nimrod Complex and associated units in the central Transantarctic Mountains, showing major events recorded by geologic relationships and geochronology (after Goodge and Fanning, 2016). Note that the time span shown by geologic patterns in the graphic log is greater than the actual duration of these events, as indicated by age brackets in the right-hand legend.

algal-archaeocyathan bioherms. The bioherms were locally ecologically zoned as a function of depositional energy and in cases coalesced to form composite bioherm complexes up to 50 m thick. Burrow-mottled mudstone and skeletal or peloidal packstone were interpreted as shallow-water, low-energy deposits formed on either side of the oolite shoal complex (Rees et al., 1989). However, stratigraphic position, lithologic characteristics, and facies relationships suggest that these deposits are entirely deeper subtidal in origin and formed basinward of the oolite shoal complex.

More recent stratigraphy and sedimentology in the vicinity of Nimrod Glacier reveals important details of the depositional history of the lower Paleozoic succession prior to and during Ross deformation (Myrow et al., 2002b). In the Holyoake Range (Fig. 12), carbonates of the upper Shackleton Limestone consist of nodular subtidal carbonates passing upward into isolated and eventually composite algal bioherms formed in a deep subtidal setting outboard from a localized oolitic shoal complex. The bioherms in turn are capped by phosphate-encrusted surfaces formed during early cementation of the bioherms

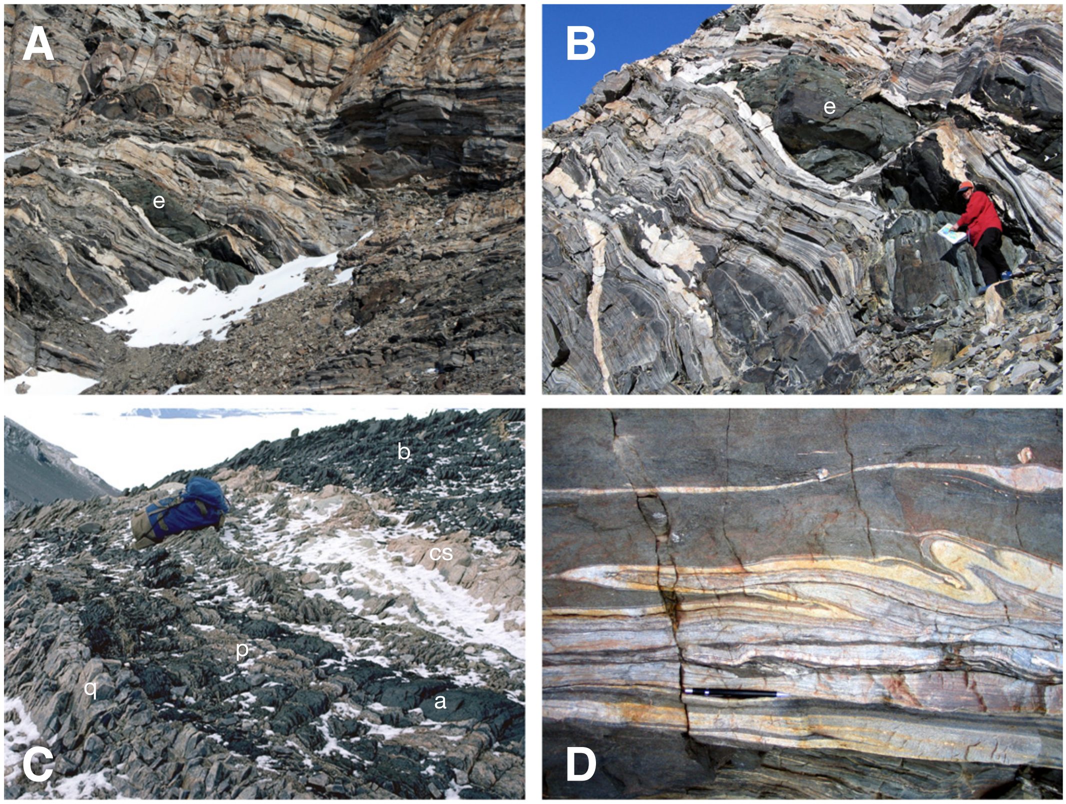


Fig. 15. Representative rocks in the Nimrod Complex and Argosy Schist. (A) Layered gneisses and amphibolites in quartzofeldspathic gneisses at Camp Ridge, western Miller Range. Dark lens-shaped features are mafic eclogites (e) of ~1.72 Ga age, formed during the Paleoproterozoic Nimrod Orogeny (Peacock and Goodge, 1995; Goodge et al., 2001). Outcrop height is about 25 m. (B) Same outcrop as in (A), showing layered gneisses in detail, with ellipsoidal bodies of dark eclogite and cross-cutting veins of aplite and pegmatite. (C) Heterogeneous metasedimentary units of the Argosy Schist at Aurora Heights in the central Miller Range, north of Argosy Glacier. Lithologies include, from left to right, quartzite (q), mixed pelitic schist (p) and amphibolite (a), light-colored calc-silicate gneiss (c), and biotite schist (b). (D) Tightly folded layered schists at Greene Ridge in the central Miller Range, south of Argosy Glacier. Folds and related kinematic features within schistose and gneissic rocks formed mainly during the Cambro-Ordovician Ross Orogeny (Goodge et al., 1993a).

that represents a complex submarine hardground. Directly above this hardground are interbedded nodular carbonate and shale, interpreted as a deep-water facies representing a response to shoaling by deposition of calcareous siltstone. This latter assemblage was defined by Myrow et al. (2002b) as the Holyoake Formation (Fig. 19) and represents a key transition into siliciclastic deposition following termination of a stable carbonate platform. The Holyoake beds in turn pass upward into a thick succession of feldspathic arenite, siltstone, pebble sandstone and shale of the Starshot Formation (Fig. 23; Laird, 1963; Laird et al., 1971, and redefined by Myrow et al., 2002b), interpreted as having been deposited in nearshore to shoreline environments. Sandstone beds commonly display hummocky cross-stratification, possibly representing storm-generated deposits (Fig. 23A), and local convolute bedding indicates post-depositional slope instability (Fig. 23D). In other cases, pebbly units have many of the characteristics of debris flow deposits, such as matrix support and lack of grading, and likely formed as shallow-marine debris flows.

The Starshot Formation is complexly interfingered with diverse units of the Douglas Conglomerate (Rees et al., 1988; Rowell et al., 1988b), consisting of interbedded conglomerate, coarse sandstone, and silty shale (Myrow et al., 2002b). Depositional features, paleocurrents, and conglomeratic facies relationships indicate that the Douglas was deposited in an alluvial-fan setting that prograded outward into a shallow-marine basin (Rees et al., 1988; Myrow et al., 2002b). The bed thickness and coarse grainsize (cobbles and boulders, including large outsized meter-scale blocks locally derived from the Shackleton Limestone) of the conglomerate indicate proximal deposition due to local tectonic uplift and erosion of the Shackleton Limestone. As shown in Fig. 19, the lower Paleozoic stratigraphy for the central TAM provides a significant new framework for understanding tectonic development of the Ross Orogen, in which pre-Ross platform and ramp deposition of carbonate is rapidly terminated by onset of fine clastics giving way to upward-coarsening and thickening molasse deposits. Interruption of carbonate deposition by phosphate precipitation just at the onset of siliciclastic deposition, marked by a coarsening- and thickening-upward succession that is eventually overridden by an alluvial-fan complex, indicates that the Shackleton Limestone was tectonically drowned by tectonic loading of thrust plates with west-over-east vergence, then overlain by a prograding wedge of syn-orogenic molasse deposits. Detrital zircon signatures within the Starshot and Douglas formations show that these clastic units are indeed dominated by Ross-age igneous material (Goodge et al., 2002, 2004a, 2004b), reflecting erosion of the Ross magmatic arc to form these deposits.

In the Shackleton Glacier area, siliciclastic, volcanic, and carbonate rocks (Greenlee Formation, Taylor Formation and Hensen Marble, respectively) comprise the late Neoproterozoic to early Paleozoic succession. The Greenlee Formation is dominated by fine-grained siliciclastic rocks with limestone near the top; although commonly considered to be Neoproterozoic in age, there is no direct evidence of depositional age and it could be correlative with the Starshot Formation (upper Byrd Group). The Taylor Formation consists of ashfall and pyroclastic tuff units, along with felsic and mafic volcanic flow units and marbles (Wade and Cathey, 1986); some of the phyric tuff units may correlate with the Wyatt Formation (see below). The Taylor Formation is Middle Cambrian in age, based on fossils in limestone beds and U—Pb zircon ages of ~505 Ma in tuffaceous units (Yochelson and Stump, 1977; Van Schmus et al., 1997; Encarnación et al., 1999).

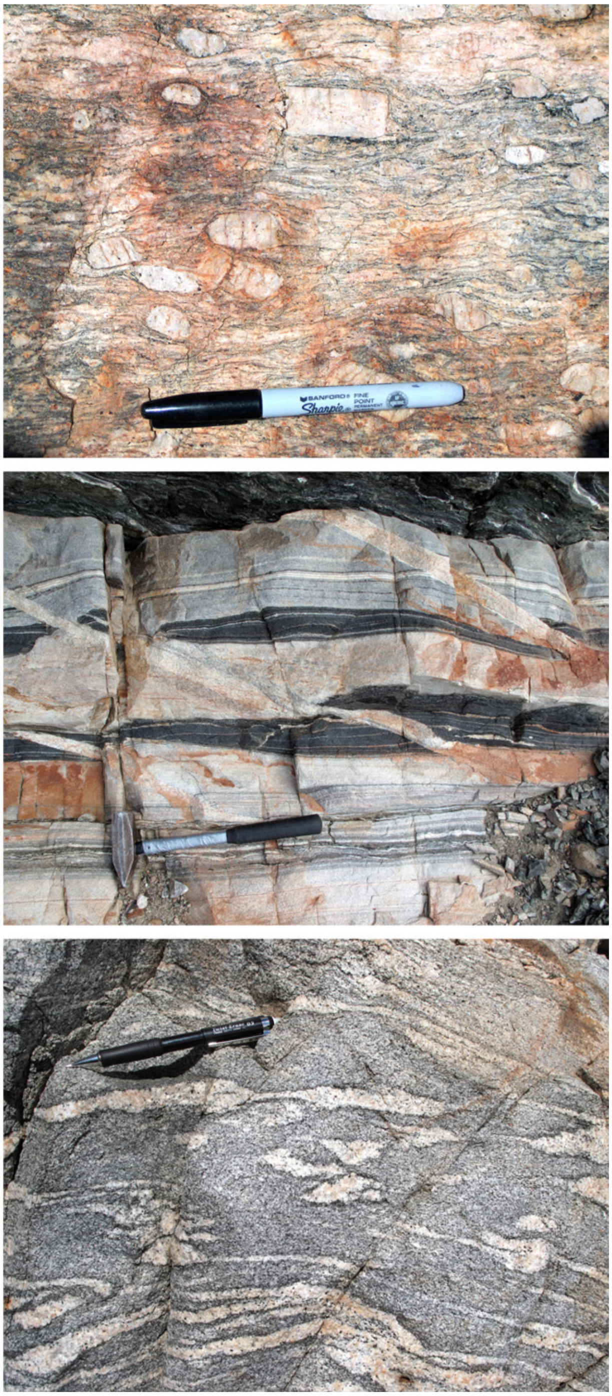


Fig. 16. Representative syn-tectonic igneous rocks emplaced within Nimrod Complex and related units during the Ross Orogeny. (A) K-feldspar megacryst-bearing granodioritic orthogneiss exposed at Milan Ridge near the Ascent Glacier in the central Miller Range. (B) Variety of syn-tectonic aplitic dikes both parallel to and discordant with gneissic layering in the Nimrod Complex. The leucocratic dikes have variable degrees of tectonite fabrics formed during movement associated with the Ross Orogeny. (C) Massive hornblende-rich diatexite-type migmatitic gneiss showing bodies and veins of feldspar-rich leucosome material decorated by dark mineral concentrations, probably formed by anatexis of Nimrod Complex gneisses during the Ross Orogeny.

3.4.4. Southern TAM

The geology of the southern TAM, generally less accessible than other areas due to the remoteness from fixed research stations, is represented by the Queen Maud Mountains extending south of Shackleton Glacier to beyond Scott Glacier (Fig. 24). Lower Paleozoic rocks in the southern TAM are most simply divided into siliciclastic metasediments (La Gorce and Duncan formations) and felsic volcanics and volcaniclastic rocks (Liv Group). This area is unique relative to other parts of the TAM in that volcanic rocks are a prominent feature of the early Paleozoic geology, providing an opportunity to study volcanic processes related to development of the Ross orogenic arc system.

Near Liv and Scott glaciers, the La Gorce Formation is comprised by interlayered meta-arenite and slate, and it represents one of the main metasedimentary units of the southern TAM (Stump, 1995). La Gorce protoliths consist of interbedded greywacke, mudstone and laminated sandy siltstones (Smit, 1981; Smit and Stump, 1986), locally showing graded bedding, conglomeratic beds, channels, and scours. Bouma sequences are also known but somewhat uncommon, indicating deposition in part by turbidite flows. These rocks are strongly folded and exhibit low-grade metamorphic assemblages, long interpreted to reflect a Neoproterozoic age based on correlation with the Beardmore Group. However, the sedimentary characteristics and structural style are similar to rocks of the Starshot Formation in the central TAM (see above), and their detrital zircon provenance signatures also indicate that these rocks have an early Paleozoic depositional age (youngest detrital zircon age populations ~550 Ma; Vogel et al., 1999). Thus, these strata are more likely Middle Cambrian to Ordovician in age. Intrusion of folded La Gorce formation by hypabyssal units of the Wyatt Formation (see below) indicates that deformation was older than ~526 Ma. Sandstones from the Duncan Formation likewise contain detrital zircons indicating a maximum depositional age of ~563 Ma (Paulsen et al., 2015).

The Liv Group is exposed discontinuously between Shackleton and Leverett glaciers. It is a diverse assemblage of Early to Middle Cambrian volcanic, volcaniclastic, clastic and carbonate rocks (Rowell and Rees, 1989; Rowell et al., 1997; Wareham et al., 2001), including the Wyatt and Ackerman formations (silicic volcanics formed in extensional basins associated with subduction-zone magmatism) and a younger association of bimodal volcanic rocks (Taylor, Fairweather and Leverett formations; Wareham et al., 2001). Although formerly considered to be Neoproterozoic in age (Stump, 1982), U—Pb geochronology indicates the Wyatt and Ackerman formations are Early Cambrian (Encarnación and Grunow, 1996). The Wyatt is a quartz- and plagioclase-phyric dacite porphyry, often massive but locally showing a weak foliation or alignment of light-colored lenses that may represent flattened pumice (Borg, 1980). Geochemically, they are dacites (Stump et al., 1986), consistent with a continental-margin arc setting. Although the Wyatt is strongly recrystallized and texturally homogeneous, it is thought to represent a pyroclastic volcanic deposit of eruptive origin (Minshew, 1967; Murtaugh, 1969; Borg, 1980; Stump et al., 1986). However, some parts of the Wyatt may be a hypabyssal intrusion within the volcanic complex, based on cross-cutting intrusive contacts of the Wyatt against the La Gorce Formation. A U—Pb zircon age of 526 Ma confirms an Early Cambrian age of this volcanic unit (Encarnación and Grunow, 1996).

Rocks of the Taylor, Fairweather and Leverett formations are a compositionally distinct bimodal association of basalts and rhyolites erupted between about 490–524 Ma (Van Schmus et al., 1997; Encarnación et al., 1999; Paulsen et al., 2018). Thus, Liv Group volcanism overlapped with emplacement of the early Paleozoic Queen Maud batholith. Trace element and Nd—Sr isotope compositions of the Wyatt and Ackerman formations indicate their magmas formed as partial melts of continental crust with an average age as old as 1.5 Ga. In contrast, compositions of basalts and basaltic andesites of the Taylor, Fairweather and Leverett formations indicate primary melting of asthenospheric mantle (Wareham et al., 2001); associated rhyolites may have formed by a mixture of fractionated mafic melt and partial melting of continental crust. Together, volcanic rocks of the Liv Group are interpreted as having erupted in an extensional setting either within or behind an active volcanic arc associated with the Ross Orogen convergent margin.

In addition to volcanic rocks, these units of the Liv Group also include marble, phyllite, quartzite, argillite and quartzite (Stump, 1982, 1986;

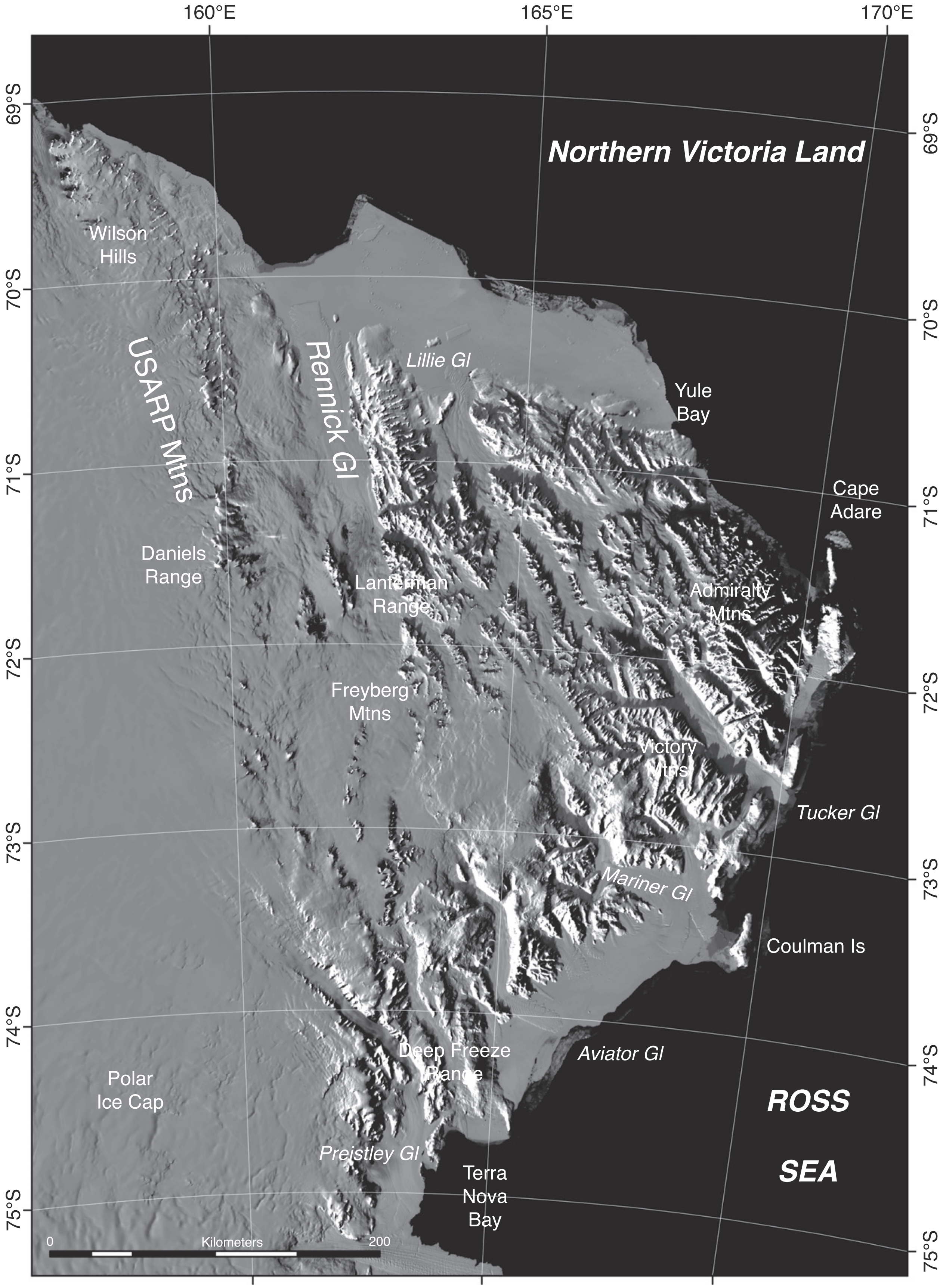


Fig. 17. MODIS image of northern Victoria Land, showing major geographic features.

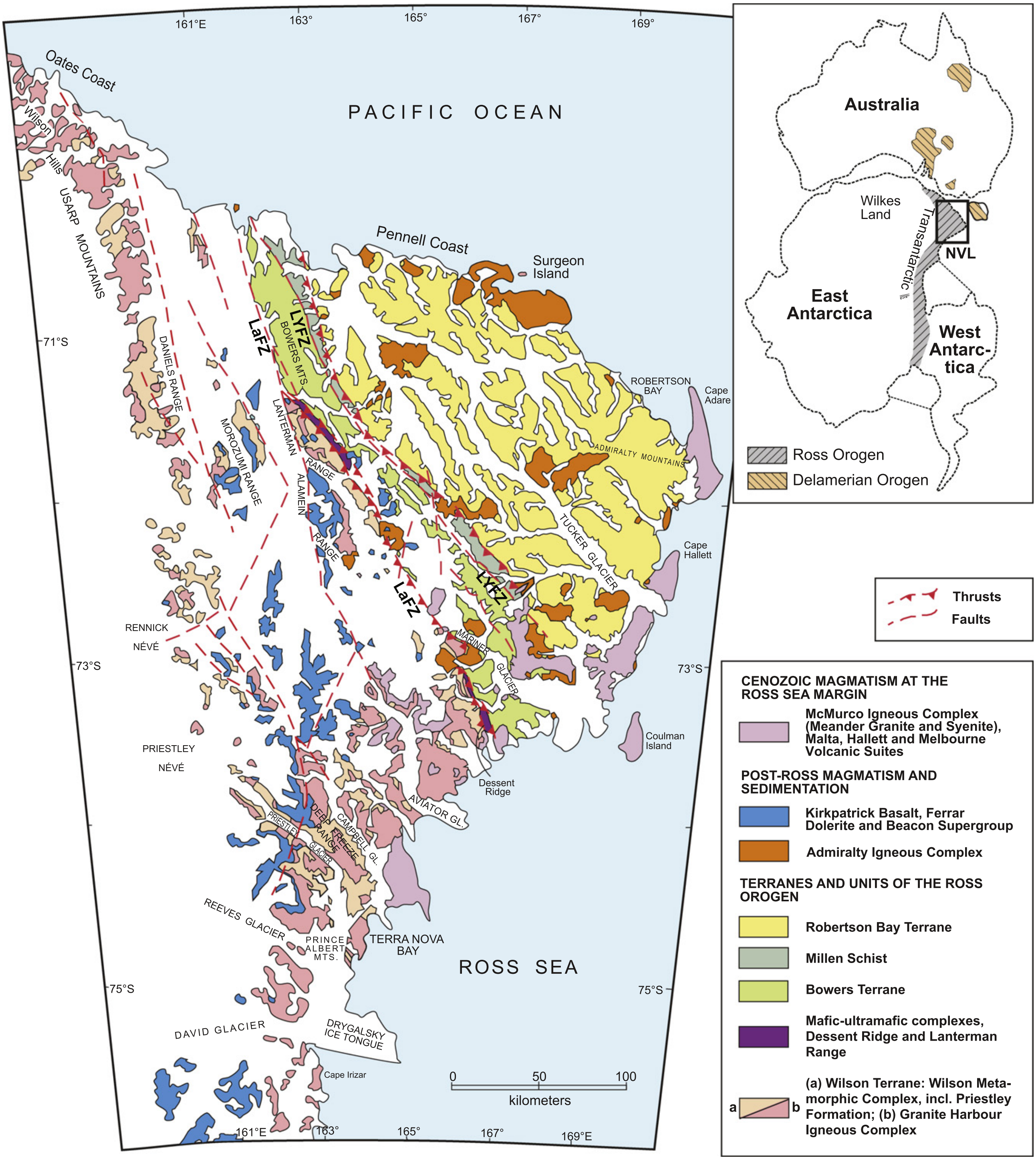


Fig. 18. Tectonic sketch map of northern Victoria Land (NVL; after Estrada et al., 2016, compiled from the German-Italian GIGAMAP program; see Pertusati et al., 2016). LaFZ, Lanterman fault zone; LYFZ, Leap Year fault zone. Inset map shows general location of NVL in context of broader Ross-Delamerian orogens in Antarctica and Australia.

Rowell et al., 1997). Sandstones from the Taylor, Fairweather, and Greenlee formations contain detrital zircons indicating maximum depositional ages of about 560–500 Ma (Paulsen et al., 2015), consistent with Cambrian depositional ages determined for other siliciclastic units in the southern TAM. Hence, these are all Cambrian strata with similar igneous sources. Similarity in detrital age signature between rocks of the Queen Maud area and the central TAM (Byrd Group) indicate that the former share a common provenance and are not exotic with respect to East Antarctica.

3.4.5. Pensacola Mountains

As in the central TAM, thick successions of unfossiliferous, turbiditic sandstone and shale in the Pensacola Mountains (Patuxent Formation) were originally thought to be Proterozoic in age (Schmidt et al., 1964, 1965; Schmidt and Ford, 1969; Storey et al., 1992), predating development of a Middle Cambrian carbonate platform (Schmidt et al., 1965; Storey et al., 1992; Rowell et al., 1992; Evans et al., 2018). However, subsequent studies support subdivision of the siliciclastic succession into distinct siliciclastic and volcanic assemblages that record episodic

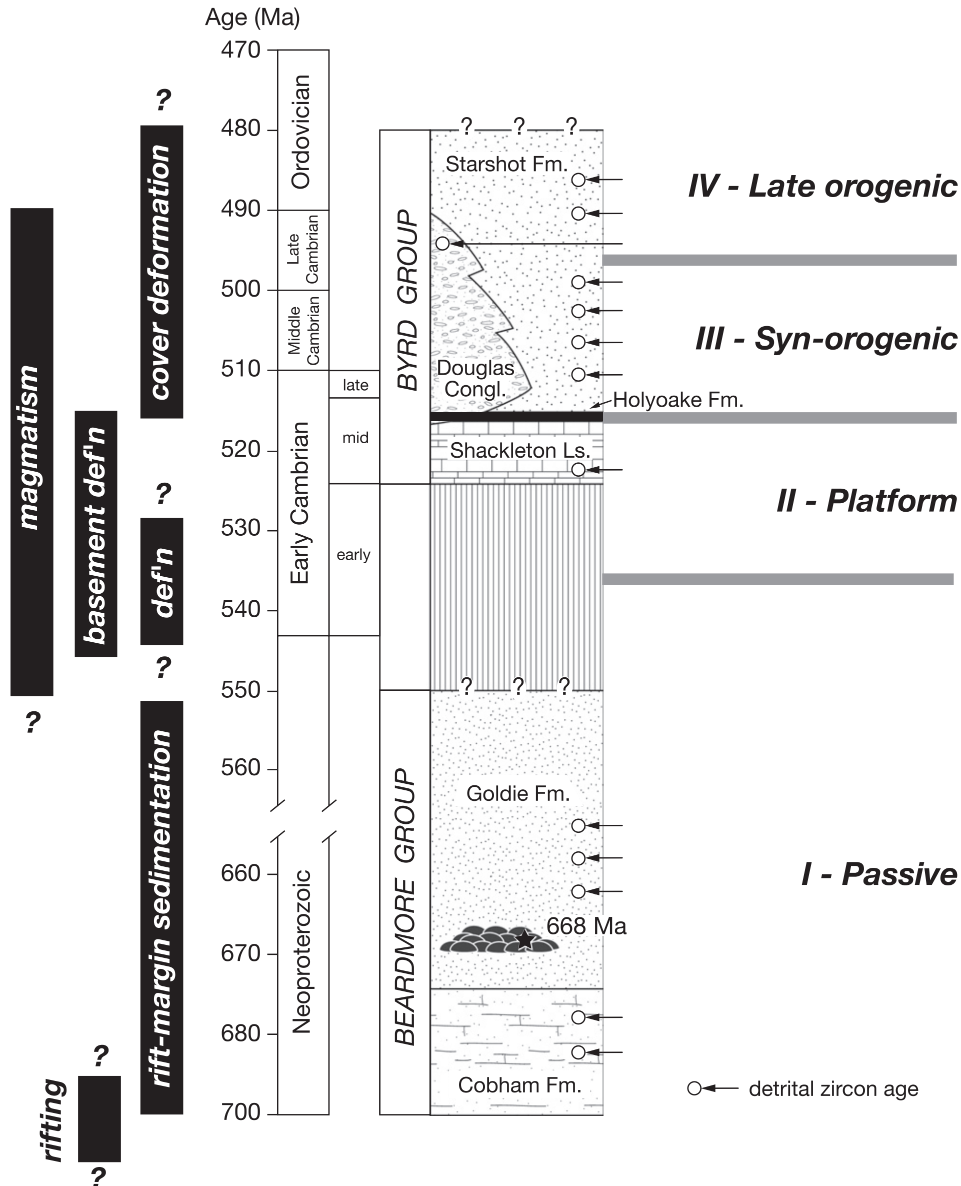


Fig. 19. Stratigraphic relationships in Neoproterozoic and lower Paleozoic sedimentary units of the central Transantarctic Mountains (after Goodge et al., 2004a). Revised stratigraphic relationships (Goodge et al., 2002; Myrow et al., 2002b) indicate passive-margin and platform deposition (stages I and II) through the middle Early Cambrian, when ramp carbonate of the Shackleton Limestone was abruptly overlapped by upward-coarsening siliciclastic deposits of the upper Byrd Group (stages III and IV; Holyoake, Starshot, and Douglas formations). Integration of biostratigraphic, chemostratigraphic, and geochronological data indicate that Shackleton carbonate deposition terminated abruptly ca. 515 Ma (Myrow et al., 2002b). Timespans for geotectonic events in the central Ross Orogen summarized by black bars. Circles indicate units sampled for detrital mineral age determinations (Goodge et al., 2002, 2004a, 2004b).

tectonism, magmatism, and active-margin sedimentation during the Neoproterozoic–Cambrian transition. In this view, the Patuxent is restricted to those strata in the Patuxent Range and Schmidt Hills that are coeval with Late Cambrian (505–500 Ma) volcanic rocks of the Gambacorta Formation and Gorecki Felsite units, and which likely overlie the Middle Cambrian Nelson Limestone (Millar and Storey, 1995; Van Schmus et al., 1997; Rowell et al., 2001). Sandstones from this redefined Patuxent have a single tectonic cleavage and contain detrital zircons as young as ~495 Ma, indicating latest Cambrian or younger deposition. The Patuxent Formation therefore represents deposition in a Late Cambrian to Ordovician basin that was subsequently affected by a younger deformation.

Exposed in the eastern Neptune Range is a succession of similar sandstone and shale that is difficult to distinguish on sedimentological grounds. However, this inboard sandstone unit, named the Hannah Ridge Formation (Rowell et al., 2001), unconformably underlies the Nelson Limestone and contains detrital zircons no younger than ~560 Ma, which indicate that the Hannah Ridge sandstones are distinctly older at about 560–510 Ma. These rocks were affected by at least two deformation phases of the Ross Orogeny, including a Middle Cambrian deformation not observed in the younger, outboard Patuxent rocks (Storey et al., 1992). Detrital zircon age patterns in clastic units from both the Patuxent and Hannah Ridge formations in the Neptune Range indicate Early to Late Cambrian depositional ages (Goodge et al., 2004b), rather than in the Neoproterozoic. Detrital zircons in the Hannah Ridge Formation are as young as ~556 Ma and suggest that this unit is Lower Cambrian in age; in the Patuxent Formation, the youngest grain population is ~495 Ma, restricting the formation to Late Cambrian age. Rowell et al. (2001) inferred that the Hannah Ridge clastics and Schneider Hills Limestone of the Argentina Range are deep- and shallow-water Lower Cambrian facies correlatives, respectively, beneath the Middle Cambrian Nelson Limestone. A preponderance of

Fig. 20. Interbedded quartzites, slates and fine-grained schists in the Beardmore Group (Goldie Formation) at Cotton Plateau, near Nimrod Glacier, central TAM. Note high-angle spaced cleavage in quartzite beds, parallel to pencil, and lower-angle refracted cleavage in the slate beds.

Grenville and Pan-African zircon ages indicate that the Hannah Ridge Formation, despite an Early Cambrian age, might be representative of the East Antarctic passive margin association, rather than a result of syn-orogenic (Ross) deposition.

3.5. Cambro-Ordovician granite batholith

The convergent plate-boundary setting of the Cambrian-Ordovician Ross Orogen produced a volumetrically prolific continental-margin magmatic arc constructed mostly within older Proterozoic to early Paleozoic crust (Figs. 9, 25; Black and Sheraton, 1990; Borg et al., 1987, 1990; Armienti et al., 1990; Allibone et al., 1993a, 1993b; Borg and DePaolo, 1994; Rocchi et al., 1998; Goodge et al., 2012; Hagen-Peter and Cottle, 2016, 2018). Granitoids of this magmatic belt form a widespread batholith and are referred to as the Granite Harbour Intrusive series (after the type locality at Granite Harbour near McMurdo Sound; Gunn and Warren, 1962). The magmatic belt is chiefly calc-alkaline in character, reflecting a convergent-margin origin associated with subduction of paleo-Pacific oceanic lithosphere beneath cratonic East Antarctica, although in some areas it contains unique adakitic, alkaline and A-type magmatism that may indicate slab melting or upper-plate extension (Allibone et al., 1993b; Hall et al., 1995; Allibone and Wysoczanski, 2002; Cottle and Cooper, 2006a; Hagen-Peter and Cottle, 2016). Magmatism is mainly represented by exhumed plutonic bodies at current levels of exposure and only a few areas of the southern Transantarctic Mountains contain coeval felsic volcanic rocks (Van Schmus et al., 1997; Encarnación et al., 1999; Wareham et al., 2001). The magmatic belt was emplaced at all stages of orogenic development, from early pre- to syn-orogenic melts to post-kinematic intrusions (Figs. 26A-D; Goodge et al., 1993b, 2012; Allibone et al., 1993a; Encarnación and Grunow, 1996).

The main phase of calc-alkaline intrusion occurred between about 520–480 Ma. An older suite of alkaline intrusions in the Koettlitz Glacier area of southern Victoria Land (including gabbro, diorite, carbonatite, syenite and A-type granite with ages between about 550–530 Ma) is thought to indicate an early period of crustal (intra-arc?) extension prior to the main phase of Ross Orogen contraction and calc-alkaline magmatism (Rowell et al., 1993; Hall et al., 1995; Encarnación and Grunow, 1996; Cooper et al., 1997; Read et al., 2002; Cottle and Cooper, 2006b; Hagen-Peter and Cottle, 2016), and may signal a change in subduction-zone dynamics. Regional isotopic and geochemical variations in the calc-alkaline granitoids reveal increasing crustal components toward the craton (to the west in local geographic coordinates), best explained by subduction-generated melting beneath an east-facing continental-margin arc (Borg et al., 1987, 1990; Armienti et al., 1990; Rocchi et al., 1998; Goodge et al., 2012). The magmatic series of southern Victoria Land in particular consists of early I-type intrusions, succeeded by increasing levels of crustal contamination and late-stage melt production as a result of Ross orogenic crustal thickening (Allibone et al., 1993b). Calc-alkaline magmatism peaked between ~515–505 Ma in the Dry Valleys area (Cox et al., 2000; Hagen-Peter and Cottle, 2016), and alkali-calcic plutonism persisted until ~490 Ma (Allibone et al., 1993a, 1993b). Sr and Nd isotopic data indicate that granitoid magmagenesis in the central TAM occurred in a convergent continental margin-arc system that may have involved significant melting of older crust (Borg et al., 1990; Borg and DePaolo, 1994; Goodge et al., 2012).

More generally, Ross magmatism was concomitant with tectonic deformation (Cox, 1993; Goodge et al., 1993b, 2012; Allibone et al., 1993a; Rowell et al., 1993; Hall et al., 1995; Jones, 1997; Read and Cooper, 1999; Musumeci, 1999), recording intra-arc displacements through time. Some fabrics in the granitoid belt appear related mostly to the emplacement process (e.g., Allibone et al., 1993a), but in other cases the strains are developed in response to regional orogenic displacement attributed to oblique subduction (e.g., Goodge et al., 1993a, 1993b; Jones, 1997; Musumeci, 1999; Cook and Craw, 2001).

Despite the importance of magmatism in the orogenic process, reliable U—Pb crystallization ages do not exist in many areas, making it difficult to evaluate changing magma compositions, isotopic variations, and their tectonic significance through time. Some areas have received detailed petrologic, geochemical and isotopic study (e.g., the Dry Valleys and related areas of southern Victoria Land; Allibone et al., 1993a, 1993b; Encarnación and Grunow, 1996; Cooper et al., 1997; Cox et al., 2000; Allibone and Wysoczanski, 2002; Read et al., 2002; Cottle and Cooper, 2006a, 2006b; Hagen-Peter and Cottle, 2016, 2018), whereas many broader regions have been studied in less detail. In the central TAM, for example, there was until recently (Goodge et al., 2012) very poor age control despite being the focus of important early isotopic study (Gunner, 1976; Borg et al., 1990).

U—Pb ages for most calc-alkaline intrusions in the Ross Orogen are between about 520–480 Ma (Cambrian to Early Ordovician), yet the age of earliest Ross magmatism is difficult to determine because the belt is deeply eroded beneath a Gondwanide overlap succession and further covered by young glacial deposits and the modern ice cap across inboard segments of the Transantarctic Mountains. Questions thus remain concerning the initiation of Ross magmatism and its geochemical evolution over time. The oldest dated intrusion ages are ~550 Ma from granite and quartz syenite exposed near Skelton Glacier (Rowell et al., 1993; Encarnación and Grunow, 1996), indicating that early plutonism may have been alkaline in character. Intrusions in several areas of southern Victoria Land and the central TAM yield ages between about 545–530 Ma (Goodge et al., 1993b; Hall et al., 1995; Cooper et al., 1997; Mellish et al., 2002; Read et al., 2002; Cottle and Cooper, 2006a; Stump et al., 2006), reflecting ongoing magmatism through the Early Cambrian. Dated granitoids in the well-studied Dry Valleys region track a continuous evolution from early alkaline, to adakitic, calc-alkaline (main phase), and late alkali-calcic magmatism by ~480 Ma (Allibone and Wysoczanski, 2002). Many of the intrusions emplaced between about 550–530 Ma have A-type or alkaline geochemical compositions, possibly signifying extension and lower-crustal melting in the continental-margin arc environment (Cottle and Cooper, 2006a).

Geochronology of calc-alkaline granitoids exposed in southern Victoria Land and the central TAM indicates that subduction was initiated by at least 550 Ma (e.g., Rowell et al., 1993; Goodge et al., 1993b; Cox et al., 2000; Allibone and Wysoczanski, 2002; Cottle and Cooper, 2006a; Hagen-Peter and Cottle, 2016). However, lower Paleozoic syn- to post-orogenic, molasse-type siliciclastic rocks contain significantly older populations of locally-derived detrital igneous zircons (Goodge et al., 2002, 2004a; Paulsen et al., 2015), indicating that volumetrically significant magmatism was underway by at least 600 Ma. Detrital

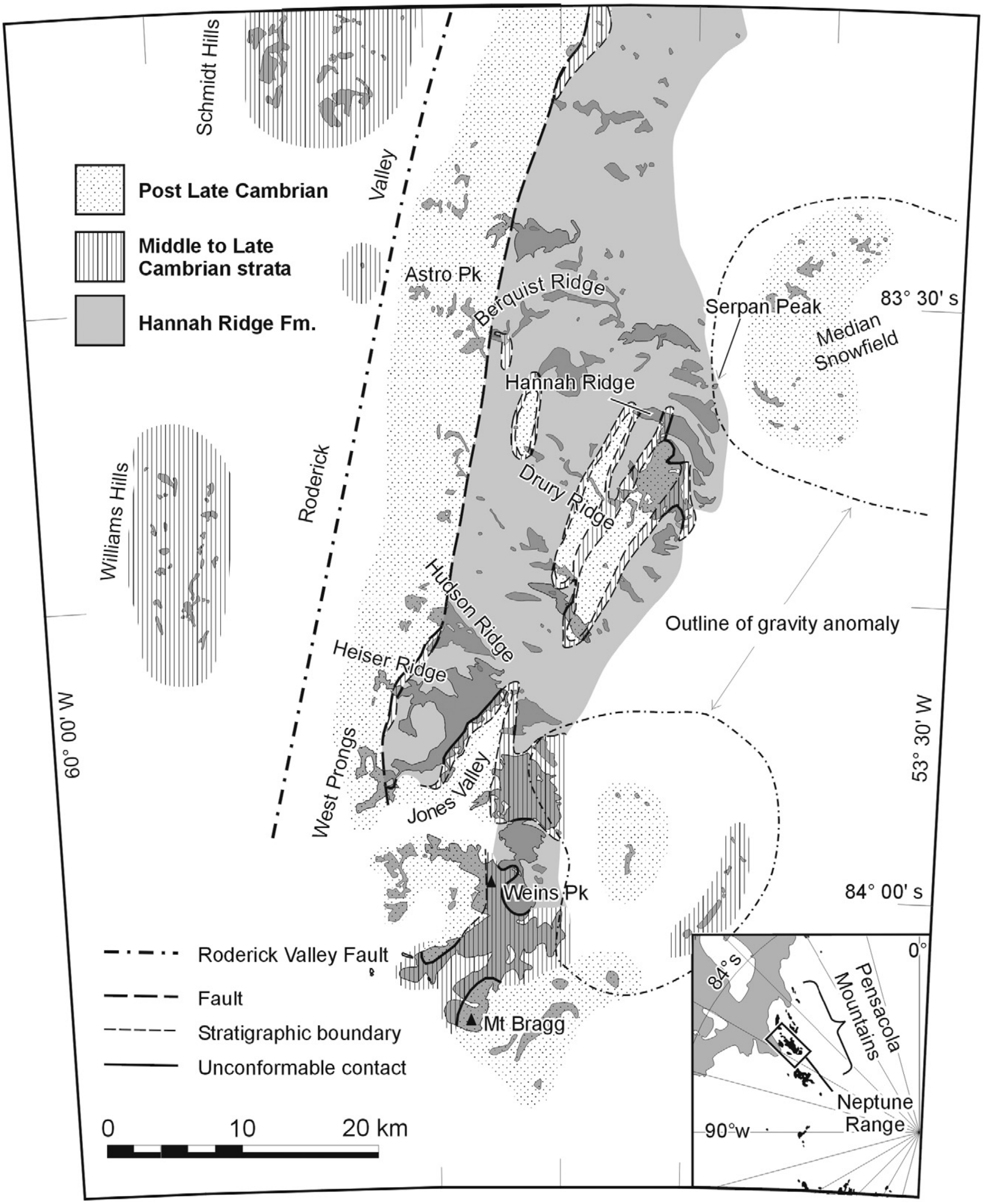


Fig. 21. Simplified geologic map of the Neptune Range, Pensacola Mountains, highlighting outcrops of the Hannah Ridge Formation, plus Cambrian and post-Late Cambrian successions (from Curtis et al., 2004).

muscovite ages confirm a Ross Orogen source for these young molassic deposits (Goodge et al., 2004a). Dating of glacially-eroded granitoid erratics collected from the Nimrod Glacier catchment with ages of 590–565 Ma likewise indicate an early start to Granite Harbour magmatism (Goodge et al., 2010, 2012). As inferred from the detrital zircon compositions, it appears that early magmatic components of the Ross arc were eroded and deposited in forearc-basin successions, yet initiation of convergent-margin magmatism by ~590–600 Ma fits well with the timing of Pan-African orogenesis related to Gondwana amalgamation (see Goodge, 1997; Cawood, 2005). Based on the known ages of Ross magmatism, subduction initiation therefore occurred by ~600 Ma, following Neoproterozoic rifting of the Austral-

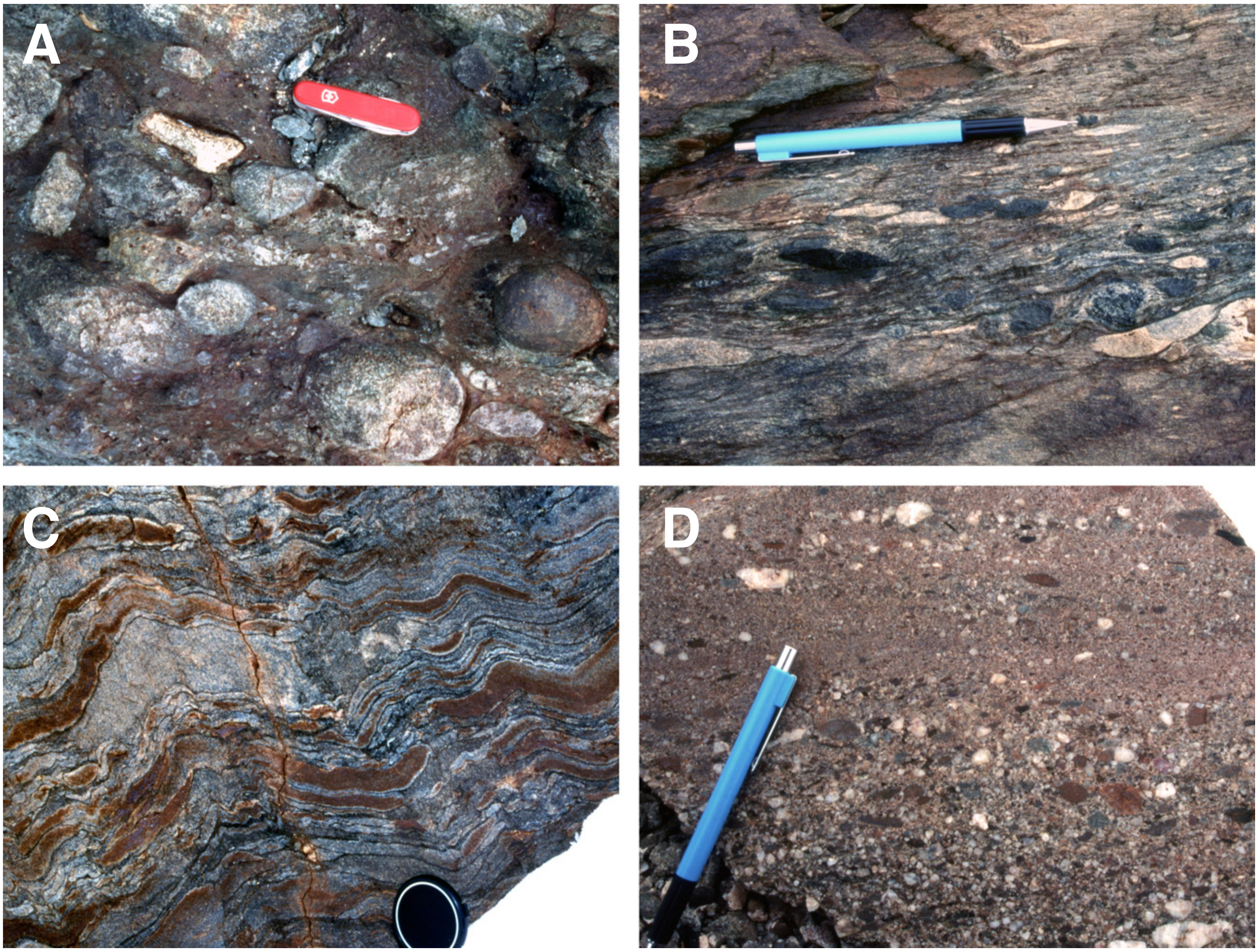


Fig. 22. Conglomeratic unit associated with Ross tectonism in northern Victoria Land. (A) Polymict Husky Conglomerate in Lanterman Range, dominated by mafic and felsic volcanic clasts. (B) Flattened clasts within deformed Husky Conglomerate. (C) Flattened and folded lenticular clasts in the Lanterman Conglomerate, northeast Lanterman Range. (D) Pebble to granule conglomerate of the Molar Formation, Lanterman Range near Sledgers Glacier.

Antarctic margin, dated to between about 680–585 Ma (Preiss, 2000; Foden et al., 2001; Goodge et al., 2002; Direen and Crawford, 2003).

3.6. Devonian magmatism

A temporally and geochemically distinctive suite of early Paleozoic granitoids, the Admiralty Intrusives, occurs only in northern Victoria Land. Originally described by Harrington (1958) and Harrington et al. (1964, 1967), these plutonic rocks intrude both the Bowers and Robertson Bay terranes. It is a calc-alkaline to calcic suite that varies from granodiorite to tonalite and diorite, and they have mainly I-type affinity. Geochemical compositions and correlation with similar intrusions in Marie Byrd Land (Pankhurst et al., 1998; Yakymchuk et al., 2015) indicate that magmatic-arc activity was tied to subduction outboard of contemporaneous craton-margin sedimentary basins (Elliot, 2013). The Admiralty intrusions are distinguished by their epizonal, post-tectonic character (Vetter et al., 1983). K—Ar and Rb—Sr whole rock-mineral isochron ages show that the Admiralty suite is considerably younger than the Granite Harbour Intrusives (ages of about 380–390 Ma; Vetter et al., 1983; Stump, 1995), but to date there are no published U—Pb zircon constraints on emplacement age. The Admiralty suite shows Sr- and Nd-isotope patterns that indicate a distinct crustal source beneath the Bowers and Robertson Bay terranes (Borg et al., 1987), but the relationship of this crustal block to East Antarctica is uncertain. The variations in isotopic composition indicate greater proportion of more evolved continental crust toward the east, interpreted to indicate that accretion of the Robertson Bay terrane occurred by impingement of a distinct crustal block against East Antarctica as a result of east-directed subduction, thereby generating the Admiralty magmas (Borg et al., 1987).

An areally-limited exposure of rhyolitic ignimbrites occurs at Gallipoli Heights near the Freyberg Mountains and other areas in northern Victoria Land. This volcanic unit is thought to be related to the Admiralty igneous complex and overlaps each of the older terranes. A zircon U—Pb age of 356 Ma reported by Fioretti et al. (2001) indicates that it is contemporaneous, if not cogenetic, with the Admiralty intrusives.

3.7. Gondwana sequence

Ross Orogen tectonic activity diminished through the Early Ordovician period, in most areas by about 480–470 million years ago. During the Ordovician, the TAM occupied a narrow equatorial to subtropical range of paleolatitudes from about 0–20°S (Torsvik and Cocks, 2017), providing a paleoenvironment suitable for intensive weathering and erosion. Prolonged denudation beginning in the Middle Ordovician reduced the Ross mountain belt to a continent-wide erosional surface of low relief, called the Kukri Erosion Surface (Isbell, 1999). This surface is well exposed in many places as an unconformity that separates basement rocks below from sedimentary and volcanic successions of the Beacon Supergroup above. It is an easily identifiable marker used to determine the magnitude of younger differential uplift.

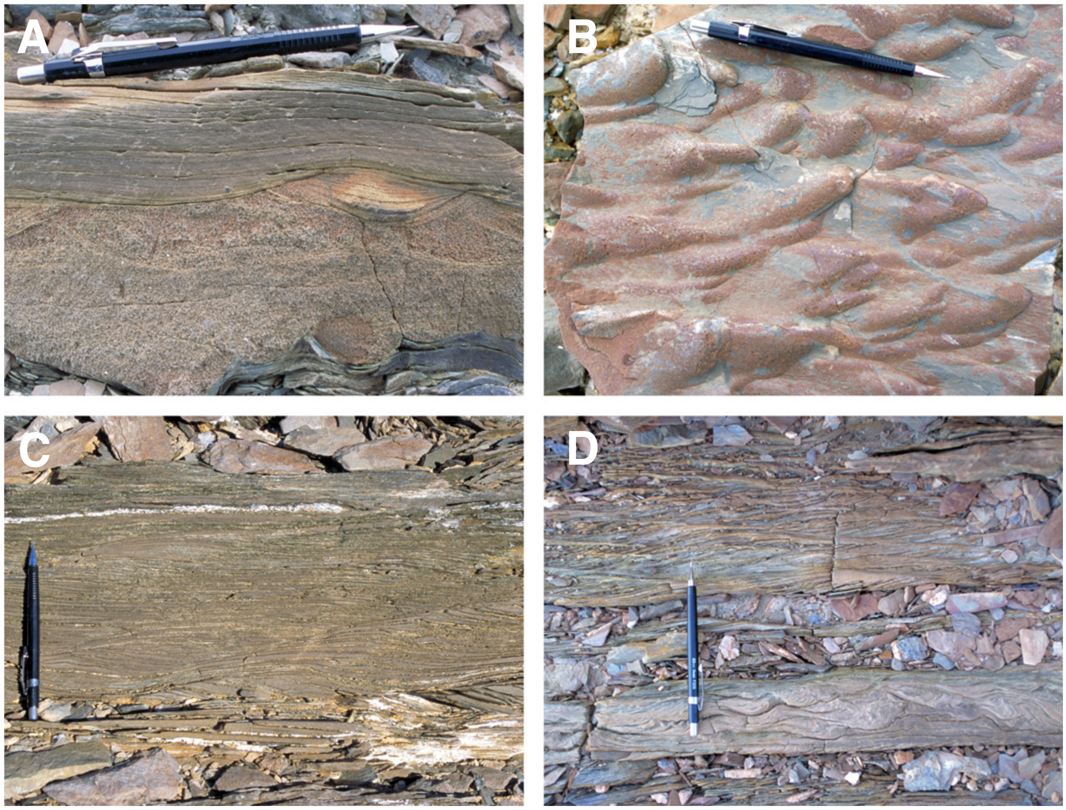


Fig. 23. Sedimentary structures in Starshot Formation. (A) Hummocky cross-beds in interbedded coarse sandstones and siltstones near Mt. Ubique, Starshot Glacier area, indicating storm deposition (Myrow et al., 2002a). (B) Flute casts near Mt. Ubique, Starshot Glacier area, indicating current direction (here right to left). (C) Climbing ripples in fine-grained sandstone near Errant Glacier, central TAM. (D) Climbing ripples (top) and convolute beds (bottom) in fine-grained sandstones near Masquerade Ridge, Lowery Glacier area. Convolute bedding indicates down-slope soft-sediment movement after deposition due to gravity instability, perhaps triggered seismically.

By Devonian time, the TAM sector of East Antarctica was tectonically quiet and paleogeographically situated in a more temperate position between about 30–60°S latitude (Torsvik and Cocks, 2017) while beginning a slow southward drift. In the Carboniferous, East Antarctica and the other Gondwana continents started more rapid polar movement to higher latitudes; the TAM sector reached latitudes of about 65–80°S in the Carboniferous and continued a southward migration through the Permian and Triassic periods to higher latitudes of about 75–90°S such that by ~280 Ma the TAM were situated over the South Pole, remaining in a polar to subpolar position until ~250 Ma. During this slow southward drift of ~60° between Devonian and Early Jurassic time (at least 170 million years), about 2500–3000 m of terrestrial sediment, mostly clastic sequences of quartz-rich fluvial conglomerate, sandstone and mudstone, were deposited. These Beacon Supergroup strata are widespread, extending from northern Victoria Land through the TAM to the Ohio Range of the Horlick Mountains, and beyond to the Pensacola Mountains and Shackleton Range (Fig. 27). This well-known mid-Paleozoic to lower Mesozoic Gondwana sequence includes Devonian to Carboniferous(?) shallow-marine and nonmarine clastics, Upper Carboniferous(?) to Lower Permian glacial and glacial-marine rocks, Lower Permian marine, deltaic, fluvial and lacustrine rocks, Upper Permian fluvial, lacustrine, and deltaic coal measures, and a thick succession of Triassic fluvial rocks and Early Jurassic volcaniclastics (Figs. 28, 29; see McKelvey et al., 1970; Collinson et al., 1994; Barrett, 1991; Elliot, 1996, 2013, Schöner et al., 2007; Bradshaw, 2013; see also Faure and Mensing, 2011). Correlative successions extend from South America to Australia, Africa and India, suggesting a broad network of terrestrial basins (Veevers and Powell, 1994; Veevers, 2004).

Between Devonian and Jurassic time, the Beacon succession is dominated by clastic sedimentary rocks, deposited mainly in intracratonic and foreland basins, and varying from cratonic to magmatic arc provenance (Fig. 28). Basal Devonian strata consist mainly of nonmarine sandstones and siltstones deposited in subsiding intracratonic basins overlying Ross Orogen basement and having a cratonic provenance. Early Permian glacial and glacial-marine deposits with cratonic provenance were succeeded by a Middle to Late Permian succession of fluvial-deltaic and siliciclastic platform strata within interconnected intracratonic basins, which by Late Permian to Triassic time evolved into a widespread, axial foreland basin system along the present-day TAM margin of East Antarctica and having a dominantly arc provenance (Fig. 28; Collinson et al., 1994; Veevers, 2004; Elliot and Fanning, 2008; Elliot, 2013; Elliot et al., 2015). Folded Permian strata in the Ellsworth and Pensacola mountains were probably on the outer margin of this foreland basin. Upward into the Lower Jurassic section, the sediments are dominated by fluvial braidplain deposits of reworked siliciclastic material with both Jurassic arc and cratonic sources. These strata mark the transition from a compressional-type foreland basin succession to an active extensional basin dominated by input of volcaniclastic material. They also serve as the substrate to Jurassic volcanic and volcaniclastic rocks of the Kirkpatrick Basalt series, erupted onto a terrestrial landscape.

Beacon strata contain rich plant, invertebrate, vertebrate and trace fossil assemblages critical for paleogeographic and paleoenvironmental reconstructions marking the end of major glaciations on the Pangea supercontinent. Distinctive paleoenvironmental indicators such as coal beds, tillites (glacigenic deposits), and plant and vertebrate fossils have long been used for correlation of Beacon with coeval successions in other Gondwana continents. Beacon strata include Permian and early Triassic fluvial and lacustrine deposits containing extensive *Glossopteris* leaf-litter beds, petrified forests, and fossil crayfish and burrows, indicating a high-latitude terrestrial environment with freshwater habitats fed by glacial meltwater (Babcock et al., 1998; Isbell et al., 2001;

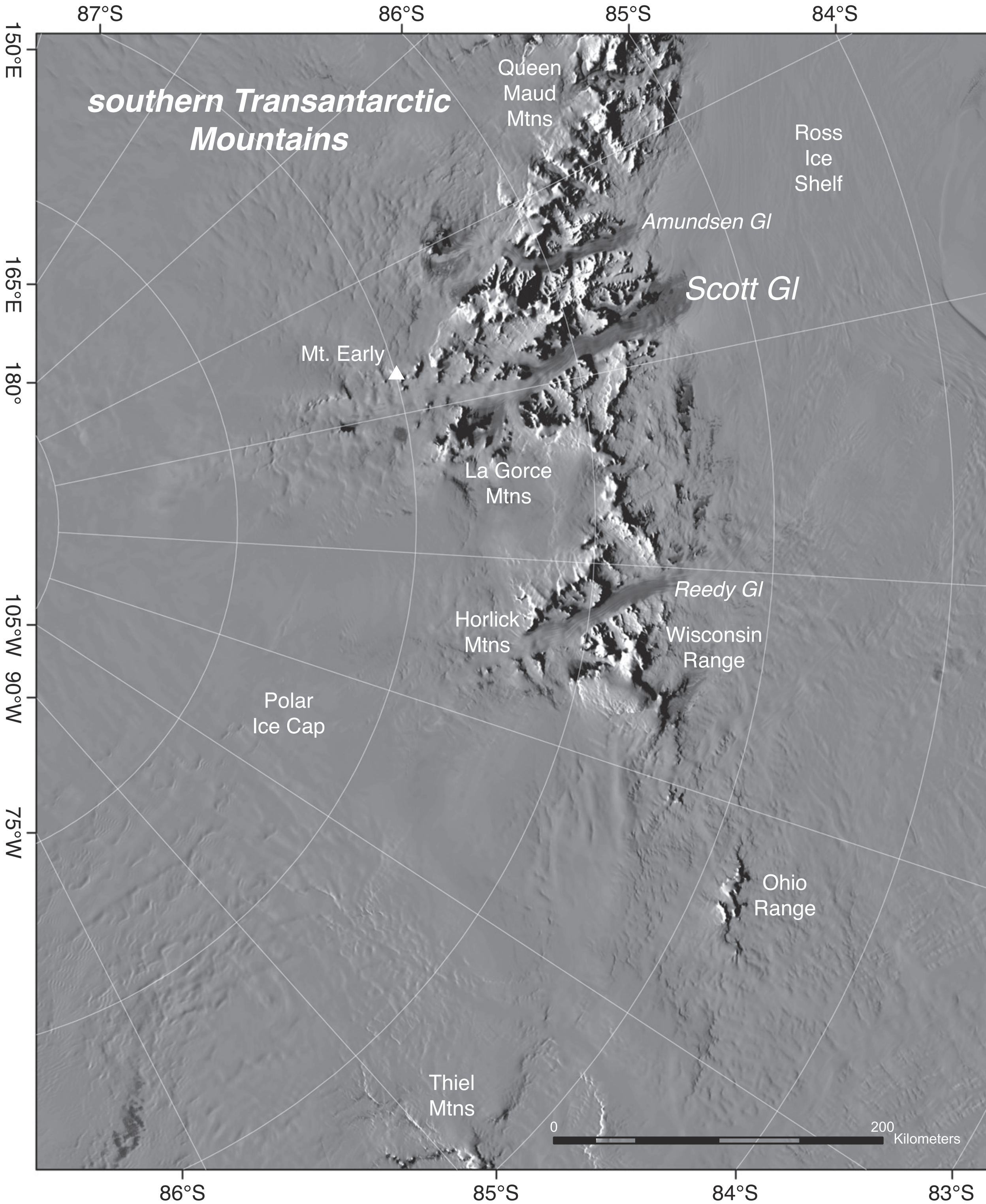


Fig. 24. MODIS image of the southern TAM, showing major geographic features.

Miller and Isbell, 2010). By Triassic time, the TAM sector of East Antarctica had drifted slightly northward to lower paleolatitudes of 65–75°S along with its African and Australian craton neighbors (Torsvik and Cocks, 2017), although some Triassic sediments were deposited in near-polar conditions during a period of pronounced warming. Deposits of this age contain tetrapod fossils of *Lystrosaurus* and *Cynognathus* zones, including mammal-like reptiles (synapsids) and amphibians (Colbert, 1986), and anatomically well-preserved fossil plants and pollens, some as silicified remnants from diverse high-latitude forests (Escapa et al., 2011). The TAM sector of East Antarctica probably reached its most northerly paleolatitude position of ~55°S at the end of greater Pangea time (Torsvik and Cocks, 2017), and stratigraphically higher Beacon deposits of the TAM contain Jurassic vertebrates, both dinosaur and pterosaur faunas, suggesting a moderate-climate terrestrial ecosystem. Thus, the Gondwana sequence of the TAM records a progressive terrestrial climate shift from glacial, to

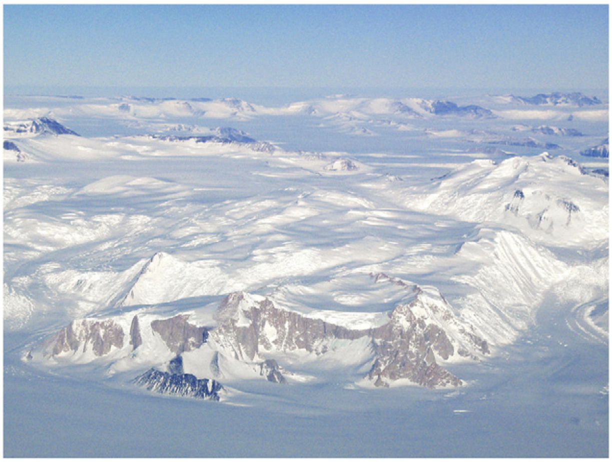


Fig. 25. View looking southwest to outcrops of light-colored Granite Harbour intrusives at the level of the Ross Ice Shelf near Wise Bay between Nimrod and Beardmore glaciers. Granites of this suite intrude crystalline and sedimentary basement rocks of the Ross Orogen and are, in turn, overlain by sedimentary strata of the Beacon Supergroup (subhorizontal beds in distant ridges).

sub-polar, wet-temperate, and more arid conditions. Significant paleoclimatic changes began with a period of Early Permian warming, which remained until ~35 Ma. The Triassic saw a seasonally wet (monsoonal) climate that became drier in the Jurassic. Antarctica reached its farthest northerly latitude by ~200 Ma (earliest Jurassic). As Gondwana started to break up about 180–170 Ma, Antarctica began to drift southward again from its more temperate latitude; a lushly vegetated surface was progressively transformed to a high-latitude (~60°S), strongly-seasonal paleoenvironment recorded by lacustrine deposits (Stigall et al., 2008). A broad outline of Beacon Supergroup stratigraphy, sedimentology and paleoenvironments follows.

Basal Beacon units are assigned to the Devonian Taylor Group, which consists of non-carbonaceous siliciclastic deposits resting unconformably on basement of the Ross Orogen. The Taylor Group is comprised mainly of quartzose sandstones deposited in shallow-marine to epicontinental basins spanning southern Victoria Land, the central TAM, the Ohio Range, and the Ellsworth Mountains (Bradshaw, 2013), and it includes texturally-mature sandstones, siltstones, mudstones and local pebbly sandstones or conglomerates. Basal sandstones such as in the Alexandra Formation typically consist of clean, thick-bedded orthoquartzites showing ripples and large cross-bed sets indicative of both shallow-marine and fluvial deposition (Fig. 30). Trace fossils indicate activity by shallow-water marine arthropods and other invertebrates in basal marine transgressive sediments of the Taylor Group (Bradshaw, 1981). Much of the Taylor Group is non-fossiliferous, but younger units in Taylor Valley contain freshwater fish fossils and bivalve crustaceans (Woolfe, 1990; Young and Long, 2005). Depositional features, paleocurrents, and detrital zircon ages from basal Devonian strata indicate deposition in subsiding basins overlying Ross Orogen basement and having a cratonic source in East Antarctica (see Elliot, 2013; Elliot et al., 2017).

Outboard of the TAM, subduction produced a long-lived Gondwana-margin magmatic arc that was active nearly continuously between the Devonian and Early Jurassic (Elliot, 2013), yet the TAM were largely unaffected and did not receive arc-derived sediment until Late Permian time. During the Carboniferous, the TAM experienced non-deposition and/or erosion. Permian-Triassic strata of the Victoria Group represent the thickest part of the supergroup and overlie a Late Carboniferous disconformity (Maya Erosion Surface). They include a heterogeneous assemblage of siliciclastic and carbonaceous sediments containing distinctive plant fossils of the *Glossopteris* flora in the lower, Permian

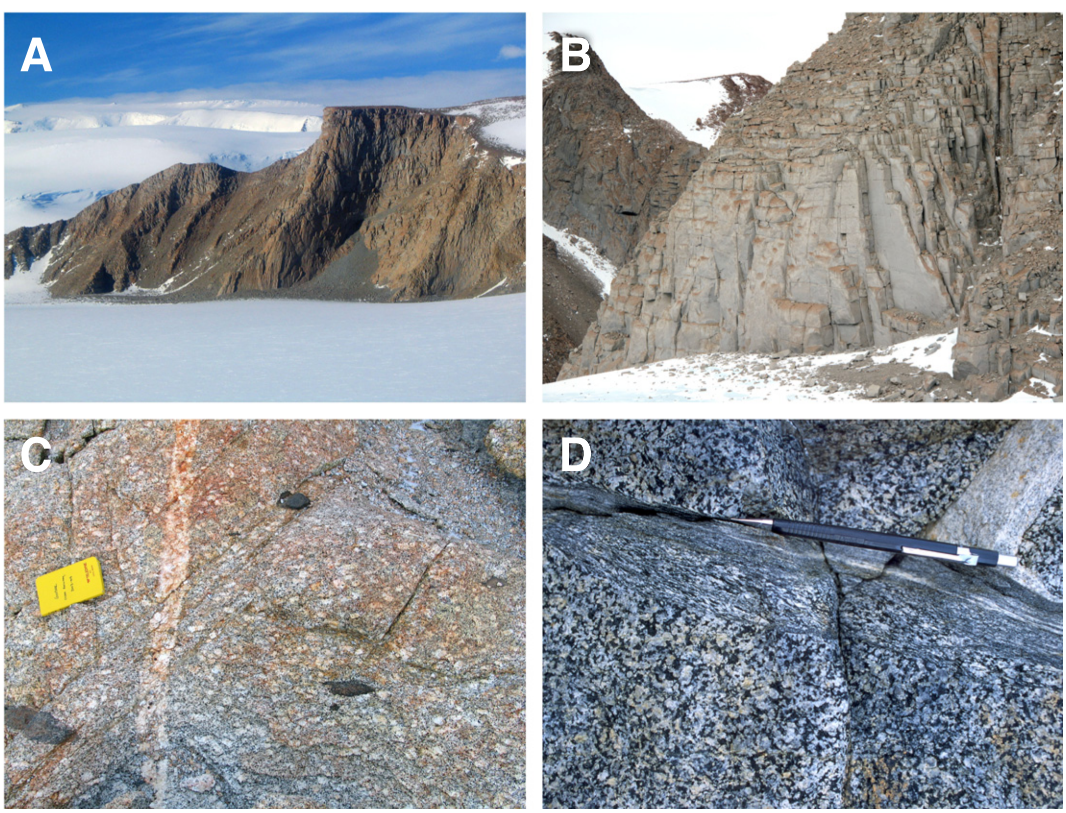


Fig. 26. Granitoids with varying styles of emplacement, central TAM. (A) Cliffs formed by the Martin Dome granite, a post-tectonic intrusion in the central Miller Range. (B) Outcrop of Martin Dome granite in the central Miller Range at Hockey Cirque, showing general lack of enclaves and prominent jointing. (C) Outcrop of granite at Kreiling Mesa in the eastern Miller Range adjacent to Marsh Glacier, showing prominent K-feldspar phenocrysts, mafic enclaves and a late-stage pegmatitic dike. (D) Foliated and deformed syn-orogenic diorite of Argo Glacier in the southern Miller Range.

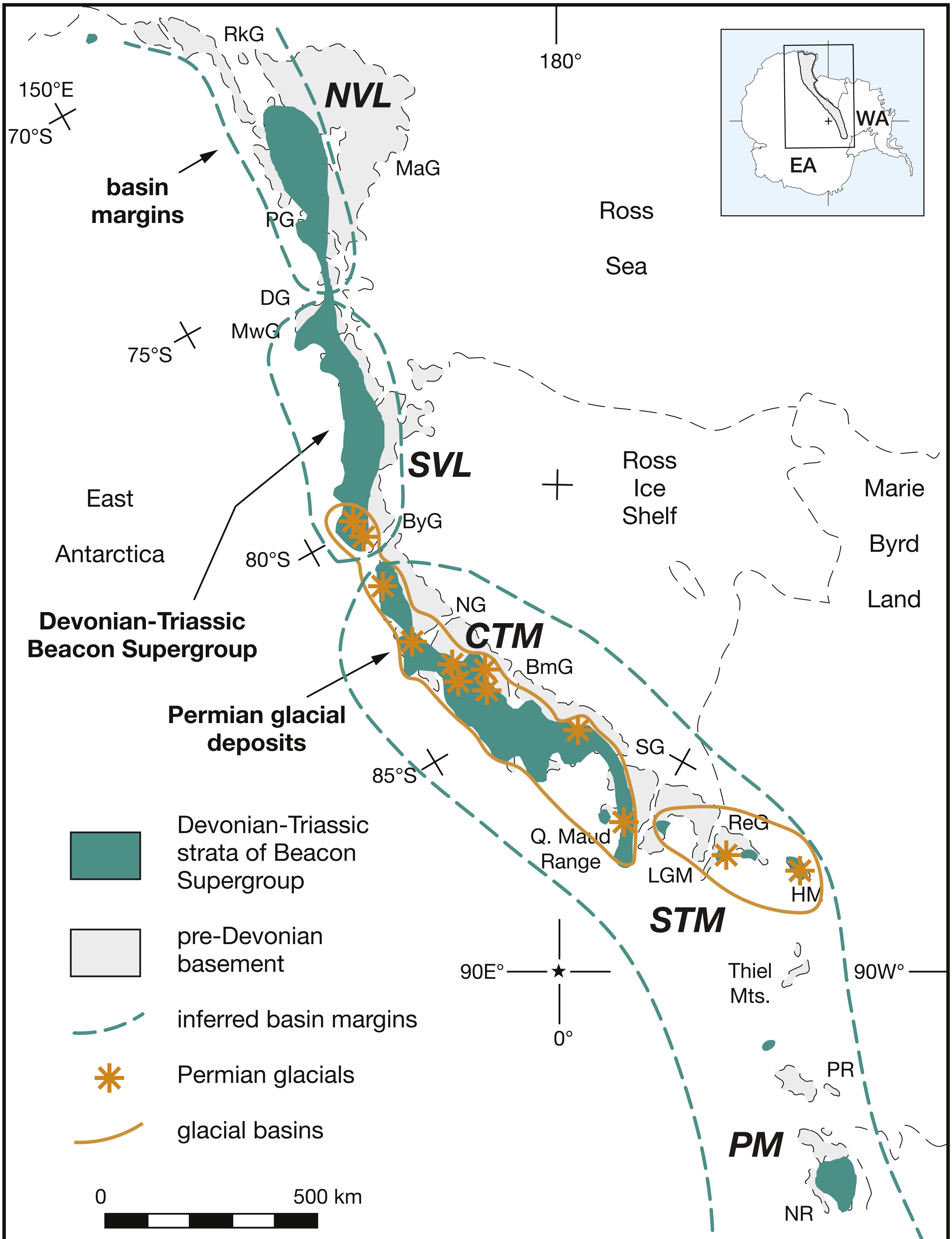


Fig. 27. Distribution of Beacon Supergroup strata in the Transantarctic Mountains. After Elliot (2013). Glacial basins and occurrence of Permian glacial deposits from Isbell et al. (2008).

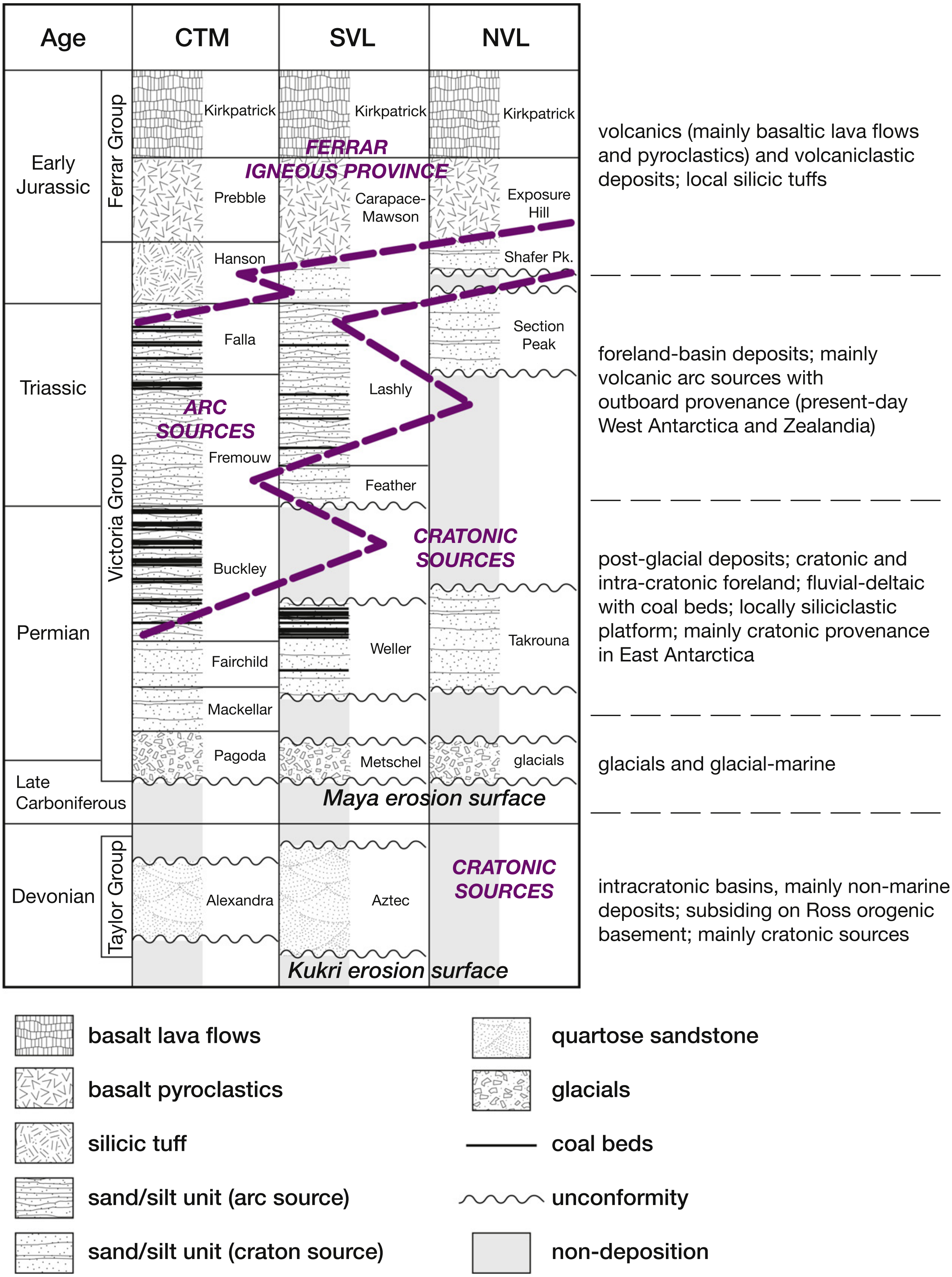


Fig. 28. Beacon Supergroup stratigraphy in the central TAM, southern Victoria Land and northern Victoria Land, showing major stratigraphic units of the Beacon Supergroup and Ferrar Group. Trends in depositional environments and sediment sources are generalized. After Elliot (2013).

units and *Dicroidium* in the upper, Triassic units. In many places, the basal unit of the Victoria Group is a massive diamictite or tillite, associated with glacial outwash and fluvioglacial deposits. These include the Metschel Tillite in southern Victoria Land, Pagoda Tillite in the Queen Elizabeth and Queen Alexandra ranges, Scott Glacial Formation in the Scott Glacier region, Buckeye Formation in the Ohio Range, and Gale Mudstone in the Pensacola Mountains. Striated clasts and basal erosion surfaces attest to the glacial origin, although the units also contain

Fig. 29. Beacon Supergroup strata make up most of this ridge on the flanks of Mt. Mackellar in the Queen Alexandra Range near Lennox-King Glacier. The light-colored rocks are beds in the Victoria Group, intruded by dark-colored sills of Ferrar dolerite in the lowest slopes and on the ridge crest.

fluvioglacial, glaciolacustrine and glacial marine sediments indicating ice-marginal sediment deposition. The Pagoda Tillite is thought to be Late Carboniferous(?) to Early Permian in age and was deposited during a period of glacial retreat across Gondwana. Based on compilation of Permian glacigenic deposits in the TAM, Isbell et al. (2008) argued that the glacial strata were deposited in two topographically isolated glaciomarine basins, surrounded by basement highs forming uplands upon which subglacial diamictites and proximal glaciomarine sediments were deposited. Glacial sediment transport was mostly along the axis of these basins (Fig. 31), separated by a glacial divide between present-day Shackleton and Scott glaciers. Contrary to previous interpretations for deposition in a continent-wide terrestrial glacial system, the findings suggest that glaciation was less widespread (temporally and spatially) than previously hypothesized, and that it is unlikely that a single, massive ice sheet covered Antarctica continuously at any time during the Carboniferous and Permian (Isbell et al., 2003, 2008).

Most of the remaining Permo-Triassic succession in the Victoria Group consists of siliciclastic rocks, dominated by sandstones, siltstones and shales with minor carbonate and/or carbonaceous units. This part of the Gondwana sequence records a transition from intra-cratonic deposition in distinct basins in northern and southern Victoria Land, to widespread deposition in an axial foreland basin by mid-Permian time (Collinson et al., 1994). Coal measures are abundant within the Victoria Group, including the Weller Coal Measures in southern Victoria Land and Buckley Coal Measures in the area of Beardmore Glacier, as well as in the Takrouna Formation in northern Victoria Land, the Queen Maud Formation in the Scott Glacier area, and the Mt. Glossopteris Formation in the Ohio Range. Locally, they disconformably overlie the older glacigenic units, indicating an abrupt climatic change during the Permian. The uppermost unit in the central TAM, the Early Jurassic Hanson Formation (Elliot, 1996), is a sandstone/shale unit that departs from the older succession in containing tuffaceous sandstones indicating input of proximal volcanic material; this unit is overlain in turn by Early to Middle Jurassic units (Prebble Formation) that contain laharic deposits and mafic pyroclastic breccias (Elliot, 2000). In broadest terms, facies architecture, paleocurrent data, and sediment compositions indicate that the Permian-Triassic succession in the Beacon Supergroup represents a transition from deposition in intra-continental basins formed on the Gondwana supercontinent to an evolving foreland basin inboard of a Gondwana margin arc (Barrett et al., 1986). Detrital zircon provenance data from the entire sequence likewise allow reconstruction of a general upward or younging pattern from cratonic to magmatic-arc sources (Fig. 28; Elliot et al., 2017), yet reverse trends are represented locally at the Permian-Triassic boundary near Shackleton Glacier (upper Buckley and lower Fremouw formations) where a transition from a Late Permian magmatic arc source, inferred to lie in West Antarctica, to more cratonic signatures indicates erosional unroofing of older basement within a Late Permian foldbelt or from the East Antarctic shield itself (Elliot and Fanning, 2008). The detrital zircon data, together with facies patterns, indicate that much of the Permo-Triassic Beacon Supergroup had an eastern orogenic source (from the direction of present-day Marie Byrd Land and West Antarctica), was deposited in a foreland basin aligned with the present-day TAM along the tectonically active edge of East Antarctica, thinned dramatically toward the craton, and the axial trough of which migrated over time across the foreland (Collinson et al., 1994). In addition to exposures along the length of the TAM, Beacon strata are also known at Horn Bluff along the coast of George V Land and in the Shackleton Range, consistent with deposition in a narrow, elongate foreland basin. These strata are correlative with Gondwanide sediments on other continents, yet they apparently did not cover East Antarctica widely unless they underlie the major ice sheets behind the Transantarctic Mountains and occupy subglacial basins (e.g., Wilkes subglacial basin).

Fig. 30. Basal Alexandra Formation sandstones (Devonian, Taylor Group) near unconformity on lower Paleozoic sedimentary rocks of the upper Byrd Group, Fazekas Hills in central Queen Elizabeth Range. Dark rocks in foreground are mainly Ferrar dolerite clasts with desert varnish in regolith. Distant hills show Ferrar sills intruding subhorizontal Beacon strata at Mt. Miller.

In northern Victoria Land, the Victoria Group is divided into three units (Collinson et al., 1986), an unnamed Upper Paleozoic diamictite, the Permian Takrouna Formation, and the late Triassic to Jurassic Section Peak Formation. Both of the latter named units rest directly on Lower Paleozoic crystalline basement and consist of terrigenous fluvial sandstone with minor calcareous and non-calcareous mudstone deposited in sandy, braided stream systems. However, the Takrouna and Section Peak units differ markedly in clast composition; the former contains abundant quartz and feldspar grains with sparse lithics, whereas the latter contains quartz, feldspar, and abundant volcanic rock fragments indicating a calc-alkaline arc source. In detail, the Section Peak contains an increasing proportion of volcanic detritus from bottom to top in the formation (Elsner et al., 2013). Paleocurrents in these strata are dominantly to the north and northwest in present-day coordinates, which places their source farther south in Victoria Land and/or the central Ross orogen. Detrital zircon age distributions in Takrouna sandstone indicate a strongly unimodal late Pan-African–age source (Goodge and Fanning, 2010); this dominant young age and its cratonic/plutonic sediment composition reflects incorporation of material from the uplifted deepest (plutonic) parts of the Ross orogen. Detrital zircon ages in the type-section of the Section Peak Formation are as young as ~190 Ma, indicating that its depositional age is late Early Jurassic to Middle Jurassic (Goodge and Fanning, 2010), not Triassic as previously thought.

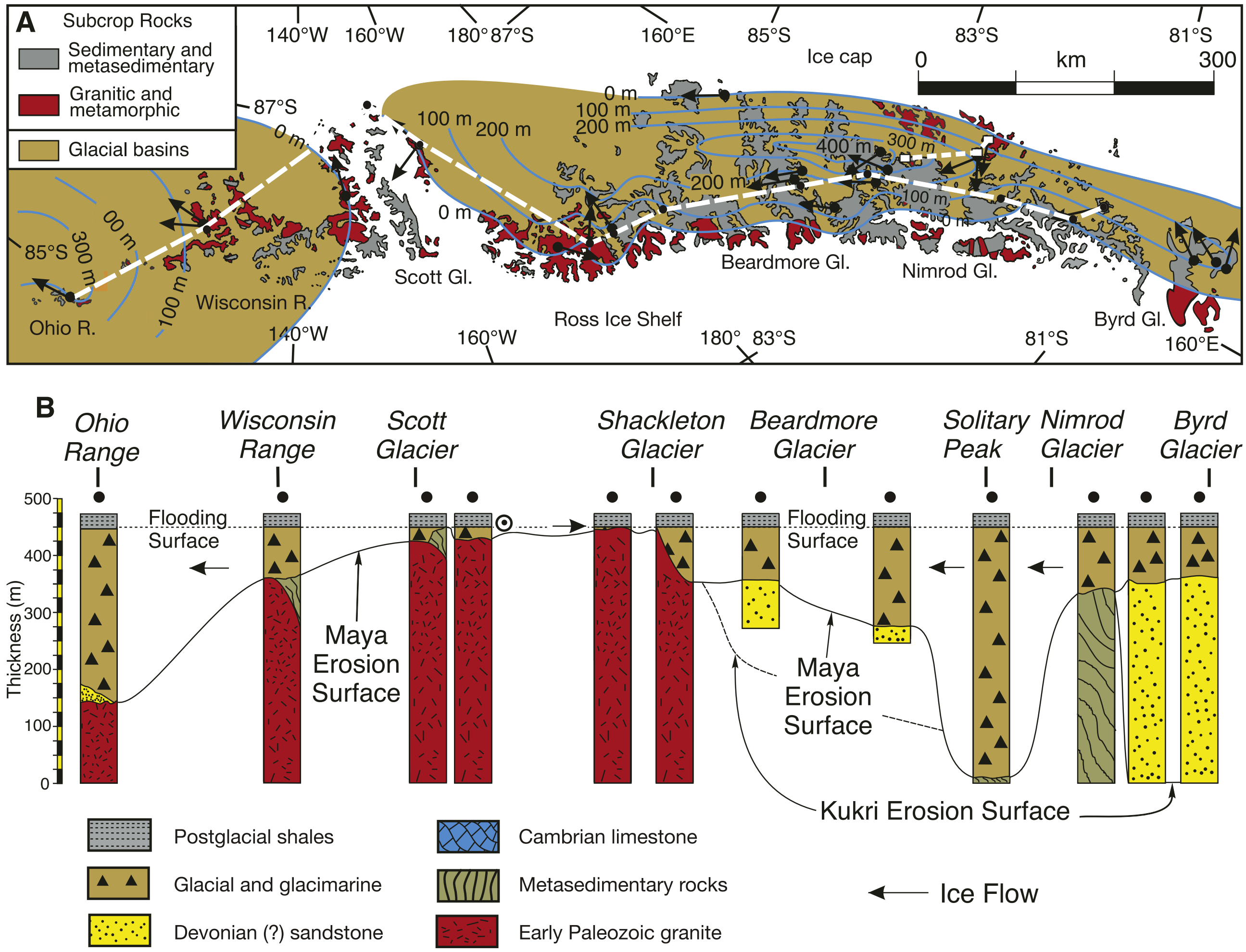


Fig. 31. Distribution of Permian tillites in the Transantarctic Mountains (after Isbell et al., 2008). (A) Map of the central and southern region showing isopachs, paleocurrent orientations, and the locations of the glacigenic basins. (B) Cross section of preglacial, glacial, and postglacial rocks parallel to the trend of the mountains.

Similarly, Elsner et al. (2013) reported maximum depositional ages ranging from about 215–195 Ma, although they reported population peaks rather than discrete zircon ages. The ages of young detrital grains therefore indicate that Section Peak deposition is restricted to the Early Jurassic (Pliensbachian) prior to the time of Ferrar dolerite sill emplacement (ca. 183 Ma; see below). The detrital signatures in this unit further indicate little input from older shield rocks, but rather a decreasing proportion of Ross Orogen basement giving way stratigraphically upward to a dominant Late Triassic to Early Jurassic magmatic source (Elsner et al., 2013), indicating progressive covering of the Ross belt and initial stages of Gondwana rifting. Capping the Victoria Group is a more recently defined unit, the Shafer Peak Formation, consisting of volcaniclastic rocks showing some characteristics of diatremes (Schöner et al., 2007).

Probably the thickest and best-studied part of the succession lies in the central TAM between Byrd and Shackleton glaciers, where the highest part of the mountain range is held up by Beacon strata interleaved with Ferrar dolerite sills (see Lindsay, 1969; Barrett et al., 1986; Collinson et al., 1994). Here the total Beacon stratigraphic thickness is over 2200 m. The basal unit, Devonian Alexandra Formation, consists of mature quartz arenite deposited in a coastal plain setting directly upon granitic and metasedimentary basement of the deeply-eroded Ross Orogen. The Lower Permian Pagoda Formation, in contrast to massive diamicts elsewhere, consists mainly of poorly-sorted conglomeratic sandstones containing striated pebbles and thought to be deposited in periglacial fluvial, deltaic and subglacial settings (Lindsay, 1970). Although some glacigenic units may have formed as ice-contact deposits during glacial retreat, much of the unit represents deposition in ice-marginal lakes and meltwater streams.

Lithofacies, paleocurrent orientations, sandstone compositions, and stratigraphic relationships of lower Beacon strata in the central TAM indicate that deposition took place on an undulating erosion surface comprising intermontane successor basins as the Ross Orogen was eroded (Isbell, 1999). Deposition of glacial sediment and sediment dispersal patterns indicate that intermontane conditions persisted into the Early Permian.

The upper Permian units in this area consist mainly of sandstones, siltstones and shales deposited in braided fluvial settings, perhaps bordering a local highland region exposing remnants of Ross basement. Coal beds, known from the Beardmore Glacier since the South Pole expedition of Shackleton in 1907, are prominent in the Buckley Formation and represent a significant source of paleoenvironmental information used in paleogeographic reconstruction. The formation consists mainly of thick-bedded sandstone intercalated with carbonaceous shale, coal beds (1–2 m), conglomeratic lenses, and occasional thin beds of limestone (Barrett et al., 1986). Plant fossils are abundant in the Buckley Formation, the most notable being *Glossopteris* leaf impressions. Sediment composition in the lower Buckley indicates mainly a cratonic source, but upward the sandstones become richer in lithic volcanic components indicating that felsic volcanism of Late Permian age was widespread.

Volcanic detritus is found in southern Victoria Land up to the base of the Middle to Late Triassic Lashly Formation. Sandstones of the upper Permian units (Buckley Formation) were deposited in aggrading alluvial plain and fluvial settings related to alluvial fan deposition proximal to the Gondwanide orogenic belt (Isbell and Macdonald, 1991), and fine-grained clastic units and coal beds were deposited in lakes and fluvial floodplains. The overlying Triassic Fremouw Formation is likewise dominated by fluvial sandstone and siltstone deposits, but notably contains rich vertebrate fossil assemblages including both reptilian and amphibian bones deposited in fluvial channels (Barrett et al., 1968; Elliot et al., 1970; Hammer et al., 1986). These include the tetrapod *Lystrosaurus*, well-known as a cosmopolitan species of Gondwana. The rest of the fauna is less cosmopolitan, but very similar to that in the Karoo, which was at a mid-latitude at that time. The upper part of the Fremouw Formation contains fossil leaves of *Dicroidium* as well as fossilized plant roots and petrified wood, indicating a moist, temperate environment. A relatively complete section across the Permian-Triassic boundary near Shackleton Glacier records the near-simultaneous (200 k.y.) decline and ultimate extinction of *Glossopteris* flora and invasion of *Lystrosaurus* fauna, synchronous with global climatic shifts toward a warmer paleoenvironment (Retallack et al., 2005; Collinson et al., 2006).

Fig. 32. Three sills of Ferrar Dolerite intruding subhorizontal strata of the Upper Permian Buckley Formation (Beacon Supergroup) at Mt. Achernar near the head of Beardmore Glacier in the Queen Alexandra Range.

3.8. Mesozoic magmatism

The Late Triassic Gondwana succession of quartzose sandstone, conglomerate, shale and coal in the Beacon Supergroup is overlain in several areas by volcanic and volcaniclastic rocks of Early Jurassic age. This transition marks a change from peri-Gondwana basin deposition to Gondwana continental breakup associated with development of a large mafic igneous province. The earliest phase of magmatic activity is recognized by scattered silicic airfall tuffs, reworked tuffs, and associated pyroclastic deposits intercalated with siliciclastic sediments in northern Victoria Land and the central TAM (see above; Schafer Peak and Hanson formations, respectively; Schöner et al., 2007; Elliot, 2013). The source of the silicic volcanic materials is unknown and may be attributed to either active-margin or rift-related volcanism. Throughout the TAM, the silicic deposits are succeeded by an extensive province of thick basalt lavas and dolerite sills, collectively belonging to the late Early Jurassic Ferrar Group (see Elliot, 2013). This mafic magmatism has both eruptive and intrusive components and marks the end of Gondwana geology in Antarctica. The following discussion focuses on the dominant magmatic activity associated with the Ferrar igneous province.

3.8.1. Ferrar magmas (Ferrar Group and Kirkpatrick Basalt)

Much of the present physiographic expression of the TAM can be traced to its Mesozoic history during early fragmentation of the Gondwana supercontinent, which resulted in continental rifting and separation of Antarctic lithosphere from parts of present-day South America and Africa. In the TAM, the large-scale plate movements led to widespread Early Jurassic igneous activity and extensional deformation generally perpendicular to the modern trend of the mountain belt. Magmas collectively referred to the Ferrar Magmatic Province erupted as basaltic flows onto both wet and dry Beacon landscape surfaces (Kirkpatrick Basalt) and they were emplaced as individual subsurface dolerite intrusions (Ferrar Group sills; Fig. 32). One of the most prominent of these, the Dufek intrusion, is similar to other layered mafic intrusions worldwide except for a lack of known economic mineral occurrences. An excellent summary of the Ferrar province is provided by Elliot and Fleming (2008).

The Ferrar Magmatic Province extends over 3000 km along nearly the full length of the TAM (Fig. 33) and is contemporaneous with similar rocks in Dronning Maud Land, southeastern Australia, and southern Africa (Karoo and equivalent flood basalt provinces; Riley et al., 2006). It is typical of continental rift-margin large igneous provinces (LIPs) related to supercontinent breakup. Ferrar magmatism represents a dramatic end to the Gondwana supercontinent, which was stable for nearly 300 m.y. between about 450–180 Ma. The province, also referred to as the Ferrar Large Igneous Province (FLIP), is characterized by tholeiitic basalt magmatism (Elliot and Fleming, 2008). Ferrar magmas are thought to result from high-temperature melting of a mantle source, either in the upper part of rising mantle plumes or associated with continental extension. In general, they are represented by high-Si basalts and andesites, with high initial $^{87}Sr/^{86}Sr$ ratios (≥ 0.708) and lithospheric trace element compositions. Although early geochronology of basaltic flows and dolerites using the K—Ar and Rb—Sr systems yielded Jurassic ages between 170 and 175 Ma (see Faure and Mensing, 2011), subsequent U—Pb dating of zircon and baddeleyite, and recalculation of $^{40}Ar/^{39}Ar$ ages using new decay constants, indicate that Ferrar magmatism occurred over a remarkably brief period of time between 180 and 184 Ma (Encarnación et al., 1996; Elliot and Fleming, 2008). Heimann et al. (1994) suggested that >500,000 km^3 of Kirkpatrick Basalt was erupted in <1 million years, and recent U—Pb ages from both intrusive and extrusive Ferrar units indicates that magmatism occurred over an interval of only 350 kyr, beginning with intrusive magmatism as early as 183 Ma (Burgess et al., 2015).

Early volcanism in the province is marked by locally preserved felsic pyroclastic deposits (Hanson Formation) overlain by extensive pyroclastic basalts of the Prebble, Mawson and Exposure Hill formations, in turn overlain by continental flood basalt flows of the Kirkpatrick Basalt (Elliot and Fleming, 2008). The mafic pyroclastic rocks comprise proximal intra-vent facies lahars and tuff breccias to distal tuffs, and they include phreatomagmatic volcanic breccias. The Kirkpatrick Basalt is an Early Jurassic expression of volcanism that progressively overtook Beacon Supergroup foreland-basin sedimentation prior to development of the broader Ferrar flood basalt magmatism (Elliot, 1970; Elliot and Fleming, 2008). Foreland basin sedimentation ended in the Late Triassic, marked by a disconformity and silicic pyroclastic volcanism within reworked sandstones and culminating in airfall tuffs; this silicic volcanism, noted above, continued at a low level during Kirkpatrick time. Kirkpatrick basalt typically forms broad mesas in several areas of the TAM, including northern Victoria Land (Mesa Range), southern Victoria Land (Allan Hills), Britannia Range near Hatherton Glacier, the Queen Alexandra Range, and in the Grosvenor Mountains and at Otway Massif near Beardmore Glacier (Faure and Mensing, 2011). Individual flow thicknesses range from 1 to over 200 m, and the lower few flows are interlayered with lacustrine and tuffaceous volcaniclastic sediments. They were mainly erupted as tabular sheet lobes, typically showing vertical joints and fractures, and massive to amygdaloidal textures. Total thickness of the Kirkpatrick lavas may have been 1500–2500 m, based on amygdule mineralogy in the lowermost flows (Elliot, 2013). The rocks are mainly subalkaline basalts to andesites, but $^{87}Sr/^{86}Sr$ ratios ≥0.710 indicate contamination with radiogenic Sr at the source or during transit through overlying continental crust

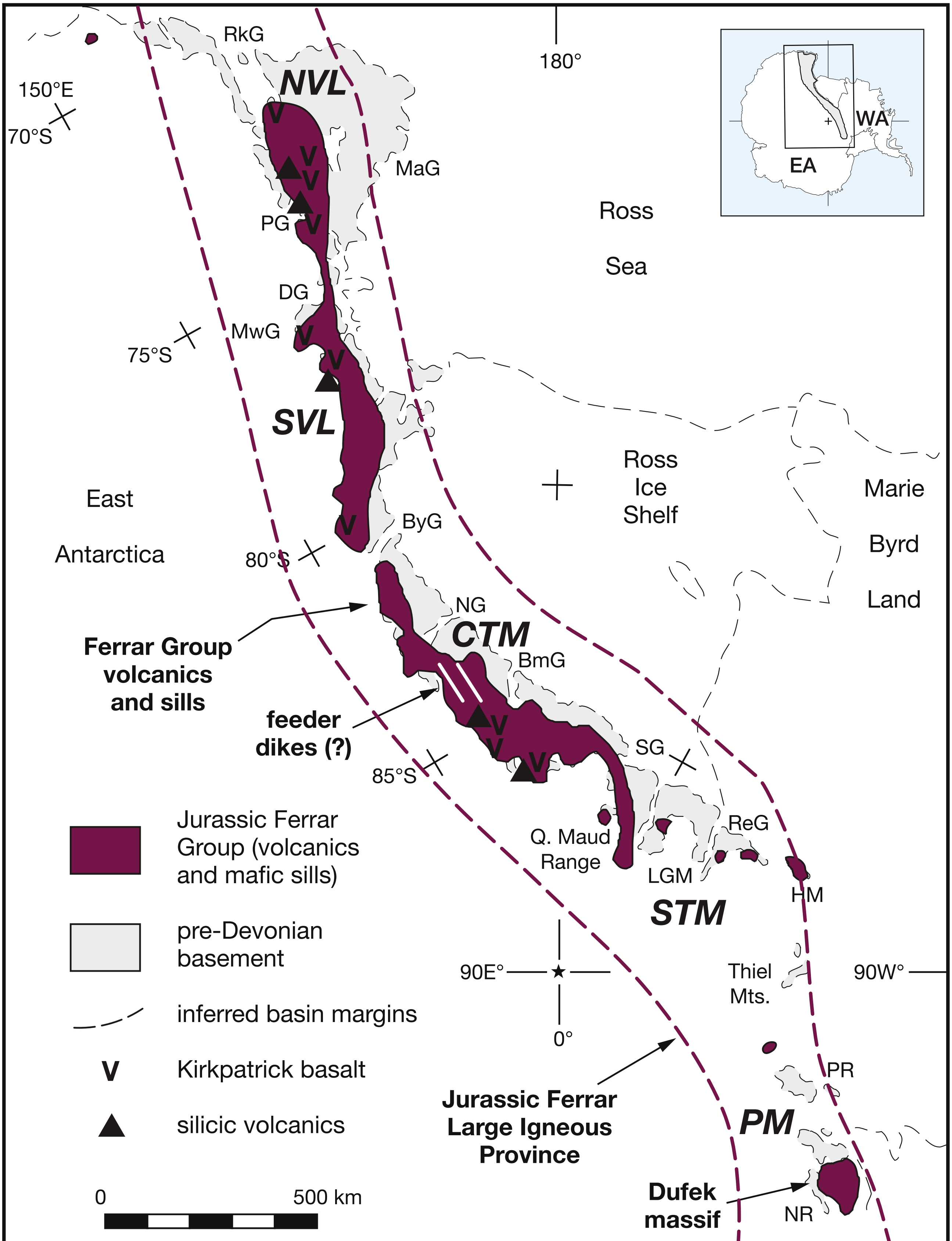


Fig. 33. Distribution of the Ferrar Large Igneous Province in the Transantarctic Mountains (after Elliot and Fleming, 2008; Elliot, 2013). Location of possible feeder dikes in the Nimrod Glacier area imaged in aeromagnetic data (Goodge and Finn, 2010).

(Mensing et al., 1984). Isotopic heterogeneity in the Kirkpatrick basalts further indicates that crustal assimilation into a primary enriched magma was an important process during early stages of magmatism (Fleming et al., 1995; Faure and Mensing, 2011).

Phreatomagmatic eruptions occurred locally, likely in topographic lows comprising a system of rift valleys, perhaps associated in early stages with a surficial climate marked by moist conditions. Jurassic magmatism was accompanied by crustal extension, which displaced some basement rocks westward toward the Gondwana plate margin and contributed to differential uplift within the present-day intraplate mountain belt. Mesozoic extension is expressed mainly by distributed, relatively small-offset fault arrays and did not result in complete rifting of Antarctica along its paleo-Pacific margin (Wilson, 1993).

Ferrar dolerite intrusions are the hypabyssal equivalent to the Kirkpatrick Basalts and represent the main expression of magmatism in the province. In many areas, Ferrar magmas were injected within Beacon strata as a swarm of laterally extensive sheet-like sills, enhanced in cliff exposures by glacial erosion (Fig. 34). Although the Ferrar sills were emplaced over a geologically brief period of time at ~180 Ma (Elliot and Fleming, 2008), they occur over the entire length of the TAM, mainly within the Beacon succession but locally invading basement rocks (Elliot and Fleming, 2004). Individual sills are commonly 100–200 m thick and can be traced for tens of kilometers. Trace-element geochemical variations within Ferrar units indicate that some in situ magma differentiation occurred during emplacement, yet uniform compositions of quenched chilled margin material from sills in northern Victoria Land and Tasmania indicate a common parent magma communicating over large distances (Hanemann and Viereck-Götte, 2004). Dikes feeding or connecting sills occur locally, allowing sills to change stratigraphic position along their length (Elliot and Fleming, 2004). Ferrar sills occur almost exclusively within Beacon strata, but in the Dry Valleys the Peneplain Sill was intruded along the Beacon-basement unconformity, and a thick Basement Sill intruding granitic country rocks was probably injected along exfoliation joints close to the unconformity between basement and overlying sedimentary units. The Basement Sill is substantially thicker (up to 700 m) and rich in orthopyroxene compared to typical occurrences (Marsh, 2004). The only large pluton of Ferrar magma is the Dufek intrusion (Ford and Himmelberg, 1991) in the northern Pensacola Mountains (Fig. 3), a layered mafic intrusion estimated to have a thickness of 8–9 km. Ferris et al. (1998) suggested that the Dufek actually comprises two separate intrusive bodies that are smaller in areal extent that earlier envisioned. Although not thought to be of economic concentration, the Dufek intrusion contains several important metals typical in layered mafic intrusions, including chromium, vanadium, copper, cobalt, nickel and platinum-group elements (Ford, 1976, 1990). Excluding the Basement Sill, which is more of a plutonic body, an aggregate thickness of the Ferrar sills of up to 1500 m (Elliot, 2013) means that the Beacon Supergroup host rocks were uplifted at least this much due to magma pressure alone.

Fig. 34. Sills of Ferrar Dolerite (dark) intruding subhorizontal strata of the Beacon Supergroup in the Warren Range of southern Victoria Land, inland of the Dry Valleys. A large raft of Beacon sandstone is trapped as a xenolith in the lower sill.

Ferrar dolerite sills offer a useful natural laboratory to study melt emplacement processes and test in situ differentiation models. In Wright Valley, temperatures of dry Ferrar melt (900–950 °C) in the Basement Sill were high enough to partially melt granitic country rocks tens of meters distance from the contact (Hersum et al., 2007). The Basement Sill itself is internally stratified with cumulate layers, yet cooled quickly enough to preserve a record of crystallization, gravity settling, and chemical differentiation expressed by a distinctive orthopyroxenite base and gabbronorite top (Bédard et al., 2007). Detailed study of the Beacon Sill near Taylor Glacier shows that this ~150 m-thick intrusion, emplaced wholly within Beacon strata, was formed by multiple melt injections despite its rapid cooling history, and thereby raising question about closed-system in situ differentiation (Zieg and Marsh, 2012).

As with the Ferrar Group in general, the Ferrar dolerites consist mainly of quartz-normative mafic tholeiite (52–56 wt% SiO_2) containing variable phenocryst populations of augite, pigeonite and, less commonly, olivine. Orthopyroxene (hypersthene) is rare except in some of the thicker, lower sills such as the Basement Sill. The dolerites are relatively uniform in major-element chemical composition but most sills over 100 m thick show evidence of in situ compositional fractionation by way of mineral composition changes (notably upward zonation in Mg composition), granophyric patches, and schlieren structures (Marsh, 2004; Faure and Mensing, 2011). Leucocratic segregations with blebby to lens- or vein-like form are common in thicker and stratigraphically lower sills, and their compositions indicate derivation by fractional crystallization of the injected melt (Zavala et al., 2011). Compared to the Kirkpatrick Basalt, the Ferrar geochemical compositions are more uniform, yet they are likewise characterized by enriched initial Sr and Nd isotopic compositions and trace element patterns indicating an important crustal component, perhaps enhanced by local wall-rock contamination (Gunn, 1966; Kyle et al., 1983; Mensing et al., 1984; Hergt et al., 1989; Fleming et al., 1995). Almost all of the Ferrar sills and most of the Kirkpatrick basalts belong to the Mt. Fazio chemical type (MFCT) of Fleming et al. (1992, 1995), which are of tholeiitic basalt composition with 2–7 wt% MgO; this series has trace element and isotopic compositions indicating either crustal contamination or melting of metasomatized continental lithosphere. In contrast, the highest lava flows in northern Victoria Land have affinity with the Scarab Peak chemical type (SPCT), consisting of evolved Fe-rich tholeiitic andesites with notably lower MgO (Elliot and Fleming, 2004). Initial Sr and Nd isotopic ratios show that the Ferrar rocks have typically assimilated <5% of crustal material (Fleming et al., 1995). A connection to supercontinent breakup seems likely, although it is not clear if this was related to rise of a mantle plume, plate-boundary forces, or to gravitational instability caused by an insulating lithosphere. Some petrogenetic models suggest that the Ferrar magmas formed by partial melting of enriched subcontinental lithospheric mantle that was chemically modified during early Paleozoic subduction along the Ross-age Gondwana margin (e.g., Kyle et al., 1983; Hergt et al., 1991; Ivanov et al., 2017). This explains the mantle-like source signatures, but there is scant evidence of direct interaction between melts and continental crust. Alternatively, the compositional uniformity and isotopic signatures are thought to reflect a common mantle source associated with a mantle plume, modified slightly by subsequent crustal contamination (Fleming et al., 1995, 1997; Storey and Kyle, 1997; Storey et al., 2001).

If the FLIP originated during rise of a mantle plume source located in the proto-Weddell Sea area, magmas must have migrated hundreds to thousands of kilometers laterally from that region (Elliot and Fleming, 2004; Vaughan and Storey, 2007; Leat, 2008). Unlike some other large igneous provinces, particularly those associated with mantle plumes, the Ferrar province in Antarctica is a uniquely linear belt. Its emplacement was probably controlled by pre-existing linear crustal structure, perhaps tracing to Neoproterozoic rifting and early Paleozoic Ross Orogen deformation, which allowed for the propagation of major dike swarms as inferred from linear magnetic anomalies in the central TAM (Goodge and Finn, 2010). Ferrar sills certainly also flowed laterally within Beacon foreland-basin sediments, following the strike direction of the beds in a linear fashion, but from geophysical anomalies magma appears to have been channelized along the axis of the TAM and migrated only in a limited way off-axis, being now covered by the East Antarctic ice sheet (Ferraccioli et al., 2009). Geochemical patterns indicate that there were compositionally discrete reservoirs of Ferrar magma in different regions of the TAM, as highlighted, for example, by contrasting MgO contents between the central TAM and northern Victoria Land (Elliot and Fleming, 2004). In addition to purely plume-driven origins of Ferrar magmas, complementary roles of intraplate tension and thermal instability during Gondwana breakup might be associated with mantle melting and long-distance transport (Elliot et al., 1999; Elliot and Fleming, 2004, 2008; Leat, 2008). Remaining problems to address with respect to Ferrar magmatism are: (1) what is the precise origin of their unusual chemistry and did it evolve over time; and (2) how, and how far, did individual Ferrar melt bodies move laterally?

3.9. Neogene volcanic province

Late Cenozoic volcanism along the western and southwestern Ross Sea margin of the TAM is marked by Oligocene and younger alkalic basalt centers (Fig. 8), the largest of which is Erebus volcano (Fig. 35). Volcanism of the McMurdo Volcanic Group began about 24–25 million years ago, and eruptions in the Erebus volcanic province (comprising the Terror Rift, Ross Island, Mount Discovery, and Mount Morning) commenced by 19 Ma. Many of the volcanoes in the region are Pliocene to recent age and now dormant (Kyle, 1990b). Morphologically, they occur mainly as small pyroclastic scoria cones along with larger central stratovolcanoes and coalesced shield volcanoes (e.g., Mt. Melbourne). The group is subdivided by geographic region into four volcanic provinces: (1) the Hallett province in coastal northern Victoria Land; (2) Melbourne province which extends inland across the TAM in northern Victoria Land (Wörner et al., 1989); (3) Erebus volcanic province in the McMurdo Sound area of South Victoria Land; and (4) two small outcrops in the southernmost area of the Queen Maud Mountains. Magmatism is a direct result of intracontinental rifting and extension along the edge of the Ross Embayment (Huerta and Harry, 2007), although the radially symmetrical form of the Erebus subprovince, and chemical and isotopic compositions of the lavas, suggest it represents the hotspot expression of a mantle plume (Kyle et al., 1992; Phillips et al., 2018). Eocene (48–23 Ma) alkali intrusives in northern Victoria Land likely represent subvolcanic magma chambers where the McMurdo-type melts were staged prior to eruption (see Nardini et al., 2009).

Fig. 35. View looking north at the edifice of Erebus volcano from the Ross Ice Shelf near McMurdo Station and Scott Base. A vapor and ash plume can be seen emanating from the summit.

Erebus volcano (3794 m elevation, 2000 km^3) on Ross Island is the world's southernmost historically active volcano (Kyle, 1990a; Oppenheimer and Kyle, 2008). It is approximately 1.3 My old (Esser et al., 2004; Harpel et al., 2004; Kelly et al., 2008), but it is persistently active and was erupting when discovered by Sir James Ross in 1841. It is at the center of the Erebus province and is flanked by the older eruptive centers at mounts Terror (<1 Ma) and Bird (3–4.5 Ma) and Hut Point Peninsula (<1 Ma). They form a series of physiographic spokes emanating radially at angles of 120° from each other, thought to reflect crustal doming during magma emplacement. The nearby Discovery subprovince includes the dormant volcanoes of mounts Discovery (<5 Ma) and Morning (<4.5 Ma), Brown Peninsula (2–3 Ma) and Minna Bluff (8–12 Ma), likewise arranged in a radial pattern.

As an exemplar of the volcanic province, Erebus is a composite stratovolcano with lower flanks resembling a shield volcano formed by low-viscosity basaltic flows, and an upper steeper cone composed of eruptive materials with higher-viscosity phonolitic composition. Like most of the volcanoes in the province, Erebus volcano is composed mainly of strongly silica-undersaturated, alkaline rocks ranging from basanite to phonolite (41–58 wt% SiO_2) in composition. The Erebus-type melts are mainly nepheline normative and rare quartz normative compositions are likely due to local crustal assimilation. The summit crater of Erebus contains an active, convecting anorthoclase-phonolite lava lake, contained within a composite caldera structure (Kyle et al., 1982). The lava lake and other vents within the Inner Crater produce persistent small (VEI 0) Strombolian eruptions (Giggenbach et al., 1973) and the upper volcano is composed of layered lava flows, bomb accumulations, and minor pyroclastic deposits (Panter and Winter, 2008). Lava flows on the summit area and cascading down the steeper upper cone display features typical in young, tube-fed lava flows, including ropy pahoehoe surfaces, glassy rinds, and tumuli found near the flow fronts. The phonolitic lavas on Erebus are notable for their large (up to 10 cm long) anorthoclase feldspar crystals. Volcanic activity has been continuous since 1972, producing Strombolian eruptions that eject volcanic bombs on the crater rim.

Reliable dating of the Erebus eruptive history has improved significantly with the advent of noble gas and cosmogenic dating methods. $^{40}Ar/^{39}Ar$ geochronology on lava flows from the flanks of Erebus gives ages ranging from 1311 ± 16 to 26 ± 4 ka (Esser et al., 2004), showing that this volcano is at least 1.3 million years old. Summit eruptions have occurred nearly continuously over the last 100,000 years, although many are <10 ka (Harpel et al., 2004). In detail, the summit flow units can be divided into an older group of pre-caldera flows with ages of 95–76 ka, and a younger group 27–21 ka, accompanied by a shift in melt composition from tephriphonolite to phonolite at ~36 ka. The accuracy of the younger $^{40}Ar/^{39}Ar$ ages (<30 ka) is marred by excess argon, however, making the younger eruptive history unreliable. More recent cosmogenic isotope exposure dating reveals that the youngest eruptive history for the summit caldera ranges from ~4.5 to 8.5 ka (Parmelee et al., 2015).

Within the Ross Island region, possible mechanisms of melting in the Cenozoic alkaline magmatic province include decompression during mantle convection coupled with contamination by lithospheric upper mantle metasomatized during earlier subduction (Finn et al., 2005; Panter et al., 2006) and by rise of a mantle plume (Phillips et al., 2018), both of which have been proposed to explain trace-element and isotopic characteristics. Constraints on the nature of sub-volcanic lithosphere in the source region are provided by xenoliths entrained in volcanic flows. Xenoliths of ultramafic and granulite composition are common in volcanic rocks of the McMurdo Volcanic Group (Kyle et al., 1987; Berg, 1991). Ultramafic xenoliths include clinopyroxenite, spinel lherzolite, wehrlite, and dunite. Spinel lherzolites record temperatures of 880–1100 °C, indicating a mantle origin at depths of 35–70 km (McGibbon, 1991; Wörner et al., 1993; Wörner, 1999). These rocks yield Neoproterozoic and early Paleozoic Rb—Sr isochron ages, indicating that mantle in the western Ross Sea region may share an evolution with overlying continental crust. The granulites are felsic to intermediate in composition and probably represent lower crustal material beneath the volcanic province (Berg, 1991). They are mostly two-pyroxene granulites and clinopyroxenites, thought to have originated at depths of 17–45 km. Xenoliths that are petrographically similar to exposed upper-crustal basement and supracrustal metasedimentary rocks are also known. Lithosphere beneath the province is thus heterogeneous and has a long, complex history, including effects of Ross-age subduction and Mesozoic breakup of Gondwana.

Neogene volcanism can also provide insight to paleoenvironmental conditions at the time of eruption. Minna Bluff is a 45 km-long peninsula formed by overlapping volcanic centers originating at Minna Hook and active between 12 and 4 Ma. As the peninsula grew, it recorded progressive changes in lava composition as well as Miocene-Pliocene paleoenvironmental conditions governing state of the ice sheet margin. Older alternating lavas, volcaniclastic deposits, and domes at Minna Hook are basanite to phonolite in composition, whereas younger basaltic scoria cones dominate in the central and western parts of the peninsula (Wilch et al., 2011). Alternating subaqueous to subaerial eruption features indicate that the eruptions occurred beneath relatively thin ice cover and a dominantly wet-based thermal regime (Wilch et al., 2011; Smellie et al., 2014). Broader consideration of volcanic patterns along the Ross Sea flank of the TAM shows that eruptions occurred in contact with both frozen-bed and thawed-bed ice, but that the basal thermal regime evolved from mainly wet-based (polythermal) to cold-based during the past 12 My (Smellie et al., 2014).

The Hallett province in northern Victoria Land, extending between Cape Adare and Coulman Island, is comprised of several large alkaline volcanoes and other scattered inland exposures of Late Miocene and Early Pliocene age (Kyle, 1990b; Smellie et al., 2011). Like their counterparts farther south, the Hallett volcanoes were active at the margin of the East Antarctic ice sheet, such that their eruptive history was likely influenced by interactions of lavas and ice. The Hallett province contains rocks of the sodic alkaline series and is dominated by bimodal compositions, including basalt, hawaiite, basanite, and trachyte-rhyolite. Magmatism has been alternatively attributed to mantle plume melting, mantle upwelling beneath continental lithosphere, and localized melting along reactivated transtensional faults (Salvini et al., 1997; Rocchi et al., 2002, 2003b, 2005; Nardini et al., 2009). Most of the volcanic rocks are of Late Miocene and Early Pliocene age (≤13.8 Ma), but near Adare Peninsula they are latest Pliocene in age with isotopic ages as young as 2.27 Ma (Armienti and Baroni, 1999). Morphologically, the volcanic structures in the Hallett province resemble shield volcanoes, although the common association of interbedded lavas, volcanic breccias and pyroclastic material is also characteristic of stratovolcanoes (Smellie et al., 2011). The rocks in this part of the Cenozoic volcanic province have been attributed to subglacial, subaerial and submarine eruptive environments. Smellie et al. (2011) interpreted the units in northern Victoria Land to be the product of glaciovolcanic eruptive process, in which both flow units and pyroclastic fall materials interacted with glaciers and proglacial water bodies.

Isolated outcrops of Neogene volcanic rocks occur in the southern TAM near Scott Glacier (Fig. 24). At Mount Early and Sheridan Bluff, olivine-bearing basalts, including hyaloclastites and pillow basalts indicative of subaqueous eruption, were erupted onto a glacially-eroded bedrock surface in the Early Miocene (Stump et al., 1980). Notably, these are the only late Cenozoic volcanics occurring on the cratonic side of the TAM. Reported K—Ar ages of 18–19 Ma established an Early Miocene age that is notably older than volcanics of the McMurdo province, and the origin of this southernmost volcanism is unclear. Recently, Licht et al. (2018) discovered erratics of basalt entrained in glacial moraines near Mt. Howe that have $^{40}Ar/^{39}Ar$ ages of ~17.5 Ma. Their mineralogy and geochemical compositions are similar to volcanic rocks of the McMurdo region, indicating a petrogenetic link. Although the rocks sampled at Mt. Howe were glacially transported, they are correlated with a small, circular negative aeromagnetic anomaly identified by Studinger et al. (2006) that is consistent with the presence of a reversely-magnetized subglacial volcanic center. Licht et al. (2018) suggested that the Miocene volcanism in this area is related to opening of the West Antarctic Rift System and may support an hypothesis of lithospheric foundering beneath the southern TAM interpreted from seismic S-wave anomaly profiles (Shen et al., 2018), offered to explain both the Cenozoic volcanism and uplift history.

3.10. Neogene glacial deposits and landscape

The Neogene (late Cenozoic) history of the Transantarctic Mountains is contained within deposits of the Sirius and Pagodroma groups and other unnamed glacigenic sequences. These deposits provide both a record of landscape evolution, ice-mass extent and paleoenvironmental conditions during a critical period of ice-cap growth and expansion. Although it is generally agreed on the basis of marine sediment records and ice-sheet modeling (Zachos et al., 1996; Lear et al., 2000; DeConto and Pollard, 2003; Hill et al., 2007) that continental-scale glaciation in East Antarctica was initiated ~34 Ma at the Eocene/Oligocene boundary in response to opening of Southern Ocean circulation around Antarctica and a global decline in atmospheric CO_2, the duration and areal extent of the East Antarctic ice sheet over time is highly debated. Global marine sediment records and ice sheet models indicate that small ephemeral ice sheets first appeared in Antarctica by 36 Ma and grew to continental scale until 26 Ma at the onset of Late Oligocene warming. Between about 26–14 Ma the Antarctic ice sheets were variable in extent and/or ephemeral, but since ~14 Ma the East Antarctic ice sheet has been relatively permanent (Zachos et al., 2001). High topography in the TAM make it likely that alpine glaciation likewise initiated there by ~34 Ma (Wilson et al., 2012). The Sirius deposits, mainly in the McMurdo Sound/Dry Valleys area of southern Victoria Land and the Beardmore Glacier area of the central TAM, provide conflicting evidence of ice sheet stability versus periodic ice-mass loss accompanied by marine incursions during periods of climate moderation. Whereas some evidence indicates that Antarctic ice sheets were relatively stable and largely unaffected by global climate change since the middle Miocene (e.g., Denton et al., 1993; Sugden et al., 1995; Marchant et al., 1996; Wilson et al., 2002), marine diatoms within Sirius deposits indicate that a dynamic, fluctuating temperate ice sheet existed through the late Pliocene in East Antarctica (e.g., Prentice et al., 1986; Webb et al., 1984, 1994).

Mercer (1968, 1972) first recognized a series of massive lodgement tills resting on Beacon Supergroup and Ferrar Dolerite mesas that contain a variety of lithic clast types within a fine-grained matrix. These deposits are now included in a broadly defined Sirius Group (McKelvey et al., 1991), an association of Pliocene glacigenic strata that were deposited by wet-based glacial processes. The Sirius deposits include a variety of glacial, glaciomarine, and glaciolacustrine facies, including poorly-stratified lodgement tills and diamicts, and glaciolacustrine, proglacial and fjordal-marine sediments. The Sirius deposits have been well studied in the Dominion Range (McKelvey et al., 1991), along the flanks of Beardmore, Shackleton and Reedy glaciers (Webb et al., 1996; Harwood and Webb, 1998; Wilson et al., 1998), and at Mount Feather and Table Mountains in the Dry Valleys (Wilson et al., 2002; Dickinson and Bleakley, 2005). Since the deposits were first described, other workers have discovered a rich variety of lithic clasts, detrital minerals, paleosols, and fossil biota, including well-preserved wood, plant fragments, insects, mollusks, fish, and microfossils such as diatoms (Harwood, 1986; Webb et al., 1996; Passchier, 2001; Retallack et al., 2001; Wilson et al., 1998, 2002; Ashworth and Kuschel, 2003; Ashworth and Preece, 2003; Ashworth and Thompson, 2003;

Ashworth and Cantrill, 2004; Goodge et al., 2010). Notably, the Sirius Group deposits contain well-preserved leaves and woody stems of the shrub *Nothofagus*, which grew in periglacial settings during periods of warmer and more humid climate. A well-preserved fossil assemblage in the western Olympus Range includes mosses, pollen, insects, ostracods, and diatoms, preserved in periglacial lake sediments deposited ~14 Ma (Lewis et al., 2008). The organisms in this assemblage indicate that summer temperatures averaged at least 5 °C, but subsequent climatic cooling led to their extinction shortly thereafter.

In the Beardmore Glacier area, the mostly non-marine Meyer Desert Formation contains fossil wood, plant roots, fossil plant assemblages and invertebrates that indicate deposition in a lacustrine or periglacial setting (Webb et al., 1994; Ashworth and Cantrill, 2004). The fossils include pollen, seeds, fruits, flowers, leaves, wood, and in situ plants, including *Nothofagus*, mosses and liverworts, conifers, and angiosperms. The periglacial environment in which these plants lived was composed of moraines, glacial outwash streams, well-drained gravel ridges, and poorly drained depressions. Elsewhere, thick glacial diamict units are interrupted by glacial-lacustrine and glacial-fjordal deposits, indicating that during Sirius deposition the ice edge extended to the margin of the TAM where it transitioned to pro-glacial lake and fjordal settings. The TAM, therefore, represented a natural barrier to ice-flow, at times overtopped by ice that carved fjordal valleys outward toward an early Ross Sea. The elevations of glacial deposits perched on modern valley margins (e.g., Sirius deposits at The Cloudmaker along Beardmore Glacier) are ~700 m above the modern glacier level, indicating the ice elevations were once much higher near the coast. At Oliver Bluffs, however, the Meyer Desert Formation is essentially at the same level as the modern glacier, indicating that ice levels have remained fairly uniform.

Webb et al. (1984) ignited a long-running debate about stability of the ice sheet by suggesting that deposits of the Sirius Group contained marine diatoms that indicated large-scale waning of the East Antarctic ice sheet and broad incursion of shallow marine basins into the interior of East Antarctica. In their view, the East Antarctic ice sheet has been quite variable in extent, possibly including several periods of collapse and regrowth. Subsequent ice-sheet models (e.g., Clapperton and Sugden, 1990) indicated general stability of the ice sheets, but a considerable amount of debate has ensued, in particular raising questions about the autochthonous nature of the microfossils (e.g., Barrett et al., 1997; Kellogg et al., 1997; Harwood and Webb, 1998). Dating of volcanic ashes within Neogene deposits in the Dry Valleys area indicate a switch from warm- to cold-based glaciation ~14 Ma, with little glacial erosion between 13 and 4 Ma and preservation of an old landscape (Marchant et al., 1993, 1996; Lewis et al., 2006, 2007, 2008). Debate about the Sirius Group and correlative deposits is compounded by uncertainty in its depositional age and stratigraphic variation along the TAM. Most workers agree that the Sirius is at least Pliocene in age (ca. 2.5–5 Ma), but some argue that an even older Miocene or Oligocene age is possible (Wilson et al., 2002). To date, the age of the Sirius Group is unresolved and beyond the scope of this brief discussion. However, even disregarding the uncertainty regarding the origin of marine diatoms, the presence of tundra-type plant and insect populations indicate that the TAM region of Antarctica experienced warmer climate conditions than the present-day.

Because they are presently ice-free, the Dry Valleys preserve a rich record of glacial landscape evolution. Sugden and Denton (2004) summarized landscape evolution in the broad region surrounding the Dry Valleys as follows: (1) fluvial planation and dissection since ~55 Ma, related to rift-margin uplift of the TAM; (2) local glaciation under temperate conditions beginning about 34–31 Ma and persisting until ~17 Ma, during a change from temperate to polar climate; and (3) expansion across the TAM of the East Antarctic ice sheet between about 15–13.5 Ma, during which time meltwater features scoured the landscape locally toward the coast. Glacial and lacustrine sediments dated to ~14 Ma in the Olympus Range, however, indicate that glacial advance occurred since that time (Lewis et al., 2006, 2007, 2008). These authors also cite glacial geologic evidence that the landscape was modified very little since ~13.6 Ma, mainly restricted to local glacial and subaerial erosion; preservation of the glacial deposits related to this landscape history indicate little tectonic uplift since ~14 Ma. Cosmogenic exposure age dating of boulders in Neogene glacial deposits of the Dry Valleys further indicates that the landscape existed under polar desert conditions yet has been ice-free for at least 3 m.y. (Brook et al., 1995). These age data also suggest little or no uplift in the Dry Valleys region over that time period.

One of the most unique geomorphic features in the TAM is the Labyrinth in the upper Wright Valley, one of the McMurdo Dry Valleys. Here, a series of deeply-incised channels cut into bedrock, mainly of Ferrar dolerite, with some individual channels as much as 250 m deep and 600 m wide (Fig. 7; Lewis et al., 2006). These authors provide evidence that the network of large channels was carved by huge subglacial floods of fast-flowing meltwater >12 million years ago, based on the age of an overlying volcanic ash deposit. It is possible that the flooding resulted from episodic drainage of subglacial lakes in East Antarctica, indicating variable Neogene climate patterns. The meltwater responsible for carving these channels was funneled to the Ross Sea and Southern Ocean, where it may have influenced oceanographic and climate patterns during the Miocene. For the channel morphology to be preserved, very slow rates of erosion are implied, perhaps over millions of years.

4. Structural and tectonic architecture

4.1. Crustal structure of Precambrian basement

Seismic velocity data indicate that crustal thickness varies from ~20 km in the Ross Sea basin, to 40–45 km at the range crest, and about 35–40 km in inland East Antarctica (Lawrence et al., 2006a; Chaput et al., 2014; Hansen et al., 2016). Gravity models indicate that thinner crust (~30 km) underlies the northern Wilkes Subglacial Basin (Ferraccioli et al., 2001), a long-wavelength down-warp behind the Transantarctic Mountains that extends from the Oates Coast to southern Victoria Land (Fig. 8); it is thought to contain thin crust overlain by several kilometers of sediment fill, but its origin is enigmatic (Studinger et al., 2004; Ferraccioli et al., 2001, 2009). Some seismic data indicate that there is a small crustal root beneath the TAM (≤5 km) but that otherwise the Moho is uniformly flat, extending >1300 km inland (Lawrence et al., 2006a). However, a different analytical approach led Hansen et al. (2009) to conclude that there is no crustal root beneath the TAM. Whether or not the uplifted TAM are supported isostatically by buoyant crust depends on the presence or absence of a root, and must await further testing. Seismic velocity and body-wave tomography data also indicate that a prominent transition between high- and low-velocity lithospheric mantle underlies the TAM between about 50–150 km inboard of the present-day range front (Watson et al., 2006; Lawrence et al., 2006b), providing evidence for a sharp lithospheric discontinuity between thick, dense cratonic lithosphere of East Antarctica and an outboard region beneath the Ross embayment characterized by warm, thin lithosphere. New seismic data indicate, however, a shallow zone of low-velocity upper mantle lithosphere extending as much as 350 km inland of the southern TAM and overlying a deeper high-velocity root (Shen et al., 2018). These authors suggest that sinking of cold cratonic lithosphere and incursion of warmer mantle above is the cause of high elevations and uplift of the mountain range, as discussed further below.

In the central TAM, exposures of Precambrian basement, coupled with high-resolution magnetic data, other nearby aeromagnetic transects, and satellite magnetic and seismic tomography data (Goodge and Finn, 2010), show that the shield in this region comprises an Archean craton modified both by Proterozoic magmatism and early Paleozoic orogenic basement reactivation. The magnetic anomaly pattern over exposed geology of the Nimrod Glacier region provides direct imaging of the crystalline basement and supracrustal rocks of the TAM, including differentiation of a Precambrian metamorphic terrain, Granite Harbour plutons, Ferrar dolerites, and Ross-age thrust faults within the outboard sedimentary molasse belt. In contrast to other areas, the relationships there between basement and supracrustal sequences are well defined and correlate well with the known geology.

High-amplitude satellite and aeromagnetic anomalies define the extent of a large igneous province not recognized in exposure but interpreted to represent a Proterozoic igneous terrain lying inboard of exposed Archean-Paleoproterozoic basement (Goodge and Finn, 2010). Independent evidence for the existence of the so-called Nimrod igneous province is provided by glacially-derived granitoid clasts with ages of ~2.01, 1.88–1.85, ~1.79, ~1.57, 1.50–1.41, and 1.20–1.06 Ga that were sourced from the same subglacial region (Goodge et al., 2008, 2010, 2017). Magnetic anomaly patterns distinguish crystalline basement reworked during the high-grade Ross Orogeny from the unmodified Precambrian craton. Basement structures linked to the Ross Orogeny are imaged 50–100 km farther west than previously known, bounded by inboard upper-crustal Proterozoic granites of the Nimrod igneous province. These geographically defined structures form a zone of reactivated Precambrian basement similar to inliers observed in Australia along the margins of the Curnamona Province. Because the two basement domains show similar trends but different anomaly amplitudes and wavelengths, it is likely that Ross reactivation of the crystalline basement rocks was focused along older cratonic trends. Conversely, the angular relationship evident in the magnetic structure between basement and supracrustal (rift-margin and molasse-basin sediments) rocks probably reflects strain partitioning within the Ross Orogen between crystalline basement (oblique slip) and supracrustal rocks (orthogonal shortening), thought to be a result of oblique convergence (Goodge et al., 1993a; Goodge, 1997).

Magnetic contrasts between craton and rift-margin sediments define the Neoproterozoic rift margin, likely reactivated during Ross orogenesis and Jurassic extension. Interpretation of satellite magnetic and aeromagnetic patterns suggests that the Neoproterozoic rift margin of East Antarctica is offset by transfer zones to form a stepwise series of salients tracing from the central TAM northward through the western margin of the Wilkes Subglacial Basin, to the coast at Terre Adélie (Fig. 8; Goodge and Finn, 2010; discussed further below). These Neoproterozoic structures may have been reactivated during the Cenozoic, providing a pathway for Miocene and younger volcanic rocks (Wilson, 1999).

Isotopic data from the Granite Harbour Intrusions and their host rocks enabled Borg et al. (1990) to divide crust of the central and southern TAM into three distinct basement provinces: (a) Archean-Proterozoic crust (presently exposed in the Miller and Geologists ranges) distinguished by depleted-mantle Nd model ages (T_{DM}) ≥ 2.0 Ga; (b) Proterozoic crust underlying much of the mountain belt, with T_{DM} = 1.8–1.3 Ga; and (c) an outboard crustal province with T_{DM} = 1.2–1.1 Ga. Further work in the Horlick Mountains to the south expanded the latter province to include crust with T_{DM} between 1.4 and 1.1 Ga (Borg and DePaolo, 1994). Metamorphic and pre-Ross igneous rocks in the Nimrod Complex have Nd model ages between 3.5 and 2.7 Ga (Borg et al., 1990; Borg and DePaolo, 1994), confirming the antiquity of the most inboard exposed crust sampled by Granite Harbour Intrusions in the Miller Range. These older basement rocks yield igneous and metamorphic crystallization ages of ~3.1, ~2.9, and ~1.7 Ga (Goodge and Fanning, 1999, 2016; Goodge et al., 2001). No rocks representing crust of the two outboard provinces are known. The boundary between the two inboard Archean and Proterozoic isotopic provinces appears to underlie Marsh Glacier (Fig. 12; Goodge and Finn, 2010; Goodge et al., 2012), marking a fundamental geological, geophysical and geochemical divide that likely influenced the movement and composition of Granite Harbour Intrusion magmas during emplacement. This boundary may also correspond to the ancient (Neoproterozoic) rift margin formed during Rodinia breakup that is recognized on the basis of rift-margin stratigraphy (Goodge et al., 2002, 2008; Myrow et al., 2002b) and geophysical characteristics (Finn et al., 2006; Goodge and Finn, 2010).

4.2. Neoproterozoic rift margin

The presence of Precambrian cratonic basement along the western side of the TAM, where such rocks are not exposed, is revealed by geophysical methods that image through the ice cover. Gravity and magnetic data, for example, show that thick continental lithosphere beneath the ice cap traces the western limit of the modern TAM (Studinger et al., 2004, 2006; Goodge and Finn, 2010; Ferraccioli et al., 2009). East Antarctic cratonic lithosphere is thought to be a key part of the Paleoproterozoic to Mesoproterozoic Columbia supercontinent assembly that includes Australia, India and Laurentia. The long-lived association of East Antarctica, Australia and Laurentia likely persisted from about 1.9–1.2 Ga, to be succeeded as part of Neoproterozoic Rodinia by ~1.1 Ga based on correlation of Proterozoic features (Goodge et al., 2001, 2008, 2017; Goodge and Fanning, 2016). Beneath and to the east of the TAM, Antarctic lithosphere is thinner and younger. The coincidence of this change in lithospheric character with the TAM suggests that the modern mountain belt overlies an ancient continental rift margin. Geological, stratigraphic and geochronological data from rare outcrops indicate that rifting occurred between about 750–680 Ma (Goodge, 2002; Goodge et al., 2002, 2004b; Wysoczanski and Allibone, 2004; Cooper et al., 2011), separating what became East Antarctica to the west from a conjugate continental plate to the east (again, using local geographic coordinates as shown in Fig. 8). Clastic strata and volcanic rocks of the Beardmore, Skelton, and Koettlitz groups are the main expressions of this rift margin in the TAM. Early ideas based on paleogeographic and paleomagnetic data suggested that East Antarctica rifted from present-day Laurentia (Moores, 1991; Dalziel, 1991, 1997), and this interpretation is supported by a variety of geological evidence, including correlation of igneous and metamorphic basement geology, glacial erratic signatures, distinctive igneous isotopic signatures, sedimentary provenance relations, detrital zircon isotopic signatures, distinctive IOCG mineralization, and paleomagnetism (see discussion and references in Goodge et al., 2017).

The resulting geometry and nature of the late Precambrian rift margin in East Antarctica shaped subsequent geologic events in the TAM. Between the time of rift separation and convergence linked to the Ross Orogeny, the paleo-Pacific continental margin of Antarctica was blanketed by late Neoproterozoic clastic sediment, interlayered with minor volcanic material, and culminating in deposition of thick Lower Cambrian reef carbonates deposited on a mature continental platform during a period of global sea-level rise (Laird et al., 1971; Myrow et al., 2002b). Marine fauna in the carbonates suggest East Antarctica resided in a low-latitude position and was geographically linked with other extant continents (Rees et al., 1989; Rowell and Rees, 1991).

Aeromagnetically, the Neoproterozoic rift margin of East Antarctica is expressed by a contrast between high-amplitude positive anomalies and relatively less magnetic terrain to the east (Fig. 8). In the central TAM transect (Goodge and Finn, 2010), the rift margin is inferred to separate reworked basement from the immediately adjacent Ross belt, including outboard supracrustal rocks, and Granite Harbour and Ferrar magmatic rocks. Farther north, the rift margin as defined by the outer edge of highly magnetic craton is more widely separated from the main Ross orogenic belt, possibly by intervening Ross magmatic or rift-margin remnants (Ferraccioli et al., 2009), suggesting that attenuated rift-margin crust and/or a Ross accretionary province underlie the TAM and adjacent Wilkes Subglacial Basin. Long-wavelength magnetic patterns along the inner Ross Orogen between the South Pole area and the Oates Coast offshore northern Victoria Land indicate that the Neoproterozoic rift-margin associated with breakup of Rodinia in East Antarctica forms a step-wise system of salients and embayments that may have formed as rift-margin transfer zones. Although such accommodation zones are based mainly on interpretation of satellite magnetic anomaly patterns, they likely played a role in guiding regional deformation patterns related to Ross orogenesis, Jurassic extension and Cenozoic rifting. For example, Foley et al. (2011) found ~1 km of south-side-up displacement on fault(s) inferred to underlie Byrd Glacier, with integrated movement between about 180–40 Ma, such that inherited Neoproterozoic structures may have guided the locus of this younger displacement. Thinned Precambrian crust inferred to lie east of the rift margin was not imaged magnetically in the central TAM because of modification by Neoproterozoic and younger tectonic events (Goodge and Finn, 2010), but recent aeromagnetic data acquired over the Ross Ice Shelf indicate that thinned orogenic crust like that in the TAM may extend beneath the eastern Ross Sea (Tinto et al., 2019). If this interpretation of the potential-field data can be substantiated with seismic data and other observations, these results may indicate that a tract of highly extended East Antarctic or Ross Orogen crust may underlie the eastern Ross Sea, thereby providing an explanation for truncation of Ross Orogen trends and a more detailed picture of the structure of the Rodinia rift margin.

4.3. Active Ross margin of Gondwana

The Ross Orogen, one of the world's longest orogenic belts, was active during the latest Neoproterozoic and early Paleozoic amalgamation of Gondwana (see Goodge, 2002, for a summary). Whereas the western rift margin of East Antarctica coincided with breakup of Rodinia, formation of the Gondwana supercontinent transformed the TAM margin of Antarctica to an active convergent boundary. Subduction along this margin of Antarctica occurred in response to closure of the ancient Mozambique Ocean and collision within the East African Orogen beginning about 600–500 million years ago (widespread features of this age also comprise the Pan-African Orogen). The resulting Ross Orogeny in Antarctica refers to the period of latest Proterozoic and early Paleozoic tectonic activity related to continental-margin subduction and deformation. Together with the Delamerian Orogen in Australia and the Pampean Orogen in Argentina, the Ross belt thus represents tectonic activity associated with a convergent continental margin along the outer, paleo-Pacific rim of Gondwana (see Flöttmann et al., 1993; Rapela et al., 1998; Foden et al., 2002, 2006; Cawood, 2005).

The present-day Transantarctic Mountains (Fig. 9) are underlain by Archean and Proterozoic cratonic basement, upper Proterozoic and lower Paleozoic marginal-basin assemblages, and an early Paleozoic oceanic-arc remnant, described above, all affected by early Paleozoic deformation attributed to plate-margin convergence and engulfed by a granitic batholith system. Ross activity can be reconstructed chiefly from spatial and temporal patterns of sedimentation, deformation, and magmatism, which reflect oblique plate convergence along the active Gondwana margin. Based on lithotectonic assemblages, trace-element and isotopic patterns of calc-alkaline arc magmas, *P-T* conditions of metamorphism, and style of contractional deformation, the Ross Orogen is considered by most workers to be a Cordilleran-type, active continental-margin orogenic belt. Possible modern analogs include the Andean margin of South America, or convergent systems developed along continental microplates such as at the Sumatra or Japan margins of the Indian and western Pacific oceans. As in the Andes today, however, there are a number of uncertainties regarding timing and sequence of events, allochthonous nature of the lithotectonic assemblages, and possible oblique or margin-parallel kinematics. The location, scale, and geochemical characteristics of the Ross magmatic arc seem to require subduction beneath continental lithosphere, and the observed sedimentation and deformation patterns suggest both a low-latitude paleogeographic position and sinistral-oblique paleo-Pacific underflow. There is considerable debate, however, about the relative obliquity of subduction through time and its influence on magmatic patterns.

As geochronology improves, a detailed sequence of events spanning the period 550–480 Ma is being extended to at least 600 Ma (Fig. 36). Subregions of the orogen differ in detail, but the active continental margin witnessed rift-basin inversion, carbonate deposition, clastic molasse-type sedimentation, bimodal and calc-alkaline magmatism, regionally diachronous volcanism, high-grade basement reactivation, oceanic arc interaction, and transpressional deformation partitioned between basement and supracrustal assemblages. Initial deformation linked to Ross activity is preserved in deep-seated crystalline basement as well as in younger rift-margin deposits and can be traced to ~540 Ma, and convergent-margin metamorphism is evident as early as ~615 Ma. Volumetrically significant magmatism was underway in most areas by ~550 Ma, whereas the youngest post-tectonic plutons are ~480 Ma. Many syn-orogenic sedimentary deposits, as well as Neogene glacial erratics, contain igneous detritus with ages of ~580–600 Ma, suggesting early erosion of a continental-margin magmatic belt that is a signature feature of Ross activity. It appears, therefore, that the Ross orogenic cycle was punctuated by a series of linked but diachronous events spanning as much as 145 m.y.

The breadth and character of these deformation, metamorphic, magmatic and sedimentation patterns suggest that the Ross Orogen was similar in scale to other large mountain belts, and it is well-exposed today as basement to the modern TAM. Orogenic features related to Ross shortening and magmatism can be traced from Victoria Land southward along the main spine of the TAM to the Queen Elizabeth and Queen Maud mountains, then to the Ellsworth and Pensacola Mountains. A few key aspects of the Ross events in different regions of the TAM are outlined below, again from north to south.

4.3.1. Northern Victoria Land

Many of our ideas concerning tectonic evolution of the Ross Orogen stem from geological study in northern Victoria Land, although as we will see the geologic and petrologic patterns there differ significantly with other parts of the orogen. Northern Victoria Land is underlain by three major late Neoproterozoic and early Paleozoic tectonic elements, as noted earlier, which are variably deformed and metamorphosed. The presence of map-scale contractional structures (mainly upright folds and thrusts), discontinuities between different metamorphic *P*/*T* types, and early to middle Paleozoic I-type plutonic suites are all indicative of a convergent-margin tectonic setting in the latest Precambrian to early Paleozoic (Grew et al., 1984; Bradshaw et al., 1985; Gibson and Wright, 1985; Borg et al., 1987; Kleinschmidt and Tessensohn, 1987; Flöttmann and Kleinschmidt, 1991a, 1991b; Dallmeyer and Wright, 1992; Goodge and Dallmeyer, 1996; Ricci et al., 1997; Schüssler et al., 1999). Others have stressed the role of strike-slip tectonics (Weaver et al., 1984) or proposed the accretion of allochthonous terranes (Bradshaw et al., 1985), yet numerous connections are apparent between the various tectonic elements and reflect a coherent convergent-margin architecture (see, for example, Tessensohn and Henjes-Kunst, 2005; Federico et al., 2006; Rocchi et al., 2011).

Metamorphic rocks of the Wilson Group to the west consist dominantly of quartzofeldspathic layered paragneisses characterized by low-*P*/*T* parageneses, polydeformation, and abundant migmatitic/plutonic complexes (Kleinschmidt and Skinner, 1981; Babcock et al., 1986). An important metamorphic break is inferred to underlie Rennick Glacier, separating inboard low-*P*/*T* gneisses to the west from medium- to high-*P*/*T* schists and gneisses to the east in the Lanterman, Salamander and Mountaineer ranges (Fig. 37; Grew et al., 1984; Kleinschmidt and Tessensohn, 1987; Talarico et al., 1998). A similar pattern occurs farther south near Terra Nova Bay and the Deep Freeze Range, where polymetamorphic gneisses with early moderate-*P*/*T* parageneses are distinguished from high-*T* granulites and migmatites (Lombardo et al., 1987; Castelli et al., 1991). Wilson Group gneisses are separated from the Bowers terrane by steeply-dipping faults and shear zones (Wodzicki et al., 1982; Gibson, 1984; Roland et al., 1984; Sandiford, 1985; Capponi et al., 2002), but the age and tectonic significance of

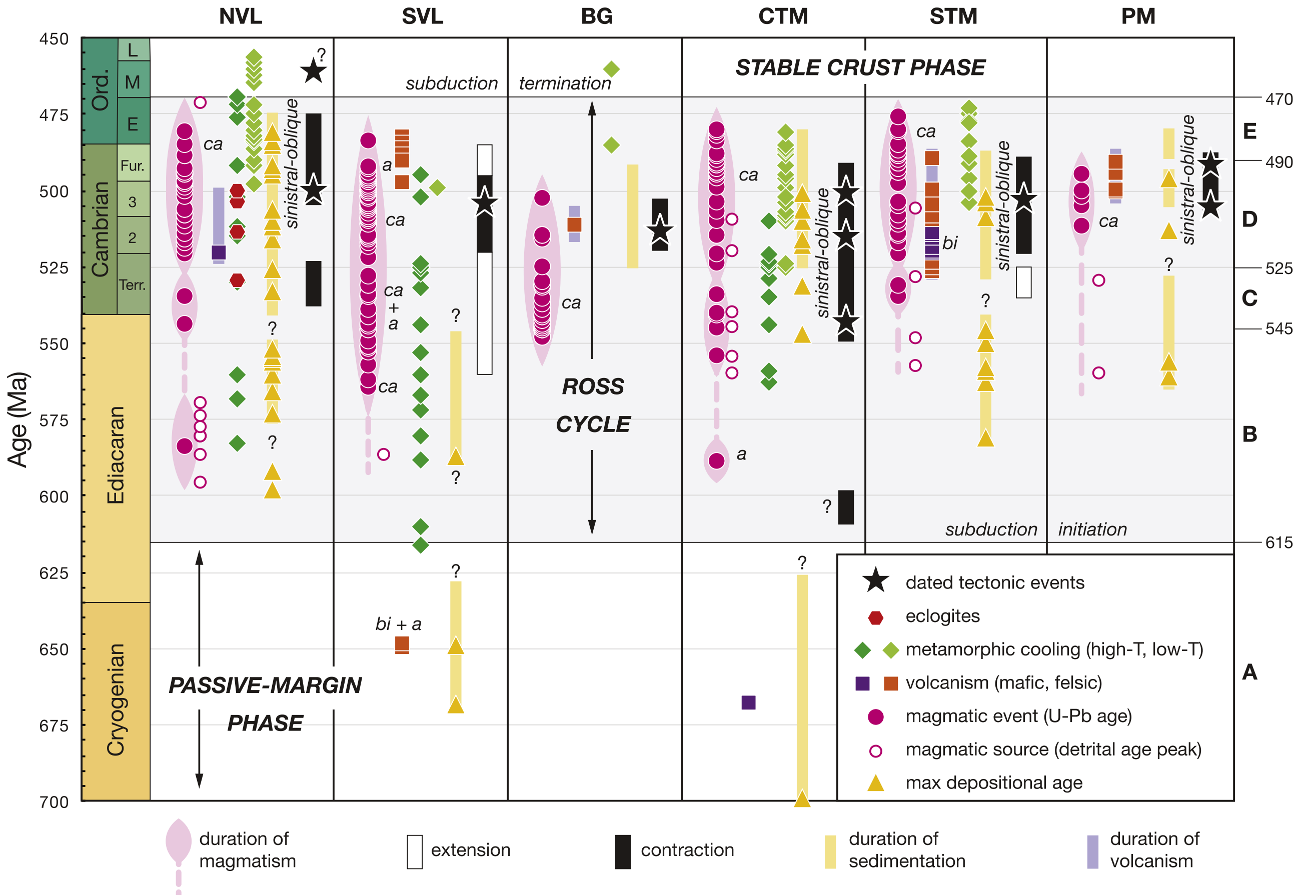


Fig. 36. Timeline showing important tectonic events leading up to and during the Ross Orogenic cycle. References to dated events cited in text. Events with geochronological control shown by symbols in legend, and duration of events inferred from stratigraphic, magmatic and structural relations shown by colored vertical bars indicated below diagram. Cryogenian to early Ediacaran phase of extension and subsidence during a pre-orogenic passive-margin phase between about 670–650 Ma is marked by bimodal and mafic volcanism and siliciclastic sedimentation. Onset of Ross orogenic cycle marked by ca. 615 Ma high-grade metamorphism and magmatism commencing by ca. 590–565 Ma. Continuity of magmatism between about 590–475 Ma is shown by major peaks in detrital-zircon age spectra (white circles with red outline) from syn-orogenic siliciclastic deposits. Periods of convergent-margin upper-plate contraction and extension (black and white bars, respectively) inferred from regional structural data and alternating magmatic compositions, although data from NVL, CTM, STM, and PM indicate strain partitioning during sinistral-oblique underflow. Ordovician upper bound of Ross orogenic cycle and establishment of stable post-orogenic crust is marked by end of magmatism and low-T metamorphic cooling ages in all areas. Total duration of the Ross cycle is therefore in the range of about 145 m.y. NVL, northern Victoria Land; SVL, southern Victoria Land; BG, Byrd Glacier area; CTM, central Transantarctic Mountains; STM, southern Transantarctic Mountains; PM, Pensacola Mountains. Letters A-E correspond to periods shown in paleotectonic maps (Fig. 52).

these zones are controversial. In northern Victoria Land the Ross Orogeny resulted in pronounced folding of Lower Ordovician rocks in the Bowers and Robertson Bay terranes (Bradshaw et al., 1985; Gibson and Wright, 1985), in diachronous cleavage development within the Robertson Bay Group (Dallmeyer and Wright, 1992), and ductile thrusting of Wilson Group metamorphic rocks (Kleinschmidt and Tessensohn, 1987; Flöttmann and Kleinschmidt, 1991a; Schüssler et al., 1999).

4.3.2. Southern Victoria Land

Metasedimentary rocks in southern Victoria Land comprise a highly complex, polydeformed metamorphic terrane inundated by magmatic rocks. As noted earlier, the metamorphic rocks pre-date emplacement of the Granite Harbour intrusives (Early Cambrian to Ordovician alkaline and calc-alkaline rocks), but a lack of fossils, strong deformation, and high-*T* regional metamorphism obscure their stratigraphic and age relationships (e.g., Findlay et al., 1984). Pre-granitic host rocks belonging to the Skelton and Koettlitz groups are exposed in separate areas, but they both include marbles, migmatitic schists and orthogneisses, amphibolite, calc-silicate gneiss, meta-arkose and rare pelitic schist, interlayered at all scales (Findlay et al., 1984; Cox, 1993). The character of the metamorphic lithologies and available geochronology suggest the protoliths are heterogeneous marginal-basin deposits and interlayered minor volcanic units, probably accumulated in a rift-margin setting (Goodge et al., 2004b; Wysoczanski and Allibone, 2004; Cooper et al., 2011). No known elements of the pre-Neoproterozoic East Antarctic craton are present. Intrusive rocks comprising the Granite Harbour batholith dominate the exposed sub-Beacon geology of southern Victoria Land, particularly in the Dry Valleys area, but, as noted below, the batholith is represented by distinct compositional phases at different stages in its evolution.

4.3.3. Central TAM

Ross activity affected both crystalline basement (Nimrod Complex and Argosy Schist) and supracrustal successions (Beardmore and Byrd groups). Ductile L-S tectonite fabrics and folds of Ross age are pervasive in the high-grade terrain of the Miller and Geologists ranges, and kinematic features at all scales record top-to-the-SE (local coordinates) displacement through a minimum structural thickness of 12–15 km (Goodge et al., 1993a). Shear fabrics in the basement are distinctly oblique in their orientation relative to coeval contractional structures observed within outboard supracrustal units (Goodge, 1997), suggesting a sinistral-oblique transpressional plate margin during Ross time (Fig. 38). A host of mineral chronometers constrain the age of peak igneous activity, deformation, metamorphism, and cooling in the basement assemblage through the Ross orogenic cycle between about 540–485 Ma (Goodge and Dallmeyer, 1992, 1996; Goodge et al.,

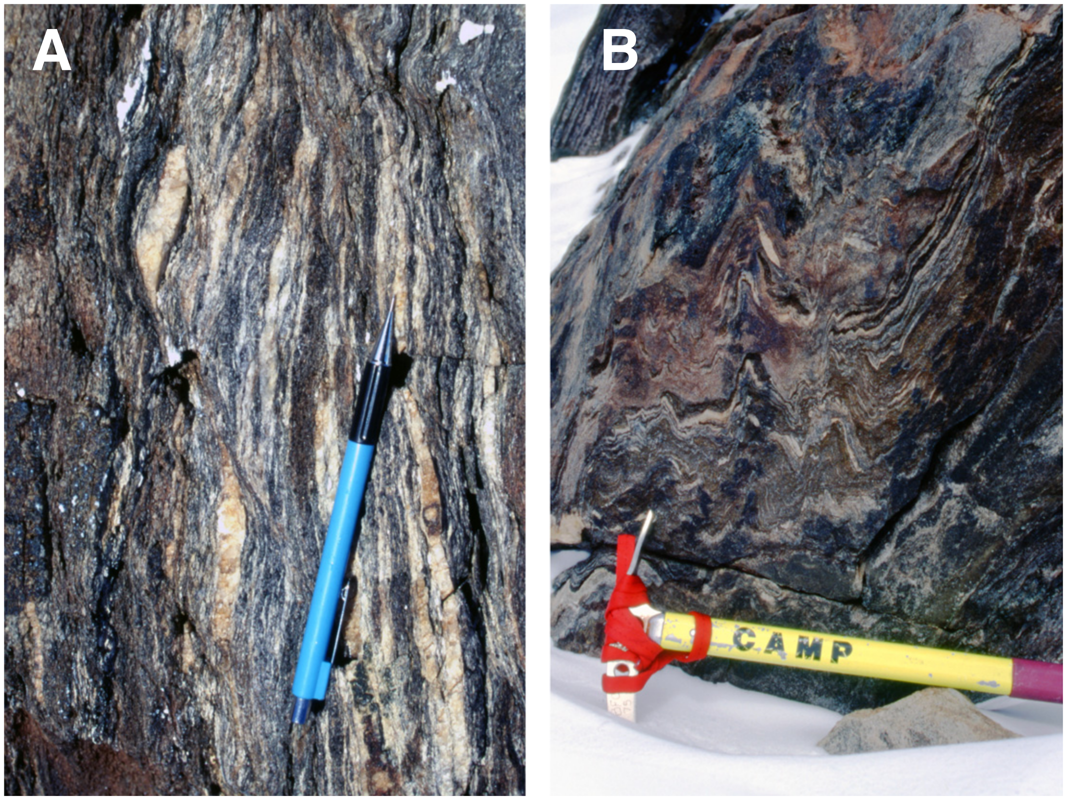


Fig. 37. Schists and gneisses of the Lanterman Metamorphic Complex in the Lanterman Range, northern Victoria Land. (A) Sheared pelitic schist with offset quartz-rich veins. Pencil for scale. (B) Quartzofeldspathic gneiss with representative layering. Ice axe for scale.

1993b, 2001, 2012; Goodge and Fanning, 1999, 2016), permitting a distinction of Ross from older events and an assessment of basement reactivation during plate-margin orogenesis. High-grade Ross metamorphism and deformation likely peaked ~525 Ma, based on U—Pb dating of syn-kinematic monazite in Argosy pelitic schists (Goodge et al., 1993b). The effects of Ross-age dynamothermal activity on Nimrod Complex gneisses is also shown by zircon crystals with texturally distinct overgrowths on older cores, as well as newly crystallized metamorphic zircon. Zircon overgrowths in these gneisses have ages of about 545–490 Ma (Goodge and Fanning, 1999, 2016; Goodge et al.,

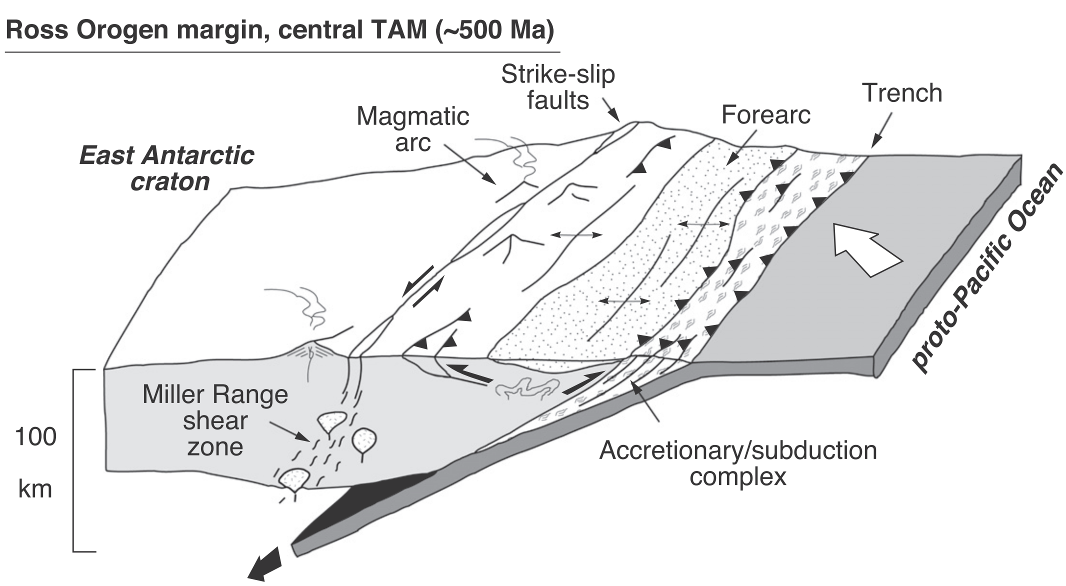


Fig. 38. Schematic diagram of Transantarctic Mountains plate-boundary regime at ~500 Ma (after Goodge et al., 1993a). In this model, relative plate motions involving left-oblique subduction between the East Antarctic shield and proto-Pacific oceanic lithosphere are partitioned into both contractional and strike-slip components of deformation. Inboard strike-slip faults that become shallow with depth away from the subducting plate diffuse into broad zones of ductile shear in the root zone of a magmatic arc represented at depth by the Granite Harbour intrusives. The Miller Range shear zone formed as a result of strike-parallel ductile displacement at depths >25 km. Deformation in the forearc region occurred by punctuated contraction of supracrustal sedimentary rocks, including possible Neoproterozoic deformation of rift-facies Beardmore Group clastics and Middle Cambrian to Early Ordovician fold and thrust deformation of pretectonic to syntectonic Byrd Group sediments. Rocks of an accretionary subduction complex are not preserved.

2001). A compositionally diverse suite of igneous rocks that show variable development of solid-state deformation fabrics intrudes the basement metamorphic tectonites; these include tonalite, diorite and granodiorite with U—Pb zircon ages that range from about 545–505 Ma (Walker and Goodge, 1991; Goodge et al., 1993b, 2012). Variations in fabric development with age indicate progressively weakening Ross tectonism during the Early Cambrian. The U—Pb data described above all point to pronounced reactivation of crystalline basement during Ross time, followed by progressive post-orogenic cooling between about 525–485 Ma (Goodge and Dallmeyer, 1992, 1996).

Supracrustal rocks in the central TAM developed largely contractional structures expressed as upright folds and localized thrusts (Laird et al., 1971; Oliver, 1972; Goodge, 1997; Goodge et al., 2004a). Post-orogenic erosion and peneplanation is prominent here, represented regionally by the Kukri Erosion Surface (Gunn and Warren, 1962) and visible as a sharp angular unconformity (Maya Erosion Surface) beneath Beacon strata in the central TAM (Fig. 39).

4.3.4. Southern TAM

The southern TAM, from Shackleton Glacier to the Queen Maud Mountains, are underlain by early Paleozoic (mostly Cambrian) sedimentary and volcanic successions, invaded by voluminous granitoids (McGregor, 1965; Wade and Cathey, 1986). The supracrustal sedimentary and volcanic rocks show similar deformation patterns as seen farther north in the central TAM in and northern Victoria Land, consisting mainly of upright fold structures imparting a strong structural grain parallel to the modern range. Notable differences occur in the Shackleton Glacier area, however, where early contractional features defined by upright folding parallel to the main trend of the orogen, are succeeded by a late oblique or transpressional phase, resulting in formation of steeply-plunging boudins and sinistral strike-slip shear zones (Paulsen et al., 2004). Tight folds and localized shear zones trending at a high angle to the main structural grain correspond with a boundary separating areas to the south underlain by volcanic rocks from an area to the north where volcanic rocks are absent. Although it is difficult to know whether volcanism was absent north of Shackleton Glacier or simply eroded, the glacier appears to mark a structural boundary that may explain patterns in distribution and composition of magmatic rocks formed during Ross time.

4.3.5. Ross deformation

Tectonism attributed to the Ross Orogeny is widely expressed by structural shortening of upper Neoproterozoic marginal-basin strata and platform carbonates of Early Cambrian age. In many cases, the primary strains appear to be contractional with maximum shortening perpendicular to the orogenic axis. Orthogonal contraction is also the predominant style within metamorphic units of northern Victoria Land. Elsewhere, non-orthogonal shortening (e.g., Rees et al., 1987; Paulsen et al., 2004) may reflect local strain variations due to the interactions of deforming cover and inherited basement structures. Non-orthogonal deformation is also observed in the metamorphic and igneous Ross basement, which records intra-arc orogen-parallel displacements (Goodge et al., 1991, 1993a; Jones, 1997; Musumeci, 1999). Orogen-parallel ductile flow in the deeper, rheologically weaker parts of the orogen directly establishes the framework of oblique convergent-margin transpression (Goodge et al., 1993a). Alkaline A-type magmatism in southern Victoria Land is thought to reflect local extension within dilational jogs of such an obliquely convergent margin (Cooper et al., 1997; Read et al., 2002).

In northern Victoria Land the Ross Orogeny resulted in pronounced folding of Paleozoic rocks in the Bowers and Robertson Bay terranes (Bradshaw et al., 1985; Gibson and Wright, 1985), in diachronous cleavage development within the Robertson Bay Group (Dallmeyer and Wright, 1992), and ductile thrusting of Wilson Group metamorphic rocks (Kleinschmidt and Tessensohn, 1987; Flöttmann and Kleinschmidt, 1991a, 1991b; Schüssler et al., 1999). Wilson Group gneisses are separated from the Bowers terrane by steeply-dipping faults and shear zones (Wodzicki et al., 1982; Gibson, 1984; Roland et al., 1984; Sandiford, 1985; Capponi et al., 2002), which extend notably into the Wilson terrane in the Deep Freeze Range near Terra Nova Bay (Rossetti et al., 2011). Likewise, the boundary between the Bowers and Robertson Bay terranes (Millen Schist belt) has a long-lived contractional history (Crispini et al., 2014).

In the central TAM, extending from Byrd Glacier southward to Shackleton Glacier, the classic expression of Ross deformation is in upright folds of the Neoproterozoic to lower Paleozoic supracrustal successions. Perhaps most dramatically displayed are the Alpine-scale folds of thick-bedded Shackleton Limestone at Cambrian Bluff along Nimrod Glacier (Fig. 40). However, ubiquitous outcrop-scale deformation is observed within interlayered quartzites and slates of the Beardmore Group (Fig. 41), and regular upright folding and associated cleavage development in sandstone-shale sequences in the Starshot Formation (Figs. 42A-C). These contractional structures in the supracrustal rocks, in conjunction with detrital zircon geochronology and detailed mapping of east-vergent thrust patterns, provide a large-scale view of structures

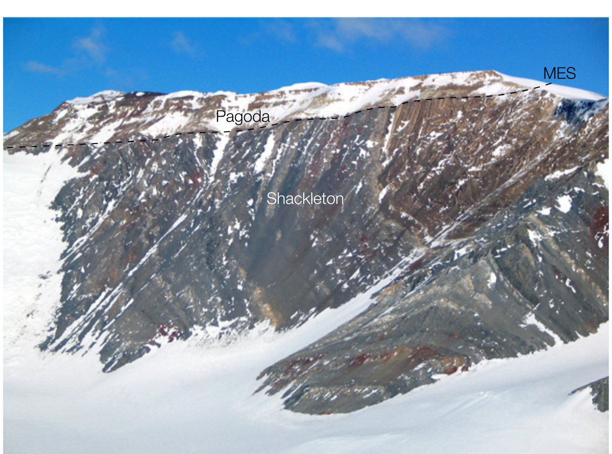


Fig. 39. Exposure of Beacon angular unconformity near Solitary Peak, central TAM. View looking south, showing subhorizontal strata of Pagoda Formation tillite (Lower Permian) overlying Shackleton Limestone along Maya Erosion Surface (MES).

Fig. 40. Cambrian Bluff on the northern margin of Nimrod Glacier and the southern end of the Holyoake Range, looking WSW (approximately up-glacier). Light-colored, thick-bedded rocks to left are Lower Cambrian Shackleton Limestone, folded and in thrust contact with underlying dark, thin-bedded siliciclastic rocks of the upper Byrd Group (Starshot Formation). Dark irregular patch in center of view is an early Paleozoic gabbro. A minimum conservative structural interpretation is shown based on geochronology (see Goodge et al., 2004a), but it is difficult to resolve geometrically from this perspective and because of the difficult outcrop access and extreme relief.

Fig. 41. Folded Goldie Formation fine-grained schists at Cotton Plateau, near Nimrod Glacier, central Transantarctic Mountains. Marking pen for scale is subparallel to fold axes.

in the central TAM (Fig. 43). The contrasting kinematic expression of orogen-normal contractional deformation in outboard supracrustal units (Beardmore-Byrd groups) with synchronous but deeper-level, orogen-parallel displacements within ductile tectonites of the Nimrod Complex and Argosy Schist during Ross time illustrate a pattern of strain partitioning that reflects oblique transpression along this part of the orogen (Goodge, 1997). Biostratigraphic and thermochronologic constraints indicate a relatively brief period of supracrustal deformation in the supracrustal rocks, between ~515 and 505 Ma (Fig. 44; Myrow et al., 2002b; Goodge et al., 2004a, 2004b; Paulsen et al., 2007). Ductile flow in the deeper parts of the orogen occurred mainly earlier, between about 540–510 Ma (Goodge et al., 1993b). Together, these contrasting temporal, kinematic, and rheological patterns reflect sinistral-oblique convergent margin activity during the Ross orogenic cycle (Fig. 45; Goodge et al., 1993b; Goodge, 1997).

Similar patterns are observed in the southern TAM and the Pensacola Mountains, underlain by latest Neoproterozoic to Cambrian sedimentary and volcanic strata. The most common deformation features in a broad area of the southern TAM are upright folds and associated axial-plane cleavage (McGregor, 1965; Stump, 1981; Stump et al., 1986), representing a consistent pattern of Ross contraction over a large area. Near Shackleton Glacier, however, polyphase Ross deformation of the Liv Group, a sequence of Cambrian volcanic, volcaniclastic, clastic and carbonate rocks, includes both contractional and strike-slip geometries (Paulsen et al., 2004, 2008). Deformation in this area is slightly younger than in the central TAM (in part <505 Ma), but metamorphic cooling ages in igneous and metasedimentary rocks between 500 and 470 Ma constrain a period of late to post-orogenic cooling and uplift that overlaps that reported from the central TAM (Goodge et al., 2004a). Similar to the central TAM, lower Paleozoic rocks in the Shackleton Glacier area also appear to record deformation in a sinistral transpressive regime that occurred from at least 540 Ma to <490 Ma (Paulsen et al., 2008, 2018). In the Pensacola Mountains area, Ross contractional deformation occurred in two pulses in the latest Middle Cambrian to early Late Cambrian, as constrained by biostratigraphy and geochronology (Fig. 46; Curtis et al., 2004). The first of these, mainly expressed in latest Neoproterozoic strata of the Hannah Ridge Formation from the Neptune Range, produced a penetrative set of steep isoclinal folds with a slaty axial-plane cleavage, which was in turn overprinted by a set of asymmetric folds with geometries interpreted to be a result of sinistral reactivation. Early Ross deformation of the Hannah Ridge Formation preceded two later events attributed to Ross activity—a middle (late Middle Cambrian to early Late Cambrian) extensional phase, marked by sediment deposition and volcanism, and a later (Late Cambrian), weakly-developed Ross contractional deformation affecting the Nelson Limestone and associated volcanic strata (Rowell et al., 2001; Curtis, 2002; Curtis et al., 2004; Curtis and Storey, 2003). Like the central TAM, there appears to be evidence for multiple events of Ross age that are the combined product of shortening and sinistral transpression/translation in later phases of displacement.

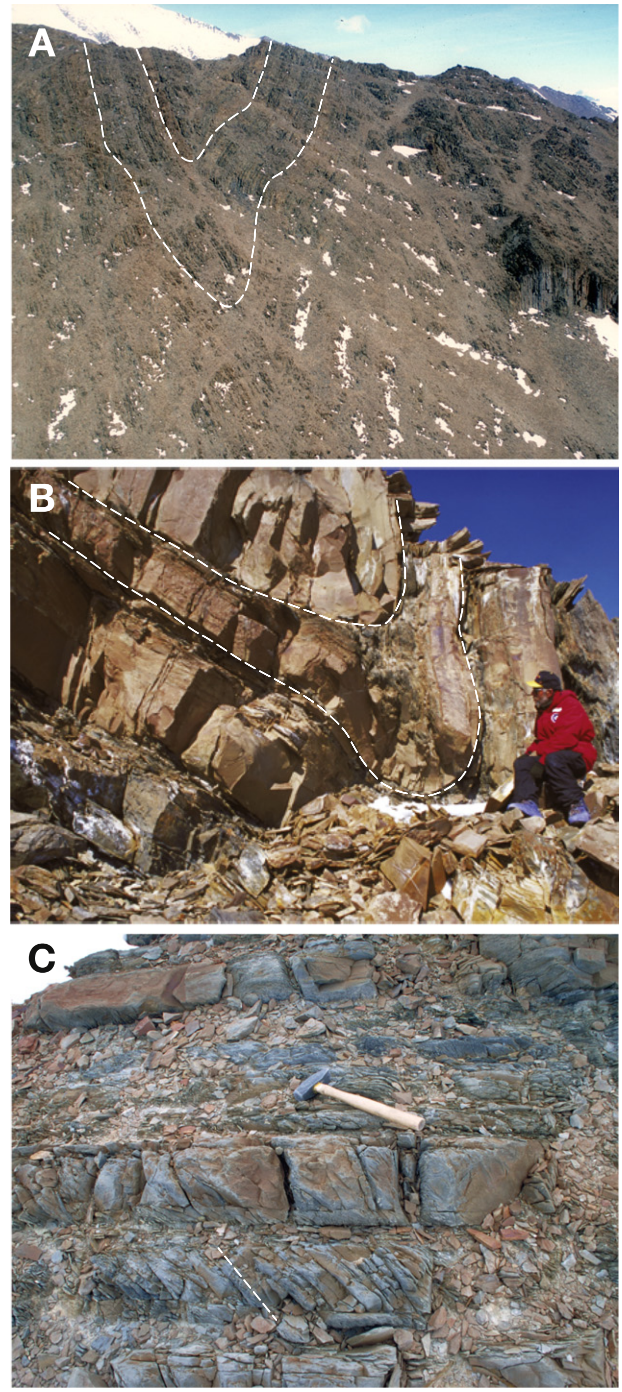


Fig. 42. Ross-age structures within the Starshot Formation. (A) Sequence of interbedded quartzites and slates at Masquerade Ridge, Lowery Glacier area, central TAM, showing upright Ross folds. View looking south. (B) Tight syncline in interbedded quartzites and slates, Masquerade Ridge, Lowery Glacier area, central TAM. View looking south, with 0.5–1.0 m-thick beds of quartzite and thin slate interbeds. Note thickening in fold hinge. (C) Interbedded sandstones and slates at Mt. Ubique, near Starshot Glacier, central TAM, showing high-angle Ross cleavage, most pronounced in slaty beds (white dashed line).

4.3.6. Ross magmatism

As summarized above in the section on the Cambro-Ordovician granite batholith, the convergent plate-boundary setting of the Ross

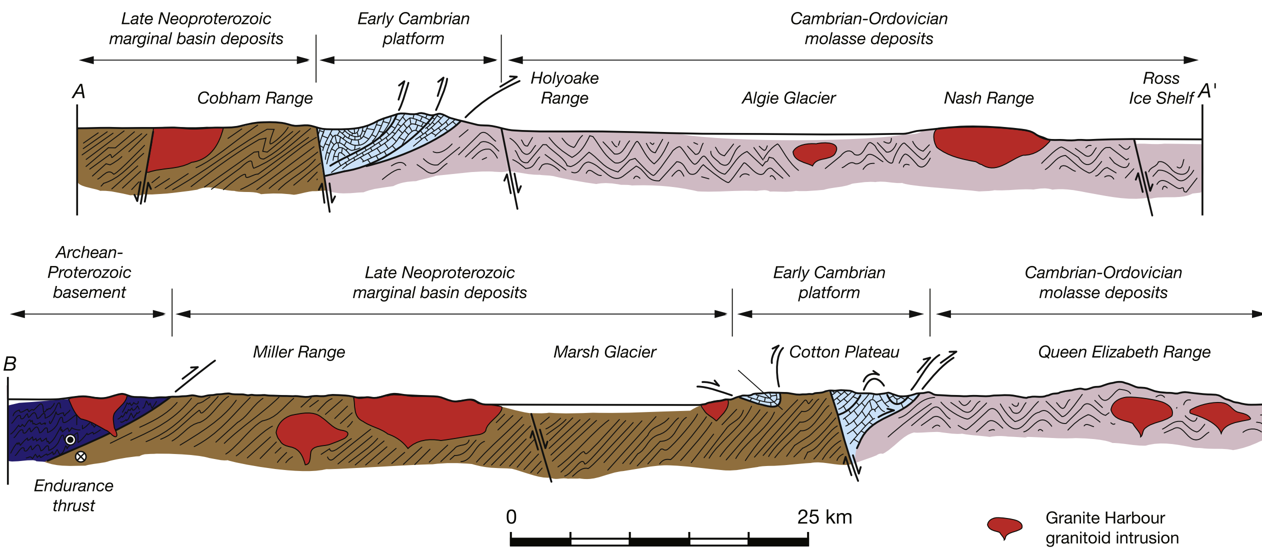


Fig. 43. Schematic geologic cross sections of the Ross Orogen in the Nimrod Glacier area of the Transantarctic Mountains (after Goodge et al., 2004a). Sections are approximately to scale with no vertical exaggeration; locations of lines A-A' and B-B′ shown in Fig. 12. Molasse deposits of the Starshot Formation in the Holyoake, Nash, and Queen Elizabeth ranges are overridden by older (Early Cambrian) carbonate of the Shackleton Limestone, yet contain clasts of the carbonate as well as quartzitic material that was probably derived from crystalline basement and marginal-basin deposits presently exposed to the west.

Orogen produced a volumetrically prolific continental-margin magmatic arc constructed mostly within older Proterozoic to early Paleozoic crust (Borg et al., 1987, 1990; Armienti et al., 1990; Allibone et al., 1993a, 1993b; Borg and DePaolo, 1994; Rocchi et al., 1998; Goodge, 2007a; Goodge et al., 2012). The batholith belt was long-lived, spanning >100 m.y. from at least 590–480 Ma (Fig. 47). The geochemical and isotopic character of igneous rocks in southern Victoria Land (Allibone et al., 1993b; Allibone and Wysoczanski, 2002) suggest two primary modes of magma origin—an early pre- to synorogenic phase overlying a continental-margin subduction zone (calc-alkaline Andean-type),

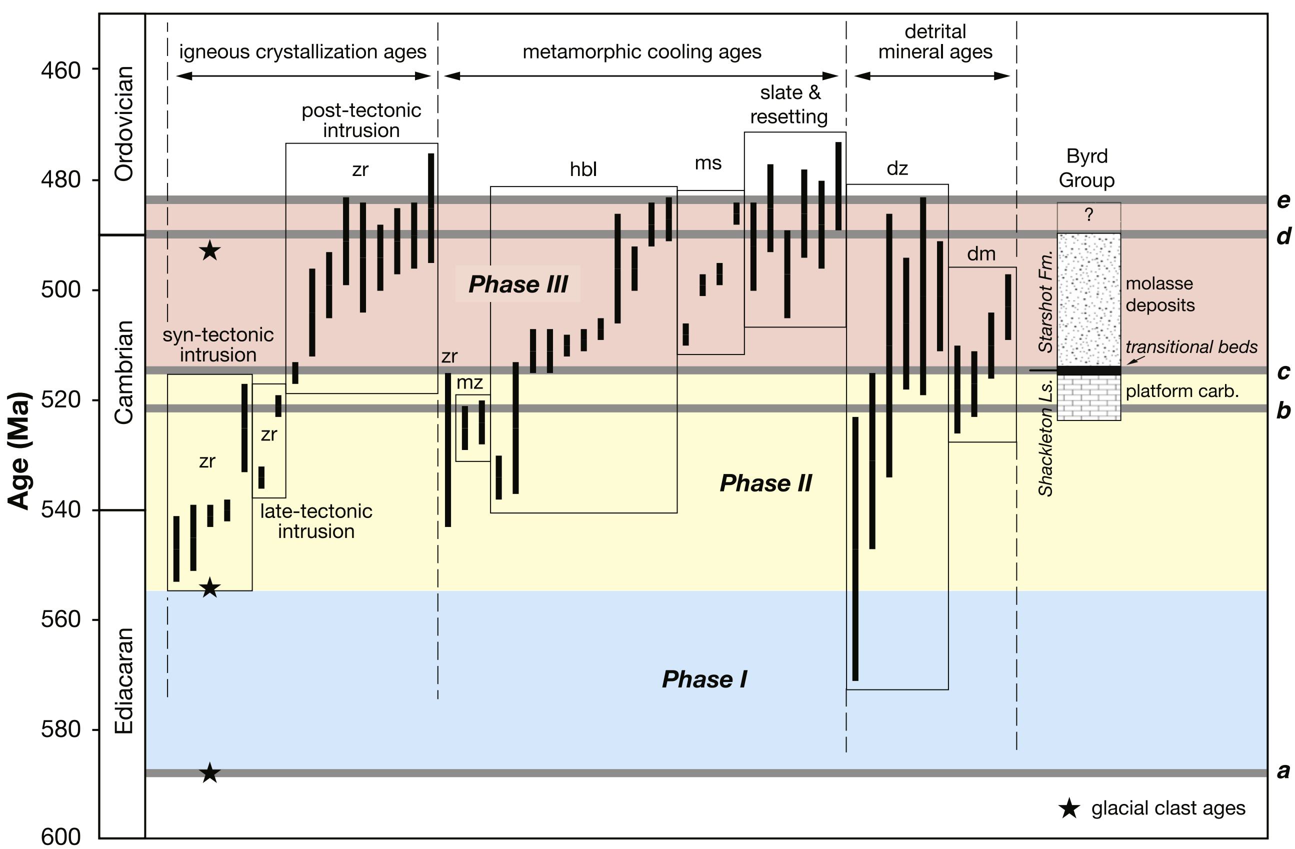


Fig. 44. Summary of thermochronological data for the Ross Orogen in the central Transantarctic Mountains (after Goodge et al., 2012). Black bars show the ages of the dated units with reported errors. Narrow, dark-gray horizontal bars show age constraints on important orogenic events: **a**, onset of magmatism; **b**, end of basement deformation; **c**, onset of supracrustal deformation; **d**, end of supracrustal deformation; **e**, end of magmatism. Sources of data given in Goodge et al. (2012). Abbreviations: dm, detrital muscovite $^{40}Ar/^{39}Ar$ ages; dz., detrital zircon U—Pb ages; hbl, hornblende $^{40}Ar/^{39}Ar$ ages; ms, muscovite $^{40}Ar/^{39}Ar$ ages; mz, monazite U—Pb ages; zr, zircon U—Pb ages.

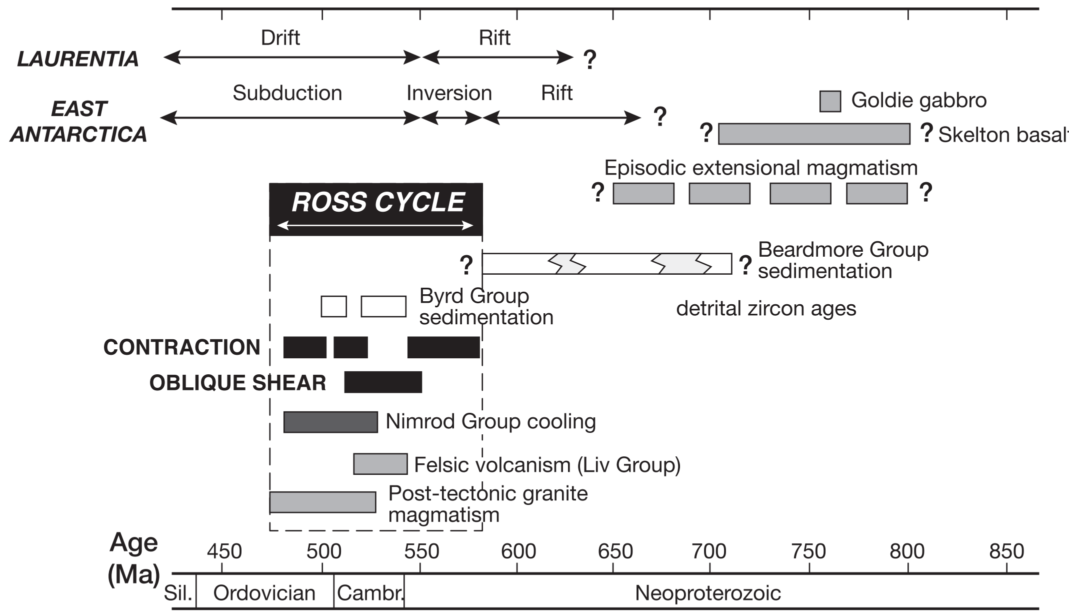


Fig. 45. Time correlation diagram, showing ages of Neoproterozoic to early Paleozoic events in the central TAM (after Goodge, 1997). The overlap in ages of sediment deposition, deformation, and magmatism provide evidence for a long-lived (~100 m.y.) Ross tectonic cycle that is expressed by different rock sequences and structures at different crustal levels.

and a second later phase indicative of melting in thickened silicic crust (high-K anorogenic-type). The magmatic belt is chiefly calc-alkaline in character, although in some areas it contains unique adakitic, alkaline and A-type magmatism that may indicate slab melting or upper-plate extension (Allibone et al., 1993b; Hall et al., 1995; Allibone and Wysoczanski, 2002; Cottle and Cooper, 2006a; Hagen-Peter and Cottle, 2016). An early period of alkaline magmatism in the Koettlitz Glacier area of southern Victoria Land (including gabbro, diorite, carbonatite, syenite and A-type granite with ages between about 550–530 Ma) is thought to indicate an early period of crustal (intra-arc?) extension

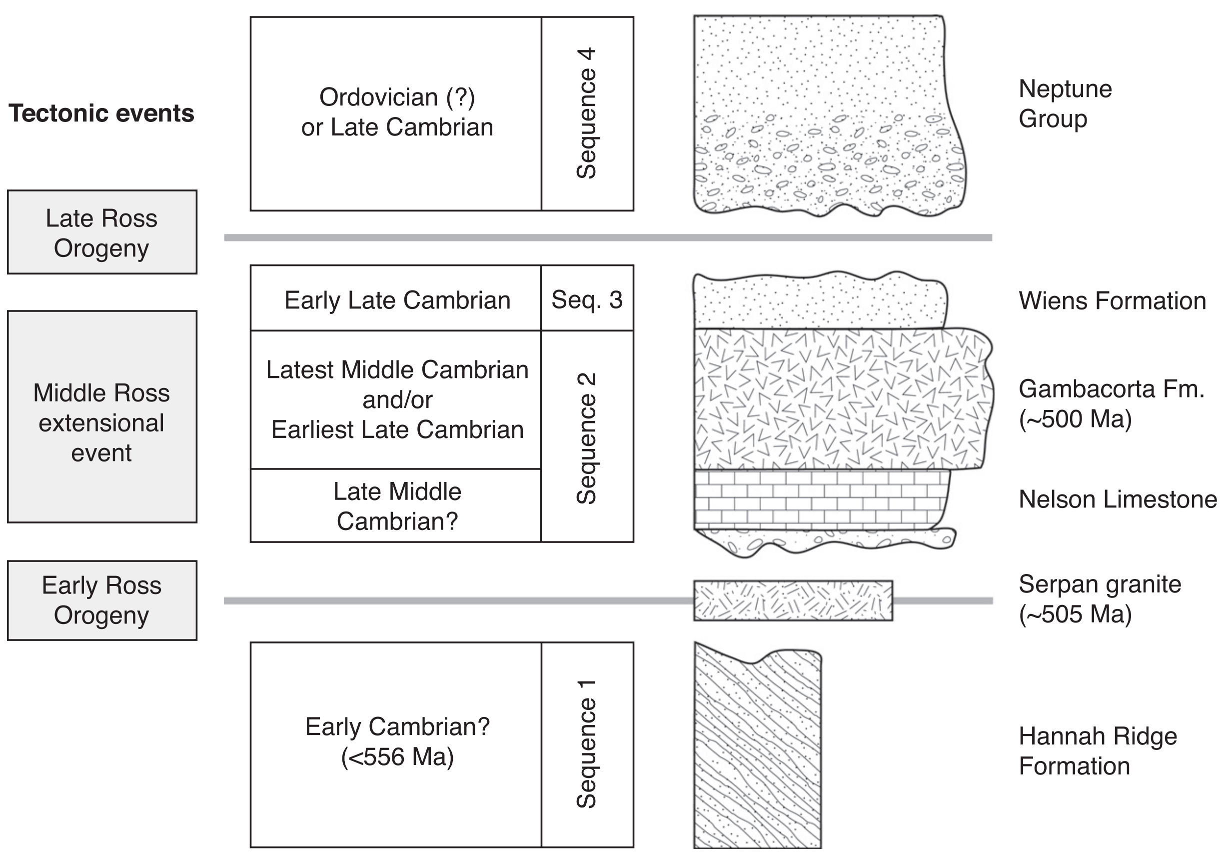


Fig. 46. Stratigraphic relations in the eastern Neptune Range (after Curtis et al., 2004), modified from stratigraphy reported by Storey et al. (1996) and Rowell et al. (2001). Two deformations, an early Ross contraction and a late Ross transpressional deformation, are documented by structural relationships and bracketed in time by a combination of biostratigraphy and geochronology.

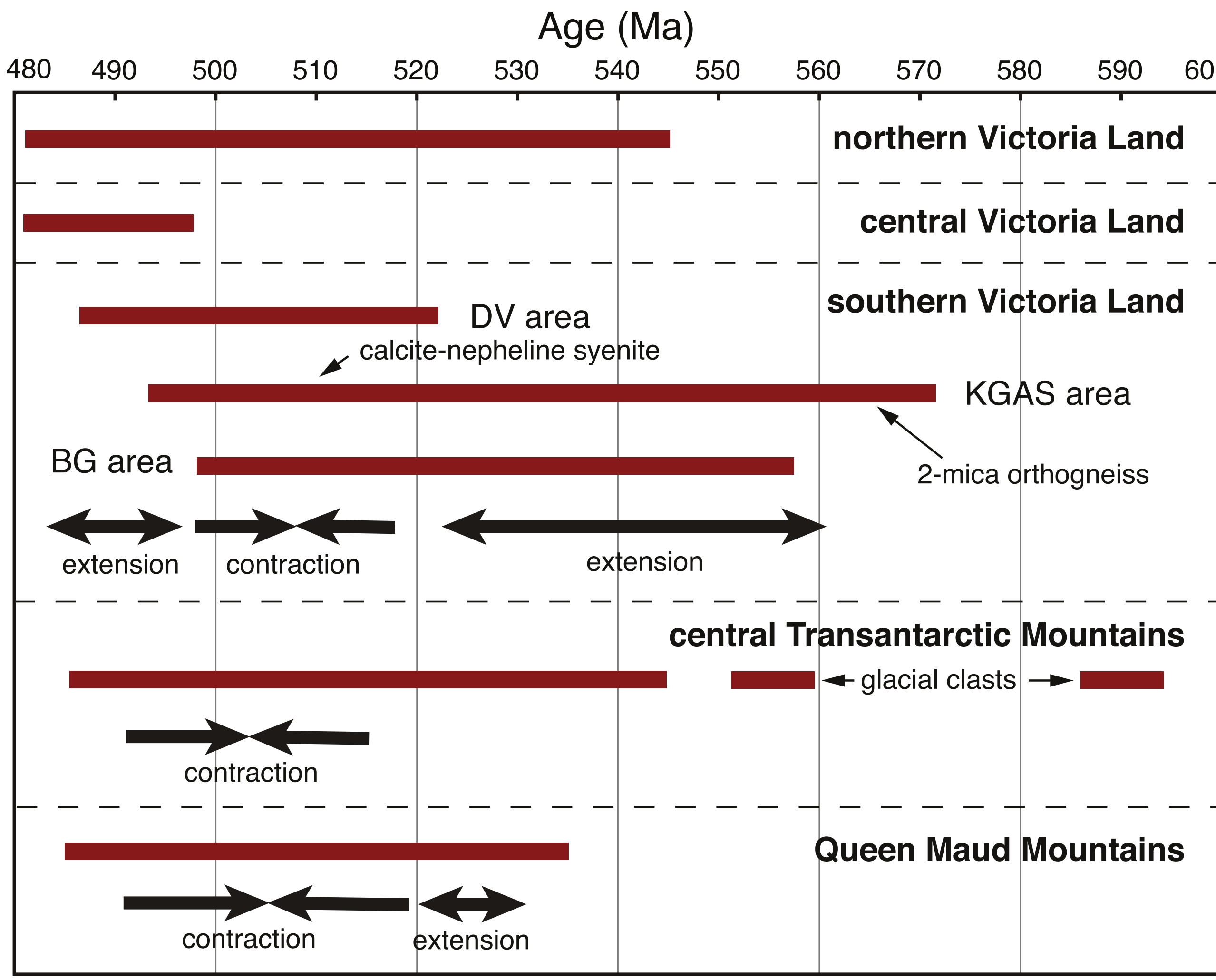


Fig. 47. Timeline summarizing zircon U—Pb age data for the Granite Harbour Intrusives along the Ross orogen, modified after Hagen-Peter et al. (2016). Periods of alternating contraction and extension indicated both by changes in syn-tectonic magma compositions and by analysis of field structures. See text for explanation.

prior to the main phase of Ross Orogen contraction and calc-alkaline magmatism (Rowell et al., 1993; Hall et al., 1995; Encarnación and Grunow, 1996; Cooper et al., 1997; Read et al., 2002; Cottle and Cooper, 2006b), and is probably not a direct product of subduction. A large body of new age and isotopic data from southern Victoria Land shows that early subalkaline along with contemporaneous alkaline and carbonatitic magmatism occurred during a phase of extension in the overriding plate ~550–525 Ma, whereas a younger subalkaline complex was emplaced during a phase of contraction in the arc section of the overlying plate ~515–505 Ma (Hagen-Peter and Cottle, 2016). Geochemical relationships and temporal diversity are explained primarily by a tectono-magmatic model involving alternating phases of extension and contraction in the overriding plate, together with local variations caused by magmatism within lithosphere of variable thickness along the margin.

Regional isotopic and geochemical variations in the calc-alkaline granitoids generally reveal increasing crustal components toward the craton (to the west in local geographic coordinates), best explained by subduction-generated melting beneath an east-facing continental-margin arc (Borg et al., 1987, 1990; Armienti et al., 1990; Rocchi et al., 1998; Goodge et al., 2012). The magmatic series of southern Victoria Land in particular consists of early I-type intrusions, succeeded by increasing levels of crustal contamination and late-stage melt production as a result of Ross orogenic crustal thickening (Allibone et al., 1993b). Northern Victoria Land hosts two syn- to post-tectonic plutonic suites (Borg et al., 1987; Kreuzer et al., 1987; Vetter and Tessensohn, 1987; Sheraton et al., 1987; Black and Sheraton, 1990; Tonarini and Rocchi, 1994; Rocchi et al., 2004; Bomparola et al., 2007; Giacomini et al., 2007). The older granitoids form a western, inboard belt of Cambro-Ordovician transitional S- to I-type intrusions (Granite Harbour Intrusives) that are correlative with plutonic rocks of similar age throughout the Transantarctic Mountains, whereas Devono-Carboniferous I-type granitoids occur to the east (Admiralty Intrusives; see below).

In detail, both cross- and along-strike studies of age and isotopic composition reveal significant variations in Ross magmatism. In the central TAM, age and isotopic data from a transect across the Ross batholith in the Nimrod Glacier area constrain timing, spatial variation, and origin of the magmatism (Goodge et al., 2012). Notably, this transect is one of the few places where the orogenic arc extends into the East Antarctic cratonic basement, thus helping to constrain both craton and arc evolution. Age patterns show that magmatism was initiated as early as ~590 Ma following latest Neoproterozoic rifting, that the magmatic belt is long-lived, lasting over ~100 m.y., and that the locus of magmatism shifted oceanward over time. Early syn-orogenic magmatism was focused within the leading edge of the cratonic basement, perhaps guided by strain partitioning during oblique subduction; younger magmas intruded a forearc sedimentary molasse basin, itself eroded from the earlier established arc system (Goodge et al., 2004a, 2012). Broadening of the arc during the later phases of Ross convergence indicates rollback of the subducting plate hinge and thickening of the developing forearc during continuing orogenic contraction. Inherited zircon components indicate melting of lower crust similar to the Nimrod Complex by large degrees of fractional melting at high temperature. However, Sr and Nd isotopic compositions vary systematically across the belt, indicating that melt compositions were controlled more by subduction processes than by assimilation of existing crust in the cratonic upper plate. Farther north in southern Victoria Land, age and Sr-Nd-Hf isotopic data from a heterogeneous sample suite indicate relatively minor degrees of crustal assimilation for primitive, mantle-derived melts that differentiated to form significant new crust and variable degrees of crustal assimilation during emplacement of more evolved granitoids (Hagen-Peter and Cottle, 2018). Together, data from this part of the Ross batholith indicate that the arc magmas evolved mainly as juvenile contributions, perhaps sourced from the mantle wedge, with subordinate crustal reworking.

Magmatism was concomitant with tectonic deformation of the Ross Orogen from northern Victoria Land to the Queen Maud Mountains (Cox, 1993; Goodge et al., 1993b; Allibone et al., 1993a; Rowell et al., 1993; Hall et al., 1995; Encarnación and Grunow, 1996; Jones, 1997; Read and Cooper, 1999; Musumeci, 1999; Paulsen et al., 2013), recording intra-arc displacements through time. Some fabrics in the granitoid belt appear related mostly to emplacement process (e.g., Allibone et al., 1993a), but in other cases the strains are developed in response to regional orogenic displacement (e.g., Goodge et al., 1993b, 2012; Jones, 1997; Musumeci, 1999).

The oldest intrusion ages from dated outcrops are ~550 Ma obtained from granite and quartz syenite exposed near Skelton Glacier (Rowell et al., 1993; Encarnación and Grunow, 1996; Hagen-Peter and Cottle, 2016), indicating that early plutonism may have been alkaline in character. Intrusions in several areas of southern Victoria Land and the central TAM yield ages between about 545–530 Ma (Goodge et al., 1993b, 2012; Hall et al., 1995; Cooper et al., 1997; Mellish et al., 2002; Read et al., 2002; Cottle and Cooper, 2006a; Stump et al., 2006), reflecting ongoing magmatism through the Early Cambrian. Dated granitoids in the well-studied Dry Valleys region track a continuous evolution from early alkaline, to adakitic, calc-alkaline (main phase), and late alkali-calcic magmatism by ~480 Ma (Allibone and Wysoczanski, 2002). Many of the intrusions emplaced between about 550–530 Ma have A-type or alkaline geochemical compositions, possibly signifying extension and lower-crustal melting in the continental-margin arc environment (Cottle and Cooper, 2006a; Hagen-Peter and Cottle, 2016), but the main phase of calc-alkaline intrusion occurred between about 520–490 Ma. Although the inception of magmatism appears to be ~550 Ma as indicated from geochronology of exposed rocks, detrital zircon suites in lower Paleozoic syn- to post-orogenic, molasse-type siliciclastic rocks contain significantly older populations of locally-derived igneous zircons (Ireland et al., 1998; Goodge et al., 2002, 2004a; Wysoczanski and Allibone, 2004). These indicate that volumetrically significant magmatism was underway by at least 580 Ma. Glacial clasts from the Nimrod Glacier area also appear to confirm inception of Ross magmatism by ~585–590 Ma (Goodge et al., 2010, 2012). Detrital muscovite ages confirm a Ross Orogen source for these young molassic deposits (Goodge et al., 2004a). As inferred from the detrital zircon compositions, it appears that early magmatic components of the Ross arc were eroded and deposited in forearc-basin successions, yet initiation of convergent-margin magmatism by ~580–590 Ma fits well with the timing of Pan-African orogenesis related to Gondwana amalgamation (see Goodge, 1997, 2007a; Cawood, 2005; Hagen-Peter et al., 2016). Ross magmatism began after Neoproterozoic rifting of the Austral-Antarctic margin, dated to between about 680–585 Ma (Preiss, 2000; Foden et al., 2001; Goodge et al., 2002; Direen and Crawford, 2003).

4.3.7. Ross metamorphism

The thermal effects of Ross-age magmatism on basement assemblages of the TAM are well known (e.g., Adams et al., 1982), suggesting that regional advective heating greatly affected older wall-rock metamorphic assemblages. Likewise, early metamorphic studies in northern Victoria Land revealed fundamental contrasts in low-*P*/*T* vs. high-*P*/*T* metamorphism (e.g., Grew et al., 1984), indicating development of a metamorphic duality attributed to subduction-zone convergence. More recent studies have contributed significantly to this early framework, highlighting the relationships between basement and supracrustal assemblages, and the presence of (U)HP and HT metamorphism. These relationships are summarized in syntheses of metamorphic patterns in northern Victoria Land and the broader TAM (Talarico et al., 2004; Goodge, 2007a).

In northern Victoria Land, metamorphic rocks of the Wilson Group consist dominantly of quartzofeldspathic layered paragneisses characterized by low-*P*/*T* parageneses, polydeformation, and abundant migmatitic/plutonic complexes (Kleinschmidt and Skinner, 1981; Babcock et al., 1986). An important metamorphic break is inferred to underlie Rennick Glacier, separating inboard low-*P*/*T* gneisses to the east from medium- to high-*P*/*T* schists and gneisses to the west in the Lanterman, Salamander and Mountaineer ranges (Fig. 18; Grew et al., 1984; Kleinschmidt and Tessensohn, 1987; Talarico et al., 1998). A similar pattern occurs farther south near Terra Nova Bay and the Deep Freeze Range, where polymetamorphic gneisses with early moderate-*P*/*T* parageneses occur east of high-*T* granulites and migmatites (Lombardo et al., 1987; Castelli et al., 1991).

To the east of quartzofeldspathic and pelitic rocks in the Lanterman Range, characterized by the co-occurrence of kyanite and sillimanite, is a zone of schists decorated by blocks and lenses of mafic and ultramafic rocks (Grew and Sandiford, 1984; Kleinschmidt et al., 1987). These exotic tectonic blocks are thought to represent detached pieces of lower crust and mantle that mark a crustal suture between older Wilson basement and the Bowers arc terrane (Tessensohn and Henjes-Kunst, 2005; Palmeri et al., 2012). Eclogitic and coesite-bearing parageneses in these rocks are unique to northern Victoria Land and indicate high and ultra-high pressure metamorphism (Di Vincenzo et al., 1997; Palmeri et al., 2003; Godard and Palmeri, 2013). The mafic blocks in this zone record polyphase recrystallization beginning with early high-*T* eclogite formation (720–850 °C at ≥15–24 kbar) followed by lower-pressure amphibolite-facies retrogression (600 °C at ~5 kbar; Di Vincenzo et al., 1997, 2016). In the southeastern Lanterman Range, interlayered mafic eclogites and felsic gneiss contain relict high-Mg garnet + phengite (Palmeri et al., 2003, 2011), with garnet showing radial fractures around quartz pseudomorphs after coesite (Ghiribelli et al., 2002). Elsewhere in the Lanterman Range, barroisitic eclogites reached maximum conditions of about 630–720 °C and 22–26 kbar, reflecting burial depths nearly in the coesite stability field of about 80–90 km (Kim et al., 2019). Sm—Nd isochron ages of ~500 Ma date the eclogite-forming event as part of the Ross Orogeny, and the retrogressive events that occurred during rapid near-isothermal decompression are dated by white mica cooling ages of ~480 Ma (Di Vincenzo and Palmeri, 2001). More recent U—Pb ages from metamorphic zircon confirm onset of eclogite-facies metamorphism to be ~530 Ma (Di Vincenzo et al., 2016) and continuing to ~500 Ma (Kim et al., 2019). UHP rocks in the Lanterman Range attest to the substantial crustal thickening associated with collision along the Wilson-Bowers terrane boundary. Palmeri et al. (2003) attributed the eclogite-forming and subsequent rapid decompression stages to arc collision, however Di Vincenzo et al. (2016) disputed the arc-continent collision model in favor of eclogite formation during accretion of material beneath an active (subducting) continental margin.

In the southern Wilson Group, by contrast, particularly in the areas of Terra Nova Bay and the Deep Freeze Range, metamorphism is typically of moderate to high T, low-*P*/*T* type (Schubert and Olesch, 1989; Palmeri et al., 1991, 1994; Talarico et al., 1992; Borghi and Lombardo, 1994; Palmeri, 1997). Most of the metamorphic rocks in this region show evidence for a single low-*P*/*T* metamorphism that is characterized by preservation of prograde parageneses reaching the upper amphibolite facies. The highest-grade zones are commonly migmatitic, locally indicative of anatexis (Palmeri, 1997), and they are generally associated with emplacement of granitoid plutons. In the Terra Nova Bay area, for example, several prograde metamorphic zones are mapped in metasedimentary units that range from chlorite-zone of the greenschist facies to garnet-cordierite-K-feldspar-spinel assemblages of the upper amphibolite facies (Talarico et al., 1992; Borghi and Lombardo, 1994; Palmeri, 1997). Mineral reaction textures indicate the replacement of garnet + sillimanite by cordierite-bearing assemblages at lower pressure (Palmeri, 1997). The highest grade conditions achieved were about 700–750 °C at ~4.5 kbar, reflecting a geothermal gradient of 45–55 °C/km.

A cryptic early metamorphic event is preserved as granulite-facies relics in the Deep Freeze Range, where amphibolite-facies metasedimentary gneisses contain lozenges and larger mappable bodies of felsic and mafic granulite (Lombardo et al., 1987; Castelli et al., 1991; Talarico and Castelli, 1995). Some felsic rocks, for example, contain garnet + orthopyroxene + cordierite, and discontinuous mafic layers are two-pyroxene granulite. Mineral assemblages and chemical zonation indicate that granulite-facies conditions evolved from ~800 °C and 8 kbar to lower-P conditions of ~6 kbar (Talarico and Castelli, 1995), whereas the host gneisses reached peak conditions of 650–700 °C at ~4 kbar. These rocks are characterized in nearly all cases by counterclockwise paths indicating advective heating in association with magmatism and local anatexis (e.g., Borghi and Lombardo, 1994; Palmeri et al., 1994; Ricci et al., 1997). Polymetamorphic assemblages also occur in the Wilson Hills and Daniels Range areas along the Oates Coast, which contain mineral assemblages reflecting upper-amphibolite to granulite facies conditions at moderate pressures (Schüssler et al., 1999).

Despite polymetamorphism, thermochronology indicates that the principal metamorphic parageneses are related to Ross tectonism. In the Wilson Hills, Schüssler et al. (1999) obtained U—Pb ages of 494–484 Ma from metamorphic monazites, constraining this stage to the Ross timeframe. Biotite $^{40}Ar/^{39}Ar$ ages of 476–470 Ma suggest a rapid late- to post-metamorphic cooling history. In the Lanterman Range, U—Pb ages of metamorphic monazite and sphene (Goodge et al., 1995) and $^{40}Ar/^{39}Ar$ cooling ages from synkinematic hornblende and muscovite (Goodge and Dallmeyer, 1996) constrain the high-*T* decompression stage to about 500–480 Ma and a cooling rate as high as ~30 °C/m.y. (Fig. 48).

Low-grade metasedimentary rocks of the Robertson Bay Group vary from subgreenschist to greenschist facies (Buggisch and Kleinschmidt, 1991; Kleinschmidt et al., 1991). Mineral parageneses of muscovite + albite ± clinozoisite indicate intermediate-pressure conditions along a thermal gradient of ~15 °C/km, with temperatures not exceeding ~400 °C and maximum pressures of ~8 kbar (Buggisch and Kleinschmidt, 1991; Kleinschmidt et al., 1991). This indicates substantial structural thickening within the turbiditic assemblage associated with plate-margin convergence. Dallmeyer and Wright (1992) reported a series of diachronous $^{40}Ar/^{39}Ar$ ages from slates in the Robertson Bay assemblage, younging from southwest (inboard) to northeast (outboard) between ~500–460 Ma, that reflect progressive neoblastic mica formation during oceanward growth of the margin and thickening of the sedimentary cover.

In southern Victoria Land, metasedimentary rocks are invaded by voluminous syn- to postorogenic magmas, resulting in metamorphism that is mainly of low-*P/T* type following a geotherm of ~45 °C/km (Goodge, 2007a). Metamorphic grade in pre-granitic rocks of this area ranges from upper-amphibolite facies in the northern area of the Dry Valleys (Allibone, 1992; Cox, 1992; Talarico et al., 2005), to greenschist facies farther south near Skelton Glacier (Grindley and Warren, 1964; Findlay et al., 1984). Koettlitz Glacier marks a boundary between

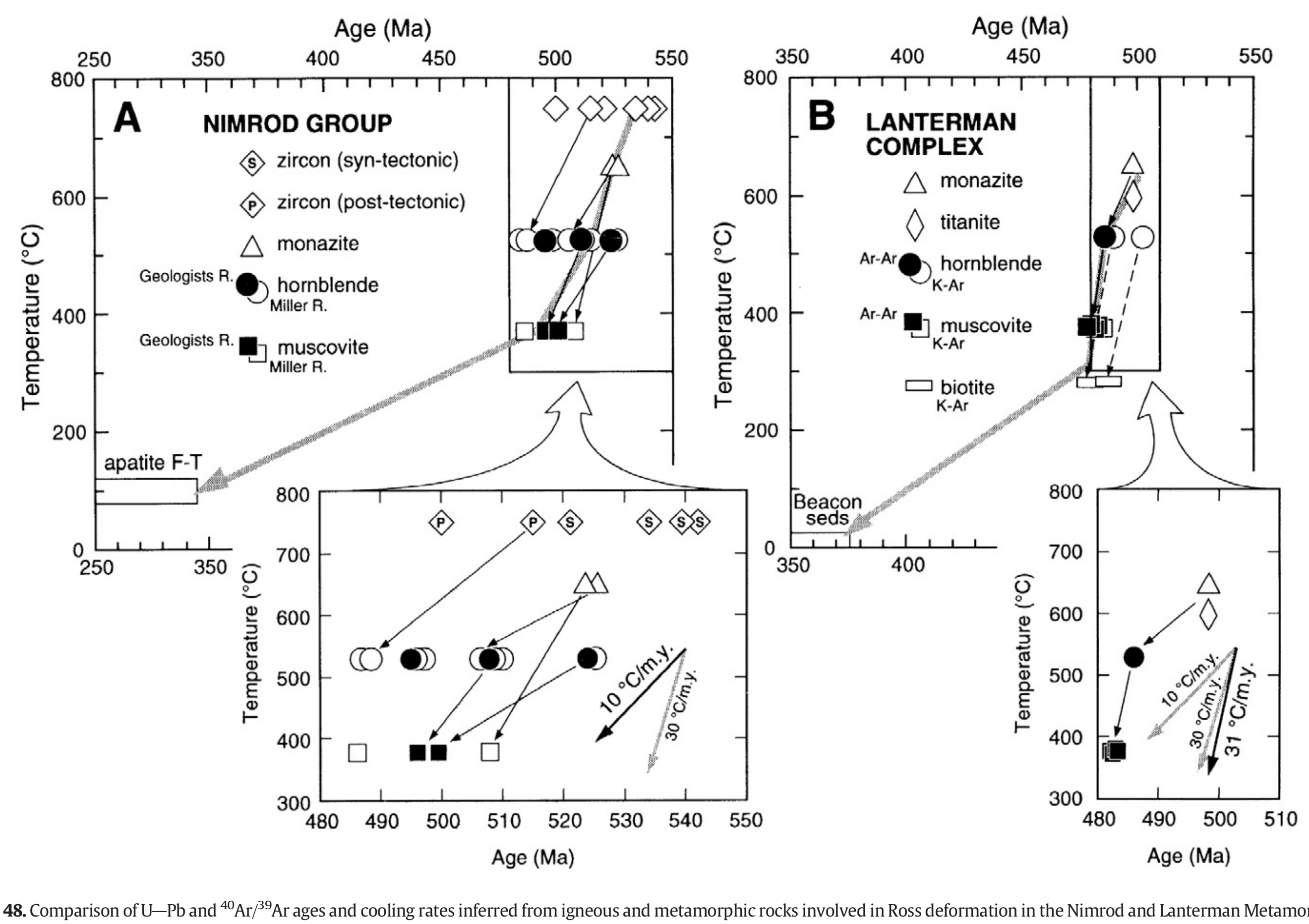


Fig. 48. Comparison of U—Pb and $^{40}Ar/^{39}Ar$ ages and cooling rates inferred from igneous and metamorphic rocks involved in Ross deformation in the Nimrod and Lanterman Metamorphic complexes (after Goodge and Dallmeyer, 1996).

high- and low-grade zones, suggesting it overlies an important regional structural boundary (Cook and Craw, 2001). Cox (1992) estimated peak metamorphic temperatures in metasedimentary rocks of Wright Valley to be 700–750 °C and ~5 kbar. Similar conditions of 650–750 °C at 4–6 kbar were obtained for schists in the Taylor Valley area associated with anatectic migmatites (Allibone, 1992), consistent with widespread evidence of synchronous partial melting. Near the Koettlitz and Ferrar glaciers, Talarico et al. (2005) found evidence of early prograde thickening associated with medium-*P* sillimanite-zone assemblages, succeeded by lower pressure assemblages indicative of decompression accompanied by regional magmatism. Thermochronologic constraints from the highest-grade parts of the northern Skelton Group indicate synchronous anatectic granite melt generation and growth of metamorphic zircon in siliceous lithologies (Encarnación and Grunow, 1996; Cox et al., 2000; Allibone and Wysoczanski, 2002; Wysoczanski and Allibone, 2004). However, recent dating of garnet and monazite reveals a more prolonged period of metamorphism, including early garnet growth ranging from about 615–570 Ma followed by progressive recrystallization of monazite to ~500 Ma (Hagen-Peter et al., 2016). The linkage between igneous activity and Ross metamorphism in southern Victoria Land is traditionally viewed as having occurred in a continental-margin magmatic-arc setting, in which the emplacement of large volumes of plutonic material caused substantially elevated regional isotherms, leading to the characteristic high-*T* metamorphism. However, the older garnet and monazite ages of 615–570 Ma provide important new insight by showing that early onset of metamorphism along a Barrovian-type *P-T* path was due to shortening and thickening prior to widespread magmatism. It is clear, nonetheless, that pluton emplacement and deformation of the surrounding host rocks continued through the broader Ross cycle, and both contributed to thickening of orogenic crust in the region.

In the central TAM, Ross metamorphism overprinted earlier assemblages in the Nimrod Complex and Argosy Schist under moderate-*P*, high-*T* metamorphic conditions (8–12 kbar; 650–750 °C) in the upper-amphibolite to lower-granulite facies (Goodge et al., 1992; Goodge and Dallmeyer, 1996). Peak metamorphism is best expressed in lithologically varied rocks of the Argosy Schist, including syn-kinematic kyanite + garnet + muscovite + biotite + quartz in pelites, hornblende + plagioclase ± garnet ± clinopyroxene ± clinozoisite in mafic rocks, diopside + scapolite in calc-silicates, and by thermobarometry. Inclusions of staurolite and kyanite in garnet from Argosy Schist indicate a prograde *P-T* path across the kyanite stability field, and late syn-kinematic growth of sillimanite after kyanite in the presence of muscovite reflects waning deformation along a combined cooling and decompression path. These conditions are consistent with the widespread presence of syn- to late-kinematic diatexites (Goodge et al., 1993b). Evidence for post-kinematic Ross metamorphism occurs locally within narrow thermal aureoles of the ~500 Ma post-tectonic plutons. In these areas, basement ductile deformation fabrics were partially annealed or entirely obliterated by development of poikiloblastic and massive granoblastic textures. Locally, Fe-rich pelites show evidence of staurolite + garnet + muscovite replaced by chloritoid grown across an earlier foliation (Goodge and Dallmeyer, 1996). The chloritoid-producing retrograde reactions probably occurred at $P \le 5$ kbar and $T \le 550$ °C. Mineral cooling ages from tectonites in the Nimrod Complex range from about 525–485 Ma and define a syn- to late-orogenic cooling rate of ~10 °C/m.y. (Goodge and Dallmeyer, 1996).

Outboard (to the east) of the crystalline basement, siliciclastic and calcareous rocks of the Beardmore and Byrd groups are characterized by subgreenschist to greenschist-facies regional metamorphic assemblages, including chlorite + muscovite ± biotite in pelites and albite + epidote + calcite in calcareous rocks (Goodge, 1997, 2007a). Contact zones in the vicinity of granitoid plutons commonly show conspicuous biotite and amphibole poikiloblasts, with sillimanite-garnet and diopside-bearing assemblages in pelitic and calcareous rocks, respectively. These parageneses reflect regional greenschist-facies conditions overprinted locally by sharp thermal gradients to low-*P* hornblende-hornfels facies. Maximum conditions may have reached 550–600 °C, but generally were less than ~400 °C. Dating of detrital and metamorphic minerals in the upper Byrd Group syn-orogenic deposits constrains the age of late Ross metamorphism in the supracrustal assemblages (Fig. 44; Goodge et al., 2004a). $^{40}Ar/^{39}Ar$ ages for metamorphic biotite and slate suggest regional metamorphism between ~490–480 Ma, synchronous with minor Ar loss in detrital muscovites from the same feldspathic arenites. These ages correspond with or are slightly younger than emplacement ages of late granitoid intrusions in the region, suggesting a regional geotherm elevated locally by advective heating. They also correspond with cooling ages from the crystalline basement terrain, reflecting regional cooling of the entire crustal orogen at this time, probably controlled by erosional exhumation (Goodge and Dallmeyer, 1996; Goodge et al., 2004a).

P-T-t paths for metamorphic assemblages in northern Victoria Land, southern Victoria Land, and the central Transantarctic Mountains are shown in Fig. 49, as summarized below. A comparison of the *P-T* paths shown in the four panels shows that metamorphic assemblages in different parts of the Ross Orogen can be divided into three general types: (1) near-isobaric, counterclockwise paths along steep geothermal gradients indicative of low-*P/T* metamorphism; (2) clockwise paths characterized by variable maximum pressures but generally indicating late-stage decompression following medium- to high- *P/T* metamorphism; and (3) steep clockwise compression and decompression paths along low geothermal gradients, in which the rocks experienced HP-UHP conditions and were then rapidly exhumed. Although these distinct paths are generally synchronous during the broad time period of Ross activity, they reflect the different positions of rock assemblages within the orogen—both in a lateral direction relative to the convergent margin and in terms of crustal level—which in many cases are separated by fundamental intraorogen structures. Although a number of such structures are inferred from discontinuous outcrop and geophysical modeling, the best-documented Ross-age boundaries appear to be contractional faults and shear zones. There is no clear evidence of large-scale lateral translation.

4.4. Tectonic models for the Ross Orogen

The principal characteristics of the Ross Orogen are regional contractional deformation, locally with sinistral transpressional or strike-slip movement, emplacement of widespread granitoid magmas ranging from calc-alkaline to alkaline character, local silicic and/or bimodal volcanism, deposition of thick syn-orogenic siliciclastic materials in forearc and foreland basins, and variable metamorphism in both high-temperature and high-pressure regimes. These processes were active during four distinct phases spanning about 615–470 Ma (Fig. 36). In detail, deformation was partitioned into both orogen-normal and orogen-parallel displacements, suggesting that plate convergence was oblique. The vast scale of magmatism forming the Ross batholith belt, including early alkaline compositions and main-phase calc-alkaline rocks, is most certainly a product of convergent-margin magmatism. As such, the calc-alkaline Ross-age igneous rocks represent significant primary magmatic additions to the Antarctic lithosphere. Evidence for subduction of paleo-Pacific oceanic lithosphere beneath cratonic East Antarctica comes primarily from geochemical and isotopic variations in granitoid magmas, which show a westward increase in continental signature. Ross-age igneous rocks span at least 100 million years during the orogenic cycle and include intrusions that predate deformation, are synchronous with it, or cut across deformation features. They intrude older metamorphic roots of the orogen, as well as young orogenic deposits. Ross metamorphism is highly variable in character, and includes high-temperature magmatic-arc metamorphism, high-pressure metamorphism due to crustal thickening and oceanic-arc collision, and low-grade metamorphism associated with seaward growth by plate-margin accretion. Geochronologic data indicate only a short time-lag of about 35–40 m.y. between rift-related

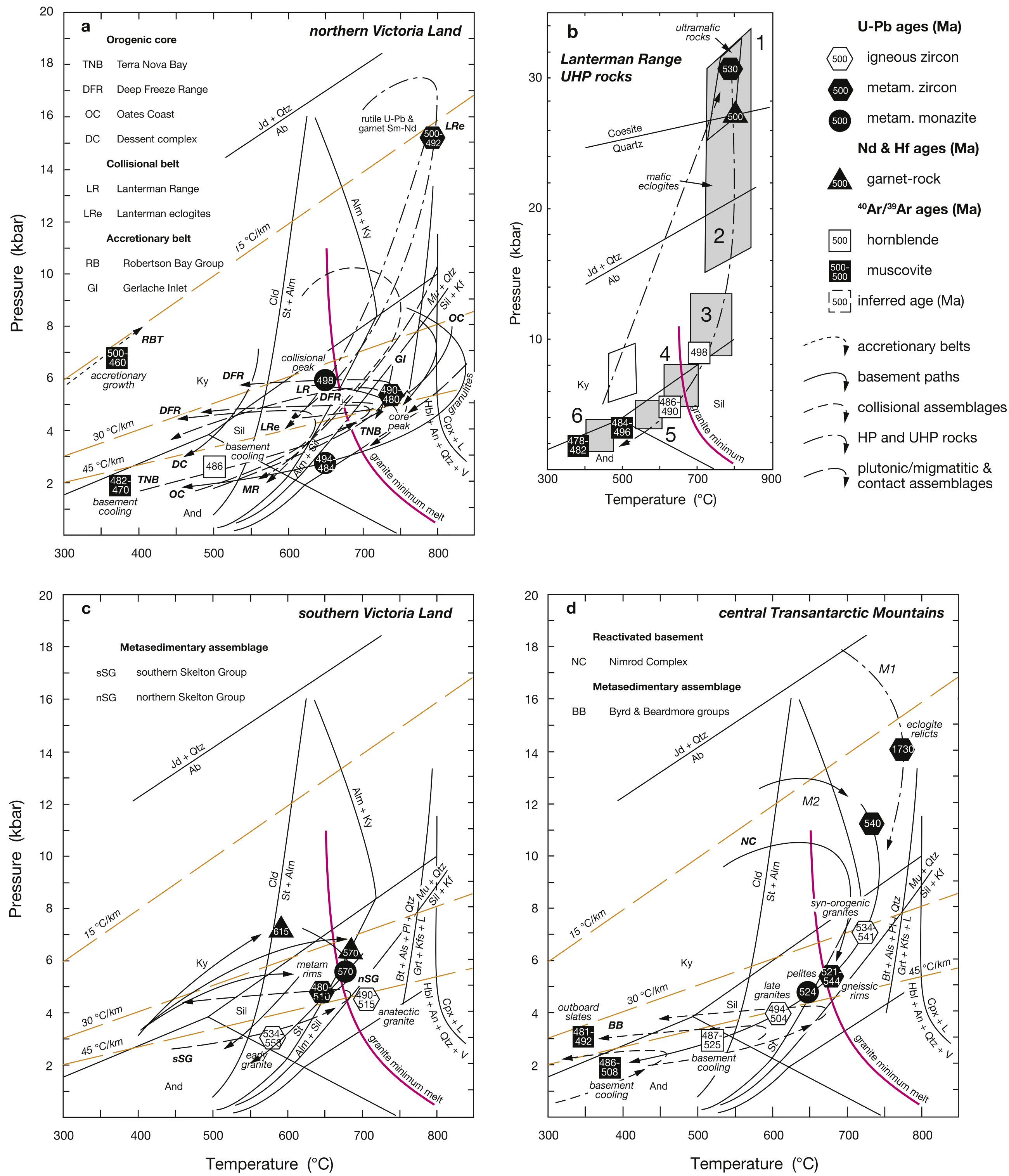


Fig. 49. *P-T-t* diagrams for three segments of the Ross orogen (after Goodge, 2007a). Ages of dated metamorphic events noted (solid where individual mineral cooling ages are available; dashed where inferred from regional relationships). General phase equilibria are shown with reference geotherms of 15, 30, and 45 °C/km. Sources of data given by Goodge (2007a). (A) Northern Victoria Land. Multiple *P-T* paths reflect different tectonic units not observed in other areas. In general, three types of *P-T* paths are obtained from metamorphic assemblages in northern Victoria Land, including extreme decompression from high-*P* and UHP conditions, near-isothermal decompression associated with thickening and denudation, and near-isobaric heating and cooling associated with anatexis and melt emplacement. (B) *P-T* conditions for UHP rocks in northern Victoria Land (updated to show stages 1–6 for ultramafic rocks and mafic eclogites reported by Palmeri et al., 2011). Note change in scale from previous panel. (C) Southern Victoria Land (updated with data from Hagen-Peter et al., 2016). Peak metamorphic conditions reached low to moderate pressure within the sillimanite zone, locally achieving minimum-melt conditions as shown by widespread anatectic granite. (D) Central Transantarctic Mountains. Basement rocks in Nimrod Complex and Argosy Schist units show clockwise M2 cooling and decompression path after achieving peak Ross Orogen temperatures at ~8–12 kbar, whereas heating and isobaric cooling path for supracrustal units is inferred from variable low-grade contact assemblages related to emplacement of Granite Harbour intrusives. Note that eclogitic blocks in Nimrod Complex gneisses yield Paleoproterozoic metamorphic zircon ages (M1; Goodge et al., 2001).

volcanism and initial metamorphic grain growth. Regional metamorphism in pre-Ross sedimentary assemblages is typically of medium grade, but high-temperature rocks and migmatites that formed by local partial melting occur in the Miller Range (Nimrod Complex) and Mountaineer Range (Wilson Group); eclogites, rocks formed at very high pressures, in northern Victoria Land attest to profound crustal thickening during Ross convergence. Thick accumulation of orogenic clastic sediments (mainly deposited in forearc basins in northern Victoria Land, the central TAM, and the Pensacola Mountains) reflect significant erosion within the mountain belt, consistent with thermochronologic evidence of rapid late-orogenic denudation.

Different tectonic models have been invoked to explain early Paleozoic structural and petrologic patterns, all involving some manifestation of a convergent continental-margin orogenic belt. Important perspectives on the Ross Orogeny come from integration of deformational, magmatic, and sedimentation patterns in different areas, which provide constraints on crustal thickening, arc development, magmatism, syntectonic denudation, exhumation, and accretionary growth. In northern Victoria Land, Kleinschmidt and Tessensohn (1987) recognized the importance of linking tectonic units to one another by geologic process in a convergent setting. In their early synthesis, an offshore oceanic arc (Glasgow Volcanics) was accreted against the plate margin due to consumption of oceanic crust, leading to thickening and erosion to produce a series of forearc deposits (Molar Formation and Leap Year Group). Their model invokes two parallel, west-dipping subduction zones during the early Ross Orogen, with the outer zone being sustained following accretion of the inner Bowers arc. Fundamentally, however, this model was among the first to invoke continuous subduction of oceanic lithosphere westward beneath cratonic East Antarctica. By integrating deformation, magmatic, and sedimentation patterns, they suggested that convergence and crustal shortening were related to westward accretionary growth of the Ross margin, the progressive timing of which was confirmed by Dallmeyer and Wright (1992) to be between ~500–460 Ma. The framework for this part of the orogen explained metamorphic zonations and temporal variations among syn- and post-tectonic plutonic rocks in terms of an evolving convergent margin that culminated in oceanic-arc accretion in the Late Cambrian and Early Ordovician. The significance of structural shortening, both within crystalline basement and cover sequences, is shown by opposing thrust directions across the orogen from the inner foreland and cratonic interior to the outer forearc and accretionary belt (Flöttmann and Kleinschmidt, 1991a, 1991b, 1993). That the region experienced significant crustal thickening as part of the late-stage accretion process is shown by the incorporation of high-*P* exotic slivers, some of them eclogitic, yielding Ross crystallization ages (Kleinschmidt et al., 1987; Ricci et al., 1996; Di Vincenzo et al., 1997; Palmeri et al., 2003) and cooling patterns in the metamorphic basement core (Goodge and Dallmeyer, 1996; Schüssler et al., 1999). This general model is supported by distinctive metamorphic patterns that reflect tectonothermal conditions within a convergent system (Ricci et al., 1997; Talarico et al., 2004).

Despite long-standing evidence for regional contraction, particularly in northern Victoria Land (e.g., Kleinschmidt, 1992), evidence continues to emerge for subordinate but tectonically important features, including transpression related to oblique subduction (see above) and intra-arc extension. The latter is recorded episodically in volcanic complexes associated with volcaniclastic basin formation (e.g., Wareham et al., 2001; Curtis et al., 2004) and in the variable compositions of Granite Harbour plutonic rocks (e.g., Hall et al., 1995; Cooper et al., 1997; Read et al., 2002; Cottle and Cooper, 2006b). Evidence of crustal extension is found primarily in southern Victoria Land, the southern TAM, and the Pensacola Mountains. Thus, structural styles vary from principally contractional in northern Victoria Land to extensional in the southern TAM and Pensacola Mountains. Variations along the orogen may be related to position and distance from a convergent pole of rotation (Goodge, 2002), variations of oblique convergence on an irregular margin, or to the dominant effect of arc accretion in northern Victoria Land compared to areas farther south. Curtis et al. (2004) suggested that the patterns of alternating contraction, transpression, and extension could be an expression of tectonic 'switching' (Collins, 2002) along a consistently subducting Ross margin, in which changes in subduction angle and convergence rate, as well as periodic accretion of oceanic seamounts, might lead to discrete pulses of tectonic activity. This is consistent with a concept of alternating intra-arc contraction and extension, expressed by variations in arc magma compositions and structural style (Hagen-Peter et al., 2016).

Key insights to tectonic development of the Ross Orogen come from observations in northern Victoria Land, where the Bowers arc terrane is thought to have been accreted as an exotic oceanic crustal sliver. For example, Ricci et al. (1997) proposed a coherent tectonic model involving early convergence and development of an accretionary complex, followed by a later phase of oceanic-arc collision/accretion that led to collapse of the margin and widespread metamorphic overprinting. This model highlights the importance of crustal shortening that occurred in two main modes—arc accretion coupled with eclogite-facies and UHP metamorphism along the intervening suture zone, and opposite-verging contraction within inboard basement and supracrustal rocks suggestive of a large-scale crustal flower structure. Contraction along the suture zone and its concomitant high pressures are indicative of large-scale crustal doubling as a direct result of collision. Farther west, significant shortening on deeply rooted thrust systems eventually exhumed granulitic lower crust (Schüssler et al., 1999). Considerable uplift is suggested to account for a common record of decompression up to 6–8 kbar during Ross time, corresponding to 20–30 km of exhumation. Borghi and Lombardo (1994) stated the important role of erosionally-enhanced exhumation, as evident from synorogenic clastic materials in both the Bowers and Robertson Bay terranes. Extensional structures, though not widely recognized to date, also probably played an important role in the exhumation process. Along major suture boundaries such as the eastern side of the Lanterman Range, rapid and large-magnitude exhumation may have been accommodated by buoyant effects of the underthrust arc complex. The final stages of Ross orogenic evolution involved continued west-directed plate convergence to produce the Robertson Bay accretionary assemblage, but it is not clear if this represents a true accretionary complex formed along the paleotrench, or a coherent but deformed forearc basin assemblage. Provenance and paleocurrent indicators have not resolved this issue, but diachronous $^{40}Ar/^{39}Ar$ cooling ages obtained from slates in this assemblage clearly show the eastward propagation of a metamorphic-deformation front that probably reflects progressive seaward migration of the trench. Continued underflow along the convergent boundary led to emplacement of postorogenic Devonian granites.

This traditional view of tectonic development in northern Victoria Land as dominated by discrete arc accretion and crustal thickening events was challenged by Federico et al. (2006, 2009), who envision the various tectonic elements in this area as evolving progressively together as a coherent arc, back-arc and trench-accretionary complex system during Gondwana-margin convergence. In their model, interactions between two continental plates, East Antarctica to the west and an 'eastern' continent, along an obliquely west-dipping subduction zone beneath the craton caused development of a long-lived continental-margin magmatic arc (Granite Harbour Intrusives) within the inboard metasedimentary complex of the cratonic margin (Wilson Group) as a result of southwest-directed subduction. As the two continental masses approached one another, slab rollback, perhaps due to impingement of the incoming eastern continent, led to intra-arc extension and formation of an offshore back-arc basin. This basin was the site of Bowers-type volcanism and deposition of immature siliciclastic rocks such as the Molar Formation. Renewed and/or accelerated subduction led to partial subduction or collision of the eastern continental margin, leading to UHP metamorphism of both oceanic, mantle and continental materials, followed by exhumation of the high-P rocks and the initiation of siliciclastic sedimentation (Robertson Bay Group) to cover the outboard continental block. Continent or microcontinent collision induced compression in the back-arc area and incipient crustal failure, whereas insertion of continental crust into the subduction zone provoked a jump of subduction to the back-arc basin and HP-UHP metamorphism followed by eclogite exhumation. A key difference between this and other models is the mode of formation of the Bowers volcanic rocks and the nature of oceanic arc accretion (see Federico et al., 2009).

A third class of models links all of the Wilson, Bowers and Robertson Bay terranes into a coherent convergent-margin system involving subduction beneath East Antarctic lithosphere and development of an accretionary-type orogen that juxtaposed cratonic basement, rift-margin and marginal-basin sediment, and arc- and back-arc volcanic and volcaniclastic rocks into one evolving system along continent-ocean sutures and subsidiary thrust zones (Tessensohn and Henjes-Kunst, 2005; Rocchi et al., 2011). It is noteworthy that sedimentary units in each of the major terranes in northern Victoria Land have similar detrital provenance signatures, including dominant Ross and Grenvillian sources with minor cratonic populations, indicating that each assemblage is generally autochthonous with respect to the Ross margin of East Antarctica. These models emphasize that the depositional patterns of lower Paleozoic rocks in northern Victoria Land are quite different from other regions in the TAM and tie volcanism and clastic deposition together in an evolving, dynamic active-margin tectonic setting.

Despite extensive study, the fragmentary nature of the rock record in northern Victoria Land leaves many questions about the origin of these terranes unanswered. What is the significance of the continental-margin arc in the Wilson terrane, and are the older host rocks autochthonous with respect to continental Antarctica? What is the origin of the Bowers units, and how did collapse during late-stage convergence cause accretion of the Bowers terrane and development of HP-UHP metamorphic rocks? Likewise, are there relicts or fragments of continental crust (perhaps as rifted ribbons) beneath the Robertson Bay turbidite succession? Key lines of evidence come from detrital-zircon age records and isotopic data in igneous materials, discussed above, which point to an affinity with the Antarctic continental margin. Tessensohn and Henjes-Kunst (2005) argued that the inboard Wilson terrane is autochthonous relative to cratonic East Antarctica, and that the outboard Bowers and Robertson Bay assemblages represent active-margin elements that were successively accreted to the evolving orogen during collapse of an accretionary-type system involving materials with similarly cratonic signatures. More recently, Rocchi et al. (2011) likewise emphasized that northern Victoria Land evolved with a western Pacific-type, active-margin tectonic architecture at the boundary between the subducting paleo-Pacific plate and continental Gondwana (Fig. 50). In their view, the convergent-margin system experienced periodic convergence, back-arc extension, and accretion of non-exotic elements during continuous oceanic underflow, as found in the modern western Pacific realm. As suggested for both the Ross Orogen in the central TAM and Delamerian-Lachlan orogens in Australia, the tectonic relationship between major geologic units can be explained by a single evolving subduction zone, although a combination of slab roll-back, arc migration, and inner-margin contraction is reminiscent of earlier double-subduction models and may help to explain outboard Ross-age magmatism as seen at Surgeon Island (Fioretti et al., 2005b). Rocchi et al. (2011) make several key points: (1) the Tiger arc is an older (~535 Ma) igneous assemblage that pre-dates the Bowers terrane, and represents an oceanic arc built in response to oceanward migration of the trench during inboard arc extension; (2) the Bowers assemblage, despite earlier interpretations as an oceanic arc, is quite variable geochemically with significant MORB-like elements, and is better considered as a back-arc basin succession of volcanics and clastic marine to continentally-derived deposits reflecting a period of extension outboard of the Wilson continental-margin arc during formation of a broad trough-like offshore basin; (3) HP-UHP rocks decorating the boundary between the Wilson and Bowers terranes have similar geochemical characteristics as the Bowers volcanics and probably represent deeply entrained materials during collapse of the combined back-arc/oceanic arc system against the continental lithospheric backstop; (4) the Robertson Bay turbidite succession was deposited outboard of the contracted margin, but has continental provenance signatures like in the Lachlan belt; and (5) although distinctive, the history represented in northern Victoria Land can be tied together with the convergent-margin history developed simultaneously farther to the south in other areas, reflecting along-strike variations in the Ross Orogen. Whichever model best explains the geologic relationships found in northern Victoria Land, it is clear that this part of the Ross Orogen is different from other areas because of the inclusion of mafic oceanic volcanic rocks and a flysch-like sedimentary belt hosting a younger (Devonian) granitoid complex indicating hidden crystalline basement distinct from that inboard of the Ross belt elsewhere.

In southern Victoria Land, the main expression of Ross events is low-*P/T* regional metamorphism and plutonism. The area is characterized by syn- to postkinematic emplacement of large volumes of granitoid magmas and, as in northern Victoria Land, there is abundant evidence for contemporaneous migmatite formation and anatexis. Contrary to both northern Victoria Land and the central TAM, there is no evidence of allochthonous accretion, no record of significant structural thickening, and no exposed pre-orogenic crystalline basement. Allibone and Wysoczanski (2002) suggested that ~20 km of exhumation has taken place since Ross time, but much of this may have occurred since the Devonian according to apatite and feldspar thermochronology (Fitzgerald, 1992; Calvert and Mortimer, 2003). Therefore, although the metamorphic patterns are consistent with the thermal structure of a continental-margin arc system, the structural and kinematic patterns are not as evident. Inherited shape of the earlier rift margin may play a role—northern Victoria Land as a crustal salient may have experienced greater collisional/accretional interactions, and the more inboard position of the central TAM relative to crystalline rocks of the East Antarctic craton may have led to greater involvement of older basement.

The central TAM show clear evidence of crustal thickening, although differing from northern Victoria Land because here there is no early Paleozoic arc interaction. Convergent-margin shortening instead led to ductile reactivation of older crystalline basement, intracrustal structural shortening, and perhaps overthrusting of the crystalline rocks upon autochthonous Neoproterozoic rift-margin deposits (Fig. 51; Goodge et al., 1993a, 2004a, 2004b), although importantly the kinematic regime is transpressional. Orogenic development of the Ross Orogen in the central TAM can be divided into four principal phases. In the passive-margin stage (Fig. 51A), marginal-basin sedimentation of shoreline and shallow-marine deposits (Beardmore Group) occurred after rifting and concurrently with minor mafic volcanism at ~670 Ma (Goodge et al., 2002). During the active platform and incipient arc stage from about 580–515 Ma (Fig. 51B), discontinuous deposition of Lower Cambrian shelf carbonate (Shackleton Limestone) was accompanied by early continental-margin volcanism, as indicated by the detrital-zircon record (Goodge et al., 2002, 2004b). True calc-alkaline plutons intruded by ~550 Ma (Goodge et al., 1993b, 2012). The principal period of synorogenic activity from about 515–490 Ma (Fig. 51C) was characterized by intra-arc deformation of basement units (both metamorphic rocks and older parts of the sedimentary succession), continued magmatism, erosion of the supra-orogen arc, and deposition of siliciclastic material (Holyoake and Starshot formations) in a forearc setting, overlapping older sedimentary units. Transport direction to east (present-day coordinates) is known from paleocurrents and the igneous arc source (Myrow et al., 2002a; Goodge et al., 2004a). As any such deposits are covered by the modern ice sheet, foreland-basin deposition is inferred at this time. In the final late-orogenic stage from about 490–480 Ma (Fig. 51D), the youngest post-tectonic granitic magmas intruded Cambrian units of the synorogenic succession, while continued deposition of siliciclastic materials occurred in alluvial-fan/fluvial

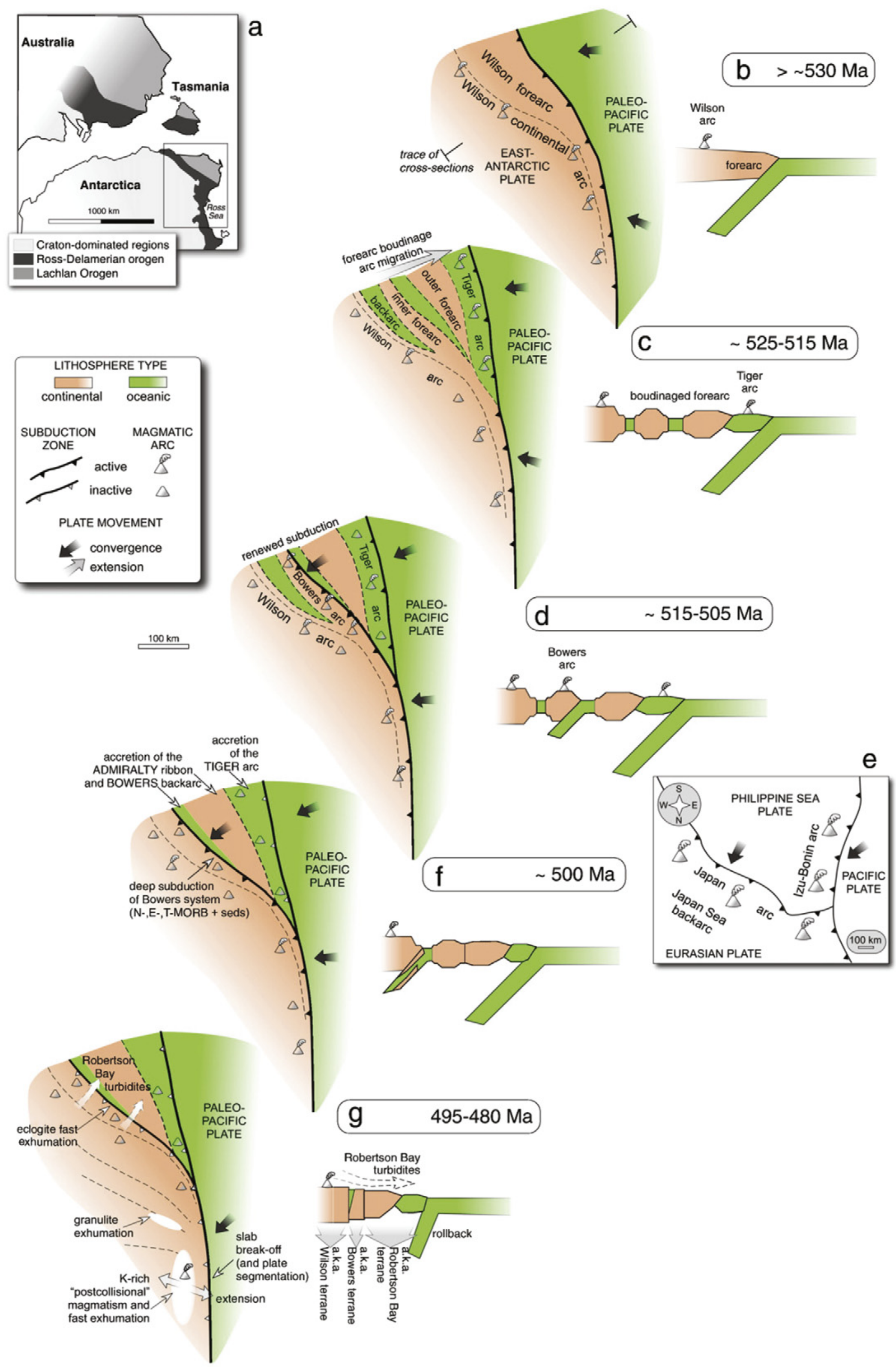
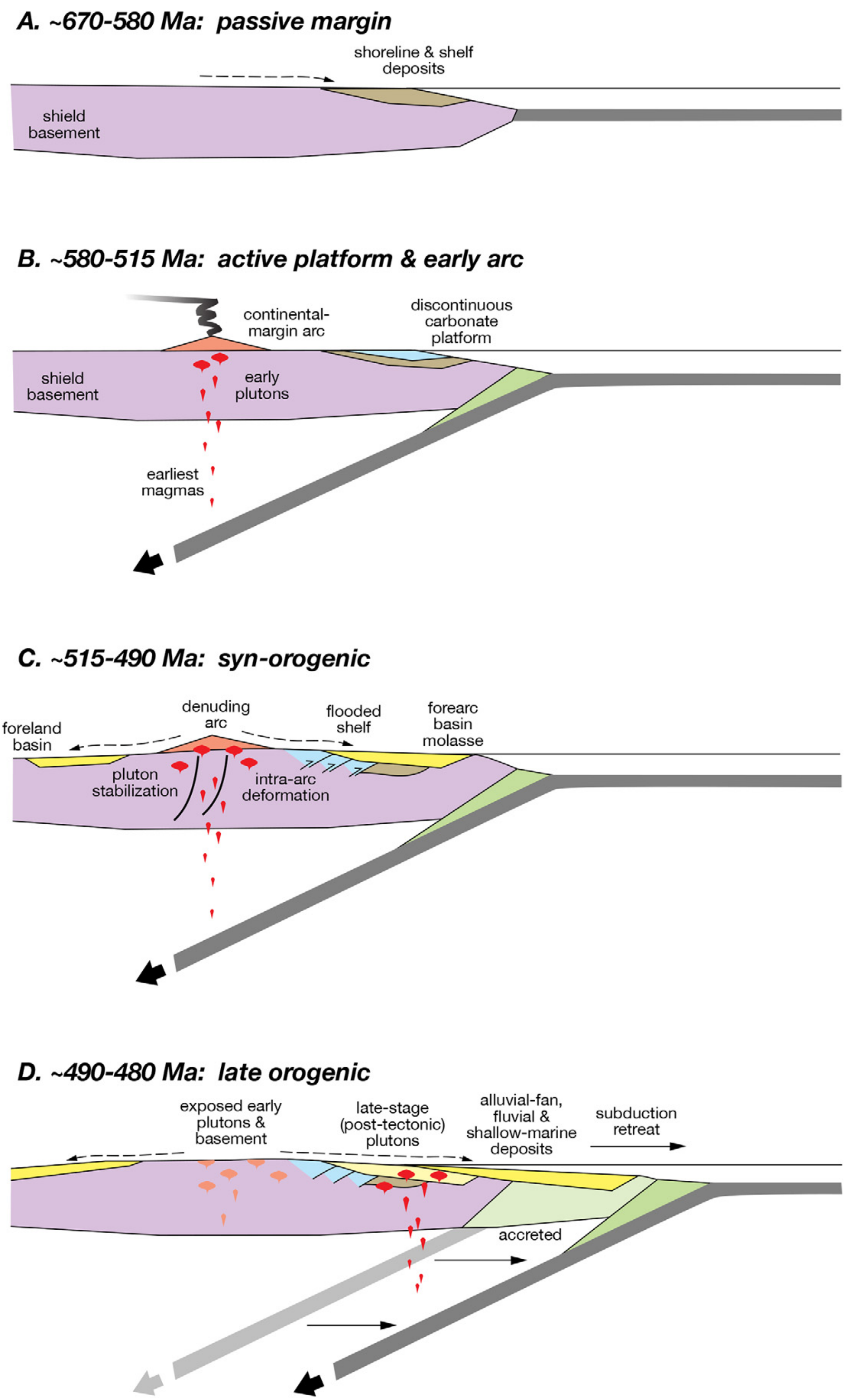


Fig. 50. Sequence of tectonic reconstructions for the Ross Orogen in northern Victoria Land (after Rocchi et al., 2011). (a) Overall correlation of Paleozoic terranes within Antarctica, Australia and Tasmania. (b) Model of the geodynamic configuration of northern Victoria Land in Early Cambrian time. (c) Early–Middle Cambrian extensional event, with trench retreat, forearc boudinage, arc migration, and backarc(s) opening. (d) Resumption of convergence with onset of the Bowers volcanic arc during the Middle Cambrian. (e) Comparison of Middle Cambrian configuration of northern Victoria Land with the present-day setting of the Japan area. (f) Accretion of the Admiralty crustal ribbon and the Bowers arc–backarc system with (ultra)high-pressure subduction/underthrusting of part of the Bowers complex. (g) Late orogenic stage with fast exhumation of eclogites, sediment shed to the northeast and post-collisional potassic magmatism.


A. ~670-580 Ma: passive margin
shoreline & shelf deposits
shield basement
B. ~580-515 Ma: active platform & early arc
continental-margin arc
discontinuous carbonate platform
shield basement
early plutons
earliest magmas
C. ~515-490 Ma: syn-orogenic
foreland basin
denuding arc
flooded shelf
forearc basin molasse
pluton stabilization
intra-arc deformation
D. ~490-480 Ma: late orogenic
exposed early plutons & basement
late-stage (post-tectonic) plutons
alluvial-fan, fluvial & shallow-marine deposits
subduction retreat
accreted

(Douglas Conglomerate) and shallow-marine (upper Starshot and Dick Formations) settings. Oceanward retreat of the subduction zone to the east (present-day coordinates) is inferred in order to explain offshore migration of the magmatic axis. The record of moderate-*P* metamorphism within reactivated basement gneisses is consistent with these regional deformation patterns. Furthermore, the significant decompression recorded by basement metamorphism was manifested by forearc deposition of syn-orogenic molasse deposits. The coupled record of contemporaneous basement denudation and siliciclastic deposition, bracketed to within a few million years' duration (Fig. 44; Goodge et al., 2004a), indicates rapid exhumation of the orogenic core. Thus, the metamorphic record appears to be one of erosionally controlled thickening and denudation, yet no known evidence exists for structural extension in this area, as might be expected within continental-margin arc basement.

Fig. 52 illustrates evolution of the Ross Orogen with a series of tectonic maps showing the major features discussed above and compiled temporally in Fig. 36. The aim of this geographically-based compilation is to highlight the major sedimentary, igneous, metamorphic and tectonic features that co-evolved during five distinct time periods. The distribution of these events is generalized but consistent with both the temporal evolution represented in Fig. 36 and with the tectonic models discussed above. As such, the tectonic relationships shown in these time slices may help inform future exploration of both local details and orogen-wide tectonic patterns.

Important limitations or uncertainties with this compilation include the following. (1) A cratonic rift margin is assumed (Fig. 52A), based on geophysical trends (Goodge and Finn, 2010). Wide gaps exist between the exposed geology in the TAM proper (shown in light gray) and the inferred craton margin, particularly in northern Victoria Land, which means that significant parts of the Ross Orogen record may be missing. (2) Despite efforts by many workers to link Ross Orogen processes in apparently disparate areas such as northern Victoria Land, southern Victoria Land, and the central TAM, the stark differences in geologic features making up the active, convergent margin make it difficult to connect the tectonic elements that are separated by significant gaps. Constructing viable geometries during critical time periods such as the Early to Late Cambrian (Fig. 52D) is quite problematic, yet comparisons between different sectors can point to areas that may help to resolve existing uncertainties. (3) Geochronological data are more abundant at certain times and in particular areas. Due to the sparseness of the existing geochronological datasets, using this 'clumpy' record to infer broad temporal patterns may lead to erroneous conclusions. Of course, continuing efforts to build a more geographically complete chronologic record will be a major benefit. On the contrary, these and other problems may help lead to new research.

4.5. Cenozoic uplift of the Transantarctic Mountains front

The Transantarctic Mountains are one of the world's major Cenozoic mountain ranges, spanning >3500 km and reaching elevations of about 4500 m, yet they are a continuing enigma because they formed adjacent to and contemporaneously with the West Antarctic Rift System (WARS; Fig. 1), one of the largest extensional provinces on Earth. They are widely classified as a rift-shoulder mountain belt situated between the WARS and cratonic East Antarctica underlying the polar ice cap. A characteristic feature of the TAM is a relatively flat summit area, sloping gently toward the polar ice cap and dropping precipitously to the level of the Ross Ice Shelf across a steep escarpment of up to 3500 m relief over as little as 60 km (Olivetti et al., 2018). Crustal thicknesses vary from 25–30 km across the WARS to a maximum of ~45 km beneath parts of the TAM and a broadly uniform thickness of about 35–40 km across the adjacent East Antarctic craton (Lawrence et al., 2006a; Chaput et al., 2014; Hansen et al., 2016; Heeszel et al., 2016; Ramirez et al., 2017). A compilation of seismic data shows that mean crustal thickness in West Antarctica is 24 km whereas it is 40 km in East Antarctica (O'Donnell and Nyblade, 2014). Notably, crustal thickness beneath much of the TAM is about the same as in cratonic East Antarctica despite the higher elevations (Hansen et al., 2016; Ramirez et al., 2017).

Cenozoic uplift of the TAM is further enigmatic because it is a noncompressional mountain belt (Fitzgerald, 2002) and most workers link uplift of the TAM to formation of the WARS. Therefore, understanding development of the modern TAM will also inform us about formation of the WARS, a distributed rift system similar in scale to the East African Rift and the Basin and Range province of North America. The WARS has a protracted history of extension beginning with Jurassic separation of East and West Gondwana, Cretaceous stretching between East and West Antarctica (generally between about 150–100 Ma; McFadden et al., 2010), Late Cretaceous opening of the Ross Sea and separation of New Zealand crustal blocks (about 83 Ma; McAdoo and Laxon, 1997; Eagles et al., 2004; Mortimer et al., 2019), and focused Cenozoic extension in the western Ross Sea associated with active volcanism (Behrendt, 1999; Siddoway, 2008; Faccenna et al., 2008; Vignaroli et al., 2015). However, an absence of contemporary relative motion between East and West Antarctica across the WARS — as indicated by infrequent seismic activity, negligible geodetically-constrained motion, and marine magnetic anomalies indicating that relative motion ended by ~11 Ma (Winberry and Anandakrishnan, 2003; Donnellan and Luyendyk, 2004; Granot and Dyment, 2018) — makes it difficult to directly evaluate the geodynamic relationship between the WARS and TAM.

Regionally, the wide extensional province of the Ross Embayment and Campbell Plateau developed rapidly between 105 and 98 Ma, synchronous with separation of Antarctica and Australia (Müller et al., 2016; Williams et al., 2019). Episodic Early and Late Cretaceous exhumation in the TAM is mainly recorded by low-temperature thermochronology (see below; Fitzgerald, 2002), but the geological expression of Eocene and younger exhumation is shown by pronounced movement along steep, orogen-parallel normal faults causing high topographic relief within the TAM (Fig. 53). Displacement along range-parallel normal faults is most evident by comparing elevations of the basal Beacon unconformity (Kukri Erosion Surface) between fault blocks. With few exceptions, major range-front faults are covered by the Ross Ice Shelf at the base of the mountains, but they are inferred to underlie the sharp geomorphic break (Figs. 8, 9). Geologic mapping reveals an asymmetric pattern formed mainly by down-to-the-east (toward the Ross Embayment) normal faults (e.g., Gunn and Warren, 1962; Lindsay et al., 1973; Fitzgerald, 1994). Displacement on individual structures defining this rift-bounding extensional system is up to several hundred meters, with cumulative vertical displacement of 5 km, which ultimately drops Beacon strata to the level of the Ross Ice Shelf near Cape Surprise (Barrett, 1965). Miller et al. (2010) estimated the vertical offset of the Kukri Erosion Surface at Cape Surprise to be ~2.5 km relative to the range crest. Sedimentary fill in the adjacent narrow Victoria Land Basin is up to 14 km thick, making the aggregate differential displacement on the range-bounding structures as much as 17–18 km. Differences in elevation of the Kukri Erosion Surface laterally across major outlet glaciers indicate that there are young, perhaps reactivated, high-angle transverse faults underlying the glaciers that have accommodated slight differential movements between major structural blocks (Fig. 8).

Fig. 51. Model of the late Neoproterozoic and early Paleozoic tectonic evolution of the East Antarctic margin in the central Transantarctic Mountains (after Goodge et al., 2004a). Crustal thicknesses approximately to scale, but sedimentary basins exaggerated in thickness for clarity. (A) Passive-margin stage. (B) Platform and incipient arc stage. (C) Synorogenic stage. (D) Late-orogenic stage. Oceanward retreat of the subduction zone to the east (present-day coordinates) is inferred in order to explain offshore migration of the magmatic axis. See text for discussion.

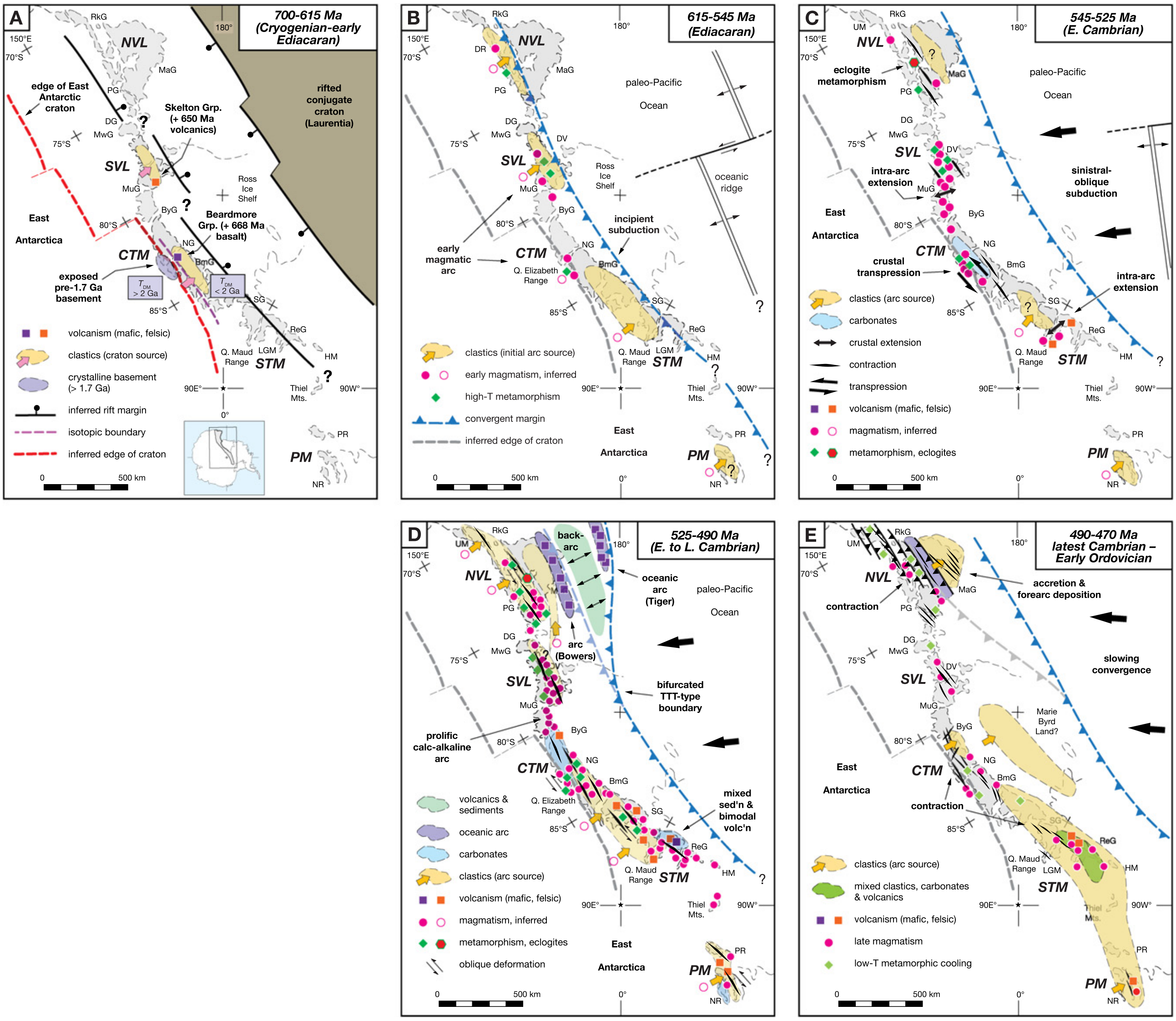


Fig. 52. Paleotectonic maps for five key time periods prior to and during the Ross Orogenic cycle. Key geologic units and events for each area discussed in text and shown with respect to time in Fig. 36. Locations of geologic units and dated features are diagrammatic only. Inset in (A) shows location of Transantarctic Mountains (gray base in each map). NVL, northern Victoria Land; SVL, southern Victoria Land; CTM, central Transantarctic Mountains; STM, southern Transantarctic Mountains; PM, Pensacola Mountains. Other geographic symbols: BmG, Beardmore Gl.; ByG, Byrd Gl.; DG, David Gl.; DR, Daniels Range; DV, Dry Valleys; HM, Horlick Mts.; LGM, La Gorce Mts.; MaG, Mariner Gl.; MuG, Muluck Gl.; MwG, Mawson Gl.; NG, Nimrod Gl.; NR, Neptune Range; PG, Priestley Gl.; PR, Patuxent Range; ReG, Reedy Gl.; RkG, Rennick Glacier; SG, Scott Gl.; UM, USARP Mountains.

One of the principal approaches to understanding uplift of the TAM is by examining the exhumation history provided by low-temperature thermochronology, in particular with apatite fission-track (AFT) ages (see Fitzgerald, 2002, and Baldwin et al., 2019, for summaries). Apatite fission-track studies are most commonly applied through vertical profiles in granitic rocks of the Granite Harbour suite where exposed in areas of high relief because apatite is a common accessory mineral in granitoids, it has a relatively simple cooling history following in situ crystallization, and because a vertical array of samples allows for evaluation of temperature vs. time as a sample passes through its respective closure temperature (e.g., Mt. Kyffen at the lower Beardmore Glacier; Fig. 54). Studies of this type place important quantitative age and rate constraints on the timing and magnitude of crustal uplift, and therefore the tectonic mechanisms for formation of the TAM. Application of the AFT method reveals that the TAM underwent episodic uplift and exhumation, first in the Early to Late Cretaceous, but that the principal uplift of the range as we know it today began in Eocene time (Fitzgerald and Gleadow, 1988; Fitzgerald, 1992, 1994, 2002; Balestrieri et al., 1997; Miller et al., 2010). AFT data from the TAM reveal the following general patterns (Fig. 55): (1) slow cooling from about 250–120 Ma, synchronous with Beacon deposition and continuing into the Cretaceous; (2) episodes of faster cooling (e.g., exhumation) from about 125–110 Ma and again from about 100–80 Ma, synchronous with Early Cretaceous crustal extension in Marie Byrd Land (Siddoway, 2008) and Late Cretaceous extension between East and West Antarctica; and (3) regionally, a break in slope of AFT ages at about 55–40 Ma, indicating onset of major TAM uplift concurrent with Eocene extension of the WARS. Rocks immediately beneath the early Paleozoic Kukri Erosion Surface (that is, close to the exhumation surface) further show a thermal response to Jurassic Ferrar magmatism. Synchronous Eocene cooling ages from multiple areas of the TAM indicate regional exhumation at about the same time, yet variations between areas indicate differential uplift of fault-bounded crustal blocks (Fitzgerald, 1994, 2002; Olivetti et al., 2018).

Although apatite fission-track ages between 55 and 40 Ma are conventionally thought to record the main period of uplift related to initiation of the WARS, recent thermal history results from southern NVL, and the area of Terra Nova Bay in particular, have led to different

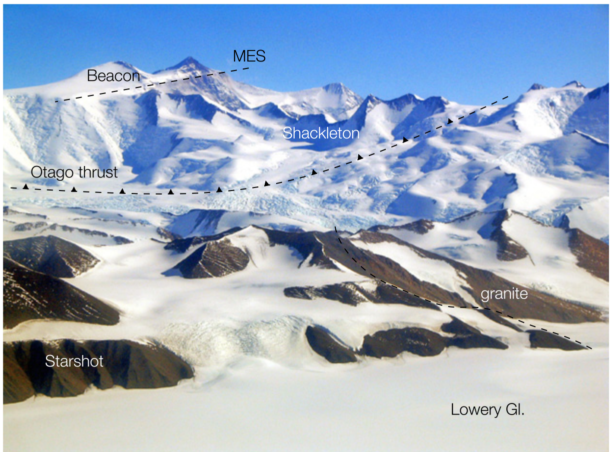


Fig. 53. View to the northeast from near Lowery Glacier, looking toward the Markham Plateau and Mt. Markham (highest peak) in the distance. Dark rocks in the foreground are deformed Starshot Formation (Middle Cambrian), structurally overlain by lighter-colored strata of the Shackleton Limestone (Lower Cambrian) along the Otago thrust. Rocks in the high peaks dipping gently to the left are Beacon Supergroup strata overlying basement on the Maya Erosion Surface (MES). Several high-angle normal faults striking roughly perpendicular to this view cause the extreme relief from the crest of the range outward toward the TAM margin.

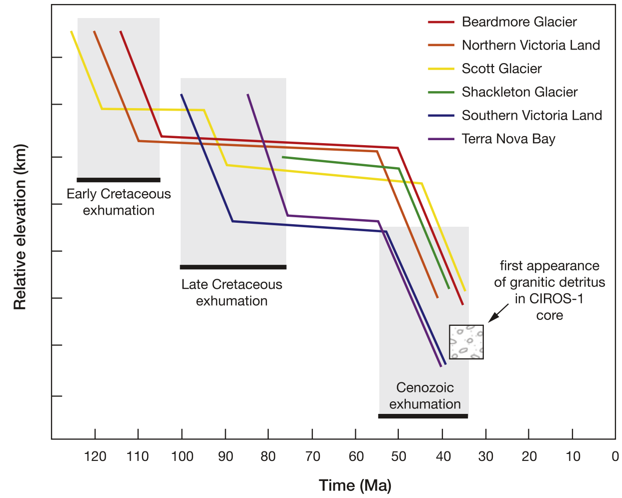


Fig. 55. Summary of exhumation patterns for different areas along the TAM, obtained from apatite fission track cooling ages (after Fitzgerald, 2002). SCG, Scott Glacier area; BDM, Beardmore Glacier area; SHG, Shackleton Glacier area; SVL, southern Victoria Land; TNB, Terra Nova Bay; NVL, northern Victoria Land.

interpretations. AFT data from these areas are thought to record a Jurassic heating event related to magmatism at about 180 Ma, followed by a long thermally stable period of slow cooling, and eventually the onset of rapid cooling caused by exhumation between 30 and 35 Ma (Lisker and Laufer, 2013; Prenzel et al., 2013, 2018). A continuous rather than episodic subsidence and exhumation history was first proposed by Lisker and Laufer (2013), who compared cooling age data with stratigraphic and paleontological trends from the Ross Sea. They postulated the development of a long-lived marine basin (Mesozoic Victoria Basin) that reflects continuous crustal extension and subsidence from Triassic to Cretaceous time, followed by uplift and inversion beginning in the Paleogene (since ~60 Ma) corresponding to initiation of the WARS. These authors further concluded that continuous subsidence in the Mesozoic Victoria Basin since ~200 Ma, and apparent lack of a thermal signal in AFT ages at ~175 Ma, precludes significant inflation and heating of the TAM orogen by Ferrar magma injection. They do not provide, however, a mechanism to explain the onset of TAM uplift at ~60–55 Ma. Thus, these authors call on development of a long-lived Mesozoic

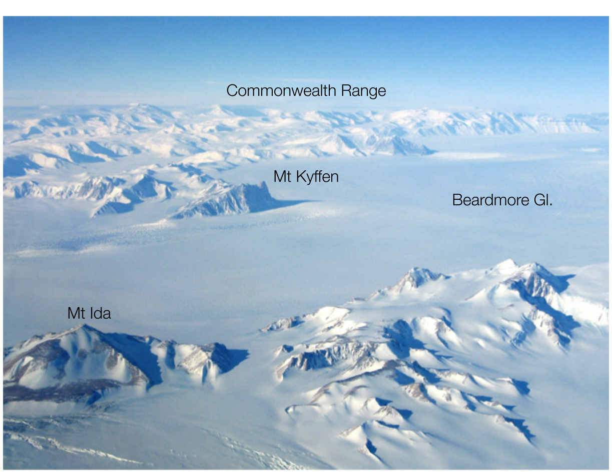


Fig. 54. Aerial view looking generally southeastward from the Queen Elizabeth Range across the lower Beardmore Glacier (flowing left), with granitoids of the Granite Harbour Intrusives in the foreground near Mt. Ida and at Mt. Kyffen (middle), and distant ridges in the Commonwealth Range underlain by Starshot Formation sedimentary strata. A thin cover of Beacon Supergroup is visible in the upper right.

basin that regulated regional thermal gradients, and which remained stable until exhumation at the Eocene-Oligocene boundary time (~34 Ma) as a result of tectonic inversion. In the view of these authors, an onset of major exhumation at ~55 Ma does not coincide with a climax of late Eocene tectonic activity at ~35 Ma, including basin subsidence, faulting and volcanism (e.g., Cooper et al., 1991; Salvini et al., 1997; Salvini and Storti, 1999; Hamilton et al., 2001; Rocchi et al., 2002, 2003b; Di Vincenzo et al., 2013). In contrast, an episodic history of uplift and exhumation since ~125 Ma appears to be well documented in several areas of the TAM (see Baldwin et al., 2019) and is best explained by early crustal extension, Australian-Antarctic breakup, extension in the Ross Embayment coupled with flexure of strong East Antarctic lithosphere, and propagation of sea-floor rifting from the Adare Trough into continental crust of the western Ross Sea. The postulate of a long-lived Mesozoic basin that experienced rapid exhumation in the Oligocene in association with development of the Terror Rift is controversial and will require further detailed study.

AFT data from the Royal Society Range and near Byrd Glacier area exemplify the variable Eocene to Oligocene exhumation histories. In the Royal Society Range, Olivetti et al. (2018) showed that topography is highly variable and that exhumation is asynchronous with respect to other areas. There, Eocene to early Oligocene exhumation appears related to dextral transtension and is not simply a product of extension along the WARS boundary. In contrast, AFT data near Byrd Glacier indicate that there was early (Cretaceous) development of a fluvial landscape which drained toward the interior of East Antarctica, rather than toward the Ross Sea (Huerta et al., 2011). These results indicate that a topographic reversal occurred since the Cretaceous, that there was rapid uplift between 30 and 20 Ma, and that the region has remained relatively stable since the Early Miocene.

Taken altogether, a simple and regionally consistent explanation of the thermal history patterns is to consider that the AFT cooling ages record two phases of TAM uplift and exhumation: an early phase of regional extension related to Cretaceous crustal extension and outward displacement of rocks presently in Marie Byrd Land during initial opening of the WARS, followed by a later phase of Paleogene extension related to differential uplift of the TAM. Nonetheless, the synchronous thermochronologies establish a temporal link between TAM uplift and WARS extension. AFT ages further indicate a Cretaceous geotherm of ~25 °C/km (Fitzgerald, 1994); therefore, following emplacement of the Ferrar magmas in Jurassic time, the crust assumed a 'normal' continental geotherm prior to onset of Paleogene extension. The fission track data do not constrain the denudation/uplift history during the late

Cenozoic, except that in the lower Beardmore Glacier region there appears to have been as much as 4 km of denudation in the last 30 m.y. (Fitzgerald, 1994).

Offshore basins of the Ross Embayment, such as the Adare Trough and Victoria Land Basin (Fig. 8), were actively extending between about 45–25 Ma, eventually leading to seafloor spreading as recorded by marine magmatic anomalies. Only minor bulk extension is recorded across these basins over the past 20 m.y. and rather has been focused within the narrow normal-fault graben of the Terror Rift since 17 Ma (Hall et al., 2007). In the TAM, however, transtensional kinematics during this time period shows that the region has been tectonically active through the Quaternary, as shown, for example, by deformed Pliocene to Pleistocene volcanic rocks (Paulsen and Wilson, 2009), transtensional fault geometries between the Transantarctic Mountains and the West Antarctic Rift System in northern Victoria Land (Vignaroli et al., 2015), and dextral strike-slip deformation since about 4 Ma at Mt. Morning in southern Victoria Land (Martin and Cooper, 2010). These deformation patterns document the general transition from Eocene NW-oriented dextral strike-slip faulting associated with geodynamics of the Ross Sea (e.g., Salvini et al., 1997), to extensional opening of the WARS and development of a transtensional boundary between the TAM and the WARS.

Because of the topographic and structural asymmetry of the TAM, and because of their proximity to the contemporaneous WARS, it is commonly proposed that uplift of the TAM rift-flank is mechanically related to Cretaceous-Paleogene development of the outboard rift province (Fitzgerald et al., 1986; Stern and ten Brink, 1989; van der Beek et al., 1994; Busetti et al., 1999; van Wijk et al., 2008). A thorough treatment of relevant geophysical data and geodynamical models is beyond the scope of this contribution, but a few points are in order here. Many workers consider that lithospheric extension, crustal thinning and widening of the Ross Sea basin created a tectonic discontinuity that led directly to uplift of the TAM along a hinge-like fault zone, thus resulting in differential cooling of the upthrown blocks. Mechanisms of lithospheric extension are sharply debated, but principally include: (a) flexural displacement at the boundary between thin, weak crust in West Antarctica and a thick elastic lithosphere in East Antarctica (Stern and ten Brink, 1989; ten Brink et al., 1997; Yamasaki et al., 2008); (b) dynamic support by thermal buoyancy or by conduction of heat from West Antarctic asthenosphere (LeMasurier and Rex, 1991; Rocholl et al., 1995; Brenn et al., 2017); and (c) collapse of an elevated, pre-existing West Antarctic plateau (Studinger et al., 2004; Karner et al., 2005; Huerta and Harry, 2007; Bialas et al., 2007), which implies that the high TAM elevations are a remnant of initially high topography and thick crust extending beneath the present-day Ross Sea. Some models also link uplift with crustal thickening due to rifting-associated underplating (Fitzgerald, 2002), or a flexural response to Cenozoic glacial erosion and not related to rifting at all (Stern et al., 2005).

Thermal structure of the East Antarctic craton adjacent to the TAM front has until recently been poorly constrained. Brenn et al. (2017) presented new seismic tomography from southern Victoria Land showing anomalous warm mantle beneath Ross Island, Terra Nova Bay, and offshore beneath the Victoria Land Basin, which they explained, respectively, as regions of shallow-mantle partial melt associated with high topography in the TAM and extension in the Terror Rift. These data support flexural uplift models for the TAM, in which variable thermal buoyancy beneath the range is the main driver of uplift. From detailed analysis of hypsometry, Olivetti et al. (2018) also concluded that the variable topography along this part of the range is linked to contrasting upper mantle thermal conditions, thereby inferring that at least parts of the range are dynamically supported. In particular, they attribute the anomalously high elevations and active exhumation in the Royal Society Range of SVL to magmatic underplating. In contrast, however, magnetotelluric data from the central TAM indicate that lithosphere in that area is stable into the upper mantle, therefore implying that the mountain range in this area is elevated by a non-thermal, flexural cantilever mechanism due to strong lithosphere able to provide mechanical support (Wannamaker et al., 2017). In the southern TAM, seismic data show a low-velocity upper-mantle anomaly that indicates lithospheric foundering beneath adjacent East Antarctica and incursion of warm upper-mantle asthenosphere from the east that provides thermal support for this area, consistent with the uplift history and Cenozoic volcanism (Shen et al., 2018). In short, the roles of flexural and thermal mechanisms for support of the modern TAM are as yet unresolved.

Despite uncertainty concerning tectonic mechanism associated with the youngest phase of TAM evolution, there is a temporal linkage between uplift in the TAM and opening of the WARS. This age relationship is well-documented, for example, by AFT cooling ages in the area near Shackleton Glacier that indicate rapid Cenozoic denudation began by ~40 Ma (Fig. 56; Miller et al., 2010). This timing is consistent with results from northern Victoria Land (ca. 55 Ma; Fitzgerald and Gleadow, 1988), southern Victoria Land (ca. 55 Ma; Gleadow and Fitzgerald, 1987; Fitzgerald, 1992), the Beardmore Glacier area (ca. 50 Ma; Fitzgerald, 1994), and the Scott Glacier area (ca. 45 Ma; Fitzgerald and Stump, 1997). Data from all of these areas indicate that Cenozoic denudation was tied to faulting across the TAM front. The coincidence in timing of the onset of denudation with extension in the WARS (Cande et al., 2000; Cande and Stock, 2006; Davey et al., 2006) supports models invoking a tectonic, and therefore causal, relationship between TAM uplift and extension in the WARS. Because initial formation of the WARS is significantly older than measured uplift in the TAM, any inferred extension caused by collapse of a thickened plateau must have occurred elsewhere (Miller et al., 2010).

5. Supercontinent record in the Transantarctic Mountains

Despite its remoteness and glacial cover, the TAM provide critical geological evidence that helps to constrain past supercontinent associations, paleogeography, timing, and tectonic process (Fig. 2). Testing of paleogeographic details is difficult, however, because the crustal structure of the East Antarctic craton is poorly known along much of its perimeter and because we lack well-dated Proterozoic paleomagnetic poles. Nonetheless, geological data from the TAM trace key stages in supercontinent evolution from Columbia (ca. 2.0–1.2 Ga) to Rodinia (ca. 1.1–0.7 Ga), Gondwana (ca. 0.61–0.45 Ga) and Pangea (ca. 0.32–0.19 Ga). Each of these major supercontinent linkages is summarized briefly below in order to provide a TAM perspective, and the reader is referred to references provided for broader details.

5.1. Columbia

The Nimrod Complex exposed in the central TAM records crust-forming and orogenic events at ~3.1, 2.5 and 1.7 Ga (Goodge and Fanning, 1999, 2016; Goodge et al., 2001). These ages are correlated in whole or part with events outside the TAM in Terre Adélie and the Shackleton Range in Antarctica, and the Gawler Craton in Australia (see Goodge and Fanning, 2016). Together, these windows of Mesoarchean to Paleoproterozoic crust comprise a coherent cratonic assemblage referred to as the Mawson Continent. The ages associated with Mawson evolution represent the beginnings of a long-lasting relationship between East Antarctica and Australia that extends to ~160 Ma at the time of Pangea breakup (Williams et al., 2019). The cratonic association of East Antarctica and Australia also included present-day India and Madagascar in the broader East Gondwana grouping. Paleogeographic reconstructions have further suggested that the combined cratons of East Antarctica-Australia-India can be restored to a position along the western edge of cratonic Laurentia in the Columbia (or Nuna) supercontinent (e.g., Zhao et al., 2002, 2004; Meert, 2002), which is supported by crustal age and isotopic data (Borg and DePaolo, 1994; Goodge et al., 2001), and by paleomagnetically constrained reconstructions (e.g., Pisarevsky et al., 2014). This supercontinent is thought to have been amalgamated between ~2.1 and

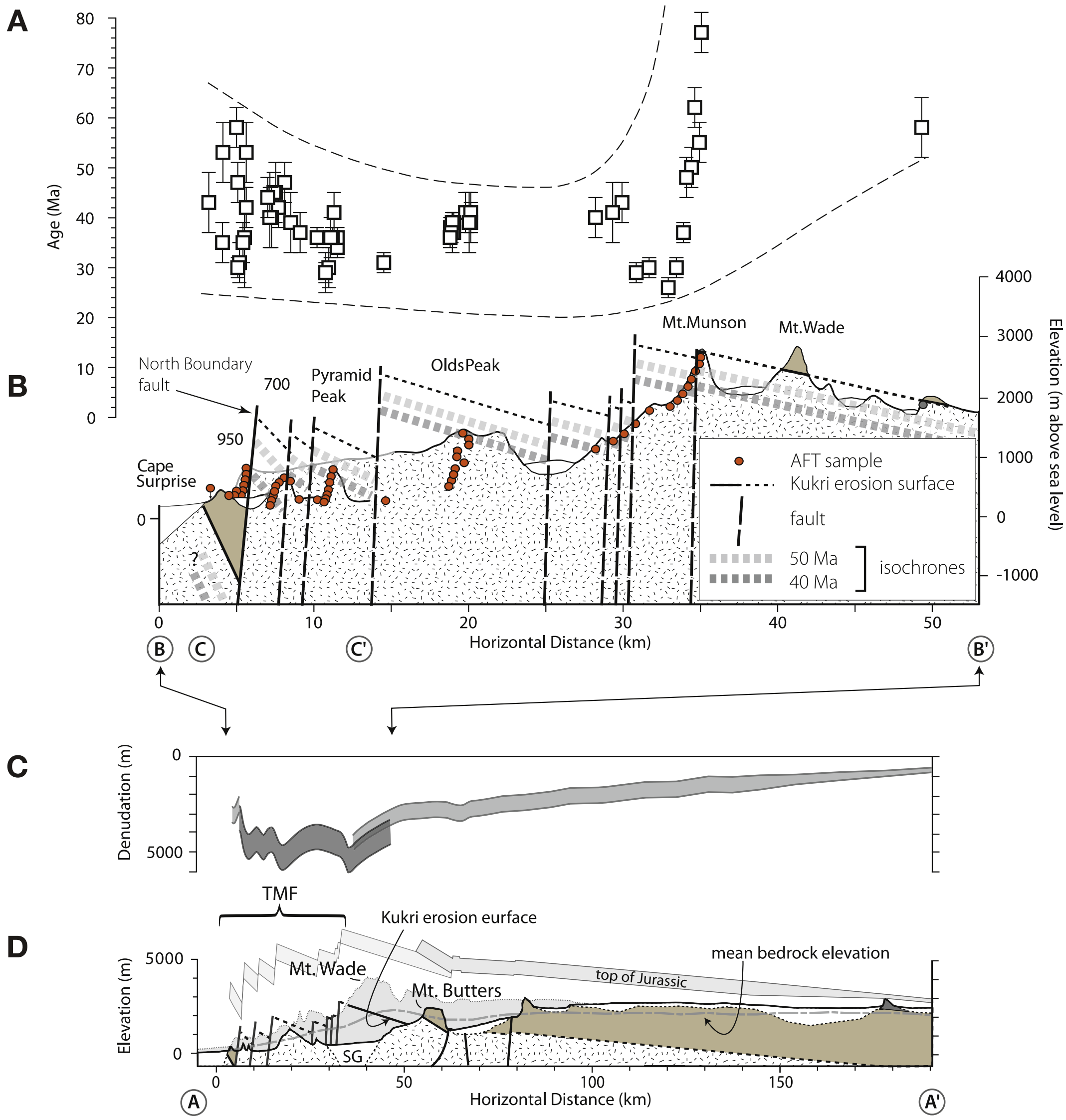


Fig. 56. Cross sections of the TAM front near Shackleton Glacier, showing apatite fission-track ages and calculated magnitudes of denudation (after Miller et al., 2010). (A) Fission-track ages (squares) and errors plotted above corresponding sample locations (orange circles) in (B), a cross section of the TAM front, showing AFT sample locations, 40 and 50 Ma isochrones, the projected Kukri Erosion Surface below Beacon strata (tan), and faults (dashed where inferred). (C) Estimated Cenozoic denudation profile. (D) Cross section of the TAM, from the East Antarctic Ice Sheet (right) to the Ross Ice Shelf (left). Light gray silhouette in the background marks the envelope of maximum topographic elevations between Shackleton and Liv glaciers. Vertical exaggeration is 5×.

1.8 Ga, with major orogenic activity at ~1.9 Ga and an extant assembly persisting into the Mesoproterozoic. In the early 1990's, the correlation of rocks in East Antarctica with well-known basement and rift-margin successions in the southwest U.S. part of Laurentia was revolutionary in concept (Moores, 1991; Dalziel, 1991). Although evidence supporting a so-called SWEAT association was, in hindsight, flawed by poorly known stratigraphic relationships, this provocative idea is now well supported by more direct correlation. First, Antarctic detrital zircon provenance data obtained from rift-margin successions pre-dating the Ross Orogeny show significant Grenvillian and older Proterozoic age populations, including distinctive age peaks at ~1.4 Ga (Goodge et al., 2002, 2004a). The age and isotopic compositions of the 1.4 Ga zircons overlap those of unique Laurentian A-type granitoids (Goodge and Vervoort, 2006; Goodge et al., 2008), indicating that Laurentian-type crust lies in East Antarctica. Mesoproterozoic siliciclastic rocks from Tasmania show similar age and isotopic correlation with potential Laurentian sources (Mulder et al., 2015). Second, age and isotopic data obtained from igneous glacial erratics eroded from the interior of East Antarctica and deposited along the craton-ward edge of the TAM provide a unique record of previously unrecognized, ice-covered crust ranging in age from ~2.0 to 1.1 Ga (Goodge et al., 2008, 2010, 2017). The ages and isotopic compositions of these igneous clasts match quite closely their counterparts in western Laurentia, particularly at ages of ~1.86, 1.57, 1.45 and 1.21 Ga, which links central East Antarctica with western Laurentia between about 1.9–1.2 Ga as part of the Columbia supercontinent (see full discussion by Goodge et al., 2017). Third, the Paleoproterozoic association of central East Antarctica, southern Australia, and southwestern Laurentia within Columbia is further supported by correlation of distinctive ~1.6 Ga volcanic breccias and associated mineral deposits in northwestern Canada and eastern Australia (e.g., Thorkelson et al., 2001a, 2001b; Furlanetto et al., 2016).

The correlated ages and isotopic compositions of Proterozoic igneous rocks from the East Antarctic interior, southern Australia, and southwestern Laurentia thus support the concept of a paleogeographically-linked cratonic assemblage at the heart of the Columbia supercontinent, formed initially between ~2.0–1.8 Ga. Younger intra-cratonic or craton-margin tectonism occurred between 1.8 and 1.4 Ga, and Mesoproterozoic intracratonic magmatism occurred at ~1.45 and 1.22 Ga, culminating in the assembly of Rodinia. The age and isotopic signatures shared between central East Antarctica, southwestern Laurentia, and southern Australia thus attest to the assembly and relative continuity of a Proterozoic supercontinent that persisted between ~2.0 and 1.2 Ga prior to rifting and eventual breakup in the late Neoproterozoic (see Goodge et al., 2004b, 2008, 2017; Medig et al., 2014; Mulder et al., 2015; Goodge and Fanning, 2016).

5.2. Rodinia

Fundamental changes in Earth's linked tectonic, climatic, and biotic systems during the late Neoproterozoic to early Paleozoic transition coincided with the assembly and breakup of Rodinia (see Nance et al., 2013 for general discussion and references). Fragmentation of the Rodinia supercontinent, and subsequent amalgamation of Gondwana, coincided with global mountain building, continental erosion, climate shifts, species diversification, sea-level fluctuations, and changes in sea-water composition. Pertinent to this discussion, the two landmark papers by Moores (1991) and Dalziel (1991) focused attention on a key element of Rodinia during this critical period of time, helping to revitalize interest in Proterozoic tectonics and global paleogeography. Moores noted strong similarities among the tectonic belts of East Antarctica, Australia, and Laurentia, in particular a possible fit between Proterozoic orogenic belts and rift-margin successions in Laurentia and East Antarctica. Dalziel used similar geologic constraints for a Rodinia reconstruction and developed these ideas further by proposing a paleomagnetically-constrained breakup sequence. Geologic evidence supporting such a connection between East Antarctica and Laurentia was limited by poor age control, subsequent stratigraphic revision, and poor geographic continuity, yet these papers drew attention to the little-known geology of the TAM and spawned lively scientific debate for years afterward.

Although numerous alternative scenarios have been proposed for Rodinia, refined global reconstructions based on paleomagnetic data and supported by geological correlation show the TAM margin of East Antarctica, in continuity with the Neoproterozoic margin of eastern Australia, as conjugate to western Laurentia from ~1080 to 725 Ma (so-called SWEAT model; Dalziel, 1997; Torsvik, 2003; Meert, 2003; Swanson-Hysell et al., 2012). Recent geological evidence appears to confirm the cratonic linkages and Neoproterozoic rift-margin associations proposed earlier by Moores (1991) and Dalziel (1991). With the Columbia association of East Antarctic, Australian and Laurentian cratons as a starting point at ~1.2 Ga (see Goodge et al., 2017), a relationship between the TAM sector of East Antarctica and western Laurentia continued well into Neoproterozoic time as part of the Rodinia supercontinent assembly, as shown by rift-margin sedimentary and volcanic rocks in the Beardmore and Skelton groups of the TAM. Siliciclastic rocks of the Beardmore Group have a cratonic provenance in East Antarctica that includes distinctive detrital zircon age populations at 1170, 1540, 1800, and 2510 Ma (Goodge et al., 2002, 2004; Myrow et al., 2002; Goodge and Fanning, 2016), overlapping ages of Neoarchean, Paleoproterozoic and Grenvillian crust in Laurentia. Similar detrital zircon age signatures and bimodal volcanism in the Skelton Group (Wysoczanski and Allibone, 2004; Cooper et al., 2011), as well as sedimentary-volcanic assemblages in southeast Australia (Crawford et al., 1997, 2003; Preiss, 2000), indicate extension and rifting along the Austral-Antarctic margin related to supercontinental breakup. Further, Beardmore Group sedimentary whole-rock Nd-isotope compositions match Neoproterozoic strata from the Great Basin of Utah, Nevada and California (Farmer and Ball, 1997), and individual ~1.4 Ga detrital zircon Hf-isotope compositions match those from equivalent-age A-type granitic intrusions in western Laurentia (Goodge and Vervoort, 2006; Goodge et al., 2008), both indicating similar sedimentary composition and provenance of corresponding rift margins of East Antarctica and Laurentia. The Beardmore rift-margin assemblage includes mafic pillow lavas that were dated to ~670 Ma (Goodge et al., 2002), which are quite similar in age to felsic volcanic clasts in conglomerates of the Skelton Group dated to ~650 Ma (Cooper et al., 2011). These ages reflect the time of rifting along the East Antarctic margin, which is also similar to Sturtian ages of volcanism associated with a rift-to-drift transition in western Laurentia between 690 and 640 Ma (e.g., Windermere Supergroup strata in southeast Yukon, Pigage and Mortensen, 2004; northern Rocky Mountains, Ferri et al., 1999; central Idaho, Lund et al., 2003; southern Idaho, Fanning and Link, 2004; Lund, 2008). In East Antarctica, rift-margin subsidence ended by ~615 Ma, whereas in western Laurentia it continued into the Cambrian (Bond et al., 1984), reflecting the different subsequent early Paleozoic histories of these conjugate margins. Finally, in addition to widespread Grenvillian detrital zircon signatures in Neoproterozoic siliciclastic rocks, Grenville-age rocks recovered from glacial sites along the TAM and dredged from the South Tasman Rise attest to the presence of Mesoproterozoic crust akin to the type area in southwestern Laurentia (Goodge et al., 2010; Fioretti et al., 2005a). If the South Tasman Rise site is restored to a position along the modern TAM (e.g., Mulder et al., 2015), then the occurrence of Grenville-age crust in central East Antarctica may represent an extension of the Grenville orogenic belt, which extends into the southwest U.S. before being truncated abruptly in Texas and New Mexico.

Despite a more solid understanding of the Neoproterozoic history along the TAM margin, still uncertain are the position of the rift margin, the geometry of rifting, the extent of crustal thinning, the extent of rift-margin sedimentation, the location of possible transform offsets, and the influence of these structural patterns on later orogenesis (see Goodge and Finn, 2010, for discussion). Details such as these may best be addressed by additional geophysical observation.

5.3. Gondwana

Between latest Neoproterozoic to early Paleozoic time, the TAM sector of East Antarctica evolved from a passive, drifting margin to an active, subducting margin. A principal driver of this tectonic change is thought to be closure of the Mozambique Ocean and collision between East and West Gondwana, which focused deformation along the East African Orogen propagating between Dronning Maud Land in Antarctica through southern and eastern Africa, India and Madagascar (Hoffman, 1991; Goodge, 1997, 2007a; Fitzsimons, 2000; Jacobs and Thomas, 2004; Boger and Miller, 2004; Boger, 2011). This Pan-African activity was characterized in the TAM by an Andean-type convergent plate margin along the southern outer perimeter of East Gondwana. Subduction of paleo-Pacific oceanic lithosphere beneath the active Gondwana margin of continental East Antarctica produced the spectrum of deformational, metamorphic, igneous, and sedimentary features characterizing the Ross Orogen (see above). This convergent-margin activity spanned as much as 145 million years between about 615–470 Ma, reflecting a prolonged period of sustained underflow. Subduction was initiated along this margin of Antarctica between ~650 and 615 Ma, as constrained by the youngest age of rift-margin sedimentation (Cooper et al., 2011) and the earliest record of Ross Orogen metamorphism (Hagen-Peter et al., 2016).

Principal Gondwana-era features in the Ross belt of the TAM include a prolific, largely calc-alkaline, continental-margin magmatic arc constructed within Proterozoic to early Paleozoic crust, thick marginal-basin siliciclastic deposits, ultra-high pressure eclogites locally, and structures indicative of oblique convergence and transpression. Between northern Victoria Land and the Pensacola Mountains, major orogenic trends—including timing of events, pace and character of magmatism, deformation patterns, metamorphic regimes, and sedimentary provenance changes—can be attributed to variations in convergent-margin dynamics. Differential convergence led to significant variations in the timing and character of events along the length of the orogen, including: (1) inherited rift-margin geometry exerted a major control on all orogenic processes, as shown by contrasts in magmatic, metamorphic and deformational patterns; (2) sinistral-oblique subduction, recorded by partitioned and/or transpressional structures; (3) diachronous onset of magmatism, from ~580 Ma in northern Victoria Land to ~510 Ma in the Pensacola Mountains; (4) variable influence of overlying cratonic crust during magma evolution, ranging from mantle-dominated signatures in northern and southern Victoria Land, to strong cratonic signatures in the central TAM, and continentally-influenced rift-type magmas in the southern TAM; (5) periodic intra-arc contraction and extension linked to varying magmatic styles; (6) HP-UHP metamorphism restricted to domains characterized by arc/back-arc construction and subsequent rapid thickening; and (7) a flood of syn-orogenic siliciclastic sediment with a dominantly Ross Orogen provenance, signaling initial orogenic activity in many areas. Active Gondwana-margin tectonism in the TAM had waned by ~450 Ma, beginning a phase of tectonic quiescence, but it is not clear whether subduction itself had ceased or that plate-margin activity moved farther offshore. Contractional deformation continued in the Lachlan fold belt of eastern Australia through the Silurian and Middle Devonian (Gray and Foster, 2004) and convergent arc magmatism was active again in Antarctica by the Devonian (Admiralty intrusives in northern Victoria Land and granitoids in Marie Byrd Land), together indicating continuity of offshore convergence.

5.4. Pangea

The largest of the known supercontinents formed by the amalgamation of Gondwana and Laurussia at ~320 Ma. Pangea is the best understood supercontinent because the Phanerozoic record of ocean and terrestrial paleoenvironments, continental paleogeography, and seafloor history are all well-constrained (e.g., Torsvik and Cocks, 2017). For the TAM sector of Antarctica, global 'ice-house' conditions and moderate to high southerly latitudes during the Carboniferous to mid-Permian (about 330–280 Ma) forced cold-climate processes, but these moderated under greenhouse conditions during Triassic and Jurassic time. Although the TAM do not hold a terrestrial Carboniferous stratigraphic record, local igneous occurrences expressed by the Admiralty intrusives and Gallipoli volcanics in northern Victoria Land attest to convergent-type magmatism at ~350 Ma that likely was more significant offshore along the southern margin of Pangea.

The principal Pangean stratigraphic records in the TAM span Permian to Jurassic time, providing key lines of evidence for supercontinent paleogeography. During the Permian ice-house period, the Gondwana portion of Pangea lay wholly in the southern hemisphere and the TAM sector of East Antarctica was in a near-polar position, as recorded by tillites of Early Permian age. By ~250 Ma, East Antarctica had migrated northward and the Gondwanide strata include mid- to late-Permian coal beds mixed with volcanic materials, indicating a warming climate and arc magmatism produced by peripheral subduction. *Glossopteris* and other distinctive species prevailed even at high southern latitudes and persisted through the Permian. Mild conditions extended through the Triassic (by 230 Ma), marked in the central TAM by high-latitude coal beds. As noted above, although Permian and Triassic plate-margin convergence and arc magmatism are well-documented in New Zealand, Marie Byrd Land, Thurston Island, the Antarctic Peninsula and Patagonia, the principal evidence in the TAM for an active southern margin of Pangea at this time comes from detrital sediment provenance records, which indicate increasing influence of arc-derived materials into terrestrial basins relative to cratonic sources (e.g., Elliot et al., 2017).

By late Early Jurassic time (~180 Ma), the Gondwana portion of Pangea was positioned over a large lower-mantle thermal anomaly (Torsvik and Cocks, 2017), leading to magmatism and mechanical instability in the overlying supercontinental lithosphere. The central Karoo magmatic center of southern Africa was actively erupting at this time, and mafic magmas of the Ferrar system were propagating along the TAM as dikes, sills and larger layered intrusions. These tectonomagmatic events were the trigger (or the response) to Gondwana and Pangea breakup, notably separating East and West Gondwana along a line separating Africa from East Antarctica, Madagascar, and India by ~170 Ma. Although becoming progressively isolated from all other continents from this point forward, it is notable that Antarctica and the TAM have been in a high-latitude sub-polar to polar position since Jurassic time.

6. Summary and the future of geologic research

The Transantarctic Mountains provide a fragmentary record of supercontinent history during the late Neoproterozoic and early Paleozoic transformation from Rodinia to Gondwana. They also provide a unique but semi-continuous record of Gondwana-wide sedimentation, large igneous province magmatism, Mesozoic and Cenozoic uplift histories, and Neogene volcanism, rifting and landscape evolution. The TAM contain a well-preserved record of the following tectonic elements:

1) a Precambrian craton hosting rocks that formed between 3.0 and 1.7 Ga, represented by the crystalline assemblage of the Nimrod Complex and Argosy Schist, and imaged geophysically beneath the adjacent ice sheet;
2) a Neoproterozoic continental rift margin (notably represented by the Beardmore Group in the Nimrod Glacier area, and correlative strata in other areas), probably formed about 670–650 Ma;
3) a discontinuous Lower Cambrian passive-margin platform, exemplified by the Shackleton Limestone in the central TAM and correlative units in other areas, and developed intermittently into the Middle Cambrian (e.g., Nelson Limestone in the Pensacola Mountains);
4) the early Paleozoic, convergent-margin Ross Orogen, active between about 580–480 Ma, and characterized by regional metamorphism, contractional to oblique-slip deformation, prolific granitoid batholith magmatism (Granite Harbour intrusives), silicic to bimodal continental-margin volcanism, oceanic arc development (Bowers terrain), and active-margin molasse-type siliciclastic sedimentation resulting from tectonic thickening and uplift (upper Byrd Group and correlative units);
5) middle Paleozoic crustal stability and formation of a supercontinent-wide pre-Devonian erosion surface (Kukri Erosion Surface) and succeeding pre-Permian Maya Erosion Surface;
6) middle Paleozoic to Jurassic intracontinental and foreland-basin deposition with both cratonic and arc sediment sources (Beacon Supergroup);
7) volcanism and intrusion related to the emplacement of Middle Jurassic magmas comprising the Ferrar Large Igneous Province;
8) Cretaceous to Neogene uplift and cooling, at least in part related to modern uplift of the TAM;
9) Neogene volcanism in the McMurdo Magmatic Province, likely related to an upwelling mantle plume at the edge of the Ross embayment; and
10) Neogene erosion and deposition of glacial deposits that record early growth and evolution of the Antarctic ice sheets.

Further research is needed to address each of the geologic elements of the TAM discussed in this summary paper. Although specific research problems exist within a given area, broad first-order questions that can continue to stimulate new research include the following:

1) What is the Mesoproterozoic and older history of crystalline cratonic basement along the TAM margin? Where do such rocks extend beneath the continental ice sheet? What correlations can be used to contrain paleogeographic ties to conjugate cratons in Rodinia and Columbia?
2) What was the configuration of the Neoproterozoic rift margin, over what time period did it form, and how did the geometry of the margin control later tectonic events? Can we separate Neoproterozoic structures from Mesozoic and Cenozoic features?

3) How does the tectonic history of the Ross orogen vary in space, time and process? Specifically, what can integrated petrologic studies of metamorphism, deformation, and thermochronology reveal about crustal conditions, displacements, and tectonic processes? How allochthonous are different terranes? What do cooling and exhumation rates indicate about the role of structural extension in denudation for the orogen as a whole? What patterns will emerge in space and time from more detailed thermochronology? Can geophysical remote sensing be used to extrapolate outcrop geology to ice-covered areas of the adjacent continental shield?
4) How does early Paleozoic magmatism vary in time and space along the Ross Orogen, and what do these variations say about the interplay between intra-arc extension and compression? What can isotopic data reveal about variations in arc basement, source regions, and melting mechanism? What are the petrogenetic processes that link magmatism and metamorphism?
5) What do Neoproterozoic, lower Paleozoic and Mesozoic sediment provenance tell us about age, transport pathways, and sources of deposition? What are the roles of local Antarctic vs. far-traveled inter-cratonic sources, and what does this tell us about supercontinent history? How are basin deposition and tectonics linked through time?
6) What do variations in Beacon Supergroup depositional environment and chemical composition tell us about late Paleozoic and Mesozoic paleoclimate? Can we distinguish global and regional climatic patterns? What do biostratigraphic trends reveal about faunal and floral evolution at high latitudes?
7) What is the origin of Ferrar magmas and what do their compositions tell us about magma evolution and crustal interaction? How far-traveled are the Ferrar magmas, how strongly channelized were they in terms of flow direction, and what were the emplacement mechanisms? What does the magma plumbing system look like in detail, and what does this imply about crustal paleostress?
8) What is the bounding structure between the TAM and WARS provinces? How does its geometry vary with depth? How does surface geology inform and connect with subsurface geophysical data? Are there fragments of the TAM in Marie Byrd Land or beneath the Ross Ice Shelf?
9) What are the mechanisms of TAM uplift and support? How do thermal histories vary from region to region, and what do they tell us about exhumation mechanism? How do regional fault patterns reflect the uplift process, what is the timing and sequence of deformation, and how did it contribute to Cenozoic landscape evolution? How did the tectonic regime change from extension to transtension or strike-slip? What is the magnitude and significance of Cenozoic transtension?
10) How does the Cenozoic denudation history relate to tectonic and glacial process? How are glacial history and TAM uplift linked? What are the feedbacks between glacial erosion and uplift rate?
11) What does the history of Neogene sediment deposition and landscape evolution tell us about growth and stability of the East Antarctic ice sheet? How did long-term ice sheet history vary in space, time and basal regime? How do the East and West Antarctic ice sheet interact? How are surface processes linked to both tectonic, climatic and biological influence?

Many of these questions will not be answered by single studies, and most of them should stimulate multidisciplinary approaches. One of the outstanding needs in TAM geology at all timescales is for a broader database of precise geochronology, thermochronology, and exposure ages. Continuing efforts to sample new materials and obtain precise, robust age information will be a requirement in order to make progress in crustal evolution of the basement terrains, sources of sediment, temporal and spatial patterns of magmatism, and uplift and landscape histories.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

I am fortunate to have had the opportunity to work with many wonderful colleagues over a period of years, including Vickie Bennett, David Dallmeyer, Don DePaolo, Mark Fanning, Carol Finn, Vicki Hansen, Kathy Licht, Paul Myrow, Mike Pope, Bert Rowell, Jeff Vervoort, Nick Walker, and Ian Williams. I owe a special debt to Scott Borg who very trustingly invited me to participate in my first Antarctic field work in 1985; his introduction launched a lifelong passion. I thank several colleagues who provided generous feedback on sections of an earlier manuscript, including Allan Ashworth, Jim Collinson, David Elliot, Paul Fitzgerald, Georg Kleinschmidt, and Phil Kyle; all shortcomings are my responsibility. Spencer Niebuhr of the Polar Geospatial Center at the University of Minnesota helped make the DEMs used in some of the figures. The manuscript was substantially improved by very constructive comments from Christine Siddoway and an anonymous reviewer, for which I am thankful. Last, I am grateful to the NSF Office of Polar Programs for support of field research projects.

References

Adams, C.J.D., Gabites, J.E., Grindley, G.W., 1982. Orogenic history of the central Transantarctic Mountains: New K-Ar age data on the Precambrian-lower Paleozoic basement. In: Craddock, C. (Ed.), Antarctic Geoscience. University of Wisconsin Press, Madison, pp. 817–826.
Allibone, A., Wysoczanski, R.J., 2002. Initiation of magmatism during the Cambrian-Ordovician Ross orogeny in southern Victoria Land, Antarctica. Geological Society of America Bulletin 114, 1007–1018.
Allibone, A.H., 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, A.H., Cox, S.C., Graham, I.J., Smillie, R.W., Johnstone, R.D., Ellery, S.G., 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, A.H., Cox, S.C., Smillie, R.W., 1993b. Granitoids of the Dry Valleys area, southern Victoria Land: geochemistry and evolution along the early Palaeozoic Antarctic craton margin. New Zealand Journal of Geology and Geophysics 36, 299–316.
American Geographical Society, 1969, Geologic Map of Antarctica, Antarctic Map Folio Series, Folio 12, 1:1,000,000.
Andrews, P.B., Laird, M.G., 1976. Sedimentology of a Late Cambrian regressive sequence (Bowers Group), northern Victoria Land, Antarctica. Sedimentary Geology 16, 21–44.
Armienti, P., Baroni, C., 1999. Cenozoic climatic change in Antarctica recorded by volcanic activity and landscape evolution. Geology 27, 617–620.
Armienti, P., Ghezzo, C., Innocenti, F., Manetti, P., Rocchi, S., Tonarini, S., 1990. Isotope geochemistry and petrology of granitoid suites from Granite Harbour Intrusives of the Wilson Terrane, North Victoria Land, Antarctica. European Journal of Mineralogy 2, 103–123.
Ashworth, A.C., Cantrill, D.J., 2004. Neogene vegetation of the Meyer Desert Formation (Sirius Group) Transantarctic Mountains, Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 213, 65–82.
Ashworth, A.C., Kuschel, G., 2003. Fossil weevils (Coleoptera, Curculionidae) from latitude 85°S Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 191, 191–202.
Ashworth, A.C., Preece, R.C., 2003. The first freshwater molluscs from Antarctica. Journal of Malacological Studies 69, 89–92.
Ashworth, A.C., Thompson, F.C., 2003. A fly in the biogeographic ointment. Nature 423, 135–136.
Babcock, L.E., Miller, M.F., Isbell, J.L., Collinson, J.W., Hasiotis, S.T., 1998. Paleozoic-Mesozoic crayfish from Antarctica; earliest evidence of freshwater decapod crustaceans. Geology 26, 539–542.
Babcock, R.S., Plummer, C.C., Sheraton, J.W., Adams, C.J., 1986. Geology of the Daniels Range, North Victoria Land, Antarctica. In: Stump, E. (Ed.), Geological Investigations in Northern Victoria Land. 46, pp. 1–24 Washington, D. C., American Geophysical Union, Antarctic Research Series.
Baldwin, S.L., Fitzgerald, P.G., Malusà, M.G., 2019. Crustal exhumation of plutonic and metamorphic rocks: Constraints from fission-track thermochronology, *in* M. G. Malusà and P. G. Fitzgerald, eds., Fission-Track Thermochronology and its Application to Geology: Springer Textbooks in Earth Sciences. Geography and Environment 235–257. https://doi.org/10.1007/978-3-319-89421-8_13.
Balestrieri, M.L., Bigazzi, G., Ghezzo, C., 1997. Uplift-denudation of the Transantarctic Mountains between the David and the Mariner glaciers, northern Victoria Land

(Antarctica); constraints by apatite fission-track analysis, *in* VII international symposium on Antarctic earth sciences, Siena. Italy 547–554.
Barrett, P.J., 1965. Geology of the area between the Axel Heiberg and Shackleton Glaciers, Queen Maud Range, Antarctica, part 2—Beacon Group. New Zealand Journal of Geology and Geophysics 8, 344–363.
Barrett, P.J., 1991. Devonian to Jurassic Beacon Supergroup of the Transantarctic Mountains and correlatives in other parts of Antarctica. In: Tingey, R.J. (Ed.), Geology of Antarctica. Clarendon Press, Oxford, pp. 120–152.
Barrett, P.J., Baillie, R.J., Colbert, E.H., 1968. Triassic amphibian from Antarctica. Science 161, 460–462.
Barrett, P.J., Elliot, D.H., Lindsay, J.F., 1986. The Beacon Supergroup (Devonian–Triassic) and Ferrar Group (Jurassic) in the Beardmore Glacier area, Antarctica. In: Turner, M.D., Splettstoesser, J.F. (Eds.), Geology of the Central Transantarctic Mountains. 36, pp. 339–428 Washington, DC, American Geophysical Union, Antarctic Research Series.
Barrett, P.J., Bleakley, N.L., Dickinson, W.W., Hannah, M.J., Harper, M.A., 1997. Distribution of siliceous microfossils on Mount Feather, Antarctica, and the age of the Sirius Group, *in* VII international symposium on Antarctic earth sciences, Siena. Italy 763–770.
Bédard, J.H.J., Marsh, B.D., Hersum, T.G., Naslund, H.R., Mukasa, S.B., 2007. Large-scale mechanical redistribution of orthopyroxene and plagioclase in the Basement Sill, McMurdo Dry Valleys, Antarctica: Petrological, mineral-chemical and field evidence for channelized movement of crystals and melt. Journal of Petrology 48, 2289–2326.
van der Beek, P., Cloetingh, S., Andriessen, P., 1994. Mechanisms of extensional basin formation and vertical motions at rift flanks: Constraints from tectonic modelling and fission-track thermochronology. Earth and Planetary Science Letters 121, 417–433.
Behrendt, J.C., 1999. Crustal and lithospheric structure of the West Antarctic Rift System from geophysical investigations — a review. Global and Planetary Change 23, 25–44.
Berg, J.H., 1991. Geology, petrology, and tectonic implications of crustal xenoliths in Cenozoic volcanic rocks of southern Victoria Land. In: Thomson, M.R.A., Crame, J.A., Thomson, J.W. (Eds.), Geological Evolution of Antarctica. Cambridge University Press, Cambridge, UK, pp. 311–315.
Bialas, R.W., Buck, W.R., Studinger, M., Fitzgerald, P.G., 2007. Plateau collapse model for the Transantarctic Mountains-West Antarctic rift system; insights from numerical experiments. Geology 35, 687–690.
Black, L.P., Sheraton, J.W., 1990. The influence of Precambrian source components on the U-Pb zircon age of a Palaeozoic granite from northern Victoria Land, Antarctica. Precambrian Research 46, 275–293.
Boger, S.D., 2011. Antarctica — before and after Gondwana. Gondwana Research 19, 335–371.
Boger, S.D., Miller, J.M., 2004. Terminal suturing of Gondwana and the onset of the Ross-Delamerian Orogeny: the cause and effect of an early Cambrian reconfiguration of plate motions. Earth and Planetary Science Letters 219, 35–48.
Bomparola, R.M., Ghezzo, C., Belousova, E., Griffin, W.L., O'Reilly, S.Y., 2007. Resetting of the U-Pb zircon system in Cambro-Ordovician intrusives of the deep freeze Range, northern Victoria Land. Antarctica: Journal of Petrology 48, 327–364. https://doi.org/10.1093/petrology/eg1064.
Bond, G.C., Nickleson, P.A., Kominz, M.A., 1984. Breakup of a supercontinent between 625 and 555 Ma: new evidence and implications for continental histories. Earth and Planetary Science Letters 70, 325–345. https://doi.org/10.1016/0012-821X(84)90017-7.
Borg, S.G., 1980. Petrology and Geochemistry of the Wyatt Formation and the Queen Maud batholith, Upper Scott Glacier Area, Antarctica [M.S. Thesis]. Arizona State University, p. 100.
Borg, S.G., DePaolo, D.J., 1994. Laurentia, Australia, and Antarctica as a late Proterozoic supercontinent: constraints from isotopic mapping. Geology 22, 307–310.
Borg, S.G., Stump, E., Chappell, B.W., McCulloch, M.T., Wyborn, D., Armstrong, R.L., Holloway, J.R., 1987. Granitoids of northern Victoria Land, Antarctica: Implications of chemical and isotopic variations to regional crustal structure and tectonics. American Journal of Science 287, 127–169.
Borg, S.G., DePaolo, D.J., Smith, B.M., 1990. Isotopic structure and tectonics of the central Transantarctic Mountains. Journal of Geophysical Research 95, 6647–6669.
Borghi, A., Lombardo, B., 1994. Petrological evidence of mono- and poly-metamorphic complexes in the Gerlache Inlet-Black Ridge high-grade belt (Wilson Terrane, northern Victoria Land, Antarctica). Terra Antarctica 1, 10–13.
Bradshaw, J.D., 2007. The Ross Orogen and Lachlan Fold Belt in Marie Byrd Land, northern Victoria Land and New Zealand: implication for the tectonic setting of the Lachlan Fold Belt in Antarctica: U. S. Geological Survey and the National Academies; USGS OF-2007-1047, short. Research Paper 59. https://doi.org/10.3133/of2007-1047.srp059.
Bradshaw, J.D., Andrews, P.B., Field, B.D., 1983. Swanson Formation and related rocks of Marie Byrd Land and a comparison with the Robertson Bay Group of northern Victoria Land, *in* Oliver, R. L., James, P. R. and Jago, J. B., eds., Antarctic Earth Science: Australian Academy of Science. Canberra 274–279.
Bradshaw, J.D., Weaver, S.D., Laird, M.G., 1985. Suspect terranes and Cambrian tectonics in northern Victoria Land, Antarctica, *in* Howell, D. G., ed., Tectonostratigraphic Terranes of the Circum-Pacific Region: Earth Science Series no. 1: Houston, Circum-Pacific Council for Energy and Mineral. Resources 467–479.
Bradshaw, M.A., 1981. Palaeoenvironmental 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, M.A., 2013. The Taylor Group (Beacon Supergroup): the Devonian sediments of Antarctica, *in* Hambrey, M. J. et al., eds., Antarctic Palaeoenvironments and Earth-Surface Processes: Geological Society, London. Special Publications 381, 67–97.
Brenn, G.R., Hansen, S.E., Park, Y., 2017. Variable thermal loading and flexural uplift along the Transantarctic Mountains, Antarctica. Geology 45, 463–466. https://doi.org/10.1130/G38784.1.
ten Brink, U. S., Hackney, R. I., Bannister, S., Stern, T. A., Makovsky, Y., 1997, Uplift of the Transantarctic Mountains and the bedrock beneath the East Antarctic ice sheet: Journal of Geophysical Research, 102, 27,603–27,621.
Brook, E.J., Brown, E.T., Kurz, M.D., Ackert, R.P.J., Raisbeck, G.M., Yiou, F., 1995. 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.
Buggisch, W., Kleinschmidt, G., 1991. Recovery and recrystallization of quartz and 'crystallinity' of illite in the Bowers and Robertson Bay terranes, northern Victoria Land, Antarctica. In: Thomson, M.R.A., Crame, J.A., Thomson, J.W. (Eds.), Geological Evolution of Antarctica. Cambridge University Press, Cambridge, pp. 155–159.
Buggisch, W., Repetski, J.E., 1987. Uppermost Cambrian (?) and Tremadocian conodonts from Handler Ridge, Robertson Bay Terrane, North Victoria Land. Antarctica: Geologisches Jahrbuch 66, 145–185.
Burgess, C.J., Lammerink, W., 1979. Geology of the Shackleton Limestone (Cambrian) in the Byrd Glacier area: New Zealand Antarctic. Record 2, 12–16.
Burgess, S. D., Bowring, S. A., Fleming, T. H., Elliot, D. H., 2015, High-precision geochronology links the Ferrar large igneous province with early-Jurassic ocean anoxia and biotic crisis: Earth and Planetary Science Letters, 415, 90-99, doi.org/https://doi.org/10.1016/j.epsl.2015.01.037.
Burrett, C.F., Findlay, R.H., 1984. Cambrian and Ordovician conodonts from the Robertson Bay Group, Antarctica. and their tectonic significance: Nature 307, 723–726.
Busetti, M., Spadini, G., van der Wateren, F.M., Cloetingh, S.A.P.L., Zanolla, C., 1999. Kinematic modelling of the West Antarctic Rift system, Ross Sea. Antarctica: Global and Planetary Change 23, 79–103.
Calvert, A.T., Mortimer, N., 2003. Thermal history of Transantarctic Mountains K-feldspars, southern. Victoria Land: Terra Antartica 10, 3–15.
Cande, S.C., Stock, J.M., 2006. Constraints on the timing of extension in the Northern Basin, Ross Sea. In: Fuetterer, D.K., Damaske, D., Kleinschmidt, G., Miller, H., Tessensohn, F. (Eds.), Antarctica; Contributions to Global Earth Sciences. Springer-Verlag, Berlin-Heidelberg, pp. 319–326.
Cande, S.C., Stock, J.M., Mueller, R.D., Ishihara, T., 2000. Cenozoic motion between East and West Antarctica. Nature 404, 145–150.
Capponi, G., Crispini, L., Meccheri, M., 2002. Tectonic evolution at the boundary between the Wilson and Bowers Terranes (northern Victoria Land, Antarctica); structural evidence from the Mountaineer and Lanterman Ranges, *in* Gamble, J. a., Skinner, D. N. B., and Henrys, S. a., eds., Antarctica at the close of a millennium; proceedings of the 8th International Symposium on Antarctic Earth Sciences: Wellington. The Royal Society of New Zealand 105–112.
Castelli, D., Lombardo, B., Oggiano, G., Rossetti, P., Talarico, F., 1991. Granulite facies rocks of the Wilson Terrane (northern Victoria Land, Antarctica): Campbell Glacier, *in* Ricci, C. a., ed. Earth science investigations in Antarctica: Rome, Memorie della Societa Geologica Italiana 46, 197–203.
Cawood, P.A., 2005. Terra Australis Orogen: Rodinia breakup and development of the Pacific and Iapetus margins of Gondwana during the Neoproterozoic and Paleozoic. Earth-Science Reviews 69, 249–279.
Chaput, J., Aster, R. C., Huerta, A., Sun, X., Lloyd, A., Wiens, D., Nyblade, A., Anandakrishnan, S., Winberry, J. P., Wilson, T., 2014, The crustal thickness of West Antarctica: Journal of Geophysical Research, 119, 378-395, doi.org/https://doi.org/10.1002/2013JB010642.
Clapperton, C.M., Sugden, D.E., 1990. Late Cenozoic glacial history of the Ross Embayment, Antarctica. Quaternary Science Reviews 9, 253–272.
Colbert, E.H., 1986. In: Turner, M.D., Splettstoesser, J.E. (Eds.), Triassic vertebrates in the Transantarctic Mountains. 36. Geology of the central Transantarctic Mountains, Washington, D.C, pp. 11–35 American Geophysical Union, Antarctic Research Series.
Collins, W.J., 2002. Hot orogens, tectonic switching, and creation of continental crust. Geology 30, 535–538.
Collinson, J.W., Pennington, D.C., Kemp, N.R., 1986. Stratigraphy and petrology of Permian and Triassic fluvial deposits in northern Victoria Land, Antarctica. In: Stump, E. (Ed.), Geological Investigations in Northern Victoria Land. 46, pp. 211–242 Washington, D.C., American Geophysical Union, Antarctic Research Series.
Collinson, J.W., Elliot, D.H., Isbell, J.L., Miller, J.M.G., 1994. Permian-Triassic Transantarctic basin, *in* Veevers, J. J., and Powell, C. M., eds., Permian-Triassic Pangean basins and foldbelts along the Panthalassan margin of Gondwanaland: Boulder, Geological Society of America. Memoir 173–222.
Collinson, J.W., Hammer, W.R., Askin, R.A., Elliot, D.H., 2006. Permian-Triassic boundary in the central Transantarctic Mountains, Antarctica. Geological Society America Bulletin 118, 747–763.
Cook, Y.A., 2007. Precambrian rift-related magmatism and sedimentation, South Victoria Land, Antarctica. Antarctic Science 19, 471–484.
Cook, Y.A., 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, 403–416.
Cook, Y.A., 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, 133–143.
Cooper, A.F., Worley, B.A., Armstrong, R.A., Price, R.C., 1997. Synorogenic alkaline and carbonatitic magmatism in the Transantarctic Mountains of South Victoria Land, Antarctica, *in* Ricci, C. a., ed., the Antarctic Region: Geological Evolution and Processes: Siena. Terra Antartica Publication 245–252.
Cooper, A.F., Maas, R., Scott, J.M., Barber, A.J.W., 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, A.K., Davey, F.J., Hinz, K., 1991. Crustal extension and origin of sedimentary basins beneath the Ross Sea and Ross Ice Shelf, Antarctica. In: Thomson, M.R.A., Crame, J.A., Thomson, J.W. (Eds.), Geological Evolution of Antarctica. Cambridge University Press, Cambridge, pp. 285–291.

Cooper, R.A., Jago, J.B., MacKinnon, D.I., Shergold, J.H., Vidal, G., 1982. Late Precambrian and Cambrian fossils from northern Victoria Land and their stratigraphic implications. In: Craddock, C. (Ed.), Antarctic Geoscience: Madison, Wisconsin. University of Wisconsin Press, pp. 629–633.
Cooper, R.A., Jago, J.B., Rowell, A.J., Braddock, P., 1983. Age and correlation of the Cambrian-Ordovician Bowers Supergrouop, northern Victoria Land, *in* Oliver, R. L., James, P. R., and Jago, J. B., eds., Antarctic earth science: Canberra, ACT, Australian Academy of. Science 128–131.
Cottle, J.M., Cooper, A.F., 2006a. 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.
Cottle, J.M., Cooper, A.F., 2006b. 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.
Cox, S.C., 1992. Garnet-biotite geothermometry of Koettlitz Group metasediments, Wright Valley, South Victoria Land, Antarcica. New Zealand Journal of Geology and Geophysics 35, 29–40.
Cox, S.C., 1993. Inter-related plutonism and deformation in South Victoria Land. Antarctica: Geological Magazine 130, 1–14.
Cox, S.C., Parkinson, D.L., Allibone, A.H., Cooper, A.F., 2000. Isotopic character of Cambro-Ordovician plutonism, southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 43, 501–520.
Cox, S.C., Smith Lyttle, B., the GeoMAP team, 2019. Geological Mapping Update of Antarctica (GeoMAP). Scientific Committee on Antarctic Research, Cambridge, United Kingdom https://www.scar.org/science/geomap/home/.
Crawford, A.J., Stevens, B.P.J., Fanning, M., 1997. Geochemistry and tectonic setting of some Neoproterozoic and early Cambrian volcanics in western New South Wales. Australian Journal of Earth Sciences 44, 831–852.
Crawford, A. J., Meffre, S., Symonds, P. A., 2003, 120 to 0 Ma tectonic evolution of the Southwest Pacific and analogous geological evolution of the 600 to 220 Ma Tasman fold belt system: Geological Society of America, Special Paper, 372, 383-403.
Crispini, L., Capponi, G., Federico, L., and Talarico, F., 2007, Gold bearing veining linked to transcrustal fault zones in the Transantarctic Mountains (northern Victoria Land, Antarctica): in Antarctica: A Keystone in a Changing World - Online Proceedings of the 10th ISAES, edited by A.K. Cooper and C.R. Raymond et al., USGS Open-file Report 2007-1047, Extended Abstract 212, 4 p.
Crispini, L., Federico, L., Capponi, G., Talarico, F., 2009. First finding of syntectonic gold mineralization in northern Victoria Land (Antarctica): a clue for the. Paleo-Pacific margin of Gondwana: Rendiconti Online Societa Geologica Italiana 5, 66–67.
Crispini, L., Federico, L., Capponi, G., 2014. Structure of the Millen Schist Belt (Antarctica): Clues for the tectonics of northern Victoria Land along the paleo-Pacific margin of Gondwana. Tectonics 33, 420–440. https://doi.org/10.1002/2013TC003414.
Curtis, M.L., 2002. Palaeozoic to Mesozoic polyphase deformation of the Patuxent Range, Pensacola Mountains, Antarctica. Antarctic Science 14, 175–183.
Curtis, M.L., Storey, B.C., 2003. Early Palaeozoic near-surface deformation in the Neptune Range, Antarctica: implication for the Ross and Gondwanian orogenies. Journal of the Geological Society 160, 629–642.
Curtis, M.L., Millar, I.L., Storey, B.C., Fanning, C.M., 2004. Structural and geochronological constraints of early Ross orogenic deformation in the Pensacola Mountains, Antarctica. Geological Society of America Bulletin 116, 619–636.
Dallmeyer, R.D., Wright, T.O., 1992. Diachronous cleavage development in the Robertson Bay terrane, northern Victoria Land, Antarctica: Tectonic implications. Tectonics 11, 437–448.
Dalziel, I.W.D., 1991. Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent. Geology 19, 598–601.
Dalziel, I.W.D., 1992. Antarctica: a tale of two supercontinents: Annual Reviews of Earth and Planetary. Sciences 20, 501–526.
Dalziel, I.W.D., 1997. Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis. environmental speculation: Geological Society of America Bulletin 109, 16–42.
Davey, F.J., Cande, S.C., Stock, J.M., 2006. Extension in the western Ross Sea region-links between Adare Basin and Victoria Land Basin. Geophysical Research Letters 33, 5.
Debrenne, F., Kruse, P.D., 1986. Shackleton limestone archaeocyaths. Alcheringa 10, 235–278.
DeConto, R., Pollard, D., 2003. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2. Nature 421, 245–249.
Denton, G.H., Sugden, D.E., Marchant, D.R., Hall, B.L., Wilch, T.I., 1993. East Antarctica ice sheet sensitivity to Pliocene climate change from a dry valleys perspective. Geografiska Annaler. 75A, 155–204.
Di Vincenzo, G., Palmeri, R., 2001. An ^{40}Ar-^{39}Ar investigation of high-pressure metamorphism and the retrogressive history of mafic eclogites from the Lanterman Range (Antarctica): evidence against a simple temperature control on argon transport in amphibole. Contributions to Mineralogy and Petrology 141, 15–35.
Di Vincenzo, G., Palmeri, R., Talarico, F., Andriessen, P.A.M., Ricci, C.A., 1997. Petrology and geochronology of eclogites from the Lanterman Range, Antarctica. Journal of Petrology 38, 1391–1417.
Di Vincenzo, G., Rossetti, F., Viti, C., Balsamo, F., 2013. Constraining the timing of fault reactivation: Eocene coseismic slip along a late Ordovician ductile shear zone (northern Victoria Land, Antarctica). Geological Society of America Bulletin 125, 609–624. https://doi.org/10.1130/B30670.1.
Di Vincenzo, G., Grande, A., Rossetti, F., 2014. Paleozoic siliciclastic rocks from northern Victoria Land (Antarctica): Provenance, timing of deformation, and implications for the Antarctica-Australia connection. Geological Society of America Bulletin 126, 1416–1438. https://doi.org/10.1130/B31034.1.
Di Vincenzo, G., Horton, F., Palmeri, R., 2016. Protracted (~30 Ma) eclogite-facies metamorphism in northern Victoria Land (Antarctica): Implications for the geodynamics of the Ross/Delamerian Orogen. Gondwana Research 40, 91–106.
Dickinson, W.W., Bleakley, N.L., 2005. Facies control on diagenesis in frozen sediments: the Sirius Group; Table Mountain and Mt Feather, Dry Valleys. Antarctica: Terra Antarctica 12, 25–34.
Direen, N.G., Crawford, A.J., 2003. Fossil seaward-dipping reflector sequences preserved in southeastern Australia: a 600 Ma volcanic passive margin in eastern Gondwanaland. Journal of the Geological Society of London 160, 985–990.
Donnellan, A., Luyendyk, B.P., 2004. GPS evidence for a coherent Antarctic plate and for postglacial rebound in Marie Byrd Land. Global and Planetary Change 42, 305–311. https://doi.org/10.1016/j.gloplacha.2004.02.006.
Eagles, G., Gohl, K., Larter, R. D., 2004, High-resolution animated tectonic reconstruction of the South Pacific and West Antarctic margin: Geochemistry, Geophysics, Geosystems, 5, Q07002, doi.org/10.1029/2003GC000657.
Elliot, D.H., 1970. Jurassic tholeiites of the central Transantarctic Mountains, Antarctica, *in* Gilmour, E. H., and Stradling, D., eds., Proceedings of the second Columbia River Basalt symposium: Cheney. Eastern Washington State College Press 301–325.
Elliot, D.H., 1996. The Hanson Formation: a new stratigraphical unit in the Transantarctic Mountains, Antarctica. Antarctic Science 8, 389–394.
Elliot, D.H., 2000. Stratigraphy of Jurassic pyroclastic rocks in the Transantarctic Mountains. Journal of African Earth Sciences 31, 77–89.
Elliot, D.H., 2013. The geological and tectonic evolution of the Transantarctic Mountains: a review: *in* Hambrey, M. J., Barker, P. F., Barrett, P. J., Bowman, V., Davies, B., Smellie, J. L. and Tranter, M. (eds), Antarctic Palaeoenvironments and Earth-Surface Processes. Geological Society of London, Special Publication 381, 7–35.
Elliot, D.H., Fanning, C.M., 2008. Detrital zircons from upper Permian and lower Triassic Victoria Group sandstones, Shackleton Glacier region, Antarctica: evidence for multiple sources along the Gondwana plate margin. Gondwana Research 13, 259–274.
Elliot, D.H., Fleming, T.H., 2004. Occurrence and dispersal of magmas in the Jurassic Ferrar large Igneous Province, Antarctica. Gondwana Research 7, 223–237.
Elliot, D.H., Fleming, T.H., 2008. Physical volcanology and geological relationships of the Jurassic Ferrar large Igneous Province, Antarctica. Journal of Volcanology and Geothermal Research 172, 20–37.
Elliot, D.H., Colbert, E.H., Breed, W.J., Jensen, J.A., Powell, J.S., 1970. Triassic tetrapods from Antarctica. Evidence for continental drift. Science 169, 1197–1201.
Elliot, D.H., Fleming, T.H., Kyle, P.R., Foland, K.A., 1999. Long-distance transport of magmas in the Jurassic Ferrar large Igneous Province, Antarctica. Earth and Planetary Science Letters 167, 89–104.
Elliot, D.H., Lyons, W.B.L., Everett, R., 2007. TransAntarctic Mountains TRANsition Zone (TAM TRANZ Project): Multidisciplinary Research in the Central and Southern Transantarctic Mountains: Byrd Polar Research Center, Miscellaneous Series 430. The Ohio State University, Columbus, Ohio (99 pp).
Elliot, D.H., Fanning, C.M., Hulett, S.R.W., 2015. Age provinces in the Antarctic craton: evidence from detrital zircons in Permian strata from the Beardmore Glacier region, Antarctica. Gondwana Research 28, 152–164.
Elliot, D.H., Fanning, C.M., Isbell, J.L., Hulett, S.R.W., 2017. The Permo-Triassic Gondwana sequence, central Transantarctic Mountains, Antarctica: Zircon geochronology, provenance, and basin evolution. Geosphere 13, 155–178. https://doi.org/10.1130/GES01345.1.
Elsner, M., Schöner, R., Gerdes, A., Gaupp, R., 2013. Reconstruction of the early Mesozoic plate margin of Gondwana by U–Pb ages of detrital zircons from northern Victoria Land, Antarctica: *in* Harley, S. L., Fitzsimons, I. C. W., Zhao, Y., eds., Antarctica and Supercontinent Evolution: Geological Society, London. Special Publications 383, 211–232.
Encarnación, 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.
Encarnación, J., Fleming, T.H., Elliot, D.H., Eales, J.V., 1996. Synchronous emplacement of Ferrar and Karoo dolerites and the early breakup of Gondwana. Geology 24, 535–538.
Encarnación, J., Rowell, A.J., Grunow, A.M., 1999. A U-Pb age for the Cambrian Taylor Formation, Antarctica: Implications for the Cambrian time scale. Journal of Geology 107, 497–504.
Escapa, I.H., Taylor, E.L., Cúneo, R., Bomfleur, B., Bergene, J., Serbet, R., Taylor, T.N., 2011. Triassic floras of Antarctica: Plant diversity and distribution in high paleolatitude communities. PALAIOS 26, 522–544.
Esser, R.P., Kyle, P.R., McIntosh, W.C., 2004. ^{40}Ar/^{39}Ar dating of the eruptive history of Mount Erebus, Antarctica: volcano evolution. Bulletin of Volcanology 66, 671–686.
Estrada, S., Läufer, A., Eckelmann, K., Hofmann, M., Gärtner, A., Linnemann, U., 2016. Continuous Neoproterozoic to Ordovician sedimentation at the East Gondwana margin - Implications from detrital zircons of the Ross Orogen in northern Victoria Land, Antarctica. Gondwana Research 37, 426–448.
Evans, K.R., Mckenna III, L.W., Lieberman, B.S., Weichert, W.D., Macleod, K.G., 2018. Geology of the Nelson Limestone, Postel Nunatak, Patuxent Range, Antarctica. Antarctic Science 30, 29–43. https://doi.org/10.1017/S0954102017000396.
Faccenna, C., Rossetti, F., Becker, T.W., Danesi, S., Morelli, A., 2008. Recent Extension Driven by Mantle Upwelling beneath the Admiralty Mountains (East Antarctica): Tectonics, 27, TC4015. https://doi.org/10.1029/2007TC002197.
Fanning, C.M., Link, P.K., 2004. U-Pb SHRIMP ages of Neoproterozoic (Sturtian) glaciogenic Pocatello Formation, southeastern Idaho. Geology 32, 881–884. https://doi.org/10.1130/G20609.1.
Farmer, G.L., Ball, T.T., 1997. Sources of Middle Proterozoic to early Cambrian siliciclastic sedimentary rocks in the Great Basin: a Nd isotope study. Geological Society of America Bulletin 109, 1193–1205.
Faure, G., Mensing, T.M., 2011. The Transantarctic Mountains: Rocks. Heidelberg, Springer, Ice, Meteorites and Water (804 p).

Federico, L., Capponi, G., Crispini, L., 2006. The Ross orogeny of the transantarctic mountains: a northern Victoria Land perspective. International Journal of Earth Sciences 95, 759–770.
Federico, L., Crispini, L., Capponi, G., Bradshaw, J.D., 2009. The Cambrian Ross Orogeny in northern Victoria Land (Antarctica) and New Zealand: a synthesis. Gondwana Research 15, 188–196.
Ferraccioli, F., Coren, F., Bozzo, E., Zanolla, C., Gandolfi, S., Tabacco, I., Frezzotti, M.L.E., 2001. Rifted(?) crust at the East Antarctic Craton margin: gravity and magnetic interpretation along a traverse across the Wilkes Subglacial Basin region. Earth and Planetary Science Letters 192, 407–421.
Ferraccioli, F., Armadillo, E., Jordan, T., Bozzo, E., Corr, H., 2009. Aeromagnetic exploration over the East Antarctic Ice Sheet: a new view of the Wilkes Subglacial Basin. Tectonophysics 478, 62–77. https://doi.org/10.1016/j.tecto.2009.03.013.
Ferri, F., Rees, C., Nelson, J., Legun, A., 1999. Geology and Mineral Deposits of the Northern Kechika Trough between Gataga River and the 60th Parallel. Vancouver, British Columbia Ministry of Energy and Mines, p. 122.
Ferris, J., Johnson, A., Storey, B., 1998. Form and extent of the Dufek intrusion, Antarctica, from newly compiled aeromagnetic data. Earth and Planetary Science Letters 154, 185–202.
Findlay, R.H., Skinner, D.N.B., Craw, D., 1984. Lithostratigraphy and structure of the Koettlitz Group, McMurdo Sound, Antarctica. New Zealand Journal of Geology and Geophysics 27, 513–536.
Finn, C.A., Müller, R.D., Panter, K.S., 2005. A Cenozoic diffuse alkaline magmatic province (DAMP) in the SW Pacific without rift or plume origin. Geochemistry, Geophysics, Geosystems 6 (G3) Q02005.
Finn, C.A., Goodge, J.W., Damaske, D., Fanning, C.M., 2006. Scouting craton's edge in paleo-Pacific Gondwana. In: Fuetterer, D.K., Damaske, D., Kleinschmidt, G., Miller, H., Tessensohn, F. (Eds.), Antarctica; Contributions to Global Earth Sciences; Proceedings of the 9th International Symposium of Antarctic Earth Sciences. Springer-Verlag, Berlin-Heidelberg, pp. 165–173.
Fioretti A.M., Black P. Varne R., 2001, U-Pb Zircon SHRIMP dating of the Gallipoli Volcanics, Northern Victoria Land (Antarctica): EUG XI, Strasbourg, LS08: Age growth and evolution of Antarctica (AGEANT), 08.04.-12.04.02.
Fioretti, A.M., Black, L.P., Foden, J., Visonà, D., 2005a. Grenville-age magmatism at the South Tasman rise (Australia). A new piercing point for the reconstruction of Rodinia: Geology 33, 769–772. https://doi.org/10.1130/G21671.1.
Fioretti, A.M., Capponi, G., Black, L.P., Varne, R., Visonà, D., 2005b. Surgeon island granite SHRIMP zircon ages: a clue for the Cambrian tectonic setting and evolution of the Palaeopacific margin of Gondwana (northern Victoria Land, Antarctica). Terra Nova 17, 242–249. https://doi.org/10.1111/j.1365-3121.2005.00606.
Fitzgerald, P.G., 1992. The Transantarctic Mountains of southern Victoria Land: the application of apatite fission track analysis to a rift shoulder uplift. Tectonics 11, 634–662.
Fitzgerald, P.G., 1994. Thermochronologic constraints on post-Paleozoic tectonic evolution of the central Transantarctic Mountains, Antarctica. Tectonics 13, 818–836.
Fitzgerald, P.G., 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, J., Skinner, D.A., Henrys, S. (Eds.), Antarctica at the Close of a Millennium, Proceedings of the 8th International Symposium on Antarctic Earth Science: Wellington. 35, pp. 453–469 Royal Society of New Zealand Bulletin.
Fitzgerald, P.G., Gleadow, A.J.W., 1988. Fission-track geochronology, tectonics and structure of the Transantarctic Mountains in Northern Victoria Land, Antarctica. Isotope Geoscience 73, 169–198.
Fitzgerald, P.G., Stump, E., 1997. Cretaceous and Cenozoic episodic denudation of the Transantarctic Mountains, Antarctica: New constraints from apatite fission track thermochronology in the Scott Glacier region. Journal of Geophysical Research 102 (B4), 7747–7765.
Fitzgerald, P.G., Sandiford, M., Barrett, P.J., Gleadow, A.J.W., 1986. Asymmetric extension associated with uplift and subsidence of the Transantarctic Mountains and Ross embayment. Earth and Planetary Science Letters 81, 67–78.
Fitzsimons, I.C.W., 2000. A review of tectonic events in the East Antarctic Shield and their implications for Gondwana and earlier supercontinents. Journal of African Earth Sciences 31, 3–23.
Fitzsimons, I.C.W., 2003. Proterozoic basement provinces of southern and southwestern Australia and their correlation with Antarctica, *in* Yoshida, M. and Windley, B. F., eds., Proterozoic East Gondwana: Supercontinent Assembly and Breakup: Geological Society, London. Special Publications 206, 93–130.
Fleming, T.H., Elliot, D.H., Jones, L.M., Bowman, J.R., Siders, M.A., 1992. Chemical and isotopic variations in an iron-rich lava flow from the Kirkpatrick Basalt, North Victoria Land, Antarctica: Implications for low-temperature alteration. Contributions to Mineralogy and Petrology 111, 440–457.
Fleming, T.H., Foland, K.A., Elliot, D.H., 1995. Isotopic and chemical constraints on the crustal evolution and source signature of Ferrar magmas, North Victoria Land, Antarctica. Contributions to Mineralogy and Petrology 121, 217–236.
Fleming, T.H., Heimann, A., Foland, K.A., Elliot, D.H., 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.
Flöttmann, T., Kleinschmidt, G., 1991a. Kinematics of major structures of North Victoria and Oates Lands, Antarctica, *in* Ricci, C. a., ed., Earth Science Investigations in Antarctica: Rome, Geological Society of Italy. Memoir 273–282.
Flöttmann, T., Kleinschmidt, G., 1991b. Opposite thrust systems in northern Victoria Land, Antarctica: Imprints of Gondwana's Paleozoic accretion. Geology 19, 45–47.
Flöttmann, T., Kleinschmidt, G., 1993. The structure of Oates Land and implications for the structural style of northern Victoria Land. Antarctica: Geologisches Jahrbuch E47, 419–436.
Flöttmann, T., Gibson, G.M., Kleinschmidt, G., 1993. Structural continuity of the Ross and Delamerian orogens of Antarctica and Australia along the margin of the paleo-Pacific. Geology 21, 319–322.
Foden, J., Barovich, K.M., Jane, M., O'Halloran, G., 2001. Sr-isotopic evidence for late Neoproterozoic rifting in the Adelaide Geosyncline at 586 Ma: implications for a Cu ore forming fluid flux. Precambrian Research 106, 291–308.
Foden, J., Elburg, M.A., Dougherty-Page, J., Burtt, A., 2006. The timing and duration of the Delamerian Orogeny: Correlation with the Ross Orogen and implications for Gondwana assembly. Journal of Geology 114, 189–210.
Foden, J.D., Elburg, M.A., Turner, S.P., Sandiford, M., O'Callaghan, J., Mitchell, S., 2002. Granite production in the Delamerian Orogen, South Australia. Journal of the Geological Society 159, 557–575.
Foley, D., Stump, E., Van Soest, M., Whipple, K., Hodges, K., 2011. Differential movement across Byrd Glacier, Antarctica, as indicated by geomorphological analysis and apatite (U-Th)/he Thermochronology. Geological Society of America Abstracts with Programs 43, 608.
Ford, A.B., 1976. Stratigraphy of the layered gabbroic Dufek intrusion. Antarctica: U.S. Geological Survey Bulletin 1405–D (36 pp).
Ford, A.B., 1990. The Dufek intrusion of Antarctica. In: Splettstoesser, J.F., Dreschoff, G.A.M. (Eds.), Mineral Resources of Antarctica: Antarctica Research Series. American Geophysical Union, Washington, D.C., pp. 15–32.
Ford, A.B., Barrett, P.J., 1975. Basement rocks of the south-Central Ross Sea, Site 270. In: Hayes, D.E. (Ed.), Initial Reports, Deep Sea Drilling Project 28. US Government Printing Office, Washington, DC, pp. 861–868.
Ford, A.B., Himmelberg, G.R., 1991. Geology and crystallization of the Dufek intrusion. In: Tingey, R.J. (Ed.), Geology of Antarctica. Clarendon Press, Oxford, pp. 175–214.
Furlanetto, F., Thorkelson, D.J., Rainbird, R.H., Davis, W.J., Gibson, H.D., Marshall, D.D., 2016. The Paleoproterozoic Wernecke Supergroup of Yukon, Canada: relationships to orogeny in northwestern Laurentia and basins in North America, East Australia, and China. Gondwana Research 39, 14–40.
Gair, H.S., Sturm, A., Carryer, S.J., Grindley, G.W., 1969. The geology of northern Victoria Land, *in* Craddock, C., ed., Geologic maps of Antarctica: Antarctic Map Folio Series: New York. American Geographical Society Folio 12, Sheet 13.
Ghiribelli, B., Frezzotti, M.-L., Palmeri, R., 2002. Coesite in eclogites of the Lanterman Range (Antarctica); evidence from textural and Raman studies. European Journal of Mineralogy 14, 355–360.
Giacomini, F., Tiepolo, M., Dallai, L., Ghezzo, C., 2007. On the onset and evolution of the Ross-orogeny magmatism in North Victoria Land - Antarctica. Chemical Geology 240, 103–128.
Gibson, G.M., 1984. Deformed conglomerates in the eastern Lanterman Range North Victoria Land. Antarctica: Geologisches Jahrbuch B60, 117–141.
Gibson, G.M., Wright, T.O., 1985. Importance of thrust faulting in the tectonic development of northern Victoria Land, Antarctica. Nature 315, 480–483.
Gibson, G.M., Tessensohn, F., Crawford, A.J., 1984. Bowers. Supergroup rocks west of the Mariner Glacier and possible greenschist facies equivalents: Geologisches Jahrbuch B60, 289–318.
Giggenbach, W.F., Kyle, P.R., Lyon, G., 1973. Present volcanic activity of Mt. Erebus, Ross Island, Antarctica. Geology 1, 135–136.
Gleadow, A.J.W., Fitzgerald, P.G., 1987. Uplift history of the Transantarctic Mountains: new evidence from fission track dating of basement apatites in the Dry Valleys area. southern Victoria Land: Earth and Planetary Science Letters 82, 1–4.
Godard, G., Palmeri, R., 2013. High-pressure metamorphism in Antarctica from the Proterozoic to the Cenozoic: a review and geodynamic implications. Gondwana Research 23, 844–864.
Goodge, J.W., 1997. Latest Neoproterozoic basin inversion of the Beardmore Group, central Transantarctic Mountains, Antarctica. Tectonics 16, 682–701.
Goodge, J.W., 2002. From Rodinia to Gondwana: Supercontinent evolution in the Transantarctic Mountains. In: Gamble, J., Skinner, D.A., Henrys, S. (Eds.), Antarctica at the Close of a Millennium, Proceedings of the 8th International Symposium on Antarctic Earth Science: Wellington. 35, pp. 61–74 Royal Society of New Zealand Bulletin.
Goodge, J.W., 2007a. Metamorphism in the Ross Orogen and its bearing on Gondwana margin tectonics, *in* Cloos, M., Carlson, W. D., Gilbert, M. C., Liou, J. G., Sorensen, S. S., eds., Convergent margin terranes and associated regions; a tribute to W. G. Ernst: Boulder, Colorado. Geological Society of America 185–203.
Goodge, J.W., 2007b. Transantarctic Mountains: Geology, *in* Riffenburgh, B., ed., Encyclopedia of the Antarctic: New York. Routledge Taylor and Francis Group 1007–1012.
Goodge, J. W., Dallmeyer, 1996, Contrasting thermal evolution within the Ross Orogen, Antarctica: Evidence from mineral $^{40}Ar/^{39}Ar$ ages: Journal of Geology, 104, 435-458.
Goodge, J.W., Dallmeyer, R.D., 1992. $^{40}Ar/^{39}Ar$ mineral age constraints on the Paleozoic tectonothermal evolution of high-grade basement rocks within the Ross orogen, central Transantarctic Mountains. Journal of Geology 100, 91–106.
Goodge, J.W., Fanning, C.M., 1999. 2.5 billion years of punctuated Earth history as recorded in a single rock. Geology 27, 1007–1010.
Goodge, J.W., Fanning, C.M., 2002. Precambrian crustal history of the Nimrod Group, central Transantarctic Mountains. In: Gamble, J., Skinner, D.A., Henrys, S. (Eds.), Antarctica at the Close of a Millennium, Proceedings of the 8th International Symposium on Antarctic Earth Science: Wellington. 35, pp. 43–50 Royal Society of New Zealand Bulletin.
Goodge, J.W., Fanning, C.M., 2010. Composition and age of the East Antarctic Shield in eastern Wilkes Land determined by proxy from Oligocene-Pleistocene glaciomarine sediment and Beacon Supergroup sandstones, Antarctica. Geological Society of America Bulletin 122, 1135–1159.
Goodge, J.W., Fanning, C.M., 2016. Mesoarchean and Paleoproterozoic history of the Nimrod complex, central Transantarctic Mountains, Antarctica: Stratigraphic revisions

and relation to the Mawson Continent in East Gondwana. Precambrian Research 285, 242–271.

Goodge, J. W., Finn, C. A., 2010, Glimpses of East Antarctica: Aeromagnetic and satellite magnetic view from the central Transantarctic Mountains of East Antarctica: Journal of Geophysical Research, 115, no. B09103, 1-22, doi:https://doi.org/10.1029/2009JB006890.

Goodge, J.W., Vervoort, J.D., 2006. Origin of Mesoproterozoic A-type granites in Laurentia: Hf isotope evidence. Earth and Planetary Science Letters 243, 711–731. https://doi.org/10.1016/j.epsl.2006.01.040.

Goodge, J.W., Borg, S.G., Smith, B.K., Bennett, V.C., 1991. Tectonic Significance of Proterozoic Ductile Shortening and Translation along the Antarctic Margin of Gondwana: Earth and Planetary Science Letters, 102, 58-70 (See Also Erratum, 104, 116).

Goodge, J.W., Hansen, V.L., Peacock, S.M., 1992. Multiple petrotectonic events in high-grade metamorphic rocks of the Nimrod Group, central Transantarctic Mountains, Antarctica, *in* Yoshida, Y., Kaminuma, K., and Shiraishi, K., eds., recent Progress in Antarctic Earth Science: Tokyo. Terra Scientific 203–209.

Goodge, J.W., Hansen, V.L., Peacock, S.M., Smith, B.K., Walker, N.W., 1993a. Kinematic evolution of the Miller Range shear zone, central Transantarctic Mountains, Antarctica, and implications for Neoproterozoic to early Paleozoic tectonics of the East Antarctic margin of Gondwana. Tectonics 12, 1460–1478.

Goodge, J.W., Walker, N.W., Hansen, V.L., 1993b. Neoproterozoic-Cambrian basement-involved orogenesis within the Antarctic margin of Gondwana. Geology 21, 37–40.

Goodge, J.W., Walker, N.W., Dallmeyer, R.D., 1995. Thermal and kinematic history of the Ross orogen. Antarctica: Geological Society of America Abstracts with Programs 27, 126.

Goodge, J.W., Paulsen, T., Deering, S.K., Encarnación, J., Watkeys, M., 1999. Progressive deformation of supracrustal rocks in the Ross Orogen, Central Transantarctic Mountains: 8th International Symposium on the Antarctic Earth Sciences: Wellington. New Zealand 121.

Goodge, J.W., Fanning, C.M., Bennett, V.C., 2001. U-Pb evidence of ~1.7 Ga crustal tectonism during the Nimrod Orogeny in the Transantarctic Mountains, Antarctica: implications for Proterozoic plate reconstructions. Precambrian Research 112, 261–288.

Goodge, J.W., Myrow, P., Williams, I.S., Bowring, S., 2002. Age and provenance of the Beardmore Group, Antarctica: Constraints on Rodinia supercontinent breakup. Journal of Geology 110 (4), 393–406.

Goodge, J.W., Myrow, P., Phillips, D., Fanning, C.M., Williams, I.S., 2004a. Siliciclastic record of rapid denudation in response to convergent-margin orogenesis, Ross Orogen, Antarctica. In: Bernet, M., Spiegel, C. (Eds.), Detrital Thermochronology—Provenance Analysis, Exhumation, and Landscape Evolution of Mountain Belts: Boulder. 378, pp. 101–122 Colorado, Geological Society of America Special Paper.

Goodge, J.W., Williams, I.S., Myrow, P., 2004b. 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, 1253–1279.

Goodge, J.W., Vervoort, J.D., Fanning, C.M., Brecke, D.M., Farmer, G.L., Williams, I.S., Myrow, P.M., DePaolo, D.J., 2008. A positive test of East Antarctica-Laurentia juxtaposition within the Rodinia supercontinent. Science 321, 235–240.

Goodge, J.W., Fanning, C.M., Brecke, D.M., Licht, K.J., Palmer, E.F., 2010. Continuation of the Laurentian Grenville province across the Ross Sea margin of East Antarctica. Journal of Geology 118, 601–619.

Goodge, J.W., Fanning, C.M., Norman, M., Bennett, V.C., 2012. Temporal, isotopic and spatial relations of early Paleozoic Gondwana-margin arc magmatism, central Transantarctic Mountains, Antarctica. Journal of Petrology 53, 2027–2065. https://doi.org/10.1093/petrology/egs043.

Goodge, J.W., Fanning, C.M., Fisher, C.M., Vervoort, J.D., 2017. Proterozoic crustal evolution of central East Antarctica: Age and isotopic evidence from glacial igneous clasts, and links with Australia and Laurentia. Precambrian Research 299, 151–176.

Gould, L.M., 1931. Cold: The Record of an Antarctic Sledge Journey: New York, Brewer, Warren and. Putnam, p. 275.

Granot, R., Dyment, J., 2018. Late Cenozoic unification of East and West Antarctica. Nature Communications 9, 3189. https://doi.org/10.1038/s41467-018-05270-w.

Gray, D.R., Foster, D.A., 2004. Tectonic evolution of the Lachlan Orogen, Southeast Australia: historical review, data synthesis and modern perspectives. Australian Journal of Earth Sciences 51, 773–817.

Grew, E.S., Sandiford, M., 1984. A staurolite-talc assemblage in tourmaline-phlogopite-chlorite schist from northern Victoria Land, Antarctica, and its petrogenetic significance. Contributions to Mineralogy and Petrology 87, 337–350. https://doi.org/10.1007/BF00381290.

Grew, E.S., Kleinschmidt, G., Schubert, W., 1984. Contrasting metamorphic belts in North Victoria Land. Antarctica: Geologisches Jahrbuch B60, 253–264.

Grindley, G.W., 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, G.W., 1972. Polyphase deformation of the Precambrian Nimrod Group, central Transantarctic Mountains. In: Adie, R.J. (Ed.), Antarctic Geology and Geophysics. Universitetsforlaget, Oslo, pp. 313–318.

Grindley, G.W., Laird, M.G., 1969. Geology of the Shackleton Coast, Antarctica. In: Bushnell, V.C., Craddock, C. (Eds.), Geologic Map of Antarctica, Antarctic Map Folio Series, Folio 12, Sheet. American Geographical Society, New York, p. 15.

Grindley, G.W., Warren, G., 1964. Stratigraphic nomenclature and correlation in the western part of the Ross Sea, in Adie, R. J., ed., Antarctic geology: Amsterdam. North Holland Publishing Company 314–333.

Grindley, G.W., McGregor, V.R., Walcott, R.I., 1964. Outline of the geology of the Nimrod-Beardmore-Axel Heiberg Glaciers region, Ross Dependency, *in* Adie, R. J., ed., Antarctic Geology: New York. North-Holland Publ. Co. 206–218.

Grunow, A.M., Encarnación, J., 2000. Terranes or Cambrian polar wander: New data from the Scott Glacier area, Transantarctic Mountains, Antarctica. Tectonics 19, 168–181.

Gunn, B.M., 1966. Modal and element variation in Antarctic tholeiites. Geochimica et Cosmochimica Acta 30, 881–920.

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

Gunn, B.M., Warren, G., 1962. Geology of Victoria Land between the Mawson and Mulock Glaciers. Antarctica: New Zealand Geological Survey Bulletin 71.

Gunner, J.D., 1976. Isotopic and geochemical studies of the pre-Devonian basement complex, Beardmore Glacier region, Antarctica: Ohio State University. Institute of Polar Studies Report No. 41.

Hagen-Peter, G., Cottle, C., 2016. Synchronous alkaline and subalkaline magmatism during the late Neoproterozoic–early Paleozoic Ross orogeny, Antarctica: Insights into magmatic sources and processes within a continental arc. Lithos 262, 677–698.

Hagen-Peter, G., Cottle, C., 2018. Evaluating the relative roles of crustal growth versus reworking through continental arc magmatism: a case study from the Ross orogen, Antarctica. Gondwana Research 55, 153–166.

Hagen-Peter, G., Cottle, C., Smit, M., Cooper, A.F., 2016. Coupled garnet Lu–Hf and monazite U–Pb geochronology constrain early convergent margin dynamics in the Ross orogen, Antarctica. Journal of Metamorphic Geology 34, 293–319.

Hall, C.E., Cooper, A.F., Parkinson, D.L., 1995. Early Cambrian carbonatite in Antarctica. Journal of the Geological Society of London 152, 721–728.

Hall, J. M., Wilson, T. J. Henrys, S., 2007, Structure of the central Terror Rift, western Ross Sea, Antarctica, *in* Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES, edited by A.K. Cooper and C.R. Raymond et al., USGS Open-File Report 2007-1047, Short Research Paper 108, 5 pp.; doi:https://doi.org/10.3133/of2007-1047.srp108.

Hamilton, R., Sorlien, C.C., Luyendyk, P., Bartek, L.R., 2001. Cenozoic tectonics of the Cape Roberts rift basin and Transantarctic Mountains front, southwestern Ross Sea, Antarctica. Tectonics 20, 325–342.

Hammer, W.R., Ryan, W.J., Tamplin, J.W., DeFauw, S.L., 1986. New vertebrates from the Fremouw Formation (Triassic), Beardmore Glacier region. Antarctica: Antarctic Journal of the United States 21, 24–26.

Hanemann, R., Viereck-Götte, L., 2004. Geochemistry of Jurassic Ferrar lava flows, sills and dikes sampled during the joint German-Italian Antarctic Expedition 1999-2000. Terra Antartica 11, 39–54.

Hansen, S.E., Julià, J., Nyblade, A.A., Pyle, M.L., Wiens, D.A., Anandakrishnan, S., 2009. Using S wave receiver functions to estimate crustal structure beneath ice sheets: An application to the Transantarctic Mountains and East Antarctic craton. Geochemistry Geophysics Geosystems 10, Q08014. https://doi.org/10.1029/2009GC002576.

Hansen, S.E., Kenyon, L.M., Graw, J.H., Park, Y., Nyblade, A.A., 2016. Crustal structure beneath the Northern Transantarctic Mountains and Wilkes Subglacial Basin: Implications for tectonic origins. Journal of Geophysical Research Solid Earth 121, 812–825. https://doi.org/10.1002/2015JB012325.

Haran, T., Bohlander, J., Scambos, T., Fahnestock, M., 2005. MODIS Mosaic of Antarctica (MOA) Image Map: Boulder, Colorado (U.S. National Snow and Ice Data Center).

Haran, T., Bohlander, J., Scambos, T., Painter, T., Fahnestock, M., 2014. MODIS Mosaic of Antarctica 2008-2009 (MOA2009) Image Map: Boulder, Colorado. U.S. National Snow and Ice Data Center. https://doi.org/10.7265/N5KP8037.

Harley, S.L., Kelly, N.M., 2007. Ancient Antarctica; the Archean of the East Antarctic Shield. In: Van Kranendonk, M.J., Smithies, R.H., Bennett, V.C. (Eds.), Earth's Oldest Rocks: Developments in Precambrian Geology. Elsevier, Netherlands, pp. 149–186.

Harley, S.L., Fitzsimons, I.C.W., Zhao, Y., 2013. Antarctica and supercontinent evolution: Historical perspectives, recent advances and unresolved issues. In: Harley, S.L., Fitzsimons, I.C.W., Zhao, Y. (Eds.), Antarctica and Supercontinent Evolution. 383, pp. 1–34 Geological Society of London, Special Publication.

Harpel, C.J., Kyle, P.R., Esser, R.P., McIntosh, W.C., Caldwell, D.A., 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.

Harrington, H.J., 1958. Nomenclature of rock units in the Ross Sea region, Antarctica. Nature 182, 290.

Harrington, H.J., Wood, B.L., McKellar, I.C., Lensen, G.J., 1964. The geology of Cape Hallet-Tucker Glacier district. In: Adie, R.J. (Ed.), Antarctic Geology: Amsterdam. North Holland, The Netherlands, pp. 220–228.

Harrington, H.J., Wood, B.L., McKellar, I.C., Lensen, G.J., 1967. Topography and geology of the Cape Hallett District. Victoria Land, Antarctica: Bulletin - New Zealand Geological Survey 80, 100.

Harvey, R. P., 2003, The origin and significance of Antarctic meteorites: Geochemistry (Chemie der Erde), 63, 93-147, doi.org/https://doi.org/10.1078/0009-2819-00031.

Harwood, D.M., 1986. Diatom Biostratigraphy and Paleoecology with a Cenozoic History of Antarctic Ice Sheets [PhD Dissertation Thesis]: The Ohio State University.

Harwood, D.M., Webb, P.N., 1998. Glacial transport of diatoms in the Antarctic Sirius Group: Pliocene refrigerator. GSA Today 8, 1–8.

Heeszel, D.S., Wiens, D.A., Anandakrishnan, S., Aster, R.C., Dalziel, I.W.D., Huerta, A.D., Nyblade, A.A., Wilson, T.J., Winberry, J.P., 2016. Upper mantle structure of central and West Antarctica from array analysis of Rayleigh wave phase velocities. Journal of Geophysical Research 121, 1758–1775. https://doi.org/10.1002/2015JB012616.

Heimann, A., Fleming, T.H., Elliot, D.H., Foland, K.A., 1994. 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.

Henjes-Kunst, F., Schüssler, U., 2003. Metasedimentary Units of theCambro-Ordovician Ross Orogen in northern Victoria Land and Oates Land: Implications for Their Provenance and Geotectonic Setting From Geochemical and Nd-Sr Isotope Data: Terra Antartica. 10 pp. 105–128.

Henjes-Kunst, F., Roland, N.W., Dunphy, J.M., Fletcher, I.R., 2004. SHRIMP U–Pb dating of high-grade migmatites and related magmatites from northwestern Oates Land

(East Antartica): evidence for a single high-grade event of. Ross-orogenic age: Terra Antartica 11, 67–84.
Hergt, J., Peate, D., Hawkesworth, C., 1991. The petrogenesis of Mesozoic Gondwana low-Ti flood basalts. Earth and Planetary Science Letters 105, 134–148.
Hergt, J.M., Chappell, B.W., Faure, G., Mensing, T., 1989. The geochemistry of Jurassic dolerites from Portal Peak, Antarctica. Contributions to Mineralogy and Petrology 102, 298–305.
Hersum, T.G., Marsh, B.D., Simon, A.C., 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.
Hill, D. J., Haywood, A. M., Hindmarsh, R. C., Valdes, P. J., Lunt, D. J., 2007, Modelling high latitude climates and ice sheets during the mid-Pliocene warm period: Eos, Transactions, American Geophysical Union, 88, no. 52.
Hoffman, P.F., 1991. Did the breakout of Laurentia turn Gondwanaland inside out? Science 252, 1409–1412.
Huerta, A., Blythe, A.E., Utevsky, E., 2011. Collapse of a Mesozoic West Antarctic plateau: evidence from low temperature thermochronology and geodynamical modeling. Geological Society of America Abstracts with Programs 43, 147.
Huerta, A.D., Harry, D.L., 2007. The transition from diffuse to focused extension: Modeled evolution of the West Antarctic Rift system. Earth and Planetary Science Letters 255, 133–147.
Iltchenko, L.N., 1972. Late Precambrian Achritarca of Antarctica. In: Adie, R.J. (Ed.), Antarctic Geology and Geophysics: Oslo, Norway. Universitetsforlaget, pp. 599–602.
Ireland, T.R., Flöttmann, T., Fanning, C.M., Gibson, G.M., Preiss, W.V., 1998. Development of the early. Paleozoic Pacific margin of Gondwana from detrital-zircon ages across the Delamerian orogen: Geology 26, 243–246.
Isbell, J., Lenaker, P., Askin, R., Miller, M., Babcock, L., 2003. Reevaluation of the timing and extent of late Paleozoic glaciation in Gondwana: Role of the Transantarctic Mountains. Geology 31, 977–980.
Isbell, J.L., 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, J.L., Macdonald, D.I.M., 1991. Alluvial stratigraphic sequences within the Permian Transantarctic foreland basin, Beardmore Glacier area. Antarctica: Antarctic Journal of the United States 26, 13–14.
Isbell, J.L., Miller, M.F., Babcock, L.E., Hasiotis, S.T., 2001. Ice-marginal environment and ecosystem prior to initial advance of the late Palaeozoic in the Mount Butters area of the central Transantarctic Mountains, Antarctica. Sedimentology 48, 953–970.
Isbell, J.L., Koch, Z.J., Szablewski, G.M., Lenaker, P.A., 2008. Permian glacigenic deposits in the Transantarctic Mountains, Antarctica, *in* Fielding, C. R., Frank, T. D., Isbell, J. L., eds., Resolving the late Paleozoic Ice Age in Time and Space: Geological Society of America special Paper 441. Geological Society of America 59–70.
Ivanov, A.V., Meffre, S., Thompson, J., Corfu, F., Kamenetsky, V.S., Kamenetsky, M.B., Demonterova, E.I., 2017. Timing and genesis of the Karoo-Ferrar large igneous province: New high precision U-Pb data for Tasmania confirm short duration of the major magmatic pulse. Chemical Geology 455, 32–43.
Jacobs, J., Thomas, R.J., 2004. Himalayan-type indenter-escape tectonics model for the southern part of the Neoproterozoic–early Paleozoic East African–Antarctic orogen. Geology 32, 721–724.
Jacobs, J., Bauer, W., Fanning, C.M., 2003a. Late Neoproterozoic/early Palaeozoic events in central Dronning Maud Land and significance for the southern extension of East African Orogen into East Antarctica. Precambrian Research 126, 27–53.
Jacobs, J., Fanning, C.M., Bauer, W., 2003b. Timing of Grenville-age vs. Pan-African medium- to high-grade metamorphism in western Dronning Maud Land (East Antarctica) and significance for correlations in Rodinia and Gondwana. Precambrian Research 125, 1–20.
Jones, S., 1997. Contrasting structural styles during polyphase granitoid intrusion, South Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 40, 237–251.
Jordan, H., Findlay, R.H., Mortimer, G., Schmidt-Thome, M., Crawford, A., Mueller, P., 1984. Geology of the northern Bowers Mountains. North Victoria Land, Antarctica: Geologisches Jahrbuch B60, 57–81.
Karner, G.D., Studinger, M., Bell, R.E., 2005. Gravity anomalies of sedimentary basins and their mechanical implications; application to the Ross Sea basins, West Antarctica. Earth and Planetary Science Letters 235, 577–596.
Kellogg, T.B., Burckle, L.H., Kellogg, D.E., Fastook, J.L., 1997. A new mechanism for diatom emplacement and concentration in glacigenic deposits. Antarctic Journal of the United States 32, 29–30.
Kelly, P.J., Dunbar, N.W., Kyle, P.R., McIntosh, W.C., 2008. 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.
Kim, T., Kim, Y., Cho, M., Lee, J.I., 2019. P–T evolution and episodic zircon growth in barroisite eclogites of the Lanterman Range, northern Victoria Land, Antarctica. Journal of Metamorphic Geology 37, 509–537. https://doi.org/10.1111/jmg.12474.
Kleinschmidt, G., 1981. Regional metamorphism in the Robertson Bay Group area and in the southern Daniels Range, North Victoria Land. Antarctica - A preliminary comparison: Geologisches Jahrbuch B41, 201–228.
Kleinschmidt, G., 1983. Trends in regional metamorphism and deformation in northern Victoria Land, Antarctica, *in* Oliver, R. L., James, R., Jago, J. B., eds., Antarctic earth science: Canberra, Australian Academy. Science 119–122.
Kleinschmidt, G., 1992. Structural observations in the Robertson Bay Terrane and their implications. Polarforschung 60, 128–132.
Kleinschmidt, G., Skinner, D., 1981. Deformation styles in the basement rocks of North Victoria Land. Antarctica: Geologisches Jahrbuch B41, 155–199.
Kleinschmidt, G., Tessensohn, F., 1987. Early Paleozoic westward directed subduction at the Pacific margin of Antarctica. In: McKenzie, G.D. (Ed.), Gondwana Six: Structure, Tectonics, and Geophysics. American Geophysical Union, Washington, D. C, pp. 89–105.
Kleinschmidt, G., Schubert, W., Olesch, M., Rettmann, E.S., 1987. Ultramafic rocks of the Lanterman Range in North Victoria Land, Antarctica. Petrology, geochemistry, and geodynamic implications: Geologisches Jahrbuch B66, 231–273.
Kleinschmidt, G., Mazzoli, C., Sassi, F.P., 1991. The pressure character of the low-grade metapelites from Robertson Bay Terrane and Bowers Terrane, northern Victoria Land (Antarctica), *in* Ricci, C. a., ed., Earth Science Investigations in Antarctica: Rome, Geological Society of Italy. Memoir 283–289.
Kreuzer, H., Höhndorf, A., Lenz, H., Müller, P., Vetter, U., 1987. Radiometric ages of pre-Mesozoic rocks from northern Victoria Land, Antarctica, *in* McKenzie, G. D., ed., Gondwana six: Structure, Tectonics, and Geophysics: Washington, D. C., American Geophysical Union. Geophysical Monograph 40, 31–47.
Kyle, P.R., 1990a. Erebus Volcanic Province: Summary. In: LeMasurier, W.E., Thomson, J.W. (Eds.), Volcanoes of the Antarctic Plate and Southern Oceans: Antarctic Research Series. American Geophysical Union, Washington, D.C., pp. 81–88.
Kyle, P.R., 1990b. McMurdo Volcanic Group Western Ross Embayment: Introduction. In: LeMasurier, W.E., Thomson, J.W. (Eds.), Volcanoes of the Antarctic Plate and Southern Oceans: Antarctic Research Series. American Geophysical Union, Washington, D.C., pp. 18–25.
Kyle, P.R., Dibble, R.R., Giggenbach, W.F., Keys, J., 1982. Volcanic activity associated with the anorthoclase phonolite lava lake, Mount Erebus, Antarctica. In: Craddock, C. (Ed.), Antarctic Geoscience. University of Wisconsin Press, Madison, pp. 735–745.
Kyle, P.R., Pankhurst, R.J., Bowman, J.R., 1983. Isotopic and chemical variations in Kirkpatrick Basalt Group rocks from southern Victoria Land, *in* Oliver, R. L., James, P. R., and Jago, J. B., eds., Antarctic earth science: Canberra, Australian Academy of. Science 234–237.
Kyle, P.R., Wright, A.C., Kirsch, I., 1987. Ultramafic xenoliths in the late Cenozoic McMurdo Volcanic Group, Western Ross Sea segment, Antarctica. In: Nixon, P. (Ed.), Mantle Xenoliths. Wiley, New York, pp. 287–293.
Kyle, P. R., Moore, J. A., Thirlwall, M. F., 1992, Petrologic evolution of anorthoclase phonolite lavas at Mount Erebus, Ross Island, Antarctica: J. Petrol. 33, 849–875, doi.org/ https://doi.org/10.1093/petrology/33.4.849.
Laird, M.G., 1963. Geomorphology and stratigraphy of the Nimrod Glacier-Beaumont Bay region, southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 6, 465–484.
Laird, M.G., 1981. Lower Paleozoic rocks of the Ross Sea area and their significance in the Gondwana context. Journal of the Royal Society of New Zealand 11, 425–438.
Laird, M.G., 1991. The late Proterozoic-Middle Paleozoic rocks of Antarctica. In: Tingey, R.J. (Ed.), The Geology of Antarctica: Oxford Monograph on Geology and Geophysics. Clarendon Press, Oxford, pp. 74–119.
Laird, M.G., Bradshaw, J.D., 1983. New data on the lower Paleozoic Bowers Supergroup, northern Victoria Land, *in* Oliver, R. L., James, P. R., Jago, J. B., eds., Antarctic earth science: Canberra, Australian Academy of. Science 123–126.
Laird, M.G., Mansergh, G.D., Chappell, J.M.A., 1971. Geology of the central Nimrod Glacier area, Antarctica. New Zealand Journal of Geology and Geophysics 14, 427–468.
Laird, M.G., Bradshaw, J.D., Wodzicki, A., 1982. Stratigraphy of the Upper Precambrian and lower Paleozoic Bowers Subgroup, northern Victoria Land, Antarctica. In: Craddock, C. (Ed.), Antarctic geoscience. University of Wisconsin Press, Madison, pp. 535–542.
Lawrence, J.F., Wiens, D.A., Nyblade, A.A., Anandakrishan, S., Shore, P.J., Voigt, D., 2006a. Crust and upper mantle structure of the Transantarctic Mountains and surrounding regions from receiver functions, surface waves, and gravity: Implications for uplift models. Geochemistry, Geophysics, Geosystems 7, Q10011. https://doi.org/10.1029/2006GC001282.
Lawrence, J.F., Wiens, D.A., Nyblade, A.A., Anandakrishan, S., Shore, P.J., Voigt, D., 2006b. Rayleigh wave phase velocity analysis of the Ross Sea, Transantarctic Mountains, and East Antarctica from a temporary seismograph array. Journal of Geophysical Research 111, B06302.
Lear, C.H., Elderfield, H., Wilson, P.A., 2000. Cenozoic deep-sea temperatures and global ice volumes from Mg/ca in benthic foraminiferal calcite. Science 287, 269–272.
Leat, P.T., 2008. On the long-distance transport of Ferrar magmas. in Thomson, K., Petford, N., eds., Structure and emplacement of high-level magmatic systems, Geological Society of London Special Publication 302, 45–61.
LeMasurier, W., Rex, D., 1991. The Marie Byrd Land Volcanic Province and its Relation to the Cainozoic West Antarctic Rift System: *in* the Geology of Antarctica, Tingey, R., Ed. Clarendon Press, London, pp. 249–284.
Lewis, A.R., Marchant, D.R., Kowalewski, D.E., Baldwin, S.L., Webb, L.E., 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.
Lewis, A. R., Marchant, D. R., Ashworth, A. C., Hemming, S. R. Machlus, M. L., 2007, Major middle Miocene global climate change: evidence from East Antarctica and the Transantarctic Mountains: Geological Society of America Bulletin, 119, 1449-1461, doi: 10.1130B26134.1.
Lewis, A.R., Marchant, D.R., Ashworth, A.C., Hedenaes, L., Hemming, S.R., Johnson, J.V., Leng, M.J., Machlus, M.L., Newton, A.E., Raine, J.I., Willenbring, J.K., Williams, M., Wolfe, A.P., 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: Washington, D. National Academy of Sciences, C, pp. 10676–10680.
Licht, K. J., Groth, T., Townsend, J. P., Hennessy, A. J., Hemming, S. R., Flood, T. P., Studinger, M., 2018, Evidence for extending anomalous Miocene volcanism at the edge of the East Antarctic craton: Geophysical Research Letters, 45, 3009–3016, doi.org/https://doi.org/10.1002/2018GL077237.
Lindsay, J. F., 1969, Stratigraphy and sedimentation of lower Beacon rocks in the central Transantarctic Mountains, Antarctica: Institute of Polar Studies Report No. 33, The Ohio State University, Columbus, (58 pages).

Lindsay, J.F., 1970. Depositional environment of Paleozoic glacial rocks in the central Transantarctic Mountains. Geological Society of America Bulletin 81, 1149–1172.

Lindsay, J.F., Gunner, J., Barrett, P.J., 1973. Reconnaissance geologic map of the Mount Elizabeth and Mount Kathleen quadrangles. Transantarctic Mountains, Antarctica: US Geological Survey Washington, DC 1, 250,000.

Lisker, F., Laufer, A.L., 2013. The Mesozoic Victoria Basin: Vanished link between Antarctica and Australia. Geology 41, 1043–1046.

Lombardo, B., Cappeli, B., Carmigiani, L., Gosso, G., Memmi, J., Montrasio, A., Palmieri, R., Pannati, F., Pertusati, P.C., Ricci, C.A., Salvini, F., Talarico, F., 1987. The metamorphic rocks of the Wilson terrane between David and Mariner Glaciers, North Victoria Land. Antartica: Memorie della Societa Geologica Italiana 33, 99–130.

Lund, K., 2008. Geometry of the Neoproterozoic and Paleozoic rift margin of western Laurentia: Implications for mineral deposit settings. Geosphere 4, 429–444.

Lund, K., Aleinikoff, J.N., Evans, K.V., Fanning, C.M., 2003. SHRIMP U-Pb geochronology of Neoproterozoic Windermere Supergroup, central. Idaho: Implications for regional synchroneity of Sturtian glaciation and associated rifting: Geological Society of America Bulletin 115, 349–372. https://doi.org/10.1130/0016-7606(2003)115<0349:SUPGON>2.0.CO;2.

Marchant, D.R., Denton, G.H., Swisher III, C.C., 1993. Miocene-Pliocene-Pleistocene glacial history of Arena Valley, Quartermain Mountains, Antarctica. Geografiska Annaler, Series A, Physical Geography 75, 269–302.

Marchant, D.R., Denton, G.H., Swisher III, C.C., Potter Jr., 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.

Marsh, B., 2004. A magmatic mush column Rosetta Stone; the McMurdo dry valleys of Antarctica. Eos, Transactions, American Geophysical Union 85, 497–502.

Martin, A.P., Cooper, A.F., 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. https://doi.org/10.1017/S095410201000026X.

McAdoo, D.C., Laxon, S., 1997. Antarctic tectonics: Constraints from an ERS-1 satellite marine gravity field. Science 276, 556–560.

McFadden, R. R., Siddoway, C. S., Teyssier, C., Fanning, C. M., 2010, Cretaceous oblique extensional deformation and magma accumulation in the Fosdick Mountains migmatite-cored gneiss dome, West Antarctica: Tectonics, 29, 1–27, doi.org/https://doi.org/10.1029/2009TC002492.

McGibbon, F.M., 1991. Geochemistry and petrology of ultramafic xenoliths of the Erebus Volcanic Province. In: Thomson, M.R.A., Crame, J.A., Thomson, J.W. (Eds.), Geologic Evolution of Antarctica. Cambridge University Press, Cambridge, pp. 317–322.

McGregor, V.R., 1965. Geology of the area between the Axel Heiberg and Shackleton Glaciers, Queen Maud Range, Antarctica, part 1—Basement complex, structure and geology. New Zealand Journal of Geology and Geophysics 8, 314–343.

McKelvey, B. C., Webb, P. N., Gorton, M. P., Kohn, B. P., 1970, Stratigraphy of the Beacon Supergroup between the Olympus and Boomerang ranges, Victoria Land: Nature, 227, 1126-1128.

McKelvey, B.C., Webb, P.N., Harwood, D.M., Mabin, M.C.G., 1991. The Dominion Range Sirius Group; a record of the late Pliocene-early Pleistocene Beardmore Glacier. In: Crame, J.A., Thomson, J.W. (Eds.), Geological Evolution of Antarctica; Proceedings of the Fifth International Symposium on Antarctic Earth Sciences. Cambridge University Press, Cambridge, pp. 675–682.

Medig, K.P.R., Thorkelson, D.J., Davis, W.J., Rainbird, R.H., Gibson, H.D., Turner, E.C., Marshall, D.D., 2014. Pinning northeastern Australia to northwestern Laurentia in the Mesoproterozoic. Precambrian Reseasrch 249, 88–99.

Meert, J.G., 2002. Paleomagnetic evidence for a Paleo-Mesoproterozoic supercontinent, Columbia. Gondwana Research 5, 207–215.

Meert, J.G., 2003. A synopsis of events related to the assembly of eastern Gondwana. Tectonophysics 362, 1–40.

Mellish, S.D., Cooper, A.F., Walker, N.W., 2002. Panorama Pluton; a composite gabbro-monzodiorite early Ross Orogeny intrusion in southern Victoria Land, Antarctica. In: Gamble, J.A., Skinner, D.N.B., Henrys, S.A. (Eds.), Antarctica at the Close of a Millennium; Proceedings of the 8th International Symposium on Antarctic Earth Sciences: Wellington. New Zealand, Royal Society of New Zealand, pp. 129–141.

Ménot, R.-P., Pelletier, A., Peucat, J.-J., Fanning, C.M., Oliver, R.L., 1999. Petrological and structural constraints on the amalgamation of the Terre Adélie Craton (135°-145°E), East Antarctica. In: Skinner, D.N.B. (Ed.), 8th International Symposium on Antarctic Earth Sciences: Wellington. New Zealand, Royal Society of New Zealand, p. 208.

Mensing, T.M., Faure, G., Jones, L.M., Bowman, J.R., Hoefs, J., 1984. Petrogenesis of the Kirkpatrick Basalt, Solo Nunatak, northern Victoria Land, Antarctica, based on isotopic compositions of strontium, oxygen, and sulfur. Contributions to Mineralogy and Petrology 87, 101–108.

Mercer, J.H., 1968. Glacial geology of the Reedy Glacier area, Antarctica. Geological Society of America Bulletin 79, 471–485.

Mercer, J.H., 1972. Some observations on the glacial geology of the Beardmore Glacier area. In: Adie, R.J. (Ed.), Antarctic Geology and Geophysics: Oslo, Norway. Universitetsforlaget, pp. 427–433.

Millar, I.A., Storey, B.C., 1995. Early Palaeozoic rather than Neoproterozoic volcanism and rifting within the Transantarctic Mountains. Journal of the Geological Society of London 152, 417–460.

Miller, M.F., Isbell, J.L., 2010. Reconstruction of a high-latitude, postglacial lake: Mackellar Formation (Permian), Transantarctic Mountains: *in* López-Gamundí, O., Buatois, L. a., eds. Late Paleozoic glacial events and postglacial transgressions in Gondwana, Boulder, Geological Society of America Special Paper 468, 193–207.

Miller, S.R., Fitzgerald, P.G., Baldwin, S.L., 2010. Cenozoic range-front faulting and development of the Transantarctic Mountains near Cape Surprise, Antarctica; thermochronologic and geomorphologic constraints. Tectonics 29, TC1003 (21 pp). https://doi.org/10.1029/2009TC002457.

Minshew, V.H., 1967. Geology of the Scott Glacier and Wisconsin Range areas. Central Transantarctic Mountains. The Ohio State University, Antarctica [Ph.D. dissertation thesis].

Moores, E.M., 1991. Southwest U.S.-East Antarctica (SWEAT) connection: a hypothesis. Geology 19, 425–428.

Mortimer, N., Palin, J. M., Dunlap, W. J., Hauff, F., 2011, Extent of the Ross Orogen in Antarctica: new data from DSDP 270 and Iselin Bank: Antarctic Science, 23, 297-306, doi.org/https://doi.org/10.1017/S0954102010000969.

Mortimer, N., Campbell, H.J., Tulloch, A.J., King, P.R., Stagpoole, V.M., Wood, R.A., Rattenbury, M.S., Sutherland, R., Adams, C.J., Collot, J., Seton, M., 2017. Zealandia: Earth's Hidden Continent: GSA Today 27, 2–9. https://doi.org/10.1130/GSATG321A.1.

Mortimer, N., van den Bogaard, P., Hoernle, K., Timm, C., Gans, P.B., Werner, R., Riefstahl, F., 2019. Late cretaceous oceanic plate reorganization and the breakup of Zealandia and Gondwana. Gondwana Research 65, 31–42.

Mukasa, S.B., Dalziel, I.W.D., 2000. Marie Byrd Land, West Antarctica: Evolution of Gondwana's Pacific margin constrained by zircon U-Pb geochronology and feldspar common-Pb isotopic compositions. Geological Society of America Bulletin 112, 611–627.

Mulder, J.A., Halpin, J.A., Daczko, N.R., 2015. Mesoproterozoic. Tasmania: witness to the East Antarctica-Laurentia connection within Nuna: Geology 43, 759–762. https://doi.org/10.1130/G36850.1.

Müller, R.D., Seton, M., Zahirovic, S., Williams, S.E., Matthews, K.J., Wright, N.M., Shephard, G.E., Maloney, K.T., Barnett-Moore, N., Hosseinpour, M., Bower, D.J., 2016. Ocean basin evolution and global-scale plate reorganization events since Pangea breakup. Annual Review of Earth and Planetary Sciences 44, 107–138.

Murtaugh, J.G., 1969. Geology of the Wisconsin range batholith, Transantarctic mountains. New Zealand Journal of Geology and Geophysics 12, 526–550.

Musumeci, G., 1999. Magmatic belts in accretionary margins, a key for tectonic evolution: the Tonalite Belt of North Victoria Land (East Antarctica). Journal of the Geological Society of London 156, 177–191.

Myrow, P.M., Fischer, W., Goodge, J.W., 2002a. Wave-modified turbidites: combined-flow shoreline and shelf deposits, Cambrian, Antarctica. Journal of Sedimentary Research 72, 641–656.

Myrow, P.M., Pope, M.C., Goodge, J.W., Fischer, W., Palmer, A.R., 2002b. Depositional history of pre-Devonian strata and timing of Ross Orogenic tectonism in the central Transantarctic Mountains. Antarctica: Geological Society of America Bulletin 114, 1070–1088.

Nance, R.D., Murphy, J.B., Santosh, M., 2013. The supercontinent cycle: a retrospective essay. Gondwana Research 25, 4–29. https://doi.org/10.1016/j.gr.2012.12.026.

Nardini, I., Armienti, P., Rocchi, S., Dallai, L., Harrison, D., 2009. Sr-Nd-Pb-He-O isotope and geochemical constraints on the genesis of Cenozoic magmas from the West Antarctic Rift. Journal of Petrology 50, 1359–1375.

O'Donnell, J.P., Nyblade, A.A., 2014. Antarctica's hypsometry and crustal thickness: Implications for the origin of anomalous topography in East Antarctica. Earth and Planetary Science Letters 388, 143–155.

Oliver, R.L., 1972. Geology of an Area near the Mouth of Beardmore Glacier, Ross Dependency: *in* Antarctic Geology and Geophysics, R.J. Adie, Ed. Universitetsforlaget, Oslo, pp. 379–385.

Olivetti, V., Rossetti, F., Balestrieri, M.L., Pace, D., Cornamusini, G., Talarico, F., 2018. Variability in uplift, exhumation and crustal deformation along the Transantarctic Mountains front in southern Victoria Land. Antarctica: Tectonophysics 745, 29–244.

Oppenheimer, C., Kyle, P.R., 2008. Volcanology of Erebus volcano, Antarctica. Journal of Volcanology and Geothermal Research 177, 531–754.

Palmer, A.R., Rowell, A.J., 1995. Early Cambrian trilobites from the Shackleton Limestone of the central Transantarctic Mountains. Journal of Paleontology 69, 25–26.

Palmeri, R., 1997. P-T paths and migmatite formation: an example from deep freeze Range, northern Victoria Land, Antarctica. Lithos 42, 47–66.

Palmeri, R., Talarico, F., Meccheri, M., Oggiano, G., Pertusati, P.C., Rastelli, N., Ricci, C.A., 1991. Progressive deformation and low pressure/high temperature metamorphism in the deep freeze Range, Wilson Terrane, northern Victoria Land, Antarctica, *in* Ricci, C. a., ed., Earth Science Investigations in Antarctica: Rome, Geological Society of Italy. Memoir 179–195.

Palmeri, R., Pertusati, P.C., Ricci, C.A., Talarico, F., 1994. Late Proterozoic(?)-Early Plaeozoic of the active pacific margin of Gondwana: evidence from the southern Wilson Terrane (northern Victoria Land, Antarctica). Terra Antarctica 1, 5–9.

Palmeri, R., Ghiribelli, B., Ricci, C.A., 2003. Ultra-high-pressure metamorphism in felsic rocks; the garnet-phengite gneisses and quartzites from Lanterman Range, Antarctica. European Journal of Mineralogy 15, 513–525.

Palmeri, R., Talarico, F.M., Ricci, C.A., 2011. Ultrahigh-pressure metamorphism at the Lanterman Range (northern Victoria Land, Antarctica). Geological Journal 46, 126–136. https://doi.org/10.1002/gj.1243.

Palmeri, R., Sandroni, S., Godard, G., Ricci, C.A., 2012. Boninite-derived amphibolites from the Lanterman-Mariner suture (northern Victoria Land, Antarctica): New geochemical and petrological data. Lithos 140–141, 200–223.

Pankhurst, R.J., Weaver, S.D., Bradshaw, J.D., Storey, B.C., Ireland, T.R., 1998. Geochronology and geochemistry of pre-Jurassic superterranes in Marie Byrd Land, Antarctica. Journal of Geophysical Research 103, 2529–2547.

Panter, K.S., Winter, B., 2008. Geology of the side crater of the Erebus volcano, Antarctica. Journal of Volcanology and Geothermal Research 177, 578–588.

Panter, K.S., Blusztajn, J., Hart, S., Kyle, P., Esser, R., McIntosh, W., 2006. The origin of HIMU in the SW Pacific: evidence from intraplate volcanism in southern New Zealand and subantarctic islands. Journal of Petrology 47, 1673–1704.

Parmelee, D.E.F., Kyle, P.R., Kurz, M.D., Marrero, S.M., Phillips, F.M., 2015. A new Holocene eruptive history of Erebus volcano, Antarctica using cosmogenic ^{3}He and ^{36}Cl exposure ages. Quaternary Geochronology 30, 114–131.

Passchier, S., 2001. Provenance of the Sirius Group and related upper Cenozoic glacial deposits from the Transantarctic Mountains, Antarctica; relation to landscape evolution and ice-sheet drainage. Sedimentary Geology 144, 263–290.

Paulsen, T., Encarnación, J., Grunow, A., 2004. Structure and timing of transpressional deformation in the Shackleton Glacier area, Ross orogen. Antarctica: Journal of the Geological Society of London 161, 1027–1038.

Paulsen, T., Encarnación, J., Grunow, A., Valencia, V.A., Rasoazanamparany, C., 2008. Late sinistral shearing along Gondwana's Paleo-Pacific margin in the Ross Orogen, Antarctica: New structure and age data from the O'Brien peak area. Journal of Geology 116, 303–312.

Paulsen, T., Encarnación, J., Grunow, A.M., Valencia, V.A., Pecha, M., Layer, P.W., Rasoazanamparany, C., 2013. Age and significance of 'outboard' high-grade metamorphics and intrusives of the Ross orogen, Antarctica. Gondwana Research 24, 349–358.

Paulsen, T.S., Wilson, T.J., 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. https://doi.org/10.1130/B26333.1.

Paulsen, T.S., Encarnación, J., Grunow, A.M., Layer, P.W., Watkeys, M., 2007. New age constraints for a short pulse in Ross orogen deformation triggered by East-West Gondwana suturing. Gondwana Research 12, 417–427.

Paulsen, T.S., Encarnación, J., Grunow, A.M., Valencia, V.A., Layer, P.W., Pecha, M., Stump, E., Roeske, S., Thao, S., Rasoazanamparany, C., 2015. Detrital mineral ages from the Ross Supergroup, Antarctica: Implications for the Queen Maud terrane and outboard sediment provenance on the Gondwana margin. Gondwana Research 27, 377–391.

Paulsen, T.S., Deering, C., Sliwinski, J., Bachmann, O., Guillong, M., 2016. Detrital zircon ages from the Ross Supergroup, North Victoria Land, Antarctica: Implications for the tectonostratigraphic evolution of the Pacific- Gondwana margin. Gondwana Research 35, 79–96.

Paulsen, T.S., Encarnación, J., Grunow, A.M., Stump, E., Pecha, M., Valencia, V.A., 2018. Correlation and late-stage deformation of Liv Group volcanics in the Ross-Delamerian Orogen, Antarctica, from new U-Pb ages. Journal of Geology 126, 307–323. https://doi.org/10.1086/697036.

Peacock, S.M., Goodge, J.W., 1995. Eclogite-facies metamorphism preserved in tectonic blocks from a lower crustal shear zone, central Transantarctic Mountains. Antarctica: Lithos 36, 1–13.

Pertusati, P.C., Ricci, C.A., Tessensohn, F., 2016. German-Italian Geological Antarctic Map Programme, the. Italian Contribution: Introductory Notes to the Map Case: Terra Antartica Reports 15, 1–15.

Peucat, J.J., Ménot, R.P., Monnier, O., Fanning, C.M., 1999. The Terre Adélie basement in the East-Antarctica shield: geological and isotopic evidence for a major 1.7 Ga thermal event; comparison with the Gawler Craton in South Australia. Precambrian Research 94, 205–224.

Phillips, E.H., Sims, K.W.W., Blichert-Toft, J., Aster, R.C., Gaetani, G.A., Kyle, P.R., Wallace, P.J., Rasmussen, D.J., 2018. The nature and evolution of mantle upwelling at Ross Island, Antarctica, with implications for the source of HIMU lavas. Earth and Planetary Science Letters 498, 38–53.

Pigage, L.C., Mortensen, J.K., 2004. Superimposed Neoproterozoic and early Tertiary alkaline magmatism in the La Biche River area, southeast Yukon Territory. Bulletin of Canadian Petroleum Geology 52, 325–342. https://doi.org/10.2113/52.4.325.

Pisarevsky, S.A., Elming, S.-Å., Pesonen, L.J., Li, Z.-X., 2014. Mesoproterozoic paleogeography: Supercontinent and beyond. Precambrian Research 244, 207–225. https://doi.org/10.1016/j.precamres.2013.05.014.

Preiss, W.V., 2000. The Adelaide Geosyncline of South Australia and its significance in Neoproterozoic continental reconstruction. Precambrian Research 100, 21–63.

Prentice, M.L., Denton, G.H., Lowell, T.V., Conway, H.C., Heusser, L.E., 1986. Pre-late Quaternary glaciation of the Beardmore Glacier region. Antarctica: Antarctic Journal of the United States 21, 95–98.

Prenzel, J., Lisker, F., Monsees, N., Balestrieri, M.L., Läufer, A., Spiegel, C., 2018. Development and inversion of the Mesozoic Victoria Basin in the Terra Nova Bay (Transantarctic Mountains) derived from thermochronological data. Gondwana Research 53, 110–128.

Prenzel, P., Lisker, F., Balestrieri, M.L., Läufer, A., Spiegel, C., 2013. The Eisenhower Range, Transantarctic Mountains: a natural laboratory to evaluate qualitative interpretation concepts of thermochronological data. Chemical Geology 352, 176–187.

Ramirez, C., Nyblade, A., Emry, E. L., Julià, J., Sun, X., Anandakrishnan, S., Wiens, D. A., Aster, R. C., Huerta, A. D., Winberry, P., Wilson, T., 2017, Crustal structure of the Transantarctic Mountains, Ellsworth Mountains and Marie Byrd Land, Antarctica: constraints on shear wave velocities, Poisson's ratios and Moho depths: Geophysical Journal International, 211, 1328–1340, doi.org/https://doi.org/10.1093/gji/ggx333

Rapela, C.W., Pankhurst, R.J., Casquet, C., Baldo, E., Saavedra, J., Galindo, C., Fanning, C.M., 1998. The Pampean Orogeny of the southern proto-Andes: Cambrian continental collision in the Sierras de Cordoba. In: Pankhurst, R.J., Rapela, C.W. (Eds.), The Proto-Andean Margin of Gondwan. Special Publications, Geological Society of London, pp. 181–217.

Ravich, M.G., Klimov, L.V., Soloviev, D.S., 1965. The Precambrian of East Antarctica: Moscow (Trans. Scient. Research Institute of the Geology of the Arctic of the State Geological Committee).

Read, S.E., Cooper, A.F., 1999. New U-Pb isotopic age determinations from plutons in the Ross orogen, southern Victoria Land, Antarctica, *in* 8th International Symposium on Antarctic Earth Sciences, Wellington. New Zealand 262.

Read, S.E., Cooper, A.F., Walker, N.W., 2002. Geochemistry and U-Pb geochronology of the Neoproterozoic-Cambrian Koettlitz Glacier alkaline province, Royal Society Range, Transantarctic Mountains, Antarctica. In: Gamble, J.A., Skinner, D.N.B., Henrys, S.A. (Eds.), Antarctica at the Close of a Millennium; Proceedings of the 8th International Symposium on Antarctic Earth Sciences: Wellington. New Zealand, Royal Society of New Zealand, pp. 143–151.

Rees, M.N., Girty, G.H., Panttaja, S.K., Braddock, P., 1987. Multiple phases of early. Paleozoic deformation in the central Transantarctic Mountains: Antarctica Journal of the United States 22, 33–35.

Rees, M.N., Rowell, A.J., Cole, E.D., 1988. Aspects of the late Proterozoic and Paleozoic geology of the Churchill Mountains, southern. Victoria Land: Antarctic Journal of United States 22, 23–25.

Rees, M.N., Pratt, B.R., Rowell, A.J., 1989. Early Cambrian reefs, reef complexes, and associated lithofacies of the Shackleton Limestone, Transantarctic Mountains. Sedimentology 36, 341–361.

Retallack, G.J., Krull, E.S., Bockheim, J.G., 2001. New grounds for reassessing palaeoclimate of the Sirius Group. Antarctica: Journal of the Geological Society of London 158, 925–935.

Retallack, G.J., Jahren, A.H., Sheldon, N.D., Chakrabarti, R., Metzger, C.A., Smith, R.M.H., 2005. The Permian-Triassic boundary in Antarctica. Antarctic Science 17, 241–258.

Ricci, C.A., Talarico, F., Palmeri, R., Di Vincenzo, G., Pertusati, P.C., 1996. Eclogite at the Antarctic palaeo-Pacific margin of Gondwana (Lanterman Range, northern Victoria Land, Antarctica). Antarctic Science 8, 277–280.

Ricci, C.A., Talarico, F., Palmeri, R., 1997. Tectonothermal evolution of the Antarctic Paleo-Pacific active margin of Gondwana; a northern Victoria Land perspective, *in* Ricci, C. a., ed., the Antarctic region; geological evolution and processes; Proceedings of the VII International Symposium on Antarctic Earth Sciences: Siena. Terra Antarctica Publications 213–218.

Riley, T.R., Curtis, M.L., Leat, P.T., Watkeys, M.K., Duncan, R.A., Millar, I.L., Owens, W.H., 2006. Overlap of Karoo and Ferrar magma types in KwaZulu Natal, South Africa. Journal of Petrology 45, 541–566.

Rocchi, S., Tonarini, S., Armienti, P., Innocenti, F., Manetti, P., 1998. Geochemical and isotopic structure of the early Palaeozoic active margin of Gondwana in northern Victoria Land, Antarctica. Tectonophysics 284, 261–281.

Rocchi, S., Armienti, P., D'Orazio, M., Tonarini, S., Wijbrans, J.R., Di Vincenzo, G., 2002. Cenozoic magmatism in the western Ross Embayment: Role of mantle plume versus plate dynamics in the development of the West Antarctic Rift System. Journal of Geophysical Research 107. https://doi.org/10.1029/2001JB000515.

Rocchi, S., Capponi, G., Crispini, L., Di Vincenzo, G., Ghezzo, C., Meccheri, M., Palmeri, R., 2003a, Mafic rocks at the Wilson-Bowers Terrane transition and within the Bowers Terrane; implications for a geodynamic model of the Ross Orogeny, *in* Brancolini, G., Ghezzo, C., and Morelli, a., eds., Proceedings of the workshop on Antarctic earth sciences: Siena, Terra Antartica Publication, 145-148.

Rocchi, S., Storti, F., Di Vincenzo, G., Rossetti, F., 2003b. Intraplate strike-slip tectonics as an alternative to mantle plume activity for the Cenozoic rift magmatism in the Ross Sea region, Antarctica. *in* Storti, F., Holdsworth, R. E., and Salvini, F., eds., Intraplate Strike-Slip Deformation Belts: London, Geological Society Special Publication 145–158.

Rocchi, S., Di Vincenzo, G., Ghezzo, C., 2004, The Terra Nova Intrusive complex (Victoria Land, Antarctica): Terra Antartica Reports, 10, 1-51.

Rocchi, S., Armienti, P., Di Vincenzo, G., 2005, No plume, no rift magmatism in the West Antarctic Rift, *in* Foulger, G. R., Natland, J. H., Presnall, D. C., and Anderson, D. L., eds., Plates, Plumes, and Paradigms: Boulder, Geological Society of America Special Paper, 435-447.

Rocchi, S., Barcciali, L., Di Vincenzo, G., Gemelli, M., Ghezzo, C., 2011. Arc accretion to the early Paleozoic Antarctic margin of Gondwana in Victoria Land. Gondwana Research 19, 594–607.

Rocholl, A., Stein, M., Molzahn, M., Hart, S., Wörner, G., 1995. Geochemical evolution of rift magmas by progressive tapping of a stratified mantle source beneath the Ross Sea Rift, Northern Victoria Land, Antarctica. Earth and Planetary Science Letters 131, 207–224.

Roland, N.W., 1991. The boundary of the East Antarctic craton on the Pacific margin. In: Thomson, M.R.A., Crame, J.A., Thomson, J.W. (Eds.), Geological Evolution of Antarctica. Cambridge University Press, Cambridge, pp. 161–165.

Roland, N.W., Gibson, G.M., Kleinschmidt, G., Schubert, W., 1984. Metamorphism and structural relations of the Lanterman Metamorphics. North Victoria Land, Antarctica: Geologisches Jahrbuch B60, 319–361.

Rossetti, F., Storti, F., Busetti, M., Lisker, F., Di Vincenzo, G., Laeufer, A.L., Rocchi, S., Salvini, F., 2006. Eocene initiation of Ross Sea dextral faulting and implications for East Antarctic neotectonics. Journal of the Geological Society of London 163, 119–126.

Rossetti, F., Vignaroli, G., Di Vincenzo, G., Gerdes, A., Ghezzo, C., Theye, T., Balsamo, F., 2011, Long-lived orogenic construction along the paleo-Pacific margin of Gondwana (deep freeze Range, North Victoria Land, Antarctica): Tectonics, 30, 1-27, doi:10/1029/2010TC002804.

Rowell, A.J., Rees, M.N., 1989. Early Palaeozoic history of the upper Beardmore Glacier area: implications for a major Antarctic structural boundary within the Transantarctic Mountains. Antarctic Science 1, 249–260.

Rowell, A.J., Rees, M.N., 1991. Setting and significance of the Shackleton Limestone, central Transantarctic Mountains. In: Thomson, M., Crame, J., Thomson, J.W. (Eds.), Geological Evolution of Antarctica. Cambridge University Press, Cambridge, pp. 171–175.

Rowell, A.J., Rees, M.N., Braddock, P., 1986. Pre-Devonian. Paleozoic rocks of the central Transantarctic Mountains: Antarctica Journal of the United States 21, 48–50.

Rowell, A.J., Evans, K.R., Rees, M.N., 1988a. Fauna of the Shackleton Limestone. Antarctic Journal of the United States 23, 13–14.

Rowell, A.J., Rees, M.N., Cooper, R.A., Pratt, B.R., 1988b. Early Paleozoic history of the central Transantarctic Mountains: evidence from the Holyoake Range, Antarctica. New Zealand Journal of Geology and Geophysics 31, 397–404.

Rowell, A.J., Rees, M.N., Evans, K.R., 1992. Evidence of major Middle Cambrian deformation in the Ross orogen, Antarctica. Geology 20, 31–34.

Rowell, A.J., Rees, M.N., Duebendorfer, E.M., Wallin, E.T., Van Schmus, W.R., Smith, E.I., 1993. An active Neoproterozoic margin: evidence from the Skelton Glacier area. Transantarctic Mountains: Journal of the Geological Society of London 150, 677–682.

Rowell, A. J., Gonzales, D. A., McKenna, L. W., Evans, K. R., Stump, E., Van Schmus, W. R., 1997, Lower Paleozoic rocks in the Queen Maud Mountains: revised ages and significance, *in* Ricci, C. a., ed., the Antarctic Region: Geological Evolution and Processes: Siena, Terra Antartica Publication, 201-207.

Rowell, A.J., Van Schmus, W.R., Storey, B.C., Fetter, A.H., Evans, K.R., 2001. Latest Neoproterozoic to Mid-Cambrian age for the main deformation phases of the Transantarctic Mountains: new stratigraphic and isotopic constraints from the Pensacola Mountains. Antarctica: Journal of Geological Society of London 158, 295–308.
Salvini, F., Storti, F., 1999. Cenozoic tectonic lineaments of the Terra Nova Bay region, Ross Embayment, Antarctica: Global and. Planetary Science 23, 129–144.
Salvini, F., Brancolini, G., Busetti, M., Storti, F., Mazzarini, F., Coren, F., 1997. Cenozoic geodynamics of the Ross Sea region. Antarctica: Crustal extension, intraplate strike-slip faulting, and tectonic inheritance: Journal of Geophysical Research 102, 24,669–24,696.
Sandiford, M., 1985. Structural evolution of the Lanterman Metamorphic complex, northern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 28, 443–458.
Schmidt, C.J., Ford, A.B., 1969. Geology of the Pensacola and Thiel Mountains, *in* Bushnell, V. C., and Craddock, C., eds., Antarctic Map Folio Series, Folio 12: New York. American Geographical Society Folio 12, Sheet 5.
Schmidt, D.L., Doker, J.H., Ford, A.B., Brown, R.D., 1964. Geology of the Patuxent Mountains. In: Adie, R.J. (Ed.), Antarctic Geology. North-Holland, Amsterdam.
Schmidt, D.L., Williams, P.L., Nelson, W.H., Ege, J.R., 1965. Upper Precambrian and Paleozoic stratigraphy and structure of the Neptune Range, Antarctica: U. S. Geological Survey Professional Paper 525–D, D112–D119.
Schöner, R., Viereck-Götte, L., Schneider, J., Bomfleur, B., 2007, Triassic-Jurassic sediments and multiple volcanic events in North Victoria Land, Antarctica: A revised stratigraphic model: *in* Cooper, A. K., Raymond, C. R. et al., eds., Antarctica: A Keystone in a Changing World, National Academies Press, Washington, DC, 5 pp. doi:https://doi.org/10.3133/of2007-1047.srp102.
Schubert, W., Olesch, M., 1989. Petrological evolution of the crystalline basement of Terra Nova Bay, North Victoria Land. Antarctica: Geologisches Jahrbuch E38, 277–298.
Schüssler, U., Brocker, M., Henjes-Kunst, F., Will, H.T., 1999. P-T-t evolution of the Wilson Terrane Metamorphic Basement at Oates Coast. Antarctica: Precambrian Research 93, 235–258.
Schüssler, U., Henjes-Kunst, F., Talarico, F., Flöttmann, T., 2004. High-grade crystalline basement of the northwestern. Wilson Terrane at Oates Coast: new petrological and geochronological data and implications for its tectonometamorphic evolution: Terra Antartica 11, 15–34.
Shen, W., Wiens, D.A., Stern, T., Anandakrishnan, S., Aster, R.A., Dalziel, I., Hansen, S., Heeszel, D.S., Huerta, A., Nyblade, A., Wilson, T.J., Winberry, J.P., 2018. Seismic evidence for lithospheric foundering beneath the southern Transantarctic Mountains, Antarctica. Geology 46, 71–74.
Sheraton, J.W., Babcock, R.S., Black, L.P., Wyborn, D., Plummer, C.C., 1987. Petrogenesis of granitic rocks of the Daniels Range, northern Victoria Land, Antarctica. Precambrian Research 37, 267–286.
Siddoway, C.S., 2008. Tectonics of the West Antarctic Rift System: new light on the history and dynamics of distributed intracontinental extension, in Cooper, A. K., Raymond, C. R. et al., eds., Antarctica: a Keystone in a changing World, National Academies Press, Washington. DC 91–114.
Skinner, D.N.B., 1983. The granites and two orogenies of southern Victoria Land. In: Oliver, R.L., James, P.R., Jago, J.B. (Eds.), Antarctic Earth Science. Cambridge Univ. Press, Cambridge, pp. 160–163.
Smellie, J.L., Rocchi, S., Armienti, P., 2011. Late Miocene volcanic sequences in northern Victoria Land, Antarctica: products of glaciovolcanic eruptions under different thermal regimes. Bulletin of Volcanology 73, 1–25.
Smellie, J.L., Rocchi, S., Wilch, T.I., Gemelli, M., Di Vincenzo, G., McIntosh, W., Dunbar, N., Panter, K., Fargo, A., 2014. Glaciovolcanic evidence for a polythermal Neogene East Antarctic Ice Sheet. Geology 42, 39–41.
Smit, J. H., 1981, Sedimentology, metamorphism, and structure of the LaGorce Formation, La Gorce Mountains, upper Scott Glacier, Antarctica [M.S. thesis thesis]: Arizona State University, (83 p).
Smit, J.H., Stump, E., 1986. Sedimentology of the La Gorce Formation, La Gorce Mountains. Antarctica: Journal of Sedimentary Petrology 56, 663–668.
Stearns, L.A., Smith, B.E., Hamilton, G.S., 2008. Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods. Nature Geoscience 1, 827–831.
Stern, T.A., ten Brink, U.S., 1989. Flexural uplift of the Transantarctic Mountains. Journal of Geophysical Research 94 (B8), 10315–10330.
Stern, T.A., Baxter, A.K., Barrett, P.J., 2005. Isostatic rebound due to glacial erosion within the Transantarctic Mountains. Geology 33, 221–224.
Stigall, A. L., Babcock, L. E., Briggs, D. E. G., Leslie, S.A., 2008, Taphonomy of lacustrine interbeds in the Kirkpatrick Basalt (Jurassic), Antarctica: PALAIOS, 23, 344-355, doi.org/https://doi.org/10.2110/palo.2007.p07-029r.
Storey, B.C., Kyle, P.R., 1997. An active mantle mechanism for Gondwana break-up. Journal of African Earth Sciences 100, 283–290.
Storey, B.C., Alabaster, T., Macdonald, D.I.M., Millar, I.L., Pankhurst, R.J., Dalziel, I.W.D., 1992. Upper Proterozoic rift-related rocks in the Pensacola Mountains, Antarctica: precursors to supercontinent breakup? Tectonics 11, 1392–1405.
Storey, B.C., Macdonald, D.I.M., Millar, I.L., 1996. Early Paleozoic sedimentation, magmatism and deformation in the Pensacola Mountains, Antarctica: the significance of the Ross orogeny. Geological Society of America Bulletin 108, 685–707.
Storey, B.C., Leat, P.T., Ferris, J.K., 2001. The location of mantle plume centers during the initial stages of Gondwana break-up. In: Ernst, R.E., Buchan, K.L. (Eds.), Mantle Plumes: Their Identificaion through Time: Geological Society of America. 352, pp. 71–80 Boulder, Colorado, Memoir.
Studinger, M., Bell, R.E., Buck, W.R., Karner, G.D., Blankenship, D.D., 2004. Sub-ice geology inland of the Transantarctic Mountains in light of new geophysical data. Earth and Planetary Science Letters 220, 391–408.
Studinger, M., Bell, R.E., Fitzgerald, P.G., Buck, W.R., 2006. Crustal architecture of the Transantarctic Mountains between the Scott and Reedy Glacier region and South Pole from aerogeophysical data. Earth and Planetary Science Letters 250, 182–199.
Stump, E., 1981. Structural relationships in the Duncan Mountains, central Transantarctic Mountains, Antarctica. New Zealand Journal of Geology and Geophysics 24, 87–93.
Stump, E., 1982. The Ross Supergroup in the Queen Maud Mountains, Antarctica. In: Craddock, C. (Ed.), Antarctic Geoscience. University of Wisconsin Press, Madison, pp. 565–569.
Stump, E., 1986, Stratigraphy of the Ross Supergroup, central Transantarctic Mountains: Antarctic Research Series, American Geophysical Union, 225-274.
Stump, E., 1995. The Ross Orogen of the Transantarctic Mountains: New York. Cambridge University Press (284 p).
Stump, E., Sheridan, M.F., Borg, S.G., Sutter, J.F., 1980. Early Miocene subglacial basalts, the East Antarctic Ice Sheet, and uplift of the Transantarctic Mountains. Science 207, 757–759.
Stump, E., Smit, J.H., Self, S., 1986. Timing of events of the late Proterozoic Beardmore orogeny, Antarctica: evidence from the La Gorce Mountains. Geological Society of America Bulletin 97, 953–965.
Stump, E., Miller, J.M.G., Korsch, R.J., Edgerton, D.G., 1988. Diamictite from Nimrod Glacier area, Antarctica: possible Proterozoic glaciation on the seventh continent. Geology 16, 225–228.
Stump, E., Gootee, B., Talarico, F., 2006. Tectonic model for development of the Byrd Glacier discontinuity and surrounding regions of the Transantarctic Mountains during the Neoproterozoic – Early Paleozoic. In: Fütterer, D.K., Damaske, D., Kleinschmidt, G., Miller, H., Tessensohn, F. (Eds.), Antarctica: Contributions to Global Earth Sciences. Springer-Verlag, Berlin, pp. 181–190.
Sturm, A., Carryer, S.J., 1970. Geology of the region between the Matusevich and Tucker Glaciers, North Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 13, 408–435.
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, D.E., Marchant, D.R., Potter Jr., N., Souchez, R.A., Denton, G.H., Swisher III, C.C., Tison, J., 1995. Preservation of Miocene glacier ice in East Antarctica. Nature (London) 376 (6539), 412–414.
Swanson-Hysell, N.L., Maloof, A.C., Kirschvink, J.L., Evans, D.A.D., Halverson, G.P., Hurtgen, M.T., 2012, Constraints on Neoproterozoic paleogeography and Paleozoic orogenesis from paleomagnetic records of the Bitter Springs Formation, Amadeus Basin, central Australia: American Journal of Science, 312, 817–884, doi.org/https://doi.org/10.2475/08.2012.01.
Talarico, F., Castelli, D., 1995. Relict granulites in the Ross Orogen of northern Victoria Land (Antarctica), I. Field occurrence, petrography and metamorphic evolution. Precambrian Research 75, 141–156.
Talarico, F., Franceschelli, M., Lombardo, B., Palmeri, R., Pertusati, P.C., Rastelli, N., Ricci, C.A., 1992. Metamorphic Facies of the Ross Orogeny in the southern Wilson Terrane of northern Victoria Land, Antarctica, *in* Yoshida, Y., Kaminuma, K., Shiraishi, K., eds., recent Progress in Antarctic Earth Science: Tokyo. Terra Scientific 211–218.
Talarico, F., Ghiribelli, B., Siddoway, C., Palmeri, R., Ricci, C.A., 1998. The. Northern Victoria Land segment of the Antarctic paleo-Pacific margin of eastern Gondwana: New constraints from the Lanterman and Mountaineer Ranges: Terra Antartica 5, 245–252.
Talarico, F.M., Palmeri, R., Ricci, C.A., 2004. Regional metamorphism and P-T evolution of the Ross Orogen in northern Victoria Land (Antarctica). A review: Periodico di Mineralogia 73, 185–196.
Talarico, F.M., Findlay, R.H., Rastelli, N., 2005. Metamorphic evolution of the Koettlitz Group in the Koettlitz- Ferrar glaciers region (Southern Victoria Land, Antarctica). Terra Antartica 12, 3–23.
Tessensohn, F., Henjes-Kunst, F., 2005. Northern Victoria Land terranes, Antarctica: far-travelled or local products?, *in* Vaughan, A. P. M., Leat, P. T., and Pankhurst, R. J., eds. Terrane Processes at the Margin of Gondwana: Geological Society of London Special Publication 246, 275–291.
Thorkelson, D.J., Mortensen, J.K., Creaser, R.A., Davidson, G.J., Abbott, J.G., 2001a. Early Proterozoic magmatism in Yukon, Canada: constraints on the evolution of north- western Laurentia. Canadian Journal of Earth Sciences 38, 1479–1494.
Thorkelson, D.J., Mortensen, J.K., Davidson, G.J., Creaser, R.A., Perez, W.A., Abbott, J.G., 2001b. Early Mesoproterozoic intrusive breccias in Yukon, Canada: the role of hydrothermal systems in reconstructions of North America and Australia. Precambrian Research 111, 31–55.
Tingey, R.J., 1991. The regional geology of Archaean and Proterozoic rocks in Antarctica, *in* Tingey, R. J., ed., the geology of Antarctica: Oxford. Clarenden Press 1–73.
Tinto, K. J., Padman, L., Siddoway, C. S., Springer, S. R., Fricker, H. A., Das, I., and 25 others, 2019, Ross Ice Shelf response to climate driven by the tectonic imprint on seafloor bathymetry: Nature Geoscience, 12, 441–449, doi.org/https://doi.org/10.1038/s41561-019-0370-2.Tonarini, S., Rocchi, S., 1994, Geochronology of Cambro-Ordovician intrusives in northern Victoria Land: a review: Terra Antartica, 1, 46-50.
Tonarini, S., Rocchi, S., 1994, Geochronology of Cambro-Ordovician intrusives in northern Victoria Land: a review: Terra Antartica, 1, 46-50.
Torsvik, T.H., 2003. The Rodinia jigsaw puzzle. Science 300, 1379–1381. https://doi.org/10.1126/science.1083469.
Torsvik, T. H., Cocks, L. R. M., 2017, Earth History and Palaeogeography: Cambridge University Press, 317 pp, doi.org/10.1017/9781316225523.
Van Schmus, W.R., McKenna, L.W., Gonzales, D.A., Fetter, A.H., Rowell, A.J., 1997. U-Pb geochronology of parts of the Pensacola, Thiel, and Queen Maud Mountains, Antarctica. In: Ricci, C.A. (Ed.), The Antarctic Region: Geological Evolution and Processes. Terra Antartica Publication, Siena, pp. 187–200.

Vaughan, A.P.M., Storey, B.C., 2007. A new supercontinent self-destruct mechanism: evidence from the late Triassic–early Jurassic: Journal of the Geological Society. London 164, 383–392.
Veevers, J.J., 2004. Gondwanaland from 650–500 Ma assembly through 320 Ma merger in Pangea to 185–100 Ma breakup: supercontinental tectonics via stratigraphy and radiometric dating. Earth Science Reviews 68, 1–132.
Veevers, J.J., Powell, C.M., 1994. Permian-Triassic Pangean Basins and Foldbelts along the Panthalassan Margin of Gondwana. Geological Society of America Memoir, Boulder, p. 368.
Vetter, U., Roland, N.W., Kreuzer, H., Höhndorf, A., Lenz C., H.Besang, 1983. In: Oliver, R.L., James, P.R., Jago, J.B. (Eds.), Geochemistry, petrography and geochronology of the Cambro-Ordovician and Devonian-Carboniferous granitoids of Northern Victoria Land, Antarctica. Antarctic Earth Science: Australian Academy of Science, Canberra, pp. 140–143.
Vignaroli, G., Balsamo, F., Giordano, G., Rossetti, F., Storti, F., 2015. Miocene-to-Quaternary oblique rifting signature in the Western Ross Sea from fault patterns in the McMurdo Volcanic Group, North Victoria Land, Antarctica. Tectonophysics 656, 74–90.
Vogel, M.B., Ireland, T.R., Weaver, S.D., 1999. Geochemistry and Geochronology of the La Gorce Mountains, Central Transantarctic Mountains: *in* Skinner, D. N. B., Ed., 8th International Symposium on Antarctic Earth Sciences Programme and Abstracts. Wellington, Royal Society of New Zealand, p. 311.
Wade, F.A., Cathey, C.A., 1986. Geology of the basement complex, western Queen Maud Mountains, Antarctica: *in* Turner, M. D., and Splettstoesser, J. E., eds., Geology of the Central Transantarctic Mountains, American Geophysical Union. Antarctic Research Series 36, 429–453.
Walker, N.W., Goodge, J.W., 1991. Significance of late Archean - early Proterozoic U-Pb ages of individual Nimrod Group detrital zircons and Cambrian plutonism in the Miller Range. Transantarctic Mountains: Geological Society of America Abstracts with Programs 23, 306.
Wannamaker, P., Hill, G., Stodt, J., Maris, V., Ogawa, Y., Selway, K., Boren, G., Bertrand, E., Uhlmann, D., Ayling, B., Green, A.M., Feucht, D., 2017. Uplift of the central transantarctic mountains. Nature Communications 8, 1588.
Wareham, C.D., Stump, E., Storey, B.C., Millar, I.L., Riley, T.R., 2001. Petrogenesis of the Cambrian Liv Group, a bimodal volcanic rock suite from the Ross orogen, Transantarctic Mountains. Geological Society of America Bulletin 113, 360–372.
Watson, T., Nyblade, A., Wiens, D.A., Anandakrishnan, S., Benoit, M., Shore, P.J., Voigt, D.E., VanDecar, J., 2006. P and S velocity structure of the upper mantle beneath the Transarctic Mountains, East Antarctic craton, and Ross Sea from travel time tomography. Geochemistry, Geophysics, Geosystems 7, Q07005.
Weaver, S.D., Bradshaw, J.D., Laird, M.G., 1984. Geochemistry of Cambrian volcanics of the Bowers Supergroup and implications for early Paleozoic tectonic evolution of northern Victoria Land, Antarctica. Earth and Planetary Science Letters 68, 128–140.
Webb, P.N., Harwood, D.M., McKelvey, B.C., Mercer, J.H., Stott, L.D., 1984. Cenozoic marine sedimentation and ice-volume variation on the East Antarctic Craton. Geology 12, 287–291.
Webb, P.N., Harwood, D.M., Mabin, M.G.C., McKelvey, B.C., 1994. Late. Neogene uplift of the Transantarctic Mountains in the Beardmore Glacier region: Terra Antartica 1, 463–467.
Webb, P.N., Harwood, D.M., Mabin, M.G.C., McKelvey, B.C., 1996. A marine and terrestrial Sirius Group succession, middle Beardmore Glacier-Queen Alexandra Range, Transantarctic Mountains, Antarctica. Marine Micropaleontology 27, 273–297.
Whillans, I.M., Cassidy, W.A., 1983. Catch a falling star: Meteorites and old ice. Science 222, 55–57.
van Wijk, J.W., Lawrence, J.F., Driscoll, N.W., 2008. Formation of the Transantarctic Mountains related to extension of the West Antarctic Rift system. Tectonophysics 458, 117–126.
Wilch, T. I., Panter, K. S., McIntosh, W. C., Dunbar, N. W., Smellie, J. L., Fargo, A., Ross, J., Antibus, J., Scanlan, M., Zimmerer, M., 2011, Miocene evolution of the Minna Bluff Volcanic Complex, Ross Embayment, Antarctica: International Symposium on Antarctic Earth Science XI, Abstract PS5.10, Edinburgh, Scotland.
Will, T.M., Zeh, A., Gerdes, A., Frimmel, H.E., Millar, I.L., Schmädicke, E., 2009. Palaeoproterozoic to Palaeozoic magmatic and metamorphic events in the Shackleton Range, East Antarctica; Constraints from zircon and monazite dating, and implications for the amalgamation of Gondwana. Precambrian Research 172, 25–45.
Williams, S.E., Whittaker, J.M., Halpin, J.A., Müller, R.D., 2019. Australian-Antarctic breakup and seafloor spreading: Balancing geological and geophysical constraints. Earth-Science Reviews 188, 41–58.
Wilson, D.S., Jamieson, S.S.R., Barrett, P.J., Leitchenkov, G., Gohl, K., Larter, R.D., 2012. Antarctic topography at the Eocene–Oligocene boundary. Palaeogeography, Palaeoclimatology, Palaeoecology 335–336, 24–34. https://doi.org/10.1016/j.palaeo.2011.05.028.
Wilson, G.S., Harwood, D.M., Askin, R.A., Levy, R.H., 1998. Late Neogene Sirius Group strata in Reedy Valley, Antarctica: a multiple-resolution record of climate, ice-sheet, and sea-level events. Journal of Glaciology 44, 437–447.
Wilson, G.S., Barron, J.A., Ashworth, A.C., Askin, R.A., Carter, J.A., Curren, M.G., Dalhuisen, D.H., Friedmann, E.I., Fyodorov-Davidov, D.G., Gilichinsky, D.A., Harper, M.A., Harwood, D.M., Hiemstra, J.F., Janecek, T.R., Licht, K.J., Ostroumov, V.E., Powell, R.D., Rivkina, E.M., Rose, S.A., Stroeven, A.P., Stroeven, P., van der Meer, J.J.M., Wizevich, M.C., 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, T.J., 1993. Jurassic faulting and magmatism in the Transantarctic Mountains: Implications for Gondwana breakup, *in* Findlay, R. H., Unrug, R., banks, M. R., Veevers, J. J., eds., Gondwana eight: Assembly, Evolution and Dispersal: Rotterdam. A. A. Balkema 563–572.
Wilson, T.J., 1995. Cenozoic transtension along the Transantarctic Mountains-West Antarctic rift boundary, southern Victoria Land, Antarctica. Tectonics 14, 531–545.
Wilson, T.J., 1999. Cenozoic structural segmentation of the Transantarctic Mountains rift flank in southern Victoria Land. Global and Planetary Change 23, 105–127.
Winberry, J.P., Anandakrishnan, S., 2003. Seismicity and neotectonics of West Antarctica. Geophysical Research Letters 30, GL018001.
Wodzicki, A., Robert Jr., R., 1986. Geology of the Bowers Supergroup, central Bowers Mountains, northern Victoria Land. In: Stump, E. (Ed.), Geological Investigations in Northern Victoria Land: Antarctic Research Series: Washington, D.C.American Geophysical Union, Antarctic Research Series, pp. 39–68
Wodzicki, A., Bradshaw, J.D., Laird, M.G., 1982. Petrology of the Wilson and Robertson Bay groups and Bowers Supergroup, northern Victoria Land, Antarctica. In: Craddock, C. (Ed.), Antarctic Geoscience. University of Wisconsin Press, Madison, pp. 549–554.
Woolfe, K.J., 1990. Trace fossils as paleoenvironmental indicators in the Taylor Group (Devonian) of Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 80, 301–310.
Wörner, G., 1999. Lithospheric dynamics and mantle sources of alkaline magmatism of the Cenozoic West Antarctic Rift system. Global and Planetary Change 23, 61–77.
Wörner, G., Viereck, L., Hertogen, J., Niephaus, H., 1989. The Mt. Melbourne volcanic field (Victoria Land, Antartica); II, Geochemistry and magma genesis: Geologisches Jahrbuch, 38, no. Reihe E: Geophysik 395-433.
Wörner, G., Fricke, A., Burke, E.A.J., 1993. Fluid-inclusion studies on lower crustal gabbroic xenoliths from the Mt. Melbourne volcanic field (Antarctica); evidence for the post-crystallization uplift history during Cenozoic Ross Sea rifting. European Journal of Mineralogy 5, 775–785.
Wysoczanski, R.J., Allibone, A.H., 2004. Age, correlation, and provenance of the Neoproterozoic Skelton Group, Antarctica: Grenvilleage detritus on the margin of East Antarctica. Journal of Geology 112, 401–416.
Wysoczanski, R.J., Forsyth, P.J., Woolfe, K.J., 2003. Zircon dating and provenance of rhyolitic clasts in Beacon conglomerate, southern Victoria Land. Antarctica: Terra Antartica 10, 67–80.
Yakymchuk, C., Brown, C.R., Brown, M., Siddoway, C.S., Fanning, C.M., Korhonen, F.J., 2015. Paleozoic evolution of West Marie Byrd Land, West Antarctica. Geological Society of America Bulletin 127, 1464–1484. https://doi.org/10.1130/B31136.1.
Yamasaki, T., Miura, H., Nogi, Y., 2008. Numerical modeling study on the flexural uplift of the Transantarctic Mountains. Geophysical Journal International 174, 377–390.
Yochelson, E.L., Stump, E., 1977. Discovery of early Cambrian fossils at Taylor Nunatak. Antarctica: Journal of Paleontology 51, 872–875.
Young, G.C., Long, J.A., 2005. Phyllolepid placoderm fish remains from the Devonian Aztec Siltstone, southern Victoria Land, Antarctica. Antarctic Science 17, 387–408.
Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292, 686–693.
Zachos, J.C., Quinn, T.M., Salamy, K., 1996. High resolution (10^4 yr) deep-sea foraminiferal stable isotope time series. Paleoceanography 11, 251–266.
Zavala, K., Leitch, A.M., Fisher, G.W., 2011. Silicic Segregations of the Ferrar Dolerite Sills, Antarctica. Journal of Petrology 52, 1927–1964.
Zhao, G., Cawood, P.A., Wilde, S.A., Sun, M., 2002. Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. Earth-Science Reviews 59, 125–162.
Zhao, G., Sun, M., Wilde, S.A., Li, S., 2004. A Paleo-Mesoproterozoic supercontinent: assembly, growth and breakup. Earth-Science Reviews 67, 91–123.
Zieg, M.J., Marsh, B.D., 2012. Multiple Reinjections and Crystal-Mush Compaction in the Beacon Sill, McMurdo Dry Valleys, Antarctica. Journal of Petrology 53 (12), 2567–2591.

John W. Goodge is a Professor of geology in the Department of Earth and Environmental Sciences at the University of Minnesota Duluth. His research interests are mainly in continental tectonics, metamorphic petrology, structural geology, isotope geochemistry and thermochronology as applied to continental growth during convergent-margin and collisional orogenesis. He has studied the North American Cordillera and Superior Province of Laurentia, and has active research in the Transantarctic Mountains of Antarctica and the subglacial geology of East Antarctica. He has been on 15 research field expeditions to Antarctica between 1985 and 2019, mostly in the central Transantarctic Mountains, where he studies rock exposures, samples glacial deposits, uses geophysical techniques, and is developing a new drilling technology to access rock material beneath the ice sheet.