

Metamorphism in the Ross orogen and its bearing on Gondwana margin tectonics

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ABSTRACT

The Ross orogen of Antarctica is one of Earth's great Phanerozoic mountain belts. It is thought from igneous geochemistry, deformation patterns, and sedimentation history to be the result of late Neoproterozoic and early Paleozoic plate-margin convergence between paleo-Pacific oceanic lithosphere and continental lithosphere represented by the composite East Antarctic shield. Convergence along this margin is contemporaneous with, and tectonically linked to, amalgamation of the Gondwana supercontinent following collapse of former ocean basins and collision along the East African orogen. Although there is general agreement about the large-scale tectonic framework of the Ross orogen, there is a great deal of remaining uncertainty regarding crustal province correlation, deformation kinematics, precise timing, and plate-margin paleogeography. Our uncertainty stems from (1) a fragmentary record left by younger tectonic events that have modified and, in some cases, removed parts of the orogen, and (2) extensive ice cover. Because the basement geology of the Ross orogen is composed largely of metamorphic rocks, however, study of the metamorphic roots of the orogen should help to constrain tectonic setting, thermal structure, tectonic displacements, cooling history, and timing. Evidence in the metamorphic domains reflects 60–100 million years of continental-margin subduction, which is characterized by primary magmatic crustal accretion and low-*P/T* magmatic-arc metamorphism, crustal thickening and high-*P/T* metamorphism due to convergence and oceanic-arc collision, and high-*P/T* metamorphism associated with seaward growth of a plate-margin accretionary system.

Keywords: Antarctica, convergent-margin, orogen, Paleozoic, Transantarctic Mountains.

INTRODUCTION

The Ross orogen of Antarctica forms the basement to the modern Transantarctic Mountains and is one of Earth's great Phanerozoic mountain belts. It is thought from igneous geochemistry, deformation patterns, and sedimentation history to be the result of late Neoproterozoic and early Paleozoic plate-

margin convergence between paleo-Pacific oceanic lithosphere and continental lithosphere represented by the composite East Antarctic shield (Fig. 1; see Goodge, 2002). Convergence along this margin is contemporaneous with, and tectonically linked to, amalgamation of the Gondwana supercontinent following collapse of former ocean basins and collision along the East African orogen (Hoffman, 1991; Goodge, 1997; Fitzsimons, 2000; Veevers, 2000, 2003; Jacobs and Thomas, 2004). Prior to development of a subduction system, the eastern boundary of Gond-

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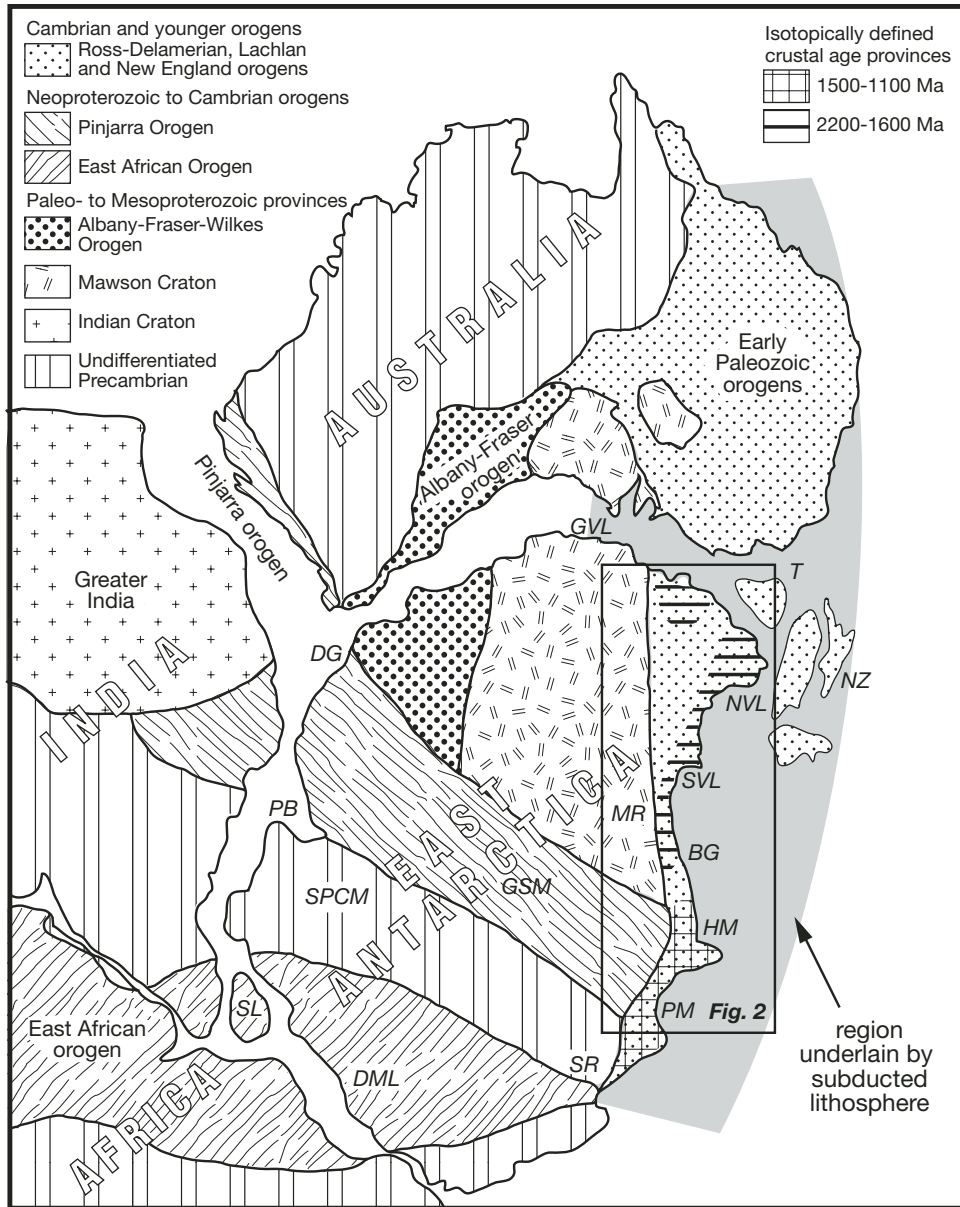


Figure 1. Map of East Antarctica in a Gondwana reconstruction (after Fitzsimons, 2003), showing ages of shields and orogens. Boundaries and extent of provinces in East Antarctic interior are conjectured from coastal outcrops and extrapolation from adjacent shields in Australia, India, and southern Africa. Basement age provinces defined by Nd isotopic data (Borg and DePaolo, 1994; Schüssler et al., 1999) are shown by heavy horizontal ruling and finer grid pattern. Gray region along Pacific margin of Austral-Antarctica shows areas of eastern Gondwana beneath which early Paleozoic lithosphere has subducted; the composite Ross-Delamerian-Lachlan orogens reflect an active accretionary margin at the time of Gondwana amalgamation along the collisional East African and Pinjarra orogens. BG—Beardmore Glacier; DG—Denman Glacier; DML—Dronning Maud Land; GSM—Gamburtsev Subglacial Mountains; GVL—George V Land; HM—Horlick Mountains; MR—Miller Range; NVL—northern Victoria Land; NZ—New Zealand; PB—Prydz Bay; PM—Pensacola Mountains; SL—Sri Lanka; SPCM—southern Prince Charles Mountains; SR—Shackleton Range; SVL—southern Victoria Land; T—Tasmania.

wana constituted a Neoproterozoic rift margin, now marked by marginal-marine deposits in eastern Australia and the Transantarctic Mountains of Antarctica. Archean and Proterozoic continental shield rocks are inferred to underlie the rift successions, as known from a few scattered occurrences and from potential-field geophysical surveys. This older shield basement thus formed a relatively rigid lithospheric backstop against which plate convergence was initiated. The resulting active margin in latest Neoproterozoic and early Paleozoic time was an Andean-style convergent continental margin, marked generally by calc-alkaline arc magmatism, tectonic shortening, metamorphism, and forearc sedimentation. Tectonic processes attributed to the Ross orogeny affected the former rift-margin sedimentary-volcanic successions as well as their underlying crystalline basement.

Although there is general agreement about the large-scale tectonic framework of the Ross orogen, there is a great deal of remaining uncertainty regarding crustal province correlation, deformation kinematics, precise timing, and plate-margin paleogeography. Major impediments to a clear understanding of the Ross history and orogenic processes include (1) poor rock exposure and difficult logistical access within the orogen, (2) inadequate knowledge of the adjacent shield provinces due to coverage by the polar ice cap, (3) a lack of high-quality mineral thermochronology in many areas, making it difficult to compare diachronous events and assess tectonic rates, and (4) incomplete preservation of tectonic elements intrinsic to plate-margin subduction, such as blueschists. Thus, it is difficult to reconstruct tectonic geometries within the orogen, the ages of events, and, perhaps most importantly, the rates of geological processes. Key questions that remain include

- Are there any direct lithologic remnants of the subduction process?
- How did basement and cover behave mechanically?
- What are the relative roles of translational versus vertical displacements in accommodating plate-margin strain?
- Are there true allochthonous materials, and if so, were they added by accretionary or collisional process?
- How quickly were the basement rocks exhumed, and what do the denudation rates tell us about tectonic process?
- What evidence, if any, exists for extensional collapse of the orogen?

In this paper, I will address these questions by reviewing what we know about metamorphism in the Ross orogen and the constraints that contrasting metamorphic patterns place on overall tectonic evolution of the active Gondwana margin. Most, if not all, of the questions listed above may not be answerable at present, but they help point the way to future research. I focus on three areas that have received the most attention in terms of their metamorphic petrology: northern Victoria Land, southern Victoria Land, and the central Transantarctic Mountains. In order to address issues of convergence mode, magnitude of crustal thickening, role of magmatism, and rates of unroofing, I provide a

synopsis of P - T regime, P - T - t paths, and geochronologically constrained exhumation rates. Because my direct experience with the Ross orogen comes mostly from study in the central Transantarctic Mountains, the geology of this region strongly influences my emphasis and understanding. I draw heavily on the published findings of many other workers, to whom I apologize for my own errors in interpretation.

TECTONIC SETTING AND TIMING OF ACTIVE GONDWANA MARGIN

East Antarctica is a critical cratonic keystone in most reconstructions of Rodinia and Gondwana. It has a long association with eastern Gondwana cratonic neighbors in present-day Australia, India, and southern Africa, which were eventually amalgamated along Grenville-age sutures during assembly of Rodinia (Fig. 1; see Fitzsimons, 2000, for a recent review). Neoproterozoic breakup of Rodinia resulted in formation of a rifted margin along the paleo-Pacific sector of Australia and East Antarctica, characterized by passive-margin subsidence, sedimentation, and minor volcanism (Laird, 1991; Stump, 1995; Preiss, 2000; Goodge et al., 2002). By the latest Neoproterozoic to Early Cambrian, the rift margin underwent major tectonic transformation to an active, subducting plate boundary, probably as a result of changes in global plate motions and plate-boundary stresses, coupled with closure of the East African orogen (Flöttmann et al., 1994; Goodge, 1997; Jacobs et al., 1998; Jacobs and Thomas, 2004). Figure 1 shows the broad region of the Austral-Antarctic continental margin inferred to have overridden paleo-Pacific oceanic lithosphere.

The latest Neoproterozoic to early Paleozoic Ross orogen in this context reflects convergent-margin activity associated temporally, and perhaps causally, with the consolidation of Gondwana (Goodge, 2002). Here, the present-day Transantarctic Mountains (Fig. 2) are underlain by Archean and Proterozoic cratonic basement, upper Proterozoic and lower Paleozoic marginal-basin assemblages, and an early Paleozoic oceanic-arc remnant, all affected by deformation attributed to plate-margin convergence and engulfed by an early Paleozoic 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 (Fig. 3). As geochronological constraints improve, a detailed sequence of events is emerging that spans at least the period 550–480 Ma. Subregions of the orogen differ in detail, but the active continental margin witnessed rift-basin inversion, carbonate sedimentation, clastic molasse-type sedimentation, bimodal and calc-alkaline magmatism, regionally diachronous volcanism, high-grade basement reactivation, arc collision, and transpressional deformation partitioned between basement and supracrustal assemblages. 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. The location, scale, and geochemical characteristics of the Ross magmatic

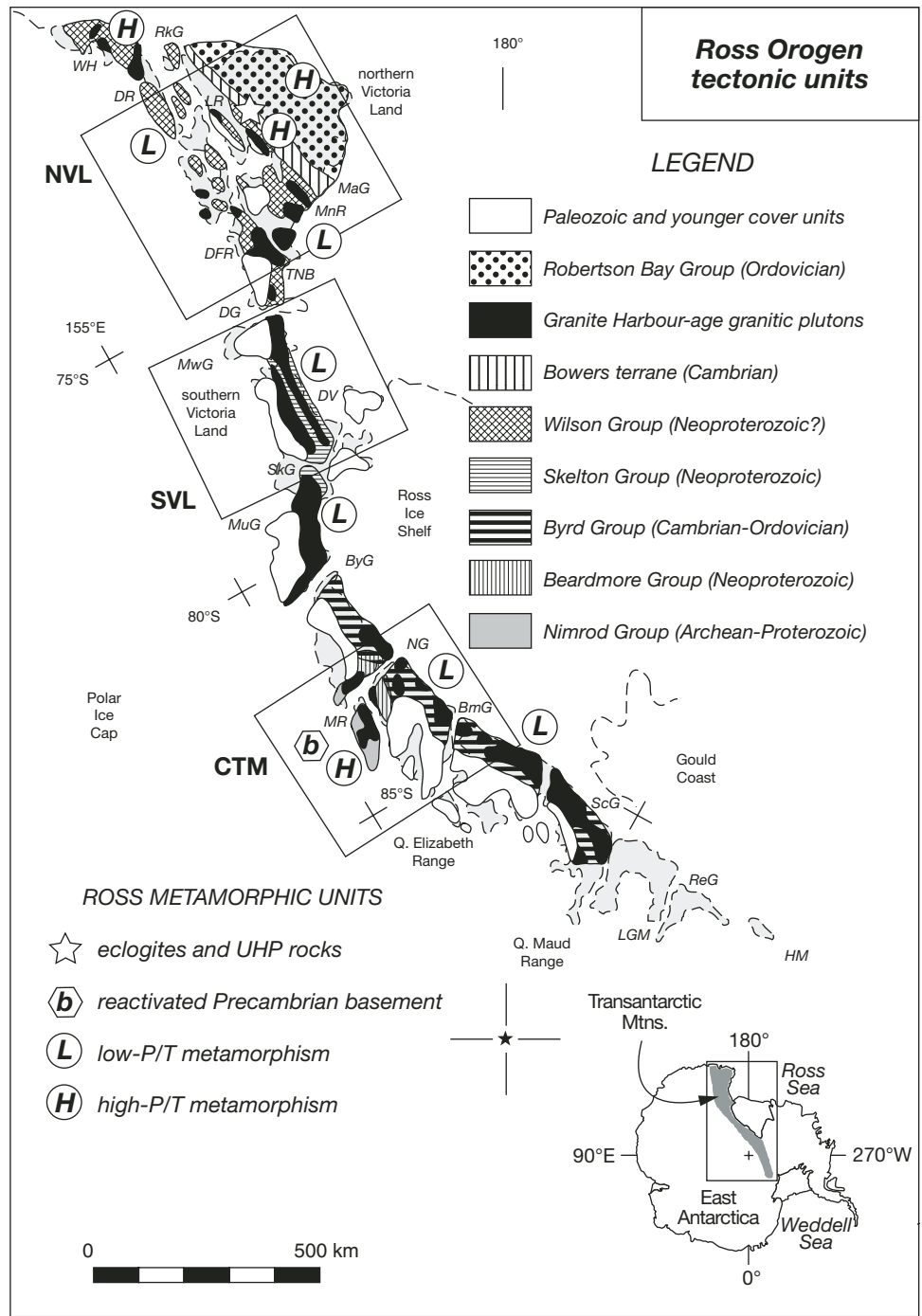


Figure 2. Simplified geologic map of the Ross orogen underlying the modern Transantarctic Mountains, showing major tectonic units affected by the Ross orogeny. Shown on a present-day geographic base with no palinspastic restoration; possibly correlative rock sequences from Marie Byrd Land are omitted because of limited outcrop and uncertainty about their pre-Jurassic paleogeography. Postorogenic Admiralty intrusives are not shown. Symbols indicate major type of metamorphism in different regions, as well as areas where Precambrian basement was reactivated. In many areas, Ross metamorphism is of low-*P/T* type, concomitant with syn- to late-tectonic granitoid generation, but areas of significant contraction in northern Victoria Land (Lanternman Range) and Queen Elizabeth Range (Miller Range) show high-*P/T* to UHP metamorphism. BmG—Beardmore Glacier; ByG—Byrd Glacier; CTM—central Transantarctic Mountains; DFR—Deep Freeze Range; DG—David Glacier; DR—Daniels Range; DV—Dry Valleys; HM—Horlick Mountains; LGM—La Gorce Mountains; LR—Lanternman Range; MaG—Mariner Glacier; MnR—Mountaineer Range; MR—Miller Range; MuG—Muluck Glacier; MwG—Mawson Glacier; NG—Nimrod Glacier; NR—Neptune Range; NVL—northern Victoria Land; PR—Patuxent Range; ReG—Reedy Glacier; RkG—Rennick Glacier; ScG—Scott Glacier; SkG—Skelton Glacier; SVL—southern Victoria Land; TNB—Terra Nova Bay; WH—Wilson Hills.

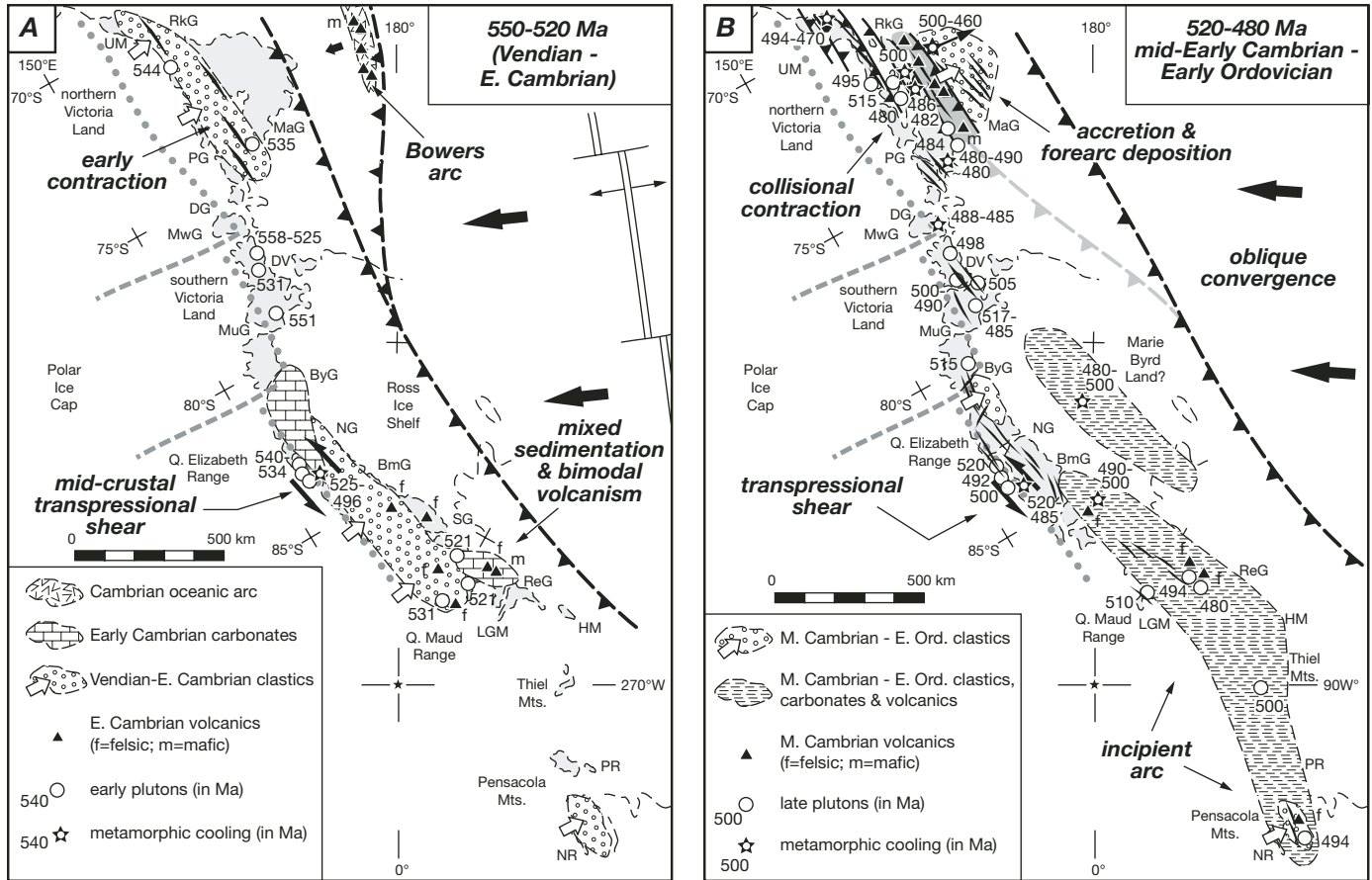


Figure 3. Principal geologic features and postulated tectonic relations during two main phases of the Ross orogeny. Geographic base as in Figure 2. Shown here are U-Pb zircon ages for plutons, and metamorphic cooling ages determined by U-Pb (monazite, sphene, zircon) and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology. Further discussion of crystallization and cooling ages in Goodge (2002). (A) Early Ross events between 550 and 520 Ma (Vendian–Early Cambrian). Northern and central segments of the Ross orogen experienced early contraction and transpression during this time, but southern segments were dominated by continued sedimentation and volcanism. Paleo-Pacific spreading ridge is diagrammatic to illustrate possible oblique convergence, but it was probably farther offshore than shown here. (B) Late Ross events between 520 and 480 Ma (middle Early Cambrian–Early Ordovician). Deformation in northern Victoria Land is dominated by contraction as a result of arc and forearc accretion; central segments of the orogen were characterized by continued transpression in crystalline basement and contraction in the supracrustal assemblages. Southern segments of orogen witnessed incipient plutonism, continued volcanism, and complex carbonate and siliciclastic deposition. Abbreviations as for Figure 2 except PG—Priestley Glacier, SG—Shackleton, and UM—USARP Mountains.

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. Some key aspects of the Ross events in Antarctica are outlined in the following paragraphs.

The convergent plate-boundary setting of the Ross orogen produced a volumetrically prolific continental-margin magmatic arc constructed upon Archean-Proterozoic basement (Borg et al., 1987, 1990; Armienti et al., 1990; Allibone et al., 1993a, 1993b; Borg and DePaolo, 1994; Rocchi et al., 1998). Calc-alkaline magmatism indicates that subduction was initiated by at least 550–530 Ma (e.g., Rowell et al., 1993; Goodge et al., 1993b; Cox et al., 2000; Allibone and Wysoczanski, 2002), yet detrital zircon

geochronology from lower Paleozoic sandstones containing arc-derived detritus suggests that volumetrically significant magmatism occurred as early as ca. 580–560 Ma (Ireland et al., 1998; Goodge et al., 2002, 2004a; Wysoczanski and Allibone, 2004). Regional isotopic and geochemical variations in granitoid rocks reveal increasing crustal components toward the craton (to the west¹), best explained by subduction-generated melting beneath an east-facing continental-margin arc. The magmatic series of

¹Geographic reference in this paper to the Antarctic continent follows the convention that E = 90° and W = 270° relative to the Greenwich (UK) meridian. This convention applies here in reference to the East and West Antarctica. However, with respect to the regional occurrences discussed here, many publications concerning the Ross Orogen refer to local north as in a direction toward East Antarctica. Therefore, regional north in the map figures is approximately along the 160°E meridian.

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). The resulting thermal effects of Ross-age magmatism on basement assemblages of the Transantarctic Mountains are well known (e.g., Adams et al., 1982), suggesting that regional advective heating has greatly affected older wall-rock metamorphic assemblages. Magmatism was concomitant with tectonic deformation (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), 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; Jones, 1997; Musumeci, 1999).

Tectonism attributed to the Ross orogeny is widely expressed by structural shortening of upper Neoproterozoic marginal-basin strata and platform carbonate 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, nonorthogonal 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. Nonorthogonal 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 convergent-margin transpression. 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 addition to the igneous and structural fingerprints of Gondwana margin activity described in the previous paragraph, a profusion of recent metamorphic studies provides an improved understanding of continental-margin activity. A review of Ross orogen metamorphism and its implications for thermal structure, exhumation history, and tectonic process are treated in the following section. Since the early 1990s, numerous studies have examined the character and history of the metamorphic belt. Of the many excellent studies undertaken, only a few are highlighted here.

ROSS METAMORPHISM

Here I consider the salient features associated with Ross orogen metamorphism by focusing on three regions that have received most attention—northern Victoria Land, southern Victoria Land, and the central Transantarctic Mountains. For each area, I review key rock types, mineral assemblages, and age rela-

tions where available. I then compare the three areas in terms of their *P-T-t* histories in order to identify common metamorphic paths and important petrotectonic relations.

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 contrast significantly with other parts of the orogen. Northern Victoria Land is underlain by three major tectonic elements (see Stump, 1995, and references therein), from west to east: (1) the Wilson Group, composed of Precambrian(?)–lower Paleozoic medium- to high-grade quartzofeldspathic schists, gneisses, and migmatites; (2) the Bowers terrane, consisting of Middle Cambrian to Lower Ordovician oceanic volcanic and clastic marine sedimentary rocks; and (3) the Robertson Bay Group, dominated by Upper Cambrian to Lower Ordovician turbiditic marine clastic rocks. The terranes are variably deformed, and regionally they host two syn- to posttectonic plutonic suites (Borg et al., 1987; Kreuzer et al., 1987; Sheraton et al., 1987; Black and Sheraton, 1990; Tonarini and Rocchi, 1994) (Fig. 2). 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 Devonian-Carboniferous I-type granitoids occur to the east (Admiralty intrusives). The presence of map-scale contractional structures, discontinuities between different metamorphic baric types, and early to middle Paleozoic plutonic suites are all indicative of a convergent-margin tectonic setting in the late 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, 1991; Dallmeyer and Wright, 1992; Goodge and Dallmeyer, 1996; Ricci et al., 1997; Schüssler et al., 1999). Some workers have also stressed the role of strike-slip tectonics (Weaver et al., 1984) or proposed the accretion of allochthonous terranes (Bradshaw et al., 1985). Talarico et al. (2004) provide a recent synopsis of regional metamorphism 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 west from medium- to high-*P/T* schists and gneisses to the east in the Lanterman, Salamander, and Mountaineer Ranges (Grew et al., 1984; Kleinschmidt and Tessensohn, 1987). 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 west of high-*T* granulites and migmatites (Lombardo et al., 1987; Castelli et al., 1991). Wilson Group gneisses are sepa-

rated 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 these zones are controversial. In northern Victoria Land, the Ross orogeny resulted in (1) pronounced folding of Lower Ordovician rocks in the Bowers and Robertson Bay terranes (Bradshaw et al., 1985; Gibson and Wright, 1985), (2) diachronous cleavage development within the Robertson Bay Group (Dallmeyer and Wright, 1992), and (3) ductile thrusting of Wilson Group metamorphic rocks (Kleinschmidt and Tessensohn, 1987; Flöttmann and Kleinschmidt, 1991; Schüssler et al., 1999).

Different tectonic models have been invoked to explain these early Paleozoic structural and petrologic patterns, all involving some manifestation of plate convergence. Kleinschmidt and Tessensohn (1987) recognized the importance of linking tectonic units to one another by geologic process and history in a convergent setting. By integrating deformation, magmatic, and sedimentation patterns, they suggested that convergence and crustal shortening were related to eastward accretionary growth of the Ross margin, the progressive timing of which was confirmed by Dallmeyer and Wright (1992). The framework for this part of the orogen explained metamorphic zonations and temporal variations among syn- and posttectonic 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, within both 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, 1991, 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 in individual areas that reflect different regimes within a convergent system (Ricci et al., 1997; Talarico et al., 2004), as summarized in the sections below.

Grew et al. (1984) first recognized contrasting patterns of metamorphism in northern Victoria Land by comparing basement rocks from the cratonward Wilson Group. This extensive metamorphic terrane is characterized to the west by andalusite + cordierite + muscovite, indicative of pervasive thermal (i.e., low-*P/T*) metamorphism, whereas outboard rocks to the east contain relict kyanite + staurolite, reflecting early metamorphism at moderate to high pressure. Most areas show late stabilization of sillimanite, but the inferred metamorphic *P-T* gradients contrast sharply from west to east. The immediate consequence of this benchmark study was recognition of zonal asymmetry centered on the orogen axis, similar to the paired-belt metamorphism characterizing many circum-Pacific regions (Ernst and

Seki, 1967; Miyashiro, 1967; Ernst et al., 1970). Subsequent studies in northern Victoria Land highlighted important distinctions within this overall framework, including evidence of preserved polymetamorphism, low-*P* granulites and migmatites, high-*P* eclogites and UHP (ultrahigh-pressure) relicts, and low-grade accretionary-complex metamorphism (Buggisch and Kleinschmidt, 1991).

Polymetamorphic Areas

Polymetamorphism reflecting early medium-*P* events overprinted by a lower-*P* stage is recognized principally in three areas of the eastern Wilson Group: the Lanterman, Mountaineer, and Daniels Ranges. In one of the first known examples, Mg-staurolite + talc relicts within pelitic units of the Lanterman Range indicate early medium-*P/T* conditions of 650–750 °C and 8–10 kbar (Grew and Sandiford, 1984), followed by a later stage of isothermal decompression to ~6 kbar. A third stage is marked by a distinctive margarite-Mg-pumpellyite assemblage indicating late-stage conditions of 300–400 °C and further decompression to ~4 kbar. In the Mountaineer Range along the boundary with the Bowers terrane, higher-grade conditions up to 750 °C and 6–7 kbar were found (Castelli et al., 1994), reflecting a similar *P-T* trajectory. In both cases, moderate-*P/T* conditions and strong ductile shortening suggest the importance of crustal thickening in this central axis of the orogen. Detailed petrologic and geochronologic study in exposures of the Daniels Range and Wilson Hills (Schüssler et al., 1999) indicate very high-grade granulite-facies rocks marked by cordierite-biotite-sillimanite-spinel assemblages in pelitic gneisses and relicts of orthopyroxene + garnet + clinopyroxene in mafic migmatites. Thermobarometry yielded conditions of ~800 °C and 8 kbar for this early M1 event, followed by lower-*P* conditions near the granulite- to amphibolite-facies transition of 700 °C and 4–5.5 kbar during continued reaction to form new cordierite (M2). Together, these examples from the outboard Wilson Group record polymetamorphic events related to early medium-*P* stages overprinted by younger low-*P* parageneses. Similar cryptic relicts of early medium-*P* metamorphism may be locally preserved in the southwestern Wilson terrane, as noted in the section below on eclogites.

Although polymetamorphism can lead to geochronological ambiguity, petrographic and mineral reaction relations indicate that the early medium-*P* parageneses are indeed related to Ross tectonism. To date the age of low-*P* amphibolite- to granulite-facies recrystallization in the Wilson Hills, for example, Schüssler et al. (1999) obtained U-Pb ages of 494–484 Ma from metamorphic monazites, constraining this stage to the Ross time frame. Biotite ⁴⁰Ar/³⁹Ar ages of 476–470 Ma suggest a rapid late- to postmetamorphic cooling history. In the Lanterman Range, U-Pb ages of metamorphic monazite and sphene (Goodge et al., 1995) and ⁴⁰Ar/³⁹Ar cooling ages from synkinematic hornblende and muscovite (Goodge and Dallmeyer, 1996) constrain at least the high-*T* decompression stage to ca. 500–480 Ma. Additional domain-scale mineral thermochronology is needed to better clarify the age of early medium-*P* events in this region.

Low-*P/T* Granulites and Migmatites

In the western Wilson Group, by contrast, particularly in the areas of Terra Nova Bay and the Deep Freeze Range, metamorphism is typically of 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, in some cases 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 the 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 grades achieved conditions of ~700–750 °C at ~4.5 kbar, reflecting a geothermal gradient of 45–55 °C/km. There are not many geochronological data from this region, but U-Pb ages for zircon, monazite, and titanite constrain the timing of amphibolite-facies metamorphism in the Terra Nova Bay area to 490–480 Ma (Klee et al., 1990). Associations with syn- and posttectonic granitoids also link this metamorphic stage to Ross events.

In addition to the well-characterized monometamorphic progression, some detailed studies distinguish a cryptic earlier metamorphic event preserved as granulite-facies relicts (Lombardo et al., 1987; Castelli et al., 1991). Concentrated in the Deep Freeze Range, amphibolite-facies metasedimentary gneisses contain lozenges and larger mappable bodies of felsic and mafic granulite (Talarico and Castelli, 1995). The felsic rocks there 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. Elsewhere within a tonalite roof pendant, Borghi and Lombardo (1994) found relicts of orthopyroxene + garnet + sillimanite + spinel + cordierite that record conditions of ~850 °C and 9 kbar; these granulite-facies rocks are overprinted by a lower-grade mineral assemblage reflecting conditions of ~700 °C and 4 kbar. Incomplete preservation of the relict granulites in northern Victoria Land makes geochronology problematic, but Sm-Nd model ages of 2.2–1.8 Ga for rocks in the Terra Nova Bay area indicate their protoliths could be Proterozoic in age and that the granulite-forming stage may in fact be a pre-Ross metamorphism (Talarico et al., 1995).

Eclogites and UHP Rocks

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. Recent studies identified eclogitic and coesite-bearing parageneses indicative of high- and ultrahigh-pressure (UHP) metamorphism (Di Vincenzo et al., 1997; Palmeri et al., 2003). Eclogitic blocks in this zone record three stages of recrystallization (Di Vincenzo et al., 1997), beginning with early eclogite formation followed by two stages of lower-*P* amphibolite-facies retrogression. The eclogitic blocks show variable preservation, but the least retrogressed of these contain omphacite + garnet + rutile. The compositions of garnet and clinopyroxene indicate conditions of 720–850 °C at ≥15 kbar during eclogite formation, followed by retrogression to conditions of 600 °C at ~5 kbar. Sm-Nd isochron ages of 500 ± 5 and 492 ± 3 Ma date the eclogite-forming event as part of the Ross orogeny, followed by rapid near-isothermal decompression. The geological setting of these blocks along the Wilson-Bowers contact zone and their geochemical composition suggest rapid exhumation of mantle material involved in subduction-accretion. Eclogitic rocks in a similar context occur elsewhere in the Ross orogen (see Peacock and Goodge, 1995; Goodge et al., 2001), but unlike the Lanterman Range examples, they equilibrated at ca. 1.7 Ga during the Paleoproterozoic Nimrod orogeny.

Further study shows that high-*P* mineral assemblages also occur in the host gneisses of the Lanterman Range, which show complex interlayering of mafic eclogite and felsic gneiss containing relict high-Mg garnet + phengite (Palmeri et al., 2003). Garnet in these gneisses contains inclusions of paragonite and phengite, and shows radial fractures around quartz pseudomorphs after coesite (Ghiribelli et al., 2002). Symplectites replacing the garnet-phengite assemblage formed during medium-*P* amphibolite-facies retrogression. Peak conditions for the coesite-bearing gneisses of ~700–750 °C and ≥26 kbar were attained along a very steep prograde *P-T* trajectory, followed by extreme decompression to pressures of ≤10 kbar during later amphibolite-facies retrogression. UHP conditions are thought to have occurred during the eclogite-forming stage ca. 500 Ma, and the retrogressive events are dated by white mica cooling ages of ca. 480 Ma (Di Vincenzo and Palmeri, 2001). The Lanterman Range gneisses are the first reported occurrence of coesite-bearing UHP rocks in the Ross orogen, and attest to the substantial crustal thickening associated with collision along the Wilson-Bowers terrane boundary. Palmeri et al. (2003) attribute the eclogite-forming and subsequent rapid decompression stages to arc collision.

Low-Grade Accretionary Assemblages

Siliciclastic sedimentary rocks of the Robertson Bay Group are characteristically of low metamorphic grade, varying from subgreenschist to greenschist facies (Kleinschmidt et al., 1991). However, a monotonous mineral paragenesis of muscovite + albite ± clinozoisite belies their importance in a petrotectonic context. White mica *b* lattice spacings indicate intermediate-*P* conditions

along a thermal gradient of ~ 15 °C/km, with temperatures not exceeding ~ 400 °C (Buggisch and Kleinschmidt, 1991; Kleinschmidt et al., 1991). This corresponds to maximum pressures of ~ 8 kbar, suggesting substantial structural thickening within the turbiditic assemblage associated with plate-margin convergence. Dallmeyer and Wright (1992) reported a series of diachronous $^{40}\text{Ar}/^{39}\text{Ar}$ ages from slates in the Robertson Bay assemblage, younging from west to east between 500 and 460 Ma, which reflect progressive neoblastic mica formation during oceanward growth of the margin and thickening of the sedimentary cover.

Southern Victoria Land

Metasedimentary rocks in southern Victoria Land make up a highly complex, polydeformed metamorphic terrane inundated by magmatic rocks. The metamorphic rocks predate 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 (Findlay et al., 1984; Stump, 1995). Nonetheless, siliciclastic and calcareous rocks in this assemblage are thought to represent late Neoproterozoic and early Paleozoic continental-margin deposits (Laird, 1991), and they correlate generally with rift-margin supracrustal successions elsewhere in the Transantarctic Mountains. Pregranitic 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). Initial division of the two groups was based on apparent differences in metamorphic grade, but Wysoczanski and Allibone (2004) suggested placing them all in the Skelton Group based on detrital mineral age data showing that the two metasedimentary assemblages have a similar provenance. The Skelton deposits are younger than 950–1050 Ma, based on their detrital zircon ages, and crosscutting pluton ages indicate that northern and southern parts of the group have minimum depositional ages of ca. 535 and ca. 551 Ma, respectively (Rowell et al., 1993; Encarnación and Grunow, 1996; Cooper et al., 1997; Read and Cooper, 1999; Read et al., 2002).

Metamorphic grade in pregranitic rocks of southern Victoria Land ranges from upper-amphibolite facies in the northern area of the Dry Valleys, to greenschist facies farther south near Skelton Glacier (Grindley and Warren, 1964; Findlay et al., 1984). Koettlitz Glacier marks the boundary between high- and low-grade zones, suggesting it overlies an important regional structural boundary (Cook and Craw, 2001). Mineral assemblages in high-grade pelitic rocks from the Dry Valleys indicate upper-amphibolite-facies metamorphism, at or near granite minimum-melt conditions. Critical assemblages include quartz-sillimanite-cordierite-biotite-garnet-K-feldspar (\pm andalusite), muscovite-K-feldspar-quartz-plagioclase-biotite, and quartz-K-feldspar-garnet-biotite-plagioclase (\pm sillimanite) (Allibone, 1992; Cox, 1992). Many of these occurrences are associated with anatectic migmatites,

reflecting conditions sufficient for partial melting. The presence of relict andalusite within sillimanite-zone rocks suggests a low- P/T prograde trajectory, and sillimanite + cordierite reflects moderate- P peak conditions. A preponderance of syn- to postkinematic granitic intrusions makes it difficult to assess the retrograde conditions (e.g., Cox, 1993; Allibone and Norris, 1992), although late-orogenic shear zones are associated with greenschist-facies mineral assemblages of unknown thermobaric type.

Mineral assemblages in a variety of rock types from the main Dry Valleys area indicate peak metamorphic conditions in the upper-amphibolite facies at moderate pressures; peak conditions farther south apparently reached only greenschist facies (Findlay et al., 1984). Cox (1992) estimated peak metamorphic temperatures in metasedimentary rocks of Wright Valley in southern Victoria Land to be 700–750 °C and ~ 5 kbar. Garnets in a variety of siliceous metasedimentary protoliths and migmatite melanosomes are weakly zoned to homogeneous in composition, providing evidence for high- T homogenization at peak conditions. Similar conditions of 650–750 °C at 4–6 kbar were obtained for schists in the Taylor Valley area (Allibone, 1992), consistent with widespread evidence of synchronous partial melting.

A general lack of mineral chronometers applied to metamorphic rocks of southern Victoria Land precludes evaluation of orogenic cooling rates and, in turn, tectonic exhumation rates. Previously published K-Ar age results do not provide adequate constraint on the timing of metamorphic mineral development, and there is a notable paucity of $^{40}\text{Ar}/^{39}\text{Ar}$ ages reported for metamorphic rocks of this region. SHRIMP (sensitive high-resolution ion microprobe) U-Pb ages for metamorphic rims on detrital zircons in amphibolite-facies metasedimentary rocks of the northern Skelton Group suggest high- T recrystallization between ca. 500 and 495 Ma (Wysoczanski and Allibone, 2004). One sample described as leucogranite is thought to be the product of local anatexis; it contains highly metamict zircon cores with outer rims that yielded a U-Pb age of 494 ± 7 Ma. This is the best estimate for the age of peak metamorphism and partial melting in the region, although there are no known constraints on the subsequent rate of cooling.

Central Transantarctic Mountains

Basement Complex

The central Transantarctic Mountains is the only section of the Ross orogen where crystalline basement rocks of the East Antarctic shield are exposed. High-grade, penetratively deformed metamorphic and igneous rocks of the Nimrod Group, well exposed in the Miller and Geologists Ranges, provide ample isotopic and geochronologic evidence of their Archean and Paleoproterozoic ancestry (Borg et al., 1990; Goodge and Fanning, 1999; Goodge et al., 2001). Showing a strong thermomechanical imprint by the Ross orogeny (Goodge et al., 1991, 1993a, 1993b; Goodge and Dallmeyer, 1992, 1996), the Nimrod Group therefore provides the best opportunity to assess the role of basement reactivation during Ross events.

Nimrod Group metasedimentary and metaplutonic lithologies include upper-amphibolite- to lower-granulite-facies inter-layered 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 (Grindley et al., 1964; Grindley, 1972; Goodge et al., 1991, 1993a; Peacock and Goodge, 1995). Medium- to high- P/T kyanite-zone mineral assemblages are widespread within the Nimrod Group, reflecting exposure of relatively deep crustal levels in this part of the Transantarctic Mountains (Grindley, 1972; Goodge et al., 1992). Initial studies suggested that the Nimrod Group was deformed only during a Precambrian high-grade metamorphic event (Nimrod orogeny of Grindley and Laird, 1969) that did not affect the younger sedimentary units. Subsequent structural, petrological, and thermochronological studies have resolved geological events at ca. 3.0, 2.5, 1.7 and 0.5 Ga, the latter corresponding to the Ross orogeny, discussed here. Pre-Ross events affecting the Nimrod Group include Archean and Paleoproterozoic magmatism and deep-crustal granulite- to eclogite-facies metamorphism (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). Although the age of these high- P relicts was initially uncertain, metamorphic zircons yielded ages of ca. 1.7 Ga (Goodge et al., 2001), thus indicating that these Paleoproterozoic mineral parageneses are not linked to Ross activity.

Ductile L-S tectonite fabrics and folds of Ross age are pervasive in the Nimrod Group, and kinematic features at all scales record top-to-the-SE (local coordinates) displacement through a minimum structural thickness of 12–15 km. Shear fabrics in the Nimrod basement are 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. A host of mineral chronometers constrain the age of peak igneous activity, deformation, metamorphism, and cooling through the Ross orogenic cycle between ca. 540 and 485 Ma (Goodge and Dallmeyer, 1992, 1996; Goodge et al., 1993b, 2001; Goodge and Fanning, 1999; C.M. Fanning, 2005, personal commun.), permitting differentiation of Ross from older events and an assessment of basement reactivation during plate-margin orogenesis. High-grade Ross metamorphism and deformation are constrained to ca. 525 Ma, based on U-Pb dating of synkinematic monazite in pelitic schists (Goodge et al., 1993b). The effect of Ross-age dynamothermal activity on the basement 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 544–521 Ma (Goodge and Fanning, 1999; Goodge et al., 2001). A compositionally diverse suite of igneous rocks that show variable development of solid-state deformation fabrics intrudes Nimrod Group metamorphic tectonites; these include

tonalite, diorite, and granodiorite with U-Pb zircon ages that range from 541 to 515 Ma (Walker and Goodge, 1991; Goodge et al., 1993b). 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 postorogenic cooling between ca. 525 and 485 Ma (Goodge and Dallmeyer, 1992, 1996).

The main phase of Ross metamorphism in the Nimrod Group occurred under moderate- P , high- T metamorphic conditions ($P = 8\text{--}12$ kbar; $T = 650\text{--}750$ °C) in the upper-amphibolite to lower-granulite facies, as shown by synkinematic kyanite + garnet + muscovite + biotite + quartz in pelites, hornblende + plagioclase ± garnet ± clinopyroxene ± clinozoisite in mafic rocks, and by thermobarometry (Goodge et al., 1992; Goodge and Dallmeyer, 1996). Inclusions of staurolite and kyanite in garnet indicate a prograde P - T path across the kyanite stability field, and late synkinematic 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 postkinematic Ross metamorphism is only locally displayed within narrow thermal aureoles of the ca. 500 Ma posttectonic plutons. In these areas, Nimrod 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 $P \leq 5$ kbar and $T \leq 550$ °C.

Supracrustal Assemblages

Outboard (to the east) of the Nimrod basement lie low-grade siliciclastic and calcareous rocks of the Beardmore and Byrd Groups (see Myrow et al., 2002, for a summary). The lower sedimentary succession includes upper Neoproterozoic to Lower Cambrian rift- to passive-margin deposits (Beardmore and lower Byrd Groups, respectively; Goodge et al., 2002), overlain by widespread molasse deposits that record deep erosion of the Ross orogen and exhumation of the igneous and metamorphic basement (upper Byrd Group; Goodge et al., 2004b). As elsewhere, igneous rocks of the Granite Harbour series intruded the supracrustal assemblages between ca. 540 and 480 Ma (Borg et al., 1990; Goodge et al., 2004a).

In the supracrustal units, siliciclastic and calcareous rocks are characterized by subgreenschist- to greenschist-facies regional metamorphic assemblages, including chlorite + muscovite ± biotite in pelites and albite + epidote + calcite in calcareous rocks. 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, though not well documented, reflect regional greenschist-facies condi-

tions 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 synorogenic deposits constrains the age of late Ross metamorphism in the supracrustal assemblages (Goodge et al., 2004a). ⁴⁰Ar/³⁹Ar ages for metamorphic biotite and slate suggest regional metamorphism between ca. 490 and 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 Nimrod Group basement, 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* Evolution and Exhumation Record**

A summary of *P-T* paths for metamorphic assemblages in northern Victoria Land, southern Victoria Land, and the central Transantarctic Mountains is shown in Figure 4. In most cases, these paths are taken directly from published sources (essentially all those shown for northern Victoria Land and the central Transantarctic Mountains), but in some cases they are inferred here based on reported *P-T* data along with petrogenetic and mineral reaction indicators for prograde and retrograde sequence. Estimates of prograde, peak, and retrograde conditions are omitted for clarity; the reader is referred to the listed sources. Also shown in Figure 4 are timing constraints provided by individual mineral chronometers in order to compare metamorphic ages and estimate cooling rates.

By comparing the *P-T* paths shown in the four panels of Figure 4, it is clear 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 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 translation. The significance of the metamorphic paths in each of these areas is discussed separately below.

Northern Victoria Land

Polymetamorphic basement complexes such as in the Wilson Hills and Daniels Range areas along the Oates Coast (OC in Fig. 4A) contain mineral assemblages reflecting upper-amphibolite to granulite-facies conditions at moderate pressures (Schüssler et al., 1999). Mineral chemistry and reaction histories are interpreted as evidence of cooling and decompression along a moderate geotherm. A similar *P-T* path is inferred for outcrops in the Lanterman Range (LR) and granulite relicts at Gerlache Inlet (GI) in the area of Terra Nova Bay (Borghi and Lombardo, 1994; Goodge and Dallmeyer, 1996). Rocks from this eastern outboard part of the Wilson Group thus indicate early thickening along a high-*P/T* path to moderate-*P* conditions, followed by clockwise decompression and cooling indicative of erosionally controlled exhumation. The record of thickening and decompression is compatible with structural evidence of basement shortening followed by late-stage extension (Roland et al., 1984; Flöttmann and Kleinschmidt, 1991, 1993; Kleinschmidt and Brommer, 1997). Dating of high-*T* minerals in the Oates Coast area indicates peak to postpeak timing of ca. 495–480 Ma (Schüssler et al., 1999), corresponding to a cooling rate of 18–25 °C/m.y. (Table 1). Similar syn- to post-metamorphic cooling rates of ~30 °C/m.y. were deduced for the Lanterman complex (Goodge and Dallmeyer, 1996).

Mafic tectonic blocks within the moderate-*P* gneissic basement of the Lanterman Range record extreme pressures in a wide zone of structural contraction separating the Wilson and Bowers terranes. Blocks in this zone record high-*P* conditions in the high-*T* eclogite facies (Fig. 4A), and some even attained extreme pressures as high as 26 kbar (Fig. 4B). The most plausible interpretation of these high-*P* parageneses is that they formed at peak conditions following a clockwise but steep geotherm. Mineral zonation and inclusion relationships in rare cases even preserve the prograde path, passing through the moderate-*P* amphibolite facies prior to attaining UHP conditions (Palmeri et al., 2003). Although the timing of UHP metamorphism is not dated directly, other eclogitic blocks from this zone yielded mineral and isochron ages of ca. 500–490 Ma. Only slightly younger hornblende and white mica cooling ages define an extreme retrograde cooling and decompression stage. The very steep *P-T* paths to extreme pressure conditions suggest significant thickening and/or westward underthrusting of terranes during convergence; the high-*P* blocks themselves likely mark a collision zone between older basement and the outboard Bowers arc. In this regard, evidence of thickening due to collision in these high-grade rocks differs dramatically from other parts of the Ross orogen.

In the inboard western Wilson terrane, particularly in the well-studied region of the Deep Freeze Range and Terra Nova Bay (DFR and TNB in Fig. 4A), granulite and migmatite terranes are characterized by low-*P* metamorphism. 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). A few exceptions show evidence

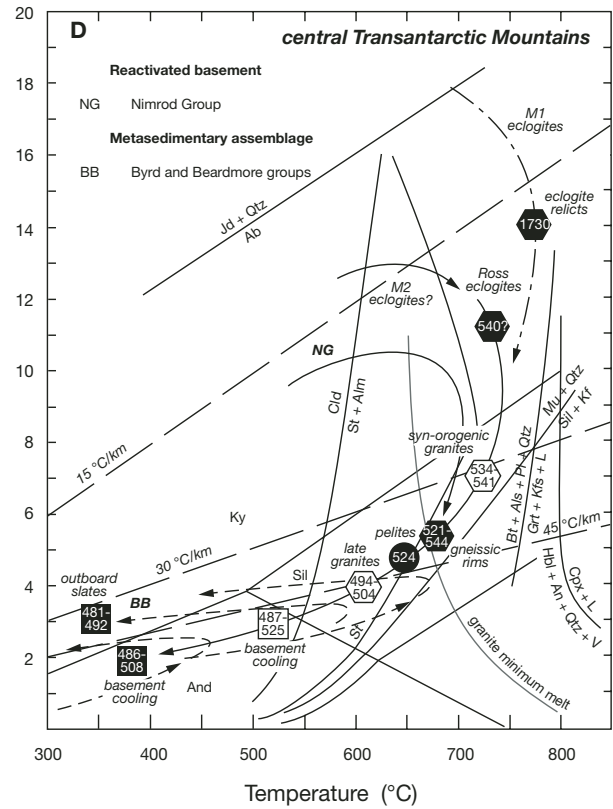
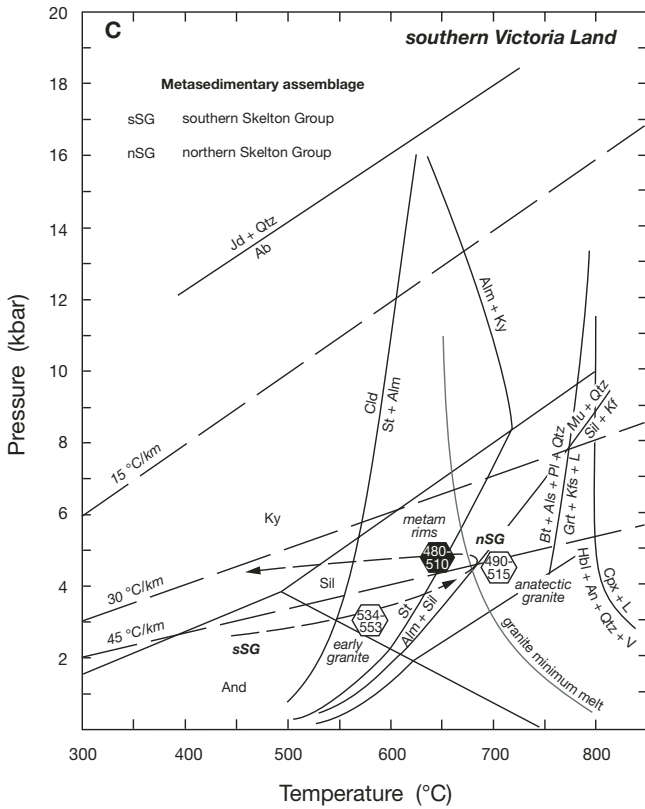
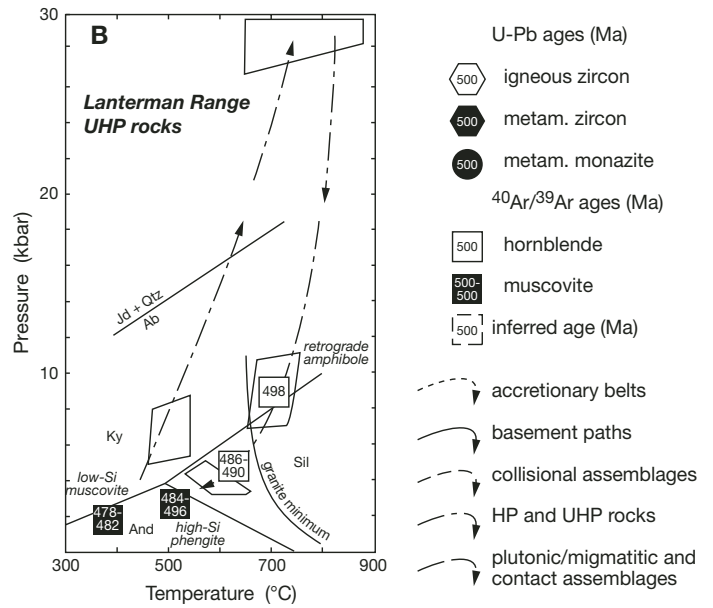
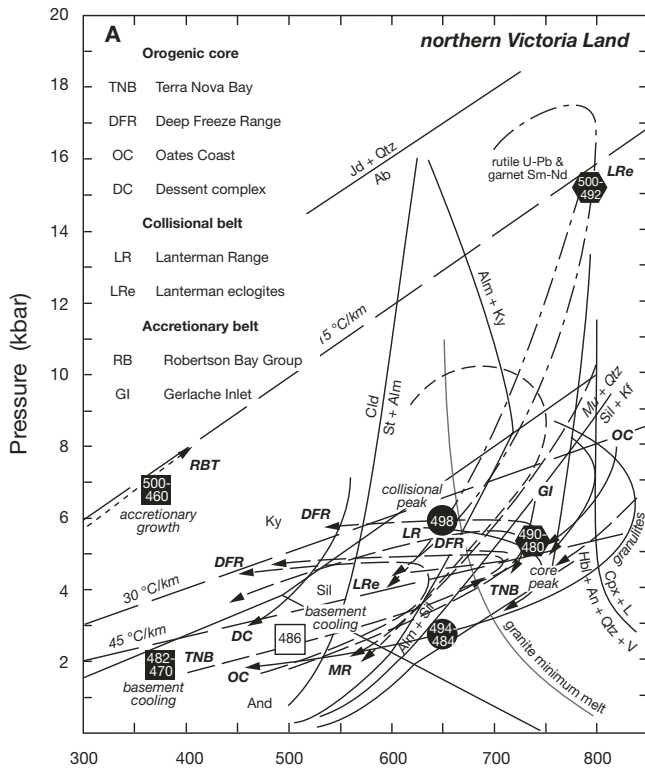


TABLE 1. COOLING AND DENUDATION RATES IN THE ROSS OROGEN

Region	Cooling rate (°C/m.y.) [†]	Denudation rate (km/m.y.) [‡]	Source [§]
Northern Victoria Land			
Lanternman Range (gneisses)	30	1.2	1
Lanternman Range eclogites and UHP rocks	>30	3–4	2, 4
Oates Coast (granulitic basement)	18–25	nd	3
Southern Victoria Land			
Skelton Group (metasedimentary rocks)	nd	(2.0)	5, 6, 7
Central Transantarctic Mountains			
Nimrod Group (reworked Precambrian basement)	10	0.4	1, 8
Byrd Group (synorogenic assemblage)	10–30	nd	9

[†]Cooling rates quoted from published sources based on thermochronology.

[‡]Denudation rates quoted from published sources using either assumed geotherm or barometry applied to cooling rate; values in parentheses inferred but not quantitatively constrained.

[§]Sources: 1—Goodge and Dallmeyer (1996); 2—Di Vincenzo et al. (1997); 3—Schüssler et al. (1999); 4—Palmeri et al. (2003); 5—Allibone (1992); 6—Cox (1992); 7—Allibone and Wysoczanski (2002); 8—Goodge and Dallmeyer (1992); 9—Goodge et al. (2004a).

Figure 4. *P-T-t* diagrams for three segments of the Ross orogen. For simplicity, *P-T* paths are shown as interpreted from published sources based on mineral compositions and equilibria; not shown is the complete range of conditions achieved in a given area. Ages of dated metamorphic events noted (solid where individual mineral cooling ages are available; dashed where inferred from regional relationships). Timing constraints from sources in text. Aluminum-silicate phase relations after Holdaway (1971); other general equilibria from Spear and Cheney (1989) and Spear (1993). Also shown are reference geotherms of 15, 30, and 45 °C/km. (A) Northern Victoria Land (principal sources include Lombardo et al., 1987; Capponi et al., 1990; Kleinschmidt et al., 1991; Palmeri et al., 1991, 1994; Talarico et al., 1992; Goodge et al., 1995; Goodge and Dallmeyer, 1996; Di Vincenzo et al., 1997; Ricci et al., 1997; Schüssler et al., 1999). 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 (from Di Vincenzo and Palmeri, 2001; Palmeri et al., 2003). Note change in scale from previous panel. (C) Southern Victoria Land (principal sources include Allibone, 1992; Cox, 1992). 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 (principal sources include Goodge et al., 1992, 2001, 2004a; Peacock and Goodge, 1995; Goodge and Dallmeyer, 1996; Goodge, 1997). Basement units in Nimrod Group show clockwise cooling and decompression path after achieving peak temperatures at ~8–10 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 Group gneisses yield Paleoproterozoic metamorphic zircon ages (M1; Goodge et al., 2001), but some blocks yield Early Cambrian ages (ca. 540 Ma; C.M. Fanning, 2005, personal commun.), suggesting either Ross-age resetting of the older eclogite zircons or some new occurrences of M2 eclogite. Mineral abbreviations follow Kretz (1983). MR—Miller Range.

of crustal thickening, but these probably reflect isolated crustal slivers. Thus, in absence of thickening and subsequent modification of the conductive crustal geotherm, the main cause of low-*P/T* metamorphism is probably advective heating associated with continental-arc magmatism. Although the petrogenesis of these rocks is well known from numerous detailed petrologic studies, the timing and cooling rates are not well constrained by metamorphic thermochronometers. Nonetheless, it is clear from geological relationships that low-*P/T* metamorphism is coeval with regional Ross magmatism.

A distinctive metamorphic occurrence in northern Victoria Land, often overlooked from a petrologic viewpoint, are the low-grade zones within the Robertson Bay Group (RB in Fig. 4A). Debate concerning the provenance of these deposits remains, but their metamorphic character is consistent with low-*T* recrystallization along a moderately steep geotherm (Buggisch and Kleinschmidt, 1991; Kleinschmidt et al., 1991), as found in many accretionary complexes. In addition to their low-grade character, these rocks show diachronous mineral and slate ages reflecting progressive eastward thickening (Dallmeyer and Wright, 1992), thought to represent oceanward trench migration during accretionary growth at this latitude of the Ross margin.

Southern Victoria Land

Metamorphic units in southern Victoria Land constitute a metasedimentary assemblage invaded by voluminous syn- to postorogenic magmas. 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. Thus, no known element of the pre-Neoproterozoic East Antarctic shield is present. Metamorphism of these rocks is a result of Ross-age plate-margin convergence, yet it is solely of low-*P/T*

type following a geotherm of ~ 45 °C/km (Fig. 4C). Quantitative reconstruction of a prograde path is not possible, due to high- T chemical homogenization of minerals such as garnet, although local preservation of andalusite relicts within sillimanite-zone parageneses indicates a prograde path at pressures less than the Al-silicate triple point. A likely P - T path is shown in Figure 4C, with near-isobaric heating to peak conditions followed by generally isobaric cooling along a counterclockwise path. 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). There is also evidence for early alkaline magmatism at ca. 530–550 Ma (Rowell et al., 1993; Hall et al., 1995; Cooper et al., 1997), but the relationship of early igneous intrusion to metamorphism is not clear. Read et al. (2002) suggested that the alkaline magmas predate the common Ross-age calc-alkaline magmas; if so, the earlier alkaline type may reflect an initial igneous response to oblique convergent underflow. As mentioned in the section on low-grade accretionary assemblages in southern Victoria Land, no reliable age data are available for either the lower-grade assemblages farther south or the prograde and retrograde segments of high-grade metamorphism.

Peak conditions in the upper-amphibolite facies, as derived from mineral assemblages and thermobarometry, apparently reached sufficient temperature to induce in situ partial melting. Despite evidence of local anatexis, however, it is not clear whether high- T ultrametamorphic conditions account for magmagenesis, or rather if large amounts of advectively carried heat from the significant volumes of granite magmas observed in southern Victoria Land contributed to the regional low- P/T metamorphism. The geochemical and isotopic character of igneous rocks in this region (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), and a second later phase indicative of melting in thickened silicic crust (high-K anorogenic-type). The linkage between igneous activity and metamorphism therefore suggests that the main expression of Ross metamorphism is 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. Pluton emplacement was accompanied by deformation of the surrounding host rocks, and both contributed to thickening of orogenic crust in the region. Upward displacement of granitic plutons through the metamorphic assemblage would force surrounding host rocks to increasing depths, which combined with regional tectonic thickening would induce increasing pressure. Although any direct evidence for it is lacking, the balance of erosional and thickening processes were likely to keep the metamorphic rocks at a generally uniform depth, helping to maintain near-isobaric prograde and retrograde conditions.

Central Transantarctic Mountains

Although they retain relics of earlier high-grade Archean and Paleoproterozoic events (Goodge et al., 1992), it is possible to distinguish thermomechanical effects of the Ross orogeny on the Nimrod basement complex (NG in Fig. 4D). The most complete record is preserved in pelitic units, where early synkinematic kyanite + muscovite + staurolite, reflecting peak conditions in the high- P part of the upper-amphibolite facies, is overprinted by late sillimanite + muscovite, suggesting decompression at temperatures below the sillimanite + K-feldspar equilibrium. These phase relations and thermobarometry indicate peak conditions of ~ 650 – 700 °C at ~ 8 kbar; peak pressures of up to 12 kbar are plausible, reflecting significant crustal thickening in the basement and a clockwise P - T path along a moderately steep geotherm. Ductile structures within the Nimrod Group are consistent with thickening, although a direct relationship with supracrustal units in the region is not observed (Goodge, 1997).

Geochronology of Nimrod Group gneisses and associated igneous rocks constrain a period of rapid postorogenic cooling within the reactivated basement complex that is associated with moderate decompression (NG in Fig. 4D). Syntectonic plutonic units emplaced within the older gneissic basement at this time reflect Ross magmatism within an active continental-margin arc. The ages and compositions of magmatic components intruding the Nimrod Group indicate that Ross magmatism was older and compositionally more diverse than shown by postorogenic granitic plutons. The latter include generally leucocratic biotite and tourmaline-muscovite-biotite granitoids. However, the regional scale and geochemical nature of the Granite Harbour batholith system suggest that magmatism was part of an Andean-style continental-margin arc. Postorogenic basement cooling is shown by hornblende and muscovite cooling ages, ranging from ca. 525 to 485 Ma. Mineral chronometers applied to the Nimrod tectonites indicate a late- to post-orogenic cooling rate of ~ 10 °C/m.y. (Table 1), probably along a P - T path of decreasing slope as shown in Figure 4D. Combined with an inferred geotherm, these cooling ages suggest a denudation rate of ~ 0.4 mm/yr. Thus, the Nimrod gneisses were strongly reconstituted during the Ross orogenic process, taking a clockwise P - T path to moderate pressures indicative of crustal thickening, followed by relatively rapid exhumation. Goodge and Dallmeyer (1996) speculated that differences in cooling rate between the Nimrod Group and Lanterman Range gneisses in northern Victoria Land can be explained by the contrasting pattern of intra-arc and collisional thickening, respectively.

Within supracrustal units of the central Transantarctic Mountains (BB on Fig. 4D), a P - T path can only be inferred from general mineral assemblages and regional geological relationships. A counterclockwise P - T path is suggested by an apparent heating stage along a relatively steep geothermal gradient to peak conditions favorable for sillimanite \pm garnet, coincident with late granite emplacement (Fig. 4D). Temperatures are more accurately inferred than pressures. Cooling ages for biotite and slate of 490–480 Ma constrain the timing of regional postoro-

genic and postmagmatic cooling, and a near-isobaric retrograde cooling phase is inferred. Although pressures along the retrograde cooling paths for both basement and cover assemblages are poorly constrained, they are shown here in a similar range. This is consistent with geological and geochronological relations in the area indicating that Nimrod basement was exhumed during Ross time, leading to deposition of the outboard molasse sequence, which itself was contracted, thickened, and thermally metamorphosed during late Ross stages.

TECTONIC SIGNIFICANCE OF ROSS METAMORPHISM

Coupled with an understanding of the deformational, magmatic, and depositional events that took place, the metamorphic record provides an important perspective on crustal process during the Ross orogeny. In general terms, metamorphism in all of the areas considered here supports the concept of a convergent continental-margin orogenic belt, where specific subbelts reflect the regional importance of crustal thickening, arc collision, magmatism, and accretionary growth. For comparison, inferred cooling and denudation rates from the different areas are listed in Table 1.

Ricci et al. (1997) summarize important features of the northern Victoria Land metamorphic evolution, and they present 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. The metamorphic record 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. Features related to thickening are overprinted by low- P/T , chiefly thermal metamorphism during late- to postorogenic magmatism. The many occurrences of migmatite and granulite gneiss in the western basement of northern Victoria Land reflect the role of high- T

metamorphism associated with long-term convergent-margin magmatism. Counterclockwise $P-T$ paths are common in these rocks, suggesting some combination of elevated geotherms in an arc basement setting, or advective addition of heat by the many plutons reaching this crustal level, or both. Some granulite relicts may predate Ross orogenesis, however, in which case their record of decompression might be evidence of Proterozoic extension within older cratonic basement.

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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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.

In southern Victoria Land, the main expression of metamorphism is of low- P/T character, and there is no clear evidence of either any older events or a different $P-T$ regime. Metamorphism in this area is associated with syn- to postkinematic emplacement of large volumes of granitoid magmas; as in northern Victoria Land, there is abundant evidence for contemporaneous migmatite formation and anatexis. The importance of magmatic accretion in the thermal budget and crustal mass balance cannot be overemphasized. Yet, contrary to both northern Victoria Land and the central Transantarctic Mountains, there is no evidence of allochthonous accretion, no record of significant structural thickening, and no exposed preorogenic crystalline basement. Peak metamorphic conditions within the meta-sedimentary assemblages in southern Victoria Land appear to be about the same as those of pluton emplacement, making it difficult to assess the magnitude and rate of exhumation. 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, differences between this section of the orogen and other areas are expected. 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 Transantarctic Mountains relative to crystalline rocks of the East Antarctic shield may have led to greater involvement of older basement.

The central Transantarctic Mountains 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 (Goodge et al., 1993a, 2004a, 2004b), although importantly the kinematic regime is transpressional. 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 synorogenic molasse deposits. The coupled record of contemporaneous basement denudation and siliciclastic deposition, bracketed to within a few million years' duration (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.

Future study of the metamorphic underpinnings within the Ross orogen will require continued effort on two fronts. First, additional field-based petrologic studies are needed, particularly with the goal of integrating metamorphism, deformation, and thermochronology. The role of structural extension in the denudation process is poorly understood in the orogen as a whole, and in many areas first-order thermochronologic data are absent that would permit an assessment of cooling and exhumation rates. Second, as much of the orogen and its adjacent continental shield are ice-covered, extrapolating the crustal architecture known from outcrop to ice-covered areas will require continued crustal imaging provided by geophysical remote sensing.

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