Contrasting Thermal Evolution within the Ross Orogen, Antarctica:
Evidence from Mineral $^{40}$Ar/$^{39}$Ar Ages

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ABSTRACT

The Nimrod Group in the central Transantarctic Mountains and the Lanternman Metamorphic Complex in northern Victoria Land of Antarctica constitute internal metamorphic basement terrains of the Ross orogen that share many first-order similarities in lithology, structure, and metamorphism. However, new $^{40}$Ar/$^{39}$Ar cooling ages determined for hornblende and muscovite from tectonites in the Geologists (Nimrod Group) and Lanternman ranges (Lanterman complex) indicate that these terrains experienced different post-kinematic cooling histories. Nimrod ductile L-S tectonites derived from igneous and sedimentary protoliths yield $^{40}$Ar/$^{39}$Ar hornblende cooling ages of 524–495 Ma and muscovite cooling ages of 499–496 Ma. These ages are interpreted to date the cooling following syn-metamorphic ductile deformation. Combined $^{40}$Ar/$^{39}$Ar and existing U-Pb age data yield an average post-kinematic cooling rate for the Nimrod tectonites of $-10^\circ$C/m.y. Metasedimentary L-S tectonites of the Lanternman complex yield $^{40}$Ar/$^{39}$Ar cooling ages of ca. 486 Ma [hornblende] and ca. 482 Ma [muscovite]. These cooling ages indicate an average post-kinematic Lanternman cooling rate of $-30^\circ$C/m.y. We interpret the contrasting thermal histories of these terrains to be the result of different modes of accretion along the orogen, due in part to oblique subduction of paleo-Pacific lithosphere beneath the East Antarctic craton. In the central Transantarctic Mountains, Nimrod cooling rates indicate relatively modest post-tectonic denudation rates ($0.4 \text{ mm/a}$), resulting from crustal thickening in an upper plate-margin setting. Contraction of adjacent continental-margin supracrustal sequences did not involve significant underthrusting, possibly as a result of a high component of margin-parallel translation. In contrast, markedly faster Lanternman cooling rates indicate more rapid denudation ($1.2 \text{ mm/a}$) of thickened crust in northern Victoria Land. Kinematic and cooling-rate data from the Lanternman complex indicate that accretion of outboard lower Paleozoic volcanic arc and continental-rise assemblages involved near-orthogonal underthrusting beneath crystalline basement, leading ultimately to rapid tectonic denudation.

Introduction

Plate convergence during the early Paleozoic Ross orogeny is signified by contractional deformation of upper Neoproterozoic and lower Paleozoic continental-margin sedimentary rocks, accretion of marine volcanic and sedimentary assemblages, and geochemical trends in syn- to post-tectonic Cambrian-Ordovician granitic plutons. Although many workers agree on a convergent setting along the early Paleozoic Pacific margin of the East Antarctic craton, the Ross orogen has been modeled in terms of subduction, collision, transpression and/or translation (e.g., Weaver et al. 1984; Bradshaw et al. 1985; Borg et al. 1987; Kleinschmidt and Tessenschn 1987, Flöttmann and Kleinschmidt 1991b; Kleinschmidt et al. 1992, Goodge et al. 1991, 1993a). For example, in northern Victoria Land, contractual displacements are well documented (e.g., Gibson and Wright 1985, Flöttmann and Kleinschmidt 1991a), yet the contrasting character of different lithotectonic assemblages has been explained by translational or oblique displacements (e.g., Weaver et al. 1984; Bradshaw et al. 1985; Gibson 1987). In the central Transantarctic Mountains, orogen-normal contraction has long been recognized in continental-margin assemblages [Laird et al. 1971, Stump 1981], but transcurrent motions have been suggested to explain rapid syn-tectonic sedimentary facies changes across the orogen [Rowell and Rees 1990], and orogen-parallel displacements are documented in high-grade basement rocks [Goodge et al. 1993a]. Because meta-
morphic rocks represent the deeper, rheologically-weaker parts of an orogen that flow in response to plate interactions, they may help to resolve along-strike variations in timing, kinematics, and tectonic processes within a convergent plate-margin framework. In particular, a comparison of the thermal histories of metamorphic basement terrains within the Ross orogen with thermochronometric data may help to distinguish between these different tectonic models.

Here we report new $^{40}$Ar/$^{39}$Ar mineral cooling ages from two metamorphic basement complexes involved in Ross deformation. These are the Nimrod Group exposed in the Geologists Range of the central Transantarctic Mountains in the vicinity of Nimrod Glacier, and the Lantermann Metamorphic Complex exposed in the Lantermann Range in northern Victoria Land (figure 1). The new age data reported herein from the Geologists Range supplement previously published $^{40}$Ar/$^{39}$Ar and U-Pb age data from the Nimrod Group and provide additional constraints on the timing of metamorphism and deformation. The $^{40}$Ar/$^{39}$Ar ages from the Lantermann complex tightly bracket the age of metamorphism and indicate that many previously reported R-Ar and Rb-Sr ages are geologically unreliable. The Nimrod and Lantermann $^{40}$Ar/$^{39}$Ar data, combined with other thermochronometric data, enable us to model the thermal behavior of the middle crust during the early Paleozoic Ross orogeny. Combined with P-T conditions of metamorphism, the thermochronometric data allow us to resolve similar but distinct P-T-t paths for the Nimrod and Lantermann terrains. These are interpreted to reflect fundamental differences in the kinematic response of middle crustal levels during convergent-margin orogenesis.

Medium- to High-P/T Rocks in the Ross Orogen

Most of the Ross orogen in the Transantarctic Mountains is underlain by upper Neoproterozoic to lower Paleozoic sedimentary and volcanic protoliths that were regionally metamorphosed under subgreenschist- to amphibolite-facies conditions. These rocks show a dominantly contractional deformation style and are cross-cut by syn- to post-tectonic calc-alkaline plutons, providing an important record of upper crustal orogenic processes. Deeper crustal levels are exposed in areas inboard of the axial part of the orogen, however. Here rocks of Neoproterozoic and older protolith age were involved in both low-P/T and high-P/T high-grade metamorphism. In northern and southern Victoria Land, abundant low-P/T paragneisses and orthogneisses are characterized by heterogeneous deformation, extensive migmatization, prolific syn-orogenic magmatism, and relatively young mineral cooling ages (e.g., Grew et al. 1984; Babcock et al. 1986; Palmer et al. 1991; Allibone 1992). In contrast, high-grade basement rocks with intermediate-to-high-P/T metamorphic assemblages are exposed primarily in two isolated areas: [1] the Nimrod Group in the central Transantarctic Mountains, and [2] the Lantermann Metamorphic Complex in northern Victoria Land (figure 1). These metamorphic rocks are unique within the Transantarctic Mountains because their high-P and high-T metamorphic parageneses are representative of relatively deep crustal levels (>25 km) within the orogen. Rocks comprising these two metamorphic terrains display many petrologic and structural similarities, as well as differences that are important for understanding along-strike variation in the character of the Ross orogen (table 1). Some of the most significant petrologic and structural relationships are highlighted below.

Nimrod Group. The Nimrod Group, exposed in the Miller and Geologists ranges of the central Transantarctic Mountains, is a lithologically diverse assemblage of penetratively deformed, high-grade gneisses and schists comprising the only known Precambrian crystalline basement in this region of the Ross orogen (figure 1). These high-grade metamorphic rocks represent an inlier of the East Antarctic craton exposed inboard of the younger Neoproterozoic to Ordovician low-grade metasedimentary sequences that comprise the deformed supracrustal parts of the Ross belt. The basement and supracrustal units are not in direct contact, both are intruded by ca. 500 Ma plutons of the Granite Harbour intrusive series. Initial studies suggested that the Nimrod Group was deformed during an early high-grade metamorphic event (Nimrod orogeny of Grindley and Laird 1969) that did not affect the younger sedimentary units (Grindley and Warren 1964). Medium- to high-P/T kyanite-zone mineral assemblages and relict eclogites are widespread within the Nimrod Group, reflecting exposure of relatively deep crustal levels in this part of the Transantarctic Mountains (Grindley 1972; Goode et al. 1992). Although the Nimrod Group is lithologically and structurally distinct from the supracrustal units, recent petrologic, structural, and geochronometric studies have shown that this basement complex was simultaneously involved with supracrustal units in Ross deformation between the latest Proterozoic and Early Ordovician (Goode et al. 1991, 1992, 1993a, 1993b; Goode and Dallmeyer 1992).
Figure 1. Location maps of Nimrod Glacier and northern Victoria Land study areas. Middle inset shows location of Nimrod Glacier (NG) and northern Victoria Land (NVL) areas; TM = Transantarctic Mountains; EA = East Antarctica; WA = West Antarctica. (A) Simplified geologic map of the central Transantarctic Mountains in the vicinity of Nimrod Glacier (after Grindley and Laird 1989; Goode et al. 1993a). Box shows location of figure 2. (B) Simplified geologic map of central part of northern Victoria Land in vicinity of Remnick Glacier (after Kreuzer et al. 1987). Box shows location of figure 3.
Table 1. Comparison of Nimrod Group and Lanternman Metamorphic Complex

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Nimrod Groupa</th>
<th>Lanternman Metamorphic Complexb</th>
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<tr>
<td>Lithologies</td>
<td>Intermediate to quartzofeldspathic layered gneiss, migmatite, amphibolite, pelvic schist, quartzite, calc-silicate gneiss, marble, granitic to granulitic orthogneiss, ultramafic and eclogite tectonic blocks</td>
<td>Homogeneous quartzofeldspathic gneiss, amphibolite, pelvic schist, quartzite, calc-silicate gneiss, extensive migmatite complexes and felsic dike swarms, ultramafic and mafic tectonic blocks</td>
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<tr>
<td>Structural fabrics</td>
<td>Early D1 rootless isoclinal folds, D2 dextral L-S shear fabrics with tight to isoclinal folds normal and parallel to L1, as well as local sheath folds, S folded above gently NW-plunging regional warps, L plunges uniformly NW; mesoscopic, microscopic and crystallographic asymmetric fabrics indicate top-SE penetrative shear within Miller Range shear zone (including Geologists Range)</td>
<td>Early D1 rootless isoclinal folds, D2 dextral L-S shear fabrics with folds normal to L1, S folded about NW-trending regional open folds, dominant D1 L plunges steeply SW (down-dip within S1, locally at oblique angles to SWS or NE), mesoscopic, microscopic and crystallographic asymmetric fabrics indicate top-NE shear, late D3 kink folds with SW-dipping axial planes and subhorizontal NW-trending axes, indicating minor top-SW displacement</td>
</tr>
<tr>
<td>Metamorphic parageneses</td>
<td>Early eclogite-facies M1 (preserved in mafic blocks only), overprinted by younger upper amphibolite to lower-granulite facies M2, M2 marked by clockwise P-T paths with syn-kinematic Ms-Ky zone succeeded by late-kinematic Sil zone; peak M1 at T = 650–750°C and P = 8–12 kbar; local M3 retrogression shown by St → Cld</td>
<td>Upper-amphibolite facies Ky-zone M1, succeeded by Sil-Ms-zone M2, M1-M2 marked by integrated clockwise P-T path and peak Ms-Ky-Sil zone conditions at T = 650–750°C and P = 5–10 kbar, M1-M2 overprinted along NE margin of Lanternman Range by green schist facies M3 during D3</td>
</tr>
<tr>
<td>Age</td>
<td>Archean to Paleoproterozoic crust formation ages (sedimentary sources). Nimrod Group includes 1.74 Ga orthogneiss, 540–520 Ma zircon and monazite U-Pb ages on D2/M2, 323–486 Ma amphibole and muscovite <em>Ar</em>/<strong>Ar</strong> cooling ages following D2</td>
<td>Age of protoliths unknown; (reversely-) discordant biotite, muscovite, and hornblende K-Ar ages of 355–483 Ma, reflecting M3 overprint on M2, M2/M1 Rb-Sr whole rock isochron ages of 550–585 Ma</td>
</tr>
<tr>
<td>Tectonic relation to adjacent supra-crustal units</td>
<td>Contact with outboard supracrustal units unexposed, inferred to be tectonic</td>
<td>Contact with outboard Bowers terrane (Middle Cambrian volcanic arc complex) is steep SW-dipping fault zone with reverse displacement (Lanternman fault)</td>
</tr>
</tbody>
</table>

a Data from Bog et al. (1990), Bennett and Fanning (1993), Goode et al. (1991, 1992, 1993a, 1993b); Goode and Dallmeyer (1992); Walker and Goode (1994) and Borg and DePaolo (1994).

Nimrod Group metasedimentary and metatropic lithologies 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 (Grindley et al. 1964; Goode et al. 1991, 1993a; Peacock and Goode 1995). All of these lithologies are exposed in the Geologists Range, although they have not been mapped in detail [figure 2].

Rocks of the Nimrod Group exposed throughout the Miller and Geologists ranges display penetrative dextral L-S tectonite fabrics characterized by composition layer-parallel shear foliation (S) and mineral elongation lineation (L1) [Goode et al. 1993a]. These D1 shear fabrics overprint early D1 rootless isoclinal folds. D1 foliations are comprised of phyllosilicate and amphibole grain-shape preferred orientation in schists and gneisses, and lenticular feldspar porphyroclasts in orthogneisses. L2 is formed by rodded quartz, crenulated mica, elongate or aligned feldspar augen, and aligned amphibole, sillimanite or kyanite, depending on host lithology. S generally dips moderately to the southwest, and L2 plunges gently to the northwest and southeast. Dextral L-S tectonite fabrics are pervasive in the Nimrod Group, and kinematic features at the macro-, meso-, and microscopic scales record principal top-to-the-SE, or left-lateral, displacement parallel to L2, through a minimum structural thickness of 12–15 km (Goode et al. 1993a). In addition to dextral shear fabrics, three types of folds formed during D2 [Goode et al. 1993a]: (1) open-to-tight, cylindrical folds of compositional layering with axes parallel to L2, present at the map to hand-sample scale; (2) mesoscopic SE-vergent cylindrical folds with axes normal to L2; and (3) subordinate mesoscopic noncylindrical shear folds elongated parallel to L2. A variety of granitic to felsic pegmatitic dikes and sills cross-
Figure 2. Generalized geologic map of the Geologists Range (from Goodge et al. 1993a), showing $^{40}$Ar/$^{39}$Ar sample locations and apparent-age release spectra. $^{40}$Ar/$^{39}$Ar apparent age spectra of mineral concentrates plotted with two-sigma, intra-group uncertainties indicated by vertical width of black bars. Experimental temperatures of argon evolution increase from left to right. Total-gas (TG), isotope-correlation (IC), and/or plateau (P) ages listed on each spectrum, increments used for determination of isotope-correlation and/or plateau ages shown by horizontal lines with arrows.
cut the Nimrod tectonites; these intrusive bodies display variable L-S fabric development and have yielded important age information on Nimrod deformation [Goode and Dallmeyer 1993b].

Rocks of the Nimrod Group were affected by two major high-temperature tectonothermal events. Evidence for the first event (M1) is cryptic and manifested by numerous mafic and ultramafic tectonic blocks hosted by layered, ductilely-deformed M1 schists and gneisses [Goode et al. 1992]. The mafic blocks contain cores of variably retrogressed eclogitic mineral assemblages, represented by symplecticites of low-Na clinopyroxene + orthopyroxene + hornblende + plagioclase + quartz with garnet, surrounded by rims of (garnet-lamphibole, Mineralogical evidence indicates that initial metamorphism of these blocks occurred in the eclogite facies at P ≈ 12–16 kbar and T = 600–900°C prior to re-equilibration during M2 [Peacock and Goode 1995]. Ductile D2 tectonism occurred under moderate-P, high-T metamorphic conditions (P = 8–12 kbar; T = 650–750°C) in the upper-amphibolite to lower-granulite facies (M2), as shown by synkinematic kyanite + garnet + muscovite + biotite + quartz in pelites, hornblende + plagioclase + garnet + clinopyroxene ± cinozoite in mafic rocks, and by thermobarometry [Goode et al. 1992]. 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.

Evidence for post-kinematic metamorphism (M3) is only locally displayed within narrow thermal aureoles of the ca. 500 Ma post-tectonic plutons. Here Nimrod tectonite fabrics were partially annealed or entirely obliterated by development of massive hornfels textures. Locally, Fe-rich pelites show evidence of staurolite + garnet + muscovite replaced by chloritoid grown across D2 foliation. The chloritoid-producing retrograde reactions probably occurred at P ≈ 5 kbar and T ≈ 550°C [Spear and Cheney 1989].

**Lanternman Metamorphic Complex.** The Lanternman Metamorphic Complex comprises the eastern part of the Wilson Group, a medium- to high-grade metamorphic terrain in the western interior region of northern Victoria Land (figure 1). Wilson Group rocks exposed in the Daniels Range and areas west of the Rennick Glacier are dominantly quartzofeldspathic, layered paragneisses characterized by andalusite + sillimanite assemblages [Kleinschmidt 1981] together with abundant migmatitic/plutonic complexes [Babcock et al. 1986]. An important metamorphic transition is inferred underlie Rennick Glacier where low-P/T Wilson gneisses exposed to the west are separated from medium- to high-P/T schists and gneisses exposed in the Lanternman, Salamander and Mountaineer ranges to the east [Grew et al. 1984; Kleinschmidt and Tessensohn 1987]. In the Lanterman Range, the Lanterman Metamorphic Complex [Roland et al. 1984; Sandiford 1985] contains relic kyanite + staurolite reflecting early metamorphism at moderate- to high-P interpreted as the signature of collisional orogenesis [Grew et al. 1984], and as the deep-seated part of a Ross-age subduction zone [Tessensohn et al. 1981; Kleinschmidt and Tessensohn 1987]. Rocks of the Lanternman complex are structurally juxtaposed with the Bowers Supergroup, a Middle to Upper Cambrian volcanic and sedimentary island arc assemblage, across the Lanterman fault. Granite Harbour-type granitic plutons intrude both the Wilson Group proper and the Lanterman Metamorphic Complex.

The Lanterman complex is dominated by quartzofeldspathic biotite gneiss, hornblende-biotite gneiss, and calc-silicate gneiss, with minor semi-pelitic schist, pelitic schist, amphibolite, tonalitic orthogneiss, tectonic schist and ultramafic lenses [Grew and Sandiford 1984, 1985; Sandiford 1985; Roland et al. 1984; Kleinschmidt et al. 1987]. Rocks in the southeastern area of the Lanterman Range represent this lithologic diversity (figure 3). Western areas expose quartzofeldspathic-to-intermediate gneisses and schists cut by granites, diorites, and tonalites of presumed ca. 500 Ma age. A variety of aplite to pegmatitic felsic dikes and veins of uncertain affinity form extensive intrusive migmatites. Lenses and discontinuous layers of amphibolite, amphibolite-facies metasedimentary host the east side of the range within a structural horizon concordant to the Lanterman fault (Gibson 1987; Kleinschmidt et al. 1987).

Rocks of the Lanterman complex consist of multiply-deformed L-S tectonites that display variably-oriented lineations and folds. In general, the rocks contain a steep northwesterly striking foliation concordant with compositional layering and deformed by moderately NW-plunging map-scale folds [Roland et al. 1984; Sandiford 1985]. Evidence for an early deformation (D1) is manifested by tight-to-isoclinal, locally rootless folds (F1) with near-vertical to steeply NW-plunging axes. The D1 structures are contained within D2 L-S tectonite fabrics, characterized by a layer-parallel foliation (S) and a mineral elongation lineation (Ls) that is
Figure 3. Generalized geologic map of the southeastern Lanterman Range (modified from Roland et al. 1984), showing $^{40}\text{Ar}/^{39}\text{Ar}$ sample locations and apparent-age release spectra. The $^{40}\text{Ar}/^{39}\text{Ar}$ apparent age spectra plotted as in figure 2.
normal to open-to-tight asymmetric folds \( F_2 \). \( L_2 \) is defined by aligned micas, fibrolitic sillimanite, and amphiboles, as well as by rodded mineral segregations, indicating that the L-S fabrics formed during high-grade metamorphism. \( L_2 \) is dominantly down-dip (SW) but plunges locally to the W and NW, suggesting a non-orthogonal component of shear (figure 3). The Lanterman tonalites display notably less penetrative L-S fabrics compared to those in the Nimrod Group, indicating either lower bulk strains, lower strain rates, or both. Although most tectonites contain orthorhombic micas of pressure (2.0 GPa) and so are not common in the Lanterman. Tonalites display a composite fabric composed of S-C fabric, discrete shear bands, tapered boudins, and rotated porphyroclasts. Mesoscopic, microscopic, and crystalllographic fabrics indicate a top-NE (contractional) displacement was dominant during \( D_2 \) (Sandiford 1985, J. W. Goode unpub. data). In the northeastern part of the range, \( D_2 \) structures are deformed by gently NE- to SE-plunging, open kink and chevron folds \( F_3 \), and they are deformed by SW-dipping \( D_3 \) extensional shear bands that indicate late-stage extension to the southwest.

Metamorphic parageneses in the Lanterman complex provide evidence for three distinct metamorphic events (Wodzicki et al. 1982; Grew et al. 1984; Grew and Sandiford 1984; Roland et al. 1984; Kleinschmidt et al. 1987). \( M_1 \) is preserved as relics of kyanite-zonite, pelitic assemblages, which are mostly replaced by sillimanite + muscovite + K-feldspar during \( M_2 \). Grew and Sandiford (1984) estimated P-T conditions for these two events to be \( T = 650-700^\circ\text{C}, P = 7-10 \) kbar, and \( T = 650-700^\circ\text{C}, P = 5.5-6.4 \) kbar, respectively. The transition from kyanite to sillimanite in pelitic rocks is thought to reflect a decrease in temperature, between \( M_1 \) and \( M_2 \) (Grew and Sandiford 1984; Roland et al. 1984). We correlate the Lanterman \( M_1 \) and \( M_2 \) with Nimrod \( M_3 \) (table 1); metamorphism of mafic and ultramafic blocks in the Lanterman complex (Kleinschmidt et al. 1987) may be similar to \( M_1 \) preserved in the Nimrod eclogite and ultramafic blocks. A final episode of Lanterman metamorphism \( M_4 \) is recognized by the formation of epidote + chlorite + actinolite greenschist-facies assemblages, concentrated along the eastern side of the Lanterman Range, for which conditions are estimated as \( T = 300-370^\circ\text{C}, P = 3-5 \) kbar (Grew and Sandiford 1984). The \( M_4 \) may represent a retrogressive phase associated with deformation along the eastern boundary of the Lanterman complex, and conditions during this event are similar to those estimated for peak prograde conditions in Bowers and Robertson Bay rocks (Wodzicki et al. 1982).

**Age Relations.** Geochronometric data reported for the Nimrod Group indicate Middle to Late Archean crust formation \( 2.8-3.3 \text{ Ga} \), Late Archean metamorphism \( (ca. 2.5 \text{ Ga}) \), Late Archean to Archon-Proterozoic sediment provenance \( (1.7-2.5 \text{ Ga}) \), and ca. 1.73 Ga magmatism (Günner 1983; Borg et al. 1990; Goode et al. 1991; Walker and Goode 1991; Bennett and Fanning 1993). McDougall and Grindley (1965), and Grindley and McDougall (1969) presented a range of hornblende and muscovite \( K-Ar \) ages \((ca. 1100-450 \text{ Ma}) \) and concluded that the older ages were associated with a tectono-thermal event they defined as the "early orogeny." Adams et al. (1982a) corroborated the wide range in mica and amphibole \( K-Ar \) ages \((470-1153 \text{ Ma}) \), although they suggested that the relatively old Neoproterozoic ages could reflect extraneous \("excess") intracrystalline argon, possibly introduced during a ca. 530-580 Ma thermal event. More recent \( ^{40}\text{Ar}^{39}\text{Ar} \) dating of muscovite and hornblende, and U-Pb dating of monazite and zircon, have documented that the high-grade Nimrod \( M_2-D_2 \) metamorphism and associated deformation occurred during the very latest Proterozoic and Early Cambrian \((550-520 \text{ Ma}) \), Very 

A comparison of Nimrod cooling ages with Isotopically controlled supracrustal deformation indicates that the Ross orogeny in the central Transantarctic Mountains was episodic over about a 50 m.y. timespan. Distinct deformation paths indicate that significant strain partitioning occurred across the orogen (Goode et al. 1993a).

The age of metamorphic basement exposed in northern Victoria Land is uncertain. U-Pb ages reported for xenocrystic zircon from a post-metamorphic 544 Ma S-type granite in the Daniels

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Range indicate a crustal source of 2.5–2.8 Ga [Black and Sheraton 1990]. Other syn- to post-
metamorphic plutons of the Wilson granitic com-
plex exposed in the Daniels Range yield U-Pb zir-
con crystallization ages of 630–650 Ma [Sheraton et al. 1987]. However, the complicated multi-
component results reported by Black and Sheraton
(1990) question the geologic reliability of the older
plutonic ages. Micaeous schists and gneisses in
the Lanterman and Salamander ranges yielded
Rb-Sr whole rock isochron ages of ca. 550 Ma [Ad-
ams and Höhndorf 1991], and a poorly defined
"scatterchron" age of ca. 610 Ma [Kreuzer et al.
1987]. K-Ar mineral ages of ca. 450–500 Ma pro-
bably reflect general post-Ross cooling [Adams et al.
1982b, Kreuzer et al. 1987]; however, several of
these ages are reversely discordant mineral pairs
and probably have no geologic significance. In ad-
dition, most samples dated by Rb-Sr and K-Ar meth-
ods were collected from eastern sections of these
ranges, adjacent to the Bowers structural zone.
Here, prominent retrogressive features, including
chlorite and blue-green amphibole parageneses
(Adams et al. 1982b) and "fully recrystallized"
greenschist-facies assemblages [Adams and Höhnd-
dorf 1991], complicate resolution of the age of
high-grade Lanterman metamorphism.

Because it is difficult to obtain reliable meta-
morphic cooling ages from high-grade, polymeta-
morphic terrains using conventional K-Ar and
Rb-Sr techniques [as evident in the Nirmrod
Group], a reassessment of the ages of Lanterman
metamorphism and deformation was undertaken.
In the context of the petrologic, structural, and age
relations noted above, new 40Ar/39Ar mineral ages
from Nirmrod teconites in the Geologists Range
and the Lanterman complex in the Lanterman
Range, were determined. These data provide more
detailed constraints on the age of metamorphism
in the two terrains than were previously available,
and they allow assessment of potential along-
orogen variations in cooling history and/or tec-
tonic chronology during Ross orogenesis.

Analytical Methods

Amphibole and muscovite concentrates from sam-
pled collected in the Geologists and Lanterman
ranges were analyzed by the 40Ar/39Ar method at
the University of Georgia. The techniques used
generally followed those described in detail by
Dallmeyer and Keppie (1987) and Dallmeyer and
Gil-Ibarsuchi [1990]. Optically pure (>99%) min-
eral concentrates were wrapped in aluminum foil
packages, encapsulated in sealed quartz vials and ir-
radiated in the U.S. Geological Survey TRIGA reac-
tor. Variations in the flux of neutrons along the
length of the irradiation assembly were monitored
with several mineral standards, including MMhb-1
[Alexander et al. 1978]. The samples were incre-
mentally heated until fusion in a double-vacuum,
resistance-heated furnace at the University of
Georgia. Temperatures were monitored with a di-
rect-contact thermocouple and controlled to 1°C
between increments, and they are accurate to
±5°C. Blank-corrected isotopic ratios were ad-
justed for the effects of mass discrimination and
interfering isotopes produced during irradiation us-
ing factors reported by Dalrymple et al. [1981] for
the TRIGA reactor. Apparent 40Ar/39Ar ages were
analyzed from the corrected isotopic ratios using
the decay constants and isotopic abundance ratios
listed by Steiger and Jäger (1977).

Intralaboratory uncertainties were calculated by
statistical propagation of uncertainties associated
with measurement of each isotopic ratio (at two
standard deviations of the mean) through the age
equation. Interlaboratory uncertainties are about
±1.25–1.50% of the quoted age. Analysis of the
MMhb-1 monitor indicates that apparent K/Ca ra-
tios may be calculated through the relationship
0.518 ± 0.005 x 39Ar/40Ar corrected. Analyses of
the amphibole concentrates were plotted on 40Ar/
40Ar vs. 39Ar/40Ar isotope correlation diagrams and
Total-gas ages were computed for each sample by
appropriate weighting of the age and percent 39Ar
released within each temperature increment. A
"plateau" is herein considered to be defined if the
ages recorded by two or more contiguous gas frac-
tions with similar apparent K/Ca ratios, each rep-
resenting >4% of the total 39Ar evolved (and to-
gether constituting >50% of the total quantity of
39Ar evolved), are mutually similar within a ±1%
intralaboratory uncertainty.

Representative grains from the mineral sepa-
rates used for 40Ar/39Ar dating were analyzed by
electron microprobe on a JEOL 733 Superprobe at
SMU. Mineral grains were mounted with epoxy in
drilled aluminum disks and polished. Beam diam-
eter under normal conditions was ~2 μm, and 10
μm for micas. Raw counts were corrected using
the procedure of Bence and Albee (1968), modified
by Albee and Ray (1970). Each major and minor
element analysis was conducted for 30 s or 60,000
counts. Well-characterized natural and synthetic
materials were used as standards; standards were
routinely analyzed and as needed if totals drifted
±1% relative. Linear drift corrections based on
analysis of standards were made for Al, Si, Mg, Ti,
and Fe. Control analyses are reproducible to better than ±2% for major elements and ±10% for minor elements. Analyses are averages of 6–8 individual spot analyses from several grains per mineral sample, and they are precise to ±1–2% for major elements. Amphibole compositions were normalized following the Ca-amphibole scheme of Laird and Albee (1981). Mössbauer determination of Fe$^{2+}$/Fe$^{3+}$ by M. D. Dyar (unpub. data) on previously analyzed amphibole concentrates from the Miller Range [Goodge and Dallmeyer 1992] show that this stoichiometric recalculation scheme predicts Fe$^{2+}$/Fe$^{3+}$ to within about 15% of actual values in most cases. Muscovite was normalized based on the phengite substitution [Fe$^{2+}$, Mg, Mn], Si $\leftrightarrow$ [Al$^{3+}$, Fe$^{3+}$, Ti, Cr], Al$^{IV}$ between pure end-member muscovite and celadonite.

$^{40}$Ar/$^{39}$Ar Results

Location coordinates and petrographic descriptions of the dated samples are given in Appendix 1 [this and other appendices in the Data Depository may be obtained free of charge upon request from The Journal of Geology]. All $^{40}$Ar/$^{39}$Ar mineral ages from the Geologists and Lanterman ranges are portrayed as age spectra in figures 2 and 3, and analytical data for hornblendes are summarized in table 2. The complete $^{40}$Ar/$^{39}$Ar analytical data are given in Appendix 2 of the Data Depository.

All of the hornblende samples display considerable intrasample variations in apparent age over the small-volume, low-temperature gas fractions. These are matched by fluctuations in apparent K/Ca ratios, which suggest that experimental evolution of argon occurred from compositionally distinct, relatively non-retentive phases. These could be represented by: [1] very minor, optically undetectable mineralogical contaminants in the amphibole concentrates; [2] petrographically unresolved exsolution or compositional zonation within constituent hornblende grains; [3] minor chloritic replacement of amphibole; and/or [4] intracrystalline inclusions. The intermediate- and high-temperature gas fractions generally display little intrasample variation in K/Ca ratios, indicating that experimental evolution of gas occurred from compositionally uniform sites. In some cases these increments rigorously define a plateau age. Most of the muscovite samples yielded young apparent ages for the lowest-temperature increment, and older well-defined plateaus over the remainder of the experiment. Apparent K/Ca ratios for the muscovites are considerably larger than the hornblendes with considerable associated uncertainties, yet they also are uniform except at the lowest-temperature increments. Because the hornblendes and muscovites display no significant and/or systematic intrasample variations, the apparent K/Ca ratios are not shown with the age spectra in figures 2 and 3.

The $^{40}$Ar/$^{39}$Ar mineral ages are interpreted to date the last cooling through temperatures required for intracrystalline retention of radiogenic argon in that mineral. Harrison (1981) suggested that a temperature of approximately 530 ± 40°C is appropriate for argon retention within most hornblende compositions in the range of cooling rates likely to be encountered in most geologic settings. Although not fully calibrated experimentally, the preliminary data of Robbins [1972] in the diffusion equations of Dodson [1979] suggest that argon is retained in muscovite at a temperature of approximately 375 ± 25°C.

Geologists Range. Nimrod Group samples from the Geologists Range include interlayered pelitic schist, amphibolite, quartzofeldspathic gneiss, and granodioritic orthogneiss. These rock types were derived from sedimentary and volcanic protoliths intruded by a granodiorite plutonic body prior to

| Table 2. $^{36}$Ar/$^{40}$Ar vs. $^{40}$Ar/$^{39}$Ar Isotope Correlations from Incremental-heating Experiments on Hornblende Concentrates from the Geologists and Lanterman Ranges, Antarctica |

<table>
<thead>
<tr>
<th>Sample</th>
<th>Isotope correlation age [Ma]$^a$</th>
<th>$^{40}$Ar/$^{39}$Ar intercept$^b$</th>
<th>MSWD</th>
<th>Increments included (°C)</th>
<th>Total $^{36}$Ar (%)</th>
<th>Calculated $^{40}$Ar/$^{39}$Ar plateau age [Ma]$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geologists Range [Nimrod Group]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>523.8 ± 2.4</td>
<td>548.7 ± 33.5</td>
<td>1.66</td>
<td>915-fusion</td>
<td>55.85</td>
<td>534.4 ± 1.9</td>
</tr>
<tr>
<td>3</td>
<td>494.8 ± 2.6</td>
<td>2203.1 ± 91.2</td>
<td>1.45</td>
<td>905-975</td>
<td>86.44</td>
<td>510.7 ± 1.4</td>
</tr>
<tr>
<td>5</td>
<td>507.8 ± 1.6</td>
<td>721.1 ± 47.6</td>
<td>1.16</td>
<td>880-985</td>
<td>91.98</td>
<td>510.8 ± 1.8</td>
</tr>
<tr>
<td>Lanterman Range [Lanterman Metamorphic Complex]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>486.1 ± 0.4</td>
<td>291.1 ± 1.2</td>
<td>1.8</td>
<td>785-fusion</td>
<td>84.82</td>
<td>487.8 ± 0.6</td>
</tr>
</tbody>
</table>

$^a$ Calculated using the inverse abscissa intercept [$^{40}$Ar/$^{39}$Ar ratio] in the age equation.

$^b$ Inverse ordinate intercept.

$^c$ Refer to table 1 in Data Depository for analytical data.

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metamorphism and deformation. The emplace-
ment age of the orthogneiss is unknown, but ptero-
graphically similar units in the Miller Range have
yielded U-Pb crystallization ages of both ca. 1.74
Ga and ca. 540 Ma [Goode et al. 1991, 1993b].
The muscovite and hornblende analyzed in this
study display textures indicating recrystallization
during D3 ductile flow [Goode et al. 1993a]. All
samples display penetrative macroscopic L-S tec-
tonite fabrics, although the amphibolite and or-
thogneiss samples have a penetrative elongation
lineation but only a poorly developed foliation.
In pelitic samples, muscovite and biotite commonly
form mica “fish” and well-developed Type II S-C
fabrics. The shear sense derived from these
mica fabrics is internally consistent with other ki-
nematic indications [Goode et al. 1993a]. Kyanite
was syn-kinematic with muscovite, whereas sill-
imanite has replaced kyanite and occurs principally
along discrete C planes, indicating late-kinematic
growth. The amphibolites show abundant textural
evidence of syn-kinematic recrystallization, in-
cluding an equigranular fine grain size of amphi-
boles, intracrystalline strain in plagioclase, and
elongate trails of granular titanite indicative of
high shear strains. The orthogneiss sample con-
tains an anastomosing foliation, mafic clots with
tapered ends, plagioclase with bent twins evident
of intracrystalline strain, and mosaics of quartz
subgrains, all indicative of solid-state ductile de-
formation. These textural relations, coupled with pet-
rologic constraints on the P-T conditions of de-
formation [Goode et al. 1992], indicate that the 40Ar/
39Ar hornblende and muscovite ages should date
cooling following the high-temperature, syn-
kinematic M3 metamorphism.

Amphiboles. Five amphiboles from the Geolo-
gists Range are paragentic horn-
blendes. The hornblendes are compositionally uni-
form, displaying similar Fe3+/Fe2+ + Mg) ratios
between 0.46 and 0.55 [Data Depository, Appen-
dix 3]. These compositions indicate relatively
high recrystallization temperatures under upper-
amphibolite to lower-granulite facies conditions
[Gilbert et al. 1982]. The amphibole concentrates
display variably discordant 40Ar/39Ar age spectra
(figure 2), which define total-gas ages ranging be-
tween 1492.7 ± 1.7 Ma [sample 2] and 512.3 ± 2.0
Ma [sample 5]. Apparent ages defined by gas
fractions evolved at intermediate and high experi-
mental temperatures display variable intrasample
relationships, as discussed below. As in the case of
the Miller Range samples [Goode and Dallmeyer
1992], the minor variation in amphibole 40Ar/39Ar
cooling ages reported here is probably related to
slight differences in mineral composition, local
strain rates, and intracrystalline dislocation densi-
ties, as would be expected under circumstances of
high-strain, high-temperature shear.

Hornblende sample 1 is from an amphibole
that yielded low-temperature apparent ages of ca.
600–2400 Ma, and a high-temperature plateau age
of 534.4 ± 1.9 Ma. The 40Ar/36Ar vs. 39Ar/36Ar iso-
otope correlation of the plateau data is well defined
[MSWD < 2]. Inverse-ordinate intercepts are not
significantly larger than the 40Ar/36Ar ratio in the
present-day atmosphere. Using the inverse-
absissa intercept (40Ar/36Ar ratio) in the age equa-
tion yields a plateau isoce corelation age of
523.8 ± 2.4 Ma. Because calculation of this iso-
tope-correlation age does not require assumption
of a 40Ar/36Ar ratio, we consider it to be geologi-
cally significant; thus the ca. 524 Ma isotope-
correlation age is interpreted to reflect the time of
cooling through ~530°C.

Sample 2 is hornblende from a garnet amphi-
bole that displays a complex, internally discordant
40Ar/39Ar age spectrum. No combination of data
yielded a meaningful isotope-correlation age. The
c. 1450 Ma total-gas age for this sample is there-
fore considered to have no geologic significance.

Samples 3 and 5 (amphibolite and orthogneiss,
respectively) yielded consistent intermediate-
to high-temperature plateau ages of 510.7 ± 1.4 Ma
[sample 3] and 508.8 ± 1.8 Ma [sample 5]. Total-
gas ages in these samples are similar, 40Ar/40Ar vs.
39Ar/40Ar isotope correlations of the plateau data
are well defined [MSWD < 2], and there is little
apparent intracrystalline contamination with ex-
traneous argon. Using inverse-absissa intersects
(40Ar/39Ar ratio) in the age equation yields plateau
isotope-correlation ages of 494.8 ± 2.6 Ma [sample
3] and 507.8 ± 1.6 Ma [sample 5]. The isotope-
correlation ages are interpreted to reflect the time
of post-metamorphic cooling.

A hornblende concentrate separated from or-
thogneiss [sample 4], yielded a complex internally
discordant release spectrum and a total-gas age of
591.0 ± 1.2 Ma. As with sample 2, no combination
of data yielded a meaningful isotope-correlation
age, and the total-gas age is considered to have no
geologic significance.

Muscovites. Two concentrates of white mica
separated from Nimrod Group schists [samples 6
and 7] were analyzed from the Geologists Range.
The white micas are nearly pure muscovite in
composition [Si = 6.13–6.21 pfu] and display moder-
ately high Ti contents [0.04–0.10 pfu], both re-
flecting high-T conditions [Data Depository, Ap-
pendix 3]. Each of these samples display internally
concordant $^{40}$Ar/$^{39}$Ar (figure 2), which define plateau ages of 499.1 ± 0.8 Ma [sample 6] and 496.4 ± 0.8 Ma [sample 7]. Total-gas ages for these samples (497.5 ± 0.8 and 496.0 ± 0.9 Ma for samples 6 and 7, respectively) are equivalent within error to the plateau ages. The plateau ages are therefore interpreted to date the time of cooling through ~375°C following metamorphism.

**Lanternman Range.** Most rocks of the Lanternman complex contain a foliation defined by compositional layering and mineral grain-shape preferred orientations. In contrast to the Geologists Range samples, which contain penetrative mineral grain-shape and mineral rod lineations, an elongation lineation is not present in all Lanternman rocks. Where present, it consists mostly of a mineral grain-shape alignment. Asymmetric fabrics indicative of shear sense are uncommon. Samples collected in the Lanternman Range for this study include mica schists and an amphibolite from an undifferentiated assemblage of interlayered metasedimentary and metavolcanic rocks. These samples are lithologically representative of the Lanternman complex, and they contain penetrative L-S deformation fabrics. The samples analyzed contain textural evidence for syn-kinematic mineral growth under medium-P amphibolite-facies conditions (Grew and Sandiford 1985; J. W. Goodge unpub. data). Textures are dominated by penetrative mica foliations, and two samples contain asymmetric S-C fabrics and mica “fish” indicative of top-to-the-northeast ductile shear. One amphibolite sample that contains only an elongation lineation displays fine- to medium-grained, equigranular amphibole. These fabrics indicate that muscovite and hornblende grains were involved in ductile flow, and that their $^{40}$Ar/$^{39}$Ar ages should define the time of cooling for these minerals following high-temperature, syn-kinematic metamorphism. Although we have not analyzed the compositions of these samples from the Lanternman Range, the mineral assemblages and mineral optical properties are consistent with high-temperature recrystallization. Roland et al. (1984) reported paragastic hornblende compositions for an amphibolite in the northwestern Lanternman Range petrographically similar to sample 8 of this study.

**Amphibole.** One hornblende concentrate from an amphibolite [sample 8] displays an internally concordant $^{40}$Ar/$^{39}$Ar age spectra (figure 3) that defines a plateau age of 487.8 ± 0.6 Ma and a total-gas age of 486.3 ± 0.5 Ma. The $^{40}$Ar/$^{39}$Ar ratio of the plateau data is well defined [MSWD = 1.8], and there is little apparent intracrystalline contamination with extraneous argon. Using the inverse-abcissa intercept ($^{40}$Ar/$^{39}$Ar ratio) in the age equation yields a plateau isotope-correlation age of 486.1 ± 0.4 Ma. This isotope-correlation age is interpreted to date cooling through ~375°C.

**Muscovites.** Four muscovite concentrates (samples 9–12) were analyzed from the Lanternman Range. These samples display internally concordant $^{40}$Ar/$^{39}$Ar age spectra (figure 3), which define uniform plateau ages of ca. 482 Ma. We interpret these ages to date the last cooling through ~375°C. Muscovite from sample 12 is from a mica schist collected at the same outcrop as the amphibolite from which hornblende sample 8 was obtained. The near-concordance of the hornblende and muscovite plateau ages at 486 and 482 Ma, respectively, and the uniformity of the muscovite ages from geographically separated samples, indicate that these samples cooled relatively quickly between ~530 and ~375°C.

**Comparison with Existing Age Data.** The hornblende and muscovite $^{40}$Ar/$^{39}$Ar ages from the Geologists Range are consistent with $^{40}$Ar/$^{39}$Ar mineral ages previously reported for samples of the Nimrod Group collected in the Miller Range (Goodge and Dallmeyer 1992). Together, these data indicate that Nimrod metamorphic rocks cooled through ~530°C between ca. 487 and 525 Ma, and through ~375°C between ca. 486 and 508 Ma (figure 4A). In contrast to conventional K-Ar dating, the $^{40}$Ar/$^{39}$Ar method allows for identification and evaluation of $^{40}$Ar contamination or loss. Furthermore, the ability to determine isotope-correlation ages from the $^{40}$Ar/$^{39}$Ar experimental data allows resolution of geologically meaningful ages even in cases where intracrystalline contamination with extraneous $^{40}$Ar is documented. The new age results presented herein provide further evidence that the large range of K-Ar ages obtained by previous workers (McDouggall and Grindley 1965; Grindley and McDougall 1969; Adams et al. 1982a) probably reflects various degrees of intracrystalline contamination with extraneous argon, rendering them geologically meaningless. The consistency of the new hornblende and muscovite $^{40}$Ar/$^{39}$Ar cooling ages in the range of ca. 525–485 Ma thus provide no geochronological evidence from the Nimrod Group for either the Nimrod or Beadmore orogenies, as has been suggested by previous workers (e.g., Adams et al. 1982a).

The Geologists Range $^{40}$Ar/$^{39}$Ar ages date cooling following the high-temperature D$_3$ ductile deformation and mineral recrystallization. U-Pb ages of syn- to post-tectonic zircons and monazites from Nimrod metasedimentary and metamorphosed rocks.
Figure 4. Temperature-time cooling histories for metamorphic tectonites of the Nimrod Group and Lanterman Metamorphic Complex. Insets show details of thermal history during Ross time constrained by data presented here. Black arrows connect mineral ages from same outcrop area or similar structural level within each terrain. Larger diagrams depict general cooling histories (gray arrows) of the metamorphic terrains into the late Paleozoic. Mineral closure temperatures (assumed): ~750°C, zircon, ~650°C, monazite, ~600°C, titanite, ~540°C, hornblende, and ~375°C, muscovite [Robbins 1972, Harrison 1981, Ghunt et al. 1988]. Insets show reference cooling rates of 10 and 30°C/m.y. [A] Nimrod Group age data include this study’s 40Ar/39Ar ages on hornblende and muscovite from the Geologists Range (black symbols), 40Ar/39Ar ages on hornblende and muscovite from the Miller Range [Goodge and Dallmeyer 1992], and U-Pb ages of zircons in igneous rocks and monazites in metamorphic rocks from the Miller Range [Goodge et al. 1993b]. Hornblende, muscovite, and monazite all correspond to cooling ages following syn-metamorphic deformation; zircon ages represent igneous crystallization ages of syn-tectonic (S) or post-tectonic (P) intrusive units. On average, Nimrod samples indicate a post-tectonic cooling rate of ~10°C/m.y. Production of cooling ages for metamorphic muscovite, hornblende, and monazite to 700°C from those samples with multiple mineral data yield similar ages to zircon crystallization ages from syn-tectonic intrusive units. Fission-track ages (F-T) on apatite from post-tectonic granite intruding Nimrod Group rocks in the Miller Range indicate basement cooling through ~100°C ca. 340–250 Ma [Fitzgerald 1994]. [B] This study’s 40Ar/39Ar mineral cooling ages for hornblende and muscovite from the Lanterman Metamorphic Complex (black symbols), monazite and titanite U-Pb ages from Lanterman tectonites [Goodge et al. 1995], and hornblende, muscovite, and biotite K-Ar ages from Granite Harbour-type plutons in the Lanterman Range [Kreuzer et al. 1987]. Muscovite ages are extremely concordant and the inferred cooling rate is ~30°C/m.y. Despite uncertainty in absolute age significance, K-Ar data indicate similar cooling rates for cross-cutting plutons [dashed lines]. Cooling to surface temperatures indicated by overlap of Devonian and younger Beacon Supergroup sediments.

[Goodge et al. 1993b] indicate that D2 was accompanied by syn-kinematic magmatism, and by late-to post-tectonic anatexic melting. The Nimrod 40Ar/39Ar mineral ages must therefore date cooling following D2, which occurred at temperatures of 650–750°C, rather than thermal resetting during late-tectonic Ross magmatism. The Geologists Range data are therefore consistent with other age data that indicate the Nimrod ductile deformation occurred in the Early Cambrian (ca. 540–520 Ma, based on timescale revisions suggested by Compston et al. 1992 and Cooper et al. 1992] and
was followed by a period of post kinematic cooling into the Early Ordovician [to ca. 485 Ma]. The ages confirmed that Nimrod metamorphic tectonites represent crystalline basement kinematically and thermally involved in Ross-age deformation.

The new hornblende and muscovite $^{40}$Ar/$^{39}$Ar ages from the Lanterman complex are nearly concordant between 486 and 482 Ma, respectively (figure 4B), and they indicate relatively rapid cooling of the Lanterman tectonites following $M_2$. The geographic distribution of samples indicates that low-grade $M_3$ retrogressive alteration along the eastern side of the range did not apparently affect the intracrystalline argon systems in the dated samples. Therefore, the 486–$\pm$482 Ma ages are interpreted to date cooling following the Lanterman $M_3$–$M_4$ metamorphism. The new $^{40}$Ar/$^{39}$Ar ages are generally older than K-Ar biotite, muscovite, and hornblende ages previously reported by Adams et al. [1982b]. Only one of their samples yielded concordant biotite-muscovite K-Ar age results at 483 Ma. Based on the $^{40}$Ar/$^{39}$Ar muscovite ages reported here, K-Ar ages < ca. 480 Ma are not considered to have geologic significance in dating Lanterman metamorphism. Adams and Höhndorf [1991] reported 550 $\pm$ 20 and 558 $\pm$ 17 Ma Rb-Sr whole rock isochron ages for “greenschist-facies” metamorphic units exposed in the Lanterman and Salamander ranges. The isochron calculations are associated with high statistical errors, and, hence, relatively high age errors. The low analytical precision and the location of these low-grade samples along the northeastern boundary of the Lanterman Range suggest that these ages are geologically unreliable.

**Thermal and Tectonic History of the Ross Orogen**

In addition to providing new age constraints on metamorphism, the $^{40}$Ar/$^{39}$Ar mineral age data from the Geologists and Lanterman ranges allow for a direct comparison of the cooling histories of these two basement terrains, and for an assessment of regional cooling and P-T patterns along the Ross orogen. Combination of the new ages with existing $^{40}$Ar/$^{39}$Ar and U-Pb data allows derivation of cooling rates for the two terrains, which in turn can help to constrain denudation rates following metamorphism. Differences in these cooling and denudation rates, and between P-T-t paths, can be modeled in terms of variations in the mode of supracrustal deformation along the Ross margin.

Temperature-Time Relations. Available $^{40}$Ar/$^{39}$Ar and U-Pb mineral ages, with appropriate minor closure temperatures, define temperature-time relations of the Nimrod and Lanterman terrains (figure 4). Both the Nimrod and Lanterman tectonites record progressive post-kinematic cooling between ca. 525–480 Ma. Metamorphic cooling rates may be calculated from the mineral ages for different minerals separated from the same rock sample or samples from the same general exposure area (shown by arrows in figure 4). For the Geologists Range samples, hornblende and muscovite ages were compared for samples from nearby exposure areas that occur at similar structural levels and exhibit textural evidence for $D_2$ ductile shear deformation. A comparison of mineral cooling ages from both the Geologists and Miller ranges yielded metamorphic cooling rates for the Nimrod Group of 5.0 to 15.7°C/m.y., with a mean cooling rate of 9.8°C/m.y. In contrast, samples of hornblende and muscovite from the same exposure in the Lanterman Range yielded a cooling rate of 31.3°C/m.y. Despite uncertainties in mineral closure temperatures, these cooling rates are relatively rapid for high-grade metamorphic terrains [Parrish 1989]. Most important, however, the Lanterman cooling rates are markedly higher than those of Nimrod tectonites.

We acknowledge that a rapid Lanterman cooling rate is based on only one hornblende age. However, the internal concordance of the plateau and isotope-correlation ages for hornblende, the concordance of the hornblende and muscovite ages, and the uniform ages among geographically separated muscovites are consistent with a relatively simple and rapid cooling history. This behavior in the mineral apparent ages therefore indicates that the range of cooling ages in the Lanterman complex is less than that in the Nimrod Group, consistent with more rapid cooling. Furthermore, U-Pb ages of 498 Ma for metamorphic monazite and titanite from the Lanterman complex [Goodge et al. 1995] yield an average linear post-metamorphic cooling rate of $\sim$17°C/m.y. We consider this to be a minimum rate over the broader temperature interval between about 650–375°C. These data corroborate interpretation of the $^{40}$Ar/$^{39}$Ar data that the Lanterman complex cooled more quickly than the Nimrod Group, and that mineral cooling ages fall within a narrower range. Furthermore, more rapid cooling of the Lanterman terrain between about 530–375°C was coincident with cooling of adjacent low-grade supracrustal terrains, and this has important implications for the tectonic history of northern Victoria Land.

In addition to these metamorphic cooling ages from Lanterman tectonites, two plutonic units in
the Lanterman Range have yielded K-Ar mineral ages (hornblende, muscovite, and biotite) ranging between 502–480 Ma (Kreuzer et al. 1987). Despite uncertainty in their emplacement ages, the K-Ar mineral ages reported by Kreuzer et al. (1987) for two granitoid samples [LA-01/02 and LA-03] yield cooling rates of ~17 and ~28°C/m.y. (Figure 4B). Because these plutonic bodies occur at similar crustal levels as the Lanterman samples presently studied, these data are consistent with interpretation of a relatively rapid basement cooling rate.

Cooling rates ≥10°C/m.y. suggest a combination of erosion of and tectonic control on unroofing (Spear 1993). Because the geologic setting and maximum metamorphic temperatures attained in these two terrains were similar, differences in the calculated cooling rates likely reflect different denudation rates controlled by erosional and/or tectonic processes. Minimal contact effects adjacent to plutons indicates that advective heating was of only local importance in the Nimrod and Lanterman thermal histories, and that conductive cooling resulted primarily from the approach of rocks to the surface. In order to compare differences in exhumation between these terrains, average denudation rates may be calculated by multiplying the cooling rates by an assumed inverse geothermal gradient of 25°C/km (reflected by the peak syn-tectonic M, conditions of 700°C and 8 kbar). This geothermal gradient is common in medium-P/T orogens (England and Thompson 1984). Ideally, denudation rates should be determined from samples collected at different elevations, because there is insufficient topographic relief represented by the samples from either area of this study, this simple cooling-rate calculation provides only a first-order approximation of denudation rates. For a geothermal gradient of 25°C/km, the corresponding denudation rates for the Nimrod and Lanterman complexes are about 0.4 mm/a and 1.2 mm/a, respectively. These denudation rates depend directly on the assumed geotherm, as well as the assumption of a steady-state post-kinematic geotherm. For example, a 30°C/km geotherm yields denudation rates of 0.3 and 1.0 mm/a, respectively. These values probably are reasonable minimum denudation rates because a 30°C/km geotherm is representative of thermally equilibrated thickened crust (Thompson and England 1984; Spear 1993).

Despite the assumptions involved in obtaining denudation rates from empirical cooling-rate data, it is possible to determine geologically reasonable estimates of denudation. The calculated Nimrod and Lanterman denudation rates of 0.4 and 1.2 mm/a are similar to those of younger collisional orogens, such as the Himalayan belt (Zeitler 1985; Copeland et al. 1987; Burbank and Beck 1991; Harrison et al. 1992). In the Himalayas, the initial phase of collision between ca. 70–20 Ma resulted in denudation rates of about 0.1–0.5 mm/a, followed by more rapid Neogene denudation rates of ≥2 mm/a. By analogy with the Himalayan example, the Nimrod and Lanterman rates are consistent with uplift induced by crustal thickening.

**Pressure-Temperature-Time Evolution.** P-T-t histories for the Nimrod and Lanterman complexes may be constructed from available age and petrologic data. These terrains experienced peak, synkinematic metamorphism at conditions of about 650–750°C and 8–12 kbar, followed by a post-kinematic stage passing through the sillimanite stability field to low-grade, retrogressive conditions. The estimated conditions of these successive metamorphic stages are depicted in figure 5 as N2–N3 for the Nimrod complex, and L1–L3 for the Lanterman complex. For the Nimrod complex, a late- to post-M1 cooling and decompression path passed from the region labeled by N2a, through N2b, and to lower temperatures between the staurolite- and muscovite-breakdown reactions. For the Lanterman complex, the post-M1 path is represented by near-isothermal decompression along a high-P/T segment between L1 and L2, followed by near-isobatic cooling to L3. These slight differences in P-T path, in which the Nimrod rocks reached higher peak temperature, and in which the Lanterman rocks underwent pronounced isothermal decompression, are consistent with the slower Nimrod cooling rates inferred from the mineral ages (see Spear 1993, p. 731).

The Nimrod and Lanterman complexes preserve similar petrologic histories manifested by medium-P/T conditions and clockwise P-T paths. Pressures of 8–12 kbar for the peak-temperature stages in each terrain correspond to depths of about 25–40 km. These depths probably represent minimum thicknesses of crust involved in Ross orogenesis because the Nimrod and Lanterman tectonites are presumably at higher pressures prior to reaching their peak prograde temperatures, and because they are not the deepest rocks presently exposed. Mineral assemblages and preserved mineral inclusions in pelitic Nimrod Group D2 tectonites indicate a prograde path through the kyanite stability field (Goodge et al. 1992). Relict eclogites in the ductile tectonites indicate that high pressures (≥12 kbar) were attained during the earlier Nimrod M, stage (N1 in figure 5; Peacock and Goodge 1995). This early stage of eclogite-facies metamorphism suggests that the Ross orogenic
Considered together, the high pressures and clockwise P-T paths are most consistent with crustal-thickening, either accompanied or followed by erosional denudation [Thompson and England 1984]. Despite their petrologic similarity, however, the Nimrod and Lanterman tectonites record different post-kinematic cooling histories. The \(^{40}\)Ar/\(^{39}\)Ar mineral ages indicate that, in general, the Lanterman rocks cooled later than and faster than those of the Nimrod Group.

**Tectonic Implications for the Ross Orogeny.** The contrast in cooling patterns of the Nimrod and Lanterman complexes has important tectonic implications for the Ross orogeny. In the central Transantarctic Mountains, low-grade siliciclastic turbidites of the Neoproterozoic Beardmore Group (Goldie Formation) and Lower to Middle Cambrian carbonates of the Byrd Group (Shackleton Limestone) are exposed outboard of the Nimrod Group. Structural relations between the Goldie and Shackleton are controversial; some workers have suggested that they are separated by an angular unconformity [Grindley and McDougall 1969, Laird et al. 1971, Stump et al. 1991], whereas others have identified fault contacts in several locations [Rowell et al. 1986]. However, both units are deformed by large-scale open folds and thrust faults [Laird et al. 1971, Rowell et al. 1986, Rees and Rowell 1991]. The Shackleton Limestone is carbonate-clast conglomerates and siliciclastic arenites [Douglas Conglomerate] interpreted as syn-orogenic foreland deposits [Rowell et al. 1988, Rees and Rowell 1991]. The Douglas Conglomerate is poorly dated, but stratigraphic relations indicate it is probably Upper Cambrian to Lower Ordovician. Tilting of these syn-orogenic sediments indicates that Ross contraction continued into the Early Ordovician, prior to emplacement of post-tectonic Granite Harbour granitoids at ca. 500–480 Ma (figure 6A).


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**Figure 5.** Synoptic P-T diagram comparing metamorphic conditions and cooling ages in the Nimrod Group and Lanterman Metamorphic Complex. Heavy dotted lines: approximate syn- to post-kinematic cooling and decompression paths for the Nimrod (black) and Lanterman (gray) terrains. Mineral cooling ages for Nimrod and Lanterman samples are plotted along the P-T paths at corresponding closure temperatures. Eclogite-facies conditions for Nimrod complex [N1] from Peacock and Goodge [1995]. Metamorphic conditions of Nimrod tectonites from Goodge et al. [1992], with their M<sub>1</sub> corresponding to the transition between syn-kinematic Ky-zone assemblages and late-kinematic Sil-zone conditions (see table 1), here shown as N2a and N2b by black polygons. Nimrod N3 from local occurrences of retrograde chloritoid. Metamorphic conditions of Lanterman tectonites from Greg and Sandford [1984], corresponding to their M<sub>1</sub>, M<sub>2</sub>, and M<sub>3</sub> (see table 1), here shown as L1, L2, and L3 by gray polygons. Nimrod and Lanterman metamorphic conditions plotted on KFASH petrogenetic grid of Spear and Cheney [1989], with isopleths of X<sub>al2m</sub> in garnet for reference. Alm = almandine, And = andalusite, Clid = chloritoid, Kf = K-feldspar, Ky = kyanite, Mus = muscovite, Qtz = quartz, Sil = sillimanite, St = staurolite. Light gray box: temperature range between Ar closure in hornblende (~530°C) and muscovite (~375°C). Nimrod cooling ages from Goodge and Dallmeyer [1992] and Goodge et al. [1993], and Lanterman cooling ages from this study and Goodge et al. [1995].

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Belt was at least 40 km thick in the central Transantarctic Mountains. Metamorphic parageneses in the Lanterman complex are also indicative of high pressures [Greg and Sandford 1984], and mafic and ultramafic blocks contained within the Lanterman tectonites are interpreted as the result of crustal collision and/or thickening [Klein-schmidt et al. 1987].
Figure 6. Comparison of tectonic events in the central Transantarctic Mountains (A) and northern Victoria Land (B). Age data for the central Transantarctic Mountains from Adams et al. (1982a), Gunner (1983), Goodge and Dallmeyer (1992), Goodge et al. (1993b), and this study. Age data for northern Victoria Land from Borg et al. (1987), Kreuzer et al. (1987), Wright and Dallmeyer (1991), Dallmeyer and Wright (1992), and this study.
Orogenesis in this area is interpreted to have resulted from left-oblique convergence between the paleo-Pacific ocean and the East Antarctic craton. This oblique convergence led to strain-partitioning between basement and supracrustal assemblages into deep-level orogen-parallel and shallow-level orogen-normal kinematic components (Goode et al. 1993a, 1993b). Upright, open folds in Beardmore and Byrd group rocks could have formed in a continental-margin forearc region like that of the Neogene Hikurangi margin of New Zealand, where marine carbonate and siliciclastic sequences are deformed by contractional structures in an oblique-subduction setting (e.g., Cashman et al. 1992; Kelsey et al. 1995).

The Lanterman complex represents the leading edge of crystalline basement in northern Victoria Land, and it contains high-temperature ductile deformation fabrics indicating dominantly top-northeast, or orogen-normal, displacement. It is in thrust contact along the Lanterman fault with the low-grade Bowers Supergroup (Kleinschmidt et al. 1984), comprised of Middle to Upper Cambrian mafic volcanic rocks (Glasgow Volcanics), and proximal volcaniclastic conglomerates and sandstones (including the Leap Year, Mariner, and Molar formations). Middle Cambrian to lowermost Ordovician siliciclastic turbidites of the Robertson Bay Group are thrust beneath Bowers rocks along the Leap Year fault. Similar to most major faults in northern Victoria Land (including those entirely within the Wilson Group [Flötmann and Kleinschmidt 1991b]), the Lanterman and Leap Year faults are dip-slip thrusts that juxtapose crystalline basement with accreted oceanic-arc and turbidite assemblages (Gibson and Wright 1985; Flötmann and Kleinschmidt 1991a, 1991b). Shortening of supracrustal rocks in northern Victoria Land may have begun as early as the latest Cambrian with deformation of the Bowers Supergroup. It probably culminated in the earliest Ordovician, following deposition of Robertson Bay Group sediments and prior to emplacement of ca. 500 Ma Granite Harbour granitoid plutons in the Wilson Group (figure 6B). Although the plutons are poorly dated, K-Ar and \(^{40}\text{Ar}/^{39}\text{Ar}\) whole rock ages on slates and metagranulites from the Bowers and Robertson Bay assemblages indicate cooling following cleavage development between ca. 460–510 Ma (Adams et al. 1982b; Adams and Kreuzer 1984; Wright and Dallmeyer 1991; Dallmeyer and Wright 1992). More importantly, Dallmeyer and Wright (1992) demonstrated regionally diachronous cleavage development in the Robertson Bay Group (from southwest to northeast) over about 40 m.y. in the Early Ordovician. They attributed this to progressive accretion and eastward thrust propagation during west-directed subduction. The \(^{40}\text{Ar}/^{39}\text{Ar}\) cooling ages date shortening within the Bowers and Robertson Bay supracrustal rocks at the same time as post-kinematic cooling ages determined for the Lanterman complex (figure 6B). This temporal overlap implies a genetic link between deformation and thickening in the supracrustal assemblages and uplift of the deep-level crystalline basement.

These geologic relations require that the plate-tectonic evolution of the Ross orogen be consistent with: (1) the Nimrod and Lanterman terrains having contrasting kinematics relative to the orogenic axis; (2) the terrains recording different cooling histories; and (3) the Ross orogen culminating in tectonic accretion of lower Paleozoic volcanic-arc and submarine-fan assemblages in northern Victoria Land that are not present in other parts of the orogen. These differences in deformation and timing along the orogen likely were primarily a result of variations in the magnitude of crustal accretion, the kinematics of convergence between the paleo-Pacific oceanic lithosphere and the East Antarctic craton, and the geometry of the plate boundary as inferred from Proterozoic rifting (figure 7).

During early stages in Ross orogenic activity (ca. 540–500 Ma; figure 7A), the convergent margin may have consisted of a single subduction zone to the south, and two trenches to the north. At the latitude of present-day northern Victoria Land, an inboard subduction zone could have dipped west beneath the East Antarctic craton, and a second outboard zone dipped in the same direction beneath the Bowers volcanic arc (Kleinschmidt and Tessensohn 1987). The northward bifurcation of subduction would have resembled that in the modern western Pacific Ocean around the Philippine plate. At this stage, the geometry of the cratonic margin and the direction of plate convergence are poorly known. Isotopic data indicate that the cratonic margin inherited from Neoproterozoic rifting may have had an irregular, step-like geometry [Borg and DePaolo 1994]. Further clarification of the rift-margin shape will provide the paleogeographic framework needed to evaluate the role of geometry on basement-cover interactions. However, the region of northern Victoria Land appears to be a long-lived cratonic salient. Relative plate motions (velocities and/or directions) along the convergent Ross margin may also have varied, although these cannot be directly constrained. Despite general agreement for ocean-continent co-
Figure 7. Tectonic scenarios of possible controls on different kinematic and cooling histories in the Nimrod and Lanterman complexes during Ross orogenesis. These diagrams highlight the roles of crustal accretion, convergence direction, and inherited continental rift-margin geometry. (A) Early stages of Ross orogenesis, ca. 540–500 Ma. Step-like geometry of East Antarctic cratonal margin inherited from earlier rifting, with separation of different segments along transform faults [thick gray lines]. Rift-margin sedimentation was dominant in southern Victoria Land (SVL) and in the central Transantarctic Mountains (CTM). Convergence along Ross margin bifurcated from south to north, with subduction zones separating oceanic volcanic arc and deep-marine turbidite sediments in northern Victoria Land (NVL). Deformation in CTM characterized by partitioned strain between arc-axis translation and forearc contraction. Major plate motion was oblique to Antarctic margin. (B) Late stages of Ross orogenesis, ca. 500–480 Ma. Outboard marine volcanic and sedimentary units were swept against the cratonal margin in the NVL area, resulting in sutures between major lithotectonic units. Accretion of volcanic and sedimentary units resulted in out-stepping and consolidation of single, west-dipping subduction zone. Deformation of supracrustal units along margin was dominated by contractional displacements, locally overprinted by late-stage extension. Block diagrams illustrate principal role of crustal accretion in NVL as compared to the CTM (thick black lines on map show approximate location of block diagrams). In NVL, accretion resulted in rapid basement uplift as a result of post-thickening extension. In contrast, contractional deformation of continental-margin sediments [no accretion] led to only modest basement uplift in the CTM. BdBG = Beadmore Group, ByG = Byrd Group; BS = Bowers Supergroup; LMC = Lanterman Metamorphic Complex; NG = Nimrod Group; RBG = Robertson Bay Group; SF = Swanson Formation (presently located in western Marie Byrd Land).

Vergence between the paleo-Pacific and the East Antarctic craton (Laird and Bradshaw 1982; Bradshaw et al. 1985; Kleinschmidt and Tessensohn 1987), the degree of relative obliquity and the consequent magnitude of orogen-parallel displacement along the Ross margin remain uncertain. The kinematics of Nimrod deformation suggest that vergence in the south was left-oblique (Goodge et al. 1993a), whereas in the north it may have been more orthogonal.

Later Ross events (ca. 500–480 Ma; figure 7B) were marked by continued convergence in the south, resulting in further contractional deformation of continental-margin sedimentary sequences (Beadmore and Byrd groups) but no significant outboard accretion. In the north, late Ross activity was dominated by collisional accretion of the Bowers arc complex as oceanic lithosphere was consumed. Deep-marine Robertson Bay turbidites were deposited outboard of the Bowers arc beginning in the Middle Cambrian, and they were accreted to the margin soon thereafter. By the end of Ross orogenic activity, a single, dominant subduction zone had developed to the east.
The age data and thermal histories of the Nimrod and Lanterman complexes described herein broadly support the tectonic scenario outlined above. In the central Transantarctic Mountains, Nimrod Group petrologic and cooling-rate data reflect crustal thickening in an upper plate-margin setting and modest post-tectonic denudation rates ($\sim$0.4 mm/a). A moderate syn- to post-kinematic cooling history for the Nimrod Group ($\sim$10°C/m.y.) is consistent with: (1) minimal late-stage retrogressive overprinting of Nimrod M$_2$, and (2) preservation of high-temperature Nimrod tectonite fabrics and crystallographic preferred-orientations, despite grain-boundary annealing (Goode et al. 1993a). These features indicate that the Nimrod tectonites remained at mid-crustal levels following the cessation of ductile shearing. Apatite fission-track data from post-tectonic Granite Harbour plutons in the Miller Range (Fitzgerald 1994) demonstrate that Nimrod crystalline basement continued to cool slowly through the Palaeozoic at an average rate of 1.5°C/m.y. (figure 4A, based on a track-retention temperature of $\sim$100°C and apatite ages of 250–340 Ma). A lack of systematic regional metamorphic gradients within the Nimrod complex indicates that thickening likely occurred by homogeneous ductile shortening, rather than by discrete thrusting and crustal duplexing. Shortening of the continental-margin sedimentary sequences (Beardmore and Byrd groups) likely did not involve significant underthrusting. Instead, they were contracted in a forearc setting, and they were structurally separated from deeper-level basement, perhaps by a high-angle translational fault or shear zones developed along the convergent plate margin (figure 7B).

In contrast, faster cooling rates ($\sim$30°C/m.y.) for the Lanterman complex indicate more rapid denudation ($\sim$1.2 mm/a) of thickened crust in northern Victoria Land. Rapid denudation following crustal thickening is consistent with syn-tectonic changes in crustal level as basement rocks passed upward through the ductile-brittle transition. This is manifested by early D$_2$ ductile deformation overprinted by low-temperature M$_2$ and extensional D$_3$ structures as the Lanterman complex came into structural contact with lower-plate rocks. Faster cooling rates are also consistent with dominantly orthogonal kinematics recorded at all crustal levels. The Lanterman kinematic and cooling-rate data indicate that accretion of outboard lower Palaeozoic volcanic-arc and continental-rise assemblages (Bowers and Robertson Bay units) involved substantial underthrusting beneath crystalline basement (see Kleinschmidt and Tessensohn 1987). Petrologic data from Bowers and Robertson Bay metasedimentary rocks indicate they were metamorphosed under high-P/T conditions as a result of being thrust “underneath a thick tectonic cover” (Kleinschmidt et al. 1991). P-T relations in all northern Victoria Land tectonic units thus indicate substantial crustal thickening as a result of convergent-margin accretion. The coincidence of the cooling ages recorded in the Lanterman complex with those of the outboard supracrustal assemblages, and the rapid post-tectonic Lanterman cooling rates, are consistent with a mechanism of tectonically induced uplift and erosion (fig. 7B).

In summary, both the Nimrod and Lanterman crystalline complexes show evidence of crustal thickening during the Ross orogeny. In response, each terrain underwent post-thickening denudation controlled in part by erosion. The Lanterman complex cooled more quickly, however, and erosion may have been enhanced in this region by late-stage orogenic accretion of the Bowers and Robertson Bay assemblages. Here, underthrusting of volcanic and sedimentary materials may have induced extensional unroofing within structurally overlying crystalline basement. The thermal and mechanical histories of these two crystalline complexes thus reflect a fundamental regional difference in the tectonic evolution of the orogen as a result of oceanic crustal accretion in the north, and displacement along an oblique, non-accreting margin in the south. These events probably marked the tectonic transfer of continental-margin and oceanic elements to the Antarctic plate during consolidation of a single, west-dipping subduction system along the southern margin of Gondwana. The timing of these Ross plate-margin orogenic events further suggests that they occurred in response to Pan-African fusion of interior Gondwana.

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