MULTIPLE PETROTECTONIC EVENTS IN HIGH-GRADE METAMORPHIC ROCKS OF THE NIMROD GROUP, CENTRAL TRANSANTARCTIC MOUNTAINS, ANTARCTICA

J. W. GOODGE\(^1\), V. L. HANSEN\(^1\) and S. M. PEACOCK\(^2\)

\(^1\)Department of Geological Sciences, Southern Methodist University, Dallas, Texas 75275, USA
\(^2\)Department of Geology, Arizona State University, Tempe, Arizona 85287, USA

Abstract: Precambrian metamorphic rocks of the Nimrod Group, exposed in the central Transantarctic Mountains, represent a small part of the East Antarctic cratonal mass that formed a portion of the Gondwana supercontinent. Their inferred position near a proto-Antarctic plate boundary offers a unique opportunity to study the relation between the Archean-Proterozoic craton and younger crustal elements formed along the active plate margin. On the basis of petrologic and structural relations, high-grade metamorphic rocks from this terrain record multiple tectonothermal events. Two of these events, represented by (1) high-P tectonic blocks within (2) a wide zone of mylonitic tectonites, reflect involvement of deep crust in a mobile continental lithosphere. These events may reflect stages in the development of an early collisional or subduction-type orogen, followed by later orogen-parallel ductile shear within thickened crust. The age of the early phase is uncertain, but the major ductile tectonite-forming deformation is probably latest Proterozoic to Early Cambrian in age. Deep-crustal tectonism as represented by the Nimrod structures differs in style, geometry and kinematics from generally coeval shallow-level contractional structures in the Beardmore and Byrd groups, yet these deformation events may together reflect an overall translational or oblique-convergence tectonic regime.

Key words: petrogenesis, high-grade metamorphism, Nimrod Group, deformation, tectonic evolution

Introduction

Metamorphic terrains with Precambrian heritage are sparse in the Transantarctic Mountains. The only terrains with a demonstrated Precambrian tectonic history are the Nimrod Group in the Nimrod Glacier area (Gunner and Mattinson, 1975; Goodge et al., 1991), the Read Group in the Shackleton Range (Pankhurst et al., 1983), and the Wilson Group in northern Victoria Land (Sheraton et al., 1987). These rocks represent areally limited and isolated parts of the East Antarctic craton near the outer edge of the Gondwana supercontinent. The importance of these rocks lies in their inferred position near a Proterozoic proto-Pacific-Gondwana plate boundary, offering the opportunity to study the relation between the Archean-Proterozoic craton and younger crustal elements formed along the active plate margin.

In this paper, we present evidence for two tectonometamorphic events within the Nimrod Group: an early high-P, high-T lower-crustal event, possibly related to subduction and/or continental collision, followed by a mid-crustal event at somewhat lower P and T, involving orogen-parallel ductile shear. These tectonic events likely had profound influence on the Late Proterozoic to early Paleozoic evolution of the Ross Sea margin of the East Antarctic craton. Here we focus on petrologic and structural evidence for these events, and we address tectonic relations between the Nimrod Group and outboard assemblages.

Geologic Setting

Rocks of the Precambrian Nimrod Group are exposed in the Miller and Geologists ranges of the central Transantarctic Mountains (Fig. 1). In terms of lithology, age, metamorphism and structural relations, these rocks are unique in the Ross Sea sector of the Transantarctic Mountains, although counterparts may exist in Victoria Land and the Shackleton Range. In the central Transantarctic Mountains in the vicinity of Nimrod Glacier, Precambrian metamorphic rocks, upper Precambrian-lower Paleozoic sedimentary sequences, and Cambrian-Ordovician granitoids unconformably underlie generally flat-lying, Devonian-Jurassic Gondwana.

sediiments (Gunn and Walcott, 1962; Grindley et al., 1964; Grindley and McDougall, 1969; Laird et al., 1971; Rowell et al., 1988; Borg et al., 1990; Goodge et al., 1991). Basement lithotectonic units in this area include: (1) the Precambrian Nimrod Group, consisting of strongly deformed high-grade gneisses and schists; (2) the Upper Proterozoic Beardmore Group, including a sequence of meta-carbonate and impure quartzite (Cobham Formation) that is conformably overlain by low-grade, unfoliated turbiditic greywacke and shale (Goldie Formation); (3) the Byrd Group, which includes Lower Cambrian shallow-water shelf carbonates (Shackleton Limestone), and unconformably overlying Middle to Upper Cambrian clastic units (Douglas Formation); and (4) Cambrian to Ordovician post-tectonic granitoid plutons (Hope suite) that intrude the units described above as part of a regionally extensive magmatic province.

On the basis of geologic and geochronologic evidence, several pre-Devonian deformation events have been recognized. These include: (1) the dominant Middle Cambrian to Early Ordovician Ross contractional orogeny; (2) an earlier, more cryptic event, the Beardmore orogeny, that produced contractional structures nearly coaxial with those of Ross age; and (3) a high-grade metamorphic and deformational history (Nimrod orogeny of Grindley and Laird, 1969) that is not expressed in younger sedimentary units. However, evidence for a distinct Proterozoic Nimrod tectonic event has been questioned by Adams et al. (1982) and Stump et al. (1991). The plate tectonic setting for each of these orogenic episodes is uncertain, although the structural styles associated with the Beardmore and Ross events are most compatible with a convergent plate-margin shortening regime.

Geologic and structural relations of Nimrod Group rocks in the Miller Range have been described by Grindley et al. (1964), Gunner (1969), and Grindley (1972). More recent field data and interpretations from both the Miller and Geologists ranges are provided by Goodge et al. (1990b, 1991), and are briefly summarized below. High-grade schists and gneisses of the Nimrod Group consist of metasedimentary and metagneissous lithologies, including layered gneiss, amphibolite, pelitic schist, orthogneiss, migmatite, and calc-silicate. These rocks are intruded by several large Hope granite plutons, which exhibit sharp contacts against the country rocks. Nimrod metamorphic rocks contain pervasive well-developed L-S tectonite fabrics, consisting of a regionally SW-dipping foliation that is concordant with compositional layering, and a gently NW- or SE-plunging mineral elongation lineation. Lineations plunge predominantly to the NW. Both mesoscopic and microscopic textural relations indicate the rocks formed during consistently SE-directed ductile shear in a direction parallel to elongation lineation (Goodge et al., 1991; Hansen and Goodge, 1991; Hansen et al., unpublished data).

Nimrod Dynamothermal Events

In this section we discuss petrologic and structural evidence for two distinct dynamothermal events. Both of these events occurred in the middle to lower crust, and, although there is only cryptic evidence for the first, they both probably resulted from large-scale crustal displacements.

---

Deep-crustal metamorphism and formation of eclogites

Evidence for the first tectonometamorphic event is derived from numerous mafic and ultramafic tectonic blocks hosted by the layered, ductilely-deformed schists and gneisses described above. Tectonites throughout the Miller and Geologists ranges enclose sub-spherical to ellipsoidal blocks of mafic and ultramafic composition that generally range in size from 0.5–50 m (Fig. 2). Tectonite foliation in the host rocks wraps around the blocks, indicating they behaved as relatively rigid bodies in the ductile matrix (Fig. 3).

Many large mafic blocks contain cores of fine-grained, partially preserved eclogitic mineral assemblages, surrounded by coarser rings of (garnet-jamphibolite (unpublished data). Initial metamorphism of blocks in the eclogite facies is indicated by pyrope-rich relict garnets ($X_{Mg} = 0.47$), Mg-rich staurotite ($Mg/Mg+Fe = 0.58$) inclusions in garnet from a block rim, and coronal plagioclase reaction rims around garnets. Subequidimensional proportions of relict garnet

![Fig. 2. Geologic map of the Gerard Bluffs area of the southern Miller Range (Goodge et al., unpublished mapping). Nimrod units divisible into four major lithologic types (grossly similar to formations designated by Grindley et al., 1964), although each subunit contains a variety of lithologies at a scale too small to represent here. All Nimrod lithologies contain pervasive L-S fabrics, and these are folded about mesoscopic upright, gently NW-plunging folds ($F_{P2}$ in text); regionally, tectonite foliation dips moderately southwest. Inset shows location within the upper Nimrod Glacier area, and shows general distribution of Nimrod metamorphic rocks (shaded) and Hope granite plutons (dash pattern). GR = Geologists Range; MR = Miller Range.](image-url)
Fig. 3. Sketch showing outcrop and mineralogical characteristics of mafic tectonic blocks. Mafic block cores contain relict eclogite-facies assemblages (light shading), and block rims contain amphibolite-facies overprint parageneses (dark shading). Pelite tectonites contain Ky-bearing assemblages indicative of high-P amphibolite-facies deformation. Plagioclase veins cross-cut the blocks, and they display curved forms and tapered ends indicating formation during block rotation. Open arrows show sense of rotation of blocks, and shear sense in tectonite matrix is indicated.

and symplectites consisting of low-Na Cpx + Opx + Hbl + Pl + Qtz suggest these rocks formed from eclogite precursors containing garnet and omphacitic pyroxene. These mineral data indicate that the mafic blocks were metamorphosed initially under eclogite-facies conditions of $P = 12–25$ kbar and $T = 600^\circ$C (based on mineral assemblages and Mg-staurolite stability relations of Schreyer, 1988). Ultramafic blocks, although they do not exhibit mineral assemblages that are uniquely diagnostic of $P$ and $T$, indicate the involvement of deep crustal or upper mantle material within the deforming zone, either as relict subduction zone enclaves, or as tectonic slivers introduced during ductile flow.

Amphibolitic rims around the mafic blocks indicate a second phase of recrystallization following the eclogite-facies event. A common assemblage of Hbl + Pl ± Grt + Bt probably formed under upper amphibolite-facies conditions and may be isofacial with assemblages in the enclosing tectonite hosts (see section below). Curvilinear veins of plagioclase that cross-cut the blocks but do not extend into the matrix (Fig. 3) show a rotational sense consistent with shear sense in the enclosing matrix, indicating they formed as part of the amphibolite-facies overprint during block rotation within the matrix.

Mid- to deep-crustal dynamothermal metamorphism

A younger event affecting Nimrod Group rocks formed a regionally SW-dipping zone of pervasive mylonitic L-S tectonites that contain a gently-plunging, NW-trending elongation lineation (Fig. 2). Numerous macro- and microscopic kinematic indicators record regionally consistent along-strike displacement in a top-SE direction (present-day coordinates) throughout an exposed (i.e. minimum) structural thickness of about 12–15 km. Several types of folding accompanied ductile deformation (Fig. 4). Asymmetric cylindrical folds with axes normal to elongation lineation ($F_D$) formed during shear and show SE vergence consistent with other kinematic indicators. Non-cylindrical sheath folds ($F_P$) also formed during SE-directed shear and indicate high bulk shear strain (Cobbold and Quinquis, 1980). In addition, open cylindrical folds with axes parallel to elongation lineation ($F_{PB}$) formed during top-SE shear and probably reflect local constrictional strain (Hansen et al., unpublished data).

Deformation of the Nimrod tectonites occurred under high-$P$, high-$T$ conditions ($P \geq 8$ kbar; $T = 700^\circ$C) in the upper amphibolite to lower granulite facies, as shown by syn-kinematic Ky + Grt + Ms + Bt + Qtz in pelites, Hbl + Pl + Grt ± Cpx ± Czo in mafic rocks, and by thermobarometry (Goodge et al., 1990a, in press). High temperatures of deformation are also demonstrated by: (1) generally homogeneous garnet compositions, indicating syn- to post-shear diffusional homogenization; (2) preservation of well-defined quartz lattice preferred orientations, showing simple shear by high-temperature, high-strain intracrystalline deformation (Fig. 5); and (3) the presence of syn-kinematic, anatectic granitic sills and pegmatitic veins, which may have thermally enhanced ductility. Late syn-kinematic growth of sillimanite after kyanite reflects waning deformation along a combined cooling and decompression path. The preservation of high-$T$ tectonite fabrics over such a wide structural zone, in which mineral recrystallization did not keep pace with deformation, indicates that strain rates were high. The

Fig. 4. Block diagrams showing different mesoscopic fold types within Nimrod L-S tectonites. Open arrows show sense of shear. (a) Non-cylindrical sheath folds ($F_P$) with nose parallel to elongation lineation ($L_{21}$). These may form at high strains from asymmetric cylindrical folds with axes normal to elongation lineation ($F_D$). (b) Generally open cylindrical folds with axes parallel to elongation lineation ($F_{PB}$) that signify minor constrictional strain.
Fig. 5. Lower-hemisphere, equal-area stereonet diagrams of quartz c-axis fabrics measured in Nimrod quartzite tectonites. Horizontal line is foliation (S), and dot is elongation lineation (L). Contour intervals are given with standard deviation; total points counted shown in parentheses. Representative samples from Miller Range (a) and Geologists Range (b). The well-developed single-girdle fabrics record activity along rhombohedral and prismatic slip systems, and they lack evidence of basal slip. Such patterns are indicative of high-temperature, high-strain simple shear deformation (Jessel and Lister, 1990).

Fig. 6. P-T-displacement evolution of Nimrod petrotectonic events. (a) P-T conditions of eclogites, constrained by general eclogite facies boundary and stability field of Mg-rich staurolite (Schreyer, 1988). Symplectite textures indicate late decompression along a nearly isothermal path to the peak conditions of Nimrod tectonites. Reference geotherms shown by dashed lines, and facies boundaries shown by dashed bands. (b) Schematic P-T diagram of Nimrod tectonite evolution, with conditions of eclogitic blocks from (a) as reference. Prograde path in Ky stability field from St + Ky inclusions in Grt (path shows general form only, actual location is undetermined). Peak tectonite conditions given from coexisting Ky + Ms + Grt and thermobarometry, as discussed in text. Late syn-kinematic growth of Sil after Ky suggests post-peak path of decompression and cooling. Preservation of quartz tectonite lattice preferred orientations reflects a period of post-kinematic, static cooling prior to post-tectonic thermal metamorphism in the vicinity of Hope granitic plutons. Age constraints are discussed in text. The complete history is one of a clockwise P-T loop such as reconstructed for collision orogens (Spear and Selverstone, 1983; Thompson and England, 1984). KFASH equilibria in (b) from Spear and Cheney (1989). Mineral abbreviations: Alm, almandine; And, andalusite; Ct, chloritoid; Kf, K-feldspar; Ky, kyanite; Sil, sillimanite; St, staurolite.
inferred high strain rates required to allow for the formation and preservation of this minimum 12–15 km-thick zone of L-S tectonites suggests that extremely rapid displacement rates operated along this ancient crustal boundary. High displacements may have allowed for tectonic incorporation of the earlier-formed deep-crustal or mantle materials into the crustal-penetrating zone, and for movement of sedimentary protoliths to deep crustal levels. We characterize this major Nimrod event as dynamothermal in nature based on the inferred high $P$-$T$ conditions, large displacements, and probable high strain rates.

**Pressure-Temperature-Displacement-Time Evolution**

The petrologic and structural relations summarized above allow us to construct a preliminary petrotectonic model for the $P$-$T$-displacement evolution of Nimrod tectonites (Fig. 6), constrained on the basis of textural, mineralogical, and thermobarometric data.

1. Mafic blocks enclosed by tectonites contain relict eclogite-facies mineral assemblages, and the preservation of Mg-rich staurolite indicates high-$P$ metamorphism (Fig. 6a). The formation of synplectitic intergrowths in these rocks suggests a general isothermal decompression path (e.g. Harley, 1985, 1991), prior to partial overprinting by amphibolite-facies parageneses around block margins. Eclogitic mineral assemblages and the occurrence of ultramafic blocks within the tectonites suggest involvement of deep-crustal or upper mantle materials, perhaps as part of a collisional orogen marked by large-magnitude crustal shortening.

2. Pelitic rocks reveal a great deal about the $P$-$T$-displacement history of Nimrod tectonites. Staurolite and kyanite inclusions in garnet record a reaction sequence involving breakdown of staurolite, defining a prograde path under high-$P/T$ conditions (Fig. 6b). Peak syn-kinematic conditions in the stability range of kyanite + muscovite imply both high $P$ and $T$ prior to late syn-kinematic growth of sillimanite along a cooling and decompression path. The attainment of peak tectonic conditions may have occurred at the same time that mafic and ultramafic blocks experienced decompression as they were incorporated into the shear zone (i.e. the $P$-$T$ paths of blocks and matrix converged during this second phase of tectonism). Ductile displacement was followed by a period of static cooling, as indicated by annealed grain boundaries. The tectonites were finally involved in contact metamorphism in the vicinity of Ross-age (Hope) plutons, as shown by local growth of radial fibrolitic sillimanite and formation of hornfels.

Constraints on the timing of these orogenic events are incomplete, and ongoing research is aimed at providing improved age control by application of high-$T$ thermochronometers. The strong thermal effects of Ross-age magmatism on Nimrod tectonites is evident from $^{40}Ar/^{39}Ar$ mineral ages, which show closure at ~500 Ma following detectable but irresolvable earlier (Proterozoic?) events (Goodge and Dallmeyer, 1992). A $^{207}Pb/^{206}Pb$ zircon age of 1.72 Ga from ductily-deformed orthogneiss provides a maximum age on ductile shear (V. C. Bennett, unpublished data), yet other deformed granitoids and syn-tectonic pegmatites give concordant U-Pb zircon ages as young as 540–520 Ma (Walker and Goodge, 1991), providing the first reliable evidence that Nimrod ductile tectonism probably lasted to latest Proterozoic to Early Cambrian time.

**Regional Tectonic Significance**

From petrologic and structural relations, we suggest a two-stage tectonic model to explain the petrotectonic evolution of the Nimrod metamorphic terrain (Fig. 7). Entrainment of eclogitic and ultramafic materials suggests either an initial phase marked by significant thickening of continental lithosphere as in a collisional setting, or development of a convergent-margin accretionary complex into which high-grade exotic blocks were mixed. Mid- to deep-crustal duc-

---

**Early to Mid-Proterozoic Nimrod Tectonics**

![Schematic diagram illustrating two-stage tectonic model for petrotectonic evolution of Nimrod metamorphic terrain. An early phase involving collision (a) and/or subduction (b) preceded a translational or transpressional phase as shown in (c). See text for details. EAC = East Antarctic craton.](attachment:image.png)
tile shear, a wide zone of displacement, a lack of brittle
deformational overprinting, and orogen-parallel displace-
ments all are consistent with a later transcrustal or
transpressional phase that may have resulted in continental-
marginal truncation. As illustrated in Fig. 7, the inferred
events may be related phases of one overall convergent
tectonic regime between rocks of the East Antarctic craton
and another craton or lithospheric fragment. The first stage
may either represent an Alpine-type continental collision
(Fig. 7a), or development of a Franciscan-type, subduction-
related accretionary complex within which high-grade mafic
and ultramafic blocks were entrained (Fig. 7b). Both of
these scenarios involve shortening, either by orthogonal or
oblique convergence along an active Antarctic plate
boundary. This early stage was followed by transcrustal to
transpressional movements within the lower part of possibly
thickened crustal lithosphere (Fig. 7c).

As noted above, thermochronological studies are in
progress to provide better constraints on the timing of these
events. Previously, others have raised the possibility that
metamorphic and deformation events in the Nimrod Group
are Late Proterozoic in age, thereby correlating them with
the Beardmore orogeny (Stump et al., 1991). Tight con-
straints on the timing of Beardmore deformation are lack-
ning, however, due to poor age control. Our field investiga-
tion of rocks of the Beardmore Group in the Shackleton
Coast area show significant differences in lithologic asso-
ciations, structural geometries and kinematics, metamorphic
parageneses, and crustal levels during orogenesis (Goode
et al., in press), indicating that Nimrod and Beardmore rocks
have experienced stylistically and kinematically different
deformations. Thermochronometric data from the Nimrod
tectonites indicate that the principal ductile deformation is
as young as about 540–520 Ma (Walker and Goode, 1991),
although it may also be older. This time period is generally
coincident with that of deposition and deformation of Lower
Cambrian Byrd Group carbonates, suggesting an orogenic
link to Ross, rather than Beardmore, contraction.

Whatever information future studies reveal in the way of
a more precise chronology, our petrologic and structural
data support the occurrence of at least two phases of mid-
to-deep crustal tectonism within rocks of the Nimrod Group
that are not recognized in outboard terranes. If these Nimrod
events are indeed as young as the profound Ross deforma-
tion, a tectonic model for the region is required that explains
the disparate metamorphic and structural histories of the
distinct lithotectonic belts. Most importantly, the along-
orogen displacements during Nimrod ductile deformation
must be reconciled with the shallow-crustal, orogen-normal
contraction recognized in the Beardmore and Byrd groups.
Structural patterns of this type may signify the operation of
a large-scale translational or transpressional regime along
the proto-Pacific Antarctic margin.

Acknowledgements

We wish to thank Scott Borg, David Dallmeyer, Brad
Smith, Ed Stump, and Nick Walker for discussion of the
ideas presented in this paper, although any fallacious inter-
pretations remain our own. This work was supported by a
grant from the U.S. National Science Foundation (DPP88-
16807).

REFERENCES

Orogenic history of the central Transantarctic Mountains: New K-Ar
age data on the Precambrian-Lower Paleozoic basement. In Antarctic
Geoscience, ed. C. Craddock, Madison, University of Wisconsin Press,
817–826.

BORG, S. G., DePAOLO, D. J. and SMITH, B. M. (1990): Isotopic
structure and tectonics of the central Transantarctic Mountains. Journal
of Geophysical Research, 95, 6647–6669.


constraints on the Paleozoic tectonothermal evolution of high-grade
basement rocks within the Ross orogen, central Transantarctic Moun-

GOODGE, J. W., HANSEN, V. L. and WALKER, N. W. (1992): Geo-
logic relations of the upper Nimrod Glacier region, central Transantarctic
Mountains: Evidence for multiple orogenic history. Antarctic Journal of
the United States, 26(5), 4–6.

GOODGE, J. W., BORG, S. G., SMITH, B. K. and BENNETT, V. C.
(1991): Tectonic significance of Proterozoic ductile shortening and
translation along the Antarctic margin of Gondwana. Earth and Plan-
etary Science Letters, 102, 58–70 (see also erratum, 104, p. 116).

GOODGE, J. W., HANSEN, V. L., PEACOCK, S. M. and SMITH, B. K.
(1990a): Deep-crustal ductile deformation within the central
Transantarctic Mountains. Eos, 71, 643.

GOODGE, J. W., HANSEN, V. L., PEACOCK, S. M. and SMITH, B. K.
(1990b): Metamorphic rocks in the Geologists and Miller Ranges,
Nimrod Glacier area, central Transantarctic Mountains. Antarctic

GRINDLEY, G. W. (1972): Polyphase deformation of the Precambrian
Nimrod Group, central Transantarctic Mountains. In Antarctic Geol-
yogy and Geophysics, ed. R. J. Adie, Oslo, Universitetsforlaget, 313–
318.

Coast, Antarctica (Sheet 15). In Geologic Maps of Antarctica, Anti-
artic Map Folio Series, Folio 12, ed. V. C. Bushnell and C. Craddock,
New York, American Geographical Society.

GRINDLEY, G. W. and McDOUGALL, I. (1969): Age and correlation of
the Nimrod Group and other Precambrian rock units in the central
Transantarctic Mountains, Antarctica. New Zealand Journal of Geol-
yogy and Geophysics, 12, 391–411.

GRINDLEY, G. W., Mcgregor, V. R. and WAlcott, R. L. (1964):
Outline of the geology of the Nimrod-Beardmore-Aval Heiberg Glac-
iers region, Ross Dependency. In Antarctic Geology, ed. R. J. Adie,

Markham region, Ross Dependency, Antarctica. New Zealand Journal

GUNNER, J. (1969): Petrography of metamorphic rocks from the Miller
Range, Antarctica. Institute of Polar Studies Report No. 32, Columbus,
Ohio State University, 44p.

GUNNER, J. and MATTINSON, J. M. (1975): Rh-Sr and U-Pb isotopic
ages of granites in the central Transantarctic Mountains. Geological

Miller Range shear zone, Transantarctic Mountains: Evidence of deep-
crustal plate boundary deformation. Geological Society of America
Abstracts with Programs, 23, 304.

HARLEY, S. L. (1985): Paragenetic and mineral-chemical relationships
in orthoamphibole bearing gneisses from Enderby Land, east Antarctica:
a record of Proterozoic uplift. Journal of Metamorphic Geology, 3, 179–
200.

HARLEY, S. L. (1991): Metamorphic evolution of granulites from the
Rauer Group, East Antarctica: evidence for decompression following
Proterozoic collision. In Geological Evolution of Antarctica, ed. M. R.


