

2.5 b.y. of punctuated Earth history as recorded in a single rock

John W. Goodge* Department of Geological Sciences, Southern Methodist University, Dallas, Texas 75275-0395, USA
C. Mark Fanning Research School of Earth Sciences, Australian National University, Mills Road, Canberra, ACT 0200, Australia

ABSTRACT

Deciphering the absolute chronology of ancient crustal rocks is often problematical because of isotopic reequilibration and/or mixing during multiple geologic events. Ion probe U-Pb age data from texturally distinct zircon crystal domains in a single sample of high-grade gneiss from the Nimrod Group in Antarctica reflect successive resorption and crystallization under disequilibrium conditions. Our data indicate that Archean crust of the East Antarctic shield, initially formed from juvenile magmas ca. 3000 Ma, extends to the central Transantarctic Mountains. Successive zircon growth ca. 2955, 1720, and 530 Ma records a sequence of distinct, widely spaced high-temperature metamorphic and/or anatexis events related to Archean, Paleoproterozoic, and Eocambrian orogenesis.

INTRODUCTION

The East Antarctic shield (Fig. 1A) is one of Earth's oldest cratonal elements. Although Antarctica is mostly ice covered, basement exposures around its outer margin record a long Early Archean to Neoproterozoic history (Tingey, 1991). Perhaps the least known part of the East Antarctic shield underlies the Transantarctic Mountains, marked chiefly by deformed Neoproterozoic and lower Paleozoic sedimentary sequences of the Ross orogen. Basement rocks of the Nimrod Group (Fig. 1) provide a rare window into the East Antarctic shield.

The Nimrod Group bears a clear metamorphic and structural imprint of Ross orogenesis ca. 550–520 Ma (Goodge and Dallmeyer 1992, 1996; Goodge et al., 1993a, 1993b), but its pre-Ross history remains obscure. U-Pb and Sm-Nd data indicate a Precambrian history (Borg et al., 1990; Walker and Goodge, 1991; Bennett and Fanning, 1993), but it is difficult to resolve specific geologic events. Here we present new SHRIMP ion probe U-Pb zircon ages from one sample of upper amphibolite facies Nimrod Group gneiss that show a punctuated succession of igneous and metamorphic events. The pre-Ross geologic history retained in this single rock correlates with other parts of the East Antarctic shield and reveals a unique record of at least three distinguishable geologic events spanning 2.5 b.y.

GEOLOGIC SETTING

The Nimrod Group (Fig. 1B) is a heterogeneous metamorphic complex of banded quartzofeldspathic to mafic gneiss, schist and quartzite, granitic to gabbroic orthogneiss, calc-silicate gneiss, relict eclogite, and pods of ultramafic rocks (Grindley et al., 1964; Grindley, 1972; Goodge et al., 1993a; Peacock and Goodge, 1995). Pervasive tectonite fabrics record mid-crustal Ross deformation (Goodge et al., 1993a) prior to Early Ordovician granitoid intrusion (Gunner and Mattinson, 1975).

Nimrod Group age data reveal a Precambrian history overprinted by younger Ross events. U-Pb zircon ages of 3.29–3.06 Ga (Bennett and Fanning, 1993), and whole-rock Nd-model ages of 3.10–2.72 Ga and $\epsilon_{Nd}(0)$ values of –33 to –28 (Borg et al., 1990; Borg and DePaolo, 1994), suggest that Nimrod protoliths include Middle to Late Archean materials. A quartzite yielded detrital zircon U-Pb ages of 2.5–1.7 Ga (Walker and Goodge, 1991), compatible with an East Antarctic shield provenance. Igneous and metaigneous rocks range from strongly deformed orthogneisses and syntectonic sills to undeformed posttectonic plutons. A tectonized orthogneiss that crosscuts gneisses structurally and lithologically equivalent to the sample discussed here has a 1.73 Ga $^{207}\text{Pb}/^{206}\text{Pb}$ crystallization age (Bennett and Fanning, 1993), reflecting Paleoproterozoic

magmatism. Syntectonic intrusive units are 540–520 Ma (Goodge et al., 1993b), whereas post-tectonic plutons are 500–475 Ma (Gunner and Mattinson, 1975). The U-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ ages from high-temperature, fabric-forming minerals indicate that the latest dynamothermal events occurred ca. 550–520 Ma (Goodge and Dallmeyer, 1992, 1996; Goodge et al., 1993b), signaling the response of cratonic basement to Ross-age plate margin deformation.

SHRIMP U-Pb RESULTS

Sample 85-20H is a banded hornblende-biotite gneiss from Camp Ridge in the west-central Miller Range (Fig. 1B). Here, heterogeneous gneiss and schist—including amphibolite, hornblende-biotite gneiss, quartzofeldspathic and pegmatitic gneiss, and muscovite-kyanite schist—enclose tectonic blocks of remnant eclogite (Peacock and Goodge, 1995). Sample 85-20H contains quartz, plagioclase, K-feldspar, biotite, and hornblende, with accessory epidote, chlorite, Fe-oxide, titanite, zircon, and apatite. The most recent metamorphic conditions were about 700 °C and 8–12 kbar (Goodge et al., 1992).

The SHRIMP U-Pb analytical procedures follow those outlined by Williams (1998) and references therein. Standard techniques were used to separate zircons and prepare a sectioned epoxy

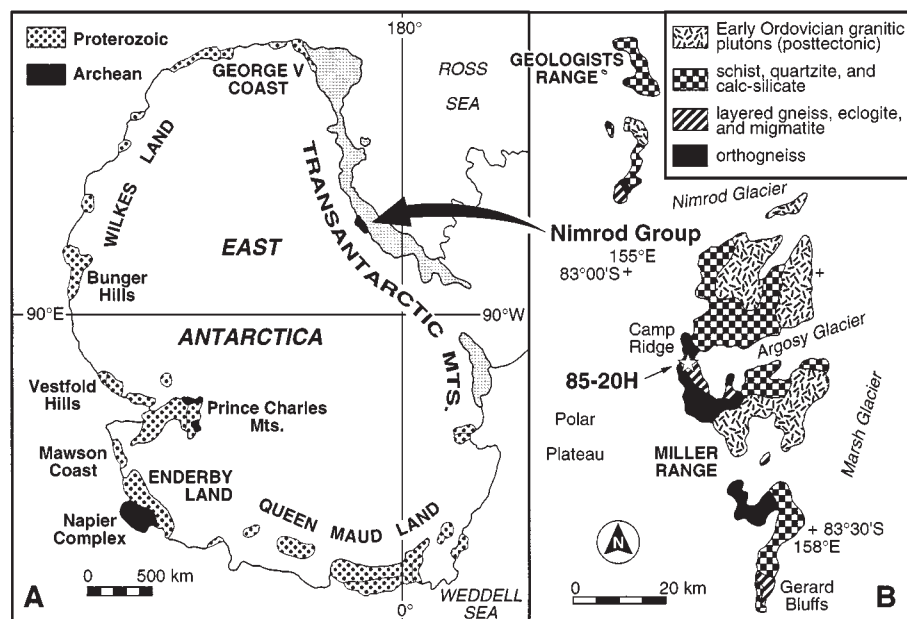


Figure 1. A: Map of Archean and Proterozoic basement in East Antarctica and location of Nimrod Group in Transantarctic Mountains. B: Major geologic units of Nimrod Group and location of sample 85-20H (star).

*E-mail: jgoodge@mail.smu.edu.

Data Repository item 9986 contains additional material related to this article.

disk with representative grains from 85-20H and the AS3 reference zircon (Paces and Miller, 1993). Cathodoluminescence (CL) images were used to identify zircon crystal domains (Fig. 2).

We analyzed 22 individual grains from 85-20H during a single extended SHRIMP II analytical session. Most grains comprise discrete centers with overgrowths, yielding 34 individual U-Pb ages (Table 1¹; Fig. 3). Errors for individual analyses are quoted at the 1 σ level; however, all age calculations are given with uncertainties at 95% confidence levels.

Cores

Most of the zircons show distinct inner cores, typically as equant or prismatic domains with

¹GSA Data Repository item 9986, Table 1, Summary of SHRIMP U-Pb zircon results for sample 85-20H from the Nimrod Group, central Transantarctic Mountains, Antarctica, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or at www.geosociety.org/pubs/ drprint.htm.

faceted to round shape. Their internal growth structure includes parallel oscillatory banding (Fig. 2A, grain 14), oscillatory sector zoning (Fig. 2, B and C, grains 2, 3, 21), and mottled texture (Fig. 2D, grain 22). Oscillatory banding and sector zoning are common in igneous zircons (e.g., Vavra, 1990), whereas the mottled texture resembles that of metamorphic recrystallization. Many cores are bounded by discontinuity surfaces (grains 1, 3, 8, 14, 21, 22) and/or embayments (grain 21, and grains not analyzed in Fig. 2, A, B, and D), reflecting partial zircon dissolution or melting after initial crystallization. We interpret that the cores crystallized from an igneous melt, followed by recrystallization and grain-boundary dissolution by metamorphism or partial melting.

Analyses of cores yield two main age populations (Fig. 3B): one with ²⁰⁷Pb/²⁰⁶Pb ages between 3139 and 3056 Ma (mean of 4 ages is 3094 Ma) and a second between 3012 and 2927 Ma (mean of 14 ages is 2980 Ma). Bennett and Fanning (1993) reported similar ages from a gneissic unit north of Argosy Glacier (populations at 3055

and 3154 Ma). One grain (3; Fig. 2B) shows a banded, low Th/U core surrounded by a wide, CL-dark rim across an irregular discontinuity, indicating igneous crystallization at 3015 Ma followed by resorption and new metamorphic growth ca. 2955 Ma. Grain 3, the only grain with an Archean core and overgrowth, indicates that magmatism was followed closely by high-grade metamorphism. All but two zircons yielded ages concordant to within 5% (Table 1; see footnote 1); slightly discordant analyses project to either 1720 or 530 Ma (Fig. 3, A and B), reflecting radiogenic Pb loss during two younger events.

We interpret the old zircons as primary magmatic grains. Their ages reflect formation of an igneous parent modified by subsequent Paleoproterozoic and late Neoproterozoic dynamothermal events. The clustered ages may reflect magmatism ca. 2980 Ma with minor inheritance of ca. 3150–3100 Ma zircon. Similarity of the zircon crystallization ages with whole-rock Nd-model ages (Borg et al., 1990) suggests that this Archean magmatism produced primary, juvenile crust of the East Antarctic shield. Although a detrital origin is possible, we favor an igneous origin on the basis of grain morphology, internal structure, correspondence with Nd isotopic data, and the discrete ages.

1720 Ma Overgrowths

A distinctive zircon domain is dark and texturally homogeneous, appearing either featureless or weakly sector zoned with CL (average Th/U = 0.28). It occurs both as cores to prismatic grains (Fig. 2C, grain 8) and as wide overgrowths on Archean cores (Fig. 2C, grain 2). Overgrowths cover cores showing rational crystal faces (grain 2) or slightly round external shapes (grains 14, 22), suggesting topotactic growth on a primary or weakly modified core. These cores and overgrowths show an absence of oscillatory zoning, consistent with metamorphic growth.

Analyses of 7 such domains yielded a weighted mean ²⁰⁷Pb/²⁰⁶Pb age of 1723 ± 14 Ma, with some discordance toward 530 Ma (Fig. 3C). Two analyses (12.1 and 20.1) yielded highly discordant ages that reflect significant Pb loss ca. 1720 and/or 530 Ma. Six of the seven domains are wide overgrowths on Archean cores with prismatic external terminations. The scale, morphology, and internal structure of these overgrowths indicate that the 1720 Ma event involved new metamorphic grain growth, as opposed to anatexis or recrystallization, because (1) oscillatory growth zoning is absent; (2) Th/U ratios are low; (3) the domains consist of both core (new grain) and rim (overgrowth), not expected if growth was by recrystallization alone; and (4) concordant, post-Archean ages signal zircon growth in disequilibrium with cores and not simple recrystallization of preexisting crystals. The 1720 Ma domains may therefore reflect high-temperature heating during crustal orogenesis and magmatism.

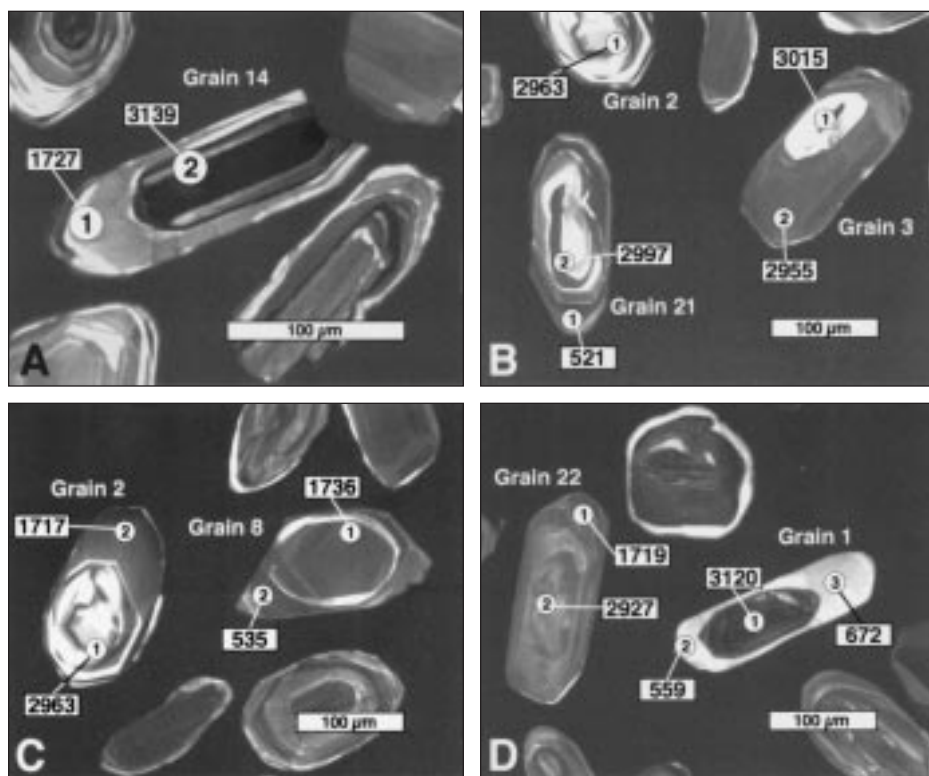


Figure 2. Cathodoluminescence (CL) images of representative zircons from 85-20H, showing locations and sizes of analysis areas. Generally, bright areas have low Th/U ratios and dark areas have higher Th/U (except for grains with $U = 10^3$ – 10^4 ppm, which also appear dark in CL). Each analyzed grain shows analysis number (circled) and interpreted U-Pb age (rectangle) in Ma (generally ²⁰⁷Pb/²⁰⁶Pb age for ca. 3000 and 1720 Ma zircons, and ²⁰⁶Pb/²³⁸U age for ca. 530 Ma zircons). A: Grain 14, showing Archean core with magmatic growth banding, and Proterozoic overgrowth. B: Grains 2, 3, and 21, showing Archean sector zoning indicative of igneous growth with possible metamorphic crystallization. Grain 3 shows Archean metamorphic overgrowth around remnant Archean core, and grain 21 shows Ross-age overgrowth on partly resorbed core. C: Grains 2 and 8, showing ca. 1720 Ma metamorphic overgrowth on Archean core (grain 2) and weakly sector zoned metamorphic core (grain 8) mantled by zoned Ross-age overgrowth. D: Grains 1 and 22, showing mottled, strongly recrystallized Archean cores with ca. 1720 and 530 Ma overgrowths (see text for discussion of 672 Ma age of grain 1.3).

530 Ma Overgrowths

The fourth type of zircon consists of thin, prismatically terminated rim overgrowths on round cores (several grains in Fig. 2, A, C, and D), and wide overgrowths (Fig. 2, C and D; grains 1, 8) and euhedral crystals with sector growth zoning (grain 4, not shown). Rims occur on both 3000 and 1720 Ma cores, many <10 μm wide. This type is bright in CL, reflecting very low Th ($\text{Th}/\text{U} \leq 0.05$). These domains are texturally homogeneous, but some show oscillatory sector zoning. Structureless overgrowths have very low U contents (≤ 25 ppm) and are probably of metamorphic origin. Zoned overgrowths have high U values (≥ 600 ppm); they occur on round or embayed cores with marked angular discordance, indicating crystallization on dissolution surfaces formed by partial melting.

Six areas of this type yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 529 ± 7 Ma (total age range of 559–521 Ma). One rim has a $^{206}\text{Pb}/^{238}\text{U}$ age of 672 Ma, either a product of open-system isotopic exchange or analysis of multiple domains. We interpret the six younger ages to reflect new zircon growth ca. 530 Ma, by either metamorphism or anatexis. They correspond with Ross orogenic activity in the region, and they overlap U-Pb ages for igneous and metaigneous rocks in the Nimrod Group (Goodge et al., 1993b).

DISCUSSION

Ours is not the first study to use the spatial resolution of the ion probe and CL imaging to isolate different zircon age domains, although few show more than two events. For example, Black et al. (1986) obtained multiple zircon ages from a granulite facies orthogneiss from Enderby Land (Fig. 1A), which they attributed to four geologic events between 3930 and 1000 Ma. Despite strong discordance and age dispersion, reflecting multidomain mixing, they reconstructed an Archean and post-Archean history. Vavra et al. (1996) distinguished multiple growth zones in zircons from granulite facies gneisses of the Ivrea zone, which they related to two stages of igneous crystallization and anatectic or metamorphic overgrowth. By combining zircon results from both metasedimentary and metaigneous lithologies, Vavra et al. (1996) deciphered a multistage Variscan and post-Variscan history.

By contrast, we obtained concordant but systematically different U-Pb ages from distinct zircon growth domains in a single rock sample. The ages recognized can be attributed to known or inferred geologic events. The morphology, element ratios, and age patterns of zircon cores with planar or oscillatory growth banding and prismatic terminations (3139–3056 Ma) suggest magmatic growth. The lack of ages older than ca. 3.1 Ga and the prismatic character of the cores suggest that this rock has an igneous, rather than sedimentary, precursor. Archean magmatism is consistent with Sm-Nd isotopic evidence for juvenile crust formation at this time (Borg et al.,

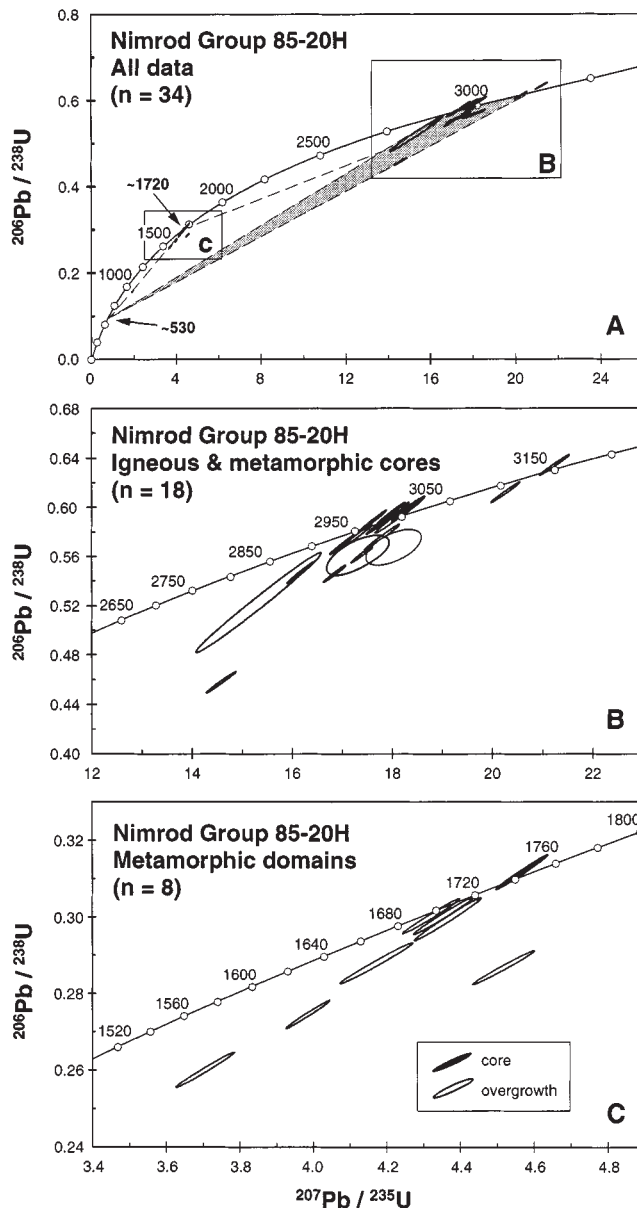


Figure 3. Concordia diagrams for sample 85-20H zircons. Uncertainties are 1σ . A: All analyses. Dashed lines show generalized mixing trends attributed to Pb-loss events ca. 1720 and 530 Ma. B: Zircon cores and grains yielding ca. 3000 Ma ages. C: Zircon core (black) and overgrowths (unfilled) yielding ca. 1720 Ma ages.

1990). Magmatism was followed closely by high-temperature metamorphism, shown by slightly younger (2955–2927 Ma) mottled or recrystallized zircons, that may be a consequence of high advective heat transfer associated with magmatism. Alternatively, the younger domains may represent postmagmatic (nonmetamorphic) recrystallization, but this is less likely because the mottled zircons give consistently younger ages than the growth zones, rather than isochronous ages with greater concordance.

Zircon overgrowths on Archean cores represent metamorphic and/or anatectic modifications to this rock ca. 1720 and 530 Ma. Cores showing round or embayed shapes indicate resorption via metamorphic mineral reaction or melting, but prismatic cores with terminated overgrowths suggest topotactic crystallization of secondary zircon. Wide overgrowths of both ages reflect

substantial new zircon growth at high temperature. Our data for the 1720 Ma overgrowths are the first to define reliably a period of Paleoproterozoic metamorphism in basement of the Transantarctic Mountains, and they correspond well with SHRIMP ages from two other Nimrod lithologies. Granodioritic orthogneiss with a crystallization age of 1733 Ma crosscuts layered gneisses near the 85-20H sample locality (Bennett and Fanning, 1993). Zircons from this orthogneiss show no evidence of inheritance, yet a 2.73 Ga Nd model age (Borg et al., 1990) indicates melting of preexisting Archean crust. An eclogitic pod enclosed by layered gneisses near Gerard Bluffs in the southern Miller Range (Fig. 1B) yielded exclusively small, equant zircons with internal sector zoning, low U contents, and low Th/U ratios, suggesting a metamorphic origin; 27 concordant SHRIMP analyses yielded a

weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1704 Ma. Together, these data reveal an important period of orogenic activity ca. 1730–1700 Ma, and they may constrain the true age of the Nimrod orogeny as originally conceived by Grindley and Laird (1969). We emphasize, however, that Paleoproterozoic orogenesis is evident only from the zircon U-Pb ages obtained by ion microprobe; the present metamorphic and structural character of the Nimrod Group is primarily a manifestation of younger Ross orogenic activity (Goodge et al., 1993a, 1993b; Goodge and Dallmeyer, 1992, 1996). Nonetheless, the SHRIMP data from three petrologically different samples indicate that the Nimrod orogeny involved 1730 Ma magmatism, followed by metamorphism ca. 1720–1700 Ma. The high pressures and temperatures attending eclogite formation and magmatism suggest that the Nimrod orogeny involved crustal thickening brought about by plate convergence and/or collision.

We interpret the 530 Ma ages from thin rims and two euhedral-crystal fragments as dating high-grade metamorphism and/or ultrametamorphism in the Nimrod gneisses during the Ross orogeny. They overlap zircon ages from syntectonic plutonic bodies and monazite U-Pb ages from pelitic schists (541–521 Ma and 524 Ma, respectively; Goodge et al., 1993b). It is difficult to distinguish between a purely metamorphic (i.e., solid state) versus melt-crystallization origin for these zircons, because the Nimrod gneisses were subject to high-temperature (about 700 °C), high-strain ($\gamma \geq 5$ –10) metamorphism at this time (Goodge et al., 1992, 1993a). However, note that (1) a fourth episode of zircon growth at the Precambrian-Cambrian transition corroborates earlier evidence of basement reactivation during the Ross orogeny; and (2) Nimrod gneisses retain clear evidence of Archean and Paleoproterozoic events despite the high-temperature effects of this youngest orogenic phase.

In the broader context of cratonal evolution, our age data firmly establish the Nimrod Group as the only known Archean crust along the Transantarctic Mountains margin of East Antarctica. Archean basement occurs in several areas of East Antarctica (Fig. 1A), in many cases as relics within younger Proterozoic metamorphic terrains. U-Pb geochronology substantiates ca. 3000 Ma magmatism in a few areas, including the Bungler Hills (Black et al., 1992), Napier Complex (Sheraton et al., 1987), and Mawson Coast (Grew et al., 1988). Among these, rocks in the Bungler Hills have a notably similar history to that of the Nimrod Group. Here, tonalitic orthogneiss with a 3003 Ma zircon age also yielded ages reflecting granulite facies metamorphism ca. 2990 Ma and a younger disturbance ca. 600 Ma (Black et al., 1992). These events signal a period of Archean magmatism tied to high-grade metamorphism, followed by younger Pan-African thermal effects. Although

reliable geochronological evidence for mid-Archean events is sparsely scattered across East Antarctica, 3100–3000 Ma appears to be a time of major magmatism, deep-crustal metamorphism, and anatexis within incipient elements of the East Antarctic shield. The zircon ages reported here document a new area of early crustal growth associated with this vibrant period of activity. Our data thus show that Archean crust formed by ca. 3.0 Ga magmatism probably extends beneath the polar ice cap to the central Transantarctic Mountains, thereby enhancing the picture of crustal age provinces in the East Antarctic shield.

ACKNOWLEDGMENTS

The Office of Polar Programs at the U.S. National Science Foundation (grant OPP-9219818) supported this work. We thank Vickie Bennett and Ian Williams for discussion of our data, and Pat Bickford and Peter Gromet for helpful reviews.

REFERENCES CITED

- Bennett, V. C., and Fanning, C. M., 1993, A glimpse of the cryptic Gondwana shield: Archean and Proterozoic ages from the central Transantarctic Mountains: *Geological Society of America Abstracts with Programs*, v. 25, no. 6, p. 49.
- Black, L. P., Williams, I. S., and Compston, W., 1986, Four zircon ages from one rock: The history of a 3930 Ma-old granulite from Mount Sones, Enderby Land, Antarctica: *Contributions to Mineralogy and Petrology*, v. 94, p. 427–437.
- Black, L. P., Sheraton, J. W., Tingey, R. J., and McCulloch, M. T., 1992, New U-Pb zircon ages from the Denman Glacier area, East Antarctica, and their significance for Gondwana reconstruction: *Antarctic Science*, v. 4, p. 447–460.
- Borg, S. G., and DePaolo, D. J., 1994, Laurentia, Australia, and Antarctica as a Late Proterozoic supercontinent: Constraints from isotopic mapping: *Geology*, v. 22, p. 307–310.
- Borg, S. G., DePaolo, D. J., and Smith, B. M., 1990, Isotopic structure and tectonics of the central Transantarctic Mountains: *Journal of Geophysical Research*, v. 95, p. 6647–6669.
- Goodge, J. W., and Dallmeyer, R. D., 1992, $^{40}\text{Ar}/^{39}\text{Ar}$ mineral age constraints on the Paleozoic tectono-thermal evolution of high-grade basement rocks within the Ross orogen, central Transantarctic Mountains: *Journal of Geology*, v. 100, p. 91–106.
- Goodge, J. W., and Dallmeyer, R. D., 1996, Contrasting thermal evolution within the Ross orogen, Antarctica: Evidence from mineral $^{40}\text{Ar}/^{39}\text{Ar}$: *Journal of Geology*, v. 104, p. 435–458.
- Goodge, J. W., Hansen, V. L., and Peacock, S. M., 1992, Multiple petrotectonic events in high-grade metamorphic rocks of the Nimrod group, central Transantarctic Mountains, Antarctica, in Yoshida, Y., Kaminuma, K., and Shiraiishi, K., eds., *Recent progress in Antarctic earth science*: Tokyo, Terra Scientific, p. 203–209.
- Goodge, J. W., Hansen, V. L., Peacock, S. M., Smith, B. K., and Walker, N. W., 1993a, Kinematic evolution of the Miller Range shear zone, central Transantarctic Mountains, Antarctica, and implications for Neoproterozoic to early Paleozoic tectonics of the East Antarctic margin of Gondwana: *Tectonics*, v. 12, p. 1460–1478.
- Goodge, J. W., Walker, N. W., and Hansen, V. L., 1993b, Neoproterozoic-Cambrian basement-involved

- orogenesis within the Antarctic margin of Gondwana: *Geology*, v. 21, p. 37–40.
- Grew, E. S., Manton, W. I., and James, P. R., 1988, U-Pb data on granulite facies rocks from Fold Island, Kemp Coast, East Antarctica: *Precambrian Research*, v. 42, p. 63–75.
- Grindley, G. W., 1972, Polyphase deformation of the Precambrian Nimrod Group, central Transantarctic Mountains, in Adie, R. J., ed., *Antarctic geology and geophysics*: Oslo, Universitetsforlaget, p. 313–318.
- Grindley, G. W., and Laird, M. G., 1969, *Geology of the Shackleton Coast, Antarctica*, in Bushnell, V. C., and Craddock, C., eds., *Geologic map of Antarctica*: New York, American Geographical Society, Antarctic Map Folio Series, folio 12, sheet 15, scale 1:1 000 000.
- Grindley, G. W., McGregor, V. R., and Walcott, R. I., 1964, Outline of the geology of the Nimrod-Beardmore-Axel Heiberg Glaciers region, Ross Dependency, in Adie, R. J., ed., *Antarctic geology*: Amsterdam, North-Holland Publishing Company, p. 206–218.
- Gunner, J., and Mattinson, J. M., 1975, Rb-Sr and U-Pb isotopic ages of granites in the central Transantarctic Mountains: *Geological Magazine*, v. 112, p. 25–31.
- Paces, J. B., and Miller, J. D., 1993, Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic process associated with the 1.1 Ga Midcontinent Rift System: *Journal of Geophysical Research*, v. 98, p. 13,997–14,013.
- Peacock, S. M., and Goodge, J. W., 1995, Eclogite-facies metamorphism preserved in tectonic blocks from a lower crustal shear zone, central Transantarctic Mountains, Antarctica: *Lithos*, v. 36, p. 1–13.
- Sheraton, J. W., Tingey, R. J., Black, L. P., Offe, L. A., and Ellis, D. J., 1987, Geology of an unusual Precambrian high-grade metamorphic terrane—Enderby Land and western Kemp Land, Antarctica: *Australian Bureau of Mineral Resources Bulletin* 223, 51 p.
- Tingey, R. J., 1991, The regional geology of Archaean and Proterozoic rocks in Antarctica, in Tingey, R. J., ed., *The geology of Antarctica*: Oxford University Press Monograph on Geology and Geophysics 17, p. 1–73.
- Vavra, G., 1990, On the kinematics of zircon growth and its petrogenetic significance: A cathodoluminescence study: *Contributions to Mineralogy and Petrology*, v. 106, p. 90–99.
- Vavra, G., Gebauer, D., Schmid, R., and Compston, W., 1996, Multiple zircon growth and recrystallization during polyphase Late Carboniferous to Triassic metamorphism in granulites of the Ivrea Zone (Southern Alps): An ion microprobe (SHRIMP) study: *Contributions to Mineralogy and Petrology*, v. 122, p. 337–358.
- Walker, N. W., and Goodge, J. W., 1991, Significance of Late Archaean–Early Proterozoic U-Pb ages of individual Nimrod Group detrital zircons and Cambrian plutonism in the Miller Range, Transantarctic Mountains: *Geological Society of America Abstracts with Programs*, v. 23, no. 5, p. 306.
- Williams, I. S., 1998, U-Th-Pb geochronology by ion microprobe, in McKibben, et al., eds., *Applications of microanalytical techniques to understanding mineralizing processes: Reviews in Economic Geology*, v. 7, p. 1–35.

Manuscript received February 1, 1999
 Revised manuscript received July 8, 1999
 Manuscript accepted July 28, 1999