Provenance of Neoproterozoic and lower Paleozoic siliciclastic rocks of the central Ross orogen, Antarctica: Detrital record of rift-, passive-, and active-margin sedimentation

John W. Goodge[†]
Department of Geological Sciences, University of Minnesota, Duluth, Minnesota 55812, USA

Ian S. Williams[‡]
Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Paul Myrow[§]
Department of Geology, Colorado College, Colorado Springs, Colorado 80903, USA

ABSTRACT

Siliciclastic rocks in the Transantarctic Mountains record the tectonic transformation from a Neoproterozoic rift-margin setting to a passive-margin and ultimately to an active early Paleozoic orogenic setting along the paleo–Pacific margin of East Antarctica. New U-Pb detrital-zircon ages constrain both the depositional age and sedimentary provenance of these strata. In the central Transantarctic Mountains, mature quartz arenites of the late Neoproterozoic Beardmore Group contain Archean and Proterozoic zircons, reflecting distal input from the adjacent East Antarctic shield, Mesoproterozoic igneous provinces, and Grenville-age parts of East Gondwana. Similarly, basal sandstones of the Lower Cambrian Shackleton Limestone (lower Byrd Group) contain zircons reflecting a dominantly cratonic shield source; the autochthonous Shackleton was deposited during early Ross orogenesis, yet its basal sandstone indicates that the inner shelf was locally quiescent. Detrital zircons from the Koettlitz Group in southern Victoria Land show a similar age signature and constrain its depositional age to be ≤670 Ma. Significant populations (up to 22%) of ca. 1.4 Ga zircons in these Neoproterozoic and Lower Cambrian sandstone deposits suggest a unique source of Mesoproterozoic igneous material in the East Antarctic craton; comparison with the trans-Laurentian igneous province of this age suggests paleogeographic linkage between East Antarctica and Laurentia prior to ca. 1.0 Ga. In strong contrast, detrital zircons from upper Byrd Group sandstones are dominated by young components derived from proximal igneous and metamorphic rocks of the emerging Ross orogen. Zircon ages restrict deposition of this syn- to late-orogenic succession to ≤520 Ma (Early Cambrian or younger). Sandstone samples in the Pensacola Mountains are dominated by Grenville and Pan-African zircon ages, suggesting a source in western Dronning Maud Land equivalents of the East African orogen. When integrated with stratigraphic relationships, the detrital-zircon age patterns can be explained by a tectonic model involving Neoproterozoic rifting and development of a passive-margin platform, followed by a rapid transition in the late Early Cambrian (Botomian) to an active continental-margin arc and forearc setting. Large volumes of molassic sediment were shed to forearc marginal basins between Middle Cambrian and Ordovician time, primarily by erosion of volcanic rocks in the early Ross magmatic arc. The forearc deposits were themselves intruded by late-orogenic plutons as the locus of magmatism shifted trenchward during trench retreat. Profound syntectonic denudation, followed by Devonian peneplanation, removed the entire volcanic carapace and exposed the plutonic roots of the arc.

Keywords: Ross orogen, Antarctica, siliciclastic rocks, U-Pb, detrital zircons.

INTRODUCTION

Siliciclastic sedimentary successions provide important records of tectonic process and orogenic cycles. Foreland-basin successions, for example, record in detail the history of collisional orogens (Beaumont, 1981; Jordan, 1981; Allen et al., 1986; Dorobek and Ross, 1995), and siliciclastic rocks document processes that occur in other active tectonic settings, including migrating triple junctions (Crook, 1989), backarc environments (Wright et al., 1990), forearc basins (Lundberg, 1983), and collisional basins (Lundberg and Dorsey, 1988). A variety of tools—including facies analysis, sequence stratigraphy, uplift studies, and detrital-mineral geochronology—are commonly used to analyze the sedimentary response to tectonism, in particular the timing, rates, and provenance of deposition.

Applying these principles to sedimentary successions spanning the late Neoproterozoic and early Paleozoic is a potentially powerful way to assess fundamental changes that occurred during this critical period in Earth history. The geologic record across this time interval reveals important changes in Earth's linked tectonic, climatic, and biotic systems (Hoffman, 1991; Knoll and Walter, 1992; Brasier, 1992; Moores, 1993; Brasier et al., 1994). Fragmentation of the Rodinia supercontinent, and subsequent amalgamation of Gondwana, coincided with global mountain building, continental erosion, climate shifts, species diversification, sea-level fluctuations, and changes in seawater composition. Craton-margin sedimentary successions that span this transition, such as found on fragments of former Gondwana (notably western and eastern Laurentia, northeastern Asia, southern Africa, eastern Australia, and the Pacific margin of Antarctica), provide records of eustatic, depositional, and tectonic change. Thick successions of clastic sediment accumulated on the Neoproterozoic rift margin of East Antarctica

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[†] E-mail: jgoodge@d.umn.edu.
[‡] E-mail: ian.williams@anu.edu.au.
[§] E-mail: pmyrow@coloradocollege.edu.

GSA Bulletin; September/October 2004; v. 116; no. 9/10; p. 1253–1279 doi: 10.1130/B25347.1; 16 figures; 1 table; Data Repository item 2004127.

(Laird, 1981), a key element in supercontinent evolution. However, unresolved stratigraphy, poor biostratigraphic control, discontinuity of outcrop, and early Paleozoic deformation in the Ross orogen (generally 480–550 Ma) obscure the depositional setting, age, and sedimentary provenance of these rocks, let alone their potential role in intercratonic correlation.

Despite these problems, a better understanding of the Late Proterozoic and early Paleozoic siliciclastic successions in Antarctica is emerging from recent studies combining field, stratigraphic, geochronological, and geochemical data (e.g., Millar and Storey, 1995; Ireland et al., 1998; Rowell et al., 2001). Integrated studies in the central Transantarctic Mountains (Fig. 1) show that clastic rocks once considered to represent a single Neoproterozoic rift-margin succession can be divided into separate Neoproterozoic and lower Paleozoic assemblages with distinctive sedimentary provenance (Goodge et al., 2002). Furthermore, stratigraphic relationships in the lower Paleozoic succession record a profound shift from passive-margin sedimentation to active uplift, erosion, and molasse deposition related to Ross orogenic events beginning in the late Early Cambrian (Myrow et al., 2002b). Building on these findings, we present new stratigraphic data and detrital-zircon ages from the major Neoproterozoic and lower Paleozoic units of the central Ross orogen, southern Victoria Land, and Neptune Range of the Pensacola Mountains. These data allow us to refine their depositional ages and track changing provenance with time. In the context of revised stratigraphic relationships (Fig. 2), the provenance characteristics form the basis for a new model explaining the relationship between tectonism and sedimentation during transition from a rift- to active-margin setting. The provenance data also help to define sedimentary-dispersal patterns and possible paleogeographic links within Rodinia and East Gondwana (i.e., southern Africa, India, Australia, and East Antarctica).

STRATIGRAPHIC FRAMEWORK

Supracrustal rocks of the central Transantarctic Mountains are traditionally divided into the Beardmore and Byrd Groups (Gunn and Walcott, 1962; Laird, 1963, 1981, 1991; Laird et al., 1971; Stump, 1982, 1995). These successions are considered, respectively, to be Neoproterozoic and lowermost Paleozoic in age (Fig. 2). The Beardmore Group was recognized as a thick clastic assemblage, mapped originally over broad areas as a single formation because of poorly resolved age and internal stratigraphy. In contrast, several distinct formations erected in the Byrd Group reflect its lithologic variation, yet correlation among the upper clastic units was likewise hampered by poor age control and discontinuous exposure. Field and geochronological studies (Goodge et al., 2002; Myrow et al., 2002b) have led to revision of the stratigraphy and age relationships (Fig. 2), summarized here. Where different from previous mapping, new stratigraphic assignment is based on geographic position, local stratigraphic relationships, sedimentary petrology, and detrital-mineral age patterns.

The Beardmore Group is a thick assemblage of unfossiliferous sandstone, shale, carbonate, diamictite, and minor volcanic rocks (Gunn and Walcott, 1962; Laird et al., 1971; Laird, 1981, 1991; Stump, 1982, 1995). It was originally mapped from Byrd Glacier to south of Beardmore Glacier (Fig. 1) and divided into the Cobham and Goldie Formations. Most workers regarded the group as a Neoproterozoic siliciclastic succession representing rift- or passive-margin deposits of the East Antarctic margin, but its depositional relationships with underlying and overlying units are controversial. The Beardmore Group is younger than crystalline basement of the East Antarctic Shield (represented by the Archean and Proterozoic Nimrod Group to the west; Figs. 1 and 2; Goodge et al., 1993a), although some have suggested that it is allochthonous with respect to the craton margin (Rowell and Rees, 1989; Borg et al., 1990; Grunow and Encarnación, 2000). A Neoproterozoic depositional age is widely inferred for the Beardmore Group because of a lack of fossils and a presumably unconformable relationship with the overlying Lower Cambrian Byrd Group (Laird et al., 1971; Stump, 1995). Others have questioned this relationship, however, on the basis of field relationships and structural features (Rowell et al., 1986; Goodge, 1997; Goodge et al., 1999). All sub-Byrd contacts that we observed in the Nimrod Glacier area are faults, including those earlier interpreted as unconformities, leaving uncertain the stratigraphic and age relationships of the Beardmore Group. A Sm-Nd isochron age of 762 ± 24 Ma for basalt and gabbro interlayered with Goldie sandstone (Borg et al., 1990) is widely cited as evidence for deposition at that time. However, a new U-Pb zircon age of 668 ± 1 Ma for the gabbroic rocks (Goodge et al., 2002) indicates that mafic magmatism, and by inference the Goldie deposits themselves, are significantly younger (Fig. 2). The age of the uppermost Goldie is unknown. Rocks mapped originally as Goldie Formation are superficially similar over broad areas (Grindley and Laird, 1969; Laird et al., 1971), yet detrital-zircon geochronology indicates that only a small proportion of these exposures contain Neoproterozoic and older age components expected of the Goldie ("inboard" type of Goodge et al., 2002). These rocks, plus the Cobham Formation, comprise the redefined Beardmore Group (Figs. 1 and 2), which is thus restricted to rocks in the eastern Cobham Range and Cotton Plateau areas of upper Nimrod Glacier (Fig. 1). Most of the rocks previously mapped as Goldie Formation contain Cambrian and older zircons; they are thus reassigned to the Starshot Formation of the upper Byrd Group.

The lower Byrd Group is represented by Lower Cambrian Shackleton Limestone, which contains a basal member of mature quartz arenite underlying meter-scale siliciclastic-carbonate cycles. Overlying carbonate includes a range of depositional facies, including shoal and ramp deposits, and archaeocyathan bioherms (Rees et al., 1989; Myrow et al., 2002b). Immediately overlying the uppermost Shackleton bioherms is a thin unit of dark shale and nodular carbonate (Holyoake Formation); it is biostratigraphically well constrained to the middle Lower Cambrian. Coarse overlying strata of the Douglas and Starshot Formations include alluvial-fan to fluvial and shoreline deposits, and they contain clasts of the Shackleton Limestone and other basement units. These rocks are themselves deformed, indicating deposition prior to final movements of the Ross orogeny. The stratigraphic relationships and ages of these upper Byrd Group strata are revised, as shown in Figure 2.

Koettlitz Group rocks in southern Victoria Land predate emplacement of Granite Harbour intrusions (Early Cambrian to Ordovician alkaline and calc-alkaline rocks), but strong deformation and high-temperature metamorphism make it difficult to assess stratigraphic and age relationships (Findlay et al., 1984). Nonetheless, Koettlitz siliciclastic and calcareous rocks are thought to represent late Neoproterozoic and early Paleozoic continental-margin deposits (Laird, 1991) and therefore correlate generally with rocks of the upper Beardmore and/or lower Byrd Groups. In the Pensacola Mountains, thick sections of unfossiliferous sandstone and shale (Patuxent Formation) were previously regarded as deep-marine deposits predating development of a Middle Cambrian carbonate platform (Schmidt et al., 1965; Storey et al., 1992; Rowell et al., 1992). On the basis of recent work in the Neptune Range (Millar and Storey, 1995; Rowell et al., 2001), the Patuxent was subdivided into distinct siliciclastic and volcanic assemblages that recorded episodic tectonism, magmatism, and active-margin sedimentation during the Neoproterozoic–Cambrian transition.

U-PB AGES OF DETRITAL ZIRCONS

We determined SHRIMP U-Pb ages for detrital zircons in eight samples of sandstone

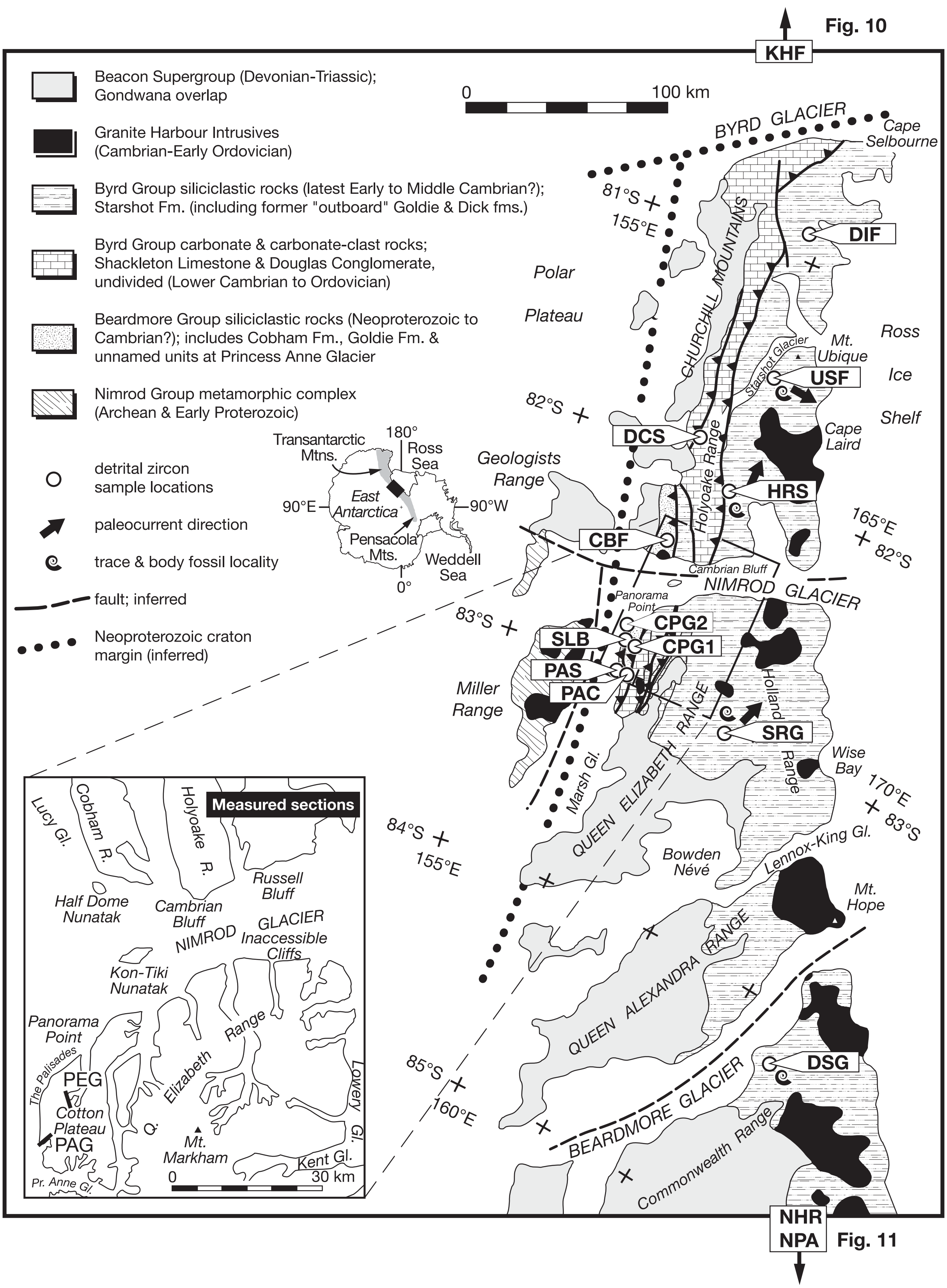
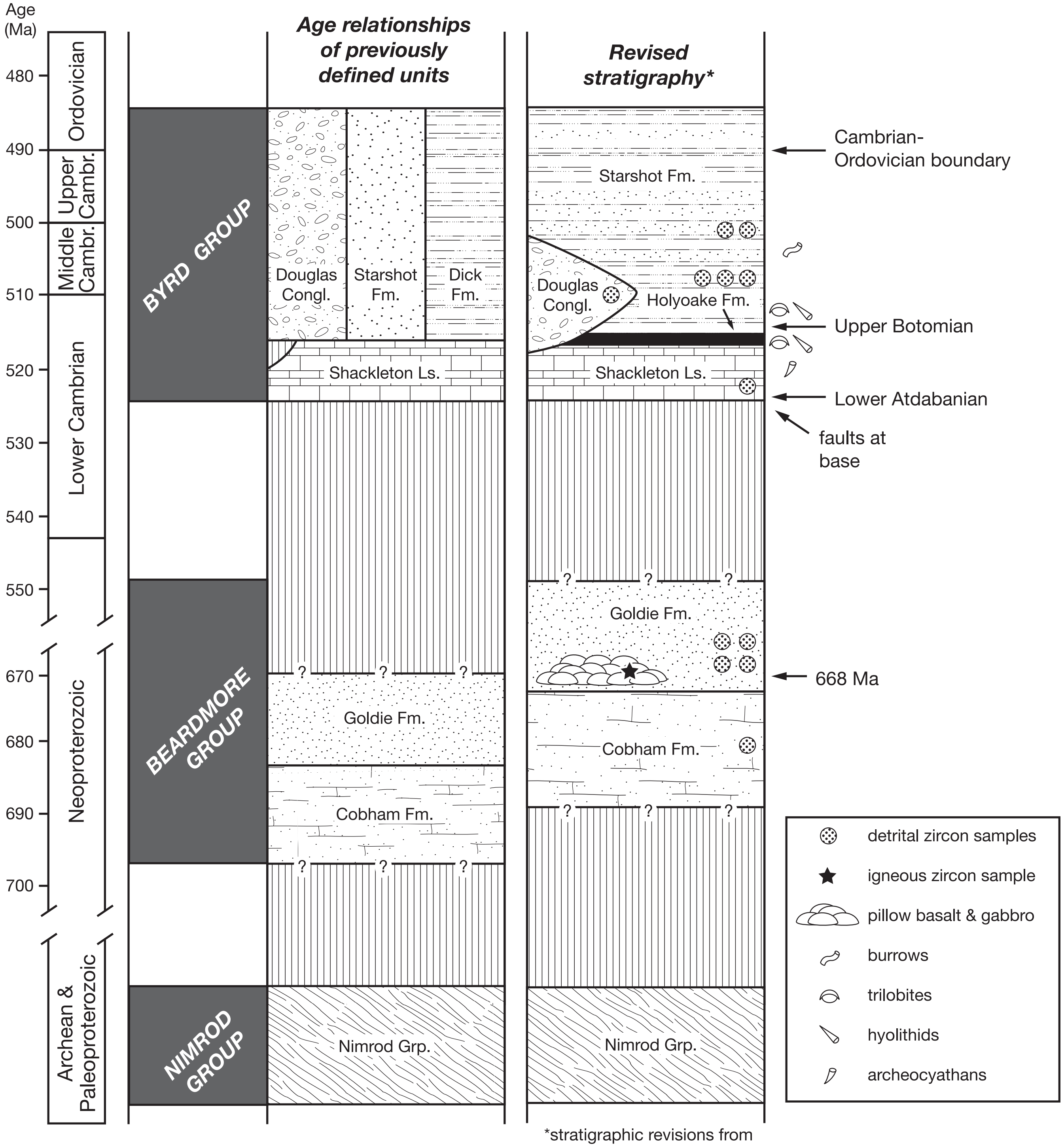


Figure 1. General geology of the central Transantarctic Mountains between Byrd and Beardmore Glaciers, showing locations of dated samples (labeled by letters in rectangles; sample information given in Table 1). Inset shows location of measured sections included in this paper (Figs. 3 and 7). Locations of samples from Koettlitz Group and Neptune Range shown in Figures 10 and 11, respectively. Division of stratigraphic units follows Myrow et al. (2002b) and Goodge et al. (2002), as shown in Figure 2.



*stratigraphic revisions from Myrow et al. (2002b)

Figure 2. Stratigraphic relationships of Neoproterozoic and lower Paleozoic sedimentary units in the central Transantarctic Mountains, based on revisions of Myrow et al. (2002b). Left-hand column shows stratigraphic relationships of traditionally recognized units. Revision shown to the right reflects field observations, fossil discoveries, and radiometric age constraints presented elsewhere (Goodge et al., 2002; Myrow et al., 2002b). Byrd Group consists of Shackleton Limestone, Holyoake Formation, Douglas Conglomerate, and Starshot Formation. Most rocks originally mapped as Beardmore Group have been shown to be Middle Cambrian and younger ("outboard" assemblage of Goodge et al. [2002]); these rocks are now included, together with the Dick Formation, within the Starshot Formation of the Byrd Group. The "inboard" Goldie (Goodge et al., 2002) represents Goldie Formation sensu stricto and has a Neoproterozoic depositional age; along with the Cobham Formation it comprises the Beardmore Group. Precise ages of the lower and upper Beardmore Group are not known; the ages shown here are permitted on the basis of available geochronology and regional geologic relationships. Stratigraphic relationships between these units are discussed in text. Circles with dot pattern indicate units for which detrital-zircon age data were obtained.

TABLE 1. SUMMARY OF DETRITAL-ZIRCON AGES, NEOPROTEROZOIC-CAMBRIAN SUCCESSIONS, TRANSANTARCTIC MOUNTAINS, ANTARCTICA

Area/stratigraphic unit	Sample number	Major zircon age populations (Ma)§	Youngest zircon grains (Ma)#	Maximum depositional age††	1.4 Ga grains (1.35–1.48 Ga) (%)	Ross grains (480–600 Ma) (%)
Byrd-Nimrod-Beardmore Glaciers area						
Byrd Group						
Starshot Formation, Cape Selbourne (formerly Dick Formation)†	DIF	510, 555, 1020, 1130, 975, 495, 695	501 ± 9 (5)	Late Cambrian	2	26
Starshot Formation, Mount Ubique	USF	520, 545, 580, 875, 995, 1035, 1080	501 ± 5 (11)	Late Cambrian	1	34
Douglas Conglomerate, Holyoake Range	DCS	520, 1050, 1600, 2320	506 ± 6 (5)	Late Middle Cambrian	-	49
Starshot/Douglas Formation, Holyoake Range	HRS	545, 495, 650, 780	510 ± 12 (3)	Middle Cambrian	-	56
Starshot Formation, Softbed Ridges (formerly Goldie Formation)†‡	SRG	560, 530, 1100, 940, 810, 720	531 ± 8 (4)	Early Early Cambrian	1	53
Starshot Formation, Dolphin Spur (formerly Goldie Formation)†‡	DSG	565, 585, 1085, 825, 1835, 1670, 1410	547 ± 12 (6)	Early Cambrian	8	25
Shackleton Limestone (basal), Cotton Plateau	SLB	1515, 1610, 1420, 1135, 1750, 970	959 ± 36 (2)	Early Cambrian	17	-
Beardmore Group						
Goldie Formation, eastern Cotton Plateau‡	CPG1	1490, 1795, 1550, 1435, 1690, 1840, 1095, 1220	1096 ± 19 (5)	Neoproterozoic	12	-
Goldie Formation, western Cotton Plateau	CPG2	1560, 1175, 1765, 2500, 1445	1174 ± 15 (11)	Neoproterozoic	9	-
conglomerate, Princess Anne Glacier	PAC	1525, 1435, 1630, 1125, 1235, 2465, 1780	1125 ± 30 (3)	Neoproterozoic	22	-
sandstone, Princess Anne Glacier	PAS	1805, 1770, 1850, 1725, 1580, 1930, 1475, 2070	1461 ± 16 (1)	Neoproterozoic	2	-
Cobham Formation, Cobham Range‡	CBF	2810, 1825, 1735, 1615, 1145	1143 ± 30 (2)	Neoproterozoic	-	-
Dry Valleys						
Hobbs Formation, Koettlitz Group	KHF	1080, 1180, 1845, 2310, 675	668 ± 19 (2)	Late Neoproterozoic	5	-
Pensacola Mountains						
Patuxent Formation	NPA	530, 575, 1050, 610, 670, 1185	513 ± 4 (7)	Late Cambrian	-	28
Hannah Ridge Formation	NHR	640, 600, 1040, 1090, 560, 765, 1145	556 ± 13 (5)	Early Cambrian	-	18

†Units originally mapped as Goldie and Dick formations; now included in Starshot Formation of upper Byrd Group (Myrow et al., 2002b).
‡Complete zircon data presented by Goodge et al. (2002); age distributions shown in Figure 12.
§Age populations to nearest 5 m.y. listed in order of decreasing relative abundance.
#Weighted mean ages and 2σ errors; number of grains in parentheses.
††Depositional age constrained by youngest discrete zircon or muscovite age population (muscovite ages presented by Goodge et al. (2004); muscovite ages in Starshot Formation are typically younger than zircon ages listed here.

from the Beardmore and Byrd Groups, the latter including the basal Shackleton Limestone, Starshot Formation, and Douglas Conglomerate, as summarized in Table 1. These new data from the central Transantarctic Mountains significantly extend earlier results from the Beardmore Group (Goodge et al., 2002). We also analyzed samples of the Koettlitz Group (Hobbs Formation) from southern Victoria Land and samples of the Hannah Ridge and Patuxent Formations from the Neptune Range of the Pensacola Mountains, in order to compare regional provenance. Sample locations and descriptions are given in Appendix DR1.[1] Zircons were analyzed on SHRIMP I and II ion microprobes at the Australian National University, following standard methods (Williams and Claesson, 1987; Pell et al., 1997). Analytical methods and grain characteristics are described in Appendix DR2 (see footnote 1). The analytical data, including isotopic measurements and grain characteristics, are given in Tables DR1–DR11 (see footnote 1; data arranged in order of inferred age).

Beardmore Group

Cobham Formation

Contact metamorphism obscures primary features in the Cobham Formation, but it is quartz rich at its base and carbonate rich near its top, suggesting sedimentation along an inner continental shelf (Laird et al., 1971). Detrital zircons from a Cobham sandstone (Goodge et al., 2002; their sample 98-229, here referred to as CBF; Fig. 1) have a generally bimodal age distribution dominated by Late Archean and Paleoproterozoic components. Zircons of Grenville orogen age (generally 900–1350 Ma) are sparse, but the youngest grains indicate a Neoproterozoic depositional age (≤1145 Ma). Grain ages and compositions indicate that the Cobham consists of a moderately mature, multicycle sediment derived from mixed sources dominated by 2.8 and 1.8–1.6 Ga crust. It may have been deposited during an active rifting stage or, more likely, during the transition to a drifting, passive margin.

Goldie Formation

The Goldie Formation in the Cotton Plateau area consists of medium to very thick beds of very fine to fine sandstone with very thin to

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[1] GSA Data Repository item 2004127, Data tables DR1–DR11 (U-Pb results of detrital-zircon analysis), is available on the Web at http://www.geosociety.org/pubs/ft2004.htm. Requests may also be sent to editing@geosociety.org.

thin beds of black shale (Fig. 3). The sandstone contains abundant large-scale hummocky cross-stratification (Fig. 4A), parallel lamination, and quasi-planar stratification, which indicate that at least part of this formation was deposited above storm wave base. The Goldie in this area also includes coarse conglomerate beds, sandstone, and intermingled pillow basalt and gabbro, together interpreted as late Neoproterozoic rift-margin deposits (Myrow et al., 2002b).

We analyzed zircons in two Goldie sandstones from the Cotton Plateau area. One sample (CPG1; 98-260 of Goodge et al., 2002) was collected within the Prince Edward Glacier section and is a mature quartz arenite with preserved framework grains modified slightly by deformation. Sample CPG1 contains detrital zircons ranging in age from 1.9 to 1.4 Ga, and 12% of the population is between 1475 and 1350 Ma. Two subpopulations of Grenville-age zircon are present; the younger of these has a weighted mean age of 1096 ± 19 Ma, suggesting a Neoproterozoic deposition age. The overall distribution of ages reflects a heterogeneous source dominated by a Paleoproterozoic and Mesoproterozoic igneous terrane.

Sample CPG2 was collected below Panorama Point (Fig. 4B), beneath basal quartzite of the Shackleton Limestone. The age distribution is dominated by Proterozoic zircons that are 1.8–1.4 Ga, with a single prominent Grenville-age population and minor Archean components (Tables 1 and DR1 [see footnote 1]; Fig. 5A). Six grains (9%) have ages in the range of 1475–1350 Ma; a large peak at 1560 Ma masks their presence, but they represent a statistically significant population. The 11 youngest concordant grains define a weighted mean age of 1174 ± 15 Ma, which gives the best estimate for the maximum depositional age of CGP2.

The two Goldie samples thus show similar age patterns, particularly in the proportions of ages between 1.9 and 1.3 Ga, notable groups at 1560 and 1765 Ma, and a prominent Grenville-age component. Their age distributions and compositional maturity reflect a cratonic source dominated by Grenville and older igneous terranes, including minor Archean exposures. Deposition presumably occurred along a thermally subsiding and extending cratonic margin. The youngest detrital-grain ages

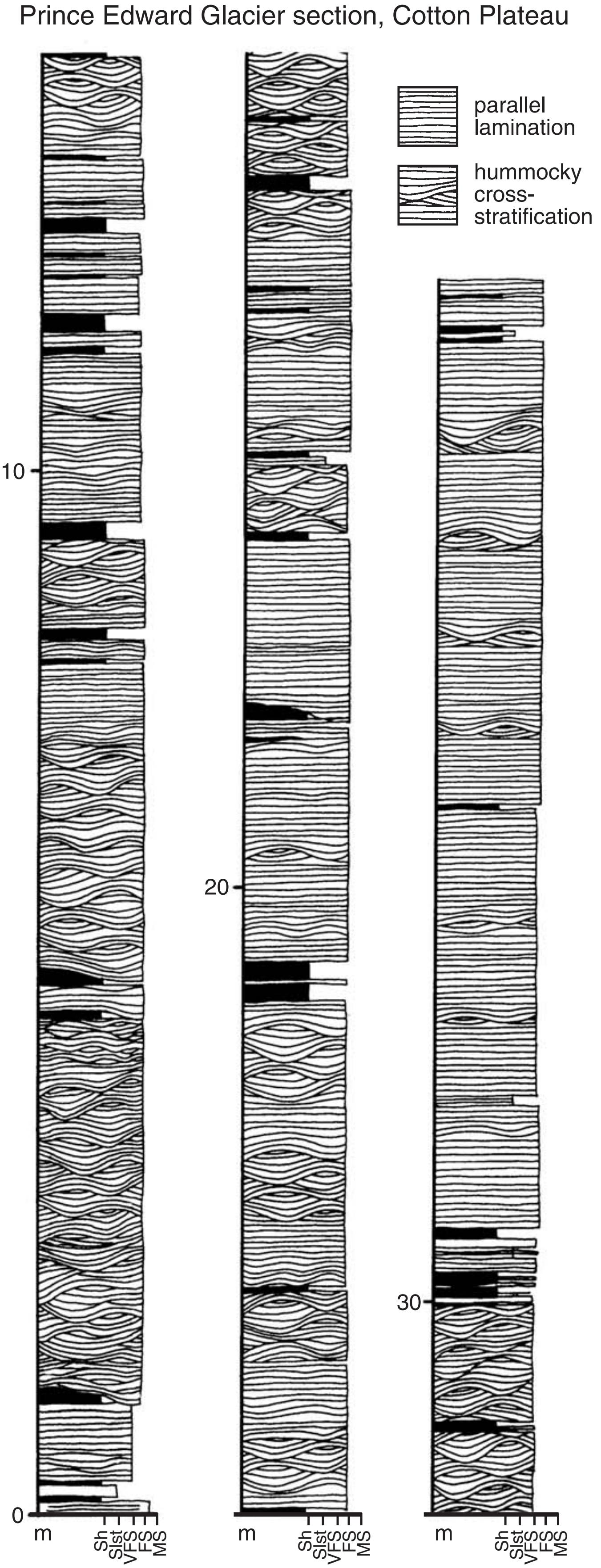


Figure 3. Measured section of Neoproterozoic (inboard) Goldie Formation from Prince Edward Glacier area of eastern Cotton Plateau (see Fig. 1 inset for location of section labeled PEG). Standard grain sizes from shale (Sh) to medium-grained sandstone (Ms).

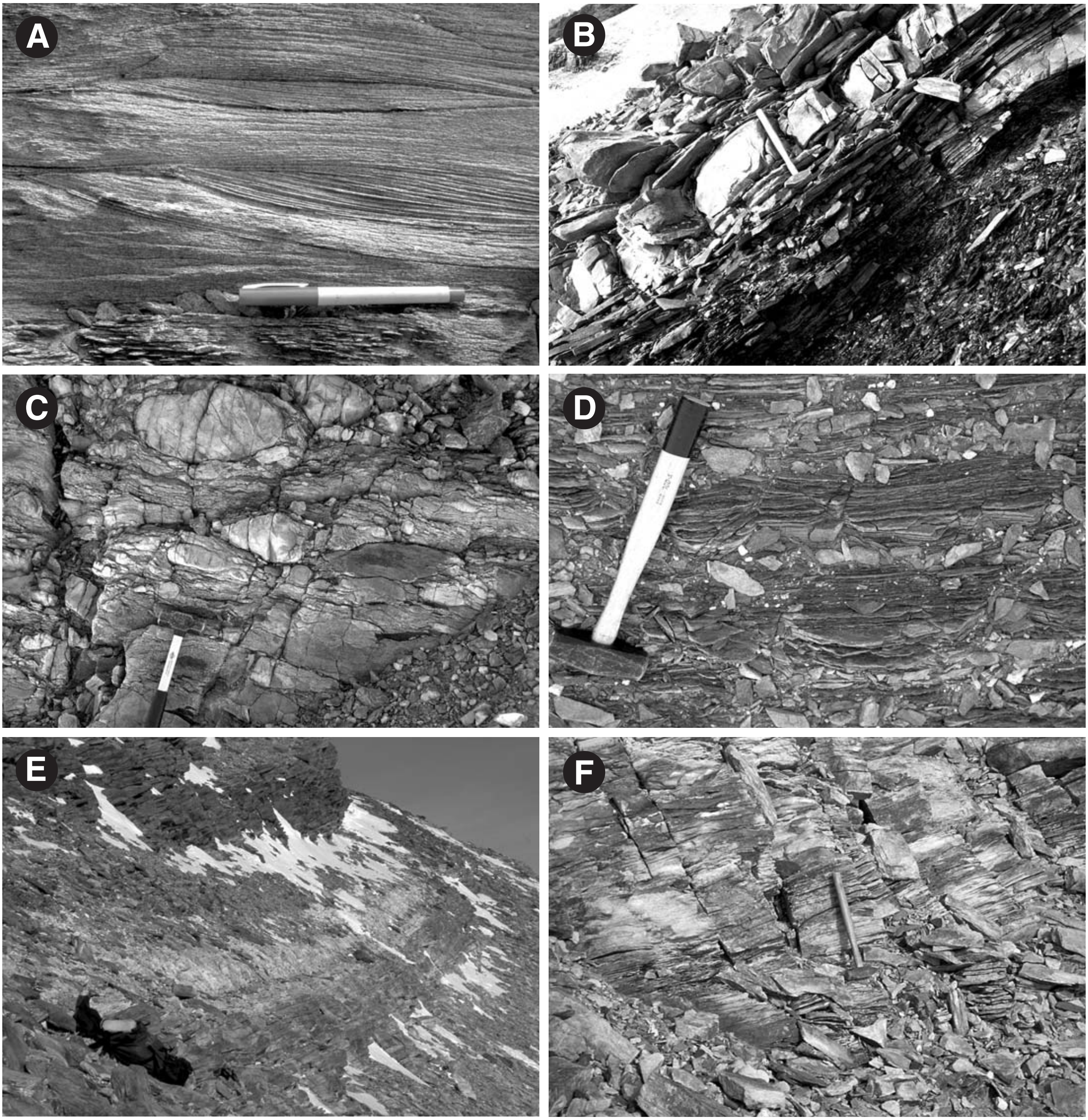


Figure 4. Outcrop features of inboard sedimentary units. (A) Fine-grained sandstone from Prince Edward Glacier section of Goldie Formation at eastern Cotton Plateau, showing "paper-thin" bedding laminations and hummocky cross-stratification. Detrital-zircon sample CPG1. Pen for scale. (B) Interbedded black shale and tabular fine-grained sandstone of Goldie Formation from western slopes of Panorama Point, below Cotton Plateau. Detrital-zircon sample CPG2. Hammer for scale. (C) Quartzite-clast conglomerate of upper Princess Anne Glacier section. Detrital-zircon sample PAC. Clasts show lozenge shapes and high aspect ratios due to deformation. Hammer for scale. (D) Fine-grained laminated calcareous sandstone of Hobbs Formation (Koettlitz Group) near Hobbs Peak in the southern Dry Valleys area. Detrital-zircon sample KHF. Hammer for scale. (E) View looking south of western slopes of Panorama Point below Cotton Plateau, showing basal sandstone beds of Shackleton Limestone (beneath pack), overlying sandstone and shale of Goldie Formation. Detrital-zircon sample SLB. (F) Close-up of basal sandstone beds of Shackleton Limestone shown in (E), showing platy parting of mature quartz arenite. Hammer for scale.

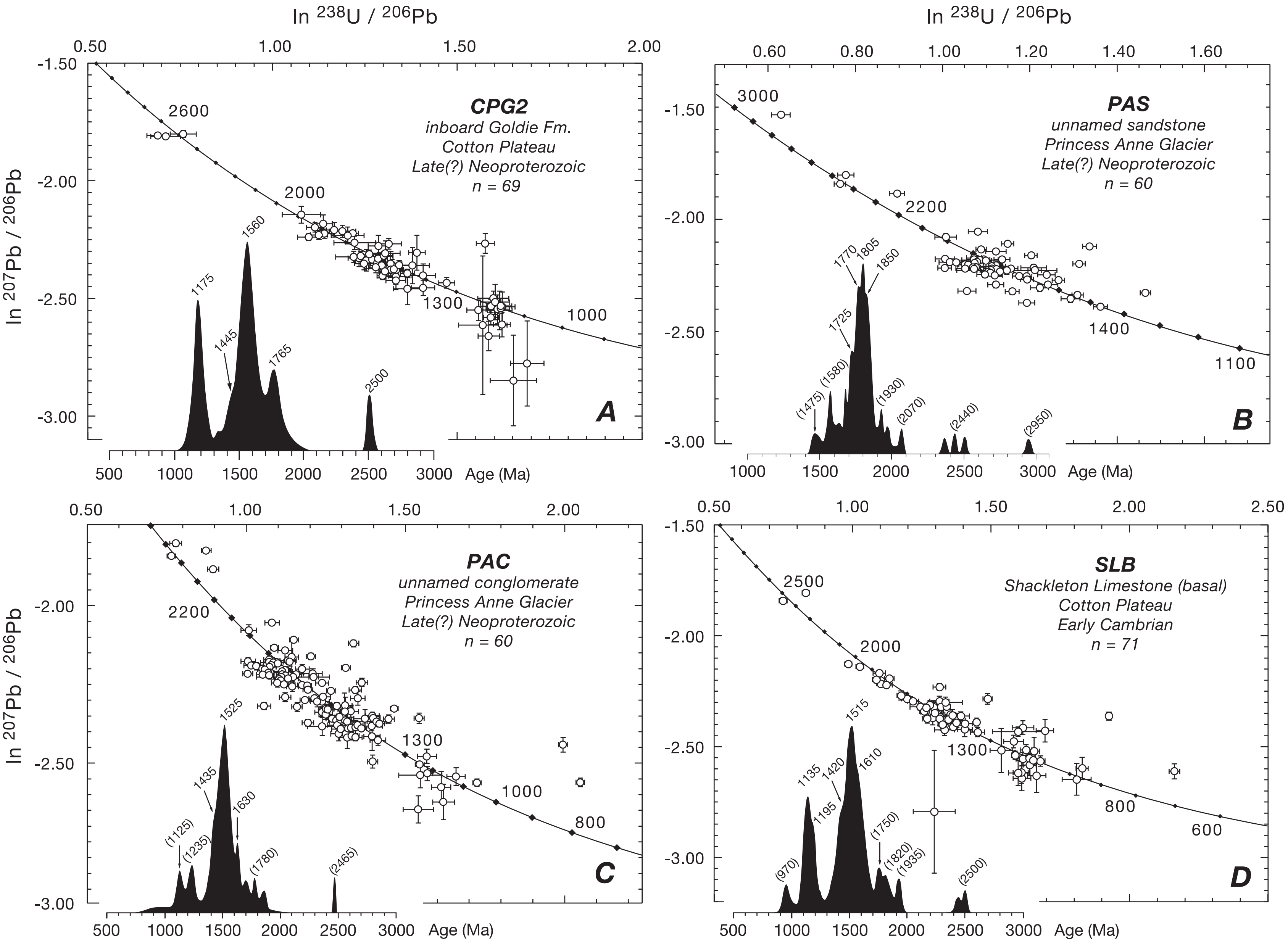


Figure 5. Logarithmic Tera-Wasserburg diagrams showing U-Pb analyses of detrital-zircon grains in sandstone samples from inboard clastic units of the Beardmore Group and basal Shackleton Limestone. The logarithmic Tera-Wasserburg plots best illustrate the full range of grain ages in a sediment and allow for better assessment of errors and potential Pb loss. Errors for individual analyses are 1σ (see Tables DR3–DR6 [see footnote 1]); *n* = number of individual grains analyzed. Insets show relative probability distributions of the zircon ages (in Ma), following Dodson et al. (1988). Ages assigned to peaks derived from multicomponent mixture modeling (Sambridge and Compston, 1994); ages in parentheses calculated as simple mean of discrete peaks.

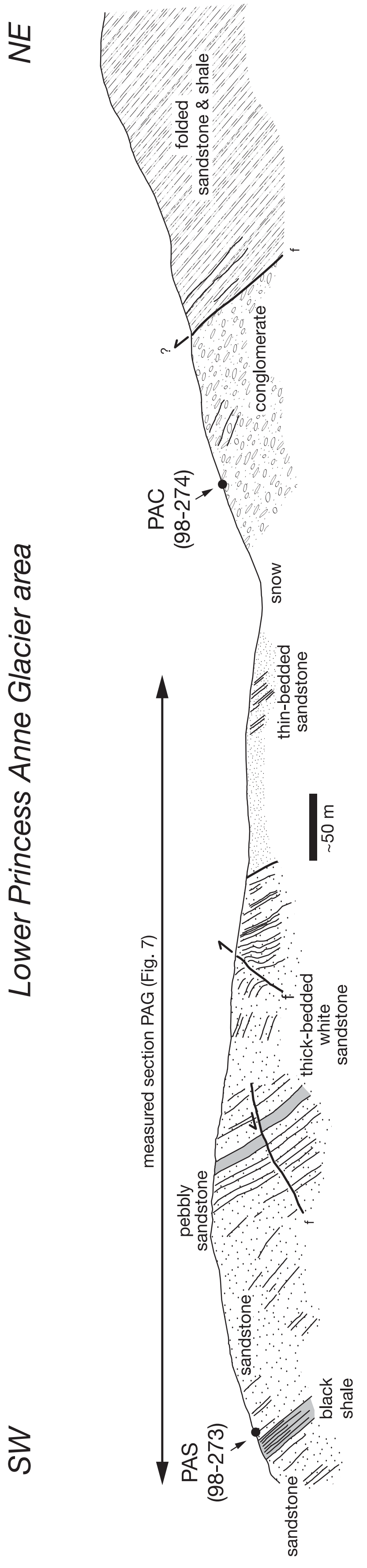


Figure 6. Drawing from mosaic of low-altitude aerial photographs showing outcrop features of major sedimentary units in the lower Princess Anne Glacier area. Sandstone and shale at northeast end of ridge are strongly folded (not indicated here); a fault is conjectured at the boundary with lower conglomerate. Locations of detrital-zircon samples PAS and PAC indicated.

indicate that deposition was latest Mesoproterozoic or younger, yet deposition continued to the late Neoproterozoic given a 668 Ma age for interlayered gabbro and associated mafic lavas (Goodge et al., 2002).

Sandstone and Conglomerate of Princess Anne Glacier

Southwest of the Cotton Plateau and near the Princess Anne Glacier outlet are enigmatic outcrops of shale, sandstone, and conglomerate (Figs. 1 and 6). There, white quartz sandstone and minor shale were mapped by Laird et al. (1971) as part of the Shackleton Limestone. The section is >500 m thick, although faulted (Fig. 7). The white, vitreous quartzite is generally massive in appearance, but parallel lamination and trough cross-bedding are evident locally. A 20-m-thick interval dominated by black shale contains evidence for shelf and shoreline deposition (e.g., mudcracks, paired mudstone drapes, hummocky cross-stratification). Coarse, trough cross-bedded conglomerate, pebbly sandstone, and thin-bedded sandstone of fluvial origin occur near the middle of the section. White, trough cross-bedded sandstone with clay drapes and reactivation surfaces typical of tidal deposits occurs directly above the fluvial units, which is overlain by ~150 m of more white quartz sandstone. Very fine and fine-grained sandstone more typical of the Goldie Formation occurs at the top of the section. The upper part of the exposure includes several tens of meters of quartzite-pebble conglomerate below folded black shale and sandstone that are superficially similar to the Goldie (Fig. 6; Laird et al., 1971), although the two intervals may be in fault contact. The conglomerate is dominated by rounded quartzite clasts (Fig. 4C) with sparse chlorite-rich lenticles of metamorphosed mafic volcanic clasts. High aspect ratios (up to 20:1) and tapered clast shapes reflect a strong, penetrative flattening strain, yet a uniform clast composition, clast-supported texture, and sandy matrix suggest a fluvial or marginal-marine depositional setting. Both successions, several hundred meters thick, are unrepresented in the lower Byrd Group just 17 km away at the Cotton Plateau.

To help resolve stratigraphic relationships, we collected two sandstone samples from the Princess Anne Glacier exposure (Fig. 6). Sample PAS is a quartz arenite collected from the measured section to the southwest. The zircon ages in PAS are dominated by Paleoproterozoic and Mesoproterozoic populations (70% of the entire distribution is between 1900 and 1650 Ma), and there are no Grenville- or Ross-age grains (Tables 1 and DR2 [see footnote 1]; Fig. 5B). The youngest grain is 1461 ± 16 Ma, yet a similarity in the age distribution with Beardmore Group samples suggests that a Neoproterozoic deposition age is likely. Although sample PAS has a Mesoproterozoic and Paleoproterozoic provenance, the absence of Grenville-age or Archean components indicates that its basin was isolated from nearby shield terranes, either because they were not exposed or because drainage flowed in a different direction. We suggest that sandstone and shale of the lower Princess Anne Glacier succession represent mature passive-margin shelf deposits of late Neoproterozoic age. Despite similarity to the basal sandstone of the Shackleton Limestone, the age distribution in PAS is quite different (as discussed below), suggesting that the lower Princess Anne section be included within the Beardmore Group. More specifically, a similarity of lithofacies and detrital-grain ages indicates that this succession can be correlated with the Cobham Formation.

Approximately midway through the upper conglomerate interval, we sampled a quartz arenite (PAC) from an interval of sandstone and black shale. Paleoproterozoic and Mesoproterozoic zircon ages dominate (Tables 1 and DR3 [see footnote 1]; Fig. 5C); most grains' ages are between 1.70 and 1.35 Ga (70%). Thirteen grains in the range of 1475–1350 Ma (22%) compose a distinct group with Th/U ratios (0.7–1.8) and growth zoning indicative of an igneous origin. The three youngest grains form a discrete subpopulation and yield a weighted-mean age of 1125 ± 30 Ma, suggesting Neoproterozoic deposition. This quartz arenite appears to represent deposition of mature craton-margin material eroded from a Proterozoic craton with minor inputs from Grenville-age belts. The stratigraphic association with conglomerate suggests that the zircon components may be either first or second cycle. The age pattern in sample PAC is similar to that of Goldie sandstone from the Cotton Plateau (e.g., CPG2, Fig. 5A), suggesting that the conglomeratic intervals in the Princess Anne Glacier area, like the sandstones beneath them, be included in the Beardmore Group.

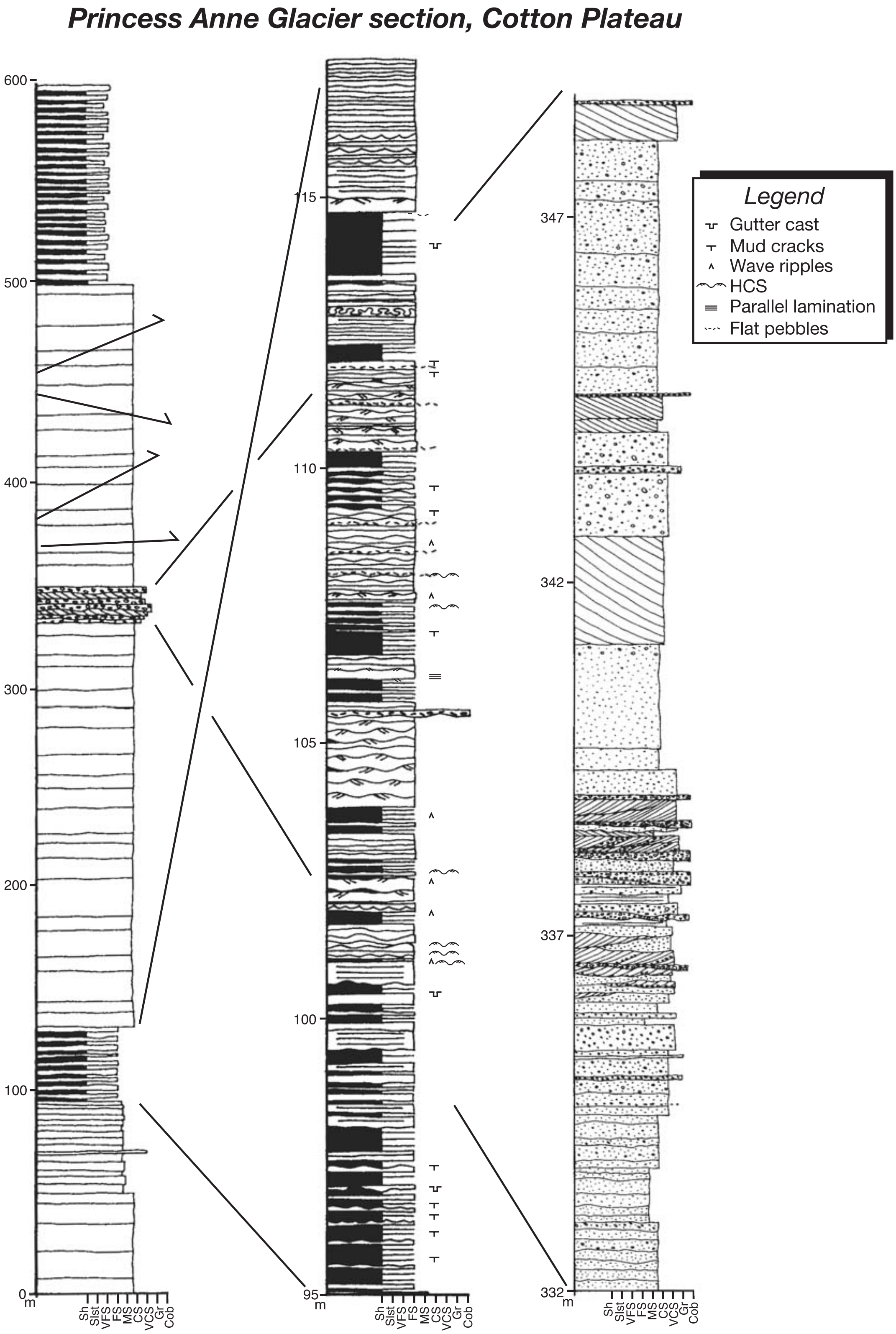


Figure 7. Measured section of sedimentary units in lower Princess Anne Glacier area (see Fig. 1 inset for location of section labeled PAG). Grain sizes as in Figure 3.

Lower Byrd Group

Basal Shackleton Limestone

The Lower Cambrian Shackleton Limestone (Laird, 1963) is the principal unit of the Byrd Group in the region (Fig. 1). Typically the Shackleton is severely deformed, but from exposures in the Holyoake Range, it was previously interpreted as a simple carbonate ramp with intertidal facies passing laterally into high-energy oolitic shoal complexes containing individual archaeocyathan bioherms (Laird et al., 1971; Rowell et al., 1988b; Rees et al., 1989). Formation thickness was estimated to be 1000–2000 m (Burgess and Lammerink, 1979; Rees et al., 1989), but most if not all lower contacts with the Goldie Formation are faulted (Rowell et al., 1986; Rees et al., 1989; Palmer and Rowell, 1995; Goodge et al. 1999), so that a definitive base of the formation has not been identified. Biostratigraphic and C isotope data indicate that the lower Shackleton is Atdabanian and the top is Botomian (Debrenne and Kruse, 1986; Rowell et al., 1988a; Palmer and Rowell, 1995; Myrow et al., 2002b).

We sampled the Shackleton Limestone on the western slopes of The Palisades at the Cotton Plateau (Figs. 1, 4E). There, repeated cycles of gradationally interlayered sandstone, dolomitic sandstone, and dolomite (Myrow et al., 2002b) pass upward to limestone and finally archaeocyathan -bearing limestone of the middle formation. Sample SLB is from the prominent thin-bedded sandstone at the base of the lower interval (Fig. 4F); it is a white, well-sorted quartz arenite containing ≥95% subrounded quartz grains. The zircon age distribution is dominated by Mesoproterozoic and Grenville-age grains (Tables 1 and DR4 [see footnote 1]; Fig. 5D). There is only minor Archean and early Paleoproterozoic detritus, but the sample contains 12 grains (17%) whose ages are between 1460 and 1360 Ma. Many of these have broken, prismatic shape, and most are angular or subangular, suggesting that they are a first-cycle sedimentary component. The youngest detrital population in this Lower Cambrian sandstone is ca. 960 Ma.

Data from sample SLB indicate that Mesoproterozoic inputs dominated the Early Cambrian shelf, with minor contributions from Grenville-age, Paleoproterozoic, and Archean basement. Because the Shackleton is autochthonous, the source area for this detritus, including the ca. 1.4 Ga zircons, was probably in East Antarctica. The Shackleton was deposited during early Ross activity, as evident from ages of metamorphic and igneous rocks of the Nimrod Group (Goodge et al., 1993b; Goodge and Dallmeyer, 1992, 1996), yet it did not receive Ross-age detritus, suggesting that its depositional setting was locally quiet or isolated. Its age spectrum is strikingly similar to that of the Goldie Formation (e.g., CPG2 in Fig. 5A), suggesting either that sediment from the same sources was delivered to the passive margin during the latest Neoproterozoic and Early Cambrian or that the Shackleton may contain grains recycled from the Goldie.

Upper Byrd Group

The Shackleton Limestone is succeeded in the region by clastic deposits of the upper Byrd Group, previously assigned to the Starshot, Douglas, and Dick Formations (Fig. 2). The transition between strata of the lower and upper Byrd Group is remarkably exposed in the Holyoake Range and nearby areas (Fig. 8A). There, the uppermost Shackleton carbonate ramp is capped by archaeocyathan bioherms that are themselves deeply incised and abruptly onlapped by clastic deposits (Myrow et al., 2002b). A phosphatic hardground on the bioherms records drowning of the carbonate ramp, and interlayered nodular carbonate and black shale (Holyoake Formation; Myrow et al., 2002b) fills in among the bioherms. This formation passes upward into trilobite- and hyolithid-bearing calcareous siltstone of the Starshot Formation (Fig. 8B) and then into sandstone and conglomerate of the Douglas Conglomerate (Fig. 8C). Trilobite fauna from the lowermost siltstone of the Starshot date the onset of this transition as late Botomian. These field relationships led to stratigraphic revision of the upper Byrd Group across the region (Fig. 2); important features are noted below.

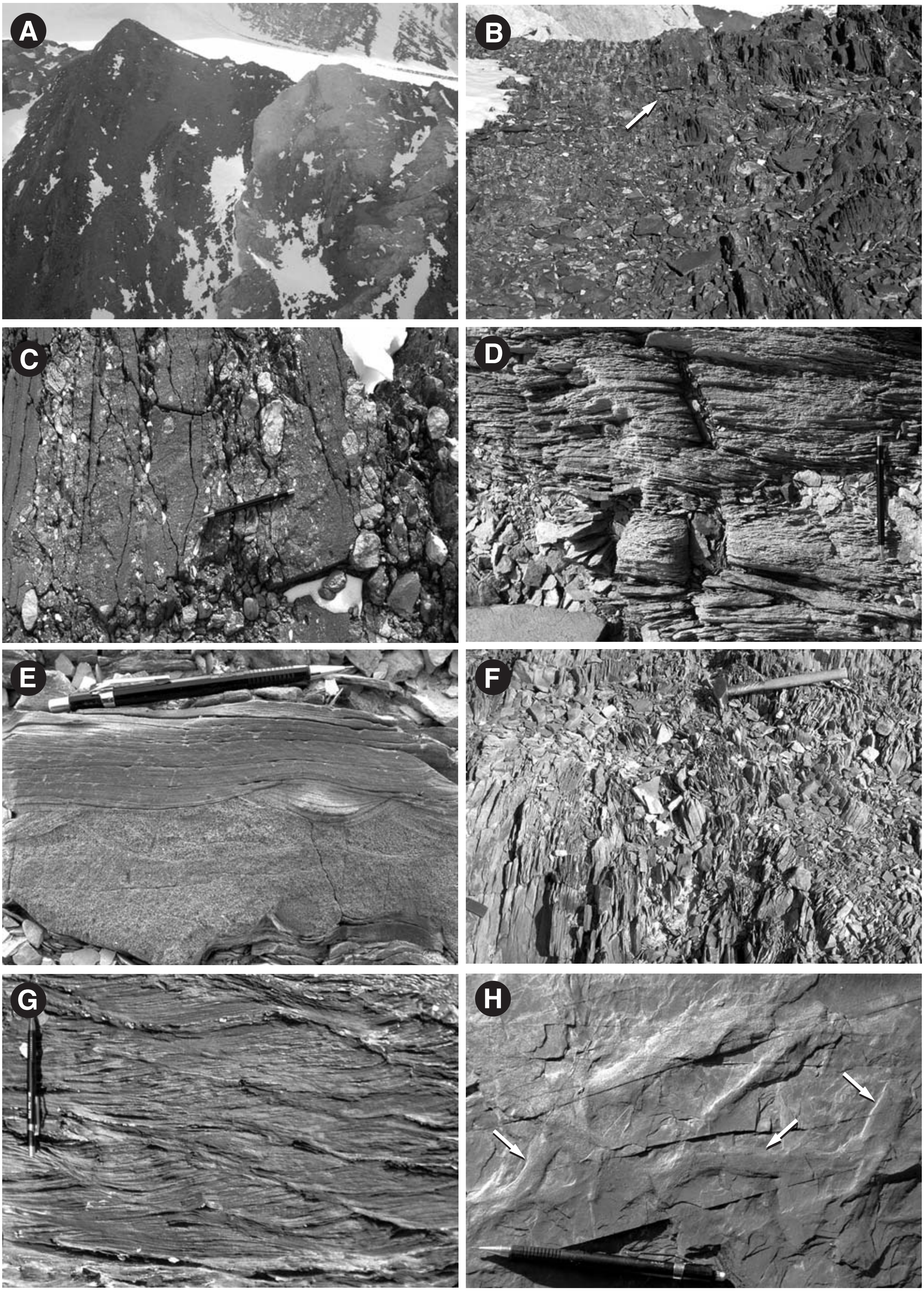
Shale, sandstone, and minor conglomerate of the Starshot Formation (Laird, 1963) are exposed in the eastern Churchill Mountains (Fig. 1), and its type section is near Mount Ubique. Clasts in conglomeratic beds include quartzite, argillite, granitoids, felsic volcanic rocks, and archaeocyathan limestone (Laird, 1964), indicating that the formation is contemporaneous with or younger than the Shackleton Limestone. Previously interpreted as deep-water turbidite and outer-shelf deposits (Laird, 1963; Laird et al., 1971), the Starshot consists mostly of inner-shelf and shoreline deposits, including wave-modified turbidites (Myrow et al., 2002a). Rare burrows occur in several sections, and the basal interval in the Holyoake Range contains Early Cambrian marine faunas (Myrow et al., 2002b). The presence of nearshore lithofacies, stratigraphic relationships with the Douglas Conglomerate, and paleocurrent patterns all suggest development of a high-relief proximal upland facing a storm-influenced sea to the east (present-day coordinates). Now included with the Starshot are siliciclastic rocks mapped previously as Goldie Formation in the Queen Elizabeth and Queen Alexandra Ranges south of Nimrod Glacier (Fig. 1); these rocks are distinguished from the Beardmore Group because they contain Cambrian detrital zircons (Goodge et al., 2002).

The Douglas Conglomerate is a distinctive coarse fanglomerate succession exposed in the Churchill Mountains that contains clasts of limestone and sandstone with minor oolitic limestone and felsic volcanic rocks (Laird, 1964). Clasts of the Shackleton Limestone (Skinner, 1964, 1965; Rowell et al., 1986), including those with folds and calcite veins, indicate that Ross deformation preceded Douglas deposition (Rowell et al., 1986). The Douglas itself is folded and contains cleavage, indicating that Ross deformation outlasted it. The Douglas was deposited in proximal to distal alluvial-fan environments, as well as marine and lacustrine settings (Rees and Rowell, 1991). It was deposited locally upon an erosional surface that truncates folded Shackleton beds (Burgess and Lammerink, 1979; Rees et al., 1988; Rowell et al., 1988b) and interfingers with Starshot sandstone (Myrow et al., 2002b). The Douglas, therefore, is a distinctly coarse succession of alluvial-fan deposits recording fan advance and subsequent retreat.

A succession of shale, siltstone, and fine-grained sandstone in the northern Churchill Mountains was previously mapped as Dick Formation (Skinner, 1964; Rees et al., 1988). On the basis of stratigraphic, petrologic, and sedimentological data, these deposits represent upper, distal parts of the Starshot Formation and thus the Dick Formation is no longer a valid lithostratigraphic term (Myrow et al., 2002b).

Starshot and Douglas Formations

We analyzed zircons from three samples of the Starshot and Douglas Formations, presented here in inferred stratigraphic order beginning with the oldest. Sample HRS was collected from near the top of an ~50 m interval of fine-grained sandstone and siltstone beds in the Holyoake Range, ~130 m above the Holyoake Formation (Figs. 1, 2). Intercalated siltstone, sandstone, and conglomerate in this interval represent interfingering of the Starshot and Douglas Formations. The sampled beds were arbitrarily designated as Douglas in section 1 of Myrow et al. (2002b), but we consider sample HRS to broadly represent the lowermost Starshot/Douglas siliciclastic interval above the Holyoake Formation. The sample is a feldspathic graywacke containing highly angular to subangular, poorly sorted grains. Lithic grains include


A
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H

slate, sutured polycrystalline quartz, and quartzite. The zircon ages define a nearly unimodal distribution (Tables 1 and DR5 [see footnote 1]; Fig. 9A); a dominant group at ca. 545 Ma (ranging from 580 to 490 Ma) represents 55% of the total distribution, and other grains are as old as 2510 Ma. The youngest discrete population of three grains yielded a weighted-mean age of 510 ± 12 Ma, which limits deposition to Middle Cambrian or younger.

The zircon provenance of sample HRS is profoundly different from older units. In contrast to inboard deposits represented by the Beardmore Group and the basal Shackleton Limestone, this sample contains detritus primarily from the Ross orogenic belt, to the exclusion of nearly any older sources. From the sedimentary grain characteristics and zircon age pattern, it appears that most material was eroded primarily from a proximal, igneous and metamorphic orogenic terrane. The onset of supracrustal deformation in the central Ross orogen, recorded by drowning of the Shackleton carbonate and influx of clastic material in the Holyoake and Starshot Formations, is well dated as latest Botomian (ca. 515 Ma) from trilobites in the lowermost Starshot beds (Myrow et al., 2002b). Sample HRS was taken from above the latest Botomian trilobite level; on the basis of the youngest detrital-zircon population in that sample, deposition of the Starshot and intercalated Douglas probably continued to at least the Middle Cambrian (≤510 Ma). We therefore consider the Holyoake and lowermost Starshot Formations as the sedimentary response to initial tectonic activity and the upper Starshot as synorogenic molasse deposits that record continued, but perhaps episodic, tectonic uplift. Because it is biostratigraphically the best constrained of the upper Byrd Group units, the distinctive detrital-zircon signature of the lower Starshot records a fundamental shift in sedimentary provenance.

In the northern Holyoake Range (Fig. 1), we sampled a sandstone interval in the Douglas Conglomerate from an outcrop of quartz-rich graywacke and feldspathic arenite (Figs. 8C, 8D). Sample DCS contains quartz, muscovite, and lithic grains, the latter including quartzite, polycrystalline quartz, and slate. Internally zoned zircon cores and mantle overgrowths indicate that most grains are igneous in origin, and some with high U indicate probable first-cycle origin. The age distribution in sample DCS is strongly unimodal (Tables 1 and DR6 [see footnote 1]; Fig. 9B), although some analyses are discordant. In addition to a dominant Ross-age population of ca. 520 Ma grains (49%), there are minor Proterozoic groups. A weighted mean age of the five youngest grains is 506 ± 6 Ma, indicating a Middle Cambrian or younger depositional age at ca. 1050, ca. 1600, and ca. 2320 Ma.

Like other samples from the upper Byrd Group, the Douglas sediment had a proximal source in the nearby Ross orogenic belt. Although clast types can be traced to the Cambrian carbonate succession and older quartzitic rocks, the relatively fresh igneous zircons in sample DCS suggest a nearby source within the Ross igneous province. The Douglas also received detritus from a composite Proterozoic terrane, although it contains no ca. 1.4 Ga grains. The absence of Archean detritus indicates that the oldest parts of any nearby shield terranes were not exposed. The dominance of fresh, Ross-age zircon is consistent with an interpretation that the Douglas reflects deposition in a proximal, synorogenic alluvial-fan setting (Rees and Rowell, 1991).

We collected sample USF from a thick succession of interbedded Starshot Formation sandstone, shale, and conglomerate near Mount Ubique in the northern Churchill Mountains (Fig. 1). The Starshot there consists chiefly of nearshore sandstone and pebble conglomerate transported by eastward-flowing paleocurrents (present-day coordinates), as indicated by convolute beds, flute marks, combined-flow ripples, and other current-generated features (Fig. 8E; Myrow et al., 2002a). Sample USF is a moderately sorted feldspathic graywacke with angular to subangular grains of quartz, feldspar, and lithic fragments (mostly shale). The age distribution is extremely mixed (Tables 1 and DR7 [see footnote 1]; Fig. 9C) but dominated by a major Ross-age population with minor Grenville-age and older inputs, including significant Paleoproterozoic and Archean groups. The principal Ross component is ca. 520 Ma, which, together with secondary populations, represents 34% of the total age distribution. Several Grenville-age components can be resolved between 1225 and 995 Ma. The youngest discrete population of 11 grains in sample USF yielded a weighted-mean age of 501 ± 5 Ma, indicating a Late Cambrian or younger depositional age.

The heterogeneous age distribution in the Starshot Formation of the Mount Ubique area suggests a highly mixed provenance, including a major contribution from the Ross belt and an unidentified Grenville-age terrane, plus minor older cratonic inputs. Most grains, like those in HRS, were probably derived from volcanic or plutonic rocks of the regionally extensive Ross igneous province. However, the more abundant Precambrian zircons in sample USF may indicate either that this area was closer to exposures of cratonic basement or that it represents a stage of deeper basement erosion. Regardless, the Starshot succession consists of syn- to late-orogenic molasse deposits reflecting significant denudation of the orogen, including its crystalline roots.

Other Starshot Samples

We sampled the Starshot Formation in the northern Churchill Mountains south of Byrd Glacier, near Mount Dick (Fig. 1). There, limestone passes up-section(?) into shale with local thin interbeds of graded carbonate-clast

Figure 8. Outcrop features of outboard sedimentary units. (A) Aerial photograph showing sharp transition from carbonate bioherms of the Shackleton Limestone (light gray at right), overlain by shale, sandstone, and conglomerate of the Holyoake Formation and Douglas Conglomerate (dark gray at left). View toward north. (B) Transition beds of nodular limestone and shale at top of Shackleton Limestone bioherm (left) grading upward to shale and thin-bedded sandstone of Holyoake and Starshot Formations, respectively (right). Detrital-zircon sample HRS collected out of view from intercalated Starshot and Douglas Formations, ~135 m above Holyoake Formation. Pencil for scale (white arrow). (C) Coarse sandstone and pebble conglomerate of distal Douglas Conglomerate from Hunt Mountain area, northern Holyoake Range. Clasts dominated by granite, sandstone, and limestone. Pencil for scale. (D) Medium-grained sandstone of the Douglas Conglomerate near Hunt Mountain yielded detrital-zircon sample DCS. Pencil for scale. (E) Tabular-bedded sandstone of Starshot Formation from Mount Ubique area, showing basal load features, graded bedding, and hummocky cross-bedding, yielded detrital-zircon sample USF. Pencil for scale. (F) Thin-bedded, fine-grained sandstone of the Dick Formation at station N, near Cape Selbourne in the northern Churchill Mountains, yielded detrital-zircon sample DIF. Hammer for scale. (G) Fine-grained sandstone of "outboard" Goldie Formation (Starshot equivalent) from Softbed Ridges in the Lowery Glacier area, showing asymmetric climbing ripples, yielded detrital-zircon sample SRG. Pencil for scale. (H) Bedding surface of fine-grained sandstone of "outboard" Goldie Formation (Starshot equivalent) from Dolphin Spur in the Beardmore Glacier area, showing horizontal burrows (white arrows), yielded detrital-zircon sample DSG. Pencil for scale.

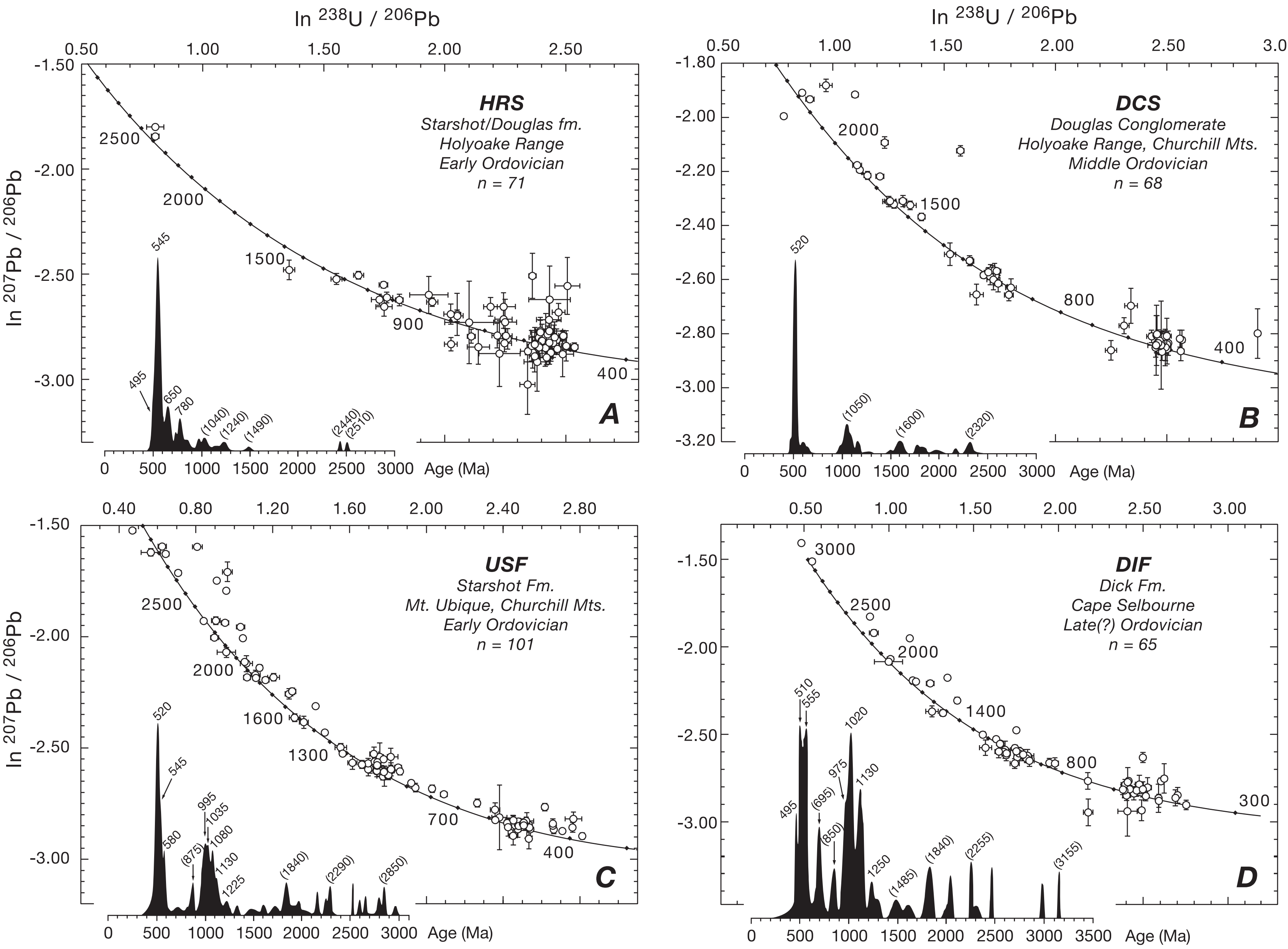


Figure 9. Logarithmic Tera-Wasserburg diagrams and relative probability distributions of detrital-zircon analyses in sandstone samples from outboard clastic units of the Byrd Group. Data presented as in Figure 5 and listed in Tables DR5–DR8 (see footnote 1).

pebble conglomerate and then into fine-grained sandstone and shale (Fig. 8F). Sample DIF is a matrix-rich sandstone with moderate sorting and highly angular to subrounded grains. Framework grains include quartz (mostly monocrystalline), plagioclase, muscovite, biotite, and lithic grains (mostly slate) and minor tourmaline, apatite, and iron-titanium oxide, indicating an igneous source and an associated metamorphic terrane. The zircon age distribution in DIF is highly heterogeneous (Tables 1 and DR8 [see footnote 1]; Fig. 9D), including (1) a dominant (26%), young, composite population at ca. 580–490 Ma; (2) minor populations at 850 and 695 Ma; (3) a composite population of 1200–950 Ma; and (4) minor contributions of Archean and Mesoproterozoic age, including a small population of ca. 1.4 Ga grains. The Ross- and Grenville-age populations generally consist of angular, prismatic grains with oscillatory growth zonation indicating an igneous origin. The youngest discrete age population of five grains gives a weighted-mean age of 501 ± 9 Ma, suggesting a Late Cambrian or younger depositional age.

Compared to other Starshot samples, DIF shows a more heterogeneous detrital-grain age pattern, including a less dominant Ross component. We interpret the age signature as indicating first-cycle input from proximal Ross- and Grenville-age sources, as well as minor Archean and Proterozoic components, several of which are known from nearby crystalline rocks of the Nimrod Group (notably ca. 3.1–3.0 and 2.5 Ga). The age distribution is quite similar to distributions found in Ordovician sandstones of eastern Australia (Williams, 1998; Ireland et al., 1998) and may indicate widespread denudation of the Tasmanide craton-margin mobile belts and their associated hinterland terranes during late-Ross and Delamerian time.

Detrital-zircon ages were also obtained from two samples, SRG and DSG, originally mapped as Goldie Formation but now included in the Starshot (Fig. 1; "outboard" Goldie samples 98-206A and 98-286G of Goodge et al., 2002). Both samples are immature feldspathic arenites (Figs. 8G and H). Detrital zircons in these samples consist mostly of late Neoproterozoic and Early Cambrian grains, including 565–560 (i.e., Ross age), 1200–1000 (i.e., Grenville age), 825–810, and ca. 720 Ma populations, with minor Archean and Proterozoic components. Early Cambrian maximum depositional ages are bracketed by the youngest grain populations of 547 ± 12 Ma in DSG and 531 ± 8 Ma in SRG (Table 1). These rocks contain 25%–50% fresh, young, locally derived zircon of igneous origin, chiefly eroded from a Ross-orogen source.

Koettlitz Group (Hobbs Formation), Southern Victoria Land

Metasedimentary rocks in southern Victoria Land include the Skelton and Koettlitz Groups (see Stump, 1995), but a lack of fossils as well as regional metamorphism, deformation, and granite intrusion obscure their age and stratigraphic relationships. The two groups are exposed in separate areas, but it is presumed that both represent Neoproterozoic deposits that predate Ross deformation and granitic magmatism (Findlay et al., 1984). A minimum age of ca. 550 Ma, bracketed by crosscutting plutons, indicates that the rocks are indeed Precambrian (Rowell et al., 1993; Encarnación and Grunow, 1996; Read and Cooper, 1999).

The Hobbs Formation, the principal unit in the Koettlitz Group (Fig. 10A), is mostly micaceous and calcareous schist, with lesser metaconglomerate, quartzite, and marble, all cut by Granite Harbour intrusive rocks (Findlay et al., 1984). Sample KHF was taken from a quartz-rich layer within calcareous Hobbs quartzite near Hobbs Peak. It is a fine- to medium-grained rock with a completely recrystallized, granoblastic to subidioblastic metamorphic texture composed chiefly of tremolite-actinolite with quartz, plagioclase, iron-titanium oxide, and sphene. The mineral assemblage suggests a calcite-cemented sandstone or sandy carbonate precursor. Oscillatory and sector-growth zonation is common in the detrital zircons, and a lack of overgrowths indicates that the rock probably did not undergo metamorphic conditions greater than amphibolite facies.

The zircon age distribution in KHF is heterogeneous but dominated by late Paleoproterozoic and late Neoproterozoic populations (Tables 1 and DR9 [see footnote 1]; Fig. 10B). Grenville-age zircons make up 56% of the total age distribution, which also includes Paleoproterozoic and minor Archean components. Two grains yielded ca. 1.4 Ga ages. The two youngest grains have a weighted mean age of 668 ± 19 Ma, which brackets the age of deposition to the latest Neoproterozoic and confirms the Vendian age suggested by Findlay et al. (1984).

This Koettlitz sample has a distribution of ages similar to that of the Goldie Formation and the basal Shackleton Limestone in the Nimrod Glacier region. Like them, KHF shows a preponderance of Grenville-age zircons relative to Paleoproterozoic and Archean components. Sample KHF contains no Ross-age detritus. The youngest grains are similar in age to 668 Ma gabbro from the Beardmore Group at the Cotton Plateau (Goodge et al., 2002), which suggests the possibility of widespread mafic magmatism, perhaps related to crustal extension, along the passive margin at the time of Koettlitz and Beardmore deposition. A similarity between the Koettlitz age pattern and the patterns of the Goldie and Shackleton sandstones and the calcareous nature of the associated Koettlitz units suggest that the Koettlitz may record platform deposition in the latest Neoproterozoic.

Hannah Ridge and Patuxent Formations, Pensacola Mountains

As in the central Transantarctic Mountains, thick successions of turbiditic sandstone and shale in the Pensacola Mountains were originally thought to be Proterozoic in age (Patuxent Formation; Schmidt et al., 1964, 1965; Schmidt and Ford, 1969; Storey et al., 1992). However, subsequent studies support subdivision of the siliciclastic succession, in which the Patuxent is restricted to those strata that are coeval with ca. 500 Ma volcanic rocks of the Gambacorta Formation and the Middle Cambrian Nelson Limestone (Millar and Storey, 1995; van Schmus et al., 1997; Rowell et al., 2001). Sandstones from this redefined Patuxent have a single tectonic cleavage and contain detrital zircons as young as ca. 495 Ma, indicating latest Cambrian or younger deposition. The Patuxent Formation therefore represent deposition in a Late Cambrian to Ordovician basin that was subsequently affected by a younger deformation. Exposed in the eastern Neptune Range is a succession of similar sandstone and shale that is difficult to distinguish sedimentologically. However, this inboard sandstone unit, named the Hannah Ridge Formation (Rowell et al., 2001), unconformably underlies the Nelson Limestone and contains detrital zircons no younger than ca. 560 Ma, which indicate that the Hannah Ridge is distinctly older at ca. 560–510 Ma. These rocks were affected by at least two deformation phases of the Ross orogeny, including a Middle Cambrian deformation not observed in the younger, outboard Patuxent rocks (Storey et al., 1992).

These age and stratigraphic relationships provide important new insight to Ross-age tectonic events in the Pensacola Mountains area. To address regional provenance significance, we analyzed two new samples of the Hannah Ridge (NHR) and Patuxent (NPA) Formations, provided to us by A.J. Rowell and W.R. Van Schmus from the Neptune Range (Fig. 11A). Sample NHR is a feldspathic graywacke showing poor sorting and angular to subrounded grains, and sample NPA is a coarse feldspathic arenite containing subangular to rounded, poorly sorted grains. Their contrasting textures are consistent with their stratigraphic division.

Hannah Ridge Formation

Sample NHR contains two dominant Neoproterozoic to Early Cambrian populations (Tables 1 and DR10 [see footnote 1]; Fig. 11B), one representing 46% of the total in the range of 1150–900 Ma (Grenville age) and a second representing 40% in the range of 650–500 Ma (Ross or Pan-African age). There are two small but distinct subpopulations at ca. 870 and 765 Ma, but there are essentially no Mesoproterozoic or Archean grains. The youngest discrete grain population is 556 ± 13 Ma, which limits deposition to a latest Neoproterozoic or younger age.

The Hannah Ridge provenance signature indicates that the sediment was deposited in a marginal basin with a major source of late Neoproterozoic detritus. Its provenance appears to be chiefly in Grenville-age roots to the Ross and Pan-African orogens flanking the Kalahari craton, because the detrital-grain ages are remarkably similar to 1090–1030 Ma basement in present-day western Dronning Maud Land, Coats Land, and the Namaqua-Natal belt (Fitzsimons, 2000b), implying that the principal source of detritus was an intermontane or upland region of the East African orogen. Because the Hannah Ridge sample is dominated by Grenville-age and Pan-African–age components and is nearly devoid of any grains older than ca. 1200 Ma, the nearby major shields (Kalahari, Indian, and East Antarctic) were likely either covered during Early Cambrian time or had drainages that flowed away from the present-day Pensacola Mountains. The younger population (650–550 Ma) is also consistent with an East African orogen provenance but, in contrast to the upper Byrd Group from the central Transantarctic Mountains, indicates that late Neoproterozoic orogenic development was not as significant in the Pensacola Mountains region at this time.

Patuxent Formation

Like the Hannah Ridge sandstone, sample NPA is dominated by Ross- and Grenville-age grains (Tables 1 and DR11 [see footnote 1]; Fig. 11C), yet the Ross components are younger. This sample contains no Proterozoic grains older than ca. 1.3 Ga, and there is one Archean grain with an age of ca. 3.0 Ga. Twelve grains (19%) gave Early Cambrian ages, and the youngest discrete grain population is 513 ± 4 Ma, limiting the age of deposition to Middle Cambrian or younger.

The ages in sample NPA are similar to those obtained by Rowell et al. (2001) for the Patuxent, whose four-grain composite $^{207}Pb/^{206}Pb$ age of 496 ± 12 Ma restricts its deposition to the latest Cambrian or Ordovician. Both data sets demonstrate that the Patuxent is notably younger than the Hannah Ridge Formation. The large number

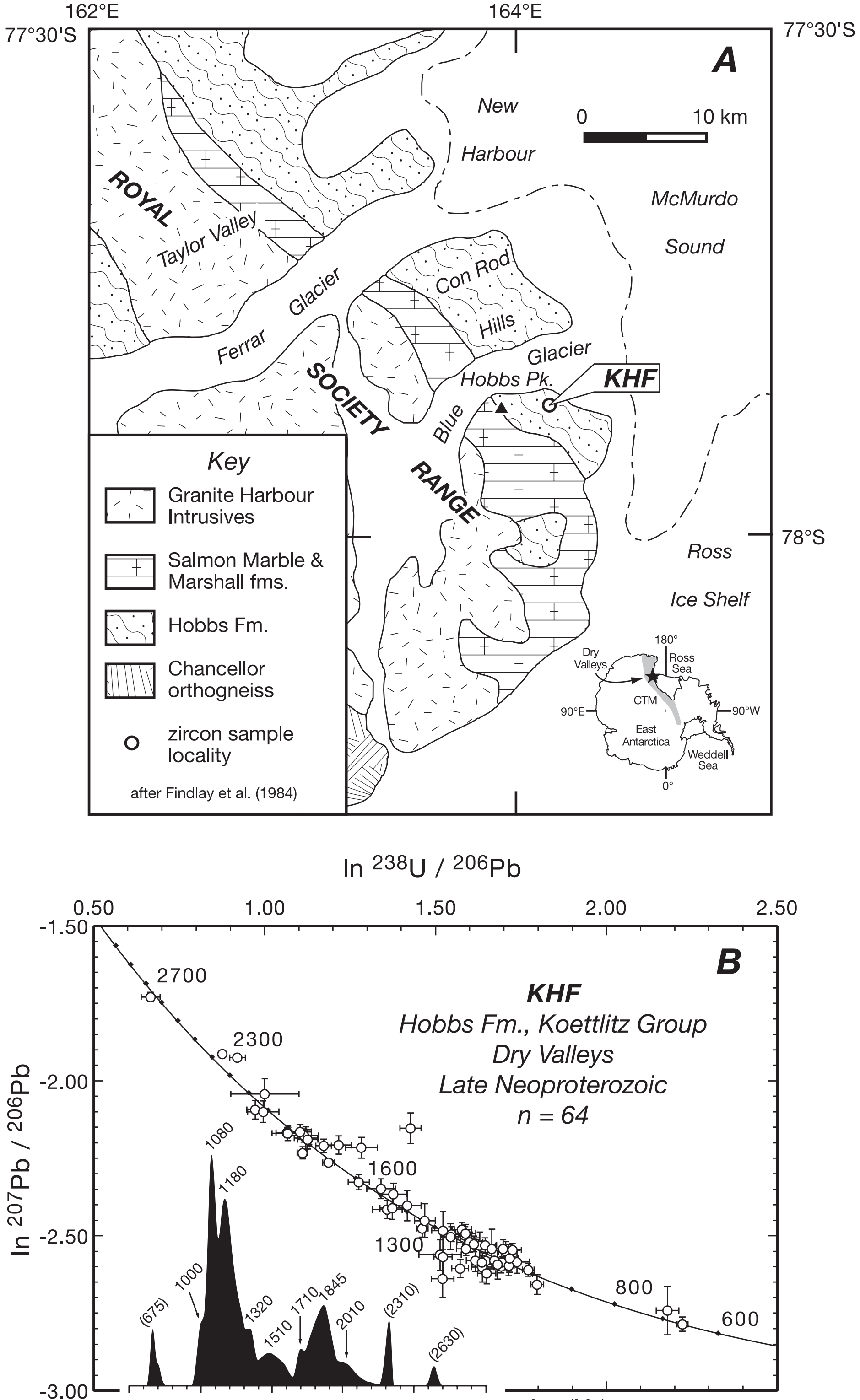


Figure 10. (A) Geologic map of the Dry Valleys area in the vicinity of Ferrar and Blue Glaciers (from Findlay et al., 1984). The Koettlitz Group sedimentary units include Salmon Marble and the Marshall and Hobbs Formations; other formations of the group are not exposed in this area. Location of detrital-zircon sample KHF from the Hobbs Formation is shown to the east of Hobbs Peak. (B) Logarithmic Tera-Wasserburg diagram and relative probability distribution of detrital-zircon analyses in sample KHF. Data presented as in Figure 5 and listed in Table DR9 (see footnote 1).

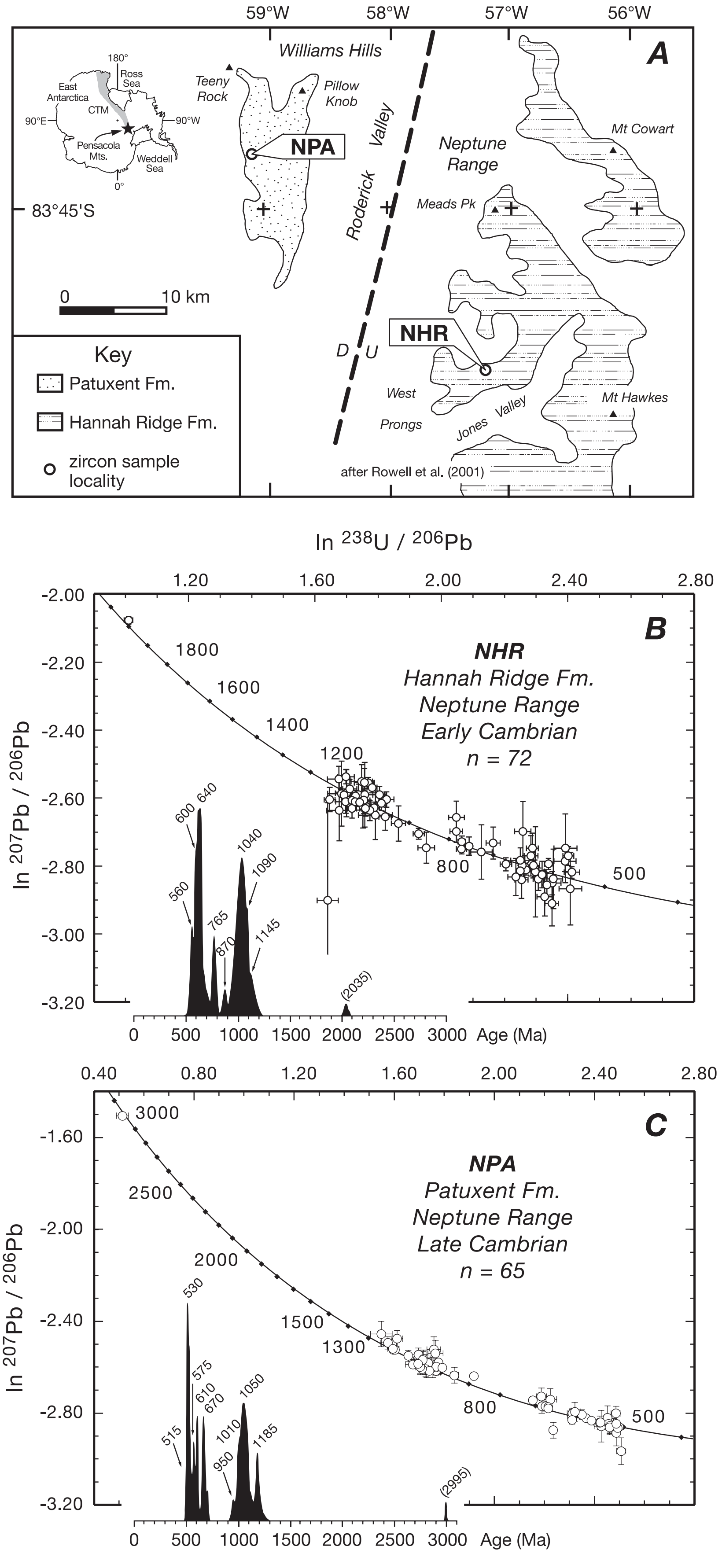


Figure 11. (A) Geologic map of the western Neptune Range and Williams Hills area (from Rowell et al., 2001). There, exposures of the Patuxent and Hannah Ridge Formations are separated by Roderick Valley, interpreted as overlying a fault boundary between the two formations. Locations of detrital-zircon samples from the Patuxent (NPA) and Hannah Ridge Formations (NHR) are shown. (B–C) Logarithmic Tera-Wasserburg diagrams and relative probability distributions of detrital-zircon analyses in sandstone samples from (B) Hannah Ridge and (C) Patuxent Formations. Data presented as in Figure 5 and listed in Tables DR10 and DR11 (see footnote 1).

of grains in sample NPA show that the Patuxent detritus is exclusively late Neoproterozoic and younger; they also document significant Early Cambrian detritus, as in the upper Byrd Group clastic rocks. Compared to the latter, however, the Patuxent contains older (680–580 Ma) grains that may represent either earlier development of the Ross belt in the Pensacola Mountains region or input of early Pan-African detritus from the southern part of the East African orogen, as suggested for the Hannah Ridge unit. The presence of significant Neoproterozoic detritus (1200–950 Ma) is consistent with erosion from a Pan-African (generally 500–600 Ma) source flanked by Grenville-age belts. The absence of other Proterozoic or Archean ages indicates either that the southern African cratons were not exposed in the Cambrian or that the Patuxent basin was isolated from them.

DISCUSSION

Stratigraphic Relationships and Depositional Associations

The detrital-zircon data presented here from siliciclastic successions of the Transantarctic Mountains, combined with regional sedimentological and stratigraphic data, permit us to divide the supracrustal assemblage of the central Ross orogen into four distinctive tectonostratigraphic packages (Fig. 12). Neoproterozoic rift-drift deposits (NRD in Fig. 12) are represented by the Cobham and Goldie Formations of the Beardmore Group, including rocks in the Princess Anne Glacier area. These contain Grenville-age and older detritus, with major inputs of Archean and Paleoproterozoic age. Despite having a distinctly old provenance, their depositional age is probably latest Neoproterozoic, as indicated by the 668 Ma age of volcanic rocks associated

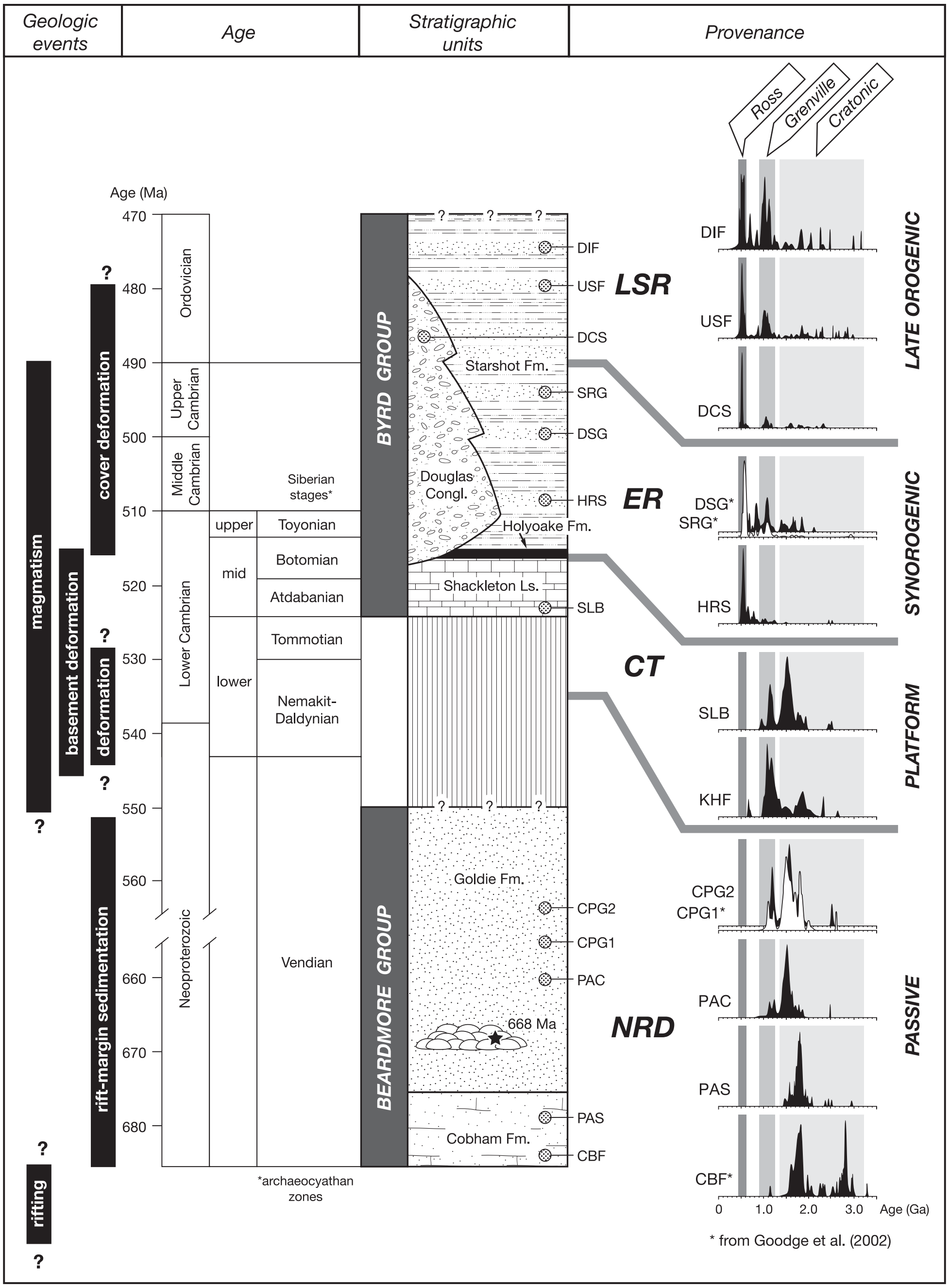


Figure 12. Correlation of stratigraphic units and summary of detrital-zircon components. Major time periods shown with Siberian biostratigraphic stages for reference. Stratigraphic units and positions as in Figure 2. Ages of geologic events in the central Transantarctic Mountains region summarized by black bars. Geochronologic constraints indicate that the Beardmore Group is certainly younger than 1000 Ma and, in part, 668 Ma or younger, but its minimum age is unknown and could be as young as Early Cambrian. Both the Shackleton Limestone and Holyoake Formation are biostratigraphically bracketed to the middle Lower Cambrian. Detrital-zircon age distributions are shown for comparison and are in order of relative depositional age based on biostratigraphic control and the youngest zircon grain populations; stratigraphic positions of samples PAS and PAC are uncertain, but we tentatively place them in the Beardmore Group. Data for samples CBF, CPG1, SRG, and DSG from Goodge et al. (2002). Note that the age spectra for two samples of Goldie Formation (CPG1 and CPG2) are superimposed for comparison, as are two samples of "outboard Goldie" (now Starshot Formation) from Softbed Ridges (SRG) and Dolphin Spur (DSG). Detrital-zircon provenance reflects four tectonic stages of development, on the basis of relative age and detrital-grain age signature: NRD—passive-margin stage of Neoproterozoic rift-drift margin, characterized by Archean and Mesoproterozoic cratonic provenance; CT—platform stage during Cambrian transgression, with mixed carbonate and siliciclastic deposition, the latter dominated by Mesoproterozoic and Grenville-age sources; ER—early Ross synorogenic stage, marked by near-complete absence of cratonic and older orogenic (Grenville) signatures and dominated by proximal, young material from the youthful Ross orogen; and LSR—late Ross orogenic stage, showing the youngest detrital components with an orogenic provenance, but also minor influx of older cratonic material.

with the Goldie Formation at the Cotton Plateau (Goodge et al., 2002). In keeping with the idea that the Goldie rests conformably upon the Cobham, we suggest that the Cobham and Princess Anne sandstone units (CBF and PAS) represent the lowermost Beardmore Group and that the Princess Anne conglomerate and the Cotton Plateau–type Goldie units (PAC, CPG1, and CPG2) make up the younger part. Lithofacies, sediment composition, and association with mafic volcanic rocks indicate that the Neoproterozoic rift-drift deposits formed in shallow water across a rifted cratonic margin during early extensional and later passive-margin tectonic phases. The detrital signatures in these units indicate a simple, two-component source consisting of Archean and Paleoproterozoic–Mesoproterozoic cratonic provinces.

Cambrian transgressive deposits (CT in Fig. 12) make up a second major package in the orogenic belt. These are mainly represented by the basal, lower Atdabanian sandstone member of the Shackleton Limestone (SLB). Its detrital signature is strikingly similar to that of the Goldie, suggesting that clastic sediment of the late Neoproterozoic passive margin shared the same source or that the basal Shackleton contains reworked Beardmore Group material. The latter would support an erosional unconformity at the base of the Shackleton. In either case, basement deformation, metamorphism, and magmatism occurred by Early Cambrian time (ca. 540 Ma; Goodge et al., 1993b; Goodge and Dallmeyer, 1992, 1996), yet this activity is not manifested as detrital input to the Shackleton. The Hobbs Formation (KHF) is latest Neoproterozoic, but it contains carbonate lithofacies suggesting a platform-type depositional setting similar to that of the Shackleton. Its dominant Grenville-age provenance is notably different from that of both Neoproterozoic rift-drift deposits and Cambrian transgressive sandstones, so direct correlation with units of the central Transantarctic Mountains is uncertain. Despite their differences, however, all of these samples reflect a mixture of Mesoproterozoic and Neoproterozoic cratonic sources immediately prior to the onset of Ross tectonism.

Two post-Shackleton tectonostratigraphic packages are represented in the upper Byrd Group; these show similar but distinctive sedimentary traits. Because of their stratigraphic position overlying the platform deposits, their immature sedimentary composition, and the dominance of Ross detrital-grain ages, these rocks represent the sedimentary response to Ross orogenesis. The detrital-grain age signature in the lowermost Starshot sample (HRS) is dramatically different from all older units, consisting almost exclusively of Ross-age igneous detritus. Other samples (SRG and DSG) show a similar dominance of Ross components, but each contain minor cratonic and Grenville-age zircons suggesting limited exposure of Precambrian basement rocks within the roots of the magmatic arc. Together, these early Ross (ER, Fig. 12) depositional units signal a fundamental shift in tectonic regime, and they are considered syntectonic in origin.

Samples of the upper Starshot Formation (USF and DIF) show similar detrital-grain age patterns as the early Ross group, but they also include significant Precambrian components that suggest yet a different or additional source. We infer these older components to represent exposure of crystalline basement underlying the Ross magmatic arc, although they could also be recycled components from Neoproterozoic and Lower Cambrian units. Sediment composition and texture indicate that these are proximal deposits, and we interpret them as a late-stage Ross (LSR in Fig. 12) lithotectonic package that received sediment from both the magmatic arc and its underlying basement. The Douglas Conglomerate is a coarse-grained time-equivalent of the Starshot that we include in the late-stage Ross group. Distal deposits of the Douglas (DCS) also contain small proportions of older basement detritus, suggesting exposure of crystalline roots of the orogen. Minimum ages of late-stage Ross detritus restrict late Ross tectonic displacements to the Early Ordovician.

Sandstones from the Pensacola Mountains contain signatures similar to those of the younger lithotectonic units in the central Transantarctic Mountains. The two Neptune Range sandstones have strikingly similar Grenville-age zircons, but differing proportions and ages of Pan-African/Ross material. Particularly noteworthy in each is the near absence of components older than ca. 1.2 Ga. The Hannah Ridge, which underlies a Middle Cambrian erosion surface, is depositionally older than its early Ross counterparts in the central Transantarctic Mountains, but its age signature indicates a young source in exposed Grenville-age and early Pan-African–age orogenic highlands. Likewise, the Upper Cambrian–Ordovician Patuxent shows a dominance of locally derived Ross-age detritus. Except for a single Archean grain, the prominent Ross- and Grenville-age components in the Patuxent sandstone are superficially similar to Starshot samples USF and DIF. Apparent differences in provenance among the Neptune Range units could result from actual source characteristics or from a diachronous and episodic orogenic record in the region (Rowell et al., 2001).

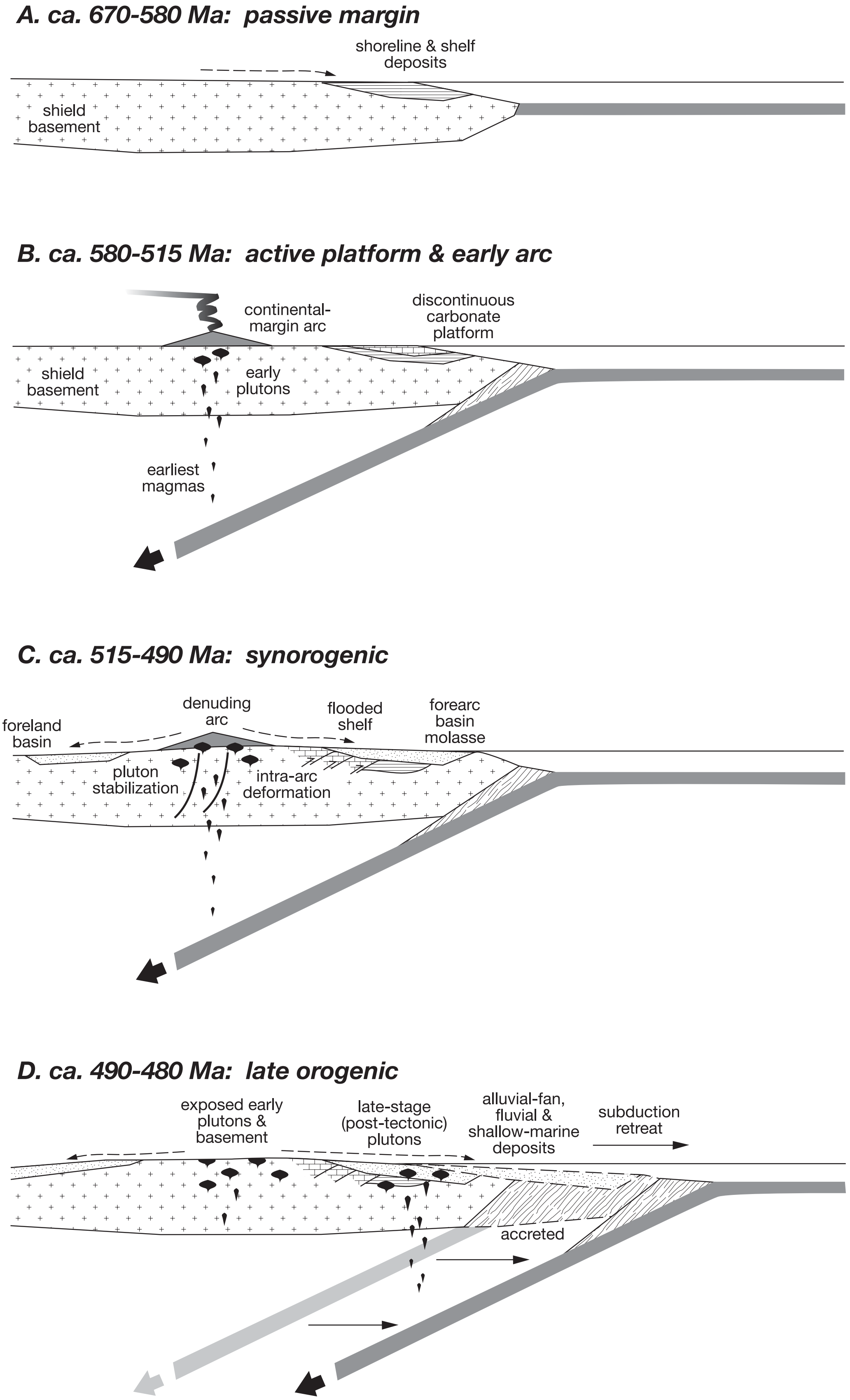
The provenance data, combined with stratigraphic, petrofacies, and paleocurrent relationships, also bear on the relationship between siliciclastic successions in the Transantarctic Mountains and the East Antarctic Shield. Some authors have considered the supracrustal rocks to be craton-margin deposits (Laird, 1991; Goodge et al., 2002), whereas others regarded at least some to be allochthonous in origin (Borg et al., 1990; Rowell and Rees, 1990; Borg and DePaolo, 1991; Grunow and Encarnación, 2000). The pre-Ross orogen units (Neoproterozoic rift-drift deposits and Cambrian transgressive deposits) represent autochthonous continental-margin deposits because of their clear cratonic provenance and stratigraphic relationship to platform carbonate. We consider rocks of the younger, syntectonic association (early Ross deposits and late-stage Ross deposits) to be autochthonous as well, because of their mutual facies relationships, depositional overlap upon platform carbonate, eastward paleocurrents, predominance of a continental-margin arc source, and the presence of carbonate-clast material suggesting proximal derivation. If an autochthonous origin is accepted, then tectonic models must account for the changing provenance of these deposits.

Tectonic Model of Passive- to Active-Margin Sedimentation

A general tectonic model that explains the detrital-zircon data, as well as stratigraphic and geologic relationships presented elsewhere (Goodge et al., 2002; Myrow et al., 2002b), is shown in Figure 13. Inferred depositional relationships at different stages of the tectonic history are shown in Figure 14. In general, the tectonostratigraphic packages defined herein correspond to the tectonic stages shown, but we use different terms to distinguish the rock units from the inferred tectonic setting.

Passive-Margin Phase (ca. 670–580 Ma)

The age of rifting along the Pacific margin of East Antarctica is debated. Some paleomagnetic data and paleogeographic models suggest breakup of Rodinia at ca. 750 Ma (Powell et al., 1993; Dalziel, 1997; Wingate and Giddings, 2000), supported in the Transantarctic Mountains by Nd isotope ages of mafic igneous rocks (Borg et al., 1990; Rowell et al., 1993). The isotopic ages are problematic, however, because of large analytical uncertainty, and more recent geochronologic data indicate that mafic volcanism is substantially younger (668 Ma; Goodge et al., 2002). Koettlitz Group sandstone contains detrital zircons of similar age (ca. 670 Ma), suggesting that extension, magmatism, and sedimentation occurred in the latest Neoproterozoic along an existing rifted margin. Given platform carbonate deposition by



A. ca. 670-580 Ma: passive margin

B. ca. 580-515 Ma: active platform & early arc

C. ca. 515-490 Ma: synorogenic

D. ca. 490-480 Ma: late orogenic

Figure 13. Model of the late Neoproterozoic and early Paleozoic tectonic evolution of the East Antarctic margin in the central Transantarctic Mountains. Crustal thicknesses approximately to scale, but sedimentary basins exaggerated in thickness for clarity. (A) Passive-margin stage, characterized by marginal-basin sedimentation of shoreline and shallow-marine deposits (Beardmore Group). Age of rifting onset unknown, but volcanism and sedimentation occurred by at least 670 Ma (Goodge et al., 2002). (B) Platform and incipient arc stage, represented by discontinuous deposition of Lower Cambrian shelf carbonate (Shackleton Limestone). Continental-margin volcanism was initiated by ca. 580 Ma, as indicated by detrital-zircon record, and true calc-alkaline plutons intruded by ca. 550 Ma. (C) Synorogenic stage, characterized by intra-arc deformation of basement units (both metamorphic rocks and older parts of the sedimentary succession), continued magmatism, erosion of the supraorogen arc, and deposition of siliciclastic material (Holyoake, Starshot, and "outboard" Goldie Formations) in forearc setting, overlapping older sedimentary units. Transport direction to east (present-day coordinates) is known from paleocurrents and igneous arc source. Foreland-basin deposition is inferred. (D) Late-orogenic stage, in which youngest post-tectonic granitic magmas intrude Cambrian units of the synorogenic succession. Continued deposition of siliciclastic materials in alluvial-fan/fluvial (Douglas Conglomerate) and shallow-marine (upper Starshot and Dick Formations) settings. Oceanward retreat of the subduction zone to the east (present-day coordinates) is inferred in order to explain offshore migration of the magmatic axis.

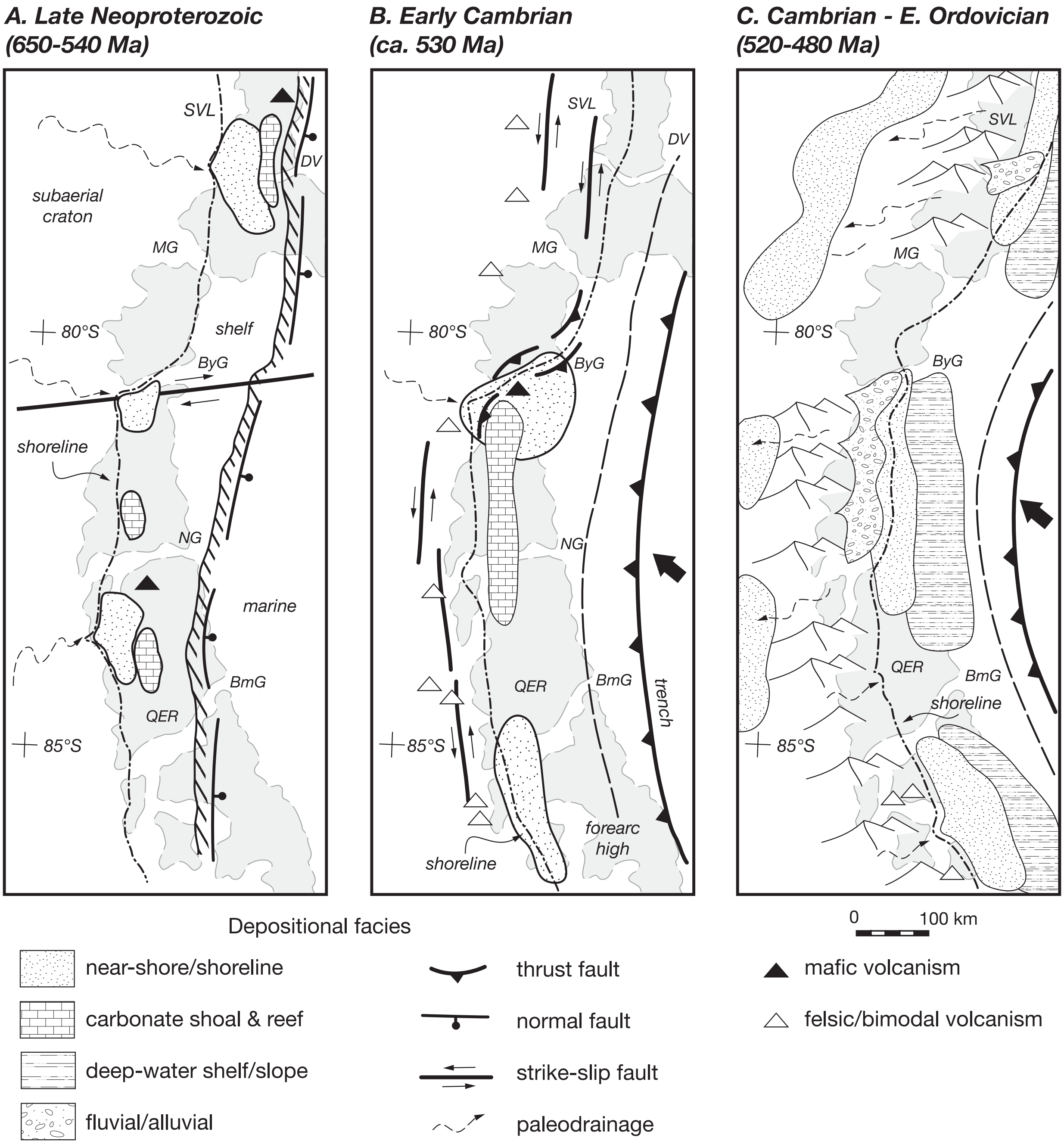


Figure 14. Reconstruction of major tectonic features and associated depositional facies along the Neoproterozoic and early Paleozoic Ross margin, shown on present-day geographic base (no palinspastic restoration). (A) Late Neoproterozoic rift margin, marked by rift-flank normal faults (hachures and faults with bar and ball) and possible transform offsets such as along Byrd Glacier. Passive margin is characterized by shoreline and shallow-shelf deposits, as well as by localized mafic volcanism related to extension. (B) Early Cambrian platform as terminal phase of passive margin during development of incipient convergent continental margin, marked by deposition of discontinuous carbonate and shoreline sandstones. Incipient magmatic arc dominated by felsic and bimodal volcanism (see references in text). Oblique plate convergence indicated by mid-crustal deformation patterns. (C) Cambrian–Ordovician convergent margin and continental-margin arc system. Orogen developed by structural and magmatic thickening and, at surface, marked by erosion yielding siliciclastic molasse deposits in alluvial-fan, fluvial, and shoreline settings. BmG—Beardmore Glacier; ByG—Byrd Glacier; DV—Dry Valleys; MG—Mulock Glacier; NG—Nimrod Glacier; QER—Queen Elizabeth Range; SVL—southern Victoria Land.

ca. 525 Ma, a rift age of ca. 670 Ma is consistent with simple thermal models of passive-margin subsidence, which suggest a general life span for subsiding rifted margins of ~150 m.y. in cases of average crustal thickness and constant sediment-input rate (e.g., McKenzie, 1978).

Provenance data indicate that the Beardmore Group accumulated along a narrow cratonic margin in the latest Neoproterozoic (Fig. 13A). Lithologic variation in the Cobham and Goldie Formations suggests deposition in shoreline and storm-influenced shallow-shelf settings (Fig. 14A). Low physiographic relief and multicycle components are likely, on the basis of sediment maturity and grain textures. Paleocurrent indicators are lacking in this succession, but the Archean and Proterozoic detrital-grain ages are well represented in the composite East Antarctic Shield (Tingey, 1991; Goodge and Fanning, 1999; Fitzsimons, 2000a; Goodge et al., 2001), making it the likely source of primary detritus. Differences in structural features across a purported unconformity at the base of the Byrd Group (Laird et al., 1971; Stump et al., 1991; Stump, 1995) may reflect a pre-Atdabanian deformation, although the nature of this boundary is obscured by faults (Rowell et al., 1986; Goodge, 1997; Goodge et al., 1999). If verified, deformation of the passive-margin deposits prior to middle Early Cambrian time would represent an early phase of Ross tectonism.

Platform Phase (ca. 580–515 Ma)

Mature quartz arenite beds of the basal Byrd Group pass cyclically upward into thick Atdabanian and Botomian carbonate deposits (Myrow et al., 2002b), representing transgression across the Neoproterozoic passive-margin deposits during the Early Cambrian global marine highstand. The inner-shelf Shackleton platform was laterally discontinuous and coeval with basement activity and magmatism related to the early Ross orogenic cycle (Figs. 13B, 14B; Rowell et al., 1992; Goodge, 1997). Regional geochemical trends in the Ross batholith indicate a continental-margin arc setting (Armienti et al., 1990; Borg et al., 1990; Allibone et al., 1993; Borg and DePaolo, 1994; Rocchi et al., 1997), and alkaline rocks as old as ca. 560–550 Ma in southern Victoria Land are interpreted as subduction related (Encarnación and Grunow, 1996; Read and Cooper, 1999; Allibone and Wysoczanski, 2002). Early and Middle Cambrian volcanic rocks are exposed farther south in the Queen Maud Mountains (van Schmus et al., 1997; Encarnación et al., 1999; Wareham et al., 2001), but to our knowledge, volcanic rocks of this age are absent in the central Transantarctic Mountains. Despite this, we postulate the existence of a regionally extensive magmatic belt as old as ca. 580 Ma on the basis of detrital-zircon ages in early Ross-type sandstones of the upper Byrd Group (Fig. 12). There are no indications of magmatic-arc detritus dating to 580 Ma in Cambrian transgressive-type sandstones from either the central Transantarctic Mountains or southern Victoria Land (Fig. 12); therefore, the latest Neoproterozoic and Early Cambrian interval was apparently characterized by both an extant siliciclastic-carbonate shelf *and* early igneous activity in a continental-margin arc setting (Fig. 13B), which may be explained by incipient subduction offshore of the rifted margin and/or a wide arc-trench gap. Although tectonic activity was recorded in adjacent crystalline basement by ca. 540 Ma (Goodge et al., 1993b), platform-type sedimentation—in both a stratigraphic and provenance sense—persisted in the central Transantarctic Mountains to ca. 515 Ma when an abrupt change occurred.

Synorogenic Phase (515–490 Ma)

The platform succession was terminated abruptly in Botomian time by interruption of carbonate production, influx of mud and silt deposits, and onlap of coarse alluvial-fluvial debris upon high-relief erosion surfaces (Myrow et al., 2002b). This initial sedimentary change may have occurred in response to flexure caused by thrust loading or negative outer-margin buoyancy related to subduction. Tectonic subsidence is marked by shale and silt beds of the Holyoake Formation, succeeded in turn by coarser fluvial-marine and alluvial-fan deposits of the Starshot and Douglas Formations. Paleocurrent, paleoslope, and facies relationships indicate offshore transport of clastic sediment to the east (present-day coordinates). The provenance of these deposits changed dramatically from a composite shield signature to a younger active-margin igneous source, in which fresh first-cycle detritus was eroded from proximal igneous and metamorphic rocks of the emerging Ross orogen (mostly 580–520 Ma). The thickening Ross orogen probably was a major physiographic barrier to transport from the East Antarctic Shield, yet small amounts of Precambrian detritus indicate either marginal drift or sediment recycling. We therefore consider the early Ross association to represent a locally derived succession of synorogenic deposits that reflects tectonically induced uplift and erosion within a convergent setting.

Together, observed stratigraphic relationships and sedimentary provenance show that the early Ross–type siliciclastic units represent synorogenic molasse deposits, eroded chiefly from the continental-margin magmatic arc to the west (Figs. 13C, 14C). Thus, they appear to be forearc deposits, although no features of an outer accretionary complex or trench are known. Older flysch deposits may exist offshore of our field area but are either buried or not preserved as a result of subsequent deformation. We speculate from tectonic geometry that a foreland-basin succession of equivalent age and provenance may underlie the polar ice cap to the west. Early to Middle Cambrian felsic volcanic units are well known in the southern Queen Maud Mountains (Stump, 1976; Encarnación and Grunow, 1996; van Schmus et al., 1997; Encarnación et al., 1999; Wareham et al., 2001), yet no early Paleozoic arc-type volcanic rocks are known from the Nimrod Glacier area. Therefore, it is likely that volcanic features of the magmatic arc in the central region of the Ross orogen were nearly completely or entirely removed by erosion, forming the chief source of material in the molasse deposits. Pebbles of rhyolite and intermediate-composition volcanic rocks in the Douglas and Starshot Formations (Laird, 1964) reflect erosion of this volcanic carapace. Erosional inversion of the arc volcanic section, as inferred in other convergent settings (Dickinson and Seely, 1986; Linn et al., 1992), is supported by isotopic compositions of the sandstones. Nd and Sr isotope compositions from the Starshot Formation (Borg et al., 1990; their “eastern Goldie Formation”) overlap with late-stage Ross granites in this region. The close match in isotopic composition is consistent with the detrital-grain age signatures, which are dominated by 580–520 Ma igneous zircons (Fig. 12). Additional age constraints from detrital muscovites, crosscutting igneous intrusions, and in situ metamorphic minerals (Goodge et al., 2004) limit the time span of molasse deposition to a brief period in the late Early to Late Cambrian. The short time lag between the age of the principal source rocks and the age of deposition is similar to cases where erosion and rapid forearc sediment-accumulation rates appear to be driven by tectonic and magmatic intra-arc thickening (Busby et al., 1998; Kimbrough et al., 2001).

Late-Orogenic Phase (490–480 Ma)

Deformation and erosion of the orogenic belt continued through the Ordovician, yielding further transport of molassic debris across the forearc region (Fig. 13D). Stratigraphically higher units in the upper Byrd Group (late-stage Ross association) are dominated by young, Ross-age magmatic components, as in the synorogenic deposits (Fig. 12), yet they also show minor Archean and Proterozoic age signatures. Some of the older age components in these rocks may represent recycled material from the deformed Neoproterozoic and Lower

Cambrian successions, but may also reflect deep incision within the orogen. We suggest that profound denudation eventually removed the entire volcanic carapace and exposed the deeper plutonic roots of the arc, consistent with rapid cooling in the source area as represented by fission-track and ^{40}Ar/^{39}Ar cooling ages in the adjacent crystalline basement (Fitzgerald, 1994; Goodge and Dallmeyer, 1992, 1996). By comparison, sandstones in the Pensacola Mountains (Fig. 11) show a similar trend toward greater Ross-age magmatic components in the younger deposits (Patuxent Formation) at the expense of older crustal ages. In both cases, however, the presence of prominent Grenville-age and early Pan-African–age or Ross-age detritus suggests a direct source of Neoproterozoic material from the Mozambique Belt/East African orogen and Grenville belt of Dronning Maud Land, as well as an emerging Ross orogen.

The syn- and late-orogenic deposits were in turn intruded by late-orogenic granitic plutons, suggesting that magmatism shifted outward during trench retreat (Fig. 13D). Trenchward migration of the magmatic axis is shown by progressively younger ages of granitoid plutons toward the present-day Ross Ice Shelf in the Dry Valleys, Nimrod Glacier, and Scott Glacier areas (Goodge et al., 1993b; Encarnación and Grunow, 1996; van Schmus et al., 1997; Allibone and Wysoczanski, 2002; J. Goodge and Fanning, 2001); the most outboard of these granitoids (ca. 500–480 Ma) intrude deformed Lower and Middle Cambrian sedimentary and volcanic rocks of the early Ross and late-stage Ross associations. Because these strata are themselves deformed, Ross tectonism in the outboard successions must have extended into at least the Early Ordovician. By the Devonian, with formation of a continent-wide peneplain surface, even deeper plutonic roots of the arc were exposed (Grindley, 1963).

Provenance Significance with Respect to Ancient East Gondwana and Rodinia

Possible source terranes inferred from the detrital-grain age data in sandstones of the Ross orogen are shown in Figure 15. Because we consider both the pre- and syntectonic sedimentary successions to be autochthonous, the major sources of detritus in these rocks are in the East Antarctic Shield and formerly adjacent cratons that have since separated. Compilations of age belts in the East Antarctic Shield and East Gondwana region (Tingey, 1991; Fitzsimons, 2000a) are used below to compare the detrital-mineral ages with possible source terranes.

The oldest passive-margin deposits contain a variety of Archean and Proterozoic components. Source terranes of similar age are widespread in East Antarctica and adjacent areas and cannot be used as distinctive tracers, although the nearby Nimrod Group could account for common age components of ca. 3.0, 2.5, and 1.7 Ga (Goodge and Fanning, 1999; Goodge et al., 2001). Neoproterozoic belts of Grenville-type affinity occur in a number of areas, and several distinctive subbelts are recognized at ca. 1175, 1080, and 960 Ma (Fitzsimons, 2000b; Boger et al., 2001). Beardmore Group sandstones appear to contain only the older of these Grenville-age subcomponents (1235–1095 Ma), suggesting that the principal source of detritus for the passive-margin deposits was restricted to the Wilkes Land sector of East Antarctica and adjacent western Australia (Fig. 15). Platform sedimentary deposits, including the lower Byrd and Koettlitz Groups, contain younger detrital components with ages between 1000 and 970 Ma in addition to the older Grenville ages, which may indicate a broader source region that included basement in southern India and the adjacent Rayner Complex of East Antarctica.

By early Paleozoic time, the principal sources of sediment had dramatically changed, although sediment transport continued to be toward the outer margin of East Gondwana. Syn- and late-tectonic deposits of the Transantarctic Mountains are dominated by local igneous and metamorphic sources in the Ross orogen. Minor cratonic-age components in these deposits, including all of the Grenville-age subbelts noted above, can be traced to the East Gondwana shield areas, either by direct input or by sediment recycling along the active margin. In contrast, sedimentary units of similar age in the Pensacola Mountains region contain distinctive detrital components of 1185–1040 and 670–600 Ma age that appear to reflect specific sources in basement of the East African orogen/southern Mozambique belt and its extension into western Dronning Maud Land. It is possible that material eroded from these Pan-African collisional belts also was transported across the East Antarctic Shield and deposited in Byrd Group basins underlying the present-day Transantarctic Mountains.

In addition to an East Gondwana provenance, our detrital-grain age data also support a paleogeographic link to western Laurentia. Several of the autochthonous passive-margin and platform units in the central Transantarctic Mountains contain significant proportions of ca. 1.4 Ga zircon (up to 22%; Table 1). Deposits of the upper Byrd Group also show trace zircons of this age, but, as with the other cratonic signatures, they are swamped by younger components. As shown by studies of Proterozoic successions (Rainbird et al., 1992) and modern beach sands (Sircombe and Freeman, 1999), where either the transport direction or the actual provenance is known, detrital-grain populations of as little as 5% are significant and reflect the source-terrane characteristics. Geologic provinces of ca. 1.4 Ga age are uncommon globally and include some small occurrences in central Africa, the Brazilian Shield, and the Cathasian block of South China (Oliver et al., 1998; Geraldes et al., 2001; Li et al., 2002). The most significant potential source of sediment of this age, however, is the widespread ca. 1.4 Ga trans-Laurentian igneous province of North America (Fig. 16). The presence of these age components in deposits of the upper Byrd Group that were derived from the west (present-day coordinates) precludes a direct source from Laurentia, because in most paleogeographic models East Antarctica and Laurentia were widely separated by this time. The persistent signature of ca. 1.4 Ga material in sandstones of the central Transantarctic Mountains, coupled with compositional and textural evidence indicating that the zircons are mostly first-cycle igneous grains, suggests that the primary source of this material in the Ross successions is a Proterozoic geologic province containing rocks of 1.4 Ga age in the central East Antarctic Shield (Fig. 16). We speculate that such a crustal province, underlying the present polar ice cap, may be an extension of Proterozoic belts in Laurentia, including the 1.4 Ga igneous rocks and their hosts in the Yavapai, Mazatzal, and Mojave provinces. Such an interpretation is consistent with the co-occurrence of 1.8–1.6 Ga zircons in the detrital-grain populations.

SUMMARY

A combination of new stratigraphic, structural, biostratigraphic, and detrital-mineral age data makes it possible to reconstruct the depositional history and provenance of upper Neoproterozoic and lower Paleozoic siliciclastic successions along the paleo–Pacific margin of East Antarctica. Our stratigraphic data indicate that these deposits record a fundamental shift from a latest Neoproterozoic rift margin to an Early Cambrian passive-margin platform and finally to a Middle Cambrian–Early Ordovician active-margin molasse basin. An important timeline in this transition is represented by the Atdabanian–Botomian platform-carbonate deposits, which are abruptly overlain by an upward-coarsening siliciclastic succession of dominantly continental strata. This transition corresponds with a major shift in detrital-zircon age and provenance signatures, as recorded in sandstone units of the Beardmore, lower Byrd, and upper Byrd Groups, from dominantly cratonic input to a

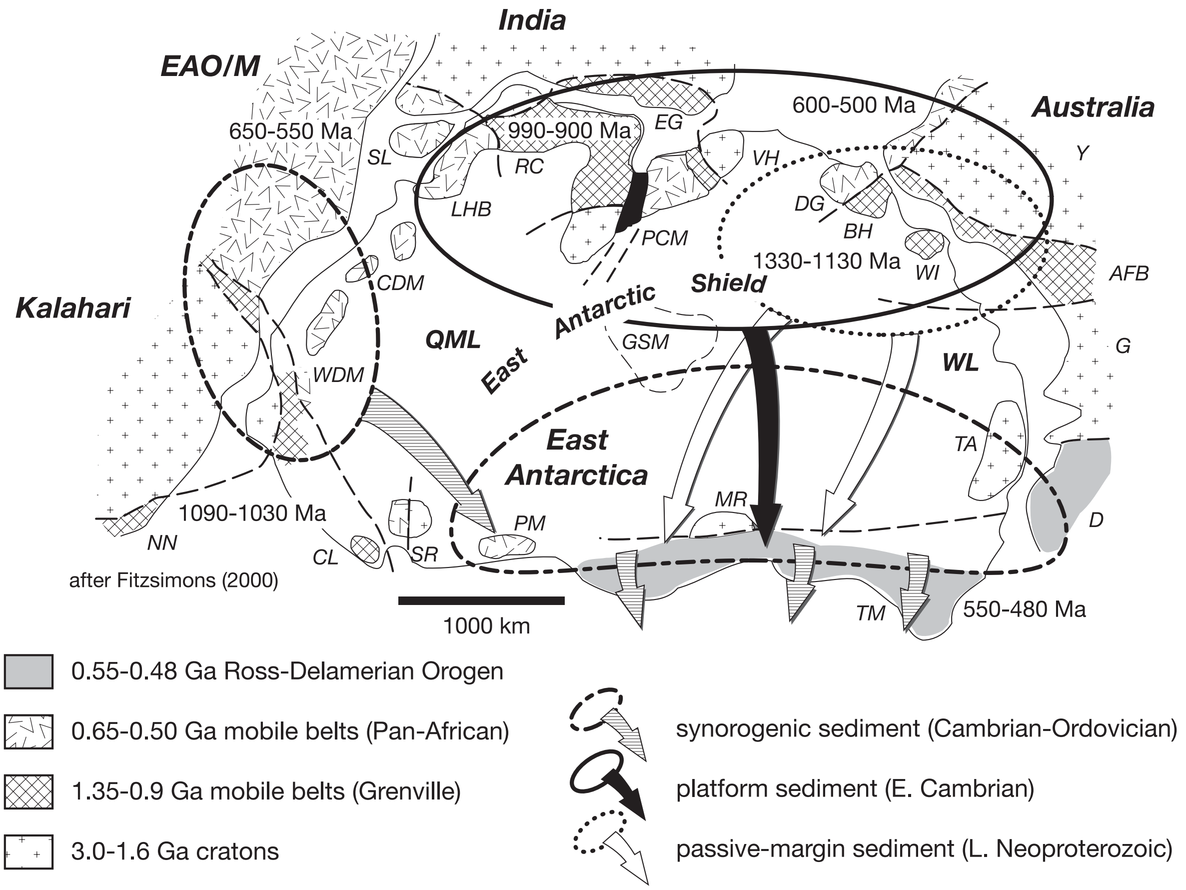


Figure 15. Map reconstruction of the major East Gondwana crustal elements in East Antarctica, southern Australia, India, and Kalahari craton of southern Africa (modified after Fitzsimons, 2000a). Arrows indicate inferred provenance for sands deposited along the rifted East Antarctic margin (currently represented by sedimentary successions in the Transantarctic Mountains, but probably deposited farther offshore when palinspastically restored). All samples show variable proportions of Archean and Proterozoic zircons that are compatible with an East Antarctic cratonic source (see Figs. 5, 9, and 12). Source areas outlined are inferred primarily on the basis of distinctive Grenville-age detrital signatures, as discussed in the text. Sediment deposited during the passive-margin and platform stages (white and black arrows, respectively) were probably derived from the East Antarctic Shield and adjacent parts of Australia and India, on the basis of the presence of distinctive Grenville-age signatures. Sediment deposited during synorogenic stage (arrows with horizontal ruling) is dominated by locally derived igneous material of the Ross magmatic arc, but includes minor cratonic components. Transport directions are compatible with paleocurrent and paleoslope data in the platform and synorogenic deposits and indicate a general movement of detritus away from the East African orogenic uplift. Abbreviations: AFB—Albany-Fraser belt; BH—Bunger Hills; CDM—central Dronning Maud Land; CL—Coats Land; D—Delamerian orogen; DG—Denman Glacier; EAO/M—East African orogen/Mozambique belt; EG—Eastern Ghats; G—Gawler craton; GSM—Gamburtsev Subglacial Mountains; LHB—Lutzow-Holm Bay; NN—Namaqua-Natal; MR—Miller Range; PCM—Prince Charles Mountains; PM—Pensacola Mountains; QML—Queen Maud Land; RC—Rayner Complex; SL—Sri Lanka; SR—Shackleton Range; TA—Terre Adelie; TM—Transantarctic Mountains containing the Nimrod, Beardmore, and Byrd Groups; VH—Vestfold Hills; WDM—western Dronning Maud Land; WI—Windmill Island; WL—Wilkes Land; Y—Yilgarn craton.

Ross-age magmatic-arc source. Biostratigraphic data presented elsewhere (Myrow et al., 2002b) show that tectonically induced drowning of the carbonate platform was coincident with active deformation of older basement and supracrustal successions. Age data from the adjacent crystalline basement (Goodge et al., 1993b) and detrital-zircon ages from the youngest part of the siliciclastic succession presented here indicate that the earliest phase of convergent-margin magmatism was operative between 580 and 540 Ma. Magmatism therefore significantly preceded the onset of siliciclastic deposition, dated at ca. 515 Ma, but continued well into the Early Ordovician, and plutons intruded the youngest siliciclastic deposits. The entire succession, therefore, recorded the tectonic transformation of a Neoproterozoic rift-drift margin to an active, convergent plate boundary by Early Cambrian time. The magmatism, deformation, and molasse deposition are all signatures of plate convergence associated with the Ross orogeny. Inception of subduction beneath the East Antarctic Shield was synchronous with, and dynamically tied to, closure of the Mozambique Ocean and collisional tectonics in the East African orogen related to the suturing of East and West Gondwana. In addition to the record of external Gondwana processes, these siliciclastic successions contain unique detrital-age and paleocurrent signatures pointing to a hidden 1.4 Ga shield terrane that may prove useful for refined reconstructions of Rodinia.

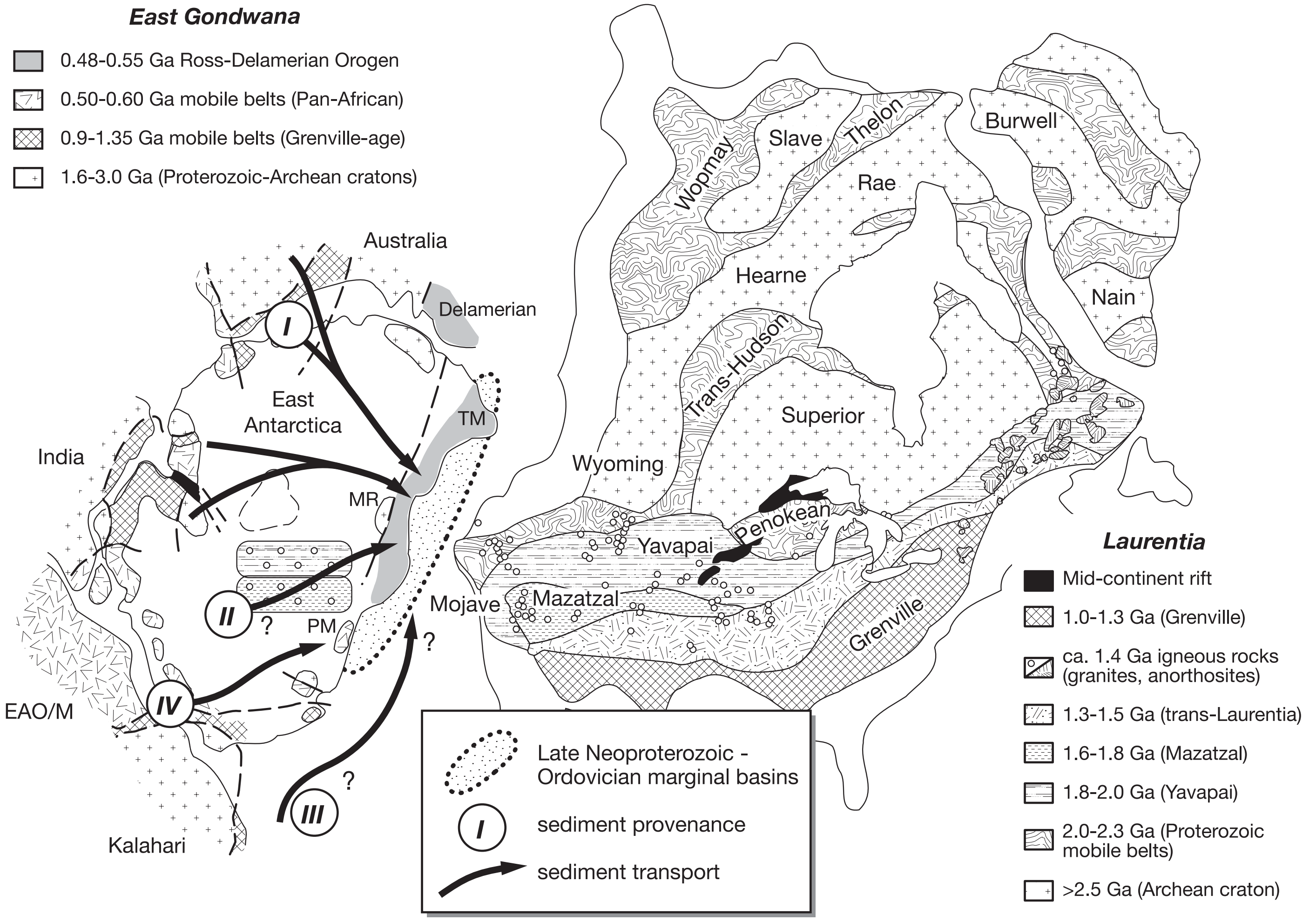


Figure 16. Postulated paleogeographic reconstruction of central Rodinia elements, emphasizing possible fit of East Antarctica–Australia and western Laurentia prior to rift separation (East Gondwana elements as in Fig. 15; Precambrian provinces of Laurentia from Hoffman, 1989; Anderson and Bender, 1989; Karlstrom et al., 1999). Note that deposition of Neoproterozoic to Ordovician successions in basins (shown by bold, black arrows pointing toward area surrounded by dotted line) of the East Antarctic margin occurred *after* separation of East Gondwana from Laurentia (not shown). Fit shown is consistent with a variety of geologic data (Ross et al., 1992; Borg and DePaolo, 1994; Barth et al., 2000; Goodge et al., 2001) but is paleomagnetically unconstrained; East Antarctica–Australia could be rotated or translated to permit a different fit. Distinctive signatures of first-cycle detrital zircons in the Beardmore and Byrd Group units suggest the possible existence of an extension of the Proterozoic Laurentian provinces into the East Antarctic Shield (speculatively shown as rounded, patterned rectangles), including the ca. 1.4 Ga trans-Laurentian igneous province (small circles). Composite detrital-zircon signatures indicate four major provenance associations: (I) Precambrian rocks of the East Antarctic Shield and their Grenville-age mobile belts; (II) Proterozoic juvenile igneous provinces; (III) external cratonic sources transported by marine longshore currents; and (IV) Grenville and Pan-African sources in Queen Maud Land and East African orogen.

ACKNOWLEDGMENTS

Field and laboratory work was supported by the National Science Foundation (OPP-9725426 and OPP-9912081). We are grateful for the logistical and helicopter support provided by the NSF and Petroleum Helicopters as well as the assistance of Shaun Norman, Sarah Deering, and Woody Fischer. Bert Rowell and Randy Van Schmus (University of Kansas) kindly provided sample material from the Hannah Ridge and Patuxent Formations. We thank Neil Gabites, Ben Jenkins, John Mya, and Shane Paxton for their assistance with the analytical work. Discussions with Richard Armstrong, Pat Bickford, Gerard Bond, Don DePaolo, Mark Fanning, George Gehrels, Trevor Ireland, Malcolm Laird, Mike Pope, and Bert Rowell, among many others, have been helpful in forming our ideas. We appreciate constructive reviews by Chris Fedo and Jim Connelly.

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MANUSCRIPT RECEIVED BY THE SOCIETY 26 FEBRUARY 2003
REVISED MANUSCRIPT RECEIVED 17 NOVEMBER 2003
MANUSCRIPT ACCEPTED 26 NOVEMBER 2003

Printed in the USA