

The Permo-Triassic Gondwana sequence, central Transantarctic Mountains, Antarctica: Zircon geochronology, provenance, and basin evolution

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ABSTRACT

The most complete Permian–Triassic Gondwana succession in Antarctica crops out in the central Transantarctic Mountains. The lower Permian strata were deposited in an intracratonic basin that evolved into a foreland basin in late Permian time. Sedimentary petrology and paleocurrent data have been interpreted as indicating a granitic (craton) provenance and a West Antarctic volcanic provenance. To address the West Antarctic provenance and evolution of the detrital input, detrital-zircon grains from nine sandstones (plus three sandstones reported previously) representing the full extent of the Permo-Triassic succession exposed on that flank of the basin, have been analyzed by sensitive high-resolution ion microprobe. Results define three provenances: an early (early to middle Permian) provenance that is dominated by zircons having Ross orogen ages (600–480 Ma); a middle (late Permian) provenance dominated by Permian zircons with subordinate older magmatic arc grains plus lesser Ross orogen-age grains; and a late (Triassic) provenance, which is quite variable and in which the predominant Triassic arc component ranges from very minor to significant and again with a component of Ross orogen-age grains. Detrital zircons imply a more extensive Permo-Triassic arc, in time and space, on the Gondwana margin than is evident from outcrop data. The zircon data are integrated into a model for basin evolution and infilling, providing broad constraints on the timing of tectonic events and the provenance.

INTRODUCTION

The Permo-Triassic Gondwana stratigraphy is best developed in the Transantarctic Mountains (Figs. 1 and 2), where it is divided into a lower Taylor Group (Devonian) and an upper Victoria Group (Permian to Triassic), the two together often referred to as the Beacon Supergroup (Barrett, 1991). In West Antarctica, Permian strata crop out in the Ellsworth Mountains (Collinson et al., 1992) and in small isolated outcrops in eastern Ellsworth Land (Laudon, 1987). Permian and Lower Triassic strata in the northern Prince Charles Mountains

(McLoughlin and Drinnan, 1997a, 1997b) are part of the East Gondwana interior rift system (Harrowfield et al., 2005) and are linked by *Glossopteris* and palynomorphs to the Transantarctic Mountains and other Gondwana successions.

Vertebrate remains and plant assemblages (*Glossopteris* and *Dicroidium* floras) provide paleontological ages for the Beacon strata, giving a Devonian age for the Taylor Group and a Permian through Triassic age for the Victoria Group (Truswell, 1991; Young, 1991). Pollen and spore analysis has established a palynostratigraphy for the Victoria Group (Schopf and Askin, 1980; Kyle and Schopf, 1982; Farabee et al., 1990) and enabled correlation with the Australasian palynostratigraphic zonation (Mantle et al., 2010). Strata in eastern Ellsworth Land and the Ellsworth Mountains have yielded *Glossopteris* and thus have Permian ages (Gee, 1989; Taylor and Taylor, 1992). Vertebrate faunas have been recovered from Lower and Middle Triassic strata (Smith et al., 2011; Sidor et al., 2014).

Sandstone petrology and paleocurrent data for the Victoria Group in the central Transantarctic Mountains (CTM) established a granitic source interpreted to be the East Antarctic craton and a volcanic source located in West Antarctica (Barrett et al., 1986). Outcrops that might be representative of the potential sources in East Antarctica are confined in CTM to the Miller Range (Fig. 3). The volcanic source has been correlated with the few isolated Permian and Triassic granitoids and gneisses along the West Antarctic margin (Pankhurst et al., 1993; Collinson et al., 1994; Pankhurst et al., 1998; Mukasa and Dalziel, 2000; Elliot and Fanning, 2008). A volcanic provenance in Permian time was also recorded from Mount Weaver in the Scott Glacier region (Minshew, 1967), and although such a source was not noted by Long (1965) for the Permian sandstones in the Ohio Range, petrological reexamination of the sandstones has revealed a volcanic component in the upper part of the section.

No unequivocal tuffs have been identified in the upper part of the Permian Buckley Formation in the CTM despite the presence of much volcanoclastic material derived from an active magmatic arc (Collinson et al., 1994). Glass shards have been identified in a number of Permian and Triassic sandstones (Collinson et al., 1994), but attempts to date the rocks have been unsuccessful. Tuff beds in the lower part of the middle informal member of the siliciclastic

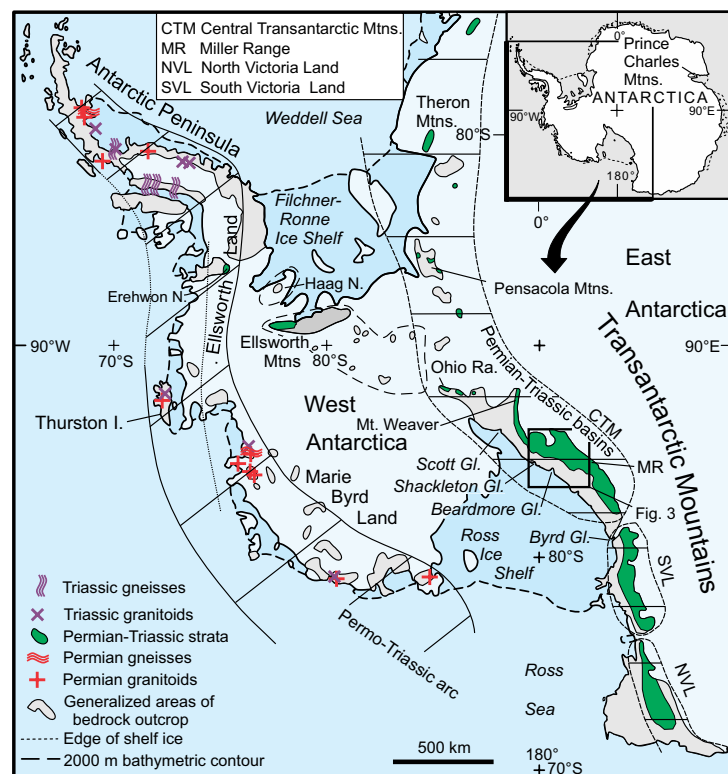


Figure 1. Location map for Antarctica. Stretched continental crust underlies the Ross Sea, Ross Ice Shelf, and interior West Antarctica through to Ellsworth Land (the Ross embayment) and was generated during Late Cretaceous to Late Cenozoic time. Stretched continental crust also underlies the Filchner-Ronne Ice Shelf region and the adjacent Weddell Sea (the Weddell embayment) but was extended during the Early–Middle Jurassic breakup of Gondwana.

Permian Polarstar Formation of the Ellsworth Mountains (Fig. 1) have yielded zircons with Late Permian U–Pb sensitive high-resolution ion microprobe (SHRIMP) ages of 258.0 ± 2.1 Ma and 262.5 ± 2.2 Ma (Elliot et al., 2016a).

The aim of this paper is to evaluate the evolution of the Permo–Triassic basin in the light of new and existing detrital-zircon geochronologic data. Specifically, this paper records new detrital-zircon data for nine sandstones and interprets the results in terms of the evolution of the basin and the source regions. An initial program of detrital-zircon geochronology (Elliot and Fanning, 2008) showed that the Permian upper Buckley Formation in the Shackleton Glacier region includes near contemporaneous igneous zircon grains. The possibility existed, therefore, that reanalysis of the young zircons in these and other samples using SHRIMP II in the higher resolution geochronology mode would provide refined and improved age data for those formations.

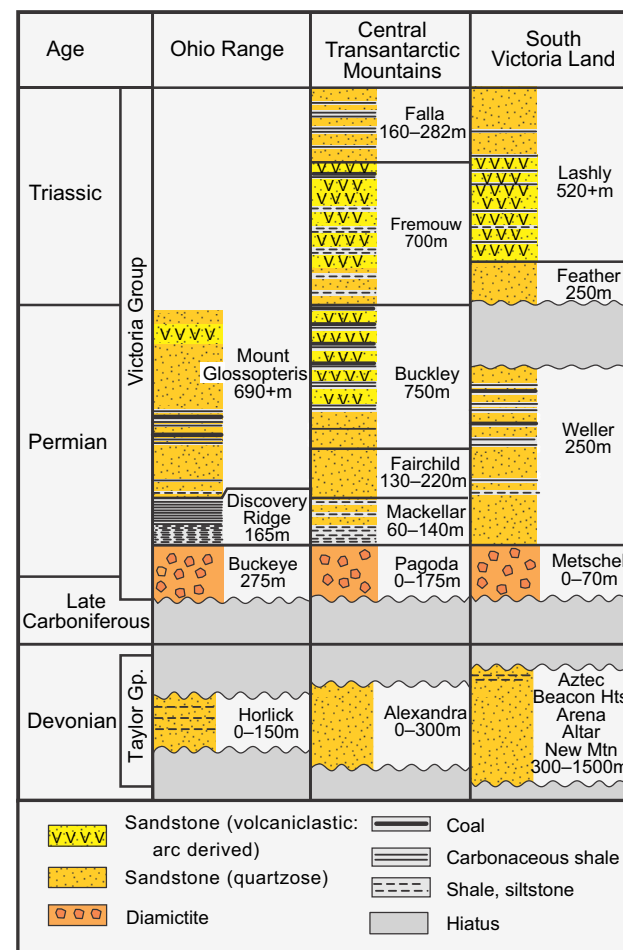


Figure 2. Simplified geologic columns for Devonian to Lower Jurassic strata in the Transantarctic Mountains (Ohio Range, central Transantarctic Mountains, south Victoria Land). Sources: Ohio Range—Long (1964, 1965); central Transantarctic Mountains and south Victoria Land—Elliot (2013). Note that the marine Horlick Formation, although a siliciclastic succession of similar Early Devonian age, is not part of the Taylor Group.

REGIONAL GEOLOGY

The pre-Devonian basement in the CTM (Fig. 3) comprises Neoproterozoic and Cambrian siliciclastic and volcaniclastic strata and limestones (Stump, 1995) intruded by granitoids emplaced during the Cambrian to Early Ordovician Ross orogeny (Goodge et al., 2012). A regional erosion surface, the Kukri

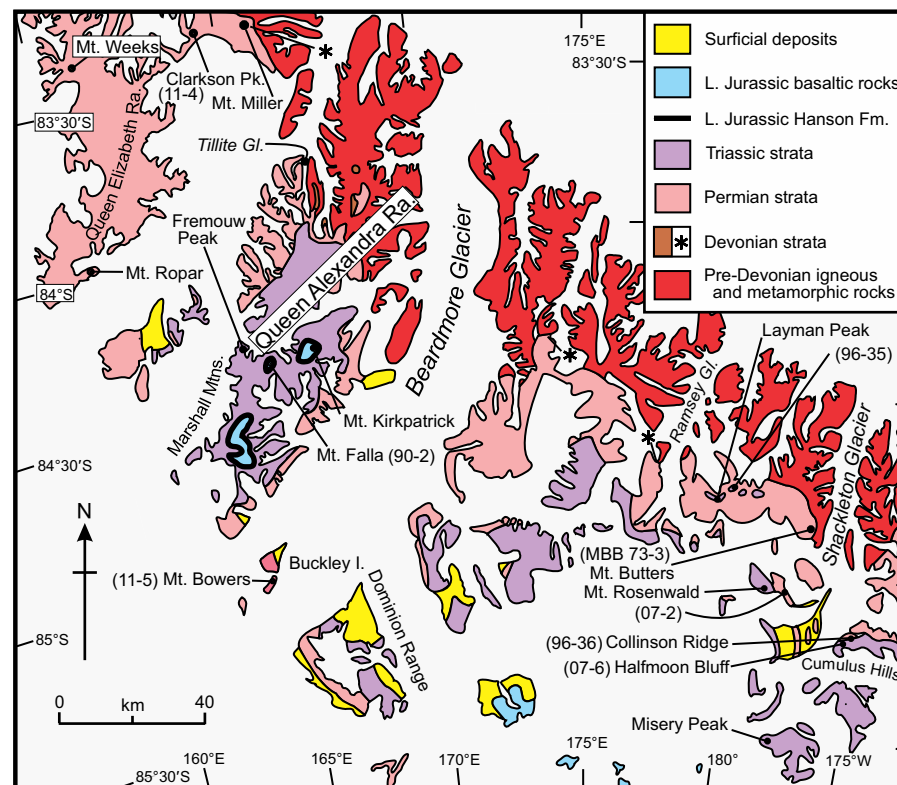


Figure 3. Geologic sketch map of the central Transantarctic Mountains. Numbers refer to locations of analyzed samples. Ra. — Range; Gl. — Glacier; I. — Island.

Erosion Surface (summarized by Isbell, 1999), was developed on those rocks and is overlain by quartzose sandstones of the Alexandra Formation of inferred Devonian age. A younger erosion surface (Maya Erosion Surface) truncates the Alexandra Formation and older strata, and on that surface, the Victoria Group (Fig. 2) was deposited. The Victoria Group is overlain by Lower Jurassic sandstones and tuffaceous beds of the Hanson Formation (Elliot et al., 2016b) and then the basaltic pyroclastic rocks and flood lavas of the Ferrar Large Igneous Province (Elliot and Fleming, 2008), which also includes massive dolerite intrusions distributed throughout the Beacon Supergroup.

The Alexandra Formation and the much thicker Devonian quartzose succession in south Victoria Land (Bradshaw, 2013) are interpreted as shallow marine deposits that grade up into alluvial plain strata and were developed on a slowly subsiding passive margin (Collinson et al., 1994; Bradshaw, 2013) or in a successor basin (Isbell, 1999). The surface truncating those strata reflects a period of tectonism, possibly linked either to the Devonian–Carboniferous active plate margin or to accretion of an allochthonous and/or para-autochthonous Late Devonian–Carboniferous arc (Elliot, 2013), during which there

was uplift and erosion prior to glacial deposition in latest Carboniferous (?) to early Permian time (Kyle and Schopf, 1982).

Glacial facies and ice flow indicators in the lower Permian Pagoda Formation (Victoria Group) suggest deposition occurred in a high-relief, topographically expressed, narrow and elongate glaciomarine and/or glaciolacustrine basin oriented subparallel to the present trend of the range (Isbell et al., 1997). Ice flow was transverse and convergent across basin margins, with glaciers only extending short distances into the basin, and was accompanied by axial mass-transport (slides and slumps) and turbidite flow (Isbell et al., 2008; Isbell, 2015). These characteristics are similar to those of fault-bounded rift basins (Isbell, 2015). Paleocurrent orientations and paleoenvironments interpreted from turbidites and deltaic facies within the overlying post-glacial Mackellar Formation indicate that sediment was fed into the narrow basin, across high-relief basin margins, from both the East Antarctic craton and from the direction of West Antarctica. Axial drainage within the basin was to the southeast (present coordinates) toward the Ohio Range. Basement rocks along the basin margins were buried and overtopped by prograding deltas and

Table S1. Locations of analyzed samples

Sample no.	Long.	Lat.
07-2-4	178° 14.2' W	85° 04.9' S
07-2-12	178° 14.2' W	85° 05.0' S
MBB 73-3	177° 26.6' W	84° 52.8' S
11-4-3	164° 30.6' E	83° 21.1' S
H3-384b	113° 25.0' W	84° 48.0' S
11-4-10	164° 34.2' E	83° 19.4' S
96-35-2	179° 51.6' W	84° 48.4' S
96-36-1	175° 15.4' W	85° 13.0' S
07-6-2	175° 19.6' W	85° 13.7' S
07-6-3	175° 20.3' W	85° 13.8' S
90-2-52	164° 40.9' E	84° 21.2' S

¹Supplemental File S1. Sample locations. Please visit <http://dx.doi.org/10.1130/GES01245.S1> or the full-text article on www.gsapubs.org to view the Supplemental File S1.

Petrographic descriptions for sandstone samples for which detrital zircon U-Pb geochronological data are provided in Tables S3-S13.

Twelve samples from the Victoria Group reported here come from the Shackleton Glacier and Queen Alexandra Range regions, and one sample from the Ohio Range. These are listed in approximate stratigraphic order (see also Fig. 4a). Geographic locations are shown in Fig. 3, and full analytical data for new detrital zircon U-Pb analyses are presented in Supplementary Tables S3-S13.

07-2-4. Fairchild Formation, Mt. Rosenwald. One hundred and thirty six meters above the base of the formation. Fine-grained sandstone, with minor plagioclase (sodic andesine) and lesser K-feldspar (orthoclase and microcline). Accessory micas (muscovite and lesser biotite). Heavy minerals include zircon and garnet, lesser opaques, and rare tourmaline. Carbonaceous shreds are scattered. Matrix of phyllosilicate shreds and some secondary silica.

07-2-12. Lower Buckley Formation, Mt. Rosenwald. Sixty four meters above the base of the formation. Medium-grained quartz-feldspathic sandstone. Much of the quartz is strongly corroded; quartz includes polycrystalline grains. Minor plagioclase (oligoclase-andesine) and traces of K-feldspar. Micas include muscovite and lesser biotite. Heavy minerals are mainly garnet and zircon, with a trace of apatite and tourmaline. Fine-grained white mica forms the abundant matrix; replaces detrital quartz grains and such replacement is probably widespread and accounts for the abundance of matrix phyllosilicate.

MBB 73-3. Pagoda Formation, Mt. Butters. Seventy three meters above the base of the formation. Medium-grained well-sorted quartz-rich sandstone. Grain margins of quartz are commonly sutured. Plagioclase (oligoclase-andesine) and lesser K-feldspar are minor. Accessory muscovite and biotite. Heavy minerals include garnet, epidote, opaques and zircon. Matrix includes patchily distributed secondary fine-grained brown phyllosilicate, and fine-grained recrystallized quartz.

11-4-3. Lower Buckley Formation, south spur of Clarkson Peak. One hundred and twenty two meters above the base of the formation and two meters above the upper contact of a major sill. Medium-grained quartz-rich sandstone, moderately well sorted, angular to sub-round grains. Sparse highly altered feldspar. Heavy minerals include garnet and zircon. Abundant siliceous matrix along with colorless and pale brown phyllosilicate flakes; largely resulting from the replacement of detrital feldspar; minor silica overgrowths on quartz grains. Scattered carbonaceous matter.

11-5-22. Upper Buckley Formation, Mt. Bowers. Thirty three meters above the lower Buckley/upper Buckley contact and 425 m above the base of the Buckley Formation. Described in Elliot et al. (2015).

11-4-10. Upper Buckley Formation, south spur of Clarkson Peak. Three hundred and eighty four meters in section (the second sandstone in the upper white cliff). Fine-grained volcanic sandstone, moderately sorted, sub-angular to sub-round. Quartz with lesser feldspar (andesine) which is highly altered and partially replaced by zeolite. Muscovite and biotite are accessory. Heavy minerals include zircon, garnet and sphene. Abundant volcanic rock fragments: grains are flow banded, microcrystalline and siliceous, fine to very fine-grained and feldspathic with or without flow texture, and microporphyritic. Sparse quartz-mica schist rock fragments. The matrix includes siliceous matter and phyllosilicate flakes and shreds. Carbonaceous matter is common.

²Supplemental File S2. Petrographic descriptions. Please visit <http://dx.doi.org/10.1130/GES01245.S2> or the full-text article on www.gsapubs.org to view the Supplemental File S2.

braided stream deposits of the Fairchild Formation. Uniform paleocurrents oriented toward the southeast together with highly interconnected channel stacking patterns suggest slow basin subsidence during braided stream deposition (Isbell et al., 1997). The sedimentology and sandstone petrology of the overlying fluvial and coal-bearing middle and upper Permian Buckley Formation and Triassic strata suggest input of detritus from both the East Antarctica craton and from the Gondwana margin in West Antarctica. With the incoming of volcaniclastic debris in upper Buckley time, the succession is interpreted to be the filling of a foreland basin related to the Gondwana plate margin (Collinson et al., 1994). This basin was initially under filled during the Permian as expressed by convergent flow across basin margins and longitudinal flow down the basin axis, whereas predominant uniform flow out of West Antarctica and oblique across the location of the upper Buckley basin axis indicates evolution into an overfilled basin during Triassic time.

The Permian section in the Ohio Range (Long, 1965; Bradshaw et al., 1984) comprises the glacialigenic Buckeye Tillite overlain by beds equivalent to the Mackellar and Fairchild formations (Discovery Ridge Formation and the lower part of the Mount Glossopteris Formation, which is marine to marginal marine). The upper part of the Mount Glossopteris Formation (700 m thick) is a fluvial succession, which consists of sandstones, finer grained beds, and coal. Paleocurrent data indicate easterly flow (present coordinates); but high in the section, one thick sandstone bed shows major flow to the south (Long, 1965), and a sample from that bed contains a high proportion of volcanic detritus.

A Permo-Triassic arc formed the active margin of Gondwana from Papua New Guinea to Patagonia and in Antarctica is represented by granitoids and gneisses in Marie Byrd Land, Thurston Island, and the Antarctic Peninsula (Pankhurst et al., 1993, 1998; Mukasa and Dalziel, 2000; Millar et al., 2002; Riley et al., 2012). By inference, that Permo-Triassic magmatic arc was the source for the volcanoclastic detritus in Victoria Group strata and in the Permian beds in eastern Ellsworth Land and the Ellsworth Mountains. The eastern Ellsworth Land Permian beds accumulated adjacent to or within the axial part of the depositional basin, whereas the Permian strata of the Ellsworth Mountains were deposited on the flank of the basin in the backarc region of the Antarctic Peninsula sector of the plate margin (Elliot et al., 2016a). In Permo-Triassic time, prior to Jurassic breakup of Gondwana, the Ellsworth Mountains were located along strike eastward from the Cape Fold Belt of South Africa in the proto-Weddell Sea region (e.g., Grunow et al., 1987; Elliot et al., 2016a).

DISCUSSION

Analytical Results

Detrital zircons from nine sandstones have been analyzed by SHRIMP; in addition, three of those plus two sandstones analyzed previously (Elliot and Fanning, 2008) have been reanalyzed in the higher resolution geochronology mode (see the Appendix). Table 1 summarizes the geochronological

results. The geographic locations of samples are given on Figure 3, except for the sandstone from the Ohio Range (see Fig. 1), and in Supplemental File S1¹. The samples are also projected onto a composite stratigraphic column for the Shackleton-Beardmore region on Fig. 4A. Petrographic descriptions of the analyzed sandstones are given in Supplemental File S2². Analytical procedures for the SHRIMP U-Pb zircon analyses are given in the Appendix, along with probability density plots, weighted mean age plots, and cathodoluminescence (CL) images for each sample. These are accompanied by discussion of each sample.

Ross orogen-age zircons predominate in the lower part of the succession (Fairchild and lower Buckley formations), and, with one exception, Permian or Triassic grains predominate in the upper Buckley and younger strata. With the exception of sample 07-2-4 from the Fairchild Formation, the age distribution of zircon grains older than 600 Ma is sufficiently scattered that no probability peaks exist, even though cumulatively they form a not insignificant proportion. A similar situation exists for the 480–385 Ma interval, except for 07-6-2, which has a cluster but no probability peak of Silurian zircons. Zircons in the Late Devonian to early Carboniferous interval are to be expected given the granitoids of that age in Marie Byrd Land. The abundance of Triassic grains in Permian beds is most probably the result of radiogenic Pb loss and the uncertainties arising from detrital mode analyses; this is supported by the weighted mean ages derived from the geochronology mode (six-scan) analyses.

The calculated weighted mean ages are interpreted as maximum ages of deposition of the host sandstones. Because these are detrital-zircon grains, no assumption can be made about the coherence of the population such as can be made for zircons in a tuff bed. Although grains were selected after examination by transmitted and reflected light and CL imaging, the grains of any one age grouping are likely to have come from many rocks and not necessarily all of precisely the same age. There can be little doubt that some of the analyzed zircons have been affected by secondary processes such as radiogenic lead loss. This is demonstrated in two samples (96-35-2 and 96-36-1; see Fig. 4A for stratigraphic positions) by grains younger than the Permo-Triassic boundary but in *Glossopteris*-bearing strata and thus almost unequivocally of Permian age (see next section).

Stratigraphic Ages

No complete section of the Buckley Formation has been measured in the Shackleton Glacier region. Hence, the position of sample 96-35-2 with respect to the non-volcanic lower Buckley is uncertain; this sample is 70 m below the Buckley Formation upper contact and ~10 m above the base of the exposed section northeast of Layman Peak (Fig. 2). Sample 96-36-1 is well located stratigraphically, coming from the top meter of the Buckley Formation at Collinson Ridge. Although the Permian/Triassic boundary had long been considered to lie at the Buckley Formation upper contact, at Collinson Ridge the Era boundary lies in a 10 m interval that begins at ~36 m above the Buckley/Fremouw

TABLE 1. SUMMARY OF DETRITAL-ZIRCON AGE PROBABILITY AND WEIGHTED MEAN AGE PLOTS

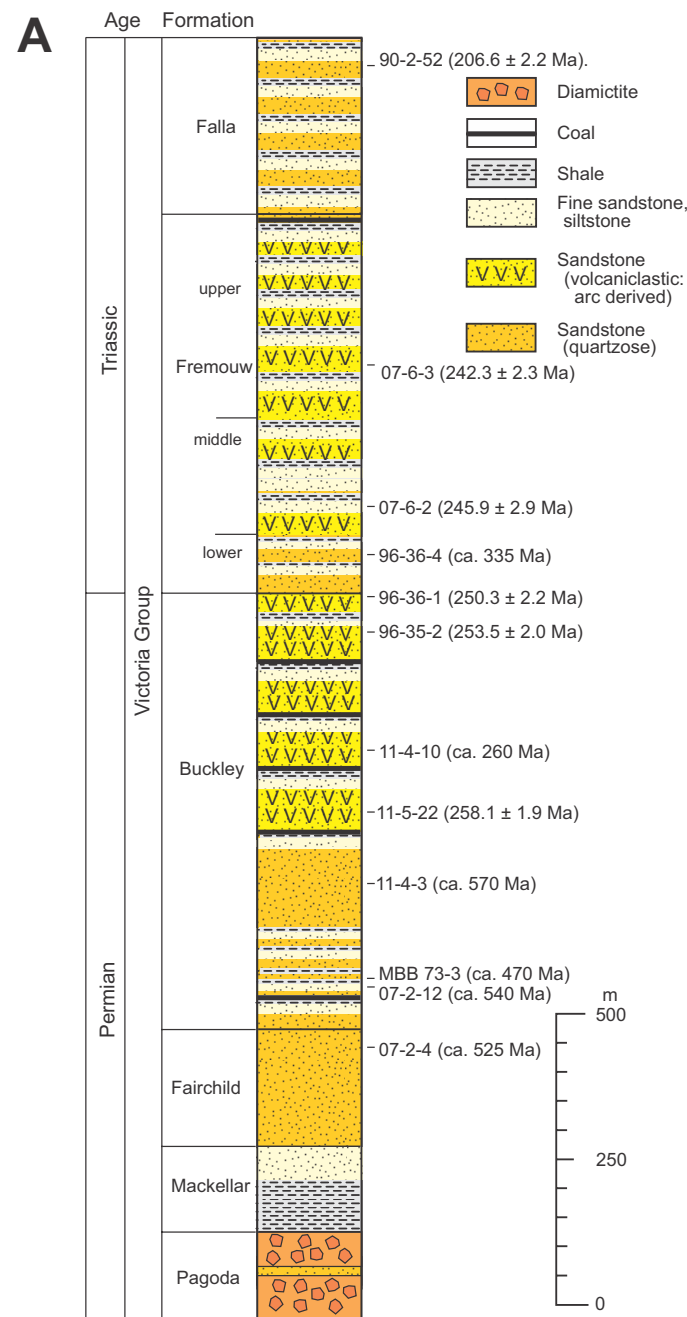
Sample no.	Archean >2.5 Ga	Proterozoic 2.5–1.1 Ga	Grenville 1.1–0.9 Ga	Neoproterozoic 0.9–0.6 Ga	Ross 600–480 Ma	Ordovician– Devonian 480–385 Ma	Lower Devonian– Early Carboniferous 385–325 Ma	Lower Carboniferous– Permian 325–252 Ma	Triassic 252–200 Ma	Weighted mean age
90-2-52	(1)	(2)	(9)	(6)	ca. 515 Ma (18)	(2)	(2)		ca. 205 Ma (30)	206.6 ± 2.2 Ma. MSWD = 1.08 (15)
07-6-3			(8)	(4)	ca. <u>570</u> , ca. 490 Ma (19)	(3)	ca. 365 Ma (14)	ca. 255 Ma (7)	ca. 240 Ma (15)	242.3 ± 2.3 Ma. MSWD = 0.78 (14)
07-6-2	(3)	(4)	(3)	(3)	(5)	(9)	ca. <u>330</u> Ma (12)	ca. 310 Ma (16)	ca. 245 Ma (15)	245.9 ± 2.9 Ma. MSWD = 1.2 (14) 309.8 ± 3.2 Ma. MSWD = 0.28 (8)
96-36-4	(4)	(2)	(3)	(11)	ca. 580 , ca. 545, ca. <u>510</u> Ma (28)	(3)	(4)	(3)	(2)	
96-36-1		(1)		(9)	(13)	(5)	(5)	ca. 260 Ma. (20)	(7)	250.3 ± 2.2 Ma. MSWD = 1.5 (16)
96-35-2		(1)		(1)		(1)		ca. 265 Ma. (41)	(16)	253.5 ± 2.0 Ma. MSWD = 1.5 (20)
H3-384b	(1)	(1)	(1)		(1)		(5)	ca. 260 Ma. (47)	(13)	
11-4-10		(3)	(5)	(5)	ca. 555 Ma (18)	(1)	(4)	ca. 260 Ma (27)	(5)	
11-5-22	(1)	(4)	(3)	(2)	(11)		(3)	ca. 260 Ma (42)	(6)	258.1 ± 1.9 Ma. MSWD = 1.2 (32)
11-4-3	(9)	(7)	(6)	(8)	ca. 570 Ma (37)	(2)				
MBB 73-3	(1)	(14)	(5)	(4)	ca. 585 , ca. 545 Ma (41)	(5)				
07-2-12	(4)	(7)	(2)	(10)	ca. 575, ca. 560 , ca. <u>540</u> Ma (36)	(1)				
07-2-4	(2)	ca. 2250 Ma (17)	ca. 1050 Ma (10)	(10)	ca. 580 Ma (17)	(2)				

Notes: Ages in bold are predominant probability peaks; those underlined are minor peaks. Total numbers of grains of any particular age range are given in parentheses (excluding repeat six-scan analyses). Probability peaks do not exist in many age intervals because the distribution of ages is too scattered. See the Appendix for probability plots, cathodoluminescence images of zircon grains, and discussion of the probability plots. Data for sample 96-36-4 and additional data for samples 96-35-2 and 96-36-1 from Elliot and Fanning (2008). MSWD—mean square of weighted deviates.

contact and ends immediately below the lowest quartzose sandstone of the Fremouw Formation; that 10 m interval lies between the last occurrence of the *Glossopteris* flora and the first occurrence of fossils of the *Lystrosaurus* fauna (Collinson et al., 2006). The Buckley/Fremouw contact is interpreted by Collinson et al. (2006) as a disconformity at many other localities, although detailed reinvestigation of the boundary at those and other localities may demonstrate continuity of some sections. Furthermore, the formational contact is

probably diachronous due to progradation of facies across the Shackleton-Beardmore area.

The interpreted depositional age for sample 96-35-2 (253.5 ± 2 Ma) is no older than the Changhsingian Stage (Fig. 4B) of the late Permian (International Chronostratigraphic Chart, 2016), whereas sample 96-36-1 has a maximum depositional age of 250.3 ± 2.2 Ma, which is within uncertainty of the age for sample 96-35-2. Nevertheless, given the 70 m of strata between the two

**B**

Period	Stage	Age
Jurassic	Hettangian	201.3 ± 0.2 Ma
Triassic	U	Rhaetian
		ca. 208.5 Ma
		ca. 227 Ma
	M	Carnian
		ca. 237 Ma
	L	Ladinian
		ca. 242 Ma
		247.2 Ma
Permian	Wuchiapingian	251.2 Ma
		252.17 \pm 0.06 Ma
		254.14 \pm 0.07 Ma

Figure 4. (A) Composite stratigraphic column for the Shackleton-Beardmore region showing the projected and approximate positions of the analyzed sandstone samples. H3-384b, the Ohio Range sandstone, comes from low in the volcaniclastic upper part of the Mount Glossopteris Formation, and its stratigraphic position on this column is not well constrained. **(B)** Permian and Triassic chronostratigraphic ages. Reproduced from the International Chronostratigraphic Chart, International Commission on Stratigraphy (2016). Note that Burgess et al. (2014) proposed an age of 251.9 Ma for the Permian/Triassic boundary.

samples, this suggests a real age difference and erosion of an actively growing magmatic arc. The age for sample 96-36-1 is younger than, but within uncertainty of, the age for the Permian–Triassic boundary (ca. 251.9 Ma; Burgess et al., 2014), yet comes from beds 37 m below the last occurrence of the *Glossopteris* flora (Collinson et al., 2006). However, *Glossopteris* has been reported to occur above the boundary in India (Pant and Pant, 1987; Bose et al., 1990) and *Lystrosaurus* below it in South Africa (Neveling, 2004; Botha and Smith, 2007). As previously noted, and setting aside the possibility of the *Glossopteris* flora continuing into the Triassic, in particular sample 96-36-1 (from ~37+ m below the paleontologically defined Permian–Triassic boundary interval) points up the uncertainties in using detrital-zircon geochronology to establish precise stratigraphic ages. The original detrital analyses (four-scan or detrital mode) for the two Buckley Formation sandstones (Elliot and Fanning, 2008) recorded a range of zircon ages that spans the Permian and indicated that source region magmatism probably occurred throughout late Permian time and probably began much earlier, which is supported by an early Permian U–Pb age for a Marie Byrd Land granitoid (Mukasa and Dalziel, 2000).

The middle member of the Fremouw Formation is recognized by the lack of quartzose channel sandstones and the dominance of green fine-grained floodplain deposits, whereas the upper member consists of volcanic sandstone with subordinate intervals of fine-grained beds (Barrett et al., 1986). Sample 07-6-2 lies at 46 m in the middle member at Halfmoon Bluff (Collinson and Elliot, 1984); the middle to upper boundary was placed at 100 m above the base of the middle member, but reexamination suggested that it should be at 170 m. Sample 07-6-3 lies at 80 m (above the revised member boundary) in the Fremouw upper member, which now has a minimum thickness of 300 m. Sample 07-6-2 has a maximum depositional age (246 ± 3 Ma) that is lower Anisian (Fig. 4B) and close to the Lower to Middle Triassic boundary (ca. 247.2 Ma; International Chronostratigraphic Chart, 2016), and sample 07-6-3 (203.5 m stratigraphically above sample 07-6-2) has a depositional age no older than 242 ± 2 Ma, which lies at the Anisian–Ladinian boundary (within the Middle Triassic). The *Cynognathus* vertebrate fauna recovered from the upper member of the Fremouw Formation in the Queen Alexandra Range has been assigned a late Scythian (late Olenekian) or early Anisian age (ca. 247 Ma) that is late Early or early Middle Triassic (Hammer, 1995), whereas Sidor et al. (2014) suggested correlation with the *Cynognathus* C subzone of the Karoo in South Africa (Abdala et al., 2005) and therefore a slightly younger age of late Anisian (ca. 244 Ma). Both of these age assignments are older than the maximum depositional age for the Fremouw upper member at Halfmoon Bluff. The maximum depositional age for sample 07-6-3 would suggest that the vertebrate fauna has a late Anisian or younger age. Nevertheless, some uncertainties must be considered. Radiogenic lead loss from the zircon grains (areas analyzed) would bias any weighted mean to younger numerical ages; considerable diachroneity in the middle to upper Fremouw Formation boundary may exist; and the numerical age assigned to the base of the Anisian is not particularly precise.

The informal members of the Fremouw Formation represent depositional facies and therefore, in a terrestrial environment, the boundaries will be sub-

ject to local conditions, and diachroneity is to be expected. The *Cynognathus* fauna comes from close to the base of the upper member of the Fremouw Formation near the type section in the Queen Alexandra Range, over 200 km from Halfmoon Bluff, and therefore chronostratigraphic correlation with upper Fremouw beds in the Halfmoon Bluff section is subject to considerable uncertainty. The geologic age assignment for the vertebrate fauna is unlikely to be in significant error.

Sample 90-2-52 comes from 43 m below the upper contact of the Falla Formation, which at the type section is marked by a lag gravel that is interpreted as a disconformity where there is also a significant change in sandstone petrology and provenance (Elliot et al., 2016b). The numerical age (207 ± 2 Ma) is early in the Rhaetian Stage of Late Triassic time. This is consistent with the palynological age assignment of Carnian to Norian for two samples collected from 150 and 220 m, respectively, below the top of the Falla Formation (Farabee et al., 1990). The numerical age also suggests that the Falla Formation probably does not extend across the Triassic/Jurassic boundary.

Provenance

The detrital-zircon results suggest three provenance scenarios that match those evident in the sandstone petrology: an early provenance recorded in the sandstones from the Fairchild and lower Buckley formations (samples 07-2-4, 07-2-12, MBB 73-3, and 11-4-3); a middle provenance recorded in the upper Buckley Formation (samples 96-35-2, 96-36-1, 11-4-10, 11-5-22, and H3-384b); and a late provenance documented in the Triassic sandstones (samples 96-36-4 [Elliot and Fanning, 2008], 07-6-2, 07-6-3, and 90-2-52).

The early provenance is dominated by zircons falling in the age span of the Ross orogen (Goodge et al., 2012; see also Adams et al., 2014). Although the analyses for two samples have been deconvolved and yield a range of probability peaks, there is no consistency, except for a prominent late Neoproterozoic peak at ca. 575–585 Ma and a lesser peak at ca. 560 Ma. Younger grains, consistent with the dated Ross granitoids (ca. 545–480 Ma), are less abundant. One of the Buckley Formation samples (MBB 73-3) has an enigmatic Middle Ordovician minor peak (ca. 470 Ma) that may reflect radiogenic Pb loss or document a very late magmatic episode that is not represented in outcrop. There is a spread of Grenvillian-age grains (ca. 900–1100 Ma), but only the Fairchild sample (07-2-4) has a significant probability peak, which lies at ca. 1050 Ma. This sample also has a minor early Mesoproterozoic cluster at ca. 2250 Ma. These sandstones were derived from the West Antarctic flank of the depositional basin, but the age spectra are similar to those of samples from Mount Bowers, which were clearly derived from the craton (Elliot et al., 2015). The paleocurrent data for the lower Buckley Formation sample MBB 73-3 are clear and indicate derivation from the West Antarctic flank (used here only in a geographic sense); for the other three, there is some uncertainty, and flow may have been less directly off West Antarctica and more nearly down the basin axis (NW to SE in present coordinates). The lower Buckley sample MBB

73-3 suggests derivation from unexposed Upper Proterozoic to lower Paleozoic granitoids in West Antarctica or from Paleozoic sedimentary successions (Ordovician Swanson Formation and Devonian Taylor Group), which were themselves probably derived to a significant extent from Ross orogen granitoids. Extension of the Ross orogen into West Antarctica is probable, but how far is unknown. The Swanson Formation (Bradshaw et al., 1983), a turbidite succession in western Marie Byrd Land, may extend eastward (subglacially), and the Devonian Taylor Group (Bradshaw, 2013) extended out into West Antarctica; zircons in both sets of strata have the Gondwana margin detrital-zircon signature (Ireland et al., 1998; Pankhurst et al., 1998; Wysoczanski et al., 2003; Elliot et al., 2015; Yakymchuk et al., 2015) of numerous upper Neoproterozoic to lower Paleozoic (Ross orogen-age) grains plus lesser numbers of Grenvillian-age grains and are therefore appropriate sources. The persistent occurrence of small numbers of Neoproterozoic (0.9–0.6 Ga), Paleo- and Mesoproterozoic (2.5–1.1 Ga), and Archean grains is, similarly, most probably the result of recycling through Swanson and Taylor Group strata.

The middle provenance, associated with the switch in paleocurrent directions following the transition from the lower to the upper Buckley Formation (Barrett et al., 1986; Isbell, 1991; Collinson et al., 1994), is dominated by zircon grains with Permian ages. The two samples remeasured in geochronology (six-scan) mode are within uncertainty of each other and therefore indistinguishable in age although separated stratigraphically. In sample 96-35-2, from 70 m below the Buckley Formation upper contact near Layman Peak, 55 of 62 grains analyzed (excluding those reanalyzed in geochronology mode) are Permian (and younger) in age and indicate a flood of grains from a magmatic arc. Sample 96-36-1, from 1 m below the upper Buckley contact, has 27 of 60 analyzed grains (excluding six-scan results) being Permian or younger in age. In sample 11-4-10, from Clarkson Peak and relatively low in the upper Buckley strata, 32 of 70 analyzed grains gave Permian and younger ages, and sample 11-5-22 from 40 m above the base of the upper Buckley strata at Mount Bowers gave Permian or younger ages for 48 out of 72 zircons analyzed. The one sandstone from the Ohio Range (H3-384b) comes from high in the stratigraphic section but is overlain by carbonaceous beds, which implies a Permian age because, regionally, Lower Triassic strata are non-carbonaceous (see Collinson et al., 2006). As noted earlier, the few zircon grains giving Triassic dates in all these samples are considered to be analyses of areas that have lost radiogenic Pb. The abrupt influx of volcanoclastic detritus argues for a significant shift in the provenance and the tapping of a magmatic arc, which had been active from at least early Permian time onward; the arc only sparsely documented in West Antarctica (Pankhurst et al., 1993, 1998; Mukasa and Dalziel, 2000) is clear for Zealandia and the Antarctic Peninsula (Wandres and Bradshaw, 2005; Barbeau et al., 2010). One sandstone has a small cluster of Carboniferous grains and three of the sandstones have minor clusters of Devonian igneous zircons, demonstrating that older magmatic arcs were a component of this new source region. However, Ross orogen-age grains are present in three of the sandstones, and still older grains are present in one of them; these grains were more likely derived by erosion of lower Permian

strata and/or recycling out of lower Paleozoic strata rather than directly from granitoids and gneisses.

The third (youngest) provenance was more diverse, reflecting a variety of sources. Principal flow directions were the reverse of those of the lower Buckley Formation (Barrett et al., 1986; Isbell, 1991; Collinson et al., 1994). The lower Fremouw sample (96-36-4) has a scattering of grains younger than ca. 380 Ma but too few for any significance to be attached. The case is different for the remaining samples that have yielded a significant number of Triassic grains and weighted mean ages have been calculated. They show that Triassic magmatic arc rocks were being eroded, as well as the Permian arc rocks that dominated the upper Buckley zircons. Carboniferous (sample 07-6-2; sample 96-36-4 [Elliot and Fanning, 2008]) and Devonian (sample 07-6-3) arc rocks formed a minor component of the source region during Fremouw time. The middle Fremouw sample (07-6-2) also has a string of Upper Ordovician to lowest Devonian grains, which have no known potential source in Antarctica. Ross orogen-age grains are present in samples 96-36-4 (lower Fremouw sandstone), 07-6-3 (upper Fremouw sandstone), and 90-2-52 (upper Falla sandstone). The Fremouw sandstones, for which paleoflow indicates derivation from West Antarctica, have both arc and Ross orogen-age grains, the latter probably derived by recycling from underlying strata and/or lower Paleozoic strata. In the case of the upper Falla sandstone (90-2-52), which comes from the axial part of the basin, the Ross-age and older zircons were not necessarily derived by recycling but might have been eroded directly from the craton or from Ross orogen foreland basin strata (Elliot et al., 2015). It should be noted that the known Ross orogen rocks were covered by Victoria Group strata in Permian and Triassic time and could not have formed the immediate source for zircons giving a “Ross orogen age.”

Regional Context—Gondwana Plate Margin

Paleocurrent data and sandstone petrology of the Victoria Group indicate that a major source of volcanoclastic detrital material lay in what is now West Antarctica (Barrett et al., 1986; Barrett, 1991; Collinson et al., 1994). Except for the Pacific rim (Marie Byrd Land and Thurston Island) and the anomalous Ellsworth-Whitmore Mountains block (Fig. 1), West Antarctica is an ice-covered Cretaceous and Cenozoic rift system (Behrendt, 1999). However, the geographic relationships of the components of West Antarctica are the result of Gondwana fragmentation and subsequent rotations and translations of the various crustal blocks, plus the later extension between Marie Byrd Land and the Transantarctic Mountains. Thus discussion of the provenance of the zircons has to be in the context of the reconstruction of Gondwana for pre-Jurassic time, specifically Permo-Triassic time. Reconstruction is not straightforward because of the lack of geologic pinning points, uncertainties in crustal block dimensions given probable collapse of free edges, the uncertain nature of the subglacial regions of West Antarctica, unknown basement lithologies beneath the sediment cover in the Ross and Weddell embayments, let alone the geol-

ogy of other submerged continental blocks generated by breakup. Some of these uncertainties in reconstructions have been discussed previously (Elliot, 2013; Elliot et al., 2016a).

The reconstruction in Figure 5 assumes continuity of geologic provinces, recognizing that there are significant uncertainties in the relationships in the eastern Marie Byrd Land–Thurston Island–southern Antarctic Peninsula region. Correlation of West Antarctic geology with the South America–southern Africa sector of the Gondwana margin is particularly complicated because of the rotations and displacements of various continental fragments, but the Lachlan orogen of southeastern Australasia (Foster and Gray, 2000; Glen, 2005) provides a framework for Marie Byrd Land and the Ross embayment, albeit with the probability of major margin-parallel displacements of terrains (DiVenere et al., 1996; Adams et al., 1998; Bradshaw, 2007; Bradshaw et al., 2009). The Lachlan orogen has a complicated history of subduction, rifting, extension, slab rollback, marginal sea formation, and magmatism (episodic from Ordovician to Carboniferous time). The Ordovician turbidites alone indicate a close and direct connection with the Marie Byrd Land–Ross embayment region of West Antarctica, the region of particular interest for this study. The New England orogen (Glen, 2005) is marginal to and outboard of the Lachlan orogen but continues the record of magmatism into the Triassic and clearly links through Zealandia to eastern Marie Byrd Land.

The probable existence of a belt of Permian intrusive and metamorphic rocks on the Panthalassic margin of Antarctica was first recognized by Craddock et al. (1964), Halpern (1972), and Wade (1972), and was subsequently confirmed by Pankhurst et al. (1998) and Mukasa and Dalziel (2000), the latter two papers also documenting Triassic granitoids and orthogneisses (Fig. 5). The Permo-Triassic arc rocks together with a few Silurian granitoids constitute the Amundsen Province of Pankhurst et al. (1998). Investigations on the Antarctic Peninsula have also documented granitoids and orthogneisses of Permian and Triassic age (Storey et al., 1996; Vaughan and Storey, 2000; Millar et al., 2002; Flowerdew, 2008; Riley et al., 2012). In contrast, in the New Zealand sector of the margin, the Permian and Triassic record is dominated by stratified successions, both volcanic arc-derived (Murihiku, Maitai, and Caples terranes) and of continental derivation (Rakaia terrane) (Mortimer, 2004; Wandres and Bradshaw, 2005). Associated igneous rocks are confined to the oceanic volcanic rocks of the early Permian Brook Street terrane and an upper Permian–Lower Triassic intraoceanic I-type batholith (Price et al., 2011; McCoy-West et al., 2014).

Older magmatic belts are recognized along the Gondwana margin (Fig. 6). A belt of Upper Devonian and Carboniferous granitoids crops out in the Western Province of New Zealand (Mortimer, 2004; Wandres and Bradshaw, 2005; Allibone et al., 2009; Tulloch et al., 2009), in Tasmania (Gray and Foster, 2004; Glen, 2005), southeastern Australia (Foster and Gray, 2000), and in the proximal north Victoria Land (Henjes-Kunz and Kreuzer, 2003) in a reconstructed Gondwana. This belt is also developed in Marie Byrd Land (Weaver et al., 1991; Pankhurst et al., 1998; Mukasa and Dalziel, 2000; Siddoway and Fanning, 2009; Yakymchuk et al., 2013, 2015), where Upper Devonian and Lower Carboniferous granitoids and sparse orthogneisses crop out. These rocks, together with

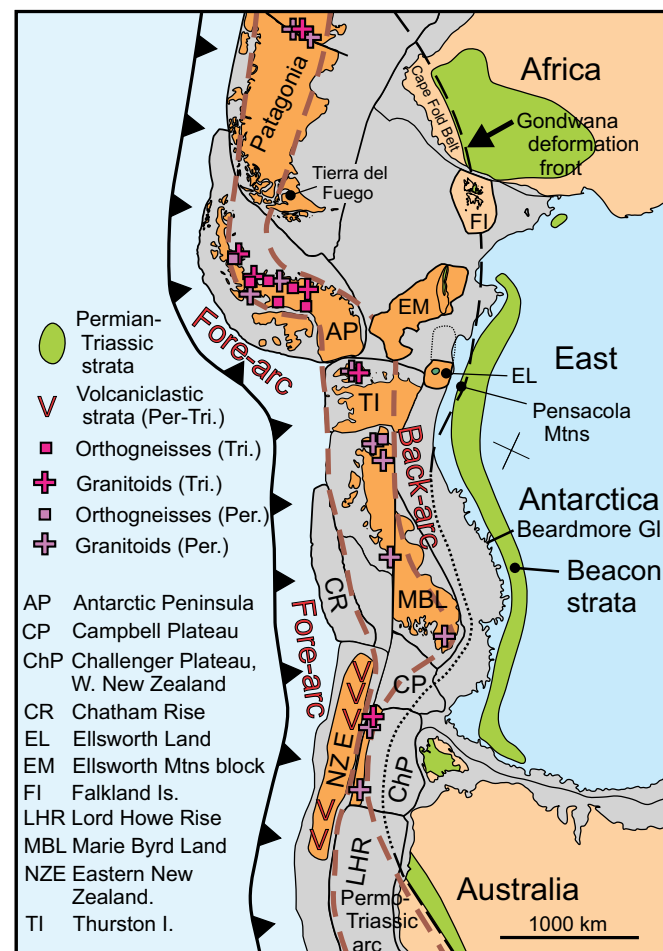


Figure 5. Gondwana reconstruction to illustrate the distribution of Upper Carboniferous, Permian, and Triassic granitoids and orthogneisses (modified from a reconstruction provided by the PLATES Project at the Institute of Geophysics at the University of Texas at Austin). Note the right lateral translation of eastern Marie Byrd Land with respect to western Marie Byrd Land (DiVenere et al., 1996). X marks present-day South Pole in Antarctica.

very sparse Cambrian orthogneisses, define the Ross Province of Pankhurst et al. (1998), which lies inboard of the Amundsen Province. Possible extension of the Ross Province into the Antarctic Peninsula is not well documented, consisting of Devonian orthogneisses in two isolated basement complexes and a single Carboniferous granitoid (Millar et al., 2002). In the Australasian context, the Silurian–lower Carboniferous and Permo-Triassic magmatic belts are spatially separated; it is possible that the Ross and Amundsen province spatial

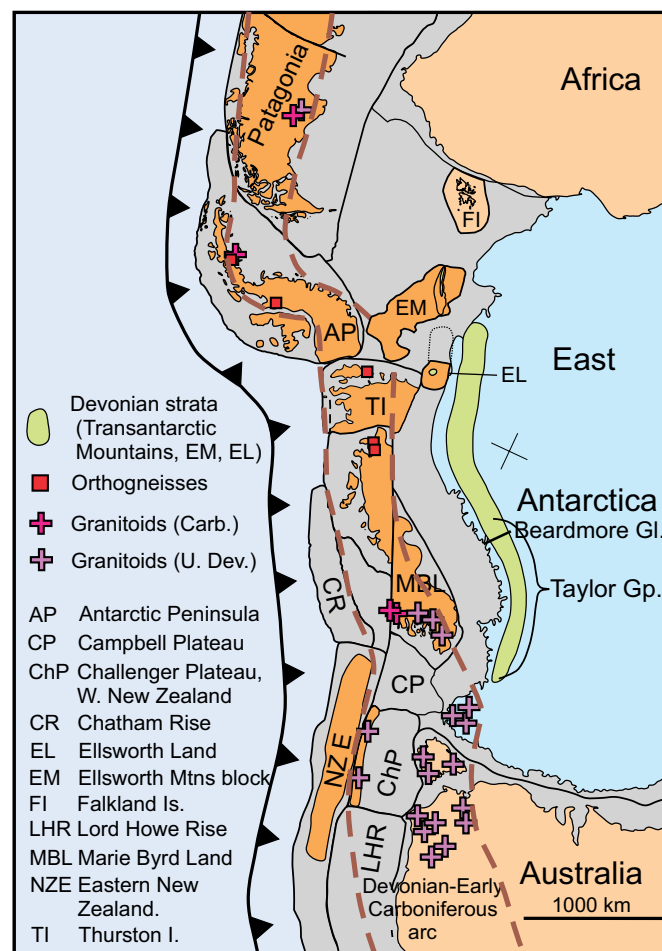


Figure 6. Gondwana reconstruction to illustrate the distribution of Upper Devonian and Lower Carboniferous granitoids and orthogneisses.

distinctions result from inadequate exposure, and there could be overlap of all the magmatic belts in Antarctica.

Although isolated Cambrian orthogneiss localities are known from eastern Marie Byrd Land (Pankhurst et al., 1998; Mukasa and Dalziel, 2000), there is little indication that the Ross orogen extended to the Permo-Triassic Gondwana plate margin; however, the occurrence of Cambrian basement in Tierra del Fuego (Pankhurst et al., 2003) suggests that a Cambrian arc might have extended along the Gondwana margin to link up with the Ross orogen. If it did extend to the Permo-Triassic plate margin, it implies that the younger mag-

matic belts were built on the outer margin of a very wide arc region of the Ross orogen or that an allochthonous ribbon of Ross orogen rocks had been detached and moved outboard. The former is regarded as improbable because the deep-water Ordovician (?) Swanson turbidites were deposited on the oceanic flank of the Ross orogen and lie inboard of the Silurian and younger magmatic arcs. The latter interpretation is advocated. The Ross orogen, including granitoids and both siliciclastic and carbonate shallow water successions of Cambrian age, may have extended for some distance outboard of its known extent but would have been mainly covered by the Ordovician and Devonian strata. The regional context of the Ross orogen is complicated by the contrast between the Cambrian strata of the CTM, north Victoria Land, and Tasmania, and the possible allochthonous nature of Tasmania (Bradshaw et al., 2009; Cayley, 2011).

The Ross orogen-age and older zircons of the early provenance are therefore attributed mainly to recycling through sedimentary strata (Swanson Formation and inferred equivalents and/or Devonian quartzose strata) and/or Marie Byrd Land paragneisses (Yakymchuk et al., 2015) that were located outboard of the Transantarctic Mountains during Permo-Triassic time, with perhaps a small component derived by direct erosion of Ross orogen rocks outboard of its known exposures. During Triassic time (late provenance time), and in particular late Falla time, the Ross orogen-age and older zircons could equally well have been derived from the craton flank of the basin.

Detrital Zircons and Basin Filling

Detrital zircons clearly indicate a major source region along the contemporaneous active Gondwana margin during late Permian through Triassic time. Studies at Mount Bowers and in the Queen Elizabeth Range demonstrated significant detrital input from the craton (Isbell, 1991; Elliot et al., 2015) on that flank of the basin, but major flow directions recorded for Permian strata (Barrett et al., 1986; Isbell, 1991; Isbell et al., 1997) suggest that the present outcrop belt of the Permian strata in CTM aligns approximately with the basin axis, with an overall sense of flow to the southeast (present coordinates) toward the Ohio Range; this regional flow pattern was gradually reversed in late Permian time.

The Pagoda Formation basin received detrital sediment from both flanks (Fig. 7), although the principal paleoflow was along the axis of an elongate basin (Isbell et al., 2008). The postglacial Mackellar Formation, deposited in a brackish to marine environment (Miller and Collinson, 1994; Jackson et al., 2012), also shows sparse evidence for derivation from the basin flanks. The overlying Fairchild Formation represents the deltaic infilling and fluvial covering of the shallow Mackellar Sea and, like the underlying Permian formations, records minor input from the basin flanks and predominantly southeasterly paleoflow (Isbell, 1991; Isbell et al., 1997). Together, the Mackellar and Fairchild formations reflect deposition in a 100–200-km-wide, elongate, slowly subsiding basin. The quartz-pebble conglomerate lenses marking the base of the Buckley Formation (Barrett et al., 1986) suggest a hiatus and a tectonically

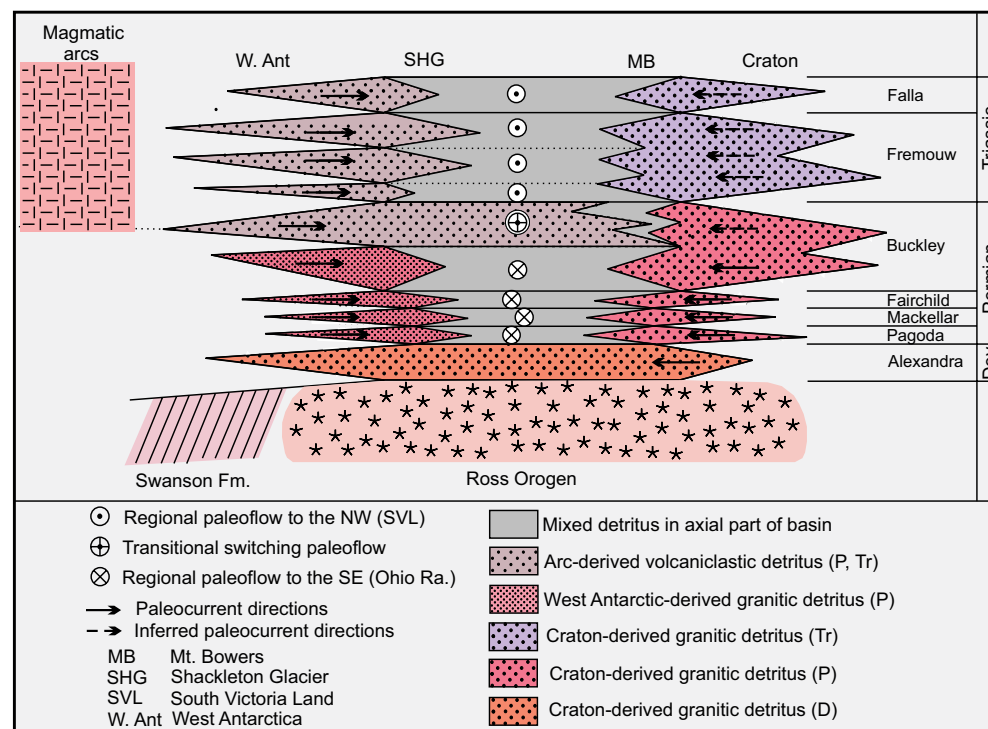


Figure 7. Schematic space-time illustration of the Victoria Group in the central Trans-antarctic Mountains to show the various detrital inputs from the basin flanks and principal paleoflow directions. The depositional basin was narrow in early Permian time, and broadened in Buckley time, as it evolved into a foreland basin. Ra. = Range.

driven change in environment. This is not observed in the sandstone petrology but is in the detrital-zircon patterns that now have a greatly diminished component of pre-Ross orogen-age grains. Furthermore, dispersal patterns were reorganized at this time, with a change from uniform southeasterly flow in the Fairchild Formation to transverse flow into the basin along the flanks of the outcrop belt and axial flow along the basin, suggesting the lower Buckley beds were deposited in a trough-shaped basin (Isbell et al., 1997). The lower Buckley depositional system was, at least locally, a low-lying alluvial plain (Isbell and Flaig, 2005) with coal deposition recorded in sections near Mount Rosenwald (below and above sample 07-2-14 in a 64-m-thick succession capped by a dolerite sill) and in the region of Mount Roper and Mount Weeks (Barrett et al., 1986) (Fig. 3).

The transition from the quartzose lower Buckley beds to the volcanoclastic upper Buckley strata must be diachronous, depending on the source regions being tapped and the locations of alluvial systems and depositional centers. At Mount Miller on the arc flank, the first occurrence of volcanoclastic detritus is ~150 m above the base of the formation and at Mount Roper (Fig. 3) on the cratonic flank at ~200 m (Barrett et al., 1986). However, at Mount Bowers, also on the cratonic flank, it occurs at 392 m (Elliot et al., 2015). Diachroneity must

reflect the migration of principal river systems across the flood plain and the depositional sites of volcanoclastic sediment, shifting entry points of prograding alluvial systems into the basin, relative uplift and relief of the basin flanks (Conaghan et al., 1982), and tectonism and sediment loading resulting in an expanding and migrating basin system (Flemings and Jordan, 1990).

The advent of volcanoclastic detritus and contemporaneous magmatic arc zircon grains, together with the associated change in paleoflow, marks the most significant event in the history of basin filling (Figs. 7 and 8). The input of volcanic detritus into the upper Buckley depositional system in late Permian time resulted in major alluvial fans prograding into and across the basin and reflected tectonism and magmatism along the plate margin. The timing of onset of volcanoclastic input to the basin is not well constrained but has to be late Permian in age, and the detrital-zircon age data suggest an age no older than ca. 260 Ma for the CTM and the Ohio Range. Zircon grains in Buckley Formation sample 90-35-2 are almost exclusively Permian in age, but other samples with significant numbers of Permian grains also have a small and older (Devonian and Carboniferous) Pacific margin component as well as Ross orogen-age clusters and older Precambrian grains. The Cambrian and older zircons, except for the Mount Bowers sample (11-5-22), could have been derived by reworking

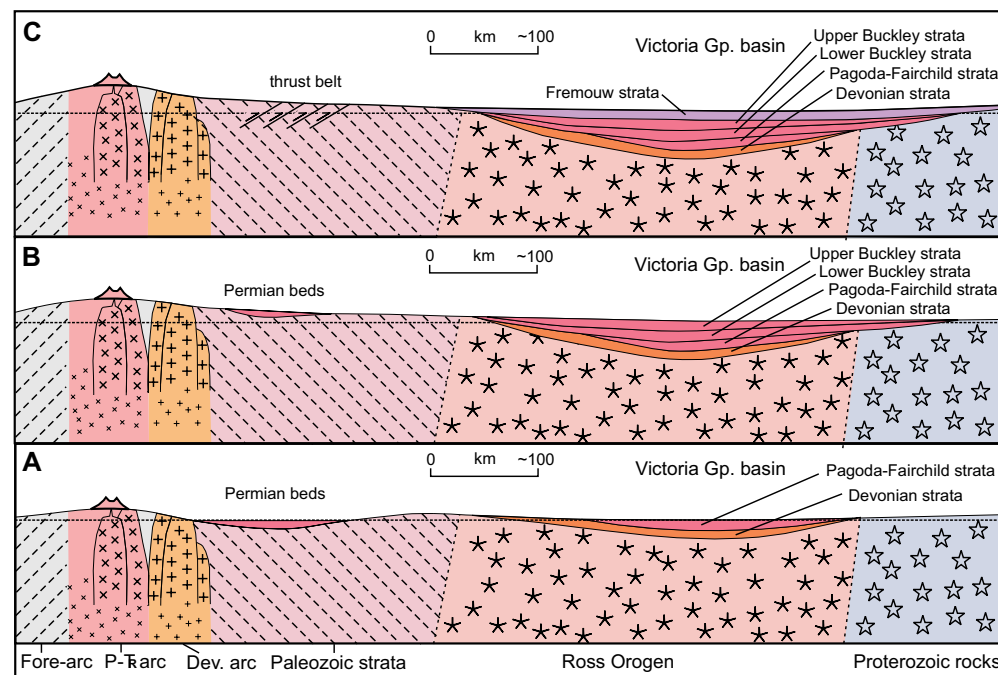


Figure 8. Schematic cross sections of the Gondwana margin and Victoria Group depositional basin in the central Transantarctic Mountains. (A) Early Permian time at the end of Fairchild deposition. (B) Latest Permian time at the end of upper Buckley deposition. (C) Middle Triassic time at the end of Fremouw deposition. These schematic cross sections illustrate the pre-Devonian crustal provinces and the Gondwana margin arc terrains related to Victoria Group deposition. They also illustrate the proposed backarc basin in which lower Permian arc-derived sediment was trapped, the release of a flood of Permian zircons from that basin and the arc in late Permian time, and the progressive onlap and expanding basin boundaries through time. The location of the inferred thrust belt is illustrative only; it could have involved strata on the basin margin. The Ross orogen Paleozoic strata contact must be a significant unconformity, but other province boundaries undoubtedly are diffuse and merge from one into another. The horizontal scale is approximate.

of the Swanson Formation, Marie Byrd Land paragneisses, and Devonian quartzose sandstones, or from unconsolidated lower Buckley beds. The Cambrian grains in the Mount Bowers sample (11-5-22) were most probably derived directly from the craton, as inferred by the paleocurrent data suggesting flow off East Antarctica (Elliot et al., 2015). The initial flood of detrital sediment with Permian zircon grains, associated with a significant tectonic event that led to the gradual reversal in regional paleoflow along the basin axis, must have spread across the basin and beyond its current extent, forming a series of low-gradient alluvial fans (Isbell, 1991). The distal margins of the fans on the cratonic flank fed into the dispersal of volcanoclastic sediment back toward the main basin axis (see Elliot et al., 2015), possibly resulting from continuing development of a forebulge.

The upper provenance, documented by the Triassic detrital zircons, is associated with strong southwesterly (present coordinates) paleoflow off West Antarctica (Vavra et al., 1981; Collinson and Elliot, 1984; Collinson et al., 2006) in the region of the Shackleton Glacier and with paleoflow veering northwesterly in the axial part of the basin in the Queen Alexandra Range region (Barrett et al., 1986; Isbell, 1991). In a general sense, this documents fans prograding off West Antarctica and a change in direction of the paleoflow on entering the axial part of the basin. However, the zircon data suggest this is oversimplified. Zircons in the quartzose sandstone of the lower member of the Fremouw For-

mation (sample 96-36-4; Elliot and Fanning, 2008) predominantly have Ross orogen ages but with scattered older Precambrian grains and a smattering of Devonian, Carboniferous, and Permian zircons. The latter were ultimately derived from the Gondwana margin but probably were recycled from upper Buckley beds. The paucity of volcanoclastic detritus in the lower Fremouw member implies that the principal source for the Ross-age grains was the craton. Input from the margin must have been largely blocked by rivers carrying the products of craton erosion and/or a hiatus in sediment supply from the margin resulting from tectonism intermittently blocking sediment dispersal from the arc. The sample from the Fremouw middle member (07-6-2) marks a return to significant Gondwana margin input with abundant grains having Early–Middle Triassic ages and a small but important set of upper Carboniferous grains. In addition, a cluster of Upper Ordovician to Silurian grains must also have come from the margin where a Silurian granitoid and an orthogneiss have been recorded (Pankhurst et al., 1998). The more quartzose sample (07-6-3) from the Fremouw upper member has a major group of Middle Triassic grains and minor upper Permian and Upper Devonian clusters. The cluster of Ross orogen–age and older grains could have come directly from the craton or by recycling through the inferred lower Paleozoic strata in West Antarctica. Zircons from the Falla Formation sample (90-2-52) exhibit a major group of near contemporaneous Late Triassic age and a minor group of Early Triassic

age, which might have been reworked from older Triassic beds or eroded directly from magmatic arc rocks. The significant cluster of Ross orogen-age grains was probably derived from the craton. Apart from the Fremouw lower member, the variability of the zircon spectra in the three remaining samples suggests that detrital inputs from the plate margin and craton sources were being mixed through reworking on a sandy braided plain (Collinson et al., 1994) and that interfingering of stream deposits with different proportions of plate margin and craton detritus was widespread.

The abrupt switch from coal-bearing Buckley strata to non-carbonaceous sedimentation in Fremouw time marks a significant environmental change. In addition to a change in climate (Collinson et al., 2006), it is probable that tectonism increased the rates of erosion in the source region and also caused erosion of older strata on the basin margin, resulting in the Victoria Group depositional system passing from an under filled to an overfilled basin (Catuneanu et al., 1998; Isbell and Flaig, 2005). Nevertheless, the fluvial environment included coal formation in late Fremouw and early Falla time.

Magmatism and Tectonism on the Gondwana Margin

Detrital zircons in the upper Permian to Upper Triassic sandstones provide additional information on the overall makeup of the Gondwana margin. Except for the McQuarrie arc in far-distant New South Wales, Australia (Glen, 2005), sources for Upper Ordovician zircon grains are unknown, which implies unexposed rocks of that age in the Antarctic sector. The few detrital zircons with Silurian ages are consistent with granitoid and orthogneiss of that age on the plate margin (Pankhurst et al., 1998). Silurian magmatic rocks are very sparsely distributed in Marie Byrd Land but, in contrast, are a major component of the Lachlan orogen. The Upper Devonian Ford granitoids (Pankhurst et al., 1998; Mukasa and Dalziel, 2000; Yakymchuk et al., 2015) were clearly the source for detrital zircons of that age in the Permian strata of the CTM. Lower Carboniferous granitoids were reported by Pankhurst et al. (1998) and Mukasa and Dalziel (2000) and formed a minor contributor to the Victoria Group. Upper Carboniferous granitoids and orthogneisses, known from eastern Marie Byrd Land and Thurston Island (Pankhurst et al., 1993, 1998), constitute a source for grains of that age found in the middle Fremouw sample (07-6-2) and in the Permian sandstone from Erewhon Nunatak in eastern Ellsworth Land (Elliot et al., 2016a). The abundance of detrital zircons with Permian ages demonstrates that the late Permian was a time of major magmatic activity, and the spread of detrital-zircon ages suggests magmatism may have been active throughout Permian time. The presence of Triassic zircons implies that granitoids and orthogneisses of that age are more widespread than might be apparent from the dated granitoids at Kinsey Ridge, western Marie Byrd Land, at Mount Murphy, eastern Marie Byrd Land (Pankhurst et al., 1998), and at Mount Brammall, Thurston Island (Pankhurst et al., 1993).

Overall, the detrital-zircon data together with the previous results from dating granitoids and gneisses in Marie Byrd Land and Thurston Island suggest

substantial magmatic activity on the Gondwana plate margin from Silurian to Late Triassic time, with major episodes in the Devonian, Permian, and Triassic, and lesser episodes during the Carboniferous. The widespread occurrence from Zealandia to the Antarctic Peninsula of Permian volcanoclastic strata, igneous rocks, and detrital zircons suggests a major tectonic adjustment, attributable to plate reorganization or increasing closure rates. Granitoids and orthogneisses along the Pacific margin must be more prevalent in time and space than is apparent from limited outcrop data in that now ice-covered region. Further, the zircon data suggest that Permian magmatism possibly started earlier than is evident in the currently exposed stratigraphic and magmatic record and was episodic to continuous through to Late Triassic time.

The Gondwana plate margin in the Antarctic sector was a complex and varied active plate boundary with at least episodic magmatism from Silurian through Triassic time, yet the lower part of the Victoria Group (Pagoda to lower Buckley formations), which was derived in part from the West Antarctic region, lacks detrital material derived from those Paleozoic magmatic arcs. The erosional products of those magmatic arcs must have been trapped between the arc and an elevated source region during early Permian time, in some type of backarc basin (Fig. 8). The flood of volcanoclastic detritus and Permian zircons indicates breaching of that barrier in late Permian time. This probably resulted from thickening of the crust, uplift of the arc, and development of a foreland fold and thrust belt, all attributable to increasing closure rates on the plate margin. Although the late Permian–Triassic Victoria Group setting is interpreted as a foreland basin, thickening of foredeep strata toward the plate margin cannot be documented because of the ice cover. The uncertainties are compounded by the fact that the intensity of deformation affecting the lower Permian foredeep strata in the Karoo of South Africa and the Falkland Islands diminished toward West Antarctica in reconstructed Gondwana (Tankard et al., 2009; Elliot et al., 2016a), suggesting that the foredeep may have shallowed in that direction. In Zealandia, only the Triassic Topfer Sandstone and Jurassic Kirwans Dolerite west of the Alpine fault (Mortimer et al., 1995) are comparable to the Victoria Group. It is not clear if and how any of the New Zealand terranes are related, particularly given the argument that they may have been translated long distances (Adams et al., 2007). The Permo-Triassic arc and associated foreland basin emerge again in the New England orogen and Sydney Basin of eastern Australia (Veevers et al., 1994).

CONCLUSIONS

1. Three distinct provenances, defined by detrital-zircon age data, are recognized and are consistent with changes in sandstone petrology.
2. The Permian magmatic arc on the Gondwana plate margin was initiated early in the Permian, reached peak activity in late Permian time, and was probably a more significant magmatic episode than that during Triassic time.
3. The detrital-zircon data show that a barrier (elevated terrain) separated the Victoria Group basin from the Gondwana margin until late Permian time.

³Supplemental Files S3–S13. Analytical results for detrital zircons in 11 sandstones. Please visit <http://dx.doi.org/10.1130/GES01245.S3> or the full-text article on www.gsapubs.org to view the Supplemental Files S3–S13.

4. A basin existed adjacent to the arc, in which arc-derived sediment was trapped, probably from late Carboniferous time until breaching in late Permian time, as a result of uplift in the arc and backarc region.

5. Detrital zircons suggest that the Triassic arc documented in the Antarctic Peninsula was more extensive in West Antarctica than is apparent from very limited exposure.

6. The Gondwana margin detrital-zircon signature of late Neoproterozoic–Early Ordovician grains and lesser Grenville-age grains persisted on a diminishing scale into the Mesozoic.

7. The Ordovician Swanson Formation and Devonian Taylor Group must be more extensive in the Ross embayment of West Antarctica in order to form the source, together with Marie Byrd Land paragneisses, for the Gondwana margin detrital-zircon signature documented in lower Permian Fairchild sandstones and for Ross orogen–age zircons in all early provenance sandstones.

8. On the assumption that *Glossopteris* does not range into the Triassic, results for a sandstone from tens of meters below the Permo-Triassic boundary illustrate some of the uncertainties in using detrital-zircon data to establish precise depositional ages.

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APPENDIX. ANALYTICAL PROCEDURES AND RESULTS

SHRIMP U-Pb Geochronology

Zircon grains were separated from total-rock samples using standard crushing, washing, heavy liquid (specific gravities 2.96 and 3.3), and paramagnetic procedures. The zircon-rich heavy-mineral concentrates were poured onto double-sided tape, mounted in epoxy together with chips of the TEMORA reference zircon, sectioned approximately in half, and polished. Reflected and transmitted light photomicrographs were prepared for all zircons, as were cathodoluminescence (CL) scanning electron microscope (SEM) images. These CL images were used to decipher the internal structures of the sectioned grains and to ensure that the ~20 μ m SHRIMP spot was wholly within a single age component within the sectioned grains.

The U-Th-Pb analyses reported herein were made using sensitive high-resolution ion microprobe (SHRIMP) II or SHRIMP reverse geometry (RG) at the Research School of Earth Sciences, the Australian National University (ANU), Canberra, Australia, following procedures given in Williams (1998, and references therein). For the detrital age spectra, between ~60 and ~70 grains were chosen in a random manner from the total zircon population, and each analysis consisted of four scans through the mass range, with a TEMORA reference zircon grain analyzed for every five unknown analyses. Previously published data for samples 96-65-2 and 96-36-1 (see Elliot and Fanning, 2008) were analyzed using SHRIMP I (at ANU), with the U/Pb calibration relative to the Duluth gabbro reference zircon FC1. The youngest grains in these two samples have now been reanalyzed in geochronology mode using SHRIMP II, each analysis consisting of six scans through the mass range, with a TEMORA reference zircon grain analyzed for every three unknown analyses. Samples H3-384b 07-6-2, 07-6-3, and 90-2-52 contain igneous grains with apparent young ²⁰⁶Pb/²³⁸U detrital ages. Because such grains have high significance with respect to the time of

deposition, selected young grains were reanalyzed in geochronology mode using SHRIMP II to gain better precision on the youngest detrital-zircon age grouping.

Overall, the data have been reduced using the SQUID Excel Macro of Ludwig (2001). The Pb/U ratios have been normalized relative to a value of 0.0668 for the TEMORA reference zircon, equivalent to an age of 417 Ma (see Black et al., 2003). Uncertainty in the reference zircon calibration for each analytical session is given in Supplemental Files S3–S13³ for each sample. Uncertainties given for individual analyses (ratios and ages) are at the one sigma level (Supplemental Files S3–S13 [see footnote 3]). Correction for common Pb was either made using the measured ²⁰⁴Pb/²⁰⁶Pb ratio in the normal manner or for grains younger than say 800 Ma (or those low in U and radiogenic Pb), the ²⁰⁷Pb correction method has been used (see Williams, 1998). When the ²⁰⁷Pb correction is applied, it is not possible to determine radiogenic ²⁰⁷Pb/²⁰⁶Pb ratios or ages. In general, for grains younger than ca. 800 Ma, the radiogenic ²⁰⁶Pb/²³⁸U age has been used for the probability density plots (and for areas that are low in U and therefore radiogenic Pb). The ²⁰⁷Pb/²⁰⁶Pb age is used for grains older than ca. 800 Ma or for those enriched in U. Tera and Wasserburg (1972) concordia plots, probability density plots with stacked histograms, and weighted mean ²⁰⁶Pb/²³⁸U age calculations were carried out using Isoplot/Ex (Ludwig, 2003).

As a general comment about the methods used, for detrital-zircon age spectra, we have analyzed grains at random within the total zircon aliquot that was poured (not hand selected) onto double-sided tape and cast into an epoxy disk. From paired reflected and transmitted light images of the zircon population, a photographic pair was selected, and where possible, every zircon grain within those photographs was analyzed. Initially the transmitted light image was used to locate an area within any one grain that was free of cracks and inclusions and so of good-quality zircon. Having chosen that area, the CL image was then used to ensure that the area analyzed was of a single zircon component, i.e., there was no overlap of two CL-structured areas. Further, at this stage, the area selected for analysis of any one grain was, on the basis of the CL image, the youngest component in that grain.

Following this detrital age spectrum procedure, it is often apparent that there are some analyses that are either younger than the inferred stratigraphic age or very close to that age. In this situation, it is then important to revisit those grains and determine in geochronology mode a more precise and accurate date on the specific zircon area and/or grain. In this manner, reanalysis of those grains in higher precision mode yields a better defined estimate for the time of deposition. In the case of the samples analyzed in this study, a few of the younger analyses were subsequently determined to be of areas that were clearly altered and had lost radiogenic Pb. Such analyses have not been included in the final weighted mean age calculation for the youngest age grouping for that sample.

Results

The geographic locations of samples are given on Figure 3, except for the sandstone from the Ohio Range (Fig. 1), and in Supplemental File S1 (see footnote 1). The samples are also projected onto a composite stratigraphic column for the Shackleton-Beardmore region on Figure 4A.

07-2-4; Fairchild Formation, Mount Rosenwald; 136 m above the base of the formation. Detrital-zircon grains are principally broken and/or round to subround crystals, although a few euhedral grains are present. The CL images show that a number are oscillatory-zoned igneous crystals, amongst which a few exhibit sector zoning, although many exhibit only poorly defined to indistinct zoning. A number are homogeneous under CL, suggesting a metamorphic origin. The age spectrum (Fig. 9) shows a principal peak at ca. 580 Ma, but deconvolution using the mixture modeling algorithm (Isoplot) yields a prominent peak at ca. 580 Ma and three lesser groupings at ca. 525 Ma, ca. 565 Ma, and ca. 610 Ma, all within the age span of the Ross orogen (Goode et al., 2012). There are minor Grenville-age and early Mesoproterozoic peaks at ca. 1050 Ma and ca. 2250 Ma.

07-2-12; lower Buckley Formation, Mount Rosenwald; 64 m above the base of the formation. Zircon grains are mainly round to subround, with some broken fragments of presumed euhedral crystals. Internal CL characteristics range from strong oscillatory zoning to homogeneous unzoned grains of possible metamorphic origin; some grains have distinct cores. The age spectrum is dominated by grains in the range 535–610 Ma (Fig. 10). This main cluster can be deconvolved into three more prominent subgroupings at ca. 540 Ma, ca. 560 Ma, and ca. 575 Ma, with other minor subgroups at ca. 515 Ma and ca. 605 Ma. These correspond with the upper Neoproterozoic to Lower Ordovician Ross orogen; many of these grains are homogeneous, suggesting a metamorphic origin. There is a scattering of older ages back to ca. 3 Ga.

MBB 73-3; lower Buckley Formation, Mount Butters; 73 m above the base of the formation. Zircon grains from this sandstone are mainly broken and round to subround crystals. A wide

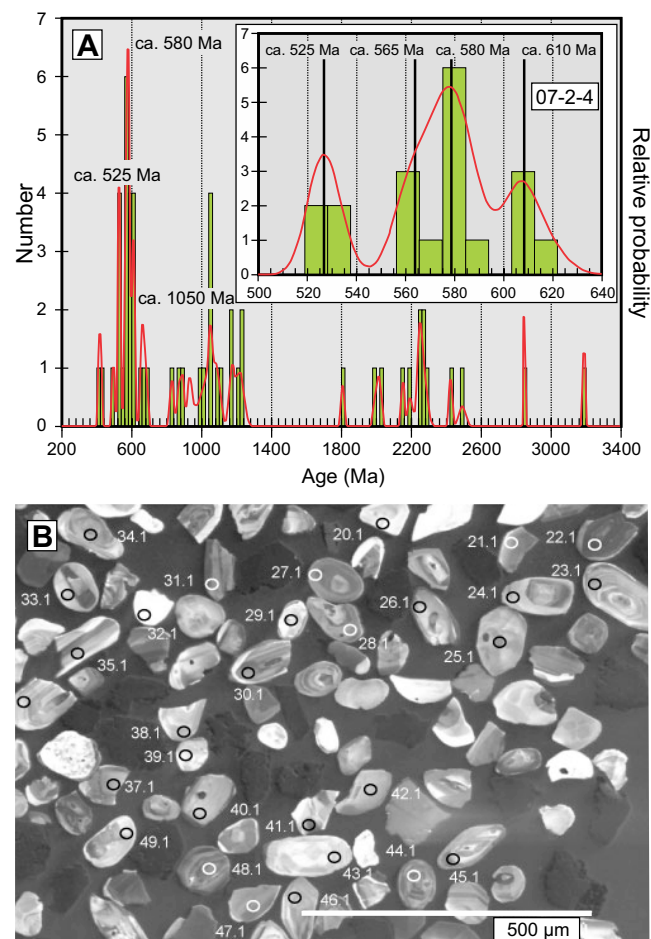


Figure 9. (A) U-Pb zircon age-probability density plot and (B) cathodoluminescence (CL) image for Fairchild Formation sandstone sample 07-2-4.

variety of CL characteristics are present, including oscillatory and rare sector zoning, as well as complex interiors indicative of more than one period of zircon crystallization. Homogeneous, possibly metamorphic, zircon occurs sparsely. The broad and irregular pattern of the predominant component of the age spectrum lies in the range 530–600 Ma, with prominent peaks at ca. 545 and ca. 585 Ma (Fig. 11). These ages fall in the range of the upper Neoproterozoic to Lower Ordovician Ross orogen. Minor clusters have Early to Middle Ordovician (ca. 470 Ma) and late Grenvillian (ca. 930 Ma) ages. A scattering of older ages is also present.

11-4-3; lower Buckley Formation, south spur of Clarkson Peak; 120 m above the base of the formation (immediately above the 250-m-thick sill marking the top of section Z2 in Barrett et al., 1986). Zircon grains form a heterogeneous population with round to subround grain shapes the more dominant; many of these are broken fragments of prismatic crystals. Well-defined oscillatory zoning is not common, with many of those grains exhibiting weak zoning and some having complex

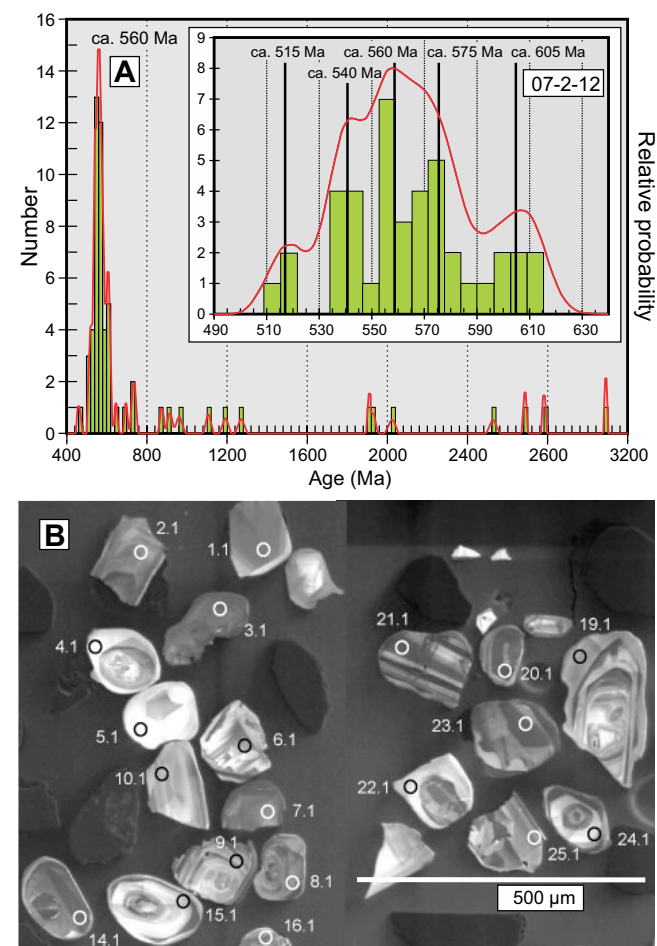


Figure 10. (A) U-Pb zircon age-probability density plot and (B) cathodoluminescence (CL) image for lower Buckley Formation sandstone sample 07-2-12.

internal structure. Grains without internal zoning are also present, and these are probably of metamorphic origin. The zircon age spectrum (Fig. 12) is dominated by grains in the range 520–600 Ma, with a dominant peak at ca. 570 Ma, again corresponding with the Ross orogen. Older grains are scattered through the Precambrian and include eight grains of Archean age.

11-5-22; upper Buckley Formation, Mount Bowers; 33 m above the contact between the lower Buckley and upper Buckley members, and 425 m above the base of the formation. The sample is described in Elliot et al. (2015). The zircon population (48 of 72) is dominated by grains of Permian age with a probability peak at ca. 260 Ma. The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age for 32 analyses is 258.1 ± 1.9 Ma (mean square of weighted deviates [MSWD] = 1.2) (Fig. 13). There is a minor Ross-age peak (Elliot et al., 2015). The Permian grains are predominantly euhedral (or broken) crystals with oscillatory zoning and often with terminations. Ross-age grains are mainly broken, subround, and with oscillatory zoning. Older grains are round to subround and have weak or complex zoning.

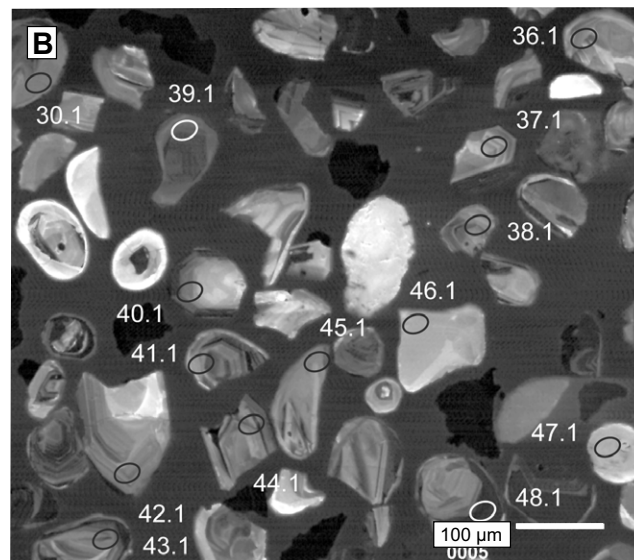
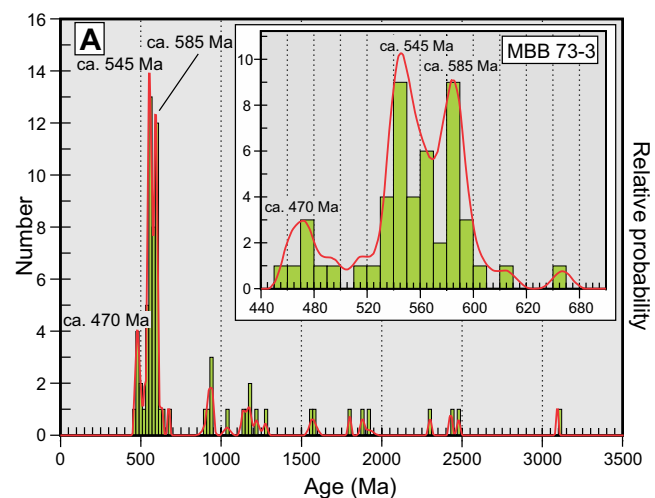


Figure 11. (A) U-Pb zircon age-probability density plot and (B) cathodoluminescence (CL) image for lower Buckley Formation sandstone sample MBB 73-3.

H3-384b; Mount Glossopteris Formation, Terrace Ridge, Mount Schopf, Ohio Range; 390 m above the base of the section (Long, 1964, 1965). The zircon grains are predominantly elongate to stumpy, euhedral (or broken) crystals, including many with pyramidal terminations. The CL images show that fine oscillatory zoning is very common, with a few grains having sector zoning. Carboniferous grains are similar to those of Permian age. Grains older than Carboniferous are round or subround, broken, and with weak to strong oscillatory zoning. The initial detrital

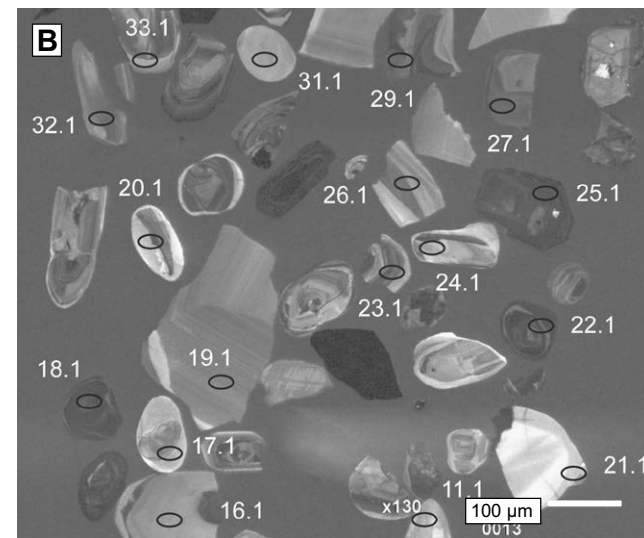
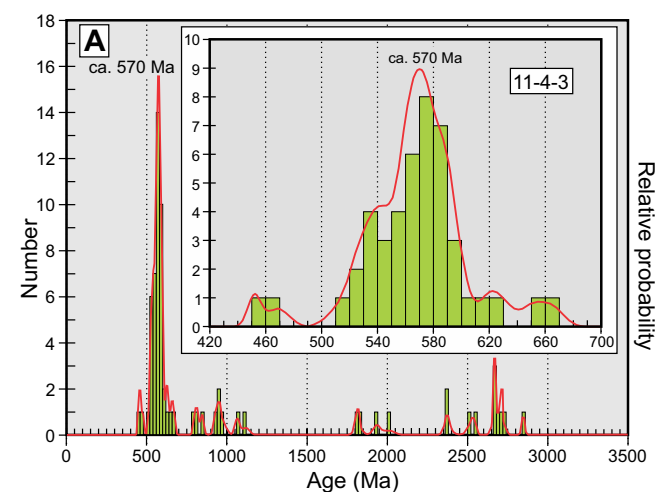


Figure 12. (A) U-Pb zircon age-probability density plot and (B) cathodoluminescence (CL) image for lower Buckley Formation sandstone sample 11-4-3.

age spectrum (four-scan data) showed a dominant peak at ca. 270 Ma with a minor but significant grouping around 245 Ma. Many of the analyses yielding young ages plotted above the Tera-Wasserburg concordia due to enrichment in common Pb. It was suspected that the areas analyzed had also lost radiogenic Pb, and so, a number of the youngest Permian-age grains were reanalyzed in geochronology mode. Unfortunately, not all the Triassic grains could be reanalyzed. In the composite plot of the original detrital data, together with the updated geochronology analyses of 15

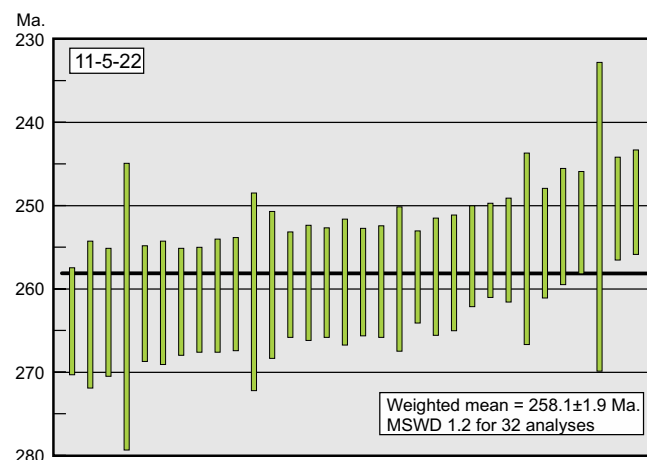


Figure 13. U-Pb zircon weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age plot for upper Buckley Formation volcanic sandstone sample 11-5-22.

grains, there remains a subordinate grouping at ca. 245 Ma that is not considered to be geologically meaningful due to inferred radiogenic Pb loss. The composite probability density plots show the dominance of Permian grains with the main peak at ca. 270 Ma and slightly lesser peak at ca. 260 Ma (Fig. 14). This suggests that an age of ca. 260 Ma may represent the best estimate of the maximum age of deposition.

11-4-10; upper Buckley Formation, south spur of Clarkson Peak; 330 m above the base of the formation. The age spectrum is dominated by Permian grains with the principal probability peak at ca. 260 Ma, a minor but prominent peak at ca. 555 Ma, and small clusters of grains at ca. 360 Ma and ca. 1100 Ma (Fig. 15). The Permian grains have $^{206}\text{Pb}/^{238}\text{U}$ ages that range from ca. 250 to ca. 275 Ma, and a depositional age no older than ca. 260 Ma is implied. Most of the Permian (32 grains) and Devonian (four grains) zircons are euhedral, equant to prismatic, crystals of which some are broken; pyramidal terminations are common; all have strong oscillatory zoning, indicating igneous crystallization. The minor but prominent grouping at ca. 555 Ma has, in detail, a range in ages from ca. 500 Ma to ca. 600 Ma, again corresponding with Ross orogen ages, and the 1100 Ma peak lies in the Grenville-age range. Most grains older than Devonian are round to subround, commonly broken, and with less well defined CL zoning.

96-35-2; upper Buckley Formation, near Layman Peak; 70 m below the top of the formation. Analytical data for the detrital age spectrum of 60 grains have been published in Elliot and Fanning (2008). The youngest 23 grains, out of the 58 Permian grains originally analyzed, have been reanalyzed in six-scan geochronology mode in order to provide a better estimate of the depositional age. The zircons are dominated by stumpy euhedral grains, with many retaining crystal terminations, and showing well-developed oscillatory zoning (note that in Elliot and Fanning, 2008, figure 5 is mislabeled: fig. 5a should be 96-36-4, and fig. 5c should be 96-35-2). The analyses form a single tight grouping close to or within uncertainty of the Tera-Wasserburg concordia, indicating that the areas analyzed are dominated by radiogenic Pb and essentially unaffected by radiogenic Pb loss. Twenty of the 23 reanalyzed zircon grains give a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 253.5 ± 2.0 Ma (MSWD = 1.5) (Fig. 16), which is interpreted as the maximum age of deposition.

96-36-1; upper Buckley Formation, Collinson Ridge; 1 m below the top of the formation. Analytical data for the detrital age spectrum of 60 grains have been published in Elliot and Fanning (2008). Zircons in this sample include more broken and abraded grains than in 96-35-2, suggesting a higher degree of surface transport. Nevertheless, there are whole and broken euhedral crystals, some of which are elongate, suggesting volcanic or subvolcanic crystallization. Zoning includes fine concentric growth patterns, broad and ill-defined zones, as well as occasional sector zoning. From Elliot and Fanning (2008, fig. 7), apart from the dominant Permian grouping, there are also

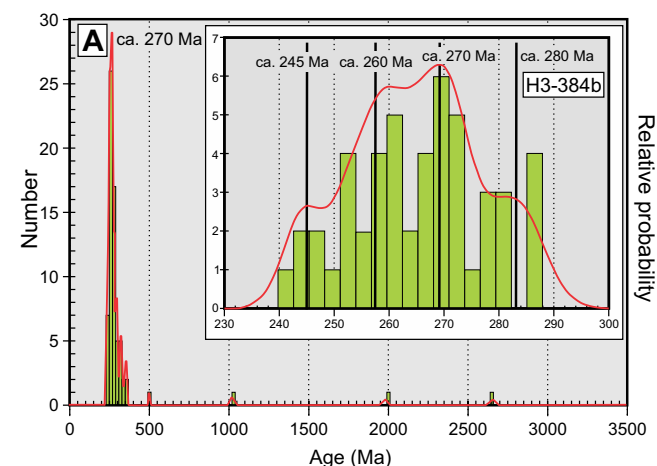


Figure 14. (A) U-Pb zircon age-probability density plot and (B) cathodoluminescence (CL) image for Mount Glossopteris Formation sandstone sample H3-384b. Note that only the geochronology data for the Permian grains have been included in the plots.

some Devonian grains at ca. 360 Ma and a Cambrian cluster with weak probability peaks at ca. 520 Ma and ca. 540 Ma. For the current study, the 22 grains reanalyzed in six-scan mode form a slightly dispersed cluster, close to or within uncertainty of the Tera-Wasserburg plot; some tapering off on the younger age side suggests some areas have lost radiogenic Pb. Sixteen of the reanalyzed 22 grains have a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 250.3 ± 2.2 Ma (MSWD = 1.5) (Fig. 17), which is interpreted as the maximum age of deposition.

96-36-4; Fremouw Formation, lower member, Collinson Ridge; 46.5 m above the base of the formation. Analytical data were published in Elliot and Fanning (2008), and no further analyses have been made. The published age spectrum for this sandstone is dominated by grains in the

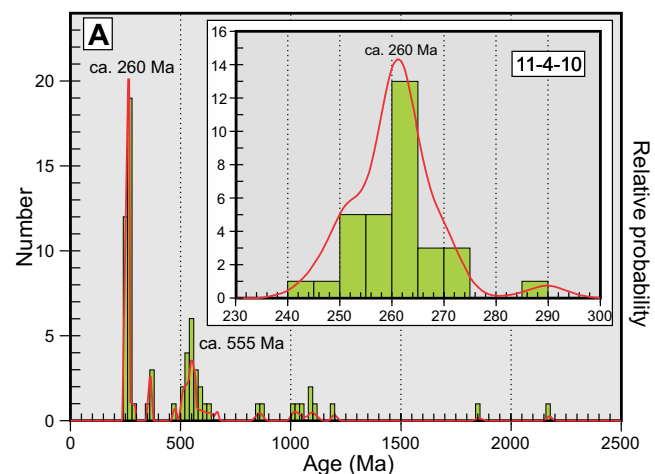


Figure 15. (A) U-Pb zircon age-probability density plot and (B) cathodoluminescence (CL) image for upper Buckley Formation volcanic sandstone sample 11-4-10.

range ca. 470–600 Ma, with a subsidiary cluster at ca. 630–660 Ma. The principal set, corresponding to the Ross orogen, shows probability peaks at ca. 545 Ma and ca. 580 Ma and a decreasing tail of younger grains. Insignificant clusters have Devonian and Permian ages, and there are scattered grains older than 660 Ma.

07-6-2; Fremouw Formation, middle member, Halfmoon Bluff; 46 m above the base of the member (which is 170 m thick where measured). Zircons in this sandstone include euhedral crystals, often broken, and round to subround grains. CL images show that oscillatory zoning is ubiquitous, but weak non-oscillatory zoning and sector zoning are also present. Most grains are of igneous origin. The initial detrital analyses recorded a main age peak at ca. 245 Ma with a secondary prominent grouping at ca. 310 Ma and then scattered older ages. There was also a small grouping

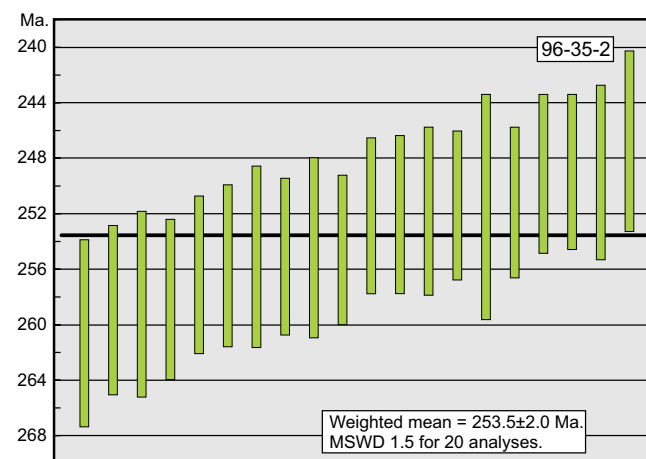


Figure 16. U-Pb zircon weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age plot for upper Buckley Formation volcanic sandstone sample 96-35-2. External uncertainties are included in the weighted mean age calculation.

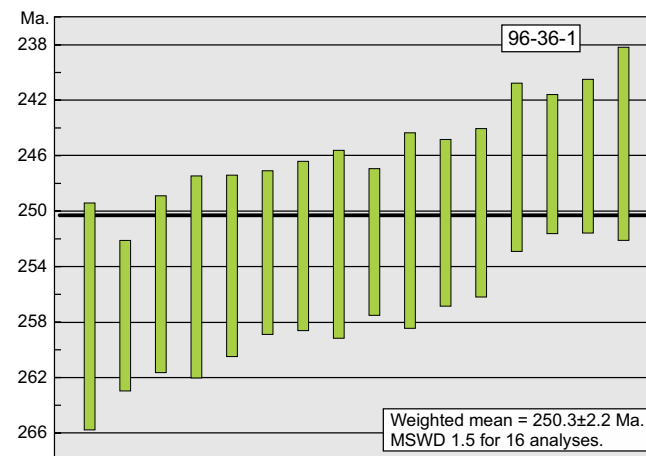


Figure 17. U-Pb zircon weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age plot for upper Buckley Formation volcanic sandstone sample 96-36-1. External uncertainties are included in the weighted mean age calculation.

of Triassic analyses around 230 Ma. It was therefore decided to reanalyze these youngest grains and a number of new grains in geochronology mode (six-scan data). The second analysis on these grains did not reproduce the younger dates, and so, it is concluded that the areas analyzed had lost radiogenic Pb; all analyses are of igneous zircon grains. The composite detrital and geochronology data set reaffirms the principal probability peak (Fig. 18A) at ca. 245 Ma and a secondary grouping at ca. 310 Ma, with dispersed ages in the range 400–500 Ma (Early Devonian to Late Cambrian).

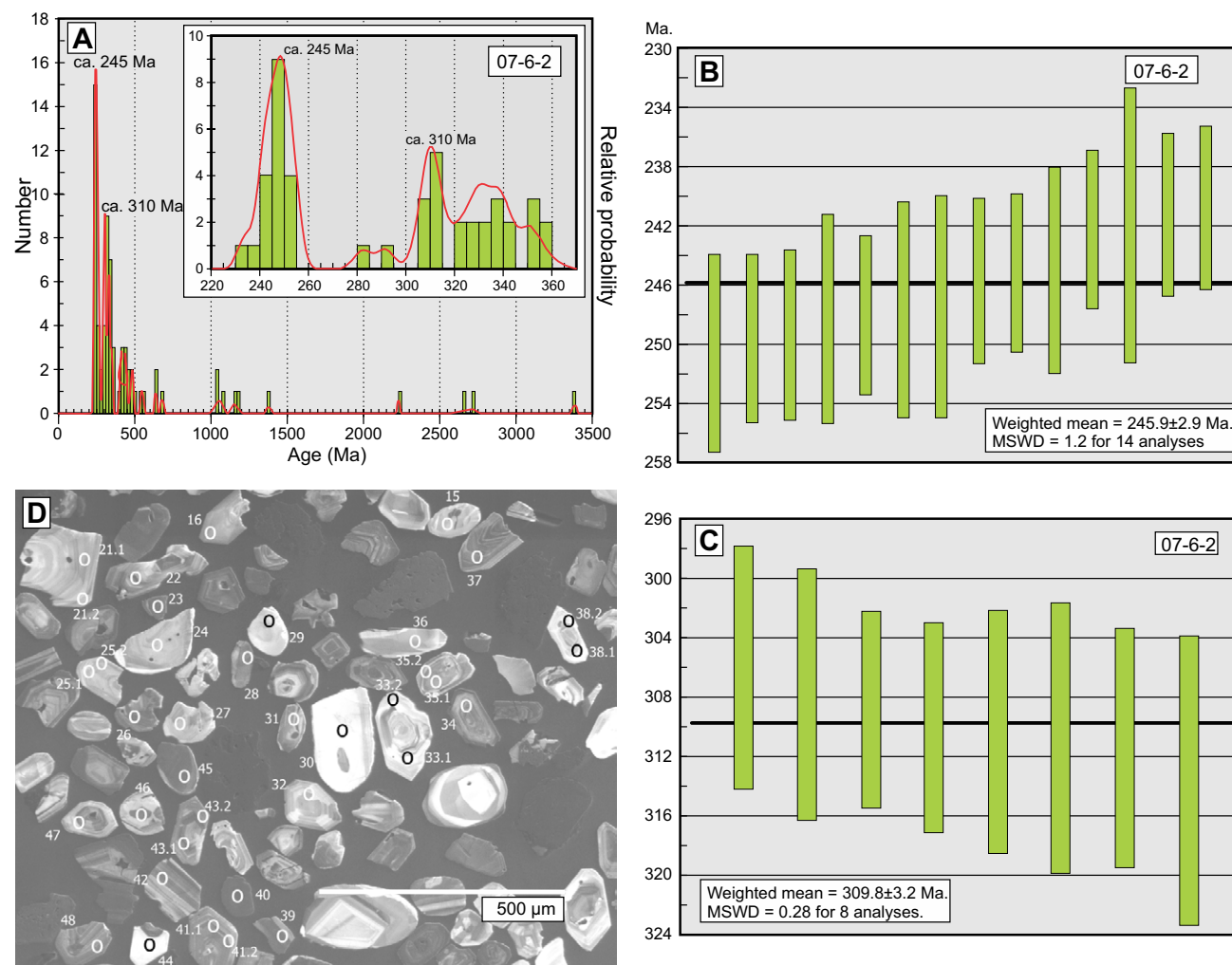


Figure 18. (A) U-Pb zircon age-probability density plot; (B) U-Pb zircon weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age plot for Permian zircons; (C) U-Pb zircon weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age plot for Carboniferous zircons; and (D) cathodoluminescence (CL) image for Fremouw Formation sandstone sample 07-6-2. Note that for the Permian grains only the geochronology data have been included in the plots. External uncertainties are included in the weighted mean age calculation.

A weighted mean for the 14 analyses in the dominant grouping gives a $^{206}\text{Pb}/^{238}\text{U}$ age of 245.9 ± 2.9 Ma (MSWD = 1.2). The older group of eight Carboniferous analyses has a weighted mean age of 310 ± 3.2 Ma (MSWD = 0.28) (Fig. 18B).

07-6-3; Fremouw Formation, upper member; Halfmoon Bluff; 75 m above the base of the member. The zircon grains are principally euhedral crystals with pyramidal terminations and in CL images exhibiting strong oscillatory zoning and scattered sector zoning. However, some, particularly the older grains, are broken fragments of euhedral crystals, and a few show weak non-oscillatory zoning or no zoning, the latter suggesting a metamorphic origin. The composite zircon

age spectrum, combining original detrital data with selected grains reanalyzed in geochronology mode (Fig. 19A) has two major peaks, one at ca. 240 Ma (Early Triassic) and the other at ca. 365 Ma (Late Devonian). There are minor older peaks at ca. 490 Ma and ca. 570 Ma, both falling in the age range of the Ross orogen. In detail (see inset Fig. 19A), the ca. 365 Ma cluster is rather diffuse, but nevertheless the ages correspond with the Upper Devonian Ford granitoids of Marie Byrd Land (Pankhurst et al., 1998; Mukasa and Dalziel, 2000; Yakymchuk et al., 2015). In terms of the dominant Early Triassic analyses, a weighted mean for 14 analyses gives a $^{206}\text{Pb}/^{238}\text{U}$ age of 242.3 ± 2.3 Ma (MSWD = 0.78) (Fig. 19B).

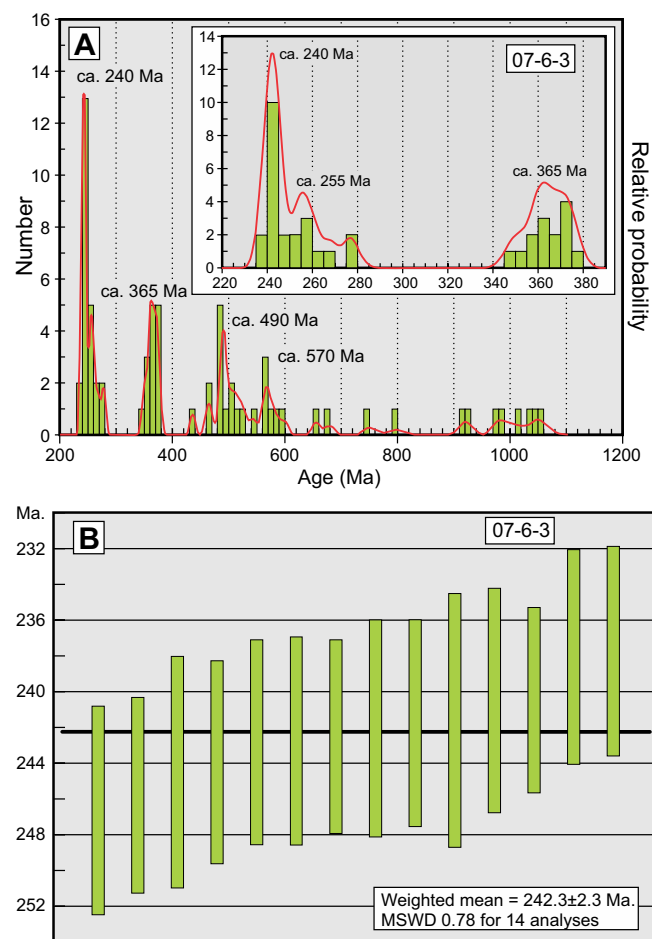
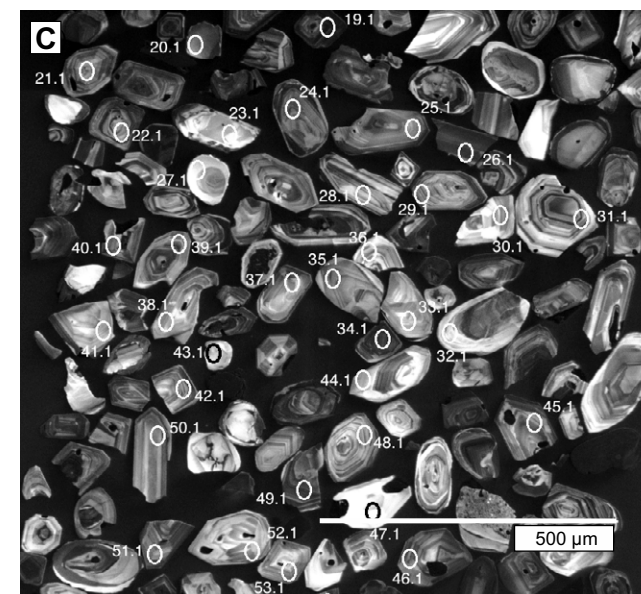


Figure 19. (A) U-Pb zircon age-probability density plot; (B) U-Pb zircon weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age plot; and (C) cathodoluminescence (CL) image for Fremouw Formation sandstone sample 07-6-3. Note that for the Permian grains only the geochronology data have been included in the plots. External uncertainties are included in the weighted mean age calculation.

90-2-52; Falla Formation, Mount Falla; 252 m in the type section of the formation. The composite zircon age spectrum, combining original detrital data with selected grains reanalyzed in geochronology mode (Fig. 20A), has a dominant age peak at ca. 205 Ma with a clustering at ca. 245 Ma, a prominent cluster at ca. 515 Ma, corresponding with Ross orogen ages, and scattered older grains including some between ca. 900–1100 Ma. In general, the Triassic grains are euhedral prisms, or occasionally fragments of prisms, with pyramidal terminations and exhibiting oscillatory CL zoning. Older zircons are more varied; many are fragments; round to subround grains are common; cores are present in many grains; and zoning may be weak and non-oscillatory. A weighted mean for 15 analyses forming the dominant age grouping gives a $^{206}\text{Pb}/^{238}\text{U}$ age of 206.6 ± 2.2 Ma (MSWD = 1.08) (Fig. 20B).

The Permian and Triassic zircon grains are euhedral, sometimes broken and forming fragments, often with terminations and exhibiting strong oscillatory zoning; the Carbonifer-



ous and Devonian grains, far fewer in number, are predominantly similar. These Devonian to Triassic zircons are mainly of igneous origin and are most probably first-cycle detrital grains. Older grains (mainly of Ross orogen age together with some Proterozoic and minor Archean grains) are commonly broken and often round to subround, which suggests recycling through sedimentary successions. Th/U ratios in igneous grains with oscillatory zoning range down to 0.02; low Th/U arises from U enrichment as part of the igneous process rather than Th depletion as would be expected in metamorphic zircon. Oscillatory zoning is relatively common, but many grains have complex zoning or have cores, reflecting incorporation of xenocrystic zircon or various stages of resorption and growth, and others display weak to very weak non-oscillatory zoning or essentially no zoning, being homogeneous. The latter are probably of metamorphic origin; however, none of those have very low Th/U ratios (<0.05).

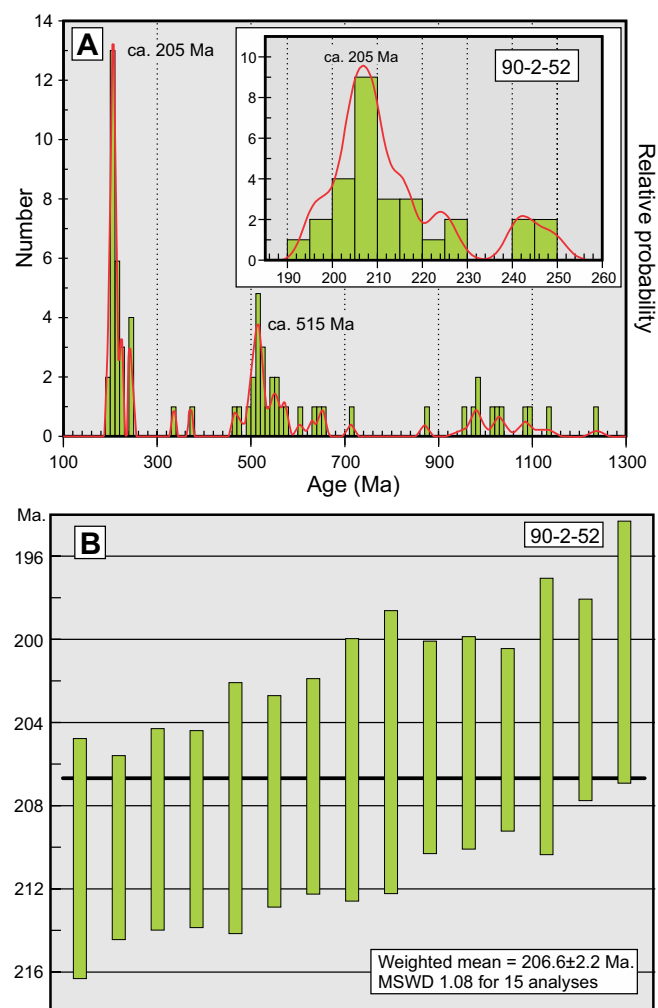


Figure 20. (A) U-Pb zircon age-probability density plot; (B) U-Pb zircon weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age plot; and (C) cathodoluminescence (CL) image for Falla Formation sandstone sample 90-2-52. Note that for the Triassic grains only the geochronology data have been included in the plots. External uncertainties are included in the weighted mean age calculation.

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