Detrital zircons from upper Permian and lower Triassic Victoria Group sandstones, Shackleton Glacier region, Antarctica: Evidence for multiple sources along the Gondwana plate margin

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Abstract

In the central Transantarctic Mountains region, siliciclastic strata of the Permian–Triassic Victoria Group (Beacon Supergroup), the Gondwana sequence in Antarctica, have both cratonic and magmatic arc provenance. Volcaniclastic strata occur in the upper part of the Permian Buckley Formation, whereas the Triassic Fremouw and Falla formations are more quartzose. Two sandstones in the upper Buckley and one near the base of the Fremouw, and immediately above the Permo–Triassic boundary, in the Shackleton Glacier region have yielded detrital zircon U/Pb SHRIMP age populations with clear evidence for a contemporaneous source. The stratigraphically lowest sample, about 70 m below the top of the Buckley Formation, is dominated by zoned igneous zircons of late Permian age. The sample from near the top of the Buckley Formation, about 40 m below the Permo–Triassic boundary, predominantly has zoned igneous zircons with the principal age peak again late Permian but with subordinate Devonian and Cambrian age peaks. The third sandstone from just above the Permo–Triassic boundary yielded zircons mainly of Neoproterozoic to Cambrian age. These results indicate a Permian–Triassic magmatic source existed during upper Buckley time, which is consistent with paleocurrent indicators of flow from the West Antarctic flank of the Permian–Triassic foreland basin, the inferred plate margin (Panthalassan) flank. The Devonian source is attributed to the Ford granodiorite suite in Marie Byrd Land, West Antarctica. Because Beacon strata cover the Cambrian Ross orogen and extend onto older basement, the Cambrian and Upper Proterozoic zircons are interpreted to be reworked from sandstones (Ordovician, Devonian, Early Permian in age) exposed in the Permian–Triassic Gondwanide orogen as a result of uplift of a fold and thrust belt by late Permian time.

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1. Introduction

The siliciclastic fill of a sedimentary basin reflects source region lithologies, which also may indicate the tectonic framework. Epeirogenic downwarping of broad regions will commonly lead to relatively mature quartz-rich sandstones, whereas, for instance, rift basins will reflect the geology of the proximal rift shoulders. In the former case, sandstone and heavy mineral petrology yields only relatively sparse data, whereas in the latter case, it can provide much provenance information. In most cases, the sand-sized grains commonly reflect mixed

sources. Detrital zircons yield complementary data, which may include: populations of grains with different ages; evidence for recycling of grains; evidence for igneous or metamorphic origin; and isotopic data that allow identification of crustal source terrains (e.g. Ross et al., 1992; Geslin et al., 1999; Hallsworth et al., 2000; Adams et al., 2002; Ross and Villeneuve, 2003; Goodge et al., 2004a,b; Link et al., 2005).

The sandstone petrology of the Victoria Group (the Permian–Triassic part of the Beacon Supergroup) as a whole has been reported (Vavra et al., 1981; Barrett et al., 1986; Collinson et al., 1994) to include quartzose sandstones of probable cratonic origin, and volcaniclastic sandstones derived from a magmatic arc. This paper reports a preliminary study of detrital zircons in sandstones from the upper Permian and

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lowest Triassic part of the Victoria Group in the Shackleton Glacier area in the central Transantarctic Mountains (CTM). It is the first step in differentiating source terrains for the Victoria Group, and infers when sources were active and the possible timing of tectonic events in the Gondwanide orogenic belt.

2. Regional geology

Devonian to Triassic Beacon Supergroup strata crop out in the Transantarctic Mountains (TAM), and overlie a pre-Devonian basement of igneous and metamorphic rocks (Fig. 1). The basement is formed mainly of Neoproterozoic to Cambrian sedimentary and volcanic strata, which were deformed, metamorphosed and intruded by granitoid batholiths in the Cambro-Ordovician Ross Orogeny (Stump, 1995). A regional erosion surface was cut across the Ross Orogen in pre-Devonian time. On this surface were deposited quartz-rich sandstones and minor finer grained beds of the Devonian Taylor

Fig. 2. Beacon Supergroup stratigraphy (Taylor and Victoria Groups) in the Transantarctic Mountains. Star on the central Transantarctic Mountains column marks the location of analyzed samples. See Collinson et al. (1994) for details of stratigraphy.

Group (Fig. 2). A second erosion surface was cut prior to deposition of the Permian–Triassic Victoria Group, the Antarctic Gondwana sequence. The Beacon strata were overlain by extrusive rocks of the Ferrar large igneous province and intruded by co-magmatic sills and dikes.

The East Antarctic craton under the polar ice sheet is inferred to include pan-African age belts, Grenville age provinces, Proterozoic domains, and Archean cratons (Fitzsimons, 2000, 2003); a large extension of the Archean-Paleoproterozoic Mawson Continent is inferred to dominate the ice-covered hinterland to the TAM and extend to adjacent areas in Australia (Fanning et al., 1996). Archean gneisses, initially emplaced at

Fig. 1. Location map for Devonian to Triassic Beacon Supergroup strata in the Transantarctic Mountains, Antarctica. EM: Ellsworth Mountains; MBL: Marie Byrd Land; TI: Thurston Island.

ca. 2.98 Ma, metamorphosed during a high-grade event at ca. 2.96 Ma and intruded by 2.5 Ga granites, form the oldest exposed basement rocks (Goodge and Fanning, 1999). These Archaean gneisses were reworked by Paleoproterozoic metamorphism and syn-tectonic magmatism at 1.7 Ga and again during the Ross Orogeny (Goodge et al., 2001; Goodge and Fanning, 2002). In outcrop they are restricted to the Miller Range region in CTM (Fig. 1).

Neoproterozoic to Ordovician strata are widespread in the TAM (Goodge et al., 2004a,b). Neoproterozoic to Lower Cambrian rift-related siliciclastic strata are confined to the Pensacola Mountains (Hannah Ridge Formation) and CTM (Beardmore Group). Cambrian to lower Ordovician siliciclastic strata and associated carbonate shelf deposits are widespread between the Byrd Glacier and the Pensacola Mountains region (Byrd Group and the correlative Patuxent Formation). Cambrian silicic volcanic rocks are common in the Queen Maud Mountains and Thiel Mountains (Pankhurst et al., 1988; Wareham et al., 2001). Granitoids were emplaced in the late Cambrian during the Ross Orogeny, both pre-deformation, the main phase of which was over by about 500 Ma, and locally post-deformation (Borg et al., 1990; summarized in Rowell et al., 2001). North of Byrd Glacier, in south and north Victoria Land (SVL, NVL), the basement is dominated by medium to high-grade metamorphic rocks, which were intruded by Ross age granitoids that again show pre-and post-tectonic phases. In SVL, the metamorphic rocks (Koettlitz Group) are probably correlative with the Neoproterozoic metasediments in CTM (Goodge et al., 2004a). Detrital zircons from the Upper Proterozoic to Lower Ordovician strata show a wide range of provenance ages, ranging back to the Archean but dominated by Cambrian and both Neo- and Mesoproterozoic ages (Goodge et al., 2004a,b).

West Antarctica is part of the dismembered Gondwana plate margin (Dalziel and Elliot, 1982), now consisting of continental blocks and severely stretched continental crust with thicknesses of 20–25 km (Winberry and Anandakrishnan, 2004). Much of West Antarctica is ice covered but outcrops through Marie Byrd Land (MBL) and Thurston Island (Fig. 1) indicate the presence of Paleozoic to Early Mesozoic (Triassic) magmatic arcs which are recorded principally as granitoids (Pankhurst et al., 1993, 1998; Mukasa and Dalziel, 2000). On the basis of geochronologic and geochemical data, an inboard Ross Province with Cambrian metagreywackes and gneisses has been defined in western MBL and an outboard Amundsen Province in eastern MBL that lacks Cambrian age rocks (Pankhurst et al., 1998). The Ross Province includes Cambrian orthogneisses, with a not well-constrained age of about 505 Ma, and Swanson Formation greywackes with metamorphic ages of 440–420 Ma (Adams et al., 1995); however, the principal rocks in the Ross Province are intrusive and belong to the Ford Granodiorite, which forms a well-defined set of Devonian plutons with an emplacement age of 375 ± 5 Ma (Pankhurst et al., 1998). This magmatic belt extends into NVL (Henjes-Kuntz and Kreuzer, 2003, and references therein), and into New Zealand (summarized in Wandres and Bradshaw, 2005); orthogneisses of that age are known from the Antarctic Peninsula (Millar et al., 2002). Carboniferous granitic bodies

with ages about 340 Ma are also present in MBL. Orthogneisses on Thurston Island and a leucogranite on the Antarctic Peninsula have similar ages. The Amundsen Province includes Ordovician to Silurian (450–420 Ma) granitoids, but it is characterized principally by a Permian–Triassic magmatic arc which crops out in central and eastern MBL and Thurston Island. Millar et al. (2002) report sparse granite and orthogneiss of that age in the Antarctic Peninsula.

Denudation following the Ross Orogeny led to the formation of the Kukri Erosion Surface throughout the TAM (Isbell, 1999). The Taylor Group was deposited on this surface and now crops out principally in SVL where the sequence, up to 1400 m thick, consists of quartzose sandstones overlain by a small interval of finer grained beds from which Devonian fossils have been recovered (Bradshaw and Webers, 1988; Bradshaw, 1991). Quartz-rich sandstones of presumed Devonian age continue south to a paleotopographic high in the Nimrod Glacier region and are present again farther south (north of the Beardmore Glacier) where thicknesses exceed 300 m (Isbell, 1999). An uncertain small thickness occurs at Mt. Hermanson between the Beardmore and Ramsey Glaciers (Fig. 3), and about 60 m is present at Sullivan Ridge in the Ramsey Glacier region (Coates, 1985). A paleotopographic high separates these siliciclastic sequences from the marine Devonian beds in the Ohio Range (Bradshaw and Webers, 1988). The Kukri surface has

Fig. 3. Locality and simplified geologic map of the Shackleton Glacier region. (Note: orientation reversed from Fig. 1).

considerable relief, locally as much as 700 m south of Byrd Glacier (Anderson, 1979).

The younger, pre-glacial (Permian) Maya Erosion Surface was superimposed on the Kukri surface and Devonian strata, and also has considerable relief (Isbell, 1999). Uncertain amounts of Devonian strata were probably removed before deposition of the Permo-Triassic Victoria Group (Collinson et al., 1994) on this surface. Three depositional basins have been recognized (see Fig. 2 for stratigraphy): intra-cratonic basins in NVL and SVL, and to the south of the Byrd Glacier a cratonic basin that evolved in middle Permian time into a foreland basin.

In this basin south of Byrd Glacier, the Permian glacial beds (Fig. 2) are overlain by post-glacial shales that transition through quartzose sandstones upwards into fluvial coal measures of Middle and Late Permian age. These are succeeded by Triassic flood plain sediments largely devoid of coal. Sedimentation ended in late Triassic time, and during the Early Jurassic a silicic volcanoclastic sequence (Hanson Formation; Elliot, 1996) was deposited in a rift setting that had developed on the earlier foreland basin. In the late Early Jurassic, Ferrar tholeiitic magmas were erupted as pyroclastic rocks and lava flows, and intruded as dolerite sills and dikes (Elliot and Fleming, in press). Given the thickness of the exposed strata, the foreland basin must have extended onto the craton and also toward the active margin.

Paleocurrent analysis of the foreland basin strata in the Shackleton Glacier region (Vavra et al., 1981; Isbell, 1991) shows derivation of detrital material from quartzose sources during the early Permian and flow generally towards the southeast along the mountain range. This pattern was replaced by magmatic arc volcanoclastic sources on the West Antarctic flank during middle and Late Permian deposition of the coal measures. Volcanoclastic sources were relatively less important in the Triassic, but paleocurrents still indicate derivation from the magmatic arc flank of the basin. Ash beds and shard-bearing sedimentary rocks show that contemporaneous volcanism continued at least into Middle Triassic time. The advent of volcanoclastic sources was accompanied by a gradual reversal in major trunk drainage and by the late Triassic the foreland basin was linked to the intracratonic basins in SVL and NVL, with paleocurrent flow towards Australia. The major paleocurrent reversal of the trunk drainage is attributed to the development of a fold and thrust belt, which is documented in the Pensacola and Ellsworth Mountains (Collinson et al., 1994).

3. Beacon strata in the Shackleton Glacier region

Taylor Group quartzose sandstones are represented by a single outcrop in the Ramsey Glacier region (Fig. 3) (Coates, 1985). In most places Victoria Group strata rest nonconformably on Neoproterozoic metasedimentary and meta-igneous rocks or on Ross granitoids (Collinson et al., 1994; Isbell, 1999). The lower Permian formations (Pagoda, Mackellar, and Fairchild) crop out in the foothills of the range, and between the Ramsey and Shackleton Glaciers are overlain by the Permian coal measures (Buckley Formation), which locally are capped by Lower Triassic beds of the Fremouw Formation. In the McGregor Glacier region the upper part of the Buckley

Formation and the Fremouw Formation are well exposed in the northern Cumulus Hills. Both the Fremouw and Falla Formations are well exposed farther south adjacent to the Shackleton Glacier (Collinson and Elliot, 1984). Paleocurrent measurements indicate derivation of the clastic debris in both the upper Buckley and lower Fremouw Formations from West Antarctica (Vavra et al., 1981; Isbell et al., 1997).

A simplified and composite stratigraphic column (Fig. 4) shows the principal sandstones in the upper Buckley and lower Fremouw flood plain sequences. The lower part was measured at Layman Peak and the upper part at Collinson Ridge, Cumulus Hills (see also Collinson et al., 2006). Samples analyzed come from 70 m (sample 35-2) and 3 m (sample 36-1) below the Buckley/Fremouw contact, and from 45 m (sample 36-4) in the Fremouw Formation, in the channel sandstone containing the first vertebrates. Sample 36-1 is 2 m above a 100+ m thick dolerite sill,

Fig. 4. Simplified stratigraphic columns for the upper Buckley Formation and lower Fremouw Formation in the Shackleton Glacier area. (see Fig. 3 for locations).

Table 1
Summary of SHRIMP U–Pb zircon results for sample 96-35-2

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total ratios				Radiogenic ratios				ρ	Age (Ma)				% disc		
							²³⁸ U/ ²⁰⁶ Pb	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±		²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±		²⁰⁷ Pb/ ²⁰⁶ Pb	±
1.1	329	224	0.68	11.4	—	0.13	24.739	0.351	0.0524	0.0012	0.0404	0.0006					255.1	3.6				
2.1	372	170	0.46	14.0	0.000130	<0.01	22.882	0.316	0.0506	0.0010	0.0438	0.0006					276.1	3.8				
3.1	494	215	0.44	18.3	0.000137	0.08	23.137	0.300	0.0524	0.0009	0.0432	0.0006					272.5	3.5				
4.1	291	125	0.43	9.9	0.000388	0.64	25.350	0.389	0.0563	0.0014	0.0392	0.0006					247.9	3.8				
5.1	209	202	0.96	7.7	0.000022	0.09	23.289	0.369	0.0524	0.0015	0.0429	0.0007					270.8	4.3				
6.1	158	159	1.00	5.7	0.000374	0.19	23.642	0.406	0.0531	0.0016	0.0422	0.0007					266.6	4.5				
7.1	299	145	0.48	10.9	—	0.14	23.450	0.340	0.0527	0.0012	0.0426	0.0006					268.8	3.9				
8.1	413	215	0.52	15.3	0.000078	0.24	23.195	0.321	0.0536	0.0011	0.0430	0.0006					271.5	3.7				
9.1	69	47	0.67	9.9	0.000094	0.16	6.003	0.109	0.0808	0.0015	0.1663	0.0030	1.824	0.064	0.0795	0.0024	0.521	992	17	1185	59	16
10.1	244	138	0.56	8.4	0.000533	<0.01	25.124	0.382	0.0509	0.0013	0.0398	0.0006					251.7	3.8				
11.1	466	190	0.41	17.5	—	0.01	22.839	0.304	0.0518	0.0010	0.0438	0.0006					276.2	3.6				
12.1	169	110	0.65	5.8	0.000832	0.34	25.086	0.429	0.0539	0.0016	0.0397	0.0007					251.2	4.3				
13.1	592	719	1.21	21.9	—	0.11	23.280	0.333	0.0526	0.0009	0.0429	0.0006					270.8	3.8				
14.1	116	48	0.41	4.6	—	<0.01	21.609	0.437	0.0509	0.0019	0.0463	0.0010					292.1	5.9				
15.1	268	113	0.42	9.0	—	0.23	25.667	0.453	0.0529	0.0014	0.0389	0.0007					245.8	4.3				
16.1	471	303	0.64	15.9	—	0.18	25.465	0.336	0.0526	0.0010	0.0392	0.0005					247.9	3.2				
17.1	299	126	0.42	10.5	0.000400	1.40	24.494	0.359	0.0626	0.0022	0.0403	0.0006					254.4	3.8				
18.1	140	117	0.83	4.9	—	0.02	24.362	0.427	0.0516	0.0017	0.0410	0.0007					259.3	4.5				
19.1	111	99	0.89	4.2	—	0.47	22.939	0.451	0.0555	0.0020	0.0434	0.0009					273.8	5.4				
20.1	238	135	0.57	23.0	0.000498	0.59	8.889	0.124	0.0671	0.0010	0.1118	0.0016					683.4	9.3				
21.1	291	161	0.55	9.7	0.000070	0.41	25.798	0.410	0.0544	0.0025	0.0386	0.0006					244.2	3.9				
22.1	630	612	0.97	22.2	0.000159	<0.01	24.340	0.299	0.0511	0.0008	0.0411	0.0005					259.7	3.2				
23.1	119	91	0.77	4.2	0.000382	0.11	24.049	0.469	0.0523	0.0019	0.0415	0.0008					262.3	5.1				
24.1	312	197	0.63	11.6	—	<0.01	23.099	0.335	0.0512	0.0012	0.0433	0.0006					273.4	3.9				
25.1	165	106	0.64	5.9	0.000167	0.37	23.880	0.407	0.0545	0.0019	0.0417	0.0007					263.5	4.5				
26.1	176	200	1.13	6.3	0.000503	0.30	23.822	0.402	0.0540	0.0016	0.0419	0.0007					264.3	4.4				
27.1	243	122	0.50	8.7	—	0.36	23.861	0.359	0.0544	0.0013	0.0418	0.0006					263.7	3.9				
28.1	132	154	1.17	4.8	—	1.23	23.562	0.440	0.0614	0.0020	0.0419	0.0008					264.7	4.9				
29.1	231	136	0.59	8.4	—	<0.01	23.700	0.362	0.0514	0.0013	0.0422	0.0007					266.5	4.0				
30.1	330	180	0.54	10.6	0.000176	0.44	26.644	0.396	0.0544	0.0013	0.0374	0.0006					236.5	3.5				
31.1	469	294	0.63	17.3	0.000056	0.15	23.331	0.299	0.0528	0.0009	0.0428	0.0006					270.2	3.4				
32.1	289	204	0.71	10.3	0.000054	<0.01	24.062	0.344	0.0506	0.0016	0.0416	0.0006					262.8	3.7				
33.1	161	102	0.63	5.5	—	0.32	25.135	0.437	0.0538	0.0022	0.0397	0.0007					250.7	4.4				
34.1	144	119	0.83	5.2	0.002122	3.73	23.903	0.431	0.0812	0.0031	0.0403	0.0008					254.5	4.8				
35.1	338	221	0.66	11.7	0.000046	0.36	24.705	0.347	0.0542	0.0012	0.0403	0.0006					254.9	3.6				
36.1	929	455	0.49	31.4	0.000388	0.48	25.453	0.297	0.0550	0.0007	0.0391	0.0005					247.2	2.9				
37.1	131	103	0.79	5.2	0.005904	8.38	21.590	0.421	0.1188	0.0228	0.0424	0.0016					267.9	10.1				
38.1	172	182	1.06	5.5	0.001488	1.62	26.840	0.504	0.0637	0.0022	0.0367	0.0007					232.1	4.4				
39.1	379	166	0.44	13.9	—	<0.01	23.422	0.311	0.0516	0.0010	0.0427	0.0006					269.5	3.5				
40.1	160	95	0.60	5.2	0.000260	0.46	26.307	0.465	0.0546	0.0017	0.0378	0.0007					239.4	4.2				
41.1	230	240	1.04	8.6	0.007169	14.46	22.891	0.356	0.1667	0.0039	0.0374	0.0010					236.5	6.3				
42.1	422	213	0.51	14.4	0.000478	0.31	25.142	0.331	0.0537	0.0014	0.0396	0.0005					250.7	3.3				
43.1	287	257	0.90	30.9	0.008686	39.55	7.975	0.595	0.3780	0.0858	0.0758	0.0159					471.0	95.0				
44.1	172	147	0.86	6.3	0.000547	0.06	23.569	0.391	0.0521	0.0015	0.0424	0.0007					267.7	4.4				

(continued on next page)

Table 1 (continued)

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total ratios				Radiogenic ratios				ρ	Age (Ma)				% disc
							²³⁸ U/ ²⁰⁶ Pb	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±		²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	
45.1	209	117	0.56	7.5	—	<0.01	23.831	0.367	0.0498	0.0013	0.0421	0.0007				265.6	4.1			
46.1	275	162	0.59	9.8	0.000091	0.92	24.172	0.352	0.0588	0.0018	0.0410	0.0006				259.0	3.8			
47.1	417	260	0.62	15.0	0.000164	<0.01	23.924	0.341	0.0503	0.0009	0.0419	0.0006				264.4	3.7			
48.1	246	112	0.46	8.2	0.000890	0.71	25.635	0.481	0.0568	0.0016	0.0387	0.0007				245.0	4.6			
49.1	164	100	0.61	6.2	0.002656	2.98	22.762	0.432	0.0755	0.0023	0.0426	0.0008				269.1	5.2			
50.1	125	82	0.65	5.0	0.000875	4.90	21.432	0.416	0.0912	0.0027	0.0444	0.0009				279.9	5.7			
51.1	890	901	1.01	34.1	0.000262	0.38	22.427	0.258	0.0550	0.0007	0.0444	0.0005				280.2	3.2			
52.1	116	61	0.53	4.1	0.000476	0.60	24.145	0.450	0.0562	0.0019	0.0412	0.0008				260.1	4.8			
53.1	79	34	0.43	2.9	0.000693	0.67	23.323	0.510	0.0570	0.0023	0.0426	0.0009				268.9	5.9			
54.1	119	114	0.96	4.0	0.000785	0.37	25.681	0.488	0.0540	0.0019	0.0388	0.0007				245.4	4.6			
55.1	33	12	0.38	1.3	0.003302	0.26	22.040	0.689	0.0541	0.0034	0.0453	0.0014				285.3	8.9			
56.1	250	75	0.30	8.8	—	<0.01	24.317	0.354	0.0499	0.0012	0.0412	0.0006				260.3	3.8			
57.1	294	107	0.37	10.7	—	0.22	23.563	0.333	0.0533	0.0011	0.0423	0.0006				267.4	3.7			
58.1	857	262	0.31	28.5	—	0.04	25.850	0.304	0.0514	0.0007	0.0387	0.0005				244.6	2.8			
59.1	151	88	0.58	5.4	—	<0.01	24.132	0.408	0.0506	0.0015	0.0415	0.0007				262.0	4.4			
60.1	136	75	0.55	4.7	0.000176	0.42	24.799	0.428	0.0547	0.0017	0.0402	0.0007				253.8	4.4			
							Age		±no std				±include std							
Younger group							249.3		2.0		1.15		2.9							
Older group							267.0		1.6		1.02		2.7							

Notes:

1. Uncertainties given at the one σ level.

2. Error in FCI Reference zircon calibration was 0.82% for the analytical session. (not included in above errors but required when comparing ²⁰⁶Pb/²³⁸U data from different mounts).

3. f₂₀₆% denotes the percentage of ²⁰⁶Pb that is common Pb.

4. For areas older than ~800 Ma correction for common Pb made using the measured ²⁰⁴Pb/²⁰⁶Pb ratio.

5. For areas younger than ~800 Ma correction for common Pb made using the measured ²³⁸U/²⁰⁶Pb and ²⁰⁷Pb/²⁰⁶Pb ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).

6. For % disc, 0% denotes a concordant analysis.

Pb* indicates radiogenic Pb.

Table 2
Summary of SHRIMP U–Pb zircon results for sample 96-36-1

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total ratios				Radiogenic ratios						ρ	Age (Ma)				% disc
							²³⁸ U/ ²⁰⁶ Pb	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±		²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	
1.1	151	81	0.54	16.6	0.000054	0.09	7.817	0.128	0.0643	0.0014	0.1285	0.0021	1.204	0.033	0.0680	0.0015	0.605	779	13	868	45	10
2.1	94	65	0.69	3.5	0.003061	2.89	23.141	0.656	0.0747	0.0030	0.0420	0.0012						265.0	7.5			
3.1	181	142	0.79	15.8	0.000090	0.09	9.839	0.157	0.0613	0.0012	0.1015	0.0017						623.5	9.7			
4.1	271	110	0.41	18.3	0.000008	0.27	12.717	0.185	0.0591	0.0011	0.0784	0.0012						486.7	7.0			
5.1	1373	229	0.17	49.4	—	<0.01	23.893	0.287	0.0511	0.0006	0.0419	0.0005						264.5	3.1			
6.1	181	91	0.50	5.9	—	0.12	26.192	0.499	0.0519	0.0027	0.0381	0.0007						241.3	4.6			
7.1	112	25	0.22	9.0	0.000168	0.57	10.769	0.233	0.0637	0.0017	0.0923	0.0020						569.3	12.1			
8.1	185	154	0.83	6.2	—	0.25	25.483	0.459	0.0531	0.0017	0.0391	0.0007						247.5	4.4			
9.1	192	247	1.29	6.8	0.000052	0.10	24.269	0.437	0.0522	0.0020	0.0412	0.0008						260.0	4.7			
10.1	110	51	0.46	5.5	0.000295	0.33	17.125	0.346	0.0565	0.0019	0.0582	0.0012						364.7	7.3			
11.1	51	11	0.22	3.0	0.001524	0.00	14.783	0.394	0.0552	0.0026	0.0676	0.0018						422.0	11.1			
12.1	843	1144	1.36	29.9	0.000157	0.05	24.246	0.295	0.0519	0.0011	0.0412	0.0005						260.4	3.1			
13.1	109	144	1.32	4.0	0.001446	0.24	23.344	0.501	0.0535	0.0021	0.0427	0.0009						269.8	5.8			
14.1	175	23	0.13	13.0	0.000089	<0.01	11.537	0.187	0.0575	0.0012	0.0867	0.0014						536.2	8.5			
15.1	250	333	1.33	8.7	—	0.14	24.794	0.404	0.0524	0.0014	0.0403	0.0007						254.5	4.1			
16.1	388	48	0.12	29.1	—	0.05	11.482	0.153	0.0586	0.0011	0.0871	0.0012						538.1	7.0			
17.1	532	211	0.40	28.8	—	<0.01	15.856	0.201	0.0530	0.0013	0.0632	0.0008						395.0	5.0			
18.1	396	286	0.72	29.5	0.000129	0.32	11.514	0.152	0.0608	0.0009	0.0866	0.0012						535.2	6.9			
19.1	96	74	0.77	3.4	0.001063	0.57	24.105	0.541	0.0560	0.0023	0.0412	0.0009						260.6	5.8			
20.1	135	80	0.59	5.1	—	<0.01	22.890	0.515	0.0496	0.0018	0.0438	0.0010						276.4	6.2			
21.1	296	129		15.3	—	<0.01	16.593	0.237	0.0536	0.0011	0.0603	0.0009						377.5	5.3			
22.1	497	713	1.43	17.5	—	<0.01	24.390	0.324	0.0509	0.0010	0.0410	0.0006						259.2	3.4			
23.1	197	164	0.83	6.9	0.000282	0.46	24.517	0.420	0.0550	0.0016	0.0406	0.0007						256.6	4.4			
24.1	176	187	1.06	6.2	0.001437	0.08	24.459	0.438	0.0521	0.0016	0.0409	0.0007						258.1	4.6			
25.1	258	246	0.95	8.6	—	0.20	25.889	0.415	0.0527	0.0014	0.0385	0.0006						243.8	3.9			
26.1	139	155	1.12	4.7	0.001072	0.35	25.520	0.503	0.0539	0.0020	0.0390	0.0008						246.9	4.8			
27.1	168	119	0.71	5.5	—	0.10	26.433	0.493	0.0518	0.0020	0.0378	0.0007						239.1	4.4			
28.1	287	206	0.72	9.7	—	0.42	25.287	0.392	0.0546	0.0014	0.0394	0.0006						249.0	3.8			
29.1	133	127	0.95	12.4	0.000038	<0.01	9.222	0.157	0.0603	0.0014	0.1086	0.0019						664.8	11.0			
30.1	129	106	0.82	10.4	0.000342	0.18	10.622	0.209	0.0608	0.0014	0.0940	0.0019						579.0	11.1			
31.1	89	94	1.06	3.1	—	0.17	24.235	0.556	0.0528	0.0024	0.0412	0.0010						260.2	5.9			
32.1	259	44	0.17	18.7	0.000125	0.21	11.907	0.169	0.0594	0.0010	0.0838	0.0012						518.8	7.2			
33.1	201	97	0.49	14.0	0.000109	<0.01	12.354	0.188	0.0572	0.0012	0.0810	0.0013						501.8	7.5			
34.1	461	293	0.64	35.9	0.000041	<0.01	11.047	0.138	0.0576	0.0007	0.0907	0.0012						559.4	6.8			
35.1	535	443	0.83	18.5	0.000022	0.22	24.865	0.323	0.0530	0.0013	0.0401	0.0005						253.6	3.3			
36.1	123	91	0.74	8.0	—	0.06	13.133	0.237	0.0570	0.0015	0.0761	0.0014						472.8	8.4			
37.1	149	173	1.16	5.3	0.000630	0.58	24.320	0.451	0.0561	0.0018	0.0409	0.0008						258.3	4.8			
38.1	130	128	0.98	4.9	—	0.31	23.040	0.443	0.0542	0.0019	0.0433	0.0008						273.1	5.2			
39.1	457	436	0.96	16.2	—	<0.01	24.265	0.361	0.0513	0.0010	0.0412	0.0006						260.4	3.8			
40.1	410	201	0.49	31.0	0.000206	0.09	11.354	0.144	0.0591	0.0010	0.0880	0.0011						543.6	6.8			
41.1	522	410	0.79	19.1	0.000260	0.55	23.473	0.299	0.0560	0.0009	0.0424	0.0005						267.5	3.4			
42.1	806	471	0.58	39.8	0.000009	0.16	17.373	0.203	0.0550	0.0006	0.0575	0.0007						360.2	4.1			
43.1	173	106	0.61	15.3	0.000052	0.29	9.714	0.150	0.0631	0.0012	0.1026	0.0016						629.9	9.5			
44.1	556	898	1.61	35.4	0.000099	0.42	13.511	0.164	0.0596	0.0007	0.0737	0.0009						458.4	5.5			

(continued on next page)

Table 2 (continued)

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total ratios				Radiogenic ratios				ρ	Age (Ma)				% disc		
							²³⁸ U/ ²⁰⁶ Pb	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	²⁰⁷ Pb/ ²⁰⁶ Pb		±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb		±	
45.1	341	47	0.14	24.6	0.000074	0.06	11.909	0.155	0.0582	0.0011	0.0839	0.0011					519.5	6.6				
46.1	1730	991	0.57	207.2	0.000025	0.04	7.171	0.076	0.0681	0.0003	0.1394	0.0015	1.302	0.015	0.0678	0.0003	0.903	841	8	861	10	2
47.1	823	300	0.37	28.3	0.000155	0.15	25.006	0.331	0.0524	0.0008	0.0399	0.0005						252.4	3.3			
48.1	381	501	1.32	14.6	0.000217	<0.01	22.371	0.308	0.0518	0.0010	0.0447	0.0006						282.0	3.9			
49.1	71	80	1.14	2.3	—	0.59	26.002	0.658	0.0557	0.0028	0.0382	0.0010						241.9	6.1			
50.1	466	113	0.24	109.7	0.000038	0.06	3.651	0.045	0.1049	0.0007	0.2737	0.0034	3.938	0.057	0.1044	0.0008	0.857	1560	17	1703	14	8
51.1	205	58	0.29	14.6	—	<0.01	12.027	0.179	0.0575	0.0011	0.0832	0.0013						515.0	7.5			
52.1	230	149	0.65	8.0	0.000037	0.06	24.616	0.390	0.0518	0.0014	0.0406	0.0007						256.5	4.0			
53.1	294	65	0.22	31.1	0.000155	0.27	8.135	0.117	0.0677	0.0049	0.1226	0.0018	1.107	0.088	0.0655	0.0051	0.181	745	10	791	164	6
54.1	542	91	0.17	48.8	—	0.13	9.539	0.114	0.0622	0.0009	0.1047	0.0013						641.9	7.5			
55.1	407	203	0.50	22.8	0.000117	0.21	15.356	0.198	0.0565	0.0009	0.0650	0.0009						405.9	5.2			
56.1	222	76	0.34	20.1	0.000029	<0.01	9.469	0.132	0.0607	0.0009	0.1057	0.0015						647.6	8.8			
57.1	150	85	0.57	10.9	0.000125	0.05	11.881	0.189	0.0582	0.0012	0.0841	0.0014						520.7	8.1			
58.1	145	191	1.31	13.2	0.000056	0.10	9.428	0.150	0.0621	0.0012	0.1060	0.0017						649.3	10.1			
59.1	999	555	0.56	50.9	—	0.13	16.864	0.199	0.0550	0.0005	0.0592	0.0007						370.9	4.3			
60.1	264	118	0.45	13.7	0.000057	0.03	16.516	0.269	0.0545	0.0011	0.0605	0.0010						378.8	6.1			
Age							±no std				±include std											
260.0							3.4				1.43				3.7							

Notes :

1. Uncertainties given at the one σ level.
 2. Error in FC1 Reference zircon calibration was 0.59% for the analytical session. (not included in above errors but required when comparing ²⁰⁶Pb/²³⁸U data from different mounts).
 3. f₂₀₆ % denotes the percentage of ²⁰⁶Pb that is common Pb.
 4. For areas older than ~800 Ma correction for common Pb made using the measured ²⁰⁴Pb/²⁰⁶Pb ratio.
 5. For areas younger than ~800 Ma correction for common Pb made using the measured ²³⁸U/²⁰⁶Pb and ²⁰⁷Pb/²⁰⁶Pb ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).
 6. For % disc, 0% denotes a concordant analysis.
- Pb* indicates radiogenic Pb.

Table 3
Summary of SHRIMP U–Pb zircon results for sample 96-36-4

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total ratios				Radiogenic ratios				ρ	Age (Ma)				% disc		
							²³⁸ U/ ²⁰⁶ Pb	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±		²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±		²⁰⁷ Pb/ ²⁰⁶ Pb	±
1.1	579	30	0.05	72.0	0.000164	0.28	6.911	0.091	0.0737	0.0007	0.1443	0.0019	1.420	0.033	0.0714	0.0014	0.573	869	11	969	39	10
2.1	91	80	0.87	23.0	–	<0.01	3.417	0.059	0.1005	0.0014	0.2934	0.0050	4.153	0.092	0.1027	0.0014	0.774	1659	29	1673	26	1
3.1	58	19	0.33	2.0	–	1.00	24.977	0.688	0.0592	0.0038	0.0396	0.0011						250.6	6.9			
4.1	66	40	0.61	9.9	–	<0.01	5.686	0.114	0.0738	0.0018	0.1763	0.0036	1.848	0.079	0.0760	0.0029	0.471	1047	20	1096	76	4
5.1	77	16	0.21	6.9	–	0.10	9.619	0.206	0.0617	0.0022	0.1039	0.0023						637.0	13.4			
6.1	412	331	0.80	32.9	–	<0.01	10.750	0.153	0.0590	0.0009	0.0930	0.0014						573.5	8.0			
7.1	249	176	0.71	19.9	0.000466	0.28	10.745	0.157	0.0614	0.0011	0.0928	0.0014						572.2	8.2			
8.1	295	164	0.56	21.8	0.000200	<0.01	11.604	0.178	0.0559	0.0010	0.0864	0.0014						534.3	8.0			
9.1	337	123	0.37	25.8	0.000150	0.06	11.232	0.155	0.0590	0.0010	0.0890	0.0013						549.5	7.4			
10.1	72	25	0.35	22.5	–	<0.01	2.741	0.051	0.1809	0.0021	0.3650	0.0067	9.128	0.200	0.1814	0.0021	0.844	2006	32	2665	19	25
11.1	101	58	0.58	6.7	–	<0.01	12.990	0.261	0.0548	0.0020	0.0772	0.0016						479.1	9.5			
12.1	482	409	0.85	32.1	–	0.07	12.893	0.169	0.0573	0.0008	0.0775	0.0010						481.2	6.2			
13.1	104	51	0.49	8.4	–	0.44	10.687	0.196	0.0628	0.0018	0.0932	0.0018						574.2	10.4			
14.1	473	117	0.25	33.4	–	<0.01	12.164	0.160	0.0564	0.0008	0.0823	0.0011						509.9	6.6			
15.1	180	77	0.43	28.4	0.000162	0.27	5.450	0.081	0.0762	0.0010	0.1841	0.0027	2.004	0.041	0.0790	0.0011	0.731	1089	16	1171	27	7
16.1	94	57	0.60	6.9	0.000394	0.16	11.650	0.239	0.0593	0.0021	0.0857	0.0018						530.1	10.7			
17.1	194	87	0.45	17.6	0.000048	<0.01	9.453	0.156	0.0599	0.0012	0.1060	0.0018						649.3	10.5			
18.1	177	138	0.78	15.6	0.000215	0.03	9.717	0.153	0.0610	0.0013	0.1029	0.0017						631.3	9.7			
19.1	339	122	0.36	17.0	0.000212	0.24	17.166	0.257	0.0558	0.0013	0.0581	0.0009						364.2	5.4			
20.1	206	123	0.60	14.5	–	0.19	12.211	0.185	0.0589	0.0014	0.0817	0.0013						506.5	7.5			
21.1	285	159	0.56	23.2	–	0.08	10.570	0.149	0.0601	0.0010	0.0945	0.0014						582.3	8.1			
22.1	137	69	0.51	11.2	–	0.31	10.500	0.173	0.0620	0.0015	0.0949	0.0016						584.7	9.4			
23.1	101	53	0.53	9.7	0.000100	7.07	8.901	0.159	0.1189	0.0149	0.1044	0.0030						640.2	17.5			
24.1	178	143	0.80	7.1	0.000081	<0.01	21.536	0.387	0.0487	0.0017	0.0466	0.0009						293.8	5.2			
25.1	45	1	0.01	3.4	–	0.23	11.289	0.313	0.0603	0.0027	0.0884	0.0025						545.9	14.9			
26.1	147	53	0.36	6.9	0.000074	<0.01	18.353	0.329	0.0523	0.0016	0.0546	0.0010						342.4	6.1			
27.1	765	277	0.36	35.3	0.000078	0.07	18.620	0.224	0.0538	0.0007	0.0537	0.0007						337.0	4.0			
28.1	114	94	0.83	8.9	0.000040	0.13	11.029	0.203	0.0598	0.0015	0.0906	0.0017						558.8	10.1			
29.1	287	81	0.28	21.8	0.000307	0.12	11.281	0.161	0.0594	0.0010	0.0885	0.0013						546.9	7.6			
30.1	255	140	0.55	11.6	0.000034	0.22	18.992	0.306	0.0548	0.0014	0.0525	0.0009						330.1	5.3			
31.1	209	155	0.74	16.8	0.000039	0.38	10.666	0.166	0.0624	0.0012	0.0934	0.0015						575.6	8.8			
32.1	111	76	0.68	7.7	0.000153	0.07	12.424	0.244	0.0578	0.0018	0.0804	0.0016						498.7	9.6			
33.1	343	163	0.48	26.6	0.001117	2.26	11.104	0.149	0.0768	0.0010	0.0880	0.0012						543.8	7.3			
34.1	72	61	0.85	2.8	0.000381	0.67	22.395	0.573	0.0573	0.0027	0.0444	0.0012						279.8	7.1			
35.1	90	46	0.52	6.9	0.000862	0.19	11.189	0.225	0.0601	0.0018	0.0892	0.0018						550.8	10.9			
36.1	96	72	0.75	6.6	–	<0.01	12.518	0.256	0.0570	0.0018	0.0799	0.0017						495.5	10.0			
37.1	209	122	0.58	17.4	0.000013	<0.01	10.314	0.180	0.0579	0.0011	0.0972	0.0017						597.9	10.2			
38.1	361	284	0.79	25.6	0.001273	2.12	12.121	0.164	0.0744	0.0011	0.0808	0.0011						500.6	6.8			
39.1	405	207	0.51	48.0	0.000033	0.06	7.257	0.093	0.0693	0.0008	0.1377	0.0018	1.307	0.023	0.0688	0.0008	0.723	832	10	894	25	7
40.1	355	106	0.30	33.7	–	0.06	9.057	0.119	0.0625	0.0008	0.1103	0.0015						674.7	8.6			
42.1	196	75	0.39	12.7	–	0.29	13.225	0.216	0.0588	0.0014	0.0754	0.0013						468.6	7.5			
43.1	61	22	0.36	24.0	0.000061	0.09	2.178	0.045	0.1747	0.0019	0.4586	0.0095	11.002	0.278	0.1740	0.0025	0.821	2434	42	2596	24	6
44.1	323	161	0.50	31.9	0.000128	0.87	8.699	0.118	0.0698	0.0009	0.1139	0.0016						695.6	9.3			
45.1	323	130	0.40	34.2	0.000189	0.20	8.097	0.111	0.0659	0.0009	0.1233	0.0017						749.3	10.0			

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Table 3 (continued)

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Total ratios				Radiogenic ratios				ρ	Age (Ma)				% disc		
							²³⁸ U/ ²⁰⁶ Pb	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±		²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±		²⁰⁷ Pb/ ²⁰⁶ Pb	±
46.1	282	274	0.97	23.4	0.000215	0.30	10.332	0.154	0.0622	0.0011	0.0965	0.0015					593.9	8.6				
47.1	566	196	0.35	41.1	0.000049	0.12	11.822	0.150	0.0588	0.0008	0.0845	0.0011					522.9	6.5				
48.1	32	18	0.55	2.6	–	1.10	10.497	0.358	0.0684	0.0035	0.0942	0.0033					580.4	19.5				
49.1	104	61	0.59	8.5	–	0.29	10.516	0.226	0.0619	0.0019	0.0948	0.0021					583.9	12.3				
50.1	508	46	0.09	78.3	0.000085	0.14	5.572	0.071	0.0756	0.0007	0.1793	0.0023	1.852	0.029	0.0749	0.0007	0.804	1063	13	1066	19	0
51.1	76	36	0.48	41.3	0.000124	0.16	1.582	0.032	0.2360	0.0021	0.6335	0.0130	20.747	0.462	0.2375	0.0021	0.920	3163	54	3103	14	-2
52.1	318	119	0.37	24.7	–	0.28	11.054	0.183	0.0610	0.0011	0.0902	0.0015					556.8	9.0				
53.1	170	50	0.30	11.2	0.000451	0.40	13.035	0.244	0.0598	0.0016	0.0764	0.0015					474.7	8.7				
54.1	325	93	0.29	26.6	0.000228	0.04	10.471	0.155	0.0599	0.0011	0.0955	0.0014					587.8	8.5				
55.1	506	320	0.63	16.9	–	0.25	25.740	0.391	0.0531	0.0013	0.0388	0.0006					245.1	3.7				
56.1	322	271	0.84	28.6	0.000311	0.11	9.670	0.145	0.0618	0.0011	0.1033	0.0016					633.7	9.3				
57.1	372	105	0.28	145.7	–	<0.01	2.192	0.029	0.1722	0.0009	0.4565	0.0061	10.865	0.156	0.1726	0.0009	0.927	2424	27	2583	9	6
58.1	37	13	0.36	3.4	0.000341	<0.01	9.430	0.328	0.0605	0.0032	0.1062	0.0038					650.4	22.1				
59.1	195	69	0.36	15.7	–	0.27	10.638	0.194	0.0615	0.0015	0.0937	0.0018					577.7	10.3				
60.1	37	43	1.17	5.1	0.000498	0.86	6.241	0.208	0.0713	0.0029	0.1612	0.0054	1.703	0.086	0.0766	0.0029	0.660	964	37	1111	76	13
							Age			±no std				±include std								
Younger group							546.2			5.8		1.34		7.3								
Older group							581.7			5.3		1.09		6.3								

Notes :

1. Uncertainties given at the one σ level.
 2. Error in FC1 Reference zircon calibration was 0.59% for the analytical session. (not included in above errors but required when comparing ²⁰⁶Pb/²³⁸U data from different mounts).
 3. f₂₀₆ % denotes the percentage of ²⁰⁶Pb that is common Pb.
 4. For areas older than ~800 Ma correction for common Pb made using the measured ²⁰⁴Pb/²⁰⁶Pb ratio.
 5. For areas younger than ~800 Ma correction for common Pb made using the measured ²³⁸U/²⁰⁶Pb and ²⁰⁷Pb/²⁰⁶Pb ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).
 6. For % disc, 0% denotes a concordant analysis.
- Pb* indicates radiogenic Pb.

but shows only laumontite grade metamorphism. Although the Buckley-Fremouw contact has long been considered the Permo-Triassic boundary (Collinson et al., 1994; Retallack et al., 1998; Krull and Retallack, 2000), in the Shackleton Glacier region it is now known to lie within the lowest part of the Fremouw Formation in a 7–10 m interval 35–45 m above the Buckley-Fremouw contact, above the last occurrence of *Glossopteris* and below the first Triassic vertebrates (Collinson et al., 2006).

4. Methods

Detrital zircon grains were separated from three middle Victoria Group sandstone samples using standard crushing, washing, heavy liquid (Sp. Gr. 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 reference zircons (FC1 and SL13), sectioned approximately in half, and polished. Reflected and transmitted light photomicrographs were prepared for all zircons, as were cathodoluminescence (CL) and Scanning Electron Microscope (SEM) images. The CL images were used to decipher the internal structures of the sectioned grains and to ensure that the ~30 μm SHRIMP spot was wholly within a single age component (usually the youngest).

The U–Th–Pb analyses were made using SHRIMP I at the Research School of Earth Sciences, Australian National University, Canberra, Australia. For each sample, zircons on the mount were analyzed sequentially and randomly until a total of at least 60 grains for each sample was reached (Vermeesch, 2004). Each analysis consists of 4 scans through the mass range, with the FC1 reference zircon analyzed for every five unknown zircon analyses; SHRIMP analytical methods follow Williams (1998) (and the references therein). The data have been reduced using the SQUID Excel Macro of Ludwig (2001). U/Pb ratios have been normalized relative to a value of 0.01859 for the FC1 reference zircon, equivalent to an age of 1099 Ma (see Paces and Miller, 1993). Uncertainties given for individual analyses (ratios and ages) are at the one sigma level (Tables 1, 2 and 3). Tera and Wasserburg (1972) concordia plots, probability density plots with stacked histograms and weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age calculations were carried out using ISOPLOT/EX (Ludwig, 2003). The “Mixture Modeling” algorithm of Sambridge and Compston (1994), via ISOPLOT/EX, was used to un-mix statistical age populations or groupings; from these groups weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages were calculated and the uncertainties are reported as 95% confidence limits.

5. Results

Sample 35-2 (ca. 70 m below the Buckley-Fremouw contact). The zircons from this sample are notably euhedral, or fragments of euhedral, doubly terminated grains with simple oscillatory-zoned internal structure when viewed by CL (Fig. 5a). Only two grains show significant external rounding (grains 9 and 20) and these provide the only two older ages at ca. 1185 Ma and ca. 685 Ma respectively (Table 1). Note that from the CL images these also are considered to be zoned igneous zircon. The

relative probability plot shows almost exclusively late Permian zircons (Fig. 6), with the principal peak at 267 ± 3 Ma and a subsidiary peak at 249 ± 3 Ma. Four grains with $^{206}\text{Pb}/^{238}\text{U}$ ages less than 240 Ma do not form a coherent peak and are interpreted to be analyses of areas within grains that have lost radiogenic Pb. The subordinate peak at ca. 250 Ma is within uncertainty of the Permian–Triassic boundary (252.6 ± 0.2 Ma; Mundil et al., 2004), but those grains also may have suffered radiogenic Pb

Fig. 5. Representative cathodoluminescence (CL) images for zircons analyzed from samples: a. 96-35-2; b. 96-36-1; c. 96-36-4. Note: areas analyzed are labeled with spot analysis numbers as in Tables 1, 2 and 3.

Fig. 6. U–Pb zircon age probability plot for sample 35-2, Layman Peak.

loss. The dominant 267 ± 3 Ma peak documents an abundance of grains from a magmatic source with essentially no dilution, during transport, from any sources with zircons of widely different ages. It should be noted that this sample and sample 36-1 are from the Buckley Formation which is characterized by the Permian plant fossil *Glossopteris*; Triassic ages cannot be given significance without further study.

Sample 36-1 (3 m below the Buckley-Fremouw contact). The zircons from this sample are equant to elongate grains that in general are subrounded to euhedral, or fragments of such grains. The CL images show a high proportion of zoned igneous zircon (Fig. 5b). Eleven of the 60 grains analyzed are considered to have metamorphic affinities (that is, homogeneous unzoned CL features) and these are not restricted solely to the older age components. The predominant population of grains is late Permian in age with a probability peak at 260 ± 3.4 Ma and a subordinate younger grouping at about 245 Ma (Fig. 7; Table 2). It is probable that radiogenic Pb loss has affected the younger grains comprising this weak shoulder on the dominant peak. With respect to the remainder of the detrital age spectrum, there

Fig. 7. U–Pb zircon age probability plot for sample 36-1, Collinson Ridge.

Fig. 8. U–Pb zircon age probability plot for sample 36-4, Collinson Ridge.

is an addition of late Devonian age grains with a peak at 370 Ma, and of early Cambrian Ross age or late Pan African age (540–510 Ma) and Neoproterozoic early Pan-African age (≈ 640 Ma) grains.

Sample 36-4 (45 m above the Buckley-Fremouw contact). The zircons from this sample similarly are equant to elongate grains but in general are subrounded in shape, or fragments of such grains. Euhedral grain shapes are not common in this sample. Twenty four of the 60 grains analyzed have homogeneous internal structure, and are considered to be of a metamorphic provenance as determined from the CL images; the remainder are zoned igneous zircon (Fig. 5c). The metamorphic grains are spread throughout the total population, though they are more common among the Cambrian and older zircons. The age population is dominated by early Ordovician to Cambrian and by Neoproterozoic zircon grains, with four separate peaks (Fig. 8; Table 3). The 460–510 Ma group may reflect erosion of post-tectonic Ross granitoids. The 530–560 Ma group is consistent with erosion of pre-tectonic Ross granitoids or Pan African age rocks. The 570–600 Ma group forms a late Neoproterozoic source, which together with the ≈ 640 Ma group comprise a Pan-African/East African Orogen age assemblage. There is also a small component of Carboniferous and Archean grains, and a scattering of poorly defined younger grains.

6. Discussion

The Permo-Triassic Gondwanide fold belt (Fig. 9), exemplified by the Cape Fold Belt in South Africa (e.g. Hälbig, 1992), is recorded in strong deformation of Permian and older strata in the displaced Ellsworth-Whitmore Mountains block (Curtis and Storey, 1996) and in gently deformed Permian strata at the distal margin of the belt in the Pensacola Mountains (Ford, 1972). Continuation of the foreland fold and thrust belt into the Ross Sea sector has been inferred and has been regarded as the cause of the major paleocurrent reversal in the Permo-Triassic Victoria Group strata (Barrett et al., 1986; Collinson et al., 1994).

Fig. 9. Gondwana reconstruction for the Antarctic sector, showing the inferred locations of orogenic belts, generalized distribution of dated plutonic rocks and orthogneisses, inferred extent of the Beacon Supergroup sedimentary basins, and the inferred Gondwana orogen structural front. All reconstructions have problems reconciling the geology, continental blocks, and space issues; this is exemplified by Tasmania which, in terms of its geology, should lie along the boundary between the Early and mid Paleozoic orogenic belts. CHP: Challenger Plateau, Lord Howe Rise, and New Zealand Paleozoic and older basement rocks; CP: Campbell Plateau, Chatham Rise, and New Zealand Paleozoic margin strata. Reconstruction modified from Fig. 1 of Elliot and Fleming (2004).

Paleocurrent indicators for the Victoria Group strata in the Shackleton Glacier region show detrital grain derivation from the West Antarctica flank of the foreland basin (Collinson et al.,

1994). The flood plain sequences reflect progradation, from mid Permian time onward, of alluvial settings from the arc flank into the basin, and a concomitant cratonward shift of the main axial drainage (Isbell et al., 1997).

The Permian zircons are igneous in origin and directly record a late Permian magmatic arc. The Devonian zircons, also igneous in origin, suggest derivation from Ford Granodiorite plutons in MBL and/or from an uncertain extension of that belt eastward toward the Antarctic Peninsula. Shifting source regions, reflecting tectonism and evolving paleodrainage systems, and/or deeper erosion down through the rising magmatic arc or its foreland probably account for the influx of Devonian zircons and the minor occurrence of Carboniferous grains.

More problematic is the presence of a major influx of Neoproterozoic and Cambrian zircon grains in the lowest Triassic sandstone (sample 36-4). In Permian and Early to Middle Triassic time, the foreland basin was separated from the intracratonic basins in Victoria Land by the Ross High located in the Darwin Glacier-Byrd Glacier region (Collinson et al., 1994). Thicknesses (>1,000 m) of Permian strata in the foreland basin suggest original continuation of the basin out onto the craton, although now eroded or hidden beneath the polar ice sheet, and also continuation of the basin toward the active margin in what is now West Antarctica. Permian foreland basin strata, and also the intracratonic basin strata of SVL, cover Devonian beds and the pre-Devonian basement; it is only north of the Dry Valley region of SVL that basement was exposed in late Permian through late Triassic time. Therefore, given detrital grain derivation from the magmatic arc flank, the pre-Devonian basement of the TAM could not have formed the immediate source for these late Proterozoic and Cambrian zircons. There is a single orthogneiss outcrop of possible Cambrian age in eastern MBL (Pankhurst et al., 1998), which suggests other gneiss and granitoid outcrops of that age might be present in the Ross Province, but no Proterozoic outcrops are known. However, detrital zircons from the Ordovician Swanson Group in MBL have an age population peak at 500–600 Ma and a subsidiary older peak at 800–1000 Ma (Pankhurst et al., 1998). Although the lowest Triassic sandstone sample lacks any significant number of grains in the 800–1000 Ma age range, if the Swanson Formation originally had extended farther east, it could have been a contributory source for the Cambrian and latest Neoproterozoic grains.

Ross age granites occur along the inner flank of the TAM and may well be present farther inboard as well as in West Antarctica, the direction of younging of that plutonic belt (Goodge et al., 2004a). Devonian sandstones formed a shallow epicontinental sequence deposited along the length of the TAM

Fig. 10. Schematic cross-section through the central Transantarctic Mountains for the late Permian to earliest Triassic, showing the Beacon foreland (Middle Permian to Late Triassic) and older (Devonian and intracratonic Early Permian) basins with respect to the inferred fold and thrust belt and magmatic arc of the Gondwana active margin.

but extending into West Antarctica (Bradshaw and Webers, 1988). The source terrain for the Devonian quartzose sandstones was the stable craton, and possibly Neoproterozoic and Cambro-Ordovician rocks involved in the Ross orogen. A Devonian Junction Sandstone sample in the Darwin Glacier region has yielded detrital zircons with the principal population peak dominated by 450–600 Ma grains, and minor peaks at 1.0–1.2 Ga, 1.4–1.7 Ga and 2.7 Ga (Wysoczanski et al., 1997, 2003). Further, assuming open connections in the Devonian epicontinental sea outboard of the TAM, zircons might also have been derived from more distal sources; this applies in particular to the Pan-African age zircons for which the nearest known source would have been near the head of the Weddell Sea (Fitzsimons, 2000, 2003) in the Shackleton Range where the East African Orogen appears to terminate. Lower Buckley and older Permian beds, deposited on the Devonian strata, also had non-volcanic sources (Collinson et al., 1994). Therefore the principal source for the late Proterozoic and Cambrian zircons is interpreted to have been Devonian and lower Permian strata and/or Swanson Group rocks, all exposed in the inferred extension of the Permo-Triassic Gondwanide fold and thrust belt (Fig. 10). The possibility of other, but no longer exposed, Lower Paleozoic and older sources in West Antarctica cannot be excluded. The younger populations indicate continuing erosion of mid Paleozoic plutonic rocks.

The appearance of these Cambrian and Neoproterozoic zircon populations in uppermost Permian and lowermost Triassic beds may mark the first record of erosion of the inferred thrust belt in this part of the Gondwanide orogen, although the onset of thrusting may well have been earlier in the Permian. In the Pensacola Mountains, Gondwana deformation can be dated only as post-Gale Mudstone tillites (Ford, 1972), and in the Ellsworth Mountains as post-Polarstar Formation or post-Middle Permian/earliest Late Permian (Collinson et al., 1994).

These zircon data suggest the need for revision of earlier interpretations (Barrett et al., 1986; Collinson et al., 1994) of Victoria Group quartzose sandstones as reflecting input primarily from a cratonic provenance into the foreland basin. Lower Buckley and older strata probably have a direct cratonic provenance but thereafter input from the active margin may have overwhelmed the sand provenance of the axial river system that flowed parallel to the range but received sediment from both the margin and craton. Further, sources of varying ages were being eroded in the active margin terrain, not just the contemporaneous Permo-Triassic magmatic arc.

7. Conclusions

Detrital zircons in the upper Buckley Formation and lower Fremouw Formation indicate several different source terrains within the Antarctic sector of the Permo-Triassic active margin of the Gondwana plate. The active magmatic arc was the principal provenance for the zircons in the Buckley volcanoclastic sandstones. The older mid Paleozoic magmatic arc granitoids contributed Devonian and Carboniferous detrital zircons as a result of unroofing of that arc and/or changes in paleo-drainage

systems. It is inferred that active tectonism in the Gondwanide orogen exposed Devonian and Lower Permian strata and Ordovician rocks, which led to recycling of Neoproterozoic and Cambrian zircons into the Victoria Group foreland basin in latest Permian to early Triassic time. This study suggests an examination of the complete Beacon Supergroup sequence in CTM will shed light on sediment provenance and tectonic evolution of the Permo-Triassic foreland basin.

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