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A North American provenance for Neoproterozoic to Cambrian sandstones in Tasmania?

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Abstract

Tasmania forms an enigmatic province within the Neoproterozoic to Cambrian history of Australia. It lies at the boundary between Australia and North America in most Rodinia reconstructions but no reliable lithostratigraphic correlations have been reported with either mainland Australia or North America. We used detrital zircon age spectra, measured by LAM-ICP-MS, of Neoproterozoic and Cambrian sandstones in Tasmania to search for evidence of correlations with these two continental blocks during the time slice critical to Rodinia breakup. The Tasmanian sandstones are dominated by 1600–1900 Ma and 1200–1500 Ma age zircons. There is little evidence for Grenville (∼1100 Ma) and Ross (∼550 Ma) Orogen sources in these sandstones, in contrast to detrital zircon age spectra of similar age rocks in South Australia. The detrital zircon age spectra of Tasmanian sandstones are different from age spectra reported from British Columbia. They are very similar to age spectra reported from Cambrian sandstones of Nevada, supporting Rodinia reconstructions that place southwestern USA near to Tasmania in the Neoproterozoic.

Keywords: zircon; age; Rodinia; tectonics; Tasmania Australia

1. Introduction

Reconstructions of Rodinia place western North America against the southeastern margin of Australia in the Neoproterozoic. In these reconstructions, Tasmania lies within the rift zone between Australia and North America at breakup, suggesting that there may be correlations between Tasmania and North America. However, a long-standing problem in the Neoproterozoic to Devonian history of Australia is the relationship between Tasmania and mainland Australia [1–5]. To resolve the role of Tasmania in continental reconstructions (global tectonic setting) [6–8] and regional tectonic settings [9,10], we need to place further constraints on its origin.

The detrital zircon age spectra of individual sandstone beds are not a complete record of all the rocks within a region. Individual beds may be derived from nearby or from distant sources. Detrital zircons can be recycled many times. In most

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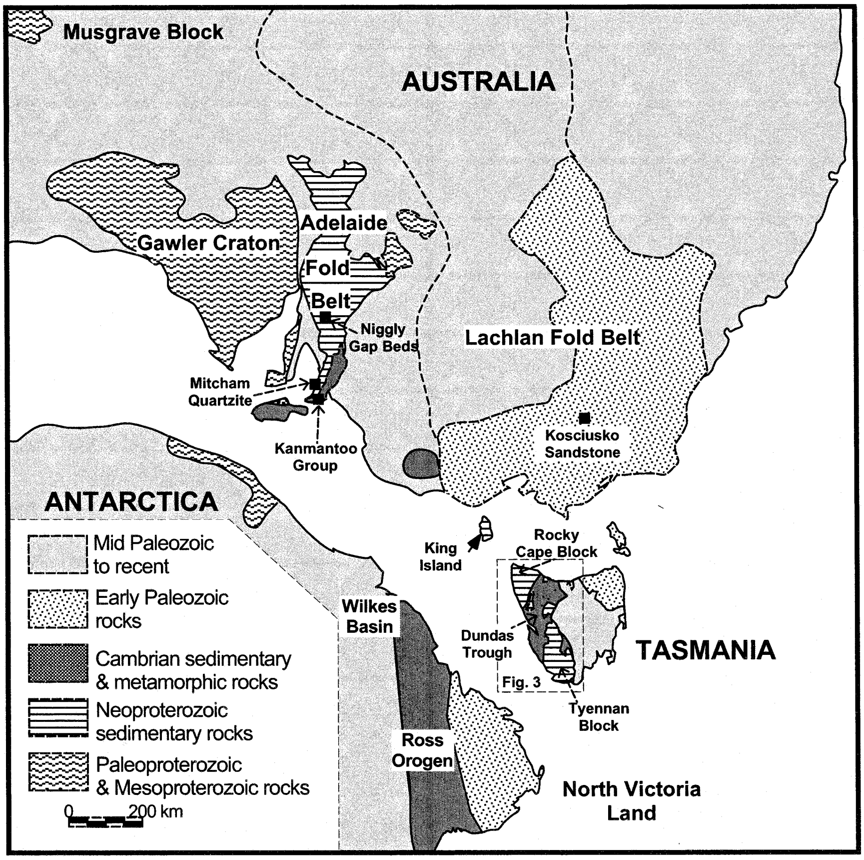

Fig. 1. Jurassic reconstruction of Australia, Antarctica and Tasmania showing fold belt boundaries. Reconstruction from [32]. Geological boundaries from [1,11,33]. Locations of zircon samples from mainland Australia are shown.

cases, there is no direct evidence for the transport path and no unique source region can be determined. However, the data included here and in other studies [11,12] suggest that the sandstones are well mixed and multiple sandstone samples from the same unit show similar age spectra. The age spectra are a reproducible signature for a basin at the time of deposition. We assume here that only a few samples are required to detect zircons from most of the sources of sediment entering a basin.

The aim of this paper is to use detrital zircon age spectra as a test for the relationships between Tasmania, mainland Australia and North America during the Neoproterozoic and early Paleozoic. The age spectra are discussed in terms of four applications ranging from the local correlation to continental reconstructions. Firstly the new zircon detrital age spectra are compared against previously reported age spectra from Tasmania to determine what changes in sandstone provenance occurred during the period 800–500 Ma in Tasmania. The complete Tasmanian data set is then used for subsequent comparisons.

The second application tests correlations between Tasmania and the evolving southeastern margin of mainland Australia. Of particular interest to this paper is the evolution of the Neoproterozoic to early Paleozoic cover in South Australia (Fig. 1) (Adelaide Fold Belt). Gondwanaland reconstructions mostly show the Early Paleozoic Delamerian Orogen extending from the Adelaide Fold Belt, west of Tasmania and continuous with the Ross Orogen in Antarctica. In these reconstructions Tasmania is often completely omitted [1] or treated as an exotic terrane [2,3]. However,

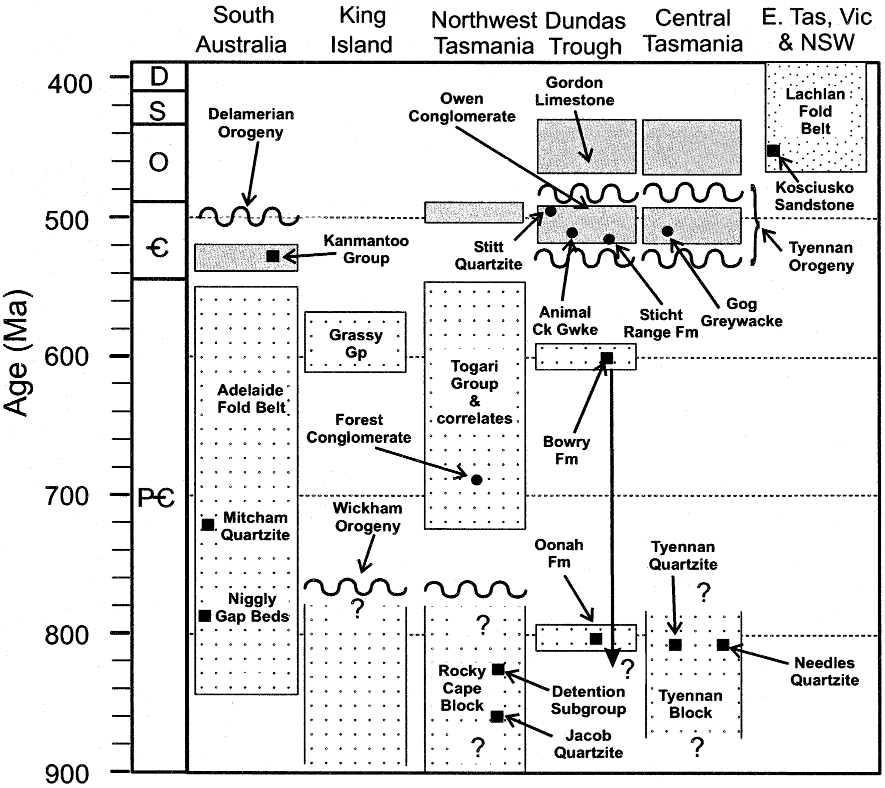

Fig. 2. Space–time diagram showing significant episodes of orogenesis and sedimentary deposition in southeastern Australia. Adapted from [4,34]. The stratigraphic position of zircon samples discussed is shown.

stratigraphic correlations [4] and paleomagnetic data [5] suggest Tasmania was attached to mainland Australia during the Neoproterozoic and again in the Late Cambrian. The zircon age spectra reported here are compared with spectra from the equivalent age sandstones in the Adelaide Fold Belt to demonstrate differences in the evolving pattern of provenance between these areas.

In the third application, we test the interpretation that Tasmania was a source for the Ordovician turbidites in the Lachlan Fold Belt [9]. Coney et al. [10] argued for the Kanmantoo Group as a source for these sedimentary rocks. More recently, detrital zircon age patterns have been used [11,12] to suggest that the sandstones in the Lachlan Fold Belt were derived from the Ross Orogen/Wilkes Basin region, Antarctica (Fig. 1), rather than in Tasmania or cratonic Australia. The zircon data from the Cambrian of Tasmania are used to further test the significance of Tasmania as a source region for the Ordovician sandstones of the Lachlan Fold Belt.

The fourth application considers possible correlations with western North America. In the SWEAT reconstruction [6], Tasmania occupies a key position close to Laurentia. We use the zircon age spectra from Tasmania to look for evidence that supports this and/or other Rodinia reconstructions based on comparison with published data from western North America.

1.1. Geology

The depositional history of pre-Ordovician Tasmania can be divided into three time slices: early Neoproterozoic (ENeoP), between 760 and 1200 Ma, late Neoproterozoic (LNeoP) between 550 and 760 Ma, and Middle to Late Cambrian [4,13]. Each of these sequences is separated by an unconformity (Fig. 2).

The ENeoP sequences were folded before deposition of the LNeoP. This folding is most commonly correlated with the 760 Ma Wickham Orogeny defined on King Island. No events of this age are known from anywhere else in southeastern Australia or New Zealand. This lack of correlation has been used to argue that Tasmania was exotic to the Australian craton [3] with suturing occurring either in the Cambrian or in the Devonian. The ENeoP sandstones contain detrital zircons, which are predominantly 1700–1800 Ma [14]. The Gawler Craton, in South Australia, is a potential source region for zircons of this age but few zircons derived from the Gawler Range Volcanics (1600 Ma) are represented in the zircon age spectra from ENeoP sandstones of Tasmania. Black et al. [14] also identified a significant component of 1400 Ma zircons in the Tasmanian sandstones but were unable to identify a source for these grains. Burrett and Berry [15] suggested the source for the 1700–1800 Ma and 1400 Ma zircons was Mexico, based on their Proterozoic reconstruction of Laurentia and Australia.

Tasmanian LNeoP geology is dominated by continental rifting. An early shallow water sequence is followed by a broad zone of tholeiitic volcanism with a nominal age of 700–550 Ma [4,16]. Calver and Walter [4] argued for a direct stratigraphic correlation between parts of the LNeoP succession and the Adelaidean stratigraphy in South Australia. The LNeoP basalts probably reflect the rifting of North America from eastern Australia associated with the breakup of Rodinia [4]. A sample of sandstone from the Forest Conglomerate at the base of this sequence (Togari Group) is included in this study.

The Cambrian in Tasmania is dominated by a Middle Cambrian rift phase with active syn-orogenic deposition and major post-collisional volcanism [16]. Seven samples from four Middle Cambrian formations were collected from western and northern Tasmania (Fig. 3). New detrital zircon age spectra are reported from these samples and compared with previously reported zircon spectra from ENeoP samples [14,17]. The analyses reported here cover a similar age range to those reported from the Adelaidean metasediments and Kanmantoo Group [11].

2. Samples, analytical techniques and methodology of comparison

Eight samples of sandstone were crushed using a mortar and pestle. The fine sand fraction (63–125 μm) was sieved, washed, separated using heavy liquids and hand picked to extract zircons. The Cambrian sandstones are partly derived from coeval Cambrian volcanics which contain 500 ± 5 Ma zircons [18]. These first cycle euhedral zircons, which form 20% of zircon grains in these separates, were excluded from the final zircon concentrates.

Between 20 and 50 grains per sample were selected for laser ablation microprobe-inductively coupled plasma-mass spectrometry (LAM-ICP-MS) U–Pb geochronology. The zircon grains were mounted in epoxy on 2.5 cm diameter circular grain mounts and polished until a portion of each grain not less than 60 μm in diameter was exposed. Grain mounts containing the samples and the standards ('02123' zircon standard and NIST SRM 612 glass) were cleaned in 2 N nitric acid for approximately 1 h prior to analysis.

LAM-ICP-MS analyses were made of the zircon cores, using the system configuration and methodology described in Suarez et al. [19] and Ketchum et al. [20]. All data were collected as time-resolved spectra and changes in $^{207}Pb/^{206}Pb$ ratio were monitored. Only three grains from one sample showed evidence of zoning. Fractured grains (along which common Pb is commonly found) were rare. Elemental fractionation of U relative to Pb occurs during ablation [19,20]. Fractionation was a particular problem in this study due to the small grain size, which necessitated rapid ablation. Data were obtained for $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$ and $^{208}Pb/^{232}Th$, but these ratios were only used to estimate discordance (real or analytical) and to identify grains with high common Pb. Most of the grains (80%) reported in this study were concordant to within the 2σ measurement error. $^{206}Pb/^{238}U$ ages are included in Table 1 as an indication of discordance, but all subsequent discussion in this paper refers only to $^{207}Pb/^{206}Pb$ ages.

All analyses are corrected for the blank, and the error taken into account. Useful data could

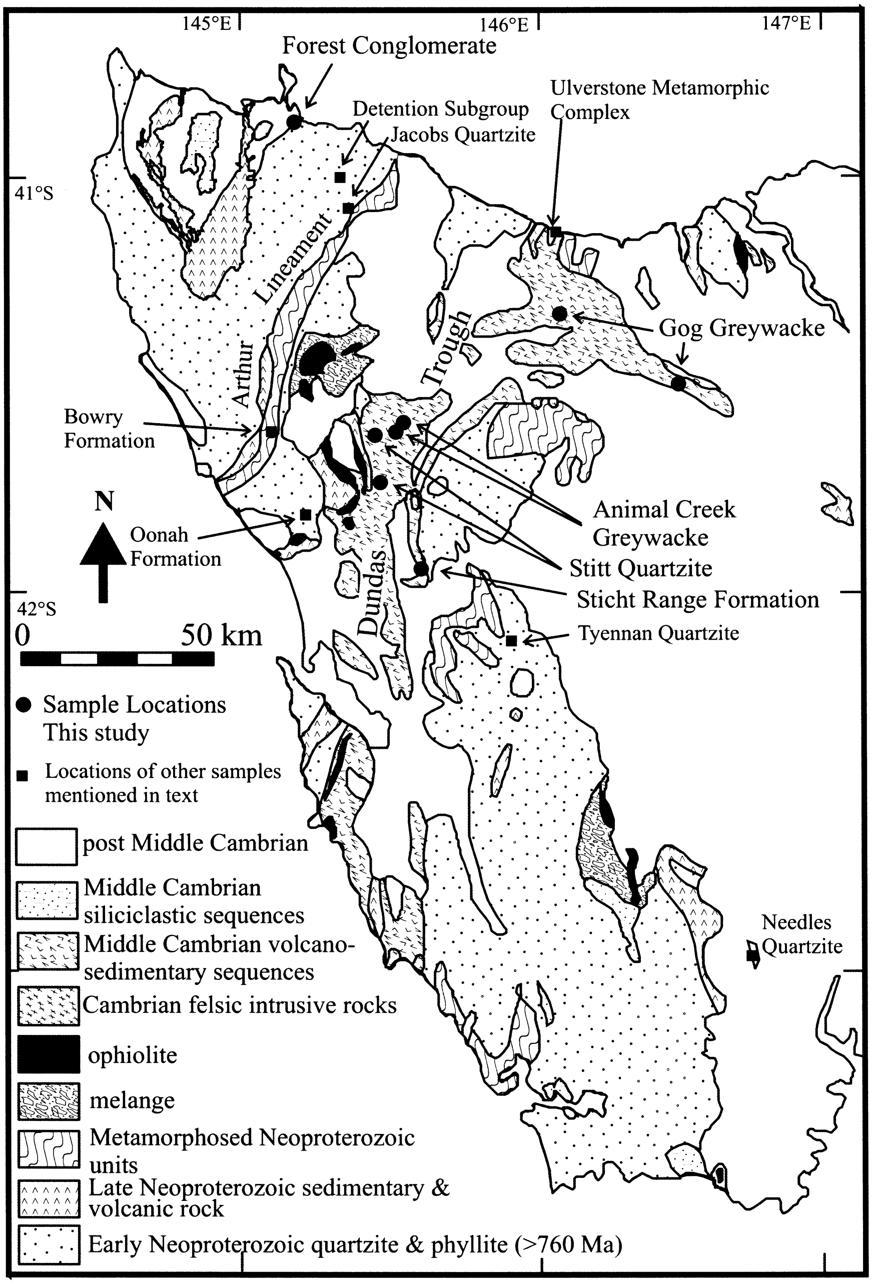

Fig. 3. Geology map of Tasmania showing location of sandstone samples reported in this paper and of other sandstones in Tasmania for which zircon age spectra have previously been reported. Geology simplified from [35].

not be acquired for ^{204}Pb due to the isobaric interference from Hg, a significant contaminant in the Ar supply gas. However, most zircons do not contain significant common Pb. For example, in detrital zircon ages from Proterozoic sandstones in southern Norway [21], 70% of grains had a $^{204}Pb/^{206}Pb$ ratio below 0.0002. This level of contamination ($^{204}Pb/^{206}Pb = 0.0002$) increases the

Table 1
$^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ radiometric age dates determined by LAM-ICP-MS analyses of individual zircon grains extracted from Tasmanian sandstones

$^{206}Pb/^{238}U$ age		$^{207}Pb/^{206}Pb$ age		$^{206}Pb/^{238}U$ age		$^{207}Pb/^{206}Pb$ age		$^{206}Pb/^{238}U$ age		$^{207}Pb/^{206}Pb$ age	
Gog Greywacke				**Sticht Range Fm.**				**Animal Creek Greywacke** (cont'd.)			
Sample:	134329	$_{4}$29800E	$_{54}$21700N	Sample:	134362	$_{3}$88700E	$_{53}$54000N	Sample:	130598	$_{3}$84400E	$_{53}$89700N
Age (Ma)	2σ error	Age (Ma)	2σ error	Age (Ma)	2σ error	Age (Ma)	2σ error	Age (Ma)	2σ error	Age (Ma)	2σ error
977	15	1008	110	1658	25	1440	66	536	9	718	82
915	10	1160	72	1233	28	1510	76	1259	15	1144	112
1071	37	1272	72	1339	8	1540	56	1170	20	1220	60
1186	37	1284	40	1488	28	1620	64	1193	19	1244	52
1190	19	1456	44	1298	38	1650	80	1437	26	1324	72
931	19	1496	106	1656	15	1690	72	1368	22	1334	36
1598	64	1740	38	1365	35	1692	96	1514	23	1528	46
1447	22	1796	48	1706	14	1716	50	1675	24	1694	30
1767	50	1818	42	1710	37	1720	18	1773	22	1742	34
1569	37	1826	44	1430	16	1722	42	1555	20	1772	38
2282	53	2480	32	1496	34	1740	52	2163	36	2738	50
Sample:	134308	$_{4}$64000E	$_{54}$00500N	1530	35	1744	58	2561	43	2740	34
Age (Ma)	2σ error	Age (Ma)	2σ error	1196	48	1746	110				
1393	15	1410	44	1582	35	1758	52	**Forest Conglomerate**			
1375	19	1446	46	1640	27	1760	60	Sample:	134314	$_{3}$57300E	$_{54}$76700N
1318	21	1600	48	1658	18	1770	34	Age (Ma)	2σ error	Age (Ma)	2σ error
1375	30	1646	74	1647	13	1776	46	734	40	1386	126
1521	21	1686	36	1507	35	1784	110	1274	78	1438	188
1372	26	1694	46	1674	18	1786	34	1310	72	1558	150
1638	18	1768	22	1773	24	1788	80	1173	51	1574	286
1607	13	1796	26	1535	27	1794	132	1260	14	1596	40
1308	15	1796	32	1473	23	1796	44	746	65	1606	78
1482	27	1902	30	1642	22	1828	46	1514	51	1614	250
1975	29	2526	20	1620	19	1834	64	1405	39	1650	88
				1535	16	1838	40	1540	54	1658	234
Stitt Quartzite				1791	25	1862	42	1062	15	1664	80
Sample	130628	$_{3}$77250E	$_{53}$75300N	1505	40	1880	42	1258	36	1664	118
Age (Ma)	2σ error	Age (Ma)	2σ error	1653	40	1888	70	1397	90	1670	92
1308	25	1356	92	1741	32	1890	52	1160	47	1680	130
1249	17	1452	74	1571	16	1896	54	1359	23	1686	72
1370	19	1472	84	1726	70	1904	86	1445	39	1688	70
1379	22	1552	50	1742	40	1904	136	1432	40	1688	88
1312	28	1560	42	2216	91	1938	66	1063	36	1694	30
1312	16	1582	68	1015	23	1944	54	1328	74	1700	192
1393	29	1624	74	1594	39	1976	74	1269	36	1700	100
1369	27	1650	64	1241	87	1984	52	1152	29	1702	80
1560	24	1668	56					1279	21	1702	108

Table 1 (*continued*)

$^{206}Pb/^{238}U$ age		$^{207}Pb/^{206}Pb$ age		$^{206}Pb/^{238}U$ age		$^{207}Pb/^{206}Pb$ age		$^{206}Pb/^{238}U$ age		$^{207}Pb/^{206}Pb$ age	
1613	37	1694	98	**Animal Creek Greywacke**				1123	69	1704	90
1521	20	1716	82	Sample:	130600	$_{3}$85300E	$_{53}$90300N	1437	17	1706	114
1561	34	1734	46	Age (Ma)	2σ error	Age (Ma)	2σ error	1316	48	1722	108
1568	42	1780	58	463	8	578	120	1579	45	1740	126
1653	19	1818	28	947	28	1242	38	1244	29	1756	82
1617	50	1858	98	999	51	1324	216	1478	12	1766	72
2143	11	1860	56	1138	52	1500	70	997	73	1772	88
1643	23	1878	22	682	54	1524	216	843	29	1772	80
1536	32	1938	112	1404	36	1670	154	1654	48	1780	216
1816	21	1956	52	1691	25	1676	66	1608	90	1780	136
1697	31	2010	76	1540	35	1696	100	1557	17	1782	48
1948	18	2220	28	950	211	1724	40	1972	110	1786	28
2117	28	2498	48	1790	115	1770	12	1879	100	1818	144
Sample:	130590	$_{3}$76800E	$_{53}$84600N	1555	29	1782	52	1560	32	1828	50
Age (Ma)	2σ error	Age (Ma)	2σ error	1386	49	1796	52	1054	59	1860	42
1182	44	1340	280	1212	43	1832	48	1349	60	1876	178
1251	36	1488	52	1131	27	1842	64	1206	51	1902	128
1416	33	1744	70	1855	16	1854	68	1362	48	1924	128
1413	38	1780	94	1500	39	1890	144	1114	34	2042	262
1991	148	1858	44	1396	38	1900	148	2238	13	2456	26
1266	131	1972	142	1516	27	2486	24	2183	19	2484	14
2168	167	2022	124	2245	61	3020	18				
2404	92	2904	74								

The 2σ errors listed are based on counting statistics.

$^{207}Pb/^{206}Pb$ apparent age by 30 million years for a zircon in the range 1600–1800 Ma. Thus, zircon age spectra based on $^{207}Pb/^{206}Pb$ ages without common Pb correction will include a tail towards high ages. However, 70% of grains will have apparent ages within 30 Ma of the 'correct age'. This is about the same as the 1σ error in our analyses. $^{208}Pb/^{232}Th$ ages are especially susceptible to common Pb contamination, and this is the basis for the '208 method' of common Pb correction [22]. We deleted 6% of measurements from our data set on the basis that these grains have an anomalously high relative $^{208}Pb/^{232}Th$ age and therefore have a high common Pb component.

The effect of Pb loss in zircons is to broaden the peaks in the age spectra with tailing to younger ages [11]. Using the LAM-ICP-MS method, Pb loss at intermediate ages cannot be detected by measuring discordance and individual zircon ages represent minimum ages of zircon growth. Clustering of grain ages is the key indicator of the age of important zircon forming events since Pb loss should disperse grain ages rather than producing clusters in the age distribution [11,21].

In making comparisons of age spectra, previous authors have largely depended on visual comparisons, either as histograms [23] or as probability distribution diagrams [11]. Sircombe [12] developed a statistical technique that involved splitting the zircon age spectra into 25 Myr bins and treating the frequency of grains in these bins as independent parameters in a principal component analysis. This technique, however, is overly complex and involves arbitrary binning (e.g., a 799 Ma age will be grouped into a different bin than an 801 Ma zircon). In this study, we have used the Kolmogorov–Smirnov (K-S) test to compare unbinned distributions of a single independent variable [24]. The data sets are converted to a cumulative distribution function and the test returns the probability that the two samples were drawn from the same distribution. For the spectra investigated here the range of probabilities varies from 10^{-34} to 0.9. We reject the hypothesis that two samples came from the same source when the probability drops below 0.05. High values, close to 1.0, indicate nearly identical age spectra. In the following discussion, the results of the K-S tests are prefixed by the letter 'p' (e.g., p. 0.3) indicating the probability that the spectra are samples from the same zircon population.

3. Results

$^{207}Pb/^{206}Pb$ zircon age spectra were obtained for eight samples from five stratigraphic elements: one sample from the LNeoP Forest Conglomerate, one sample from the Cambrian Sticht Range Formation, and two samples from each of three Cambrian stratigraphic units (Gog Greywacke, Stitt Quartzite, Animal Creek Greywacke) (Fig. 3, Table 1). Duplicate samples from the same stratigraphic units are very similar in their zircon populations for all units and have been combined (Fig. 4) for the purposes of all subsequent discussion. In total, 161 analyses are reported.

The 42 grains analyzed from the LNeoP Forest Conglomerate have ages strongly concentrated at 1700 Ma with a secondary peak at 2500 Ma (Fig. 4a). Previous studies [14,17] have reported two types of zircon age spectra from the Tasmanian Proterozoic metasediments. The majority are similar to the Forest Conglomerate (Fig. 5a) and contain mostly 1650–1850 Ma zircons with minor peaks at 1450 Ma and 2500 Ma. The Needles

Table 2
Comparison of zircon age spectra between Tasmanian samples analyzed in this study using the K-S statistic

	Forest Congl.	Animal Creek Gwke	Gog Gwke	Sticht Range Fm.
Animal Creek Formation	0.03			
Gog Greywacke	0.11	0.92		
Sticht Range Formation	0.02	0.05	0.06	
Stitt Quartzite	0.30	0.15	0.34	0.36

Numbers refer to the probability that the two samples are derived from the same zircon population. Values less than 0.05 indicate the samples are from distinctly different populations.

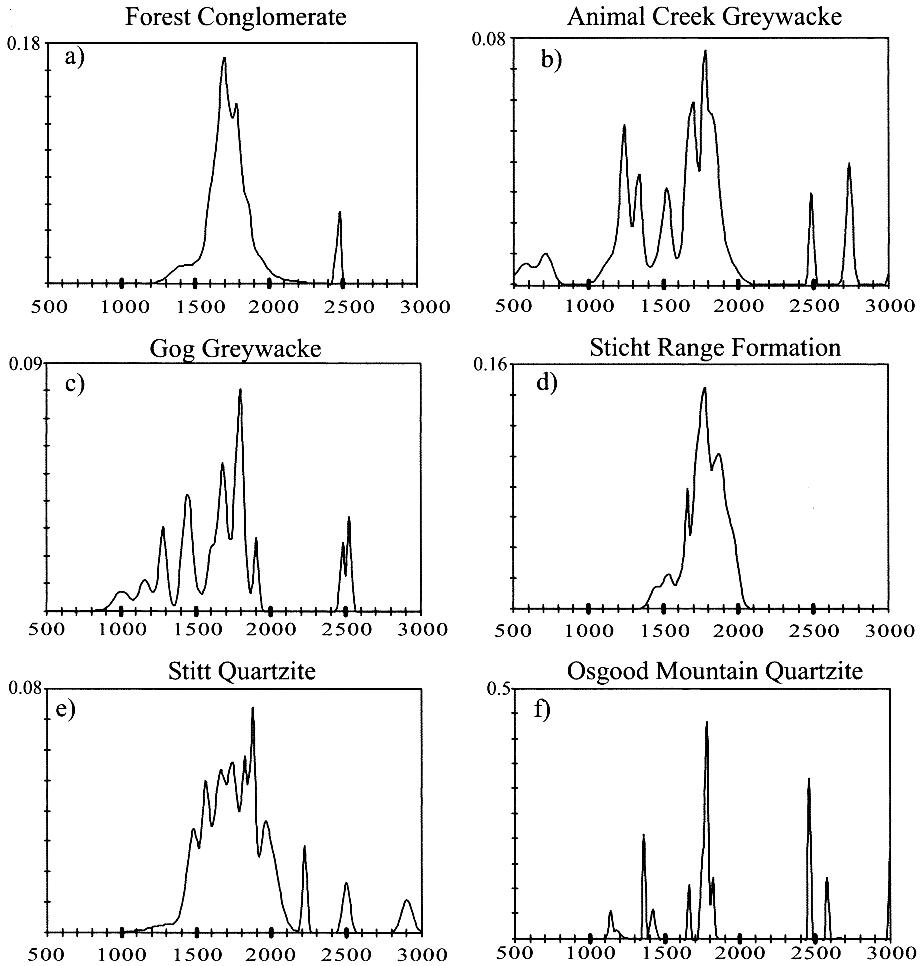

Fig. 4. Probability plots based on zircons age distributions from western Tasmanian sandstones. (a) Forest Conglomerate. (b) Animal Creek Greywacke. (c) Gog Greywacke. (d) Sticht Range Formation. (e) Stitt Quartzite. (f) Osgood Mountain Quartzite, Nevada ($^{207}Pb/^{206}Pb$ ages from [28]).

Quartzite (Fig. 3) has an age spectrum that is nearly identical (p. 0.59, Table 3) to the Forest Conglomerate. In contrast, two Proterozoic samples from northwest Tasmania (Jacobs Quartzite and Bowry Formation) differ from the Forest Conglomerate and all other ENeoP metasediments by having a significant component of zircons in the range 1200–1500 Ma (Fig. 5c,e).

The Animal Creek Greywacke lies close to the base of the Cambrian stratigraphy and is composed of greywacke, sandy siltstone, black shale and volcaniclastic rocks. The two samples from this unit yielded 31 grains, with a marked peak at 1650–1850 Ma and a small number of Archean age zircons. In addition, there is a significant proportion of younger zircons in the 1200–1500 Ma range (Fig. 4b).

The Gog Greywacke is similar in appearance, chemical composition and heavy mineral composition to the Animal Creek Greywacke. The two formations also have similar detrital zircon age spectra (Fig. 4b,c). These rocks have zircon age spectra compatible with derivation from the nearby ENeoP metasediments. There is a large component of 1200–1500 Ma zircon grains, similar to the Jacob Quartzite [14] and the Bowry Formation [17]. The Animal Creek Greywacke and the Gog Greywacke are extremely similar in zircon age spectra (p. 0.92, Table 2) and are therefore grouped together (GG/ACG) for further comparisons.

Thirty-six zircon grains were analyzed from a micaceous sandstone in the Sticht Range Formation, close to the base of the Cambrian sequence on the eastern side of the Dundas Trough (Figs. 2 and 3). The age spectrum is dominated by 1650–1900 Ma zircon grains similar to the ENeoP metasandstones from the Tyennan block [14] on which they were deposited. There is a distinct peak at 1500 Ma in the age spectrum (Fig. 4d).

A quartz wacke from the Stitt Quartzite is the youngest of the units examined. These rocks were deposited near the western edge of the Dundas Trough. The detrital zircon age spectrum has a large spread in ages from 1400 to 2000 Ma with no discrete maximum. The Stitt Quartzite is most similar to the Sticht Range Formation (p. 0.36, Table 2) for ages above 1600 Ma but has a much higher proportion of younger zircons. The Stitt Quartzite does not contain zircons with ages below 1300 Ma in contrast to the Gog Greywacke but otherwise it is very similar (p. 0.34). It is also similar to the Forest Conglomerate (p. 0.30). While, in detail, the Cambrian sandstones have different age spectra, they are all dominated by 1600–1900 Ma grains. The main variation is in the proportion of 1000–1250 Ma and 1350–1550 Ma grains.

4. Discussion

4.1. Correlations with Tasmanian rocks

Zircon age spectra in Cambrian rocks in Tasmania can be subdivided into two groups. Sandstones (Gog Greywacke, Animal Creek Greywacke, Stitt Quartzite) from the west and center of the Dundas Trough (see Figs. 3 and 4b,c,e) have maxima in the detrital zircon age spectra at ~1250 Ma, 1450–1550 Ma and 1650–1850 Ma. These samples may be derived from a source region that includes the Bowry Formation and Jacobs Quartzite (cf. Fig. 5c,e). The Sticht Range Formation is a basal unit on the eastern margin of the Dundas Trough and would be very unlikely to derive any contribution from the ENeoP metasediments to the west. The lack of 1200 Ma zircons in this sample matches the lack of this component in any of the ENeoP metasediments to the east of the Dundas Trough [14]. We conclude that, during the Cambrian, 1100–1350 Ma zircon grains were largely derived from the western side of the Dundas Trough (e.g., Jacob Quartzite and Bowry Formation, Fig. 3). The Forest Conglomerate is unconformable on the ENeoP metasediments and is very similar to most of these samples but did not receive a contribution from the Jacobs Quartzite. This may reflect the basin geometry at the time.

All the zircon age spectra recorded in the Cambrian sandstones of Tasmania reported here can be derived from locally exposed Proterozoic metasediments. There is no evidence for an external source in the provenance of these sandstones. No major new sources for detrital zircon were detected in the provenance of sandstones within Tasmania within the period 800–500 Ma.

4.2. Correlation with mainland Australia

Extensive work on zircon provenance has been carried out around the Gondwana margin [11,25]. The Cambrian Kanmantoo Group and Ordovician sandstones of the Lachlan Fold Belt (Fig. 1) are similar to each other. They have detrital zircon age spectra with major peaks at 500–600 Ma and 900–1200 Ma, and a scatter of ages back to >2000 Ma [11]. In contrast, the Adelaidean metasediments, which underlie the Kanmantoo Group, are dominated by Mesoproterozoic zircons. They have major peaks at 1100–1200 and 1600–1900 Ma and a few grains up to 2800 Ma (Fig. 5f). Despite broad similarities with the samples from Tasmania, they differ in that the 1100 Ma peak (a Grenville age source) is much more pronounced in most of the Adelaidean metasediment samples and in all of the Kanmantoo Group samples. In contrast, in Tasmanian sandstones, detrital zircons with ages between 1400 Ma and 1550 Ma are more common.

Zircons from sandstones close to the base of

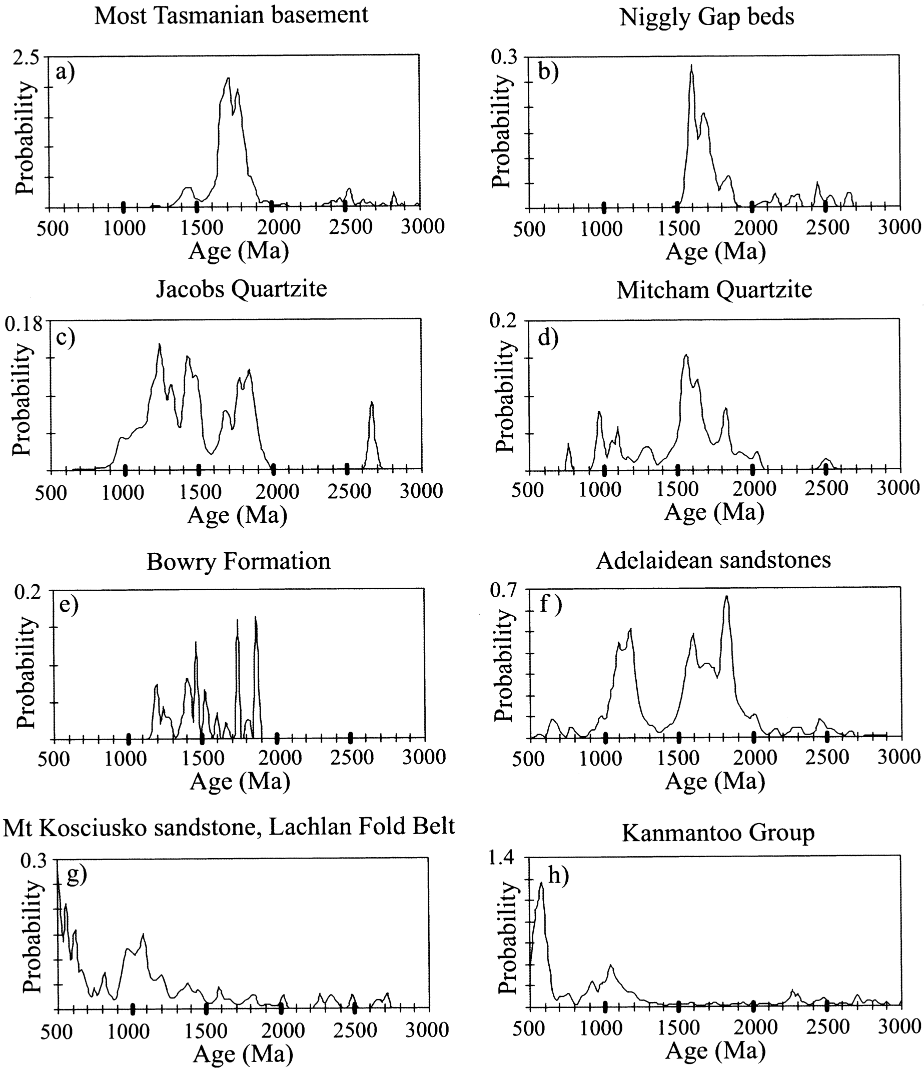

Fig. 5. Probability plots based on zircon age distributions from Eastern Australian sedimentary rocks. Data sources as indicated. (a) ENeoP sandstones from Tasmania (all data in [14] except Jacob Quartzite). (b) Niggly Gap beds [11]. (c) Jacob Quartzite [14]. (d) Mitcham Quartzite [11]. (e) Bowry Formation [17]. (f) Adelaidean metasediments (combines all Adelaidean samples of [11]). (g) Mt. Kosciusko sandstone [11]. (h) Kanmantoo Group (combines all Kanmantoo Group samples of [11]).

the Adelaidean metasediments (e.g., Niggly Gap Beds, Fig. 5b) lack the Grenville age zircons common higher up in the Adelaidean metasediment stratigraphy [11]. They have some similarities with Tasmanian rocks such as the Forest Conglomerate (p. 0.18) and Stitt Quartzite (p. 0.26). All of the Cambrian sandstones reported from Tasmania have detrital zircon age spectra extremely different from the Cambrian sandstones in the Kanmantoo Group (Fig. 5h, p. $<2\times10^{-10}$).

The oldest Adelaidean metasediments have many similarities with the Tasmanian zircon spectra (Fig. 5b) but in South Australia a new source appears and is dominant in the Kanmantoo Group (Fig. 5f,h). In contrast, Tasmania is isolated from this new source and erosion continues to recycle Mesoproterozoic zircons. Although

Tasmania may have been close to the Australian mainland at 700 Ma it was apparently isolated from this margin by the Cambrian. Preliminary data from Antarctica [26] suggest that Tasmania was also isolated from Northern Victoria Land despite their close proximity in Gondwana reconstructions (e.g., Fig. 1). This conclusion is consistent with models where Tasmania was part of a separate microcontinent in the Early Cambrian [3,27].

4.3. Lachlan Fold Belt sources

There has been considerable debate about the source for the large volume of sandstone deposited in the Lachlan Fold Belt in the Ordovician [9,11]. Tasmania is a possible source as it contains evidence for extensive uplift and erosion of the Proterozoic metasediments at the end of the Cambrian. The large number of detrital zircon ages now available from Proterozoic and Cambrian rocks in eastern Australia allows us to quantify the contribution of Tasmanian sediments to a typical Lachlan Fold Belt sandstone (e.g., Ordovician sandstone from Mt. Kosciusko [11]).

The zircon age data reported in [11,14,17,18] and all the data reported here were combined into five broad categories (Kanmantoo Group, Adelaidean metasediments, Tasmanian Proterozoic sandstones, Tasmania Cambrian sandstones and Mt. Read Volcanics). Their probability distributions were calculated over 20 Ma intervals and normalized. These normalized probability distributions were compared using a least squares calculation. This calculation indicated that the Mt. Kosciusko sandstone (Fig. 5g) derived 33% of its zircons from Adelaidean metasediments and 59% from the Kanmantoo Group. The remainder of the spectrum requires a high contribu-

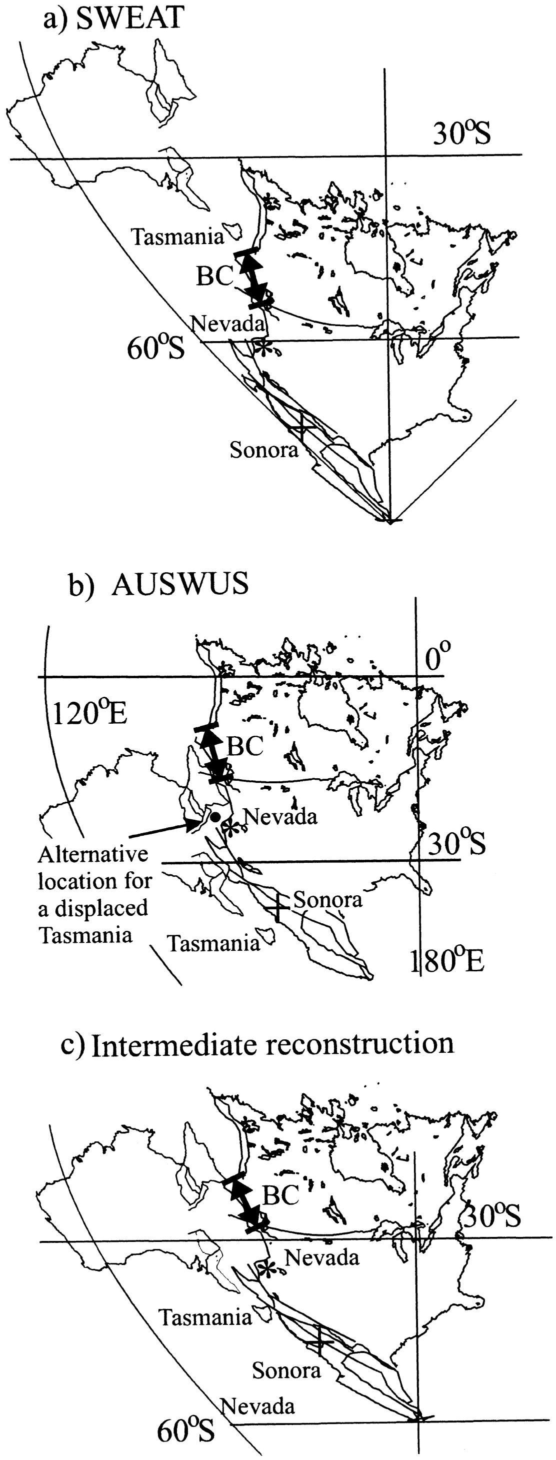

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Fig. 6. Comparison of (a) SWEAT [6], (b) AUSWUS [8,15] and (c) Rodinia reconstruction from [31], for the Neoproterozoic. Three North American domains of distinctive zircon age spectra [23] are shown: British Columbia (BC), Nevada and Sonora. The Tasmanian samples are very similar to the zircon spectra from Nevada. Maps are drawn with respect to a fixed Australia reference frame. A possible alternative location for Tasmania at 700 Ma is shown in panel b.

tion of Cambrian age zircons, such as an 8% contribution from the Mt. Read Volcanics or from other Cambrian igneous rocks such as granitoids intruding the Kanmantoo Group.

Proterozoic metasediments from Tasmania cannot be a substantial contributor to the zircon population of this Ordovician sandstone. Although Tasmanian detrital zircons share some characteristics with the older part of Adelaidean metasediment stratigraphy, by the Cambrian Tasmania was isolated from the influx of new sediment that dominates the Kanmantoo Group. In addition, sediment eroded from Tasmania in the Late Cambrian is not recorded in the Ordovician sandstones of the Lachlan Fold Belt.

4.4. Correlation with North America

Several reconstructions have suggested that North America rifted away from eastern Australia in the Neoproterozoic. In such models (Fig. 6), Tasmania is adjacent either to British Columbia [6] or to Mexico [15]. The zircon age spectra in Cambrian sandstones on the western margin of North America were summarized by Gehrels et al. [23]. The northern British Columbia zircon age spectra are centered at 1900 Ma with a large group at 2400 Ma, unlike any spectra reported from the Australian margin. In southern British Columbia, the peak is at 1800 Ma with a scatter to higher values similar to some Adelaidean samples (Mt. Terrible Formation [11]) but lacking the spread to younger ages shown by Tasmanian samples. In Nevada, the Lower Cambrian Osgood Mountain Formation [28] has a very similar zircon age spectrum to that recorded in Tasmania. It has peaks at 1800, 1400 and 1100 Ma with a scatter back to the Archean (Fig. 4f). The Osgood Mountain Quartzite contains a very similar zircon population to the Stitt Quartzite (p. 0.27). Even more startling is the similarity between this sample and the Oonah Formation (p. 0.6, Table 3, Fig. 7). Further south, in Sonora, Mexico, Cambrian sedimentary rocks have a much larger contribution of Grenvillian zircons and look less like the Tasmanian samples reported here. The 1400 Ma zircons in Sonora and Nevada are sourced from 1340–1480 Ma granitoids that are widespread in southwestern USA [29]. Zircons of this age are rare in Australia but form a minor component in the age spectrum from the Musgrave

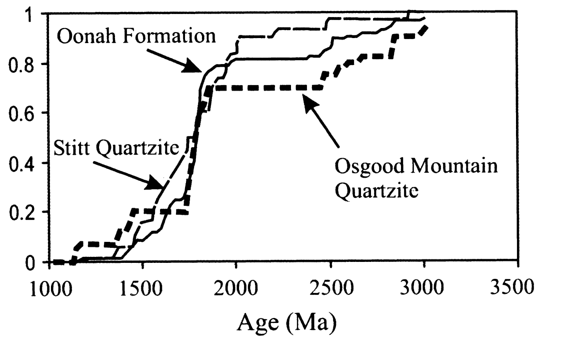

Fig. 7. Comparison of zircon age spectra from the Osgood Mountain Quartzite [28] with Oonah Formation [14] and Stitt Quartzite on a cumulative frequency plot.

Table 3
Comparison of zircon age spectra between sandstones from this study and other samples from Tasmania [11,18] and Nevada [27] using the K-S statistic

	GG/ACG	Sticht Range Formation	Stitt Quartzite	Forest Conglomerate	Osgood Mountain Quartzite
Detention subgroup	0.04	0.00	0.01	0.22	0.00
Jacob Quartzite	0.01	0.00	0.00	0.00	0.00
Needles Quartzite	0.01	0.00	0.05	0.59	0.00
Tyennan Quartzite	0.00	0.04	0.03	0.34	0.01
Oonah Formation	0.01	0.32	0.40	0.01	0.61
Ulverstone Metamorphics	0.00	0.65	0.08	0.00	0.14
Bowry Formation	0.08	0.00	0.00	0.00	0.00
Osgood Mountain Quartzite	0.01	0.07	0.27	0.01	

Numbers refer to the probability that the two samples are sourced from the same zircon population. Values less than 0.05 indicate the samples are from distinctly different populations.

Block [30]. The recognition of this component in the Tasmanian samples is an important indication of a North American source for the ENeoP sandstones. This signature has reached Tasmania before 760 Ma and therefore does not uniquely indicate that Tasmania drifted away from mainland Australia during Rodinia breakup. However, as this signature did not reach mainland Australia, it does indicate that Tasmania was closer to the Laurentia margin during the rift stage and may have been left as an isolated micro-continent when drifting occurred.

In the most common reconstruction for North America and Australia (SWEAT), Tasmania lies very close to British Columbia (Fig. 6a) which is inconsistent with the dominant 1700–1800 Ma zircons and minor component of $\sim$1400 Ma zircons found in Tasmanian sandstones. In the AUSWUS model, Tasmania lies close to Sonora and should therefore have a higher contribution from Grenvillian zircon sources. It lies far south of the closest match in detrital zircon populations from Nevada. These correlations may support arguments that Tasmania has been displaced with respect to mainland Australia since the breakup of Rodinia. This conclusion along with the lack of a Gawler Range Volcanic contribution in the Tasmanian sandstones [14] may suggest a Neoproterozoic position for Tasmania north of the Adelaide Fold Belt (Fig. 6b). Alternatively, a Rodinia reconstruction with an intermediate position (e.g., Fig. 6c, [31]) may better explain the correlations noted here and yet remain consistent with most of the other geological constraints as summarized by [15].

5. Conclusions

The zircon age spectra from the Forest Conglomerate and Cambrian sandstones in western Tasmania strongly support reworking of the zircon population from nearby Neoproterozoic metasediments. No new zircon contributions appear during the period from 760 Ma until the eruption of Mt. Read Volcanics at 505 Ma. Tasmania has remained isolated from the Grenville and Ross Orogen source that dominated the younger Adelaidean metasediments and the Kanmantoo Group provenance. Similarly, Tasmania was not a major contributor to the Lachlan Fold Belt sandstones that have been reported thus far.

In contrast, a sample from the Cambrian of Nevada matches the Cambrian of Tasmania closely. Since the rifting of this margin occurred well before the Middle Cambrian, this correlation requires recycling of the zircon population from older sandstones, at least in Tasmania. In this case there is clear evidence that the signature was carried to Tasmania much earlier, as the Neoproterozoic Oonah Formation also has this North American zircon age signature.

The different evolution of Tasmania from about 700 Ma supports the concept that Tasmania rifted from the Australian mainland during the breakup of Rodinia and remained as a separate fragment or isolated promontory until at least the Delamerian Orogeny.

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