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Chemical U–Th–Pb monazite dating and the Proterozoic history of King Island, southeast Australia*

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The Proterozoic stratigraphy of Tasmania has some common aspects with South Australia but the Wickham Orogeny (760 Ma) has been a major contrasting feature. We have used chemical U–Th–Pb monazite dating to clarify the age relationships in western King Island, which is the key area for the definition of the Wickham Orogeny. New monazite dates demonstrate that the major regional deformation on King Island occurred at 1290 Ma. The Wickham Orogeny is reinterpreted as a local deformation restricted to the contact aureole of the Cape Wickham granite. The Wickham Orogeny in Tasmania may correlate with minor felsic volcanism in the Adelaide Fold Belt, and low-angle unconformities in the Neoproterozoic of northwest Tasmania. The metamorphism on King Island is synchronous with Grenville-age (1300 Ma) orogenic events recognised in central and western Australia. The nearest known examples to Tasmania are in the Musgrave Ranges. Monazite dating of western King Island provides the first direct evidence for Mesoproterozoic basement in southeastern Australia and has major implications for Rodinia reconstructions.

KEY WORDS: geochronology, Grenville, King Island, metamorphism, monazite, Rodinia, Tasmania, uranium–thorium–lead dating, Wickham Orogeny.

INTRODUCTION

King Island occupies a key position in the geology of southeastern Australia (Figure 1). The Cape Wickham granite from King Island is the oldest reliably dated rock east of the Adelaide Fold Belt and south of Broken Hill. The Wickham Orogeny (Turner *et al*. 1998) on western King Island has been dated by correlation with these granites. Yet the Wickham Orogeny (760 Ma) is anomalous in the region with no known equivalent events anywhere in southeastern Australia or northern Victoria Land. The aim here is to test the nature of the Wickham Orogeny on King Island by looking directly at the schists rather than by correlation with the granites.

METHOD

U–Th–Pb dating is used in geology to determine the age of the minerals, which contain significant amounts of U and Th, such as zircon and monazite. Chemical U–Th–Pb dating is restricted to minerals that are extremely enriched in U and Th. Monazite is the outstanding example (Montel *et al*. 1996). It occurs widely as an accessory mineral in variably metamorphosed pelites (Overstreet 1967; Parrish 1990). Monazite grains grow in mudstones as a result of low-grade metamorphism (Kingsbury *et al*. 1993) and the abundance of metamorphic monazite increases with progressive metamorphism (Overstreet 1967; Smith & Barreiro 1990).

Monazites are typically concordant, with the measured common Pb component much less than the analytical error in electron probe microanalysis (Cocherie *et al*. 1998; Scherrer *et al*. 2000). *In situ* analysis and the high spatial resolution of electron probe microanalysis allows the correlation of monazite age with the structural environment of the monazite grains and this is a major advantage in dating of metamorphic events (Williams & Jercinovic 2002). Finally, monazite has a high closure temperature so that in medium-grade metamorphic rocks the grains close as they grow and resetting is controlled by recrystallisation: driven by strain, partial melting or hydrothermal activity (Cocherie *et al*. 1998; Seydoux-Guillame *et al*. 2002). For these reasons *in situ* chemical dating of monazite by electron probe microanalysis is revolutionising the dating of low- to medium-grade, regional metamorphic rocks. The major disadvantage of electron probe microanalysis chemical age dating is that the high detection limits on Pb ($\sim$100 ppm) restrict the application to older events and/or high-Th monazite grains.

Quantitative analyses of monazite grains were obtained using a Cameca SX50 electron probe

*Table 2 [indicated by an asterisk (*) in the text and listed at the end of the paper] is a Supplementary Paper; copies may be obtained from the Geological Society of Australia's website (www.gsa.org.au) or from the National Library of Australia's Pandora archive (http://nla.gov.au/nla.arc-25194).

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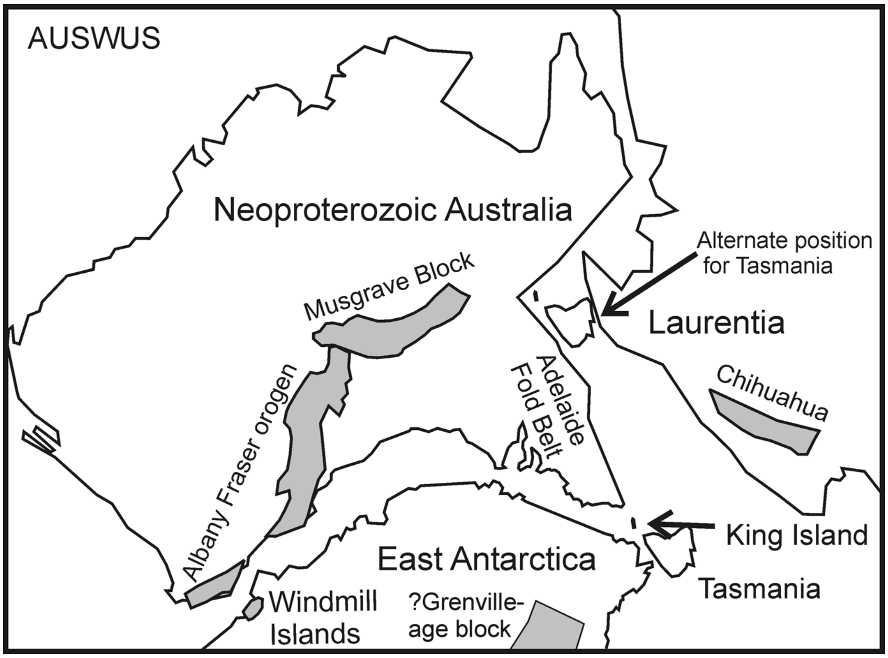

Figure 1 Location of King Island in a Neoproterozoic Rodinia reconstruction (AUSWUS version: from Burrett & Berry 2000). Alternate position for Tasmania and King Island is from Berry *et al.* (2001). Major Grenville-age belts in Australia and southwest Laurentia are shown for comparison with the position of Tasmania. The ?Grenville age block is in the approximate position suggested by Goodge *et al.* (2004).

microanalyser operated at 20kV and 100nA. The errors quoted in this work were estimated from counting statistics. The counting errors have been propagated through the age calculation using the rules for normally distributed errors (Barford 1985). They do not include any systematic errors associated with calibration, or the errors in decay constants. The electron probe microanalysis calibration was checked regularly using a monazite from the Wilson Lake Terrane, Canada [thermal ionisation mass spectrometry (TIMS) age of 1000 $\pm$ 2 (95% confidence) Ma: G. A. Jenner pers. comm.)] and reproduces the TIMS age to within error. Based on this result, we estimate that the systematic error is $< 1\%$. Weighted means and probability plots were calculated using ISOPLOT v2.49 (Ludwig 2001). For individual spot analyses, the 1σ error is quoted in the tables. All other ages are given with errors shown at the 95% confidence level.

REGIONAL GEOLOGY

King Island, located to the northwest of Tasmania, is composed of several different (meta-) sedimentary and igneous sequences (Figure 2). The western half of the island is dominated by metasediments (Gresham 1972; Blackney 1982). The metasedimentary sequence comprises more than 1000 m of dominantly quartzo-feldspathic schist with minor quartzite, pelitic schist, and rare thin calcareous lenses. The typical mineral assemblage in the schists is quartz–muscovite–biotite (–plagioclase). Pelitic schist locally contains garnet and/or andalusite.

Polyphase deformation has affected the Precambrian metasediments. The first major deformation phase (D_1) produced tight to isoclinal folds and a penetrative axial-surface cleavage (S_1) defined by muscovite. Second-generation (D_2) structures are weak in the southern areas away from the granites but include tight folds in the contact aureoles of the granite plutons (Cox 1989). Cox (1973) studied the structure in the contact aureole at Cape Wickham. Small-scale D_2 folds are open to tight structures that fold the penetrative S_1 cleavage. Within the granitic pluton, D_2 has deformed some xenoliths and produced a foliation in some of the granitic rocks. Small mylonite zones in the granite formed during D_2. The granite is interpreted as a syn-D_2 intrusion in the Cape Wickham region. Conventional U–Pb zircon dating of the Cape Wickham granite was used to define the 760 Ma age of the Wickham Orogeny (Cox 1973; Turner *et al.* 1998).

Minor granitic intrusive activity and veining post-dates D_2 folding. Third-generation open folds are also cut by minor granitic sheets and veins (Cox 1973). Upright D_4 folds post-date all granitic intrusions, but are overprinted by north–south-trending tholeiitic dykes (Cox 1973).

The granite pluton that outcrops at Cape Wickham extends down the west coast of the island to south of Currie and reappears again farther south at Cataraqui Point (Figure 2). South of Currie, only the eastern boundary of the pluton is exposed. The adjacent metasedimentary rocks are much like those at Cape Wickham, comprising quartzo-feldspathic and pelitic schist and phyllite with mafic rocks and very minor carbonate (Blackney 1982). Garnet–biotite geothermometry indicates temperatures of $520 \pm 50^{\circ}$C. Blackney (1982) interpreted the garnet to have been stabilised by high Mn contents. Garnet–andalusite–muscovite–biotite–quartz equilibria indicate a pressure of 200–300 MPa. At Cataraqui Point, the granite is deformed with common shear surfaces and cataclastic microtextures (McDougall & Leggo 1965; Streit & Cox 1998).

Outcrops in the eastern half of King Island (Figure 2) are dominated by a relatively unmetamorphosed siltstone and sandstone sequence. The relationship of this

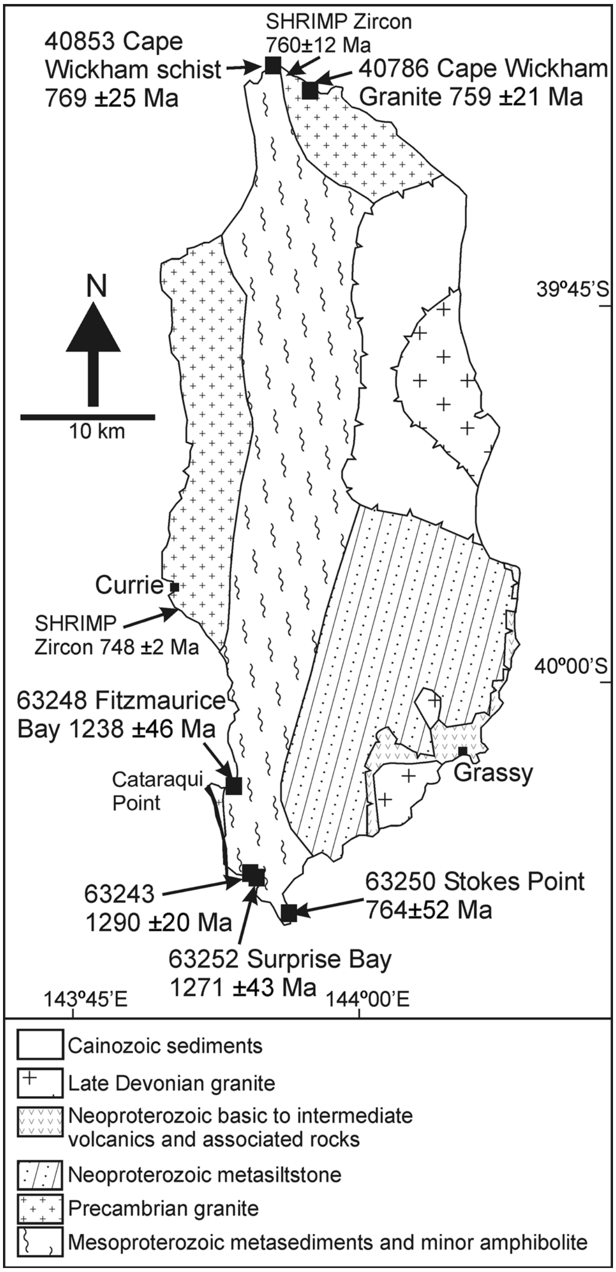

Figure 2 Geological map of King Island. Geology from Gresham (1972) and Brown *et al.* (1995). SHRIMP zircon dates are from Turner *et al.* (1998) and Black *et al.* (1997).

unit to the western sequence of schists is poorly understood. Gresham (1972) suggested the unmetamorphosed sequence unconformably overlies the schists, but this argument is inconclusive, as the contact between the two is not exposed. Calver and Walter (2000) suggested correlation of the unmetamorphosed sequence with part of the Rocky Cape Group, whereas Turner *et al.* (1998) suggested its correlation with the Burnie and Oonah Formations of northwest Tasmania. On the east coast, this sequence is overlain by a Late Neoproterozoic mafic volcanic and sedimentary sequence, the Grassy Group (Calver & Walter 2000).

The results reported here focus on the schists and granites of western King Island including rocks exposed in the far south (Stokes Point), southwest (Surprise and Fitzmaurice Bays, Cataraqui Point) and north (Cape Wickham granite and contact aureole) of King Island (Figure 2).

RESULTS

Six samples from King Island were analysed using the chemical U–Th–Pb monazite method. These included four samples of pelitic schist (63252, 63243, 63248, 63250) from southwest King Island exposed more than 1 km from Neoproterozoic granites. Two samples (40853, 40786) were included from northwest King Island to test the chemical U–Th–Pb method against the known SHRIMP age of the Cape Wickham granite. Four other samples of schist were analysed but these were dominated by xenotime or contained monazite with very low Th unsuitable for the application of this technique.

U, Th, Pb, Ca, Y, P, Fe, Al, Si and eight REEs were measured on each spot. For the six samples, 20 analyses were measured on 4–8 separate grains. Ten percent of analyses were discarded based on oxide totals or mineral stoichiometry, leaving 16–20 monazite analyses for each rock. The U, Th and Pb analyses and sample coordinates are shown on Table 1. Complete analyses are listed in Table 2*.

Surprise Bay and Fitzmaurice Bay

In higher strain rocks (63250 from Stokes Point; 63248 from Fitzmaurice Bay) the garnets are syn-S_1 with distinct quartz pressure shadows (Figure 3c). The age of garnet growth is not so clear in 63243 and 63252 (both from Surprise Bay). The latter are petrographically very similar. They are fine-grained, quartz–muscovite–biotite–garnet–feldspar schists, with minor fine-grained opaque phases. Samples 63243 and 63252 have moderate foliations, defined by quartz- and mica-rich domains. However, the individual white mica and red-brown biotite plates are multiply oriented, and reflect polyphase deformation and mineral growth (Figure 3a, b). Garnet occurs as euhedral 1 mm-diameter porphyroblasts. They are partly corroded, as are the feldspar grains, due to retrograde sericite alteration. The weak foliation development and altered garnet rims prevent clear recognition of the age of garnet growth. Porphyroblastic andalusite overgrows the foliation in 63252.

Samples 63243 and 63252 from Surprise Bay (Figure 2) both contain small 10–30 μm grains of monazite. They have a weighted mean age using the chemical U–Th–Pb method of 1273 $\pm$ 21 Ma and 1270 $\pm$ 40 Ma. The monazite grains in these samples are in textural equilibrium with the metamorphic assemblage (Figure 3b). The samples are both more than 1 km from the nearest exposed granite and garnet is part of the regional prograde metamorphic assemblage. The MSWD for both these samples is > 2, and indicates some disturbance. The cumulative probability plot for sample 63243 (Figure 4b) has a double peak suggesting two events at about 1290 and 1220 Ma. The cumulative probability plot for sample 63252 (Figure 4a) has a broad peak with a mode at 1270 Ma and a MSWD of 2.3. The probability distribution is

Table 1 U–Th–Pb contents of monazite grains and the calculated age of each analysis.

Grain	spot	Pb (ppm)	Th (ppm)	U (ppm)	Age:Ma	1σ err
63252 Surprise Bay 236200mE 5553700mN						
1	1	3531	60819	2140	1135	42
	2	2454	37710	1501	1249	61
	3	2577	42076	1624	1183	58
	4	2939	39597	1551	1418	61
2	1	2327	38496	1674	1151	62
	2	2433	37711	2120	1182	59
	3	3406	53558	1821	1243	48
3	1	4631	75238	1368	1264	37
	2	5074	75518	1550	1365	37
	3	4838	76747	1395	1294	37
4	1	1901	25262	1382	1374	85
5	1	4051	62260	1490	1310	43
	2	2869	42751	1513	1303	57
6	1	2551	40591	1591	1210	59
	2	2219	33177	1610	1250	69
7	1	2777	38093	1544	1389	63
	2	1880	25604	1464	1334	85
	3	1943	28903	1628	1229	76
Tukey's Biweight Mean (95% conf)					**1271**	**43**
MSWD			**2.3**			
63243 Surprise Bay 235900mE 5552800mN						
1	1	5662	89306	1099	1326	29
	2	5604	88491	2881	1243	27
	3	2470	37498	1252	1288	57
	4	3719	59978	1173	1268	39
2	1	4903	77553	1422	1297	32
	2	4687	71898	1371	1332	34
	3	3289	48658	1393	1339	46
3	1	10001	167499	3908	1208	17
	2	5816	91180	1464	1317	28
	3	6200	96564	2180	1299	26
4	1	4705	72564	1371	1326	34
	2	12513	191627	5912	1287	15
5	1	7667	114267	4143	1300	22
	2	6671	106229	2093	1283	24
6	1	3036	47393	1534	1258	46
7	1	3086	43848	1824	1339	48
	2	4120	61794	1803	1319	37
	3	3537	53943	1527	1302	42

Grain	spot	Pb (ppm)	Th (ppm)	U (ppm)	Age:Ma	1σ err
63250 Stokes Point 238100mE 5550300mN						
2	1	719	14326	2201	735	98
	2	1160	17683	2373	991	88
3	1	1149	25194	3908	668	61
	2	970	23587	3930	590	62
	3	1192	26694	3431	694	61
	4	1251	21919	3597	814	68
	5	1186	21197	3793	775	67
	6	940	16574	2981	783	82
4	1	1041	11611	5377	779	73
	2	1142	11589	5806	813	72
5	1	853	15548	2155	827	95
	2	1023	17944	3436	769	76
	3	1228	22679	3884	762	66
	4	1012	22929	2385	726	73
	5	1119	19772	3052	824	75
	6	965	15384	1670	1007	103
Weighted Mean (95% conf)					**764**	**52**
MSWD			**1.8**			
40853 Cape Wickham 238000mE 5613900mN						
1	1	2188	47718	5858	721	37
3	1	2368	43888	5718	829	40
	2	2309	45604	6613	755	38
4	1	1690	31236	5744	743	48
	2	1957	31304	6983	792	45
	3	1655	31518	4731	774	51
	4	1665	31202	4891	775	51
	5	1858	30058	5272	858	51
6	1	1976	35705	5301	816	47
	2	1974	35521	6928	746	43
	3	1903	36944	5668	754	44
	4	1774	35605	6401	692	44
7	1	3224	67066	7773	767	29
	2	1792	26963	4773	916	56
	3	1278	21810	4488	768	63
	4	1446	25084	4523	795	59
8	1	1284	23864	4255	747	62
	2	1327	24317	4448	750	60

(*continued*)

U–Th–Pb contents (*continued*)

Grain	spot	Pb (ppm)	Th (ppm)	U (ppm)	Age:Ma	1σ err
8	1	3895	62867	1944	1223	36
	2	9680	159640	4155	1216	17
Tukey's Biweight Mean (95% conf)					**1290**	**20**
MSWD			**2.6**			
63248 Fitzmaurice Bay 233900mE 5560600mN						
1	1	2004	25658	3580	1155	68
	2	1692	18797	2992	1265	86
	3	2807	42897	3443	1124	50
	4	1520	8375	4652	1341	96
	5	2209	26518	3390	1259	68
	6	1965	22814	2601	1341	80
2	1	2344	30426	1861	1380	71
	2	2763	44057	1508	1226	55
	3	2674	40627	1987	1230	57
3	1	4897	65030	6296	1232	33
	2	5201	70696	4364	1319	34
4	1	3755	49667	5599	1190	40
	2	3064	40046	3480	1282	52
	3	1581	18914	3896	1076	77
	4	2249	21710	3765	1399	73
	5	3286	49500	3271	1183	46
	6	2602	32438	3113	1310	62
5	1	3843	58476	3406	1197	41
	2	3798	57617	3819	1174	40
	3	3993	76504	1562	1071	35
Tukey's Biweight Mean (95% conf)					**1238**	**46**
MSWD			**3**			

Grain	spot	Pb (ppm)	Th (ppm)	U (ppm)	Age:Ma	1σ err
	3	1251	26357	4637	665	56
Weighted Mean (95% conf)					**769**	**25**
MSWD			**1.3**			
40786 Cape Wickham Gr 239700mE 5612900mN						
1	1	1999	50528	3468	714	41
	2	2125	57231	2889	704	39
2	1	2404	62503	2690	744	37
3	1	2474	63118	3207	742	35
	2	3012	62611	3416	896	34
4	1	1906	52784	2038	709	42
	2	2125	54664	2415	750	41
5	1	2421	56941	2488	819	40
	2	2037	53925	2140	739	42
6	1	2452	60291	2496	790	38
	2	2871	72790	3962	739	31
	3	2918	70276	4228	765	32
7	1	2361	56726	3128	777	38
	2	2633	64362	3444	768	35
8	1	2197	58137	2240	741	39
	2	2339	65244	2140	716	36
	3	1739	43352	1751	781	51
	4	2903	68863	5081	749	31
	5	2678	66267	3955	746	33
	6	2132	53905	2183	771	42
Weighted Mean (95% conf)					**759**	**21**
MSWD			**1.4**			

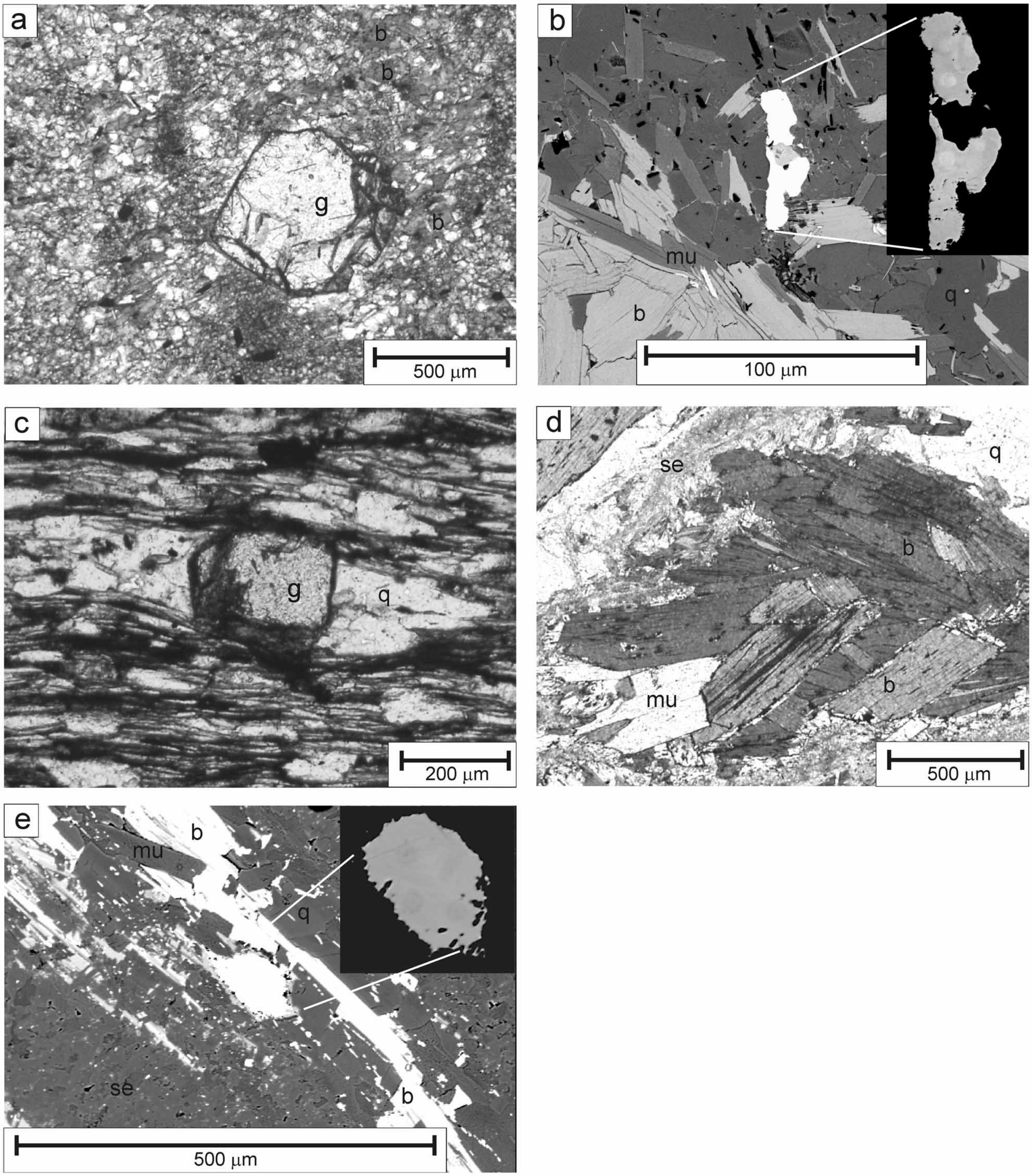

Figure 3 Textural variation of schist. (a) Sample 63243 Surprise Bay. Photomicrograph of euhedral garnet grain in fine-grain matrix of biotite muscovite and quartz. Micas are variable in orientation. (b) Sample 63243 Surprise Bay. Back-scattered electron (BSE) image of monazite grain in variably oriented mica and quartz. Monazite grain shown in more detail in inset. (c) Sample 63250 Stokes Point. Photomicrograph shows the strong foliation partly wraps around garnet with a quartz pressure shadow. (d) Sample 40853. Photomicrograph of the hinge of D_2 crenulation defined by recrystallised biotite. (e) BSE image of sample 40853. Monazite grain (shown in detail in inset) is aligned in the S_2 foliation defined by biotite. Mineral abbreviations: b, biotite; mu, muscovite; q, quartz; ser, sericite-altered feldspar; g, garnet.

asymmetric, suggesting a partial loss of Pb. Because of the high MSWD, we prefer a robust estimate such as is the Tukey Biweight Mean (as implemented by Ludwig 2001). This gives 1271 $\pm$ 43 Ma for 63252 and 1290 $\pm$ 20 Ma for 63243 (Table 1). Combining the data from the two rocks gives a weighted mean age of 1287 $\pm$ 18 Ma.

Sample 63248 from Fitzmaurice Bay comes from 200 m east of a visibly spotted hornfels zone on

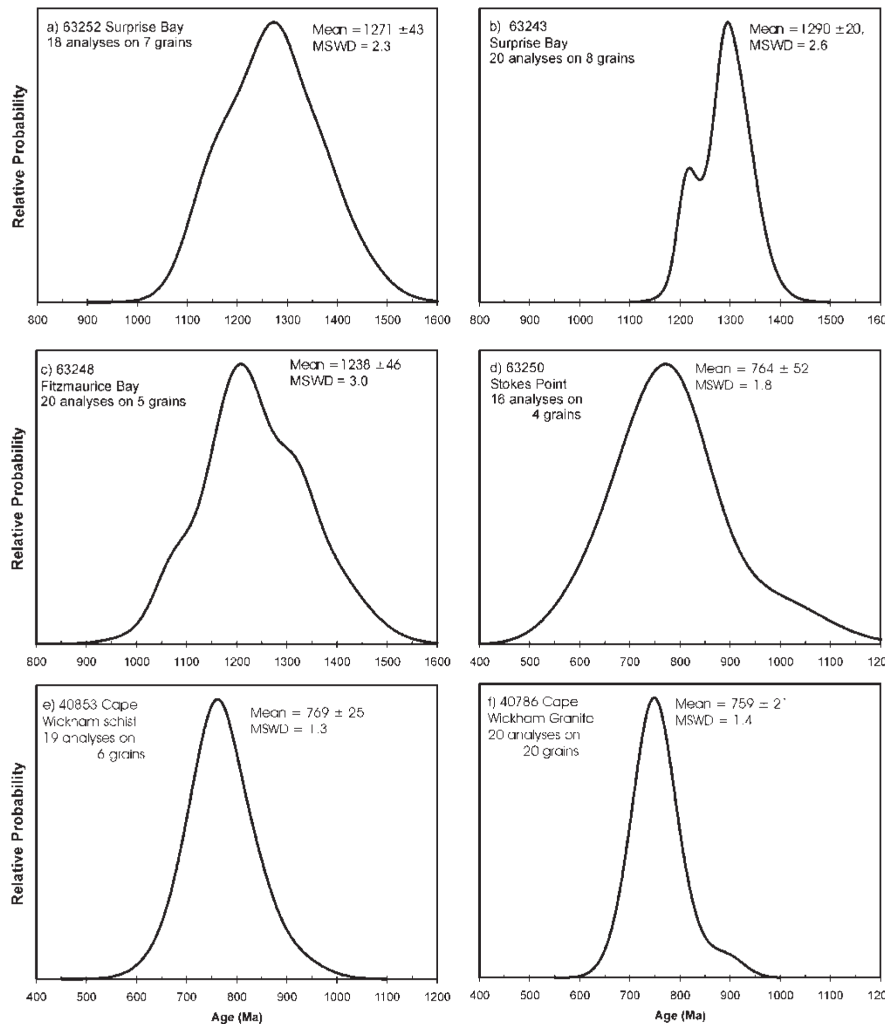

Figure 4 Cumulative probability plots based on the monazite chemical U–Th–Pb ages in Table 1. (a) 63252. (b) 63243. (c) 63248. (d) 63250. (e) 40853. (f) 40786. Plots drawn using Isoplot (Ludwig 2001).

Cataraqui Point and 500 m east of the granite contact (Figure 2). S_1 is strongly crenulated. The monazite from this sample has late halo-like overgrowths (Figure 5e, f), that are interpreted here as evidence of partial recrystallisation. The spot dates have a high MSWD (3.0) and there are bumps in the probability curve that reflect a mixed age structure. The weighted mean age is 1218 $\pm$ 41 Ma. The robust estimator predicts an age of 1238 $\pm$ 46 Ma. The weighted mean age is younger than the two samples from Surprise Bay and we interpret this, combined with the textural evidence of reaction, to indicate some Pb loss associated with the contact metamorphism and D_2 crenulation.

Stokes Point

Sample 63250 is a quartz–muscovite–biotite–garnet schist, with minor retrograde chlorite and sericite. The sample has a single strong schistosity, and has been weakly crenulated at a high angle to the schistosity. The quartz grains are elongate, and have a strong dimensional preferred orientation. The biotite is aligned with the schistosity, consistent with syntectonic growth.

The Stokes Point sample (Figure 2) contains monazites that are texturally distinct from previously described samples. The grains occur as 100 μm diameter poikiloblastic to sieve-texture grains (Figure 5g). These grains have relatively low Th (1–3%) which means the individual spot analyses give dates with very large errors. Despite this, the age population is compatible with a single age of 764 $\pm$ 52 Ma (MSWD = 1.8: Figure 4d). The rock is strongly chlorite altered but otherwise does not appear to have been subject to contact metamorphism. The age recorded matches the age of the Cape Wickham granite and the textural evidence for recrystallisation is taken here to indicate this rock has been hydrothermally altered during granite emplacement. This alteration has completely recrystallised the monazite and reset the chemical U–Th–Pb monazite age.

Cape Wickham granite and contact aureole

The contact aureole of the Cape Wickham granite is a broad zone of intense D_2 deformation and coarse schistose texture dominated by contact metamorphic mineralogy (Cox 1973, 1989). Sample 40853 is a coarse-grained, schistose metasediment, consisting of quartz, biotite, white mica and minor chlorite. The sample is intensely folded (D_2). Biotite has grown during several events but is completely recrystallised during S_2 so that no bent grains are preserved in the hinges of D_2 crenulations (Figure 3d).

Most monazite grains in this sample are apparently in equilibrium with the D_2 metamorphic assemblage (Figure 3e). The grains are 20–50 μm across and aligned in S_2. A few grains appear cracked (microboudinage) with vermicular infilling of the cracks (Figure 5i). Despite this suggestion of textural disequilibrium, the chemical U–Th–Pb monazite age on individual spots has a simple distribution and the weighted mean age is 769 $\pm$ 25 Ma (Table 1; Figure 3e). This is within error of the granite age and contrasts with most of the chemical U–Th–Pb monazite dates from schist outside the contact aureole.

As a measure of the consistency of the chemical U–Th–Pb monazite method with U–Pb zircon SHRIMP

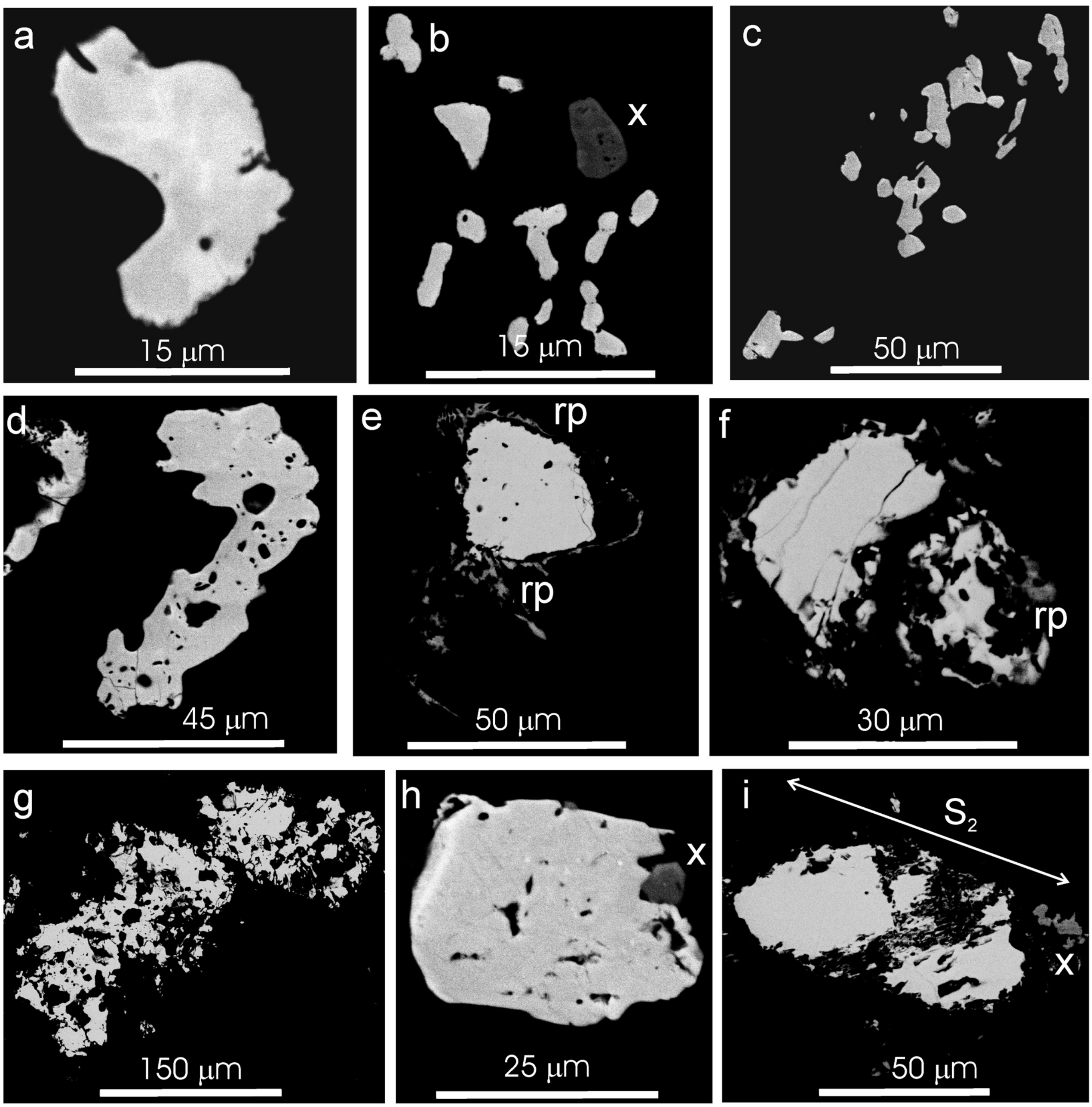

Figure 5 Back-scattered electron (BSE) images of monazite grains. (a) Sample 63243 Surprise Bay: monazite occurs as an irregular light-grey grain. (b) Sample 63243 Surprise Bay: monazite shown as a cluster of light-grey grains. (c) Sample 63252 Surprise Bay: monazite shown as a cluster of light-grey grains. (d) Sample 63252 Surprise Bay: monazite shown as irregular light-grey grain with many silicate (dark) inclusions. (e) Sample 63248 Fitzmaurice Bay: note halo of fine-grained ?monazite (rp) around the larger grain. (f) Sample 63248 Fitzmaurice Bay: note small low-Th ?monazite grains growing on corroded margins of grain labelled as rp. (g) Sample 63250 Stokes Point: large sieve-textured grain of monazite. (h) Sample 40786 Wickham Granite; light-grey regular grain of monazite. (i) Sample 40853 Cape Wickham aureole: the orientation of the S_2 fabric in this sample is shown. The grain was apparently boudinaged by stretching in the S_2 plane. Mineral abbreviations: x, xenotime; rp, low-Th, high-Ca REE-rich phosphate (?monazite).

dating, a sample of the Cape Wickham granite was included in this study. Sample 40786 is weakly foliated, medium-grained granite that contains 20 – 50 μm irregular monazite grains (Figure 5h). The monazite has a simple age population (Table 1). The weighted mean age is 759 $\pm$ 21 Ma (MSWD 1.4). The Cape Wickham granite has previously been dated by SHRIMP analysis of zircon as 760 $\pm$ 12 Ma (Turner *et al*. 1998) and 762 $\pm$ 14 Ma (Black *et al*. 1997). The chemical U – Th – Pb monazite age for the Cape Wickham granite is statistically indistinguishable from the U – Pb zircon age of the same pluton.

DISCUSSION

Prior to the present work, the conventional view was that D_1 to D_4 on western King Island were all part of the *ca* 760 Ma Wickham Orogeny (Turner *et al*. 1998). However, the field relationships described by Cox (1973) only link D_2 and D_3 to the intrusion of the granites with D_1 pre-dating all known granite bodies. D_2 outside the aureoles is much weaker (Blackney 1982). The chemical U – Th – Pb monazite dating reported here is compatible with a 760 Ma age for granite intrusion and for the contact metamorphism around the granites. Away from the granites, a much older event is recorded.

The most obvious interpretation is that the 1290 Ma event recorded in these rocks is the age of first metamorphism. This assumes the crystallisation age has been preserved through the syn-granite metamorphism. D_1 is apparently a simple tight folding event. The revised age suggests that the garnet – andalusite assemblage described from these rocks is a Mesoproterozoic regional low-P metamorphic event.

An alternative interpretation is that all monazite grains older than 760 Ma are inherited, detrital grains. However, the grains have irregular shapes typical of metamorphic origin rather than rounded detrital shapes. The grain clusters (Figure 5b, c) are totally unexpected in grains of detrital origin, as are the irregular shapes (Figure 5a, d). All the grains in samples 63243 and 63252 are the same age and chemistry (Tables 1, 2*). All the grains have a Ce/Dy close to 50 except the three high Th (> 15%) spots in 63243. The latter have high Ca and Th contents typical of a solid solution toward brabantite and this correlates with shallower REE patterns. We interpret this as evidence of a crystal chemical control on the fractionation of REEs between monazite and other mineral phases in the rock. In less deformed and metamorphosed rocks of the Rocky Cape Group where detrital grains are preserved (Holm 2002), the grains are typically variable in age. There is no evidence of a 1290 Ma concentration in monazite grains reported by Holm (2002) from Rocky Cape Group phyllite. On the basis of the textural evidence, a detrital origin for the monazite grains analysed from western King Island is implausible.

We conclude the two samples from Surprise Bay are the best indication of the real age of D_1 on western King Island and this event occurred at 1287 $\pm$ 18 Ma. The sightly lower age of the Fitzmaurice Bay sample is interpreted to be the result of partial recrystallisation caused by the *ca* 750 Ma intrusion of the granite on Cataraqui Point. The textural evidence of corrosion and recrystallisation around the grain margins supports this interpretation (Figure 5f).

Chemical U – Th – Pb dating of the Cape Wickham granite and the contact aureole support the published 760 Ma age for the granite intrusion and the contact metamorphism. We conclude that this is the age of D_2 folding. The poikiloblastic grains on Stokes Point (Figure 5g) suggest there is another Neoproterozoic granite nearby that is not exposed. The rocks in this area are more schistose than the Surprise Bay samples (cf. Figure 3a, c). There are widespread crenulations and kinks on Stokes Point (Blackney 1982) that elsewhere on western King Island are only common near the Neoproterozoic granites. The dominant cleavage in the Stokes Point area is stronger and this dominant foliation wraps around garnet porphyroblasts. In comparison, the S_1 foliation in the Surprise Bay area is truncated at the garnet margins. We interpret these relationships as evidence that the foliation at Stokes Point is a result of localised post-peak-metamorphic strain that, based on the monazite chemistry, must be syn-D_2.

Regional significance

There are major differences between Neoproterozoic sedimentation in the Adelaide Fold Belt, South Australia and the equivalent age stratigraphy in Tasmania, the Grassy Group on King Island and the Ahrberg and Togari Groups in northwest Tasmania (Calver & Walter 2000; Preiss 2000; Holm *et al*. 2003). Intermixed with the Neoproterozoic rift sediments on King Island and in northwest Tasmania are large volumes of rift-related basalts, unseen in the Adelaide Fold Belt. However, the biggest problem with this stratigraphic correlation has been the Wickham Orogeny, which has no equivalent in South Australia. The dating reported here reduces the significance of the Wickham Orogeny. We now see the Wickham Orogeny as local folding in the contact aureoles of a few granitic plutons. In southeast Australia, the only igneous event of similar age is a 780 Ma rhyolite below the base of the Burra Group, in the Adelaide Fold Belt (Preiss 2000). Li (2001) and Holm *et al*. (2003) argued that this rhyolite and the Cape Wickham granite are both related to rifting during early stages of the breakup of Rodinia. This is also consistent with the evidence from northwest Tasmania of a low-angle unconformity at the base of the Togari Group (?740 Ma: Calver & Walter 2000). In the rift scenario, the Tasmanian Neoproterozoic history is much more similar to that of southeastern Australia.

The *ca* 1290 Ma metamorphic age of King Island has important implications in Rodinia reconstructions. Many previous workers have placed North America adjacent to Australia in the reconstructions of Rodinia (Brookfield 1993; Dalziel 1991; Li *et al*. 1995). Burrett and Berry (2000) used geological correlations to refine the fit solution between Australia and Laurentia. They suggested King Island and Tasmania correlate with the Sierra Madre Oriental terrane (in Mexico), which underwent cratonisation between 1700 and 1100 Ma. The metamorphic age of western King Island discussed here is consistent with the AUSWUS reconstruction (Figure 1).

The syn-D_1 metamorphic event of western King Island is contemporaneous with the widely developed Grenville Orogeny. Clark *et al.* (2000) summarised the relationships in Grenville-age events in Australia, Antarctica and Laurentia. They recognised two stages of events, an earlier 1300 Ma event and a later 1100 – 1000 Ma event in Mesoproterozoic Australia and correlated these with the Elzeverian Orogeny (1400 – 1200 Ma) and the Ottawan Orogeny (1100 – 1000 Ma) in Laurentia. Deformation at 1300 Ma has been reported in Western Australia (Albany – Fraser Province), in central Australia (Musgrave Block) and in areas of Antarctica (Windmill Islands). Clark *et al.* (2000) interpreted the 1400 – 1200 Ma orogeny as the result of the collision of the Mawson continent with western and northern Australia. The recognition of a 1300 Ma event in King Island is surprising because Tasmania is now a long way south of the Grenville belt through central Australia.

The Grenville age is consistent with the suggestion based on detrital zircon age spectra (Berry *et al.* 2001) that Tasmania has been displaced south along the eastern Australian margin during the breakup of Rodinia. In contrast, Direen and Crawford (2003) have argued that the mafic rocks on King Island (see also Meffre *et al.* 2004) were formed by rifting along the continental margin to eastern Gondwanaland and that their position marks the original shape of the breakup margin. Their interpretation assumes Tasmania has remained static with respect to southeastern Australia since 600 Ma. The arguments of Berry *et al.* (2001) have largely been negated by the new detrital zircon age spectra reported from East Antarctica by Goodge *et al.* (2004) whose results support the existence of a hidden Grenville-age province in East Antarctica. The metamorphic age of western King Island may indicate that it lies on the margin of this hidden province rather than near the Musgrave Block.

Other Rodinia reconstructions may be influenced by these new data. Li *et al.* (2003) have argued that Tasmania is very similar to South China and they place South China between Laurentia and Australia in their Rodinia reconstruction. The data reported here support the view of Li (2001) that the Wickham Orogeny is a rift phase. Li *et al.* (2003) correlated King Island granites with the younger suite of granites in the Kangdian Rift on the western margin of the Yangtze block. The basement exposed on the western edge of the Yangtze block has 1300 – 1000 Ma ages so the new age for metamorphism in western King Island is consistent with the Rodinia reconstruction of Li *et al.* (2003).

CONCLUSIONS

The earliest recognised deformation on western King Island (D_1) occurred at 1287 $\pm$ 18 Ma. Chemical U – Th – Pb monazite dating supports a 760 Ma age for the Wickham Orogeny but this event was caused by granite intrusion with strong deformation restricted to the contact aureoles of the granite plutons. There may not have been any regional deformation associated with the Wickham Orogeny or it could have been a phase of regional extension.

The Neoproterozoic stratigraphy of Tasmania has some common features with South Australia but there are major differences. The new data on metamorphic ages reported here for King Island has removed one major problem in the correlation of the Adelaide Fold Belt with northwest Tasmania. The Wickham Orogeny (760 Ma) is now regarded as a minor event related to granite emplacement and not a substantial regional deformation. Low-angle unconformities in the Neoproterozoic of Tasmania may be related to this event. The revised Neoproterozoic history of Tasmania is more consistent with the geological history of the nearest equivalent age rocks in South Australia.

The metamorphic age for western King Island determined here is the first direct evidence for a Mesoproterozoic basement in southeastern Australia. This is a major development and will have a significant impact on future refinements to the structure of Rodinia. The earliest deformation on King Island may correlate with the 1300 Ma orogenic events in the Musgrave Block. However, a more likely interpretation is that it forms part of a 1300 Ma metamorphic belt hidden under the Transantarctic Mountains.

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SUPPLEMENTARY PAPER.

Table 2 Complete chemical analysis of monazite grains.