

Sm–Nd model ages of granitoid rocks in the Yilgarn Craton

by

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Abstract

Sm–Nd data are presented for 44 granitoid rocks from across the Yilgarn Craton. With more than 100 analyses now available, model age (T_{CR}) distributions show strong differences between the structural subdivisions of the craton. These differences are generally in keeping with recognized regional age differences but the distributions seen in the Murchison Province and Southern Cross Province apparently extend to include all areas of the Western Gneiss Terrane except the recognized ancient gneiss complexes. There are apparent T_{CR} peaks at 3.7 Ga, 3.3 Ga, 3.0 Ga and 2.7 Ga. The full range of T_{CR} is represented amongst granitic rocks with emplacement ages about 2.7 Ga. In contrast, the few available data pairs for (possible basement) gneisses show a rough correlation between T_{CR} and protolith crystallization age.

KEYWORDS: crustal evolution, Sm–Nd, Yilgarn Craton

Introduction

In the decade since Sm–Nd analyses were first carried out on Western Australian rocks (McCulloch and Wasserburg, 1978) they have been applied to a wide variety of geological problems in different areas. Amongst the data now available are more than one hundred analyses of granitoid rocks of the Yilgarn Craton, sufficient to attempt a broad-scale synthesis for this major Archaean crustal unit.

Sm–Nd model ages are commonly used as indicators of the time of extraction of crustal material from the mantle, though they are not as accurate as analytical precisions suggest and there is considerable uncertainty surrounding the process of extraction, the time span between possible stages of evolution, and the effects of crustal mixing (e.g. Harley, 1987; Arndt and Goldstein, 1987). It may be more appropriate to regard model ages as indicators of the time of derivation of felsic material from basaltic crust, whose prior age cannot be assessed. Whichever view is taken, they can be used to elucidate various aspects of Precambrian crustal evolution, particularly when used in conjunction with methods which more directly date pluton emplacement (e.g. Nelson and de Paolo, 1985). On the scale of continental or cratonic blocks, model ages alone can identify major lateral growth

trends or distinguish terranes of different ages, provided the time differences involved are sufficiently large (>100 m.y.). Major changes corresponding to the recognized margins of the Yilgarn Craton have previously been demonstrated (Fletcher et al., 1983a,b, 1985; McCulloch, 1987).

In this paper we present new Sm–Nd analyses, drawn from a variety of mapping and other projects, for a variety of granitic rocks and gneisses from across the Yilgarn Craton. To these we have added all comparable published data (to 1988) in an attempt to characterize major trends across the block. Some subsets of the data are discussed in detail, relative to complementary isotope geochronological data which are available.

Samples

Locality names and brief descriptions of all samples analysed are given in Table 1; more details on most samples can be obtained from the references listed there. Sample locations are shown in Figure 1, as are sample localities for all other data quoted in later discussion or used in plots. All samples have been classified for later discussion as gneiss ('N' in Table 1) or syn- or post-tectonic granitic rock ('G', hereafter referred to as 'granite'), though the distinction is sometimes unclear. Paragneiss from unequivocal metasedimentary sequences (e.g. Mount Narryer metasedimentary rocks) has been omitted, as have greenstone belt volcanic rocks.

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Table 1. Locations and descriptions of samples for which new Sm–Nd data are reported

<i>Location (a)</i>	<i>Latitude and longitude (b)</i>	<i>Sample number (c)</i>	<i>Description (d)</i>	<i>Ref. (e)</i>
Western Gneiss Terrane				
NARRYER GNEISS COMPLEX				
(a) Meegea Hill	26°04'50"S 116°24'00"E 26°04'40"S 116°25'05"E	80316 80322 80316 80322	(N) Leucocratic granite gneiss (?Dugel Gneiss) (N) as above	
(b) West of Mount Dugel	26°20'04"S 116°21'10"E 26°19'20"S 116°22'50"E	 80313	(G) Deformed porphyritic monzogranite (G) as above	
(c) New Forest	27°24'55"S 115°41'30"E 27°24'55"S 115°41'30"E	77270 77272	(G) Deformed porphyritic monzogranite (G) Deformed leucocratic monzogranite	
OTHER				
(d) Weiragoo Range	26°24'50"S 116°47'05"E	77391 77392	(G) Recrystallized seriate biotite monzogranite (G) Fine-grained phase of the above	
(e) Tching Range	26°31'33"S 116°52'50"E	77334 77337A	(G) Recrystallized fine-grained tonalite (G) Recrystallized fine-grained monzogranite	
(f) Mount Nicolay	27°07'25"S 116°23'35"E 27°09'20"S 116°23'25"E	77346 77350 77353	(G) Recrystallized fine-grained monzogranite cutting 77350 (Murgoo Gneiss) (N) Recrystallized fine-grained porphyritic monzogranite (Murgoo Gneiss) (N) Recrystallized porphyritic monzogranite (Murgoo Gneiss)	
(g) Greenough River crossing	28°10'35"S 115°40'20"S	77362 77366	(N) Recrystallized leucocratic granodiorite (Murgoo Gneiss) (G) Recrystallized monzogranite sheet cutting 77362	
(h) Wongan Hills		WH-5	(G) Fine-grained, grey, hypidio- to allotriomorphic granular monzogranite	1
(i) North of Narrogin	32°40'45"S 117°14'50"E	59925	(G) Even-grained monzogranite	
(j) Wickepin	32°44'25"S 117°35'30"E	59926	(G) Seriate to porphyritic monzogranite	
(k) Joyces Prospect		W-15	(N) Fine-grained leucocratic quartz–feldspar–biotite (granulite) gneiss	2
Saddleback Greenstone Belt				
(l) 6km northwest of Mount Saddleback		W-13	(G) Weakly foliated fine- to medium-grained mesocratic monzogranite	3
Murchison Province				
(m) Northwest of Tragedy Bore	27°24'S 117°19'E	17808	(G) Porphyritic granite	4
(n) South of Mardah Well	27°59'S 117°01'E	17810	(G) Foliated granodiorite	4
Southern Cross Province				
NOONDIE BATHOLITH				
(p) New Well	28°33'00"S 119°05'00"E	71125	(G) Fine-grained hornblende–biotite monzogranite	

Table 1. (continued)

	<i>Location (a)</i>	<i>Latitude and longitude (b)</i>	<i>Sample number (c)</i>	<i>Description (d)</i>	<i>Ref. (e)</i>
(q)	Little Noondie Hill	28°42'00"S 119°08'10"E	71124	(G) Allotriomorphic granular biotite monzogranite	
(r)	Bulga Downs	28°31'10"S 119°44'15"E	71122	(G) Weakly seriate hypidiomorphic granular leucocratic biotite monzogranite	
(s)	White Cloud	28°39'15"S 119°52'35"E	71123	(N) Deformed hornblende–biotite granodiorite	
DIEMALS AREA					
(t)	Rainy Rocks		UWA87975	(G) Intensely lineated recrystallized granodiorite–monzogranite	5,6
(u)	Milky Soak		UWA87955	(G) Weakly foliated porphyritic granodiorite–monzogranite	
(v)	E. Koolyanobbing		UWA81884	(N) Banded gneiss	5,6
(w)	Merredin quarry	31°27'00"S 118°17'40"E	59956A	(G) Seriate to porphyritic monzogranite	
BOORABBIN					
(x)	Boorabbin Rock	31°12'30"S 120°17'20"E	56477	(G) Biotite monzogranite	
(y)	5km north of Diamond Rock	31°32'30"S 120°32'40"E	56478	(G) Biotite monzogranite	
Eastern Goldfields Province					
(z)	Perseverance		74/120 to 74/124	(N) Silicic gneiss with a folded foliated (Perseverance Gneiss)	7
1)	Woorana Well	27°28'15"S 121°12'40"E	59046 A	(G) Seriate clinopyroxene–albite–microcline quartz syenite	8
			59046 C	(G) Crystalloblastic albite–clinopyroxene–microcline, quartz-bearing syenite	
			59047	(G) Seriate clinopyroxene–amphibole–albite–microcline alkali granite	
(2)	Mount Boreas	27°50'55"S 121°53'10"E 27°51'55"S 121°53'10"E	40591A	(G) Coarse-grained hypidiomorphic granular monzogranite	9, 10
			40592A	(G) Medium-grained biotite monzogranite	
(3)	Isolated Hill	28°44'55"S 123°46'05"S	40597A	(G) Partially recrystallized porphyritic hornblende–biotite monzogranite	11
			40597F	(G) Porphyritic leucocratic monzogranite, intruding 40597A	

(a) Letters in parentheses correspond to sites shown on Figure 1

(b) For GSWA samples only; reported to the nearest 5"

(c) Five-digit sample numbers are GSWA numbers; others are as used in references

(d) (G) = granite; (N) = gneiss

(e) References for additional field and petrographic information and/or complementary isotopic age data:

1 = Pidgeon et al. (1990); 2 = Wilde and Pidgeon (1987); 3 = Wilde and Pidgeon (1986); 4 = Muhling and de Laeter (1971); 5 = Chapman et al. (1981); 6 = Bickle et al. (1983); 7 = Cooper et al. (1978); 8 = Libby and de Laeter (1981); 9 = Bunting and Williams (1979); 10 = Stuckless et al. (1981); 11 = Bunting et al. (1976)

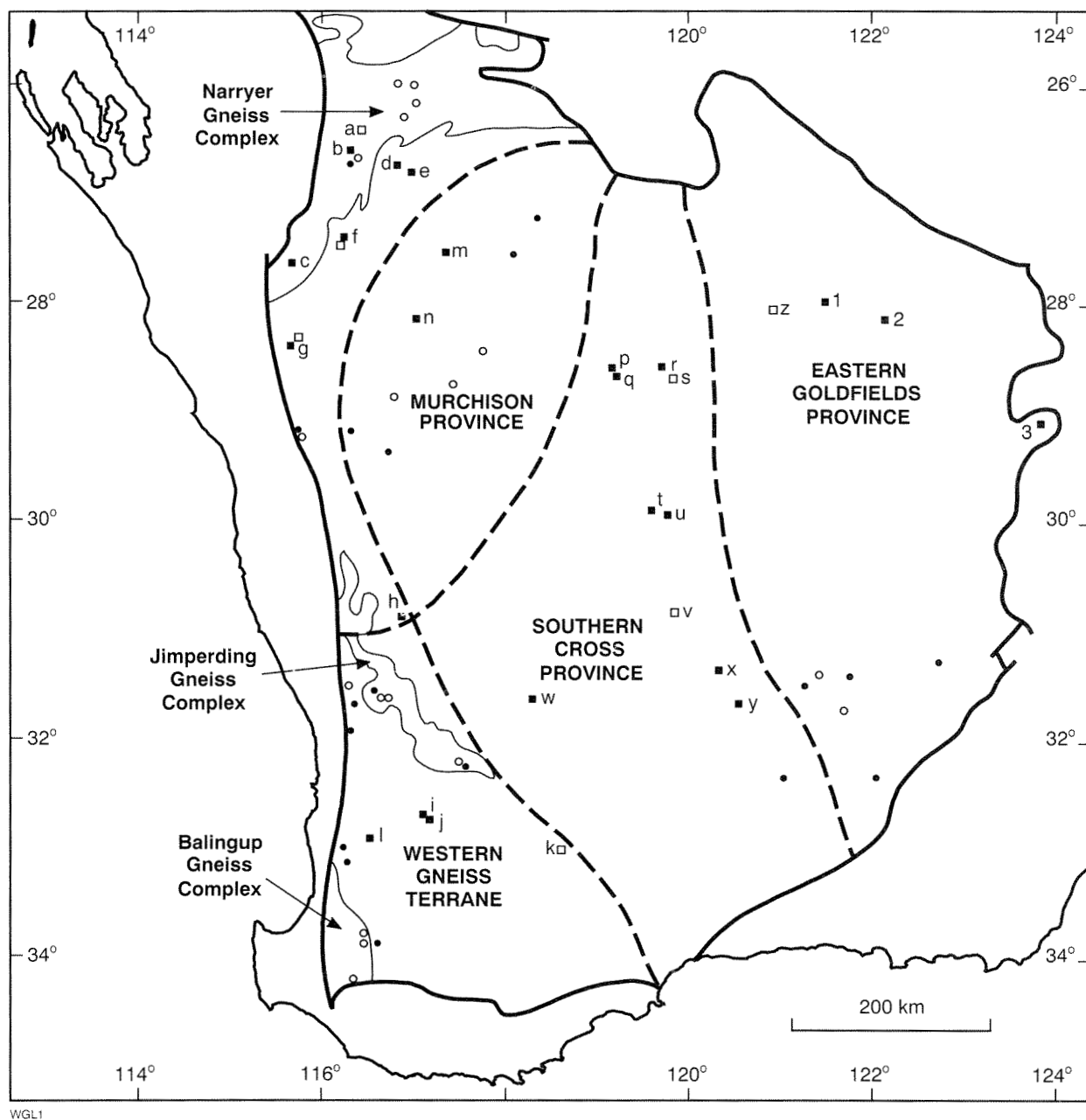


Figure 1. Major structural subdivisions of the Yilgarn Craton (after Gee et al., 1981; Myers, 1990). The dashed line is the possible extension of the Murchison–Southern Cross province boundary discussed in text. Sample localities shown by solid symbols are classified as ‘granite’, open symbols are ‘gneiss’ (see text). Lettered squares are localities given in Table 1 and the references listed there. Circles show additional sites for which published data are plotted in later figures

Analytical procedures

Data were obtained over several years, using the procedures described by Fletcher et al. (1984) and Fletcher et al. (1991). The older data are normalized to $^{146}\text{Nd}/^{142}\text{Nd} = 0.632265$ while more recent analyses use $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. The two normalizations are essentially equivalent, the measured $^{143}\text{Nd}/^{144}\text{Nd}$ values for BCR-1 being 0.512630 ± 12 and 0.512622 ± 6 (95% C.L.), respectively.

Model ages

Model ages are computed parameters which have the dimensions of time. Unfortunately, the term implies a strictly chronological significance which is not justified, and considerable caution is required in using model ages as indicators of the ages of rocks or ‘events’ (see Arndt and Goldstein, 1987, for a review of the limitations inherent in the case of Sm–Nd). In general, compari-

sons between the model ages of samples — provided the same model is used and it is equally applicable to all samples — are of greater significance than the numerical values of individual model ages.

A variety of definitions has been used for Sm–Nd model ages, the differences reflecting different assumptions about the composition and evolution of the mantle from which continental crust is derived. There is no established convention for referring to different models, and care is required when comparing model ages from different laboratories.

Earlier publications, including some from this laboratory, use

$$T_{\text{CHUR}} = \lambda^{-1} \ln \left\{ 1 + \frac{[^{143}\text{Nd}/^{144}\text{Nd}]_{\text{Sample}} - [^{143}\text{Nd}/^{144}\text{Nd}]_{\text{CHUR}}}{[^{147}\text{Nd}/^{144}\text{Nd}]_{\text{Sample}} - [^{147}\text{Nd}/^{144}\text{Nd}]_{\text{CHUR}}} \right\}$$

where λ is the decay constant of ^{147}Sm ($= 6.54 \times 10^{-12} \text{ a}^{-1}$), CHUR refers to unfractionated mantle of chondritic Sm–Nd composition, and the CHUR parameters are present-day values; the values used in this study are $[^{143}\text{Nd}/^{144}\text{Nd}]_{\text{CHUR}} = 0.51262$, and $[^{147}\text{Sm}/^{144}\text{Nd}]_{\text{CHUR}} = 0.1967$.

This model is an extreme case, ignoring the fact that the Sm–Nd system of the mantle has been fractionated, predominantly by the extraction of crustal material.

A second model which is now fairly widely used is

$$T_{\text{MORB}} = \lambda^{-1} \ln \left\{ 1 + \frac{[^{143}\text{Nd}/^{144}\text{Nd}]_{\text{Sample}} - [^{143}\text{Nd}/^{144}\text{Nd}]_{\text{MORB}}}{[^{147}\text{Nd}/^{144}\text{Nd}]_{\text{Sample}} - [^{147}\text{Nd}/^{144}\text{Nd}]_{\text{MORB}}} \right\}$$

where MORB refers to a mantle which had chondritic $^{143}\text{Nd}/^{144}\text{Nd}$ at $T \sim 4500 \text{ Ma}$ but a $^{147}\text{Sm}/^{144}\text{Nd}$ composition that leads to a present-day mantle $^{143}\text{Nd}/^{144}\text{Nd}$ corresponding to the average composition recorded in mid-ocean ridge basalts. This is also an extreme model, since (assuming a chondritic primordial earth) it implies that the dominant REE fractionation in the mantle occurred ‘instantaneously’ following formation of the earth. The model parameters used here are $[^{143}\text{Nd}/^{144}\text{Nd}]_{\text{MORB}} = 0.513151$, and $[^{147}\text{Sm}/^{144}\text{Nd}]_{\text{MORB}} = 0.2136$.

In the data tables below, both T_{CHUR} and T_{MORB} are listed: T_{CHUR} allows direct comparison with most previously published Yilgarn Craton data; T_{MORB} and T_{CHUR} together give the range of ‘reasonable’ possible model ages.

There are several more-subtle models, notably the T_{DM} of de Paolo (1981), which attempt to allow for progressive changes in mantle composition throughout the history of the earth. As yet, the dynamics of mantle evolution are not sufficiently well characterized to allow the adoption of a universally applicable model.

Another expression commonly used is T_{CR} — ‘crustal residence’ age. This is variously defined by different authors, sometimes as T_{MORB} or T_{DM} , sometimes by other more specific models (e.g. McCulloch, 1987). For the plots presented below we use $T_{\text{CR}} = (T_{\text{MORB}} + T_{\text{CHUR}})/2$ which is computationally convenient, avoids the extreme

assumptions of T_{MORB} and T_{CHUR} , and satisfies the condition that T_{CR} equals or exceeds the emplacement age in all cases where this is known for the samples considered. For Archaean samples, T_{CR} values are numerically close to T_{DM} .

Data and discussion

Sm–Nd data are given in Table 2 for the samples listed in Table 1. Data have also been drawn from published sources for some parts of the following discussion and are plotted in compilation figures. The relevant sample locations are shown in Figure 1; the sources are:

Fletcher et al. (1983a,b, 1985); de Laeter et al. (1981, 1985); Kinny (1986); Nieuwland and Compston (1981); McCulloch et al. (1983a,b); Dobos et al. (1986); Compston and Arriens (1968); Compston et al. (1986); McCulloch and Compston (1981); Claoué-Long et al. (1986b); Bunting et al. (1976), Oversby (1975); McCulloch (1987); Campbell and Hill (1988); Hill et al. (1989); Watkins et al. (1991) and J. S. Myers (1987, pers. comm.).

1. Isochron plots

In several instances, samples were chosen from sample suites which had previously been used for Rb–Sr isochron studies. In each case the Sm–Nd data disperse appreciably on isochron plots, but in no case is a simple isochron age determination possible.

Data for the Perseverance Gneiss (site z) scatter around a best-fit line (Fig. 2a) and disperse so widely that the protolith was almost certainly of mixed parentage. This supports the contention of some workers in this region (Cooper, J., 1981, pers. comm.) that it was sedimentary. Given this, the well-fitted (MSWD = 2.86) $2625 \pm 34 \text{ Ma}$ Rb–Sr isochron of Cooper et al. (1978) must date metamorphism.

The analysed samples from the Woorana Well alkaline granite (site 1) probably are cogenetic but the data spread (Fig. 2b) is not sufficient to define a precise isochron age. The best-fit line shown in Figure 2b suggests a ‘typical Yilgarn’ age of $\sim 2700 \text{ Ma}$ with initial $\epsilon_{\text{Nd}} \sim -3.0$. Rb–Sr data for seven samples from the Woorana Well locality (Libby and de Laeter, 1981) give a date, interpreted by them as an emplacement age, of $2520 \pm 113 \text{ Ma}$. Stuckless et al. (1981) propose a Pb/Pb age, based on a regional sampling of syenites including Woorana Well, of $2760 \pm 210 \text{ Ma}$. The Sm–Nd data are compatible with either of these dates; they would easily allow an age of 2760 Ma (with initial $\epsilon_{\text{Nd}} \sim -4$), and possibly as low as 2520 Ma (initial $\epsilon_{\text{Nd}} \sim 0$).

A strikingly different case is seen in the data for Isolated Hill (site 3). The two samples were chosen as typical, albeit quite distinguishable, granites from the area. They are from a suite analysed by Bunting et al. (1976) who interpreted the resulting Rb–Sr date of $2537 \pm 25 \text{ Ma}$ as a metamorphic age. The two Sm–Nd data points separate widely (Fig. 2c) with the $^{147}\text{Sm}/^{144}\text{Nd}$ of sample 40597F being extremely high for a granite, particularly for

Table 2. Sm–Nd analytical data and model ages

Location (a)	Sample Number	Sm (b) (ppm)	Nd (b) (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$ (d)	$^{143}\text{Nd}/^{144}\text{Nd}$ (d)	T_{CHUR} (e) (Ma)	T_{MORB} (e) (Ma)
Western Gneiss Terrane							
NARRYER GNEISS COMPLEX							
(a) Meegea Hill							
	80316	1.0	6.0	0.10210	0.510795 ± 10	2 922	3 197
	80322	1.4	6.9	0.12764	0.511107 ± 10	3 314	3 695
(b) West of Mount Dugel							
	80309	4.7	34	0.08323	0.510298 ± 10	3 097	3 310
	80313	9.0	62	0.08815	0.510444 ± 10	3 034	3 264
(c) New Forest							
	77270	1.7	9.8	0.10213	0.510792 ± 10	2 927	3 202
	77272	2.6	12.9	0.12131	0.511116 ± 10	3 020	3 335
OTHER							
(d) Weiragoo Range							
	77391	7.1	42	0.10303	0.510856 ± 10	2 853	3 141
	77392	7.4	36	0.12248	0.511052 ± 10	3 197	3 482
(e) Tching Range							
	77334	3.2	22.5	0.08710	0.510533 ± 10	2 884	3 132
	77337A	10.7	72	0.08979	0.510630 ± 10	2 820	3 082
(f) Mount Nicolay							
	77346	4.3	35	0.14834	0.511379 ± 10	-	-
	77350	14.3	116	0.07438	0.510079 ± 10	3 144	3 337
	77353	4.9	16.9	0.08764	0.510451 ± 10	3 011	3 243
(g) Greenough River crossing							
	77362	1.5	12.8	0.07298	0.510238 ± 10	2 916	3 135
	77366	3.0	22.6	0.07912	0.510362 ± 10	2 909	3 139
(h) Wongan Hills							
	WH-5	7.3	47	0.0956	0.510701 ± 22	2 875	3 142
(i) North of Narrogin							
	59925	5.9	34	0.1058	0.510936 ± 20	2 805	3 109
(j) Wickepin							
	59926	8.1	58	0.0846	0.510530 ± 21	2 825	3 076
(k) Joyces Prospect							
	W-15	1.3	8.0	0.0955	0.510772 ± 23	2 768	3 051
(l) Northwest of Mount Saddleback							
	W-13	3.5	18.1	0.1173	0.511239 ± 22	2 637	3 006
Murchison Province							
(m) Northwest of Tragedy Bore							
	17808	4.1	27.6	0.091*	0.510651 ± 25		
		4.7	31.3	0.0910	0.510657 ± 21	2 813	3 079
(n) South of Mardah Well							
	17810	1.9	11.8	0.098*	0.510849 ± 25		
		2.2	13.7	0.09703	0.510877 ± 11	2 650	2 954
Southern Cross Province							
(p) New Well							
	71125	3.1	21.9	0.0867	0.510583 ± 25	2 804	3 062
(q) Little Noondie Hill							
	71124	3.6	23.3	0.0926	0.510678 ± 25	2 826	3 093
(r) Bulga Downs							
	71122	3.0	22.1	0.0824	0.510369 ± 25		
		2.9	21.3	0.0821	0.510369 ± 20	2 974	3 201
(s) White Cloud							
	71123	3.3	24.0	0.0827	0.510380 ± 25	2 974	3 202

Table 2. (continued)

Location (a)	Sample Number	Sm (b) (ppm)	Nd (b) (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$ (d)	$^{143}\text{Nd}/^{144}\text{Nd}$ (d)	T_{CHUR} (e) (Ma)	T_{MORB} (e) (Ma)
(t) Rainy Rocks	UWA87975	8.6	67	0.0779	0.510474 ± 20	2 737	2 986
(u) Milky Soak	UWA87955	6.1	37	0.0995	0.510680 ± 20	3021	3 276
(v) East Koolyanobbing	UWA81884	2.8	20.6	0.0815	0.510484 ± 22	2 809	3 056
(w) Merredin quarry	59956A	5.3	39	0.0833	0.510520 ± 24	2 806	3 057
(x) Boorabbin Rock	56477	4.6	29.3	0.0949	0.510714 ± 32	2 837	3 108
(y) North of Diamond Rock	56478	4.6	31.8	0.0866	0.510593 ± 21	2 789	3 049
Eastern Goldfields Province							
(z) Perseverance Gneiss	74/120	3.1	10.6	0.176*	0.512210 ± 25	-	-
		3.1	10.6	0.1757	0.512224 ± 32	-	-
	74/121	2.3	13.1	0.1075	0.511042 ± 25	2 681	3 009
	74/122	3.1	12.2	0.154*	0.511943 ± 29	-	-
		3.0	11.8	0.1527	0.511953 ± 21	-	-
	74/123	2.5	11.1	0.1362	0.511548 ± 27	2 686	3 134
	74/124	3.6	12.1	0.181*	0.512340 ± 25	-	-
(1) Woorana Well	59046A	3.8	27.0	0.0858	0.510792 ± 25	2 500	2 796
	59046C	12.6	95	0.0807	0.510672 ± 25	2 547	2 826
	59047	13.4	82	0.0992	0.511006 ± 32	2 509	2 839
(2) Mount Boreas	40591A	12.8	109	0.0708	0.510463 ± 20	2 597	2 851
	40592A	14.1	117	0.0727	0.510467 ± 20	2 632	2 885
(3) Isolated Hill	40597A	5.5	40	0.0829	0.510655 ± 27	2 618	2 893
	40597F	1.8	5.5	0.2009	0.512788 ± 26	-	-

- (a) Lettered as in Table 1 and Figure 1. Unnumbered data are complete re-analyses
- (b) Reproducibility for small powdered samples is ~3%
- (c) Data quoted to four figures have 95% C.L., including calibration and internal precision, of $\pm 0.2\%$. A few cases (marked *) are known to have small additional uncertainties due to incomplete sample digestion. Data quoted to five figures are $\pm 0.1\%$
- (d) Normalized to $^{146}\text{Nd}/^{142}\text{Nd} = 0.632265$ or $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ (see text). Uncertainties listed are 95% C.L. in the last figures quoted and include reproducibility and precision
- (e) Defined in text; not calculated in cases with $^{147}\text{Sm}/^{144}\text{Nd} > 0.14$. Analytical uncertainties are ± 20 –40 m.y.

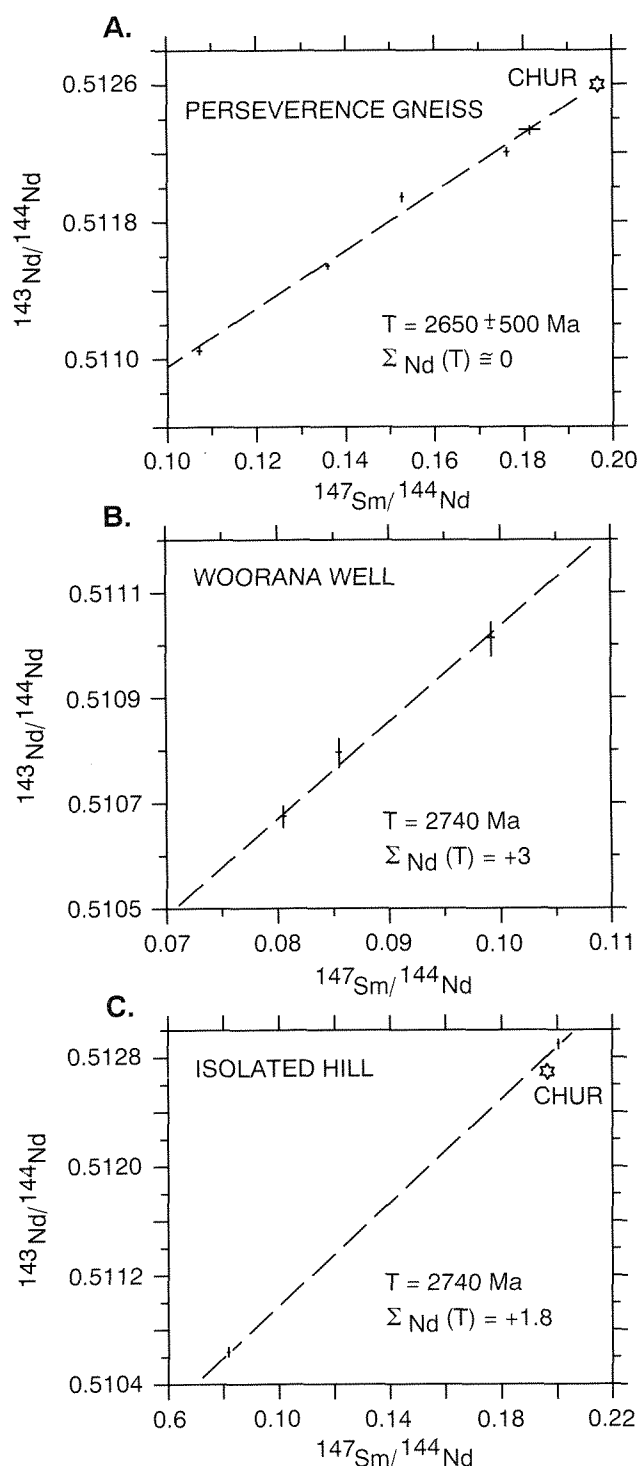
a highly fractionated one (as indicated by its high Rb/Sr). The two-point line does not define an age because the two samples are almost certainly not cogenetic. The unusual Sm–Nd character of sample 40597F is similar to that of some mixed gneiss/amphibolite rocks in the ductile deformation zone at the western edge of the ~1300 Ma Fraser Complex, about 500 km south of Isolated Hill. In that case, the samples have low Rb contents (<1 ppm) and low Rb/Sr, and the isotopic features have been interpreted as the imprint of purging of the zone by mantle-derived fluids at ~1300 Ma (Fletcher et al., 1991). There is no evidence for similar activity at Isolated Hill.

The other cases which give differing data for samples from restricted areas cannot be interpreted by isochron techniques. For Mount Nicolay, the only possible interpretation is that the components of the gneiss have not evolved as closed systems since its formation and/or that they were never fully equilibrated. Similarly, the two samples from Meegea Hill (site a) and the two from

Weiragoo Range (site d) have analytically well-defined separations, but the directions of separation have no time significance in either case.

2. Comparisons between model ages and emplacement ages

A comparison between T_{CR} and the crystallization ages of granites or the protoliths of gneisses is given in Figure 3. Only U–Pb zircon data and several examples of Pb/Pb whole rock isochron data have been accepted as giving accurate crystallization ages. The Rb–Sr system is well known to be subject to post-emplacement resetting (e.g. Bickle et al., 1983) and in some cases published Pb/Pb isochrons are not well defined or are of uncertain significance. Data have been plotted only for cases where T_{CR} and emplacement age were measured on the same samples, or where there is a well-defined correlation



WGL2

Figure 2. Sm–Nd isochron plots

- (a) Perseverence Gneiss. The alignment is probably not a valid isochron
- (b) Alkaline granitoids near Woorana Well. The isochron has large uncertainties
- (c) Granites at Isolated Hill. Despite their general similarities the two samples have very different $^{147}\text{Sm}/^{144}\text{Nd}$ and they are unlikely to be cogenetic, i.e. the 2-point line is unlikely to be a valid isochron

between the rocks analysed. Where appropriate Sm–Nd data have been averaged and the plotting symbol spans the data; for single analyses analytical uncertainties ($\pm 30 \text{ m.y.}$) are used. For plotting purposes, a minimum uncertainty of $\pm 10 \text{ m.y.}$ is applied to the emplacement ages.

The most striking feature of Figure 3 is the clustering of data for the syn- and post-tectonic granites. All the emplacement ages fall in the range 2600–2700 Ma, while the corresponding T_{CR} values span the range 2680–3310 Ma. If T_{CR} (as defined above) is a valid estimator of crustal residence age then the pre-emplacement ages of material in the granites ranges from zero to $\sim 700 \text{ Ma}$. This group of samples has representatives in all major regional divisions of the craton.

In contrast to the granites, data for the gneisses cover a wide range of both T_{CR} and crystallization age. The data are few, but they appear to define a diffuse elongate field parallel to the diagonal limiting line in Figure 3, with a mean pre-crystallization age of $\sim 200 \text{ Ma}$.

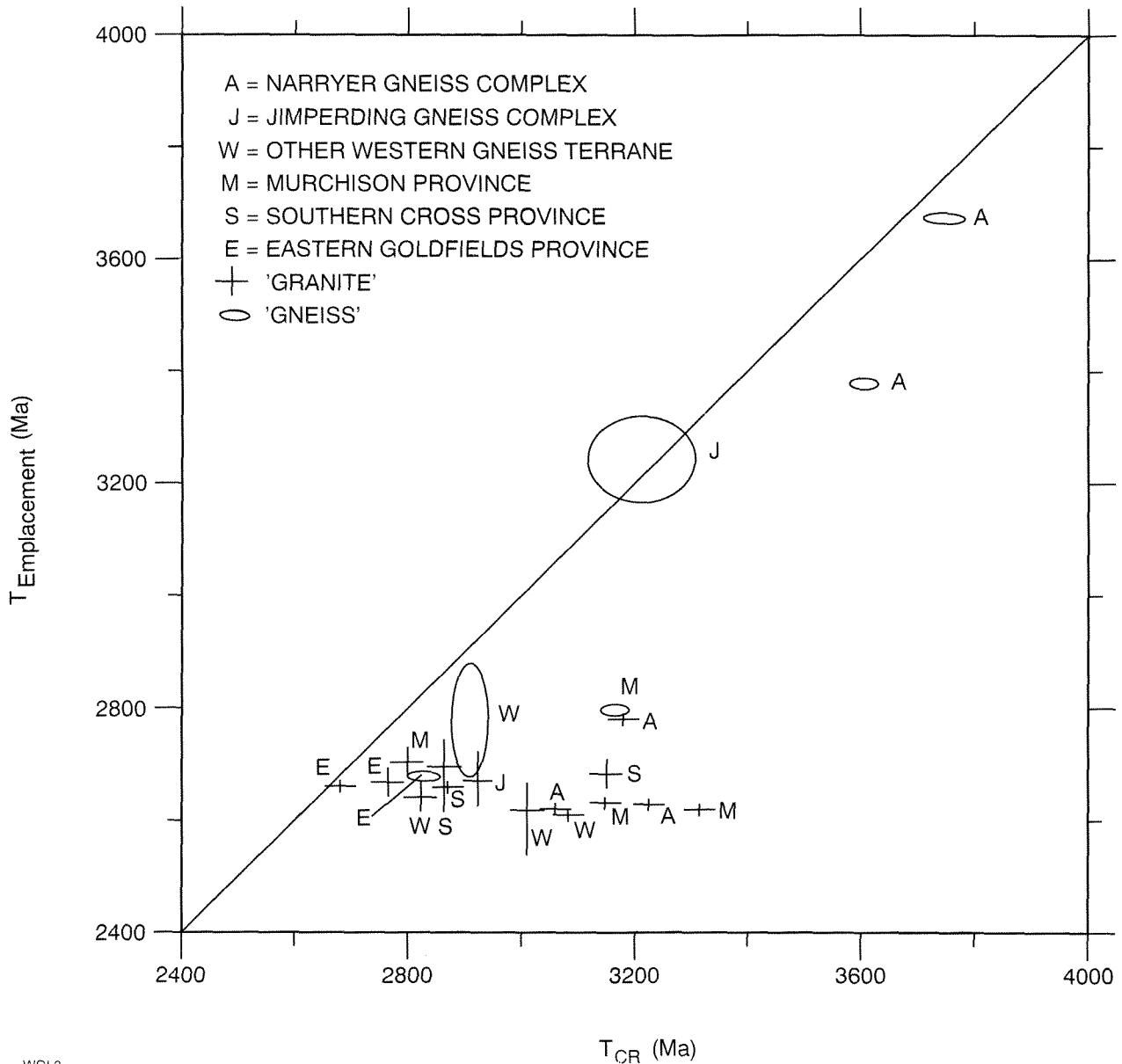
3. Narryer Gneiss Complex

The granite samples from west of Mount Dugel (site b) have been shown by zircon U–Pb analysis to be similar in crystallization age ($\sim 2.63 \text{ Ga}$) to post-tectonic granites close to Mount Narryer (Myers, J. S., 1987, pers. comm.), though the granites at the two localities are chemically distinct. The bulk compositions of the Mount Dugel granites and the two granitic samples from New Forest (site c) show some similarity to components of the old gneisses at Mount Narryer. However, their model ages clearly show them to be unrelated. Their T_{CHUR} dates range from 2927 Ma to 3097 Ma (Table 2) and are quite distinct from the 3620 Ma to 3710 Ma values recorded for Meeberrie Gneiss, and 3510 Ma to 3540 Ma for Dugel Gneiss, in the type area near Mount Narryer (de Laeter et al., 1985). Even the T_{MORB} values are less than the crystallization age of Dugel Gneiss protoliths in the type area ($3381 \pm 22 \text{ Ma}$; Kinny et al., 1988). The granites from both of the new localities appear to correlate with late Archaean granites in the Mount Narryer area, two of which have given T_{CHUR} values of 3070 Ma and 3120 Ma (de Laeter et al., 1985).

The two samples of gneiss from Meege Hill (site a), which were tentatively correlated in the field with Dugel Gneiss, give quite different model ages ($T_{\text{CHUR}} = 2922 \text{ Ma}$ and 3314 Ma , Table 2). These dates are distinctly less than the 3510 Ma to 3540 Ma values recorded for Dugel Gneiss in the type area near Mount Narryer (de Laeter et al., 1985) and at Errabiddy (Fletcher et al., 1983b).

4. Model age compilations

Compilations of all available Sm–Nd model age data (to 1988) are shown in Figure 4, for several different regional groupings. Data from published sources have been classified using the same granite/gneiss distinction applied to samples in Table 1. Data for the Jimperding and Balingup Gneiss Complexes have been grouped together



WGL3

Figure 3. Comparison between Sm-Nd model ages (T_{CR}) and emplacement (or crystallization) ages of Yilgarn 'granites' and 'gneisses'. The diagonal line represents $T_{CR} = \text{emplacement age}$; any data falling to the left of the line would invalidate the model adopted for T_{CR} .

because there are only limited data for each area and the two data sets almost completely overlap.

The top row of Figure 4 (a–d) shows data for the commonly used regional subdivisions reproduced in Figure 1. The second row (e–g, d) is a variant on this, in which the Western Gneiss Terrane is, in effect, reduced to include only the three recognized 'older' gneiss complexes, the remainder of the area of the Western Gneiss Terrane being apportioned between the Murchison and Southern Cross Provinces (following the dotted line in Fig. 1). These extensions do not change the character of the profiles for either of the provinces. That of the Southern Cross Province is still particularly narrow, even

though the augmented province includes almost half of the area of the Yilgarn Craton.

Interpretations of Figure 4 are limited by the possibly unrepresentative nature of sampling, by the constraints inherent in model ages, and by ambiguities in some of the granite/gneiss classifications. Nonetheless, some broad-scale features stand out. One is the strong decrease in recorded model ages from the extreme northwest of the craton (the Narryer Gneiss Complex, Fig. 4h) to the Eastern Goldfields Province (Fig. 4d). The existence of abundant ~3350 Ma and rare ~3650 Ma zircons in the Maynard Hills quartzite, which lies just east of sites (r) and (s) in the Southern Cross Province (Froude et al., 1983)

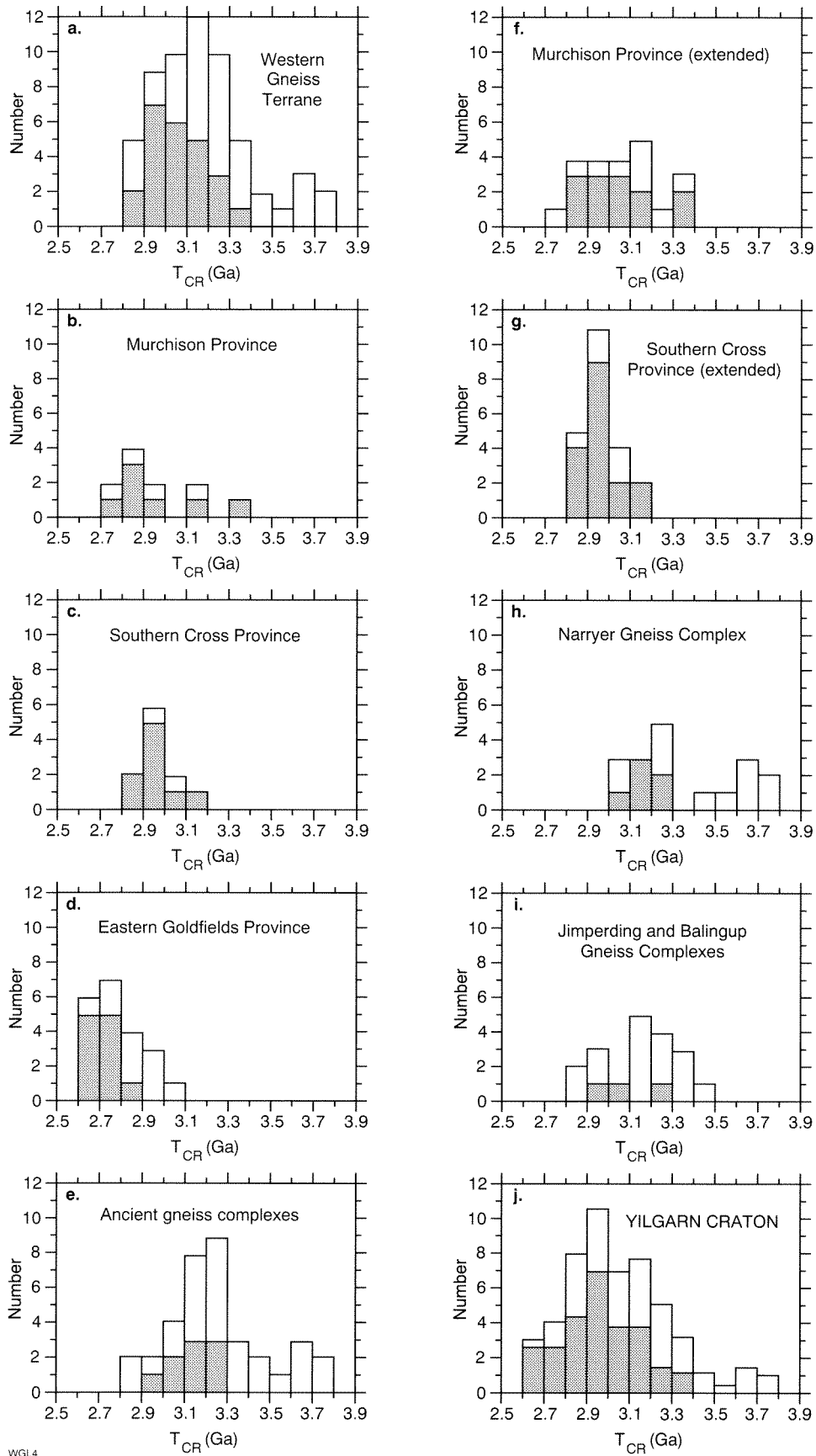


Figure 4. Compiled crustal residence ages (T_{CR}) for the Yilgarn Craton and the subdivisions outlined in Figure 1. Shaded blocks = 'granites', open blocks = 'gneisses'. Data from Table 2

and ~3400 Ma zircons at Kambalda in the Eastern Goldfields Province (e.g. Claoué-Long et al., 1986a) demonstrates that remnants of crust of at least these ages have been incorporated into the rocks now exposed in these provinces. Figure 4a shows, however, that these remnants can only be a minor component of the rock units analysed. It might be argued (e.g. Gee, 1979) that Proterozoic tilting of the Yilgarn Block has exposed older deep crustal rocks in western areas and that similar old crust may underlie the eastern provinces. This may be true, but it cannot explain the extent of the differences seen unless Archaean crust is stratified to an extent not generally recognized. As noted above, extending the central provinces to the west, to include some 'younger' high-grade areas such as the Murgoo Gneiss Complex and the Chittering Metamorphic Belt (as well as granite-dominated areas), does not change the character of their model age profiles.

Another feature in the data for the Narryer Gneiss Complex (Fig. 4h) is the bimodal distribution. This could be an artifact of sampling, since some of the gneiss samples were collected as representing possible 'oldest basement'. However, given that some of these samples fall in the younger model age group, it seems unlikely that further sampling would obliterate the bimodality.

The Southern Cross Province distribution (Fig. 4c or 4g) is remarkably narrow, considering the extent of the province (Fig. 1). This, together with the bimodal nature of the Narryer Gneiss Complex plot and the fairly narrow Eastern Goldfields profile, suggests an episodic sequence of additions of material to the craton, though it gives no clues as to how or when the provinces may have accreted into a single craton. The apparent growth pulses are at ~3700 Ma, ~3300 Ma, ~3000 Ma and ~2700 Ma. These dates are strongly model dependent, but they might be valid ages given that they correspond well with emplacement ages (established by zircon U–Pb data) for various rock types in the corresponding areas. The peaks of crustal growth are strongly associated with particular provinces and they have significant width (in time), so that in a compilation for the whole Yilgarn Craton (Fig. 4j) much of the detail is averaged out. Only the 3600–3700 Ma and 2900–3000 Ma peaks are still apparent in the total profile; the 2900–3000 Ma peak also shows up in the granites.

The Murchison Province profile (Fig. 4b or 4f) has a strong overlap with that of the Southern Cross Province (Fig. 4c or 4g), but it is somewhat broader and considerably less peaked than either the Southern Cross or Eastern Goldfields Province profiles, suggesting that material of more diverse ages is included here than is the case for the eastern granite–greenstone provinces.

The Jimperding and Balingup Complexes have a (combined) profile (Fig. 4i) quite different from that of the Narryer Complex (Fig. 4h), though the younger peak in the Narryer Complex profile falls near the centre of the Jimperding–Balingup data spread. More data would be needed from the Jimperding and Balingup complexes to make more detailed comparisons.

Conclusions

Each of the provinces of the Yilgarn Craton has a distinctive T_{CR} distribution, which probably reflects a distinct early history. Recorded values of T_{CR} range from a distinct grouping of gneisses with T_{CR} ~3.7 Ga in the Narryer Gneiss Complex to the T_{CR} ~2.7 Ga which dominate in the Eastern Goldfields Province. The regional character of the T_{CR} distributions lies predominantly in the older dates within each distribution. The rocks which these older dates represent are, however, only a minor (though very important) component of each region. For example, rocks with T_{CR} >3.4 Ga have been found only locally within the Narryer Gneiss Complex. Similarly, in the Eastern Goldfields Province, the remnants of felsic crustal material older than 3.0 Ga, whose existence is indicated by preservation of zircons of that age (but not yet by Sm–Nd model ages), constituted only a minor component of that province when the craton stabilized at about 2.6 Ga.

The Murchison Province appears to be a more mixed crustal segment than either of the other granite–greenstone provinces, and it may be transitional between the Narryer Gneiss Complex and the rest of the craton. Its T_{CR} dates span the ~3.3 Ga and ~3.0 Ga maxima seen elsewhere. It is notable that this is the only granite–greenstone province in which supracrustal sequences of two distinct ages are known to occur (Watkins and Hickman, 1990), the Luke Creek Group being ~3.0 Ga (Pidgeon and Wilde, 1990) and the Mount Farmer Group being younger, possibly ~2.8 Ga. It is not possible to rationally redefine the boundaries of the Murchison Province in a way which separates ~3.0 Ga and ~3.3 Ga model age areas, and this model age pattern apparently extends west as far as the Darling Fault and the contacts of the Narryer and Jimperding Gneiss Complexes.

The distinctive T_{CR} signature of granitoid rocks in the Southern Cross Province contrasts with the picture given by dates of major eruptive events in greenstone belts, which are similar (at ~2.7 Ga) in the Eastern Goldfields and Southern Cross Provinces (Pidgeon and Wilde, 1990). This emphasises the point that the provinces might be most readily distinguished on the basis of their early histories. In this context, the data suggest that the Southern Cross Province could be redefined to include the southern half of the Western Gneiss Terrane, except for the recognized ancient gneiss complexes within the latter.

Syn- and post-tectonic granitoid rocks have T_{CR} varying up to ~3.3 Ga, but throughout the craton they have emplacement ages of 2.6–2.7 Ga. Relatively few of the gneisses have well-determined protolith crystallization ages. These few show a crude correlation between T_{CR} and crystallization age, the majority of cases indicating crystallization from crustal material which was, at the time, no older than 300 million years.

The model ages suggest a periodicity when they are considered by structural province. There are frequency peaks at ~3.7 Ga and ~3.3 Ga in the Narryer Complex, ~3.0 Ga in the Southern Cross Province and ~2.7 Ga in

the Eastern Goldfields Province. No T_{CR} values less than ~2.6 Ga have been reported for granitoid rocks in the Yilgarn Craton, although there was widespread intrusion of mafic dykes in the early Proterozoic, and there was an apparent surge in crust formation marginal to the craton at ~2.2 Ga when development of the surrounding orogens began.

Given sufficient breadth of sampling, regional mapping of T_{CR} can provide a first-order view of the sequence of development of various crustal segments. At this level of approximation, the Narryer Gneiss Complex is the oldest crustal segment in the Yilgarn Craton and the Eastern Goldfields Province is the youngest. The remaining areas of the Western Gneiss Terrane, the Murchison Province and the Southern Cross Province are of intermediate crustal age, progressively younger from west to east. The indication of steps, or periodicity, in this progression is taken to reflect successive stages of crustal development rather than a progressive admixture of young crust with old. It is not clear whether the progression represents growth around a continental nucleus centred in the Mount Narryer area, repeated rifting of an ancient continent, or later juxtaposition of crustal plates which developed separately.

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