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FIELD GUIDE
TO THE LEEUWIN COMPLEX

ACOG
3
1995
PERTH

by

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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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Excursion Guide to the Leeuwin Complex, Western Australia

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INTRODUCTION

This field guide has been prepared as an aid for those attending the excursion to the southwest of Western Australia, held as part of the Third Australian Conference on Geochronology and Isotope Geoscience (ACOG-3), during November 1995. It presents new data on samples from the Leeuwin Complex, including major- and trace-element geochemical data and six previously undocumented U-Pb zircon dates obtained on the Sensitive High-Resolution Ion MicroProbe (SHRIMP) in Perth during early 1995. Some of the sampling sites will be visited during the excursion and the implications of these new results will be discussed.

Parts of the coastline between Dunsborough and Augusta are incorporated within the Leeuwin Naturaliste National Park. The region includes many unique natural features, such as spectacular coastline (where the Indian and Southern Oceans meet), limestone caves, Karri forests and superb local wines. Many of the sites that will be visited are environmentally sensitive and are protected. Rock samples may not be taken from any of the sites in the National Park without prior arrangement.

REGIONAL GEOLOGY

High-grade rocks of the Leeuwin Complex occur between Cape Naturaliste and Cape Leeuwin in the southwest corner of Western Australia (Fig. 1). Surface exposures are bounded from the Phanerozoic sediments of the Perth Basin to the east by the Dunsborough Fault. The complex consists predominantly of metamorphosed, even-grained and porphyritic granitic rocks, but also includes minor pegmatitic and mafic dykes and disrupted remnants of massive and layered leucogabbro and anorthosite bodies. These rocks have been metamorphosed to granulite facies and heterogeneously deformed, and parts of the complex have subsequently been recrystallized in the amphibolite facies.

Relatively few detailed investigations have been undertaken on the rocks of the Leeuwin Complex and the geological history of the complex is still poorly known. Wilde and Murphy (1990) subdivided the gneisses of the complex into seven types, largely on the basis of petrographic and mineralogical features (see Fig. 1). They interpreted variations in mineral assemblages as showing that metamorphic grades increase northward, from low pressure amphibolite facies to the south of Margaret River, to low pressure granulite facies conditions to the north, with peak metamorphic temperatures of ~ 690 °C inferred from two-pyroxene geothermometry. The presence of arfvedsonite in some of the felsic gneisses (i.e. type 3 gneisses of Wilde and Murphy 1990) is regarded as diagnostic of ‘A-type’ granitoid rocks of peralkaline affinity (Loiselle and Wones, 1979), and Wilde and Murphy (1990) proposed that the complex formed within a continental rift environment.

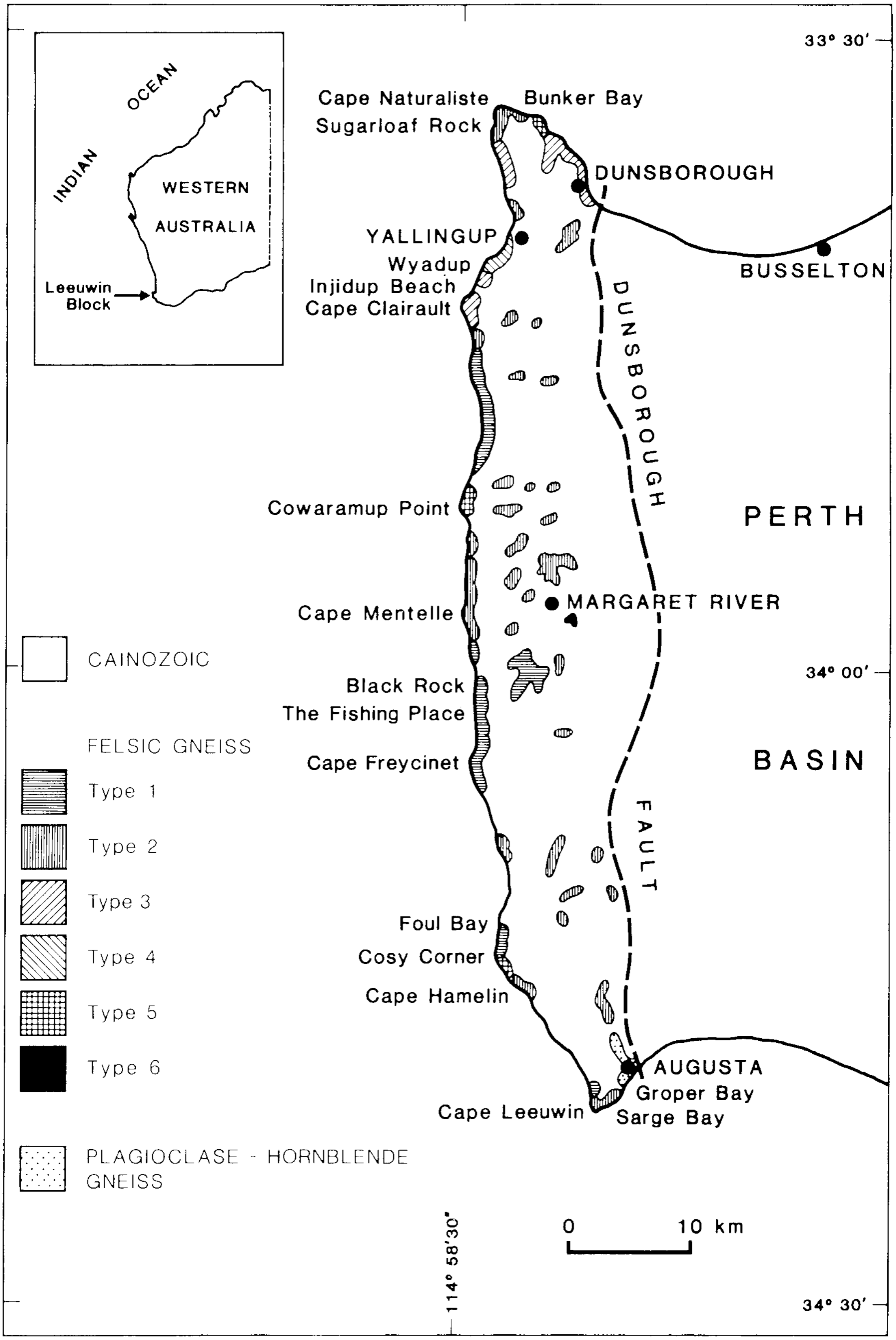

Figure 1. Generalized geological map of the Leeuwin Complex showing the distribution of main rock types identified by Wilde and Murphy (1990). Key to their rock types: type 1- layered two f'spar-gnt-bio gneiss; type 2 - layered, two f'spar-pyx/ hbl-bio gneiss; type 3 - massive to layered, alkali f'spar-Na/Fe pyx/amphibole gneiss; type 4 - layered, alkali f'spar-bio gneiss; type 5 - massive two f'spar gneiss; type 6 - massive, two pyroxene granulite.

Myers (1994) informally subdivided the gneisses of the Leeuwin Complex into an older Cowaramup gneiss and the younger Hamelin granite. He included the gabbros and anorthosites (referred to as the Augusta Anorthosite Complex) as part of the Cowaramup gneiss. The Hamelin granite was considered to have intruded the Cowaramup gneiss as large sheet-like bodies. Weakly deformed to undeformed pegmatite dykes containing magnetite, orthopyroxene, garnet and biotite, and tonalitic dykes, were emplaced during or after the peak of granulite facies metamorphism and many have been recrystallized in the amphibolite facies during cooling and uplift of the complex.

Extensive Tertiary laterite, sands and limestones overly the metamorphic rocks of the Leeuwin Complex. The limestones were formed from wind-blown calcareous sands derived from the west during periods of low sea level. The cave systems developed in Recent times by the dissolution of the carbonate within the sands by groundwater flowing along the irregular contact with the impermeable metamorphic basement rocks.

GEOCHEMISTRY OF THE LEEUWIN COMPLEX

A reconnaissance geochemical and geochronological investigation of the Leeuwin Complex is in progress in conjunction with detailed mapping undertaken by John Myers (GSWA). This work is far from completion at the time of writing, but preliminary results and some discussion of their implications are presented here to stimulate discussion.

Geochemical data obtained (at the CCWA, major and trace elements by XRF, rare earth elements by ICP-MS) on samples of felsic gneiss and metamorphosed leucogabbro and anorthosite from the Leeuwin Complex are listed in Table 1. Six of the samples listed in the table have also been dated by the SHRIMP U-Pb zircon technique. Sample localities and the U-Pb zircon dates obtained on these samples are shown in Figure 2.

Wilde and Murphy (1990) argued that the depletion in large-ion lithophile elements shown by many granulites is absent in the Leeuwin Complex gneisses. The results obtained as part of the present study confirm this finding. The precursors to the felsic gneisses are chemically mainly alkali granites characterized by relatively high K_2O, Na_2O and generally high K_2O/Na_2O. Analyses of two samples of leucogabbro are also listed in Table 1; the Cape Leeuwin anorthosite (112133) at excursion locality 1 and a leucogabbro (112142) from a coastal exposure north of Cowaramup Bay, at excursion locality 6.

The origin of the alkali granite precursors to the felsic gneisses of the Leeuwin Complex is an intriguing problem. New SHRIMP U-Pb zircon data (see below) indicate that the igneous precursors crystallized over a period of at least c. 150 Ma and therefore could not have been derived from a common parent alkali granite magma. Nd isotopic analyses of felsic gneiss samples from the Leeuwin Complex (McCulloch 1987, Black et al. 1992, Fletcher and Libby

Table 1. Geochemical data for selected rocks from the Leeuwin Complex.

GSWA No.	112131	112132	112133	112134	112135	112136	112140	112141	112142	112143	112144A	112145
SiO_2	70.1	70.7	49.2	75.3	72.8	74.1	64.4	71.9	50.3	68.2	73.5	71.3
TiO_2	0.44	0.40	0.93	0.21	0.27	0.28	0.93	0.39	2.28	0.70	0.20	0.33
Al_2O_3	13.9	14.1	25.6	12.2	14.1	13.1	15.3	12.5	19.1	14.0	13.2	12.0
Fe_2O_3	0.84	1.69	1.67	1.67	0.38	0.34	1.29	2.39	3.06	3.50	0.55	3.98
FeO	3.06	2.16	3.24	0.79	1.76	1.93	3.83	2.09	6.47	2.99	1.66	1.83
MnO	0.07	0.08	0.08	0.06	<0.05	<0.05	<0.05	0.10	0.16	0.09	<0.05	0.11
MgO	0.22	0.18	1.19	<0.05	0.26	0.28	1.20	0.27	2.63	0.49	0.06	0.25
CaO	1.84	1.29	11.50	0.55	1.66	1.60	3.28	1.68	9.83	2.63	1.02	2.01
Na_2O	3.41	3.72	3.49	3.72	2.49	2.44	3.45	3.62	4.23	4.35	3.07	4.78
K_2O	5.78	6.00	0.85	5.43	6.02	5.49	4.48	4.78	1.33	2.40	6.37	2.69
P_2O_5	0.08	0.05	0.18	<0.05	0.11	0.11	0.25	0.09	0.58	0.13	<0.05	0.06
CO_2	0.02	0.17	0.29	0.23	0.15	0.20	0.49	0.10	0.02	0.40	0.21	0.02
S	<0.01	<0.01	0.10	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.04	<0.01	<0.01
H_2O+	0.29	0.26	0.52	0.18	0.38	0.32	0.65	0.24	0.26	0.40	<0.10	0.34
H_2O-	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
O=S	<0.01	<0.01	0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01
Rest %	0.27	0.29	0.21	0.25	0.18	0.17	0.50	0.26	0.22	0.33	0.23	0.34
Total	100.4	101.1	99.0	100.7	100.7	100.4	100.1	100.5	100.5	100.6	100.3	100.1
Ba	915	452	383	826	627	520	2152	825	412	982	681	1025
Cr	<4	<4	10	8	6	<4	11	<4	<4	<4	<4	<4
Cu	<4	<4	5	<4	<4	<4	<4	7	<4	39	<4	<4
Ga	21	23	26	21	17	16	21	18	23	23	22	23
Nb	38	66	13	70	9	12	18	48	21	50	29	69
Ni	5	5	8	5	5	6	8	6	9	4	6	7
Pb	41	29	6	27	53	51	19	22	10	12	44	9
Rb	242	197	17	181	238	241	163	169	27	53	327	40
Sb	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4
Sc	6	2	9	2	4	4	7	7	20	11	<4	6
Sn	5	5	<4	9	<4	<4	<4	7	<4	7	4	9
Sr	108	57	654	40	87	77	262	109	437	186	80	139
Ta	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Th	39	41	3	23	36	46	55	17	8	27	44	12
U	3	3	2	2	2	2	<2	2	<2	2	6	<2
V	8	<3	97	4	10	11	69	3	165	9	<3	4
Y	64	98	14	97	51	41	21	78	38	77	77	117
Zn	81	118	48	132	31	38	90	75	100	71	51	55
Zr	438	579	368	374	162	176	655	490	314	808	253	923
La	53.6	185	22.6	120	66.9	72.6	191	92.7	42.3	114	130	117
Ce	133	384	48.6	262	145	159	343	199	91.7	163	253	264
Pr	16.0	44.8	6.30	33.1	16.9	19.1	35.1	24.3	12.0	19.4	28.3	34.4
Nd	58.6	161	24.7	124	60.30	68.9	110	91.3	47.7	68.5	95.9	131
Sm	13.9	29.5	4.90	27.6	13.1	15.3	16.3	20.4	11.1	15.9	20.4	30.7
Eu	2.98	2.67	2.41	4.43	1.94	1.65	3.37	3.89	3.56	1.83	2.85	6.95
Gd	15.4	36.0	5.50	32.6	14.9	17.6	19.0	24.2	12.8	18.0	24.2	35.8
Tb	2.30	4.30	0.60	4.40	1.80	2.20	1.30	3.18	1.70	2.20	3.20	5.10
Dy	11.70	20.50	2.60	23.10	9.60	9.50	4.00	17.30	8.70	9.70	16.60	26.5
Ho	2.40	3.90	0.50	4.70	2.10	1.70	0.70	3.60	1.70	1.80	3.10	5.40
Er	6.90	11.30	1.60	12.70	7.10	5.00	1.90	9.80	4.70	5.10	9.40	15.1
Tm	1.00	1.50	0.20	1.80	1.10	0.70	0.20	1.60	0.70	0.70	1.40	2.20
Yb	6.40	9.30	1.50	11.4	7.0	4.20	0.90	9.50	4.20	4.20	8.30	12.9
Lu	0.90	1.50	0.20	1.60	1.0	0.60	0.10	1.40	0.60	0.60	1.20	1.90

Key to samples listed in Table 1.

112131; coarse porphyritic (augen) granite gneiss, Cape Leeuwin, south of lighthouse, AMG zone 50, 6194400N 328600E.
112132; even-grained granite gneiss, Sarge Bay, AMG zone 50, 6195300N 328600E.
112133; anorthosite, Cape Leeuwin Road near Skippy Rock Road turnoff, AMG zone 50, 6197300N 331200E.
112134; fine-grained granite, Cosy Corner, AMG zone 50, 6207800N 318200E.
112135; augen gneiss, Redmond Beach-Isaac Rock, north of monument, AMG zone 50, 6231077N 315300E.
112136; augen gneiss, Redmond Beach-Isaac Rock, AMG zone 50, 6231600N 315200E.
112140; grey fine-grained granite dyke, from coastal exposure south of Gracetown, AMG zone 50, 6249600N 313200E.
112141; coarse even-grained granite gneiss, from coastal exposure south of Gracetown, AMG zone 50, 6249600N 313200E.
112142; leucogabbro, coast north of Cowaramup Bay, AMG zone 50, 6252200N 313800E.
112143; medium-grained granite gneiss, coast north of Cowaramup Bay, sampling site is 20 m north of 112142, AMG zone 50, 6252200N 313800E.
112144A; coarse porphyritic (augen) granite gneiss, headland south of Smith's Beach, Canal Rocks North, AMG zone 50, 6273700N 315500E.
112145; fine even-grained pink granulite facies granite, west of Meelup Beach at Gannet Rock, AMG zone 50, 6283900N 322400E.

1993), in combination with the new geochronological data obtained in this study, indicate that the precursors to the felsic gneisses were emplaced with highly negative ε_{Nd} values, and suggests that they were derived by the melting of crustal sources that included components formed during or prior to the middle Proterozoic.

The ages of the leucogabbro and anorthosite components of the Leeuwin Complex are uncertain. Black et al. (1992) state that McCulloch (unpublished data) obtained a SHRIMP U-Pb zircon age of about 700 Ma for a hornblende meta-anorthosite. However, insufficient zircon was recovered from a sample of anorthosite (112133) processed for dating as part of this study and it is possible that the zircons isolated by McCulloch from the hornblende meta-anorthosite sample may have been derived from the c. 685 Ma alkali granite precursors to the gneisses that vein the anorthosites in the southern part of the Leeuwin Complex. On the basis of field observations near Cape Leeuwin, the leucogabbro and anorthosite components are probably as old as, or older than, the c. 685 Ma alkali granite precursors to the gneisses in this area.

Proterozoic occurrences of leucogabbroic and anorthositic rocks are commonly associated with alkali granitic intrusions. Examples include the Laramie Anorthosite Complex, associated with K_2O-rich granitoid rocks of the Sherman batholith (Frost et al. 1994), the massif anorthosites of the Adirondack Mountains that occur with syenitic granites (McLelland et al. 1994), and the Chilka Lake Anorthosite complex of the Eastern Ghats of

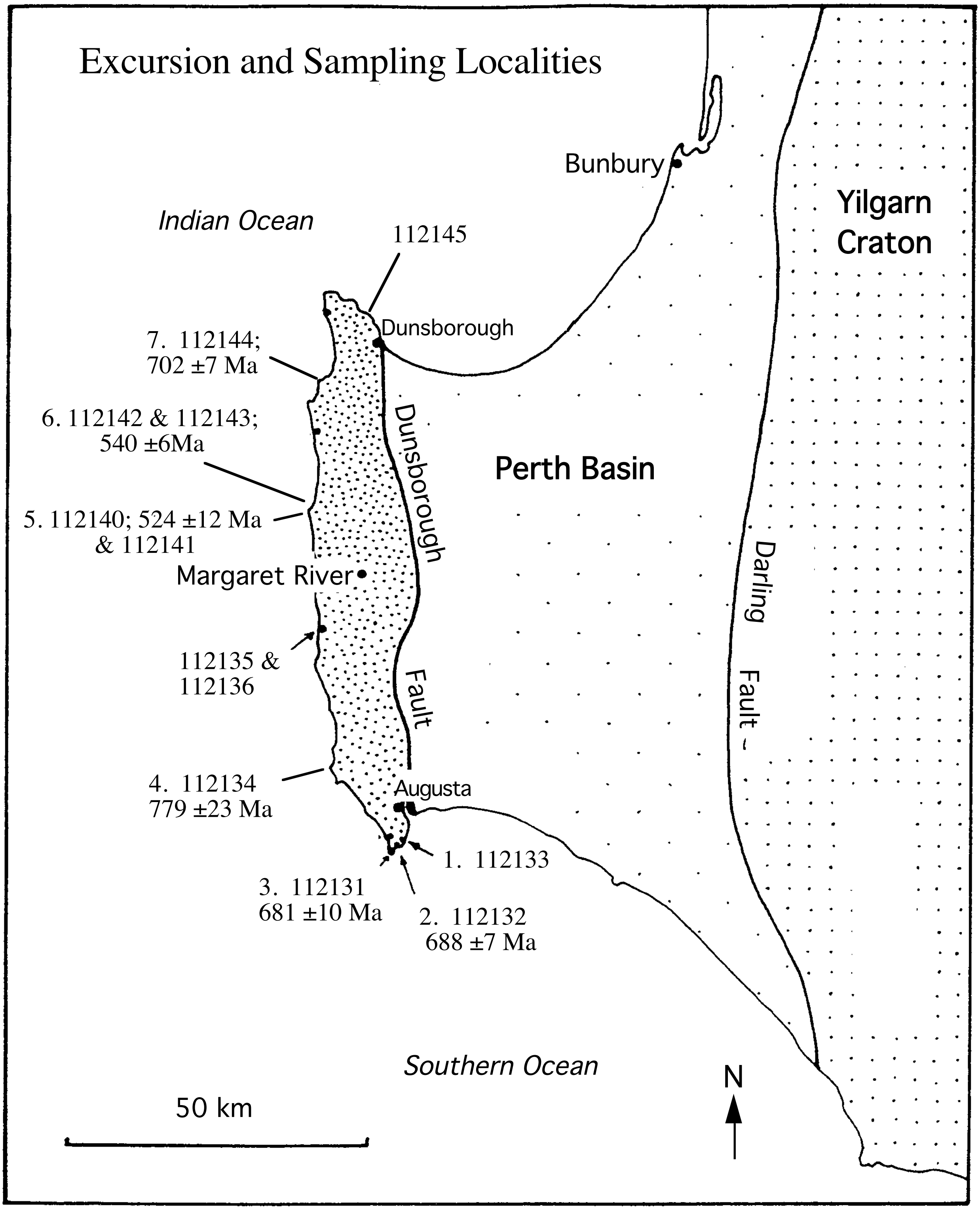

Figure 2. Excursion localities (numbered) and sampling sites for GSWA samples discussed in the text.

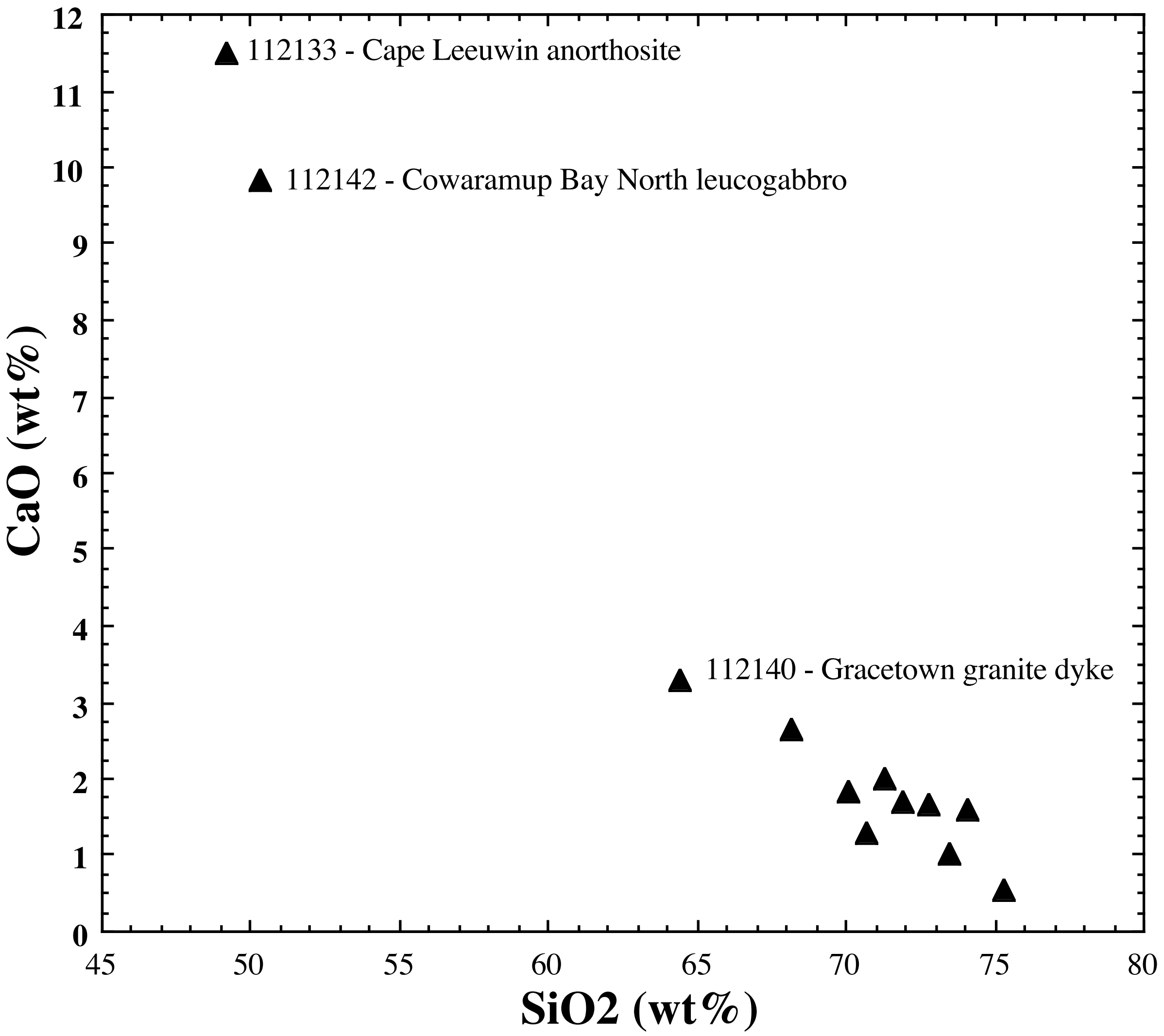

Figure 3. SiO_2 (wt%) versus CaO (wt%) for samples from the Leeuwin Complex.

India, argued by Sarkar et al. (1981) to be genetically related to closely associated alkali granites.

A plot of SiO_2 (wt%) versus CaO (wt%) for samples from the Leeuwin Complex is shown in Figure 3. The alkali granites define an array having a negative slope, possibly reflecting varying degrees of partial melting of a plagioclase-rich source region. This is consistent with the derivation of the granitoid magmas from a common lower crustal source. Geochemical data (presented below) suggest that the Gracetown granite dyke (112140) was derived from a chemically or mineralogically different source from the other granitic rocks. The Cowaramup Bay leucogabbro and the Cape Leeuwin anorthosite plot along an extension of the array defined by the alkali granites (excluding the Gracetown granite dyke, 112140).

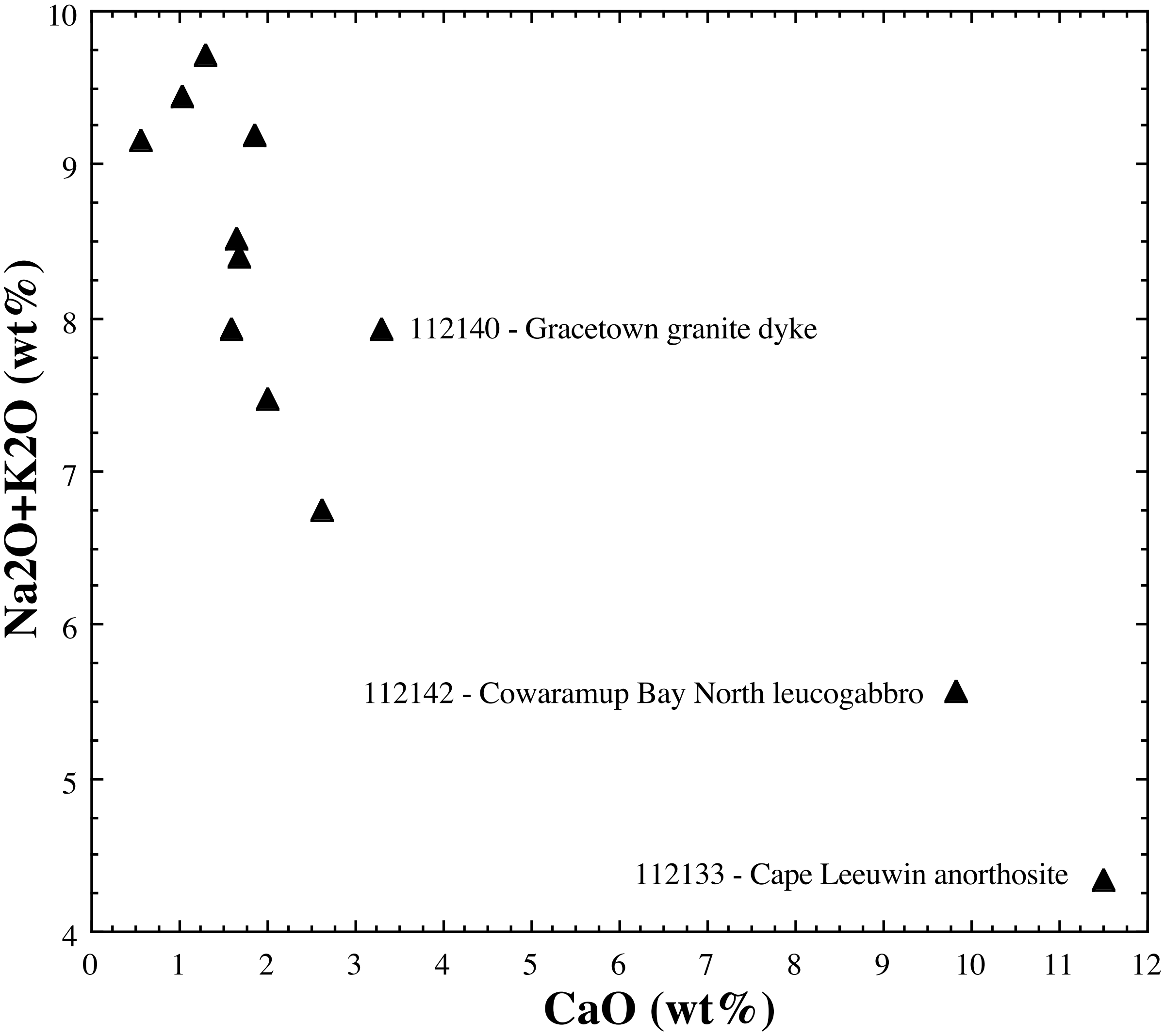

Figure 4. CaO (wt%) versus $Na_2O + K_2O$ (wt%) for samples from the Leeuwin Complex.

CaO (wt%) is plotted against $Na_2O + K_2O$ (wt%) for samples from the Leeuwin Complex in Figure 4. The alkali granites again define a steep array having negative slope on this plot. The array defined by the granitic rocks possibly also reflects varying degrees of partial melting of a plagioclase-rich source region, but may also have been influenced to some degree by feldspar fractionation during magmatic differentiation of the granitic magmas. A positive correlation is displayed by the alkali granites and leucogabbros on a plot of Sr versus CaO (see Fig. 5). These chemical trends are consistent with the hypothesis that the granitic magmas were derived by the partial melting of differentiated basaltic sources of similar composition to samples 112133 and 112142, followed by crystal fractionation.

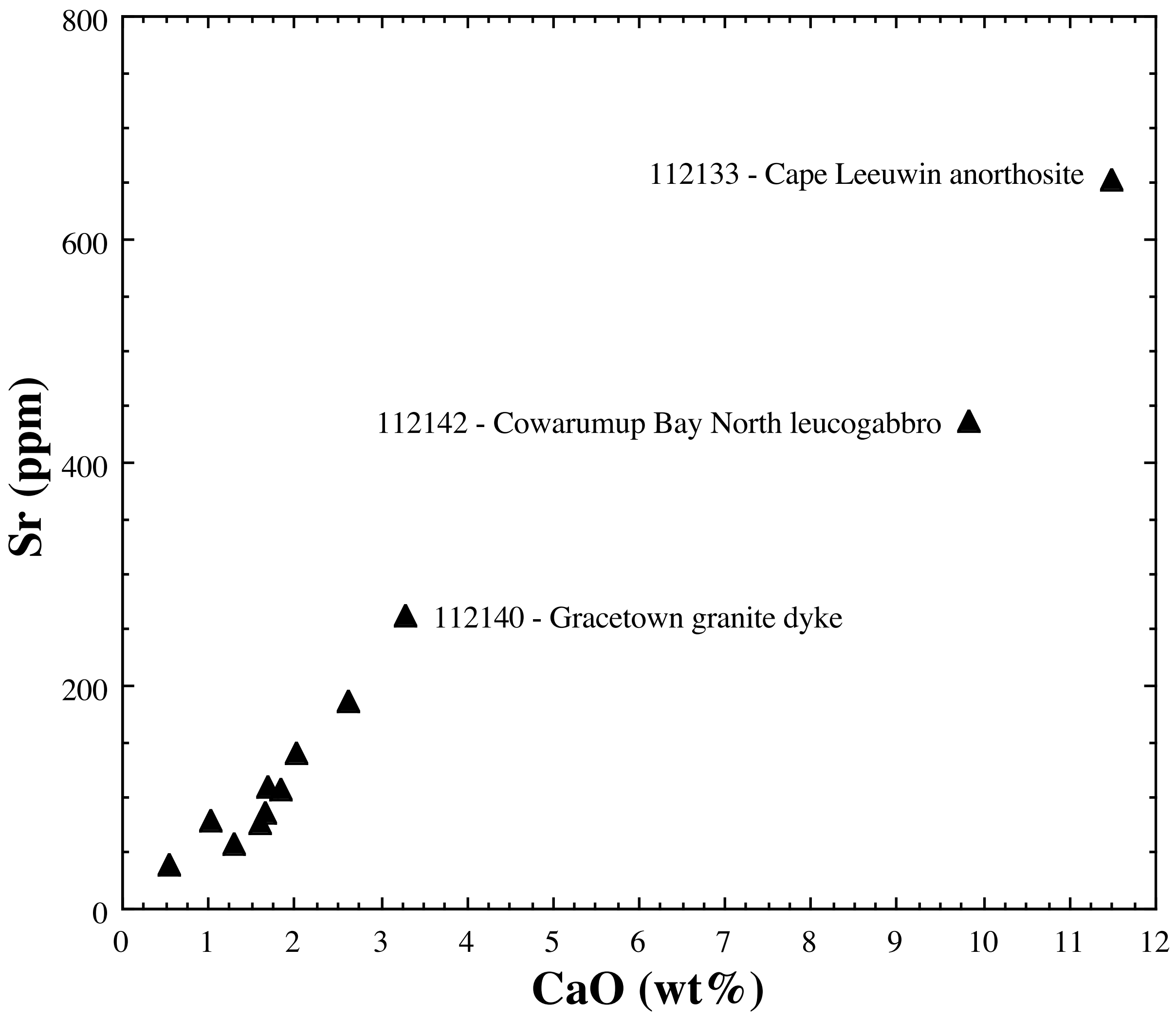

Figure 5. Sr (ppm) versus CaO (wt%) for samples from the Leeuwin Complex.

Rare earth element data for the Leeuwin Complex samples are displayed on a chondrite-normalized rare earth element diagram in Figure 6. The alkali granites display generally parallel patterns with slight enrichment in the light rare earth elements relative to the heavy rare earth elements, and with pronounced negative Eu anomalies. These patterns are typical of those of granitoid magmas derived from intracrustal sources where plagioclase is stable within the source. The similarity in the rare-earth element profiles (with the notable exception of 112140, the granite dyke from south of Gracetown) is again consistent with the hypothesis that the alkali granites were derived from a common crustal source.

Of particular interest are the patterns for the Cape Leeuwin anorthosite (112133) and the Cowaramup Bay leucogabbro (112142). The patterns for these samples are parallel to those of the alkali granites, but at considerably lower overall rare earth element abundances. The pattern of the Cowaramup Bay leucogabbro lacks a significant Eu anomaly and the Cape

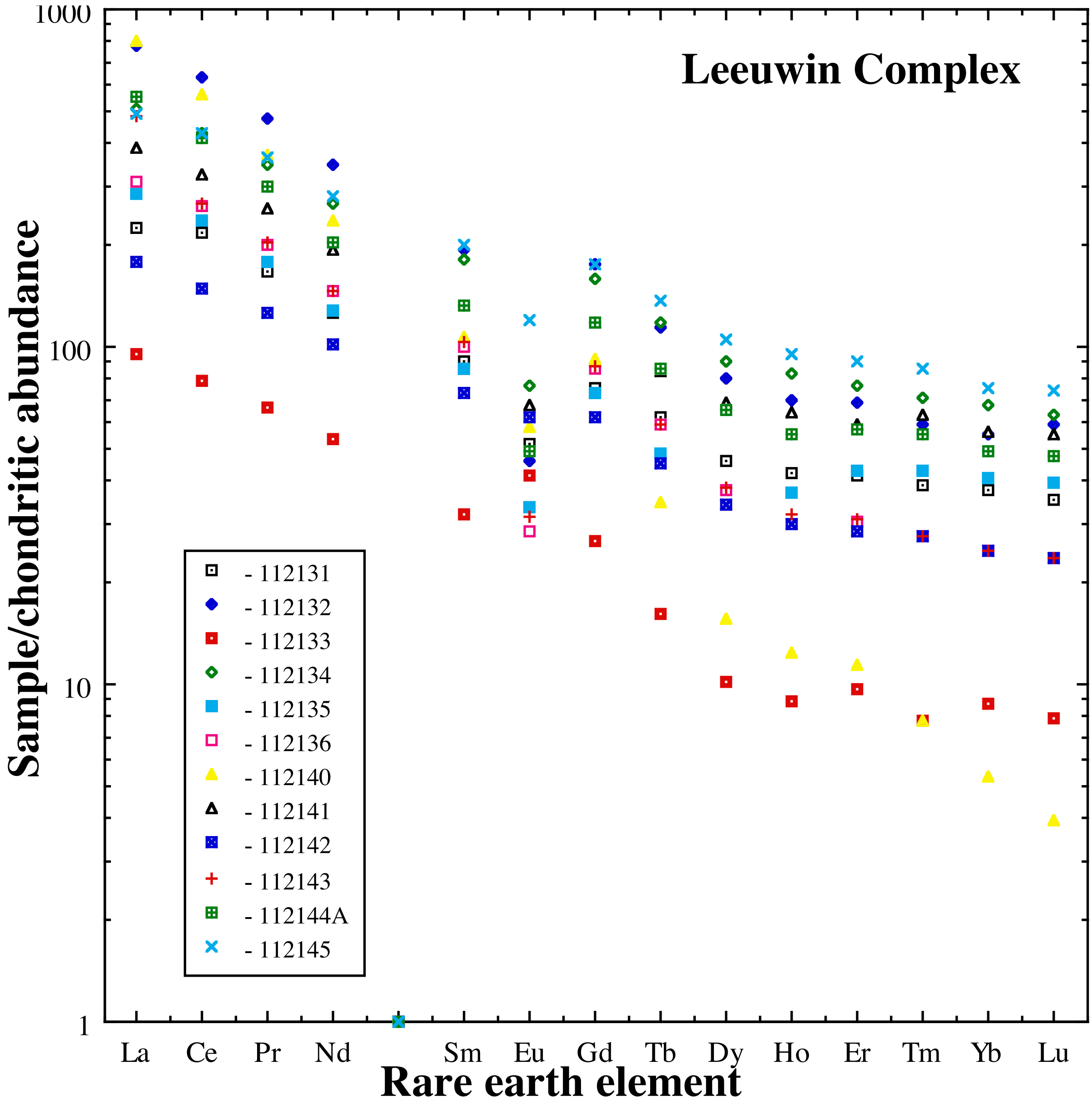

Figure 6. Chondrite-normalized rare earth element plot for samples from the Leeuwin Complex.

Leeuwin anorthosite pattern shows a positive Eu anomaly, consistent with an origin of the anorthosite from a differentiated mafic intrusion. These geochemical data indicate that the rare earth element patterns of the alkali granites could have been produced by the partial melting of lower crustal sources having rare earth element characteristics similar to those of the Cape Leeuwin anorthosite (112133) and the Cowaramup Bay leucogabbro (112142).

The rare earth element pattern of the Cowaramup Bay granite dyke (112140) is considerably steeper than those of the other granites, indicating that the granite dyke was derived from a chemically or mineralogically different source— possibly from a deeper, garnet-bearing source.

A positive correlation between CaO (wt%) and Eu/Eu* for samples from the Leeuwin Complex (not shown), with the anorthosite and leucogabbro samples plotting along an extension of the trend displayed by the alkali granite samples, demonstrates that the degree of the Eu depletion is strongly correlated with the CaO content of the samples. The negative Eu anomalies of the alkali granites may be due to retention of Eu within plagioclase-rich sources rather than high-level crystal fractionation processes.

PREVIOUS GEOCHRONOLOGY

Compston and Arriens (1968) obtained a combined Rb-Sr isochron age of 655 ±25 Ma on whole-rock and mineral samples of gneiss and pegmatite collected near Sugarloaf Rock. This was interpreted as the time of regional granulite facies metamorphism. Fletcher et al. (1985) and Fletcher and Libby (1993) reported Sm-Nd depleted mantle model ages of 2060 - 2010 Ma for gneisses recovered from boreholes penetrating the Perth Basin to the east of the Leeuwin Complex. It is, however, unclear whether these gneisses are part of the Leeuwin Complex. McCulloch (1987) and Fletcher and Libby (1993) obtained substantially younger Sm-Nd depleted mantle model ages of 1180 - 1135 Ma on gneisses from near Sugarloaf Rock and Sarge Bay. Wilde and Murphy (1990) reported a conventional U-Pb zircon date of 550 - 570 Ma from a granitic gneiss taken from an unspecified site near Meelup, northwest of Dunsborough. This was interpreted as dating igneous emplacement of the granitic precursor to the gneiss. A further two Sm-Nd model ages of 1290 and 1560 Ma were listed by Black et al. (1992) for Leeuwin Complex granitic gneisses from undisclosed localities. Black et al. (1992) also revealed that McCulloch (unpublished data) obtained SHRIMP U-Pb zircon dates of about 500 Ma and about 700 Ma for leucogranite and hornblende anorthosite samples from the Leeuwin Complex, but no further details about the samples or the results obtained were given.

New geochronology data obtained during the present study is discussed below, in reference to excursion localities.

GEOLOGICAL EVOLUTION OF THE LEEUWIN COMPLEX

The geological history of the Leeuwin Complex, inferred largely from the new data given in this guide, is summarized in Table 2. The field, petrographic and geochronological data given here indicate that peak metamorphic conditions occurred at c. 615 Ma, that the Complex experienced upper amphibolite facies metamorphism following emplacement of the 540 ±6 Ma alkali granite precursor to the Cowaramup Bay hornblende-biotite monzogranite gneiss (112143), and that the metamorphic grade was low during intrusion of the 524 ±12 Ma Gracetown biotite-hornblende monzogranite dyke.

Table 2. Summary of the geological history of the Leeuwin Complex.

U-Pb zircon age (Ma)	Interpretation
530	intrusion of granite dykes at low metamorphic grade
540	emplacement of alkali granite, deformation and recrystallization within the amphibolite facies during slow uplift and cooling
c. 615	metamorphism in the granulite facies
705 – 680	emplacement of alkali granite bodies
≥ c. 680	emplacement and differentiation of mafic intrusions within the lower crust (or ponding and differentiation of mafic magma at the crust-mantle boundary)
780	emplacement of alkali granite

The new data presented here can contribute to speculation about the origin of the Leeuwin Complex in the context of the late Proterozoic to early Phanerozoic development of Gondwana. Reconstructions of the relative positions of the Gondwana continents in the early Phanerozoic (cf. Oliver et al. 1983) generally place the southwest corner of Western Australia adjacent to the Bunger Hills region near the coast of east Antarctica. A conventional U-Pb zircon date of 516 ±1.5 Ma was obtained by Black et al. (1992) for a syenite from David Island, in the Denman Glacier region to the west of the Bunger Hills. Black et al. (1992) also obtained a SHRIMP U-Pb zircon lower concordia intercept date of 567 ±49 Ma, interpreted as the time of high-grade metamorphism, from a tonalitic orthogneiss from Cape Charcot, further to the west of the Denman Glacier. Based on garnet-whole rock Sm-Nd dating, Hensen and Zhou (1995) argued that gneisses from the Prydz Bay region of east Antarctica, about 750 km to the west of the Denman Glacier, had also experienced a granulite facies metamorphic event at c. 500 Ma. Furthermore, the Lützow-Holm and Yamato-Belgica Compexes, located more than 2400 km to the west of the Denman Glacier on the Prince Olav Coast, also record a high-grade regional metamorphism and deformation event between 555 - 520 Ma (Shiraishi et al. 1994). These studies indicate that late Proterozoic to early Phanerozoic (or Pan-African) metamorphism may have affected a large region of east Antarctica. Significantly, throughout east Antarctica, this metamorphic episode is generally a high-temperature, low-pressure event (Tingey 1991, Hensen and Zhou 1995), as in the Leeuwin Complex. These results indicate that high-grade metamorphism in the Leeuwin Complex and in parts of east Antarctica were roughly synchronous and that these areas share at least part of a common geological history.

Some continent reconstructions of Gondwanaland in the early Phanerozoic place northern India adjacent to the present west coast of Western Australia, so it is instructive to compare the geological evolution of the Leeuwin Complex with that of India. Within the Southern Granulite domain of southern Peninsular India, alkali granites and syenites were emplaced between 750 - 500 Ma, and charnockites have been dated at between 564 - 540 Ma (see summary given by Unnikrishnan-Warrier et al. 1993). Anorthosite complexes occur in association with alkaline intrusions in the Eastern Ghats region of India. One of these, the Chilka Lake Anorthosite, has been dated by the whole-rock Rb-Sr method at c. 1400 Ma (Sarkar et al. 1981). A high-grade metamorphic event between 610 and 550 Ma is also documented for Sri Lanka (Shirashi et al. 1994 and references cited therein). Although there is considerable debate about the relative positions of India, Sri Lanka and Antarctica during the early Phanerozoic, it is likely that parts of southern and eastern India, Sri Lanka, east Antarctica and the Leeuwin Complex of Western Australia share part of a common geological history.

The ‘A-type’ (or anorogenic) granitic magmatism and the metamorphism of the Leeuwin Complex has been linked to accretion of newly-formed crust to the Yilgarn Craton (Wilde and Murphy 1990), but there is no evidence that the Leeuwin Complex formed in proximity to the Yilgarn Craton. Instead, as with parts of the Albany-Fraser Orogen (Nelson et al. 1995), it appears likely that the Leeuwin Complex is an exotic continental fragment that once formed part of present-day east Antarctica, and that it has been tectonically transported (possibly by early strike-slip movement along the Darling Fault) to its present position in Western Australia during the early break-up of the Gondwana continents and the movement of India northwards relative to Australia and Antarctica.

EXCURSION LOCALITIES

LOCALITY 1: ANORTHOSITE , CAPE LEEUWIN -SKIPPY ROCK ROADS

At this locality (Cape Leeuwin Road north of Skippy Rock Road turnoff, AMG zone 50, 6197300N 331200E), a coarse-grained anorthosite containing labradorite (An_{62}), olive-green hornblende and minor opaques, titanite, accessory apatite, chlorite, biotite, phrenite, microcline, muscovite and calcite, can be seen. Deformation is heterogeneous and the rock has been thoroughly recrystallized under medium to high grade conditions, but igneous textures are preserved. Large (up to 50 mm diameter) deformed relict orthopyroxene oikocrysts are preserved and irregular diffuse pegmatitic melt patches and veins are common.

According to Myers (1990, 1994), the anorthosite occurs in a belt about 1.5 km wide that may represent a large isoclinal fold with undulating sub-horizontal plunge.

Geochemical data obtained on a sample from this site (112133) is given in Table 1. This sample did not contain sufficient zircon for analysis.

LOCALITY 2: HORNBLENDE GRANITE GNEISS, SARGE BAY

An even-grained granite gneiss occurs at this locality (AMG zone 50, 6195300N 1328600E). A sample (GSWA 112132) was taken at Sarge Bay, north of the Leeuwin Road to Cape Leeuwin lighthouse and immediately east of the junction with the Skippy Rock road. A geochemical analysis is given in Table 1. The sample is a medium-grained (c. 1 mm) granoblastic gneiss, consisting of perthite/microcline, quartz and plagioclase with lesser hornblende (dark green hastingsite with low 2V), minor biotite and accessory opaques, titanite, apatite and zircon. Distinctive features are the relatively low quartz content for a granite and the abundant accessory zircon and titanite. The original rock was an iron-rich granite, metamorphosed to medium grade or lowest high grade.

Heavy minerals were isolated from about 550g of the sample using conventional heavy-liquid and magnetic techniques. Most of the zircons extracted were clear to pale yellow, subhedral to anhedral, averaging 200 x 75 μm in size and lacking obvious internal structure. Many had mineral and fluid inclusions. This sample was analysed on the Perth SHRIMP on 6th January 1995. Seven analyses of the CZ3 standard were obtained during the analysis session and indicated a Pb*/U calibration error of 1.12 (1σ%). Similar low ^{204}Pb counts were measured on both standards and sample zircons for this and all other samples discussed herein, and common Pb corrections were made using the measured ^{204}Pb abundance and assuming Broken Hill Common Pb.

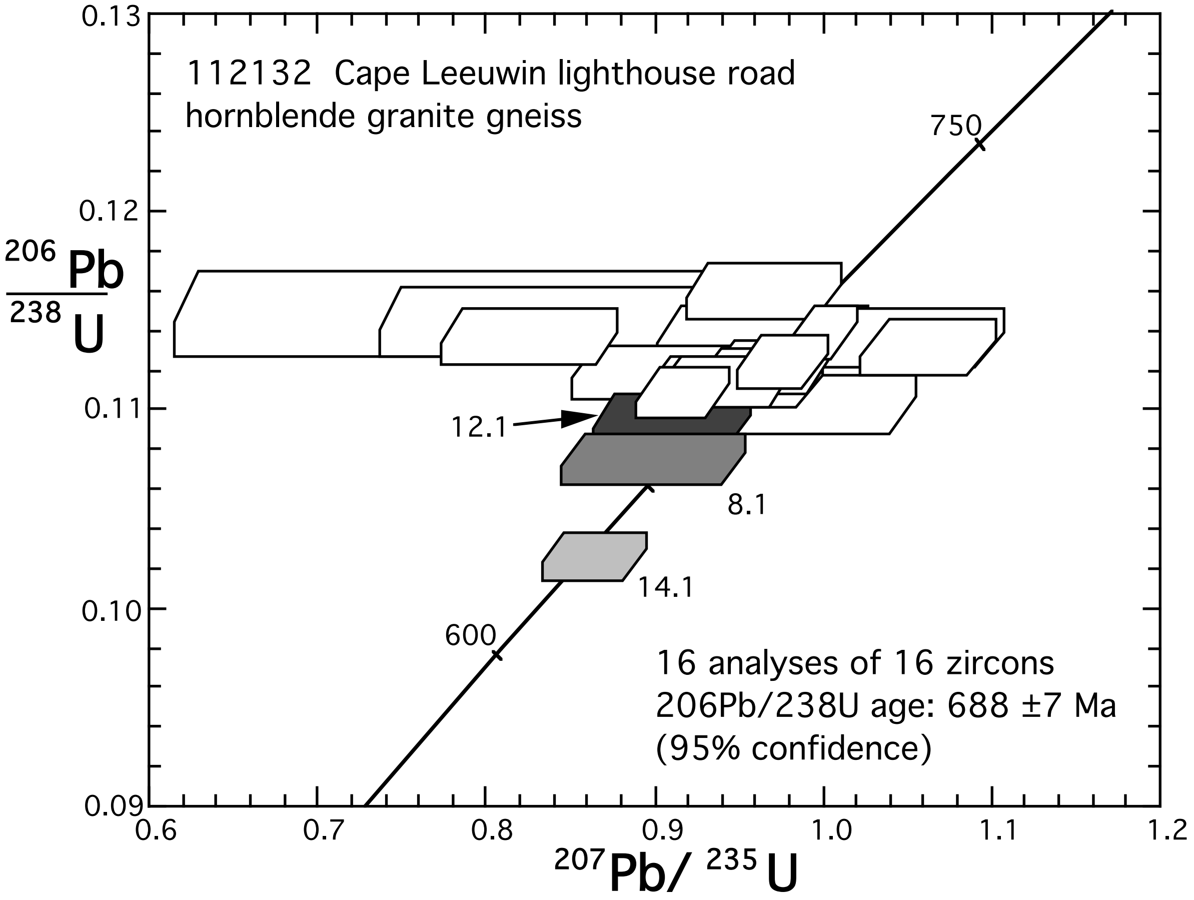

Figure 7. Concordia diagram for 112132, granite gneiss from the Leeuwin lighthouse road.

Nineteen analyses were obtained on 19 zircons. Results are shown on a concordia plot in Figure 7. Sixteen analyses have $^{206}Pb/^{238}U$ ratios almost within error of a single value (chi-squared = 1.11) indicating an age of 688 ±7 Ma. This is interpreted as the time of granite crystallization. Three analyses (12.1, 8.1 and 14.1) have $^{207}Pb/^{206}Pb$ ratios indistinguishable from the main population but have slightly lower $^{206}Pb/^{238}U$ ratios. These zircons have probably been disturbed during the metamorphic event following crystallization of the granite precursor to the gneiss.

LOCALITY 3: HORNBLENDE GRANITE GNEISS, CAPE LEEUWIN

The rock platform south of the Cape Leeuwin lighthouse (AMG zone 50, 6194400N 328600E) consists of coarse porphyritic (augen) granite gneiss. A geochemical analysis of a sample of this gneiss (112131) is given in Table 1. The gneiss consists of a coarse-grained (c. 2 mm), moderately foliated granoblastic assemblage of perthite/microcline, quartz and oligoclase, with lesser hornblende, minor biotite and accessory opaques, apatite and zircon. Minor garnet is also present. Microcline crystals are up to 6 mm across and enclose small quartz and plagioclase grains. Plagioclase crystals are commonly up to 2 mm across. Many feldspar grains are separated by a narrow zone of clear albite or untwinned K-feldspar. Hornblende is a dark green hastingsitic variety with low 2V, and forms trains which outline the foliation in the rock. Biotite forms thin plates, up to 3 mm long, and commonly shows dark oxidized margins. The original rock was an iron-rich granite, metamorphosed to medium grade or lowest high grade.

Heavy minerals were isolated from about 500g of sample using conventional heavy-liquid and magnetic techniques. Most of the zircons extracted from this sample were clear to pale yellow, subhedral to anhedral or metamorphically rounded and corroded, averaging 200 x 75 μm in size and lacking obvious internal structure. Many had mineral and fluid inclusions. This sample was analysed on the Perth SHRIMP on 25th January 1995. Eight analyses of the CZ3 standard were obtained during the entire session and indicated a Pb*/U calibration error of 1.53 (1σ%).

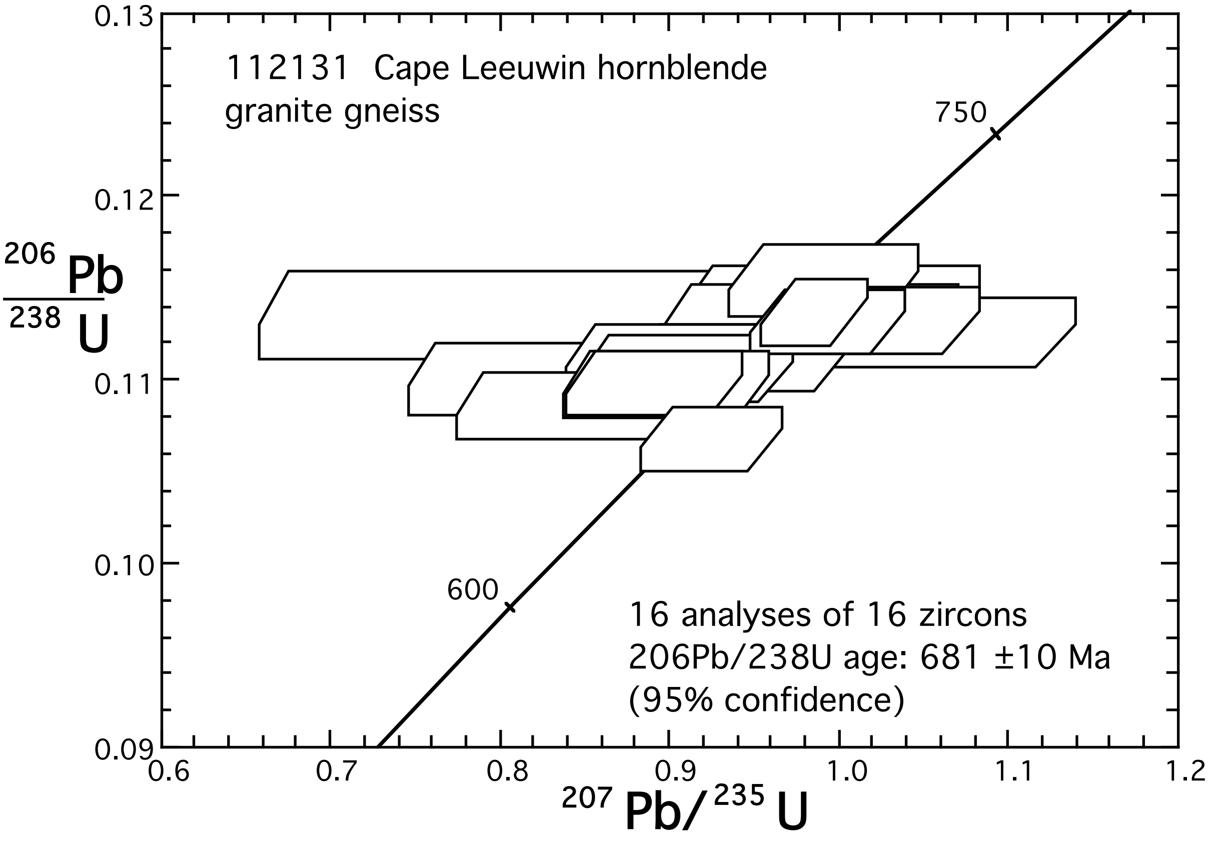

Figure 8. Concordia diagram for 112131, the Cape Leeuwin lighthouse granite gneiss.

Sixteen analyses were obtained on 16 zircons. Results are shown on a concordia plot in Figure 8. All sixteen analyses have ^{206}Pb/^{238}U ratios almost within error of a single value (chi-squared = 1.49) indicating an age of 681 ±10 Ma. This is interpreted as the time of granite crystallization.

LOCALITY 4: GRANITE GNEISS, COSY CORNER

An even-grained granitic gneiss occurs at Cosy Corner (AMG zone 50, 6207800N 318200E). The gneiss is medium- to coarse-grained, strongly foliated and granoblastic. Principal minerals are perthite, quartz and albite, with minor opaque oxides and altered amphibole, and accessory titanite, zircon, calcite and chlorite. Much of the perthite has unmixed to microcline with veins of albite, and to discrete grains of microcline and poorly twinned albite. A few grains of original plagioclase are probably oligoclase in composition. Original amphibole has been altered to secondary iron oxides, fringed by arfvedsonite. Titanite forms rounded blebs throughout the rock. The gneiss contains nebulous melt patches and has been intruded by coarse pegmatite dykes that post-date the main phase of deformation. GSWA sample 112134 was taken from among the boulders to the west of the car park. A geochemical analysis of this sample is given in Table 1.

Heavy minerals were isolated from about 550g of sample using conventional heavy-liquid and magnetic techniques. Most of the zircons extracted were clear to pale yellow, subhedral to anhedral, averaging 350 x 100 μm in size and lacked obvious internal structure. Many had mineral and fluid inclusions. This sample was analysed on 14th January 1995. Seven analyses of the CZ3 standard obtained during the analysis session indicated a Pb*/U calibration error of 2.80 (1σ%).

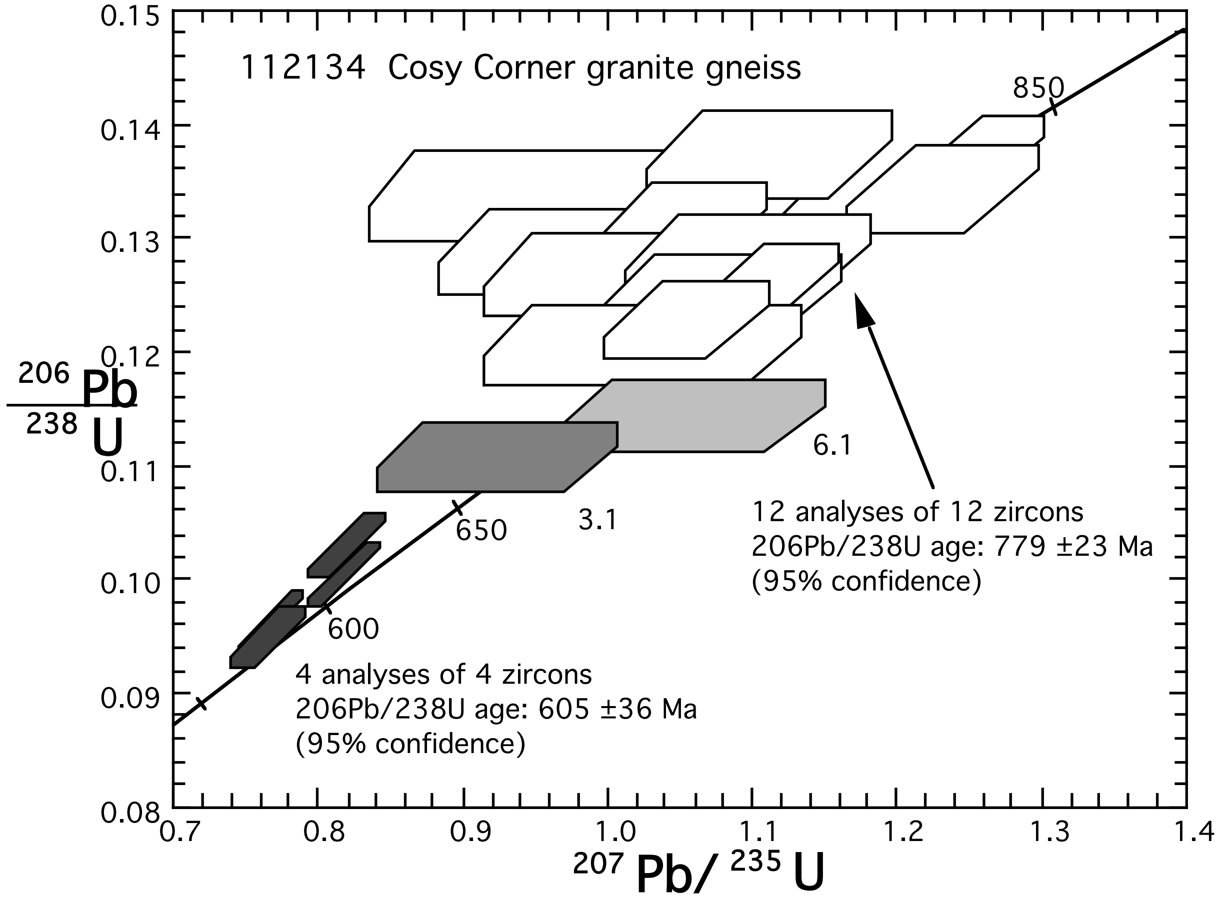

Figure 9. Concordia diagram for 112134, the Cosy Corner granite gneiss.

Eighteen analyses were obtained on 18 zircons. Results are shown on a concordia plot in Figure 9. All analyses can be placed into 4 groups. Group 1, consisting of twelve analyses, have $^{206}Pb/^{238}U$ ratios almost within error of a single value (chi-squared = 1.98) indicating an age of 779 ±23 Ma. This is interpreted as the time of granite crystallization. Groups 2 and 3, consisting of one analysis each (analyses 3.1 and 6.1 respectively), have slightly lower $^{206}Pb/^{238}U$ ratios and are probably disturbed members of Group 1 or are of sites that include both Groups 1 and 4 components. Group 4, consisting of 4 analyses (4.1, 7.1, 14.1 and 17.1), of zircons morphologically similar to those of the other groups but having substantially higher U concentrations (650 to 1327 ppm) and lower Th/U ratios, and have $^{206}Pb/^{238}U$ ratios almost within error of a single value (chi-squared = 1.45) indicating an age of 605 ±36 Ma. These zircons were probably derived from the nebulous melt patches. If this interpretation is correct, Group 4 analyses probably indicate the time of peak metamorphic conditions.

LOCALITY 5: BIOTITE-HORNBLENDE MONZOGRANITE DYKE, GRACETOWN

Along the coast about 1 km south of Gracetown (AMG zone 50, 6249600N 313200E), a grey fine-grained granite dyke can be seen to cut across the foliation in the granite gneiss at a high angle. The foliation in the gneiss has been deformed into open folds, and lenses of amphibolite are present. The dyke is even-grained, unfoliated and contains oligoclase, quartz and microcline, with lesser biotite and green hornblende, minor titanite and metamict allanite and accessory opaques, zircon, apatite and secondary calcite. Microcline forms subhedral crystals up to 2 mm across, often sieved with small blebs of quartz, and possibly originating from a granophyric intergrowth. Biotite and hornblende are commonly associated, with biotite replacing hornblende in part. Titanite is colourless and forms large masses up to 1.5 mm across. Metamict allanite forms crystals up to 1 mm across. The texture of the rock is essentially igneous and metamorphism has been low grade. The original rock was probably a mafic-rich monzogranite. A geochemical analysis of a sample taken from the dyke (112140) is given in Table 1.

Heavy minerals were isolated from about 660g of sample using conventional heavy-liquid and magnetic techniques. The zircons extracted were typically colourless to light green-yellow, euhedral to subhedral, averaging 150 x 250 μm in size. Igneous zonation could be seen in many crystals, whereas others lacked obvious internal structure. Extensive irregular pitting, possibly resulting from disruption during the polishing process, of metamict zones or melt inclusions incorporated into the crystals, was evident in most grains. Fluid inclusions were common. The sample was analysed on 7th Febuary 1995. Eight analyses of the CZ3 standard were obtained during the analysis session and indicated a Pb*/U calibration error of 2.46 (1σ%).

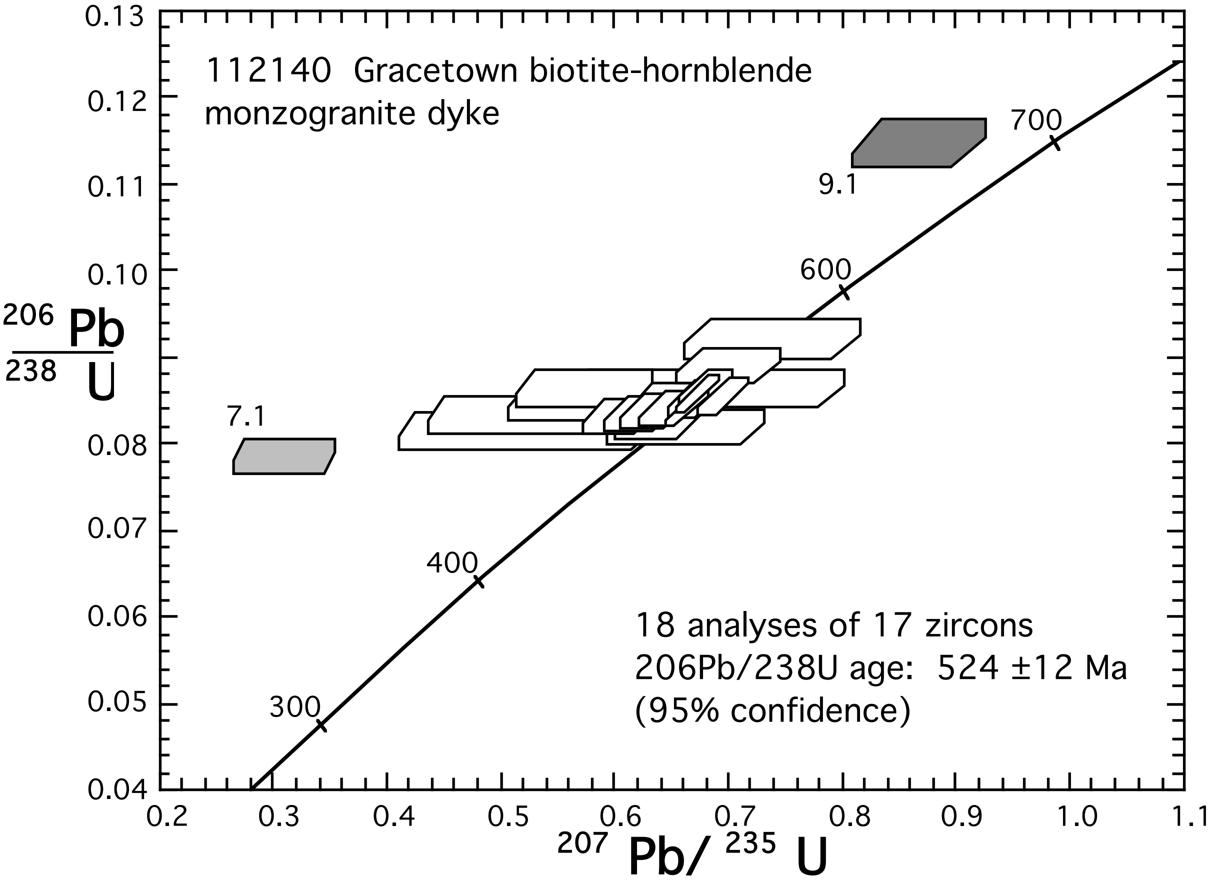

Figure 10. Concordia diagram for 112140, the Gracetown monzogranite dyke.

Twenty analyses were obtained on 19 zircons. Results are shown on a concordia plot in Figure 10. Eighteen analyses have ^{206}Pb/^{238}U ratios almost within error of a single value (chi-squared = 1.29) corresponding to an age of 524 ±12 Ma. This is interpreted as the best estimate of the time of crystallization of the monzogranite dyke. The ^{207}Pb/^{235}U age is analytically indistinguishable (517 ±12 Ma, chi-squared = 0.95) from the ^{206}Pb/^{238}U age, indicating that the population is concordant. The ^{207}Pb/^{206}Pb age is 505 ±25 Ma. Analysis 9.1 has a ^{206}Pb/^{238}U age of 699 ±17 (1σ error) and is probably a xenocryst. For analysis 7.1, the selection of Broken Hill common Pb appears to be inappropriate. Its ^{206}Pb/^{238}U age of 487 ±12 Ma (1σ error) is slightly lower than that of the main population, either because an inappropriate common Pb composition has been assumed or because of disturbance.

LOCALITY 6: HORNBLENDE-BIOTITE MONZOGRANITE GNEISS, COWARAMUP BAY NORTH

Granite gneiss, metagabbro and anorthosite occurs along the coast about 1 km north of Cowaramup Bay (AMG zone 50, 625220N 313800E). Unlike the gneisses seen so far, which generally have a steeply dipping, northerly-trending foliation, the gneiss at this locality has a weak subhorizontal foliation and weathers to form large blocky tors. A sample of the gneiss (112143) consisted of a medium-grained mosaic of quartz, oligoclase and microcline, with minor hornblende, opaques and biotite and accessory muscovite, apatite, titanite and zircon.

The average grain-size is <1 mm, the mineral orientation is negligible but there appears to be minor layering in the felsic minerals. Plagioclase twinning is poorly developed or absent; the untwinned plagioclase is often antiperthitic, containing small blebs of microcline. Hornblende is an olive-green/brown variety, and biotite is a red-brown titaniferous variety. The original rock was an iron-rich monzogranite and metamorphism is medium grade.

Heavy minerals were isolated from about 830g of sample using conventional heavy-liquid and magnetic techniques. The zircons extracted from this sample were typically colourless to light green-yellow, euhedral to subhedral, and small, averaging 60 x 100 μm in size. Igneous zonation could be seen in some crystals, but most lacked obvious internal structure. The sample was analysed on 10th Febuary 1995. Seven analyses of the CZ3 standard obtained during the analysis session indicated a Pb*/U calibration error of 1.11 (1σ%).

Nineteen analyses were obtained on 19 zircons. Results are shown on a concordia plot in Figure 11. All analyses have ^{206}Pb/^{238}U ratios almost within error of a single value (chi-squared = 1.46) corresponding to an age of 540 ±6 Ma. This is interpreted as the best estimate of the time of crystallization of the monzogranite precursor to the gneiss. The ^{207}Pb/^{235}U age is analytically indistinguishable (538 ±5 Ma, chi-squared = 1.94) from the ^{206}Pb/^{238}U age, indicating that the population is concordant. The ^{207}Pb/^{206}Pb age is 532 ±10 Ma.

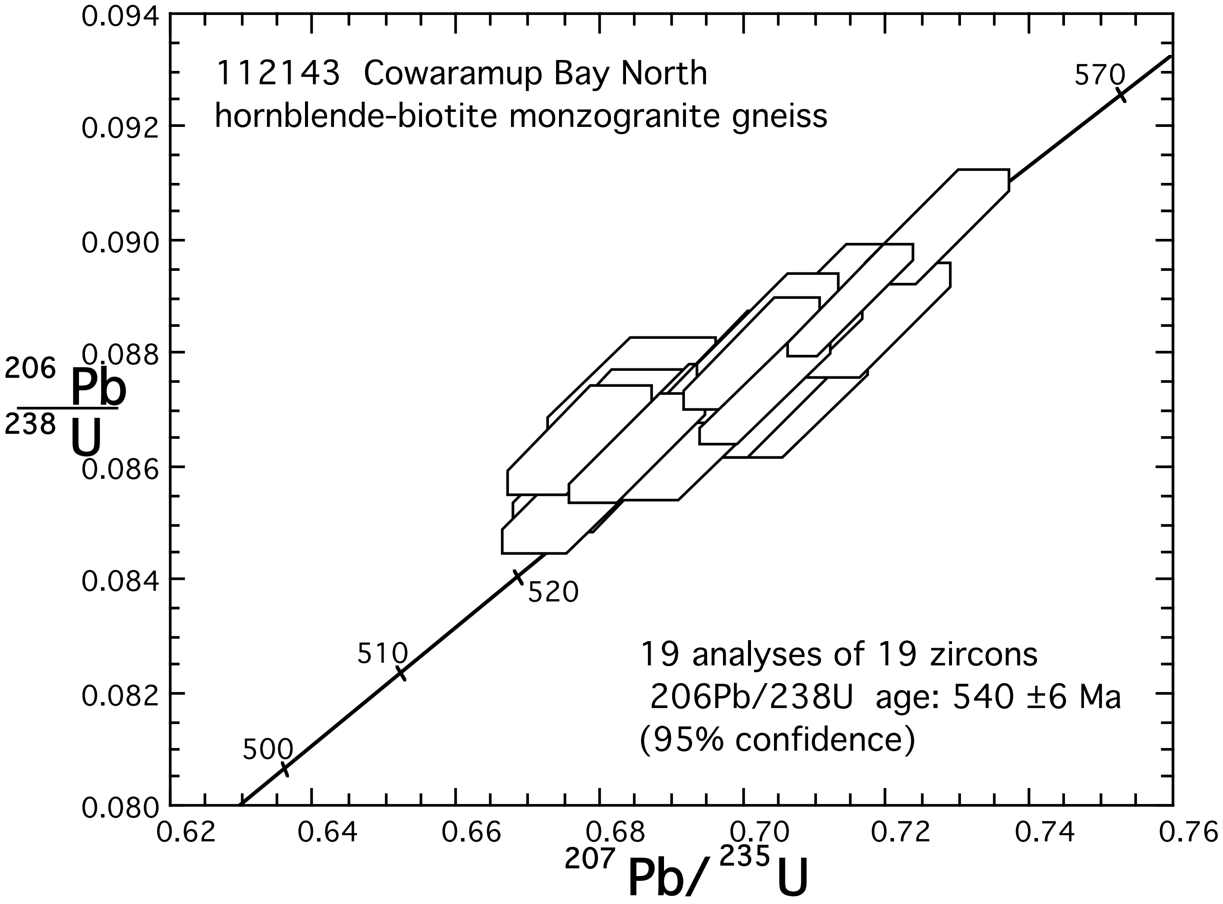

Figure 11. Concordia diagram for 112143, the Cowaramup Bay North monzogranite gneiss.

LOCALITY 7: HORNBLENDE-BIOTITE MONZOGRANITE GNEISS, CANAL ROCKS NORTH

A coarse porphyritic (augen) granite gneiss occurs on the headland south of Smiths Beach (AMG zone 50, 6273700N 315500E). Geochemical data on a sample (112144A) of this gneiss are listed in Table 1. The rock is a medium- to coarse-grained (0.5 - 4 mm), moderately foliated granoblastic gneiss containing perthite, quartz, hornblende and plagioclase with accessory biotite, opaques, apatite and zircon. Plagioclase occurs mostly as untwinned albite in large patches of myrmekitic intergrowth. The hornblende is a dark olive-green hastingsitic variety with low 2V. The original rock was granitic and metamorphism is medium grade.

Heavy minerals were isolated from about 615g of sample using conventional heavy-liquid and magnetic techniques. The zircons extracted from this sample were typically colourless to light golden-yellow, euhedral to subhedral, and large, averaging 200 x 450 μm in size. Igneous zonation and small fluid and opaque inclusions could be seen in most crystals. The sample was analysed on 14th Febuary 1995. Seven analyses of the CZ3 standard obtained during the analysis session indicated a Pb*/U calibration error of 0.99 (1σ%).

Twenty-three analyses were obtained on 23 zircons. Results are shown on a concordia plot in Figure 12. All analyses can be assigned to 4 groups. Group 1, consisting of 14 analyses, have ^{206}Pb/^{238}U ratios indicating a small amount of excess scatter (chi-squared = 2.10) and corresponding to an age of 702 ±7 Ma. For group 1 analyses, the ^{207}Pb/^{235}U age is analytically indistinguishable (705 ±8 Ma, chi-squared = 2.01) from the ^{206}Pb/^{238}U age, indicating that the population is concordant, and the ^{207}Pb/^{206}Pb age is 721 ±23 Ma. The ^{206}Pb/^{238}U age of group 1 analyses is interpreted as the best estimate of the time of crystallization of the monzogranite precursor to the gneiss. Group 3, consisting of 4 analyses (4.1, 9.1, 10.1 and 17.1), have ^{206}Pb/^{238}U ratios indicating a small amount of excess scatter (chi-squared = 1.50) and corresponding to an age of 625 ±14 Ma. The ^{207}Pb/^{235}U age is 634 ±30 Ma (chi-squared = 1.94). Group 3 analyses may give the time of a metamorphic disturbance event. The 4 analyses assigned to group 2 are interpreted to be of sites consisting of both Groups 1 and 3 components. Analysis 2.1 has a ^{206}Pb/^{238}U age of 560 ±6 Ma and ^{207}Pb/^{235}U age of 561 ±12 Ma (1σ error).

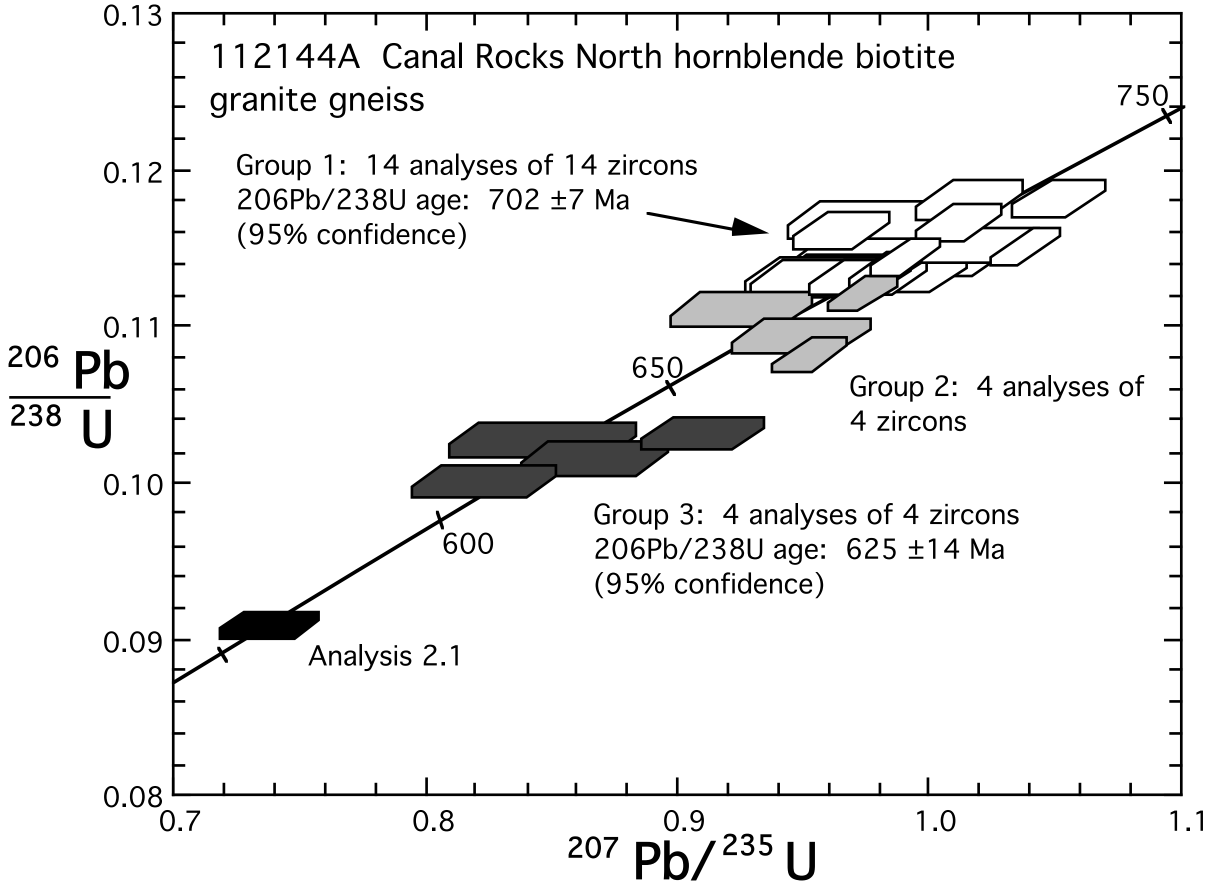

Figure 12. Concordia diagram for 112144A, the Canal Rocks North monzogranite gneiss.

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