

3.6 GEOCHEMISTRY

3.6.1 Introduction

The fundamental premise of the concept of S- and I-type granitoids, which was initially based on batholiths from southern New South Wales (Chappell and White, 1974) and extended by Chappell (1978) to the New England Batholith, is that granitoid compositions reflect the nature and composition of the respective source rocks. Thus, granitoids derived from source rocks which have experienced a sedimentary cycle should possess characteristics which clearly distinguish them from granitoids derived from pre-existing igneous source rocks. For example, if granitoids are very aluminous, depleted in Na and Ca, and enriched in K, it can be concluded that the source material was probably a sediment, rich in clays and relatively impoverished in coarser terrigenous detritus.

3.6.2 General Chemical Characteristics of S-Type Granitoids

Chappell and White (1974) considered that in granitoids the chemical feature which most successfully and most consistently indicates derivation from sedimentary source rock is a low sodium content. Thus, most S-type granitoids from southern New South Wales have high molecular ratios of $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO})$, i.e. > 1.1 , and consequently display high normative corundum (i.e. commonly $\geq 1\%$). This is usually reflected by the mineralogy, which includes aluminous minerals such as garnet and cordierite, and less commonly Al_2SiO_5 polymorphs.

Because of the ubiquitous presence of carbon and sulphur in sediments, granitoids derived from sediments tend to have low $\text{Fe}^{3+}/\text{Fe}^{3+} + \text{Fe}^{2+}$ ratios, i.e. rarely above 0.25 but frequently less than 0.2 (Chappell, 1978). Hence magnetite is characteristically absent.

Other chemical features which characterize S-type granitoids, and distinguish them from their I-type counterparts, include higher MgO, FeO and TiO_2 , and usually higher amounts of certain trace elements, e.g. Rb, Zr, Zn, Y, Ba, Cr, Ni and Cu (Hine *et al.*, 1978; Chappell, 1978). Furthermore, S-type granitoids display high SiO_2 contents, reflecting their relatively high modal quartz. In addition, the variation of SiO_2 within a suite of S-type granitoids is generally limited to a small range (Chappell and White, 1974; Hine *et al.*, 1978).

Although many features of the Hillgrove Suite fit the above criteria for S-type granitoids it will be shown that there are also some significant differences between the Hillgrove Suite granitoids and the S-type granitoids from southern New South Wales.

3.6.3 Major and Trace Element Chemistry

Chemical analyses, mesonorms and selected ratios of representative granitoids belonging to the Hillgrove Suite are listed in Table 3.12. Variations of the chemical data are graphically depicted using Harker diagrams in Figure 3.7. From these it can be seen that the Hillgrove Suite granitoids range continuously in composition from the most-mafic phase of the Dundurrabin Granodiorite (64.2% SiO₂) to the most-felsic phase of the Hillgrove Adamellite (75.5% SiO₂). Minor felsic segregations in a number of plutons and several mafic xenoliths extend this range of compositions at the high- and low-SiO₂ ends of the variation diagrams respectively.

The most mafic pluton of the Hillgrove Suite is the Abroi Granodiorite (66.4 - 68.3% SiO₂); hence samples from this pluton display high TiO₂, Al₂O₃, Fe₂O₃, FeO, MnO, MgO, CaO, P₂O₅, Sr, Zr, Nb, Zn and Cr, and low K₂O and Rb, relative to the Ingleba Adamellite which is the most felsic (72.9% SiO₂). The most-mafic xenolith analyzed comes from the Dundurrabin Granodiorite (62.9% SiO₂). This and other mafic xenoliths from the Hillgrove Suite have compositions which are remarkably continuous on variation diagrams with the trends defined by the main plutons. Al₂O₃ and Sr which show slight deviations are the only exceptions to this continuity. At the high-SiO₂ end the felsic segregations similarly continue the trends with the exception of the Rb which often does not display the characteristic late-stage enrichment in felsic granitoids (Taylor, 1965).

Most of the major element variation patterns for the Hillgrove Suite granitoids are essentially straight-line trends which show negative correlations against SiO₂ and include TiO₂, FeO, MnO, MgO, CaO and P₂O₅. K₂O also defines a straight-line trend; however, its correlation with SiO₂ is positive. The data points for Al₂O₃, Fe₂O₃ and Na₂O are somewhat more scattered but show a weak negative correlation against SiO₂. Compared to the relatively well-defined trends for the major elements, trace element trends for the Hillgrove Suite samples are notably broader. Nevertheless, moderately good negative correlations against SiO₂ are defined by Sr, Zr, Nb, Zn, Cr and Li, whereas Rb and Pb show positive correlations.

Table 3.12 Major and trace element analyses and C.I.P.W. norms of representative samples from granitoids of the Hillgrove Suite.

Sample No.†	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Catalogue No.	HRA	K14	SHKK	KKF	TOBA	WTOBA	ABGD	AB9	AB6	WOLL	RVGD	RVKY4	RVT10	RVT7
	46026	46027	46028	46029	46030	46031	46032	46033	46034	46035	46036	46037	46038	46039
<i>Oxides (wt.%)</i>														
SiO ₂	70.4	70.1	69.6	70.6	67.7	69.6	66.4	66.9	68.3	70.7	67.2	68.5	68.1	68.6
TiO ₂	0.54	0.59	0.59	0.62	0.69	0.54	0.77	0.73	0.69	0.58	0.71	0.62	0.61	0.62
Al ₂ O ₃	13.9	13.9	13.8	14.1	14.6	14.5	14.7	14.6	14.6	14.0	14.7	14.5	14.6	14.4
Fe ₂ O ₃	0.59	0.82	1.10	0.54	0.85	0.45	1.17	0.51	0.41	0.43	0.79	0.56	0.48	0.78
FeO	2.87	2.76	2.58	3.24	3.53	2.79	3.90	4.05	4.13	2.82	4.03	3.32	3.10	2.99
MnO	0.08	0.08	0.08	0.07	0.09	0.07	0.11	0.10	0.10	0.06	0.11	0.08	0.08	0.09
MgO	1.03	1.12	1.17	1.25	1.56	1.15	1.78	1.71	1.68	1.09	1.66	1.44	1.11	1.48
CaO	1.81	2.03	2.25	2.59	2.35	2.14	2.73	2.53	2.43	2.02	2.45	2.29	2.73	2.12
Na ₂ O	3.24	3.23	3.12	4.00	3.15	3.27	3.27	3.39	3.36	3.19	3.10	3.26	3.44	3.12
K ₂ O	4.08	4.03	3.78	2.21	3.82	4.05	3.32	3.39	3.51	4.17	3.53	3.74	3.85	4.08
P ₂ O ₅	0.12	0.11	0.12	0.12	0.17	0.13	0.18	0.18	0.15	0.10	0.20	0.14	0.15	0.14
S	0.02	0.005	0.01	*	0.06	*	0.06	0.03	0.03	0.01	0.06	0.01	0.02	0.01
H ₂ O	1.0	1.0	1.3	0.9	1.2	1.1	1.3	1.3	0.8	0.8	1.2	1.2	1.3	1.2
O=S	0.01	-	-	-	0.03	-	0.03	0.01	0.01	-	0.03	-	0.01	-
Total	99.67	99.78	99.50	100.24	99.74	100.09	99.66	99.41	100.18	99.97	99.71	99.66	99.56	99.63
Mg	39.0	42.0	44.7	40.8	44.6	42.4	44.9	42.9	42.0	40.8	42.3	40.2	35.9	46.9
C.I.	10.0	11.3	12.4	14.2	13.3	11.2	15.5	14.4	14.0	11.3	13.7	13.0	14.5	12.2
D.I.	80.5	79.7	78.1	76.6	74.9	78.9	71.7	72.7	74.3	80.3	72.9	76.1	76.1	77.2
<i>Trace Elements (ppm)</i>														
Rb	166	155	143	99	147	167	128	131	144	167	144	141	147	163
Sr	131	134	128	213	184	149	199	197	179	144	179	170	178	142
Y	35	36	37	34	34	39	34	33	41	35	34	31	30	32
Pb	21	21	22	16	24	*	22	23	21	25	24	22	22	31
Zr	215	214	218	219	191	167	204	208	187	214	192	200	188	203
Nb	8	8	8	9	9	8	9	10	9	8	9	7	8	8
Zn	64	64	74	50	86	*	100	76	74	60	126	74	66	78
Cr	20	20	20	30	30	25	35	50	30	25	30	40	20	20
Ni	5	5	40	-	-	12	5	-	-	-	-	-	5	10
Cu	24	24	24	10	28	*	36	32	26	20	54	18	24	34
Li	42	28	29	22	36	*	36	46	34	38	42	46	25	27
K/Rb	204	215	220	185	216	201	216	215	202	207	203	220	218	208
Rb/Sr	1.27	1.16	1.18	0.46	0.80	1.12	0.64	0.66	0.80	0.16	0.80	0.83	0.83	1.15
<i>C.I.P.W. Norms</i>														
Q	29.0	28.6	29.4	29.7	25.7	27.3	24.4	24.0	25.2	28.7	25.9	26.4	24.2	26.7
Or	24.1	23.8	22.3	13.1	22.6	23.9	19.6	20.0	20.7	24.6	20.9	22.1	22.7	24.1
Ab	27.4	27.3	26.4	33.9	26.6	27.7	27.7	28.7	28.4	27.0	26.2	27.6	29.1	26.4
An	8.2	9.3	10.4	12.1	10.5	9.8	12.4	11.4	11.1	9.4	10.8	10.4	12.6	9.6
C	1.1	0.8	0.8	0.7	1.4	1.2	1.1	1.2	1.2	0.8	1.8	1.3	0.2	1.3
Di	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hy	6.6	6.3	5.9	7.7	8.7	6.9	9.6	10.3	10.5	6.7	9.9	8.3	7.2	7.7
Mt	0.9	1.2	1.6	0.8	1.2	0.7	1.7	0.7	0.6	0.6	1.1	0.8	0.7	1.1
Il	1.0	1.1	1.1	1.2	1.3	1.0	1.5	1.4	1.3	1.1	1.3	1.2	1.2	1.2
Ap	0.3	0.3	0.3	0.3	0.4	0.3	0.4	0.4	0.3	0.2	0.5	0.3	0.3	0.3
Pr	0.0	-	0.0	-	0.1	-	0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.0
100 An/(An+Ab)	23.0	25.5	28.2	26.3	28.4	26.1	30.9	28.4	28.0	25.8	29.3	27.5	30.2	26.7

† See Appendix I

* not determined

- below detection limit

Mg = 100 Mg/Mg + Fe²⁺

C.I. = Colour Index

D.I. = Differentiation Index

Cont.../2.

Table 3.12 continued. Major and trace element analyses and C.I.P.W. norms of representative samples from granitoids of the Hillgrove Suite.

Sample No. †	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
Catalogue No.	HGA	HH270	HH272	HH273	FHG	CT13	LHGA	CT5	HH271	DUND	FDUND	DUNDX	LDUND	BKA	ENA	LENA
<i>Oxides (wt.%)</i>																
SiO ₂	68.8	74.7	72.6	68.3	74.9	75.5	77.4	66.3	67.1	69.7	64.2	62.9	75.4	71.0	69.5	77.2
TiO ₂	0.63	0.26	0.46	0.59	0.25	0.12	0.10	0.75	0.72	0.62	0.79	1.18	0.14	0.52	0.59	0.08
Al ₂ O ₃	14.5	12.8	13.5	15.4	12.8	12.7	12.8	15.0	14.2	14.4	16.0	14.4	12.4	14.0	14.2	12.2
Fe ₂ O ₃	0.78	0.38	0.59	0.51	0.34	0.11	0.14	0.78	0.87	0.50	1.00	1.70	0.21	0.66	1.06	0.20
FeO	2.99	0.93	1.64	2.76	1.21	0.90	0.25	4.47	4.28	3.38	4.12	5.58	0.79	2.54	2.52	0.14
MnO	0.08	0.02	0.05	0.06	0.04	0.03	0.01	0.10	0.13	0.10	0.17	0.28	0.03	0.08	0.08	0.01
MgO	1.27	0.33	0.66	1.04	0.44	0.15	0.04	2.15	1.91	1.16	1.64	2.52	0.24	1.07	1.08	0.06
CaO	2.24	1.09	1.54	2.30	1.05	0.53	0.59	3.40	4.53	2.32	3.51	4.03	1.19	1.64	2.02	0.58
Na ₂ O	3.16	2.73	3.03	3.70	3.12	3.32	3.42	3.32	3.36	3.64	4.50	3.43	3.60	2.98	3.24	3.08
K ₂ O	4.21	5.65	5.00	4.20	5.34	5.18	5.50	2.44	1.25	3.60	2.27	1.82	4.27	4.42	3.95	5.43
P ₂ O ₅	0.14	0.06	0.09	0.12	0.04	0.05	0.02	0.13	0.14	0.13	0.18	0.21	0.03	0.12	0.14	0.03
S	0.04	*	*	*	0.04	0.01	-	0.03	*	0.03	-	-	-	0.04	0.03	0.01
H ₂ O	1.0	0.6	0.6	0.7	0.6	0.7	0.5	0.9	1.2	0.8	1.2	1.6	0.8	1.0	1.2	0.5
O=S	0.02	-	-	-	0.02	-	-	0.01	-	0.01	-	-	-	0.02	0.01	-
Total	99.82	99.55	99.93	99.99	100.15	99.30	100.77	99.76	99.69	100.36	99.58	99.65	99.10	100.05	99.60	99.52
MG	43.1	38.7	41.8	40.2	39.3	22.9	22.2	46.2	44.3	38.0	41.5	44.6	35.1	42.9	43.3	43.3
C.I.	12.4	5.6	8.2	12.4	5.7	2.6	2.9	19.8	23.7	12.7	19.1	22.9	5.6	9.2	11.0	2.8
D.I.	77.8	90.6	86.2	79.0	90.7	93.2	96.5	67.1	64.0	78.2	68.7	60.6	90.6	81.7	79.4	95.4
<i>Trace Elements (ppm)</i>																
Rb	171	225	218	223	299	305	304	164	112	138	123	95	119	193	169	222
Sr	154	85	93	97	59	27	26	191	193	158	203	182	66	148	168	49
Y	31	24	32	32	39	28	48	30	25	36	84	42	41	30	33	24
Pb	26	*	*	*	28	24	29	18	*	20	18	14	24	28	25	24
Zr	189	139	238	234	127	87	107	185	135	210	289	219	80	200	206	77
Nb	8	4	8	11	7	4	5	8	8	8	8	10	3	7	8	5
Zn	76	*	*	*	40	30	6	94	*	98	80	120	18	70	82	8
Cr	20	10	19	34	10	10	5	80	39	20	30	50	14	30	30	5
Ni	5	6	8	11	-	-	-	10	15	-	-	-	-	-	-	-
Cu	42	*	*	*	22	4	4	28	*	36	16	40	12	40	52	32
Li	34	*	*	*	40	22	6	46	*	31	33	51	10	26	38	0.4
K/Rb	204	208	190	156	148	141	150	123	93	217	153	159	298	190	194	203
Rb/Sr	1.11	2.65	2.34	2.30	5.07	11.30	11.69	0.86	0.58	0.87	0.61	1.52	1.80	1.30	1.01	4.53
<i>C.I.P.W. Norms</i>																
Q	26.2	34.1	31.0	22.8	32.8	34.5	35.0	24.6	28.1	26.2	17.3	20.8	34.9	30.5	28.7	37.3
Or	24.9	33.4	29.6	24.8	31.6	30.6	32.5	14.4	7.4	21.3	13.4	10.8	25.2	26.1	23.3	32.1
Ab	26.7	23.1	25.6	31.3	26.4	28.1	28.9	28.1	28.4	30.8	38.1	29.0	30.5	25.2	27.4	26.1
An	10.2	5.0	7.1	10.6	4.9	2.3	2.8	10.6	20.0	10.7	16.2	18.5	5.0	7.3	9.1	2.7
C	1.0	0.4	0.5	0.9	0.1	0.8	0.2	1.0	-	0.6	0.2	-	-	1.6	1.3	0.3
Di	-	-	-	-	-	-	-	-	1.3	-	-	0.1	0.5	-	-	-
Hy	7.1	1.8	3.5	6.4	2.7	1.8	0.3	11.9	10.3	7.9	9.8	13.6	1.4	6.0	5.6	0.2
Mt	1.1	0.6	0.9	0.7	0.5	0.2	0.2	1.1	1.3	0.7	1.4	2.6	0.3	1.0	1.5	0.3
Il	1.2	0.5	0.9	1.1	0.5	0.2	0.2	1.4	1.4	1.2	1.5	2.2	0.3	1.0	1.1	0.2
Ap	0.3	0.1	0.2	0.3	0.1	0.1	0.1	0.3	0.3	0.3	0.4	0.5	0.1	0.3	0.3	0.1
Pr	0.1	-	-	-	0.1	0.0	-	0.1	-	0.1	-	-	-	-	-	-
100 An/(An+Ab)	27.6	17.8	21.6	25.3	15.8	7.6	8.8	36.3	41.3	25.3	29.9	39.0	14.3	22.6	24.9	9.3

† See Appendix I
 * not determined
 - below detection limit
 MG = 100 Mg/Mg + Fe²⁺
 C.I. = Colour Index
 D.I. = Differentiation Index

Table 3.12 continued. Major and trace element analyses and C.I.P.W. norms of representative samples from granitoids of the Hillgrove Suite.

Sample No. †	(31) ELA	(32) ELAX	(33) WBN24	(34) W	(35) KILB	(36) INGA	(37) ARG	(38) ARGX	(39) B10	(40) CDK	(41) TM2	(42) TM4	(43) LTM2	(44) GK6	(45) BA	(46) BS
Catalogue No.	46057	46058	46059	46060	46062	46063	46064	46065	46066	46067	46068	46069	46070	46071	460	46075
<i>Oxides (wt.%)</i>																
SiO ₂	68.7	68.9	68.8	70.3	68.6	72.9	68.2	69.0	69.0	74.0	70.4	69.7	75.2	71.5	72.8	76.4
TiO ₂	0.57	0.76	0.70	0.49	0.70	0.31	0.72	0.60	0.71	0.25	0.59	0.53	0.10	0.54	0.26	0.41
Al ₂ O ₃	14.2	13.9	14.1	13.9	14.4	13.3	14.7	14.6	14.6	13.0	14.5	14.7	13.6	14.2	14.3	11.1
Fe ₂ O ₃	0.76	0.79	0.58	0.35	0.46	0.35	0.31	0.41	0.96	0.53	0.58	0.25	0.04	0.93	0.13	0.39
FeO	2.32	3.27	3.27	2.31	3.69	1.45	2.99	3.62	3.24	1.32	3.13	3.24	0.83	1.90	1.60	2.68
MnO	0.07	0.10	0.09	0.04	0.09	0.04	0.10	0.11	0.10	0.06	0.10	0.09	0.04	0.07	0.04	0.07
MgO	1.58	1.27	1.35	1.74	1.54	0.44	1.35	1.34	1.30	0.44	1.63	1.49	0.24	0.87	0.54	0.72
CaO	3.00	2.77	2.49	1.77	2.35	1.10	2.64	2.35	2.69	1.36	2.35	2.08	0.82	1.84	1.56	0.87
Na ₂ O	3.15	3.20	3.19	3.48	3.27	3.24	3.47	3.70	3.43	3.08	3.96	3.46	3.46	3.43	3.08	2.30
K ₂ O	3.99	3.66	4.06	4.28	3.83	4.81	3.59	3.74	3.60	4.55	3.72	3.92	6.42	4.81	4.74	4.22
P ₂ O ₅	0.10	0.15	0.13	0.09	0.15	0.06	0.13	0.12	0.14	0.05	0.13	0.17	0.10	0.11	0.15	0.18
S	0.01	0.02	0.02	0.01	0.05	0.003	0.09	0.08	0.07	0.01	0.02	0.04	-	0.007	-	-
H ₂ O	1.2	0.8	0.9	1.0	0.9	1.0	0.8	0.6	0.8	1.0	0.8	0.8	0.6	0.7	0.53	0.6
OsS	-	0.01	0.01	-	0.02	-	0.04	0.04	0.03	-	0.01	0.02	-	-	-	-
Total	99.65	99.58	99.67	99.76	100.01	99.00	100.05	100.23	100.61	99.64	101.90	100.45	101.55	100.91	99.82	99.94
Mg	54.8	40.9	42.4	57.3	42.7	35.1	44.6	39.8	41.7	37.3	48.1	45.1	34.0	44.9	37.6	29.7
C.I.	16.0	15.0	13.9	11.2	13.4	5.8	14.6	13.2	14.7	7.2	13.7	11.8	3.2	9.9	7.7	4.9
D.I.	75.9	75.7	76.7	80.8	75.9	87.7	76.0	77.3	76.4	87.4	79.5	78.6	95.4	84.8	86.1	85.1
<i>Trace Elements (ppm)</i>																
Rb	182	157	162	172	152	280	148	96	122	187	144	144	207	212	*	277
Sr	115	125	137	145	171	68	249	241	265	105	175	175	65	124	*	40
Y	34	36	31	32	35	37	27	25	26	23	30	21	22	32	*	48
Pb	19	21	25	19	21	30	22	20	21	25	21	22	28	21	*	14
Zr	238	216	237	223	238	165	185	171	213	112	186	152	59	254	*	157
Nb	7	9	10	8	8	7	9	8	10	7	8	8	3	9	*	11
Zn	58	62	58	28	78	50	74	100	83	32	66	70	24	56	*	72
Cr	50	10	30	20	40	20	20	60	30	10	30	40	-	15	*	-
Ni	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-
Cu	22	44	30	20	26	16	30	36	28	14	20	18	10	15	*	12
Li	14	36	32	12	28	56	38	36	29	22	40	35	10	30	*	100
<i>C.I.P.W. Norms</i>																
Q	25.6	26.9	25.7	26.1	25.6	31.9	25.5	24.0	26.1	34.5	24.0	26.1	28.2	27.3	31.7	42.6
Or	23.6	21.6	24.0	25.3	22.6	28.4	21.2	22.1	21.3	26.9	22.0	23.2	37.9	28.4	28.3	24.9
Ab	26.6	27.1	27.0	29.4	27.7	27.4	29.4	31.3	29.0	26.1	33.5	29.3	29.3	29.0	26.1	19.5
An	12.8	12.8	11.5	8.2	10.7	5.1	12.2	10.9	12.4	6.4	10.8	9.2	2.6	8.4	6.8	3.1
C	-	-	0.2	0.5	1.0	0.9	0.6	0.5	0.5	0.7	-	1.4	-	0.3	1.6	1.6
Di	1.2	0.0	-	-	-	-	-	-	-	-	0.0	-	0.7	-	-	-
Hy	6.1	7.4	7.9	7.5	9.1	3.0	6.6	8.7	7.3	2.8	8.5	8.7	1.6	4.1	3.8	5.9
Mc	1.1	1.2	0.8	0.5	0.7	0.5	1.9	0.6	1.4	0.8	0.8	0.4	0.1	1.3	0.2	0.6
Il	1.1	1.4	1.3	0.9	1.3	0.6	1.4	1.1	1.3	0.5	1.1	1.0	0.2	1.0	0.5	0.8
Ap	0.2	0.3	0.3	0.2	0.3	0.1	0.3	0.3	0.3	0.1	0.3	0.4	0.2	0.3	0.4	0.4
Pr	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.2	0.1	0.0	0.0	0.1	-	-	-	0.0
100 An/(An+Ab)	32.5	32.0	29.9	21.8	27.8	15.6	29.4	25.8	30.0	19.8	24.4	23.9	8.2	22.5	20.6	13.9

† See Appendix I

* not determined

- below detection limit

Mg = 100 Mg/Mg + Fe²⁺

C.I. = Colour Index

D.I. = Differentiation Index

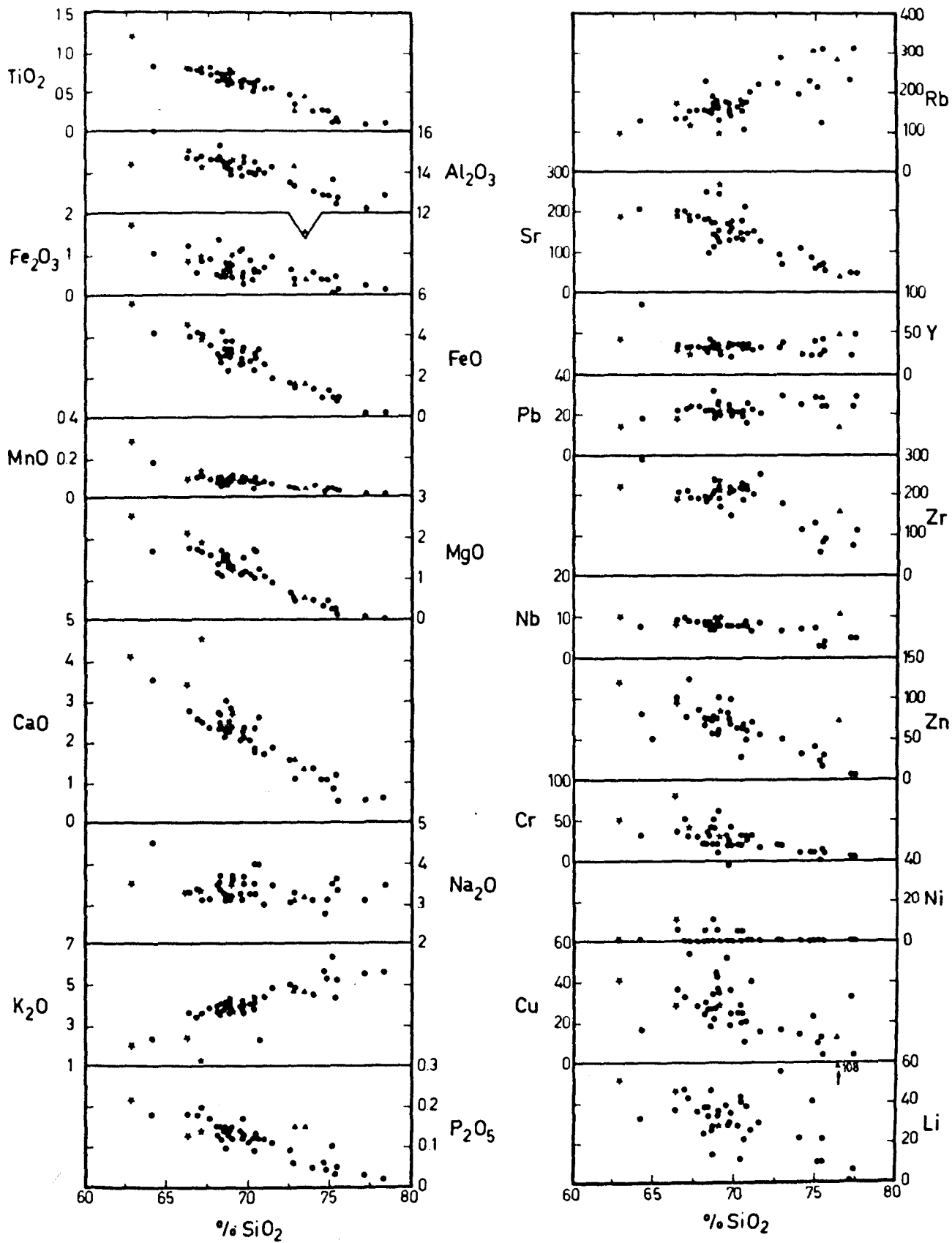


Figure 3.7 Variation diagrams for Hillgrove Suite granitoids. Stars represent xenoliths. Triangles represent samples from the Bundarra Suite. Major elements in weight %; trace elements in ppm.

The variation trends depicted in Figure 3.7 for the Hillgrove Suite granitoids are therefore consistent with interpretations that certain granitoids comprise mixtures of crystals and melt in different proportion (White and Chappell, 1977). Alternatively, the observed variations may be ascribed to the removal of varying amounts of minimum melt from compositionally uniform residual source rocks following mobilization (Hine *et al.*, 1978).

3.6.4 REE Chemistry

The REE abundances for ten selected members of the Hillgrove Suite were determined by J.D. Kleeman using instrumental neutron activation techniques. Results are listed in Table 3.13. The bracketed numbers deviate from their respective patterns and are therefore suspect.

The chondrite-normalized REE patterns for the Hillgrove Suite granitoids (Fig. 3.8) are all basically similar and show a moderate enrichment of LREE relative to HREE and a small to moderate negative Eu anomaly. La/Yb ratios, which provide a measure of fractionation between the LREE and HREE, range from 6.72 to 9.05 but show no systematic variation according to major element chemistry, SiO₂ in particular. However, the Eu anomaly (Eu/Eu*) increases from ~ 0.5 in the granodiorites to ~ 0.25 in the felsic granitoids.

Absolute abundances of Σ (determined) REE decrease slightly from the granodiorites (130 ppm) to the felsic granitoids (105). This decrease clearly corresponds to a decrease in the modal biotite, i.e. from about 16% in the granodiorite to about 6% in the felsic rocks; however, it also corresponds to a decrease in the proportion of accessory minerals, e.g. apatite, sphene, zircon and monazite, most of which occur as inclusions in the biotite. The correlation between modal biotite and REE abundances is further demonstrated by the amphibole-bearing variant of the Rockvale Granodiorite (T10; anal. 8; Table 3.13). In this sample amphibole has displaced some of the biotite, hence the amount of biotite is significantly lower than in rocks with comparable major element chemistries. Accordingly, Σ REE are low (110 ppm).

The Σ REE abundances for the Hillgrove Suite granitoids are well below the average amount of 250 ppm for granitoids given by Herrmann (1970) and below the amount for the average granodiorite of Taylor and White (1966). However, they approximate the REE abundances and patterns of S-type granitoids from the Corryong Batholith, south-eastern Australia (Price and Taylor, 1977) and felsic New Zealand extrusives (Taylor *et al.*, 1968).

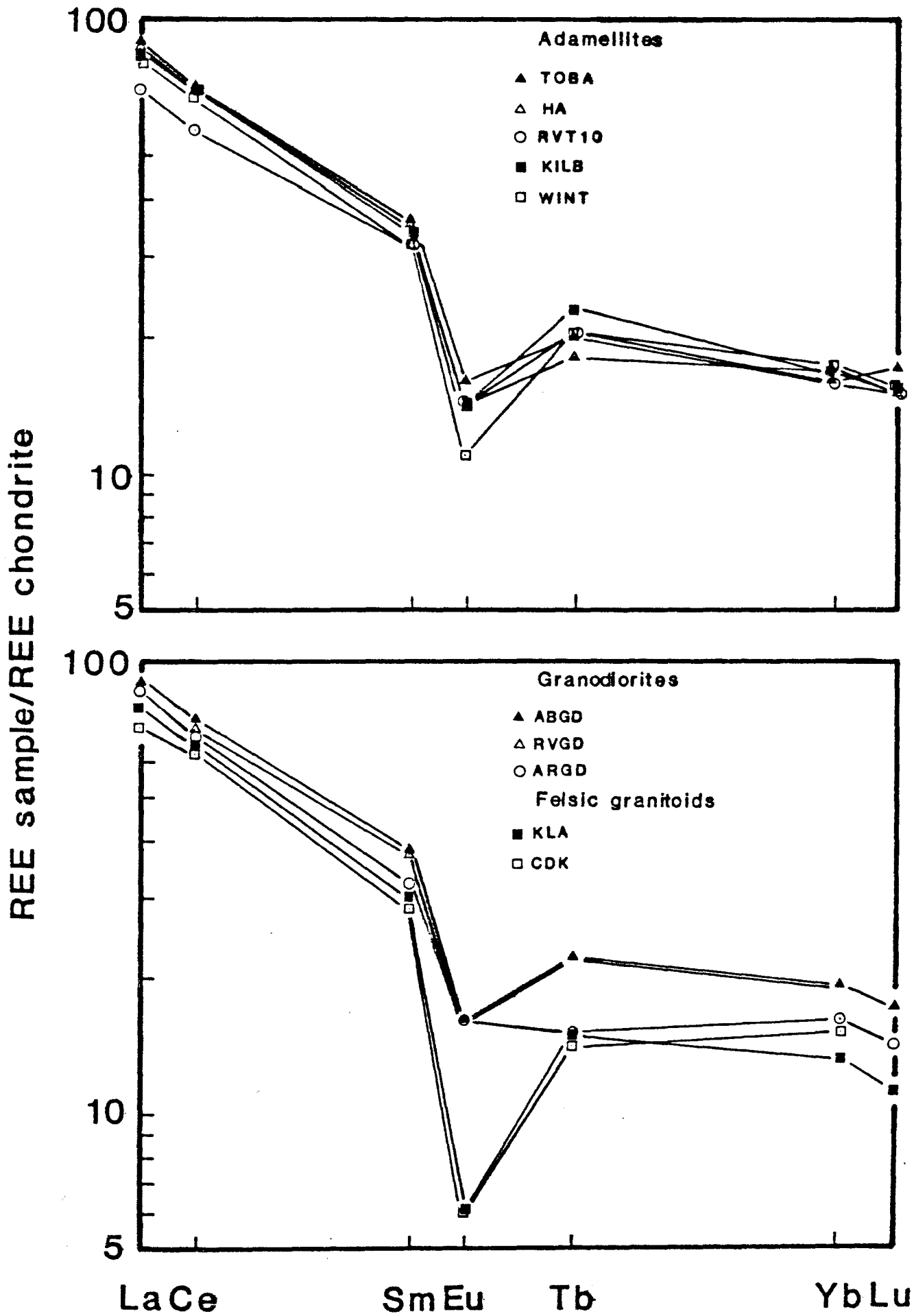


Figure 3.8 Chondrite-normalized REE patterns for Hillgrove Suite granitoids.

Table 3.13 REE abundances in Hillgrove Suite granitoids.

Sample No.	(1) ABGD	(2) RVGD	(3) TOBA	(4) HA	(5) KILB	(6) ARGD	(7) WINT	(8) RVT10	(9) KLA	(10) CDK
La	28.5	n.d.	28.0	27.4	26.9	27.0	25.1	22.1	24.8	22.4
Ce	60.2	57.7	57.5	57.3	56.6	55.6	55.3	46.1	52.9	50.1
Nd	n.d.	n.d.	n.d.	(38.5)	n.d.	n.d.	(32.0)	n.d.	(35.3)	n.d.
Sm	7.20	7.13	6.97	6.66	6.46	6.15	6.19	6.13	5.71	5.46
Eu	1.17	1.16	1.14	1.01	1.07	1.16	0.79	0.99	0.44	0.42
Tb	1.08	1.19	1.00	0.87	1.12	(0.75)	0.99	1.00	0.79	0.67
Yb	3.92	3.99	3.25	3.52	3.55	3.28	3.57	3.29	2.74	3.08
Lu	0.53	0.59	0.55	0.48	0.47	0.44	0.46	0.46	0.36	n.d.
La/Yb	7.27	-	8.62	7.78	7.58	8.23	7.03	6.72	9.05	7.27

n.d. - not detected

(1) - Abroi Granodiorite

(2) - Rockvale Granodiorite

(3) - Tobermory Adamellite

(4) - Hillgrove Adamellite

(5) - Kilburnie Adamellite

(6) - Argyll Granodiorite

(7) - Winterbourne Adamellite

(8) - Rockvale Granodiorite (amphibole-bearing variant)

(9) - Kimberley Adamellite (felsic variant)

(10) - Argyll Granodiorite (felsic variant)

3.6.5 Comparison of the Hillgrove Suite Major Element Chemistry to other S-Type Granitoids, and its Relation to the Criteria of Chappell and White (1974) for Defining S-Type Granitoids

The range of SiO₂ values for the Hillgrove Suite granitoids is well within Chappell and White's range of SiO₂ values for S-type granitoids and agrees very favourably to the range for S-type granitoids from the Kosciusko Batholith (Hine *et al.*, 1978). Some of the felsic variants of the Hillgrove Suite contain up to 75.5% SiO₂ and resemble members of the Bundarra Suite (Flood and Shaw, 1975).

The Hillgrove Suite granitoids contain approximately 1% more Na₂O than their S-type analogues in southern New South Wales. This difference in Na₂O content probably reflects a fundamental difference in the compositions of the sedimentary source rocks for the respective granitoids. Consequently, the important parameter of molecular Al₂O₃/(Na₂O + K₂O + CaO), used for distinguishing between S-type and I-type granitoids in southern New South Wales, cannot be successfully applied to the New England granitoids without slight modification. Chappell (1978) suggested that a value of 1.03 for this molecular ratio successfully discriminates between the S-type granitoids belonging to the Bundarra Suite and I-type granitoids from the southern end of the New England Batholith. Table 3.14 lists the molecular ratios of Al₂O₃/(Na₂O + K₂O + CaO) for the granitoids belonging to the Hillgrove Suite. According to Chappell (1978) this wide range of values (0.95 - 1.11) would indicate that both S-type and I-type granitoids were represented in the Hillgrove Suite. One interesting aspect of Table 3.14 is that the felsic variants of the Hillgrove Suite granitoids, with the exception of the sample from the Argyll Granodiorite, display *lower* molecular ratios of Al₂O₃/(Na₂O + K₂O + CaO) than their mafic counterparts. This may be due to their dissociation, by fractionation, from their peraluminous, restite-charged, more mafic hosts.

Fe³⁺/Fe³⁺ + Fe²⁺ ratios for Hillgrove Suite granitoids range from 0.09 to 0.33. This range is surprisingly wide and exceeds that for S-type granitoids from the Kosciusko Batholith (Hine *et al.*, 1978) and from the Bundarra Suite (Chappell, 1978). Chappell found that the Bundarra Suite granitoids could be readily distinguished from associated I-type granitoids using this ratio, which for all S-type granitoids was below 0.2. Therefore, the relatively higher Fe³⁺/Fe³⁺ + Fe²⁺ ratios for some Hillgrove Suite granitoids are not consistent with Chappell and White's conclusion that the two granitoid types may be successfully distinguished using this ratio. Possible reasons for this discrepancy and indeed for the wide range of values may include (i) the intense post-crystallization deformation suffered by many of the Hillgrove Suite plutons; (ii) differential exchange of H₂O between country rocks and granitoids during emplacement; and (iii) marked variations in the Fe³⁺/Fe³⁺ + Fe²⁺ ratios of the sedimentary source rocks.

In addition to SiO₂, the agreement between major element abundances for granitoids from the Hillgrove Suite, Bundarra Suite and S-type granitoids from the Kosciusko Batholith, is also very close, especially for TiO₂, MnO CaO and P₂O₅. In contrast, trace element abundances between these granitoids tend to show relatively poorer agreement.

Table 3.14 Molecular $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO})$ ratios for Hillgrove Suite plutons.

Henry River Adamellite	1.07
Kookabookra Adamellite	1.03 - 1.07
Tobermory Adamellite	1.08
Abroi Granodiorite	1.05 - 1.08
Wollomombi Adamellite	1.04
Rockvale Granodiorite	0.99 - 1.10
Hillgrove Adamellite	1.00 - 1.05 (xenolith = 1.05)
Blue Knobby Adamellite	1.11
Enmore Adamellite	1.07
Woodburn Adamellite	0.95 - 1.00
Eastlake Adamellite	0.98
Winterbourne Adamellite	1.02
Kilburnie Adamellite	1.04
Ingleba Adamellite	1.06
Argyll Granodiorite	1.01 - 1.02 (xenolith = 1.01)
Tia Granodiorite	0.98 - 1.07
Garabaldi Adamellite	1.00
Dundurrabin Granodiorite	0.99 - 1.02 (xenolith = 0.96)

FELSIC VARIETIES

Hillgrove Adamellite	0.98 - 1.01
Enmore Adamellite	1.02
Tia Granodiorite	0.96
Dundurrabin Granodiorite	0.98
Argyll Granodiorite	1.04

3.6.6 Chemical Comparison Between Hillgrove Suite Granitoids and New England Sediments

Psammo-pelitic rocks from several lithological associations surround the Hillgrove Suite granitoids (see Chapter 2). Felsic and mafic greywackes predominate, although in some areas pelitic rocks and conglomerates are also prominent. Cherts and calcareous sediments are minor.

In many areas, for example at Moona Plains, Wongwibinda and Tia, there is a complete textural gradation from incipiently metamorphosed greywackes, through schists to anatectic migmatites and granitoid segregations. The uncanny textural and mineralogical similarities between the highest grade metasediments and the Hillgrove Suite granitoids, combined with their intimate field relationships may suggest a close genetic relationship. To test the validity of this inference a wide range of sediments from New England were analyzed for major and trace elements (Table 3.15). Two analyses of mafic greywackes from the Baldwin Formation and three 'typical' Hillgrove Suite granitoids are also tabulated.

In general the chemical compositions of the sediments bear a strong resemblance to those of the Hillgrove Suite granitoids. However, for some of the major elements there are small but important differences. These include:

1. higher Al_2O_3 , FeO and K_2O and lower Na_2O in the pelites,
2. slightly higher Al_2O_3 and Na_2O and slightly lower TiO_2 , FeO and MgO in the felsic greywackes,
3. distinctly higher Al_2O_3 , CaO and distinctly lower K_2O in the mafic greywackes.

The Baldwin Formation greywackes have very distinctive chemistries and differ markedly from the granitoids, i.e. compared to the latter these mafic greywackes have much higher FeO, MgO, CaO, TiO_2 , Al_2O_3 and Na_2O , and much lower SiO_2 and K_2O .

A plot of K_2O v. Na_2O (Fig. 3.9) illustrates the chemical relationship between the various sediments and the granitoids, highlighting in particular their limited overlap. An interesting aspect of this plot is the location of the granitoid fields with respect to the fields for pelites and the felsic greywackes.

Minor element abundances vary between the sediments, but in general differ only slightly from those of the granitoids. Pelites are enriched in Rb, Zn and Li relative to the granitoids, whereas the greywackes, with their abundant feldspar detritus, have lower Rb, Zn, Y, Pb and Li than both the shales and the granitoids. Sr is a notable exception in that it is highest in the greywackes.

TABLE 3.15. Chemical analyses of typical New England sediments. For comparison, three Hillgrove Suite granitoids are included.

	PELITIC ROCKS					FELSIC GREYWACKES			MAFIC GREYWACKES				BALDWIN GREYWACKES		CALCAREOUS ROCKS		HILLGROVE SUITE GRANITOIDS		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
Sample No. †	3ASH	HG/ GASH	DUND SH	WB4	AB11	MPGW	RV8	KSS	LH1	WB20	10HF RVT	HGW	BGW	BCW	WB2C	AB12W	BOA	TOBA	ARG
Catalogue No.	46141	46142	46143	46144	46145	46146	46147	46148	46149	46150	46151	46152			46153	46154	46040	46030	46064
SiO ₂	67.2	66.6	64.9	60.6	67.4	71.0	71.5	70.9	64.2	68.3	67.4	66.9	54.1	57.0	74.9	60.8	68.8	67.7	68.2
TiO ₂	0.56	0.60	0.62	0.18	0.72	0.48	0.41	0.42	0.80	0.55	0.56	0.56	1.24	0.98	0.49	0.56	0.63	0.69	0.72
Al ₂ O ₃	15.6	15.9	15.5	22.0	15.2	15.1	14.2	14.0	16.4	15.4	15.6	15.5	14.7	16.4	12.1	14.8	14.5	14.6	14.7
Fe ₂ O ₃	0.44	0.83	5.77	0.49	0.49	0.69	2.64	2.65	0.98	0.65	1.54	0.78	11.34	7.74	0.30	0.73	0.78	0.85	1.31
FeO	3.65	4.32	-	2.43	4.88	2.22	-	-	4.76	3.10	2.74	3.38	-	-	2.15	3.70	2.99	3.53	2.99
MnO	0.06	0.05	0.11	0.15	0.08	0.07	0.04	0.05	0.08	0.06	0.06	0.07	0.13	0.22	0.09	0.44	0.08	0.09	0.10
MgO	1.35	1.65	2.06	2.26	2.16	0.92	0.88	0.93	2.44	1.65	1.73	1.74	5.90	2.73	0.95	1.29	1.27	1.56	1.35
CaO	1.82	1.08	1.12	0.80	1.09	2.16	2.24	0.82	3.56	2.50	4.17	4.15	5.34	4.70	6.08	14.25	2.24	2.35	2.64
Na ₂ O	2.55	2.43	1.78	3.02	1.98	4.15	4.04	4.34	4.95	3.50	2.80	3.50	4.19	6.26	1.72	0.82	3.16	3.15	3.47
K ₂ O	4.57	4.75	5.52	6.58	4.37	3.41	2.08	3.17	1.60	2.52	2.05	2.04	0.81	0.72	0.59	0.19	4.21	3.82	3.59
P ₂ O ₅	0.11	0.28	0.15	0.05	0.14	0.08	0.08	0.08	0.15	0.10	0.10	0.10	0.20	0.19	0.14	1.02	0.14	0.17	0.13
S	n.d.	0.02	-	-	0.02	0.03	-	-	0.03	0.01	-	0.01	-	-	0.07	-	0.04	0.06	0.09
H ₂ O	1.8	1.5	2.2	1.6	1.4	0.7	1.7	2.3	0.9	1.6	1.0	1.0	3.94	3.09	1.2	1.3	1.0	1.2	0.8
O=S	-	0.01	-	-	0.01	0.01	-	-	0.01	-	-	-	-	-	0.03	-	0.02	0.03	0.04
Total	99.71	100.00	99.70	100.16	99.92	100.99	99.81	99.65	100.83	99.94	99.75	99.73	101.91	100.75	100.75	99.90	99.82	99.74	100.05
<i>Trace elements (ppm)</i>																			
Rb	168	197	252	163	143	115	88	94	32	95	124	86	*	*	21	8	171	147	148
Sr	286	183	136	117	271	326	359	277	436	420	437	232	*	*	235	193	154	184	249
Y	29	36	29	27	27	18	14	25	17	18	21	16	*	*	27	36	31	34	27
Pb	30	23	27	23	51	17	18	16	11	16	21	19	*	*	10	7	25	24	22
Zr	217	157	162	183	169	174	144	180	153	152	165	141	*	*	172	176	189	191	185
Nb	10	10	9	13	12	9	5	7	4	5	7	5	*	*	6	9	8	9	9
Zn	102	156	100	104	40	80	54	64	86	66	76	66	*	*	58	96	76	86	74
Cr	5	30	50	80	5	20	15	5	40	25	30	20	*	*	50	40	20	30	20
Ni	20	20	10	20	-	28	-	-	20	10	-	-	*	*	-	20	5	-	-
Cu	35	35	36	22	6	40	16	34	36	6	16	20	*	*	56	22	42	28	30
Li	41	60	62	72	82	17	26	18	14	30	12	8	*	*	8	6	34	36	38
K/Rb	226	190	173	318	241	234	186	266	394	209	294	187	*	*	221	187	204	216	201

† See Appendix 1

* no data available.

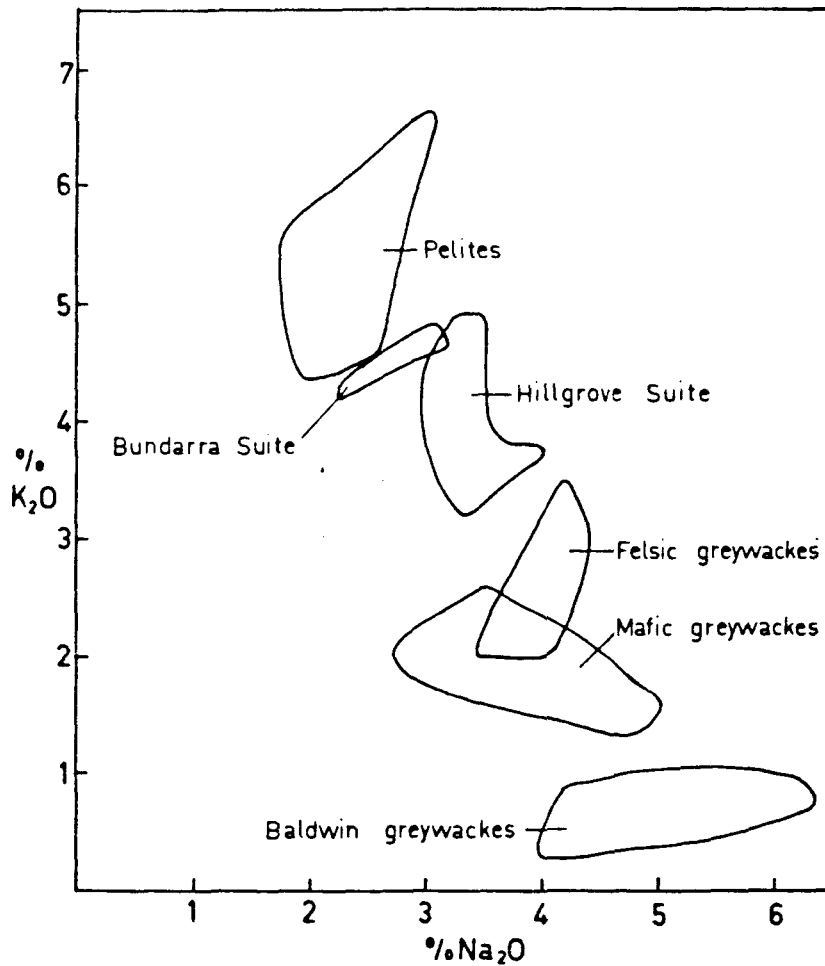


Figure 3.9 K_2O v. Na_2O plot showing relationship between specific New England sedimentary rocks. Granitoids from the Hillgrove and Bundarra Suites are included for comparison.

There are also similarities between some of the sediments, *viz.* felsic greywackes, and the Hillgrove Suite in terms of their respective REE abundances and patterns. Table 3.16 lists, in order of increasing metamorphic grade, the REE abundances for felsic greywackes and their metamorphosed equivalents from the Moona Plains area. Also included in this table are REE analyses of greywackes from the Baldwin Formation (Nance and Taylor, 1977), a gneiss from Moona Plains and, for comparison, the Argyll Granodiorite. The chondrite-normalized patterns for both low-grade and high-grade felsic greywackes resemble the pattern for the Argyll Granodiorite but differ drastically from the patterns for the gneiss and the greywacke from the Baldwin Formation (Fig. 3.10). Compared to the sediments, the gneiss is considerably enriched in REE and has a pronounced *negative* Eu anomaly. In contrast, the Baldwin Formation greywacke has low abundance of LREE (< 20 times chondrite) and a small but pronounced *positive* Eu anomaly. The gneiss from near Glen Oak homestead (Moona Plains) occurs on the western margin of the Moona Plains Complex. It appears to intrude lower-grade sediments but its precise affinity to them or to any of the calc-alkaline intrusives within the complex is not known.

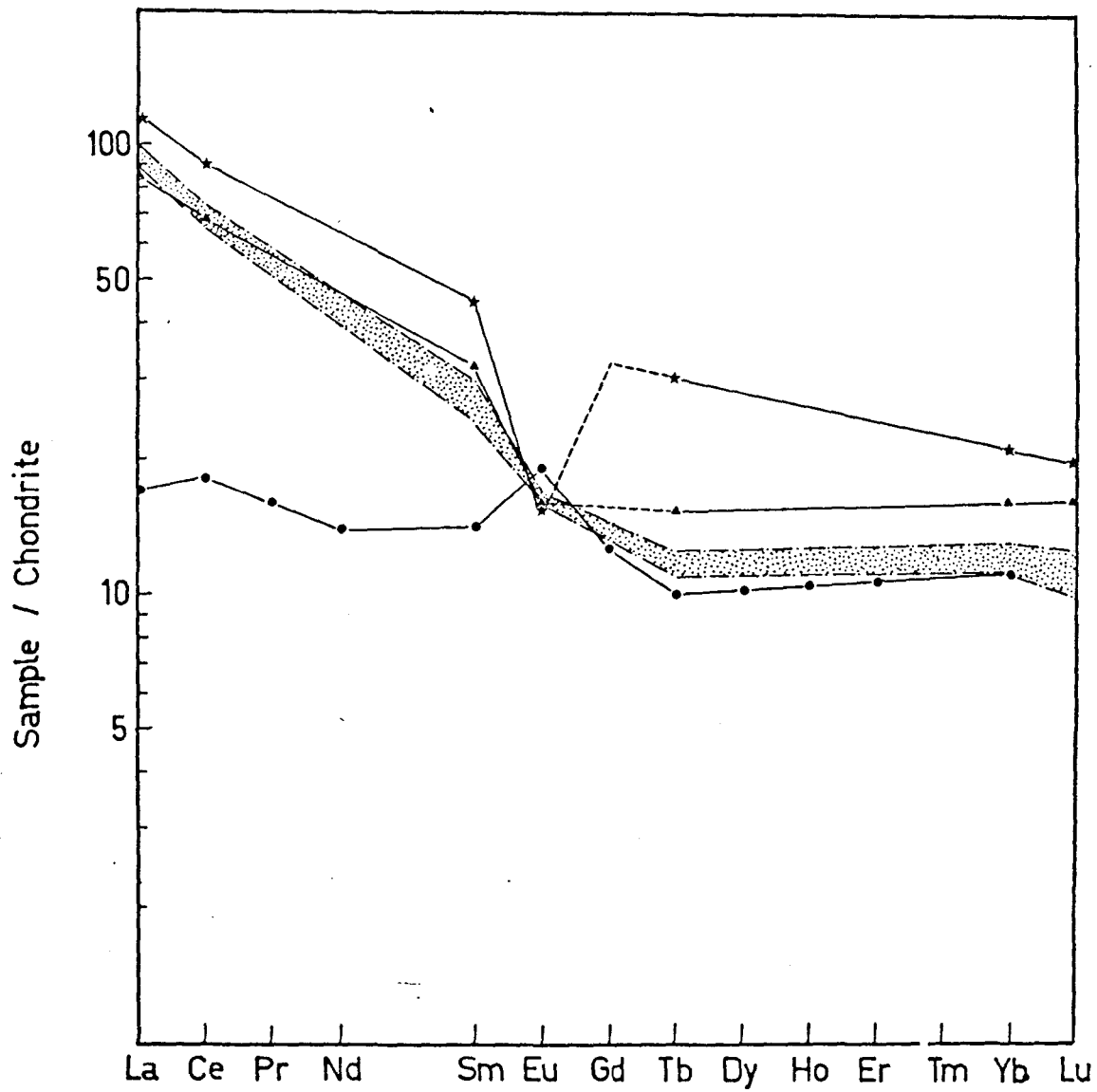


Figure 3.10 Chondrite-normalized REE patterns (dots) for low- and high-grade felsic greywackes from Moona Plains compared with patterns for mafic greywackes from the Baldwin Formation (large filled circles), the Glen Oak Gneiss, Moona Plains (stars) and Argyll Granodiorite (filled triangles).

Despite some similarities in REE patterns between the New England sediments and the Hillgrove Suite granitoids there are also some very important differences. For example, although the sediments and the granitoids have approximately the same LREE abundances, the granitoids have HREE abundances which are generally about 50% higher. This severely constrains the derivation of the granitoids by partial melting of the sediments because any melt generated to match the HREE abundances would increase significantly the LREE abundances.

Table 3.16 Comparison of REE abundances for New England metagreywackes (listed in order of increasing grade) with granitic gneiss and granodiorite from Moona Plains.

Sample No.	(1) BG	(2) MPGW	(3) MPTP	(4) W5	(5) B7	(6) OGN	(7) ARG
La	5.4	28.1	28.1	31.3	28.9	37.0	27.0
Ce	15.0	53.5	53.1	58.9	59.1	74.1	55.6
Nd	8.5	27.0	n.d.	n.d.	n.d.	n.d.	n.d.
Sm	2.70	4.70	5.08	5.21	5.71	8.67	6.15
Eu	1.40	1.24	1.18	1.22	1.03	1.09	1.16
Tb	0.48	0.55	0.58	0.61	0.53	1.49	0.75
Yb	2.3	2.28	2.24	2.67	2.58	4.35	3.28
Lu	-	0.26	0.34	0.28	0.40	0.65	n.d.

n.d. = not detected

- = not determined

(1) = Baldwin Formation greywacke (M284; Nance and Taylor, 1977)

(2) - (5) = Felsic metagreywackes from Moona Plains

(6) = Granitic gneiss, Moona Plains

(7) = Argyll Granodiorite, Moona Plains

3.6.7 Geochemical Constraints on the Derivation of the Hillgrove Suite from the Surrounding Sediments

The feasibility of deriving the Hillgrove Suite granitoids by partially melting sediments with chemical compositions similar to the surrounding psammpelitic rocks may be tested using the available chemical data. It has already

been outlined that although the granitoids and the sediments have basically similar compositions, there are some small but important differences. These differences may be attributed largely to the excess feldspar component in the sediments, i.e. mainly Al_2O_3 , Na_2O and Sr.

In addition to major elements, Rb, Sr, Zr, Y, Cr, Ni, Zn and particularly REE have been widely used to test partial melting or fractional crystallization models in the generation of granitic rocks (e.g. Albuquerque, 1977, 1978; Price and Taylor, 1977). However, up to five important assumptions are often made in these modelling procedures and this throws doubt on the credibility and accuracy of any results. These assumptions commonly include:

1. theoretical starting compositions, e.g. averaged sediments (Pettijohn, 1957; Wedepohl, 1968; Arth and Hanson, 1975; Nance and Taylor, 1976) or the North American shale composite - NACS (Haskin, 1966);
2. averaged, inadequate crystal-liquid distribution data based on volcanic rocks (Higuchi and Nagasawa, 1969; Philpotts and Schnetzler, 1970; Nagasawa and Schnetzler, 1971);
3. absence of a separate fluid phase;
4. batch melting as the only melting mechanism; and
5. approximations of melt compositions to the experimental An-free Qz-Ab-Or- H_2O system of Tuttle and Bowen (1958).

Collectively, the importance of these assumptions is enormous. Additional factors such as sampling, analytical procedures, metamorphism, etc. may compound these uncertainties even further. In view of these limitations, detailed trace element modelling of the Hillgrove Suite granitoids, based on the analyzed New England sediments, was not attempted. However, preliminary calculations showed that the difference in HREE abundances between the sediments and the Hillgrove Suite granitoids was sufficiently great to suggest that regardless of the melting mechanism, the partition coefficients used (within the known limits), and the degree of melting (as constrained by the major element concentrations), these granitoids could not be feasibly derived from the sediments which surround them.

3.7 GEOCHRONOLOGY

3.7.1 Introduction

Any hypothesis which proposes that granitoids are derived by partial melting of pre-existing source rocks must be compatible with the Sr isotopic data. Thus, granitoids derived by partial melting of sedimentary source rocks

(S-type should display Sr isotopic characteristics which distinguish them from granitoids derived from igneous source rocks (I-type). Because sediments are usually relatively enriched in ^{87}Rb , and hence ^{87}Sr , S-type granitoids often display high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (> 0.708) compared to I-type granitoids. Chappell and White (1974) used this difference in $^{87}\text{Sr}/^{86}\text{Sr}$ to distinguish between the two granitoid types in southern New South Wales.

Although the principal objective of this Sr isotopic study was to determine the age and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the Hillgrove Suite, other important additional aims were (a) to determine the extent and reason for any notable spatial variations within the Suite and (b) to establish precisely the isotopic relationship between the granitoids and surrounding sediments. The latter part of the study was intended in part to resolve the apparent dilemma expressed by some workers (e.g. Binns, 1966) between the age of the sediments (based on paleontological data) and the age of the intrusives.

In addition to the total-rock isotopic study, the biotites within both the granitoids and the adjacent metamorphics were analyzed to throw some light on the post-intrusive history of the Hillgrove Suite plutons, particularly in relation to the voluminous intrusives of the New England Suite.

3.7.2 Sampling and Analytical Procedures

All Hillgrove Suite plutons were carefully sampled for Rb-Sr analysis. In general, only the most representative rock type of each pluton was selected; however, where there was a marked variation in grain size, texture or mineralogy, up to five additional samples were analyzed. Where possible, felsic variants including veins and sheets associated with specific plutons were also analyzed. With the exception of the Dundurrabin Granodiorite (8 samples) and Hillgrove Adamellite (6 samples) extensive sampling of individual intrusions for the purpose of obtaining individual total-rock isochrons was not attempted, hence the number of samples analyzed for each intrusion was usually less than three. This approach was largely based on the assumption that members of the Hillgrove Suite represent a coherent geological unit possessing homogenous initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and having crystallized over a short time interval.

The analytical procedures used in the determinations of Rb and Sr in these samples are outlined in Appendix II.

3.7.3 Analytical Results

(a) Total-Rocks

Rb-Sr data for 44 total-rock samples of the Hillgrove Suite granitoids are listed in Table 3.17. When plotted on a conventional isochron diagram (Fig. 3.11) the data points show a linear but scattered array deviating somewhat from the ideal. In fact, the regression of these data yields a model 2 isochron* with an age of 301 m.y. \pm 10 m.y. and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7055 ± 0.0004 . The mean square of weighted deviates (MSWD) of 24.0 is high. The statistical selection of model 2 indicates that the scatter may be attributed primarily to age differences within the sample population. This is supported convincingly by field relationships which clearly demonstrate that the majority of felsic (i.e. high Rb/Sr) samples are cross-cutting. The fact that the statistical analysis prefers model 2 carries with it implications that the felsic samples, whilst not generated and intruded at the same time as the bulk of the plutons, may nevertheless have been derived from the same parent source rocks and hence may have essentially the same initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio.

It must be stressed at this point that the 44 samples analyzed belong to two very distinct categories. The major category comprises only typical granitic rocks from any one pluton whereas the minor category is composed of rocks which differ from the "norm", (a) by being considerably more felsic and often obviously late-stage and cross-cutting, (b) by displaying certain petrographic features which are atypical of Hillgrove Suite plutons, and (c) in their field occurrence, i.e. they may be intrusive into the main pluton or they may be samples from the granitoid/country rock contact. For example, the sample

* Model 1 isochrons (McIntyre *et al.*, 1966) are characterized by a value for the Mean Square of Weighted Deviates (MSWD) which does not exceed unity. These isochrons indicate that all specimens had the same initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, and that all were effectively chemically closed to the diffusion of Rb and Sr at the time of crystallization. The scatter of the points about model 1 isochrons can be assigned to experimental error. Model 2 isochrons assume variations in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio due to geochemical redistribution of Rb and Sr subsequent to crystallization. A similar effect is obtained if specimens with the same initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio have slightly different ages. Model 3 isochrons assume variations in the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio between the specimens. A combination of variations in both $^{87}\text{Rb}/^{86}\text{Sr}$ ratios may yield Model 4 isochrons.

Table 3.17 Rb-Sr isotopic compositions of Hillgrove Suite plutons

Pluton	Sample No.	Catalogue No.	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$
Henry River Adamellite	HRA	46026	166.0	131.0	3.68	0.72157
Kookabookra Adamellite	K14	46027	155.0	134.0	3.39	0.72045
"	KKF	46029	99.4	210.4	1.37	0.71119
"	KBHL	46072	158.3	132.4	3.35	0.72090
Tobermory Adamellite	TOBA	46030	147.0	184.0	2.36	0.71623
"	WTOBA	46031	167.0	148.5	3.25	0.71943
Abroi Granodiorite	ABGD	46032	128.0	199.0	1.86	0.71397
"	AB6	46034	141.0	175.0	2.33	0.71582
"	AB9	46033	130.9	196.5	1.93	0.71432
Wollomombi Granodiorite	WOLL	46035	168.7	143.4	3.40	0.72072
Rockvale Granodiorite	RVGD	46036	144.6	177.9	2.35	0.71639
"	RVT10	46038	147.1	175.5	2.42	0.71535* (2)
"	RVKY4	46037	141.0	170.0	2.40	0.71590
Hillgrove Adamellite	HGA	46040	172.4	153.8	3.24	0.71997
"	LHGA	46046	300.9	25.7	34.26	0.84441*
"	HG270	46031	227.5	87.7	7.53	0.73755* (8)
"	HG271	46048	114.2	196.8	1.67	0.71230
"	HG272	46042	223.7	94.6	6.84	0.73445* (7)
"	HG273	46043	227.1	99.3	6.64	0.73437
"	CT5	46047	154.2	177.1	2.516	0.71670
Enmore Adamellite	ENA	46054	169.2	166.1	2.95	0.71860
"	LENA	46056	222.3	49.2	13.12	0.75619* (11)

Table 3.17 continued

Blue Knobby Adamellite	BKA	46053	193.5	146.5	3.82	0.72257
Winterbourne Adamellite	WINT	46060	172.0	145.0	3.43	0.71964* (4)
Eastlake Adamellite	ELAX	46058	182.0	115.0	4.58	0.72394* (5)
Argyll Granodiorite	ARGD	46064	149.8	226.0	1.91	0.71377
"	B10	46066	122.9	260.2	1.36	0.71018* (1)
"	CDK	46067	185.3	102.0	5.26	0.72762* (3)
"	ARGX	46065	97.0	239.0	1.17	0.71040
"	KVARG	46073	133.3	208.8	1.84	0.71339
"	MPAGDSKV	46076	149.2	188.9	2.282	0.71552
Ingleba Adamellite	INGA	46063	280.9	67.5	12.07	0.75504* (10)
Kilburnie Adamellite	KA	46061	131.8	146.0	2.61	0.71659
Tia Granodiorite	TM4	46069	143.4	173.0	2.40	0.71602
"	TM2	46068	144.0	175.0	2.38	0.71585
"	LTM2	46070	176.5	62.6	8.17	0.74011* (9)
Dundurrabin Granodiorite	DUND	46049	142.0	156.4	2.623	0.71660
"	LDUND	46052	119.0	66.0	5.22	0.72635* (6)
"	DUND1	46158	147.9	158.5	2.693	0.71705
"	DUND2	46159	128.2	173.9	2.128	0.71463
"	DUND2X	46160	97.1	171.2	1.639	0.71203
"	DUND2XX	46161	230.4	161.7	4.121	0.72312
"	DUND853	46162	134.8	151.8	2.569	0.71607
"	DUNDX	46051	98.8	181.2	1.575	0.71225

* Deleted from final regression; numbers in brackets denote data points in Fig. 3.11.

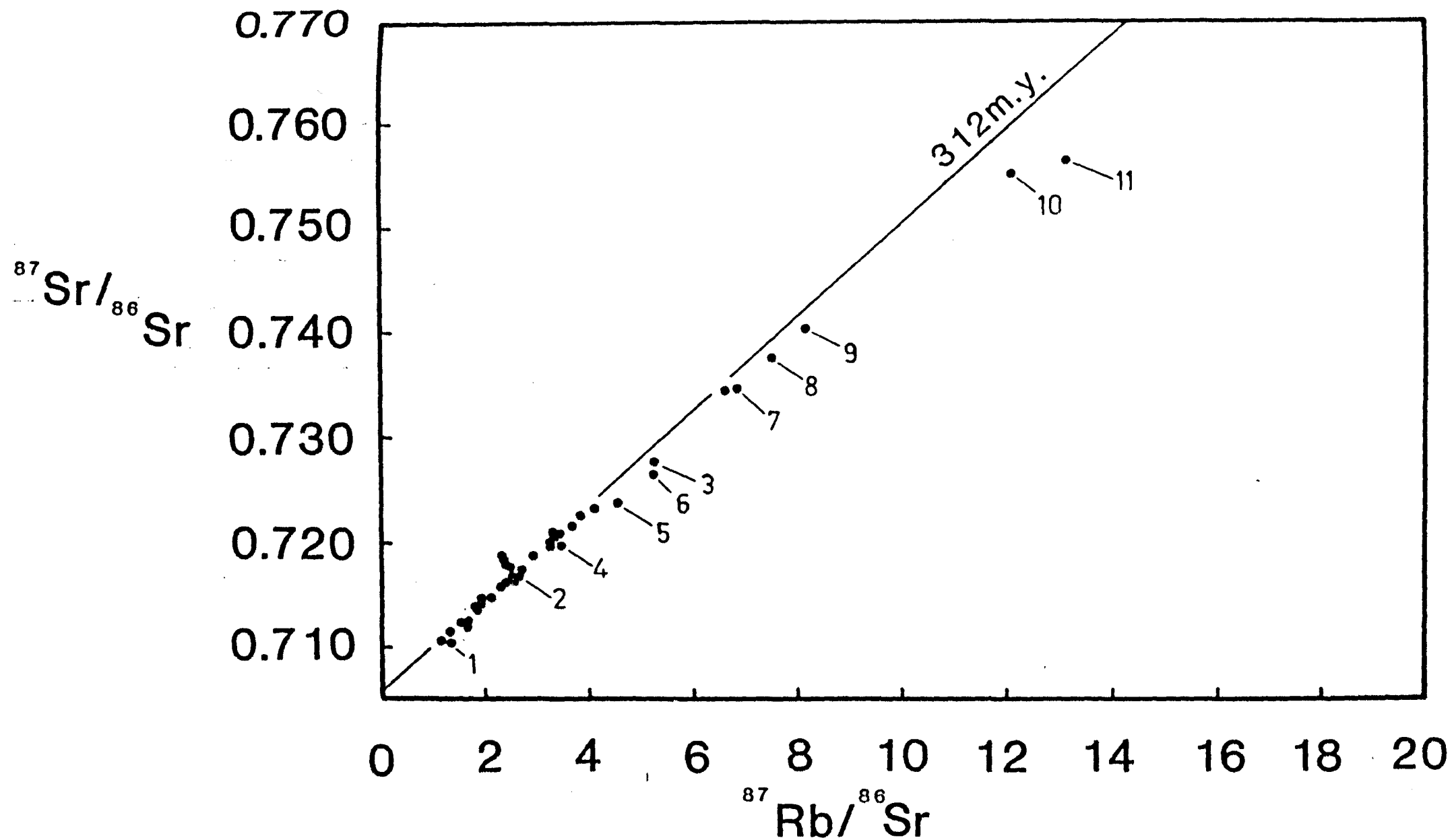


Figure 3.11 Isochron diagram for the Hillgrove Suite granitoids. Numbered samples deleted from regression (see text).

of Winterbourne Adamellite is extremely fine-grained and almost certainly represents a separate intrusive phase. Advanced weathering of the typical adamellite precluded analysis. The samples of Rockvale Granodiorite (RVT10), Eastlake Adamellite (ELAX) and Argyll Granodiorite (B10) contain significant amounts of amphibole and abundant mafic clots, and in general display unusual petrographic features.

The tendency for felsic samples from a suite of granitoids to plot below total-rock isochrons which are defined essentially by more mafic rocks is not uncommon (e.g. Brooks, 1966; Arriens and Compston, 1966; R. Page, pers.comm., L. Black, pers.comm.) and may be attributed to a particular mineralogical feature, for example, structural change in the alkali feldspar. An alternative explanation to this effect is related to variations in the chemical and isotopic compositions of the sedimentary source rocks. Thus, melting of sediments at a place in the crust other than the principal site of granitoid generation, for example, during intrusion, may result in isotopic heterogeneities within certain granitoids. A possible example of this may be seen at the western margin of the Hillgrove Adamellite where relatively "mafic" adamellite is intimately intermingled with a distinctly more felsic granitoid. Samples of this felsic granitoid (numbers 7 and 8 in Fig. 3.11) have noticeably lower $^{87}\text{Sr}/^{86}\text{Sr}$ than the isochron, hence are excluded from the final regression.

Deletion of the atypical and felsic samples from the final regression produces a considerably better-fitting isochron (MSWD = 8.6) yielding an age of $312.4 \text{ m.y.} \pm 10.2 \text{ m.y.}$ and an initial ratio of 0.70526 ± 0.00035 . This compares with the $289 \pm 25 \text{ m.y.}$ age and 0.7064 ± 0.0009 initial ratio for a 7-point (6 pluton) isochron believed by Flood and Shaw (1977) to be representative of the Hillgrove Suite.

Recently, Cameron et al. (1980) developed a regression technique for total-rock Rb-Sr samples which takes into account a particular form of open-system behaviour, i.e. local exchange of radiogenic ^{87}Sr during a metamorphic event of known age, between adjacent rock units. Two models of this technique may be particularly applicable to the Hillgrove Suite samples: the first is the free-line model which assumes that the regional distribution of Rb/Sr has remained unchanged despite local exchange of ^{87}Sr and presumably Rb between adjacent units, whilst the second (bulk earth model 2) forces the least-squares fit for the data through the present-day bulk earth value of $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$. The latter model therefore assumes that the rocks in question were part of the unfractionated Sr reservoir.

Using all 44 samples of the Hillgrove Suite in the first instance and assigning them a metamorphic age (i.e. last reset age) of 250 m.y., the ages for the free-line and bulk earth model 2 models are $308 \pm \frac{14}{12}$ and $314 \pm \frac{8}{7}$ m.y. respectively. These ages are essentially identical to that obtained by the McIntyre *et al.* (1966) method. Deleting those samples considered earlier to be inappropriate yields a free-line method age of $321 \pm \frac{12}{11}$ m.y. and a bulk earth model 2 age of $338 \pm \frac{5}{5}$ m.y.

Inherent in this relatively old bulk earth model 2 age are quite significant implications. The most important of these is that the 338 m.y. age can be interpreted as the age of the protolith to the granitoids, in this case a metasedimentary sequence. The justification for the use of the bulk earth model is based on the fact that the metasediments have been derived from predominantly intermediate essentially contemporaneous volcanics and deposited so that there was no significant change in Rb/Sr. The indicated protolith age therefore may be the minimum age of this volcanic provenance. In such an interpretation the event in which exchange of ^{87}Sr between rock units would be most extensive, without necessarily affecting the overall regional distribution of Rb/Sr, should be the fusion event that generated the Hillgrove Suite granitoids. Accepting a value of 312 m.y. for this event (mean value obtained from the McIntyre *et al.* (1966) regression) and substituting this for the later and significantly lesser metamorphic event at 250 m.y. the bulk earth model 2 age recalculated to $336 \pm \frac{5}{5}$ m.y. This is indistinguishable from the previous result and demonstrates the insensitivity of this regression technique to subsequent, less intense disturbances of the isotopic system.

(b) Minerals

The Rb-Sr data for 19 biotites separated from Hillgrove Suite granitoids are listed in Table 3.18, together with calculated ages and biotite/total-rock "initial ratios". The two most outstanding aspects of the mineral data are: (a) the significantly younger ages of the biotites compared with total-rock age for the Suite, and (b) the wide spread of ages.

The range in biotite ages can be plotted as a histogram (Fig. 3.12). From Table 3.18 and Figure 3.12 it can be seen that most biotites are younger than 290 m.y. The oldest biotite dated (293 m.y.) is from the Blue Knobby Adamellite (see Map 1), whereas the youngest biotite (242 m.y.) comes from a sample of the Abroi Granodiorite close to the Wongwibinda Fault. Three additional biotites from the latter pluton yield ages ranging from 252 m.y. to 259 m.y. and correspond closely with K-Ar biotite ages from this pluton (Binns and Richards, 1965). Similarly, Rb-Sr biotite ages from the Tobermory and Hillgrove plutons

Table 3.18 Rb-Sr isotopic compositions of biotites from the Hillgrove Suite.

Pluton	Sample No.	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	Age (m.y.)*	Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio**
Henry River Adamellite	HRA	668.84	9.86	210.28	1.45776	252	0.70846
Kookabookra Adamellite	K14	703.50	13.27	161.32	1.26679	245	0.70872
"	KKF	575.89	9.29	191.19	1.40500	257	0.70618
Tobermory Adamellite	TOBA	610.26	5.14	388.80	2.07390	248	0.70690
Abroi Granodiorite	ABGD	516.37	9.19	172.05	1.32095	252	0.70734
"	AB6	558.14	5.35	335.12	1.85849	242	0.70783
"	AB9	484.38	9.55	154.97	1.28680	259	0.70712
"	AB12	579.64	4.65	413.15	2.22762	259	***
Wollomombi Adamellite	WOLL	844.21	4.90	605.93	2.93642	259	0.70821
Rockvale Granodiorite	RVGD	572.16	4.53	423.54	2.35897	274	0.70723
"	RVT10	581.52	8.70	207.84	1.49362	267	0.70618
Hillgrove Adamellite	HGA	696.23	4.97	479.33	2.60844	279	0.70712
Blue Knobby Adamellite	BKA	825.08	14.63	174.36	1.43093	293	0.70670
Enmore Adamellite	ENA	710.44	33.50	62.73	0.95720	283	0.70685
Kilburnie Adamellite	KA	631.01	5.52	380.73	2.26919	289	0.70587
Ingleba Adamellite	INGA	1054.41	43.09	72.70	1.00386	289	0.70552
Argyll Granodiorite	ARG	730.91	9.20	251.18	1.68778	275	0.70629
Tia Granodiorite	TM4	710.21	6.96	331.28	1.97306	269	0.70676
Dundurrabin Granodiorite	DUND	615.33	4.14	511.29	2.67381	271	0.70626

* Decay constant $1.42 \times 10^{-11} \text{y}^{-1}$

** Calculated using biotite/total-rock data points

*** Total rock not analyzed

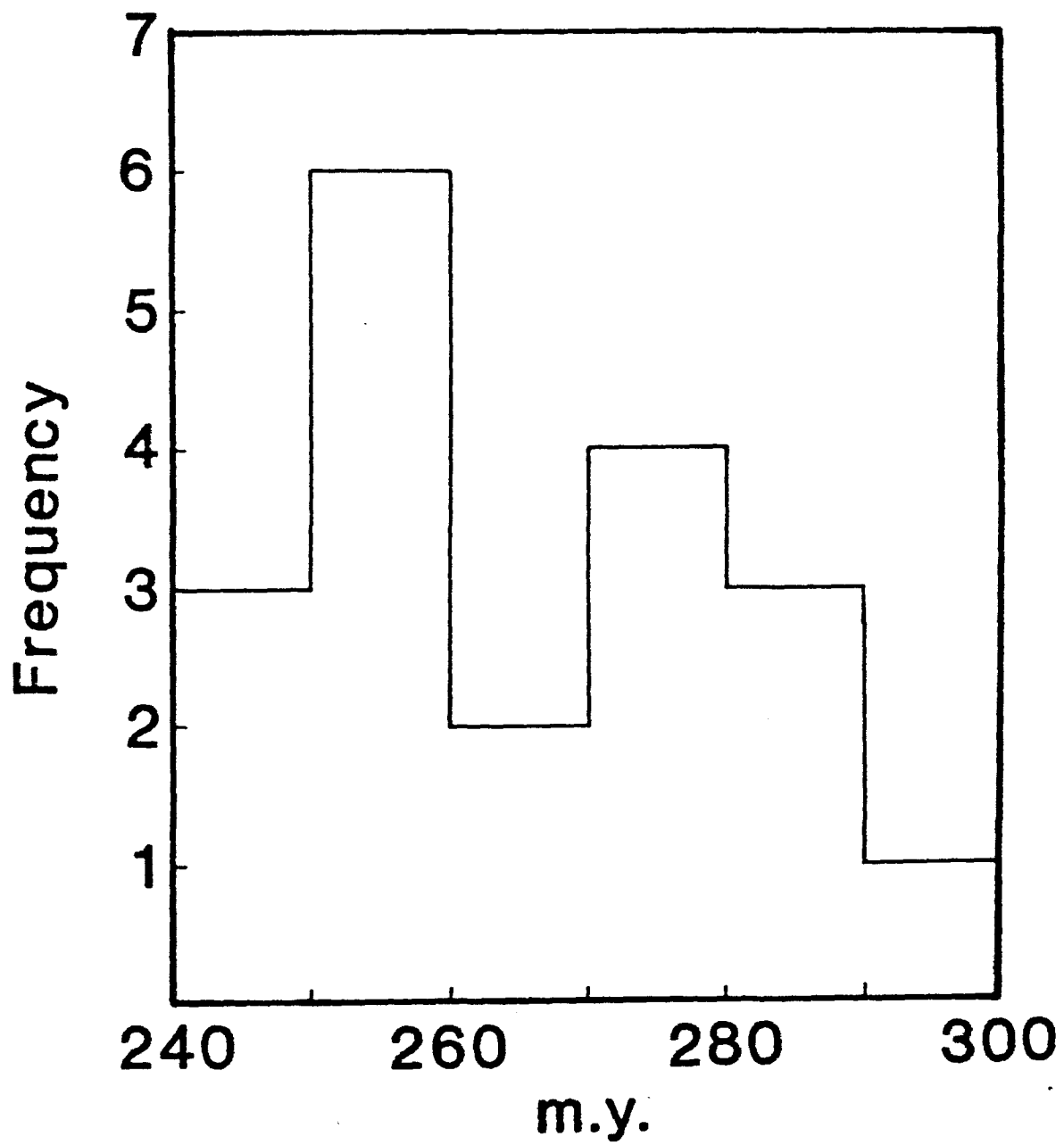


Figure 3.12 Histogram of biotite ages for Hillgrove Suite plutons

are essentially identical (within experimental error) to the respective K-Ar biotite ages determined by Cooper et al. (1963) and Binns and Richards (1965). This suggests that either deformation or metamorphism, or both, have been recorded equally by both K-Ar and Rb-Sr systems.

A further aspect of the biotite ages is their progressive decrease from ~290 m.y. in the south to ~245 m.y. in the north. The two exceptions are the biotites from the Tia and Argyll Granodiorites which show ages of 269 and 275 m.y., respectively. However, these plutons differ from the Kilburnie and Ingleba Adamellites in their close association with high-grade metamorphic rocks. This association suggests that they probably crystallized within this metamorphic environment and thus remained at relatively low levels in the crust.

3.7.4 Spatial Variations of Initial $^{87}\text{Sr}/^{86}\text{Sr}$ Ratios and Ages of Hillgrove Suite Granitoids

Although insufficient data are available to obtain isochrons for individual intrusions, the spatial distribution of initial ratios and ages within the Suite have been examined by grouping together several granitoids from a specific area. This procedure is not unreasonable in view of the close chemical and mineralogical similarities of the particular granitoids. Table 3.19 lists the results of total-rock regression analyses for three arbitrary granitoid subdivisions within the Suite, namely northern, central and southern. A fourth subdivision (eastern) is also included but comprises samples from only one pluton, the Dundurrabin Granodiorite.

From the results in Table 3.19 it is clear that the ages and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for all four groups are identical, within experimental error, to each other. Furthermore, the results show that there are no statistically significant variations in initial ratios along the length of the entire Suite. Because of the uniformity and internal consistency of these data, irrespective of the statistical treatment, it is concluded that (a) all members of the Hillgrove Suite have ages of 313 ± 16 m.y. and initial ratios of 0.7054 ± 0.0006 ; (b) the source rocks for the granitoids were essentially homogeneous isotopically, and (c) that the ages most probably reflect crystallization (\cong emplacement) rather than "inherited" ages.

This 312 ± 10 m.y. age for the Hillgrove Suite is in apparent conflict with previously accepted opinions that the Rockvale Granodiorite intrudes sediments containing Early Permian fauna. However, recent re-examination (Runnegar, pers.comm.) of these rare and deformed fossil shell fragments Atomodesma, occurring in a very limited exposure of turbidite mudstone several kilometers

Table 3.19. McIntyre et al. and Cameron et al. regressions of Hillgrove Suite subdivisions.

Group	Plutons	No. of analyses	McIntyre <u>et al.</u>			Cameron <u>et al.</u>
			Age	$^{87}\text{Sr}/^{86}\text{Sr}$	MSWD	Age(Free Line Meth)
Northern	Tobermory	2				
	Kookabookra	3				
	Henry River	1	307±	0.7057±	7.2	323 ± $\frac{26}{20}$ m.y.
	Abroi	3	19 m.y.	0.0007		.
	Rockvale	2				
	Wollomombi	1				

Central	Hillgrove	4				
	Enmore	1	310±	0.7054±	8.8	325 ± $\frac{29}{23}$ m.y.
	Kilburnie	1	18 m.y.	0.0009		
	Blue Knobby	1				

Southern	Tia	2	321±	0.7051±	0.2	320 ± $\frac{8}{7}$ m.y.
	Argyll	5	20 m.y.	0.0006		

Eastern	Dundurrabin	8	306±	0.7052±	3.5	310 ± $\frac{36}{28}$ m.y.