

GEOCHEMISTRY OF THE VOLCANIC ROCKS OF THE IPSWICH BASIN

Volcanic rocks from the base of the Ipswich Basin range from basaltic andesite lava flows to rhyolitic lava flows and pyroclastic rocks. The mafic rocks have the chemical characteristics of both island-arc (calc-alkaline) and rift-related tectonic settings. This characteristic chemistry is displayed in the trace element, whole rock, and to a lesser extent, the pyroxene chemistry of the rocks, and is consistent with the accepted tectonic setting of the Ipswich Basin (O'Brien *et al.*, 1991; Veevers *et al.*, 1994a, b), specifically that of a back-arc rift. Based on the chemistry of the rocks in the Ipswich Basin, an origin similar to the Basin and Range Province and other back-arc rifting centres is suggested for the formation of these rocks.

5.0 Introduction

Samples from all of the formally defined stratigraphic units in the Ipswich Basin that contain volcanic rocks - Brisbane Tuff; Chillingham Volcanics; Hector Tuff; Mount Crosby Formation; Sugars Basalt; and Weir Basalt - were analysed for major element and trace element whole rock compositions. Additionally, volcanic rocks from GSQ Ipswich 26 subunits E and F, one sample of the Mount Byron Volcanics, and several plutonic rocks of the South D'Aguilar Block were analysed. The Rb/Sr and Nd/Sm isotopic composition of twelve of these samples, including three each of the Brisbane Tuff and Chillingham Volcanics, two GSQ Ipswich 26, and two local plutonic rocks, has been determined.

Previously published geochemical data (Appendix C) for volcanic rocks of the Ipswich Basin are restricted to nineteen complete whole rock analyses, and several incomplete analyses: four analyses of volcanic rocks from NS 93 (Houston, 1965), and six analyses of volcanic rocks from the QA No.1 "The Overflow" (Houston, 1967a), form the only published geochemical data available for these rocks. As no material from either of these cores is preserved, Houston's data are used for comparative purposes in this chapter. Two published analyses for the Brisbane Tuff (Briggs, 1928; Houston, 1967b), two analyses of the Weir Basalt (Houston, 1965), and five analyses of the

Sugars Basalt (Houston, 1965) are used in addition to the new data presented here in Appendix A.

5.1 Analytical Procedure

All data presented in Appendix A were determined on the Macquarie University Siemens SRS-1 X-ray fluorescence spectrometer (XRF). Major elements were analysed on glass discs prepared by a method based on that of Norrich and Hutton (1969) and trace elements were analysed on pressed powder pellets with mass absorptions calculated from the major element compositions following the method of Norrish and Chappell (1967). H₂O and CO₂ were determined with a Leco induction furnace and ferrous iron was determined by ceric sulphate titration with Fe₂O₃ calculated as the difference between the total iron and the ferrous iron ($\text{Fe}_2\text{O}_3 = \text{Fe}_2\text{O}_3_{\text{(TOTAL)}} - \text{FeO} \times 1.11134$).

5.2 Major Element Analysis Results

5.2.1 Brisbane Tuff

Average analyses of the Brisbane Tuff are presented in Table 5.1, and complete lists of individual analyses and sample locations can be found in Appendix A. Because most samples of the Brisbane Tuff contain visible free carbon in the form of charcoal, the CO₂ component of the whole rock analysis was re-calculated as free carbon, and this resulted in realistic totals for the whole rock data. The source of this charcoal was probably burnt vegetation that was incorporated into the flows during emplacement.

The Brisbane Tuff is corundum normative, typically > 3%, with some >7%. Volatile contents generally exceed 2 wt% of the rock, which combined with the high normative corundum levels, implies extensive alteration, thereby degrading the usefulness of the whole rock data. Most of the alteration of the Brisbane Tuff (some believed to be vapour phase) undoubtedly occurred shortly after emplacement, during ignimbrite devitrification. It can be argued that this alteration can be considered a primary feature of the rock, as opposed to a secondary feature such as would be generated through weathering processes. It is therefore believed that the elevated water contents of all the samples can be largely attributed to the devitrification process. Friedman and Long (1984) indicate that unhydrated rhyolitic glass, flows, and tuffs,

Table 5.1 Average Composition of rhyolitic/felsic rocks of the Ipswich Basin.

Unit	Brisbane Tuff	Chillingham Volcanics		Hector Tuff	Mt. Crosby Formation	GSQ26 (E)
wt%	n=19	n=18	n=3	n=5	n=3	n=3
SiO ₂	76.31 ± 2.83	76.77 ± 3.50	<i>72.31 ± 0.57</i>	75.27 ± 4.34	71.79 ± 2.44	74.92 ± 2.78
TiO ₂	0.16 ± 0.01	0.16 ± 0.12	<i>0.23 ± 0.01</i>	0.23 ± 0.07	0.21 ± 0.03	0.12 ± 0.01
Al ₂ O ₃	11.85 ± 0.99	12.25 ± 1.78	<i>14.53 ± 0.52</i>	11.14 ± 0.95	12.80 ± 1.90	13.14 ± 1.93
Fe ₂ O ₃	1.15 ± 0.77	1.15 ± 0.94	<i>1.99 ± 0.06</i>	0.61 ± 0.05	1.97 ± 1.12	0.37 ± 0.03
FeO	0.29 ± 0.25	0.28 ± 0.40	<i>0.15 ± 0.02</i>	1.80 ± 1.53	1.17 ± 0.90	0.99 ± 0.08
MnO	0.01 ± 0.02	0.01 ± 0.02	<i>0.02 ± 0.03</i>	0.06 ± 0.05	0.05 ± 0.02	0.03 ± 0.00
MgO	0.10 ± 0.09	0.03 ± 0.04	<i>0.05 ± 0.03</i>	0.46 ± 0.24	0.80 ± 0.05	0.02 ± 0.02
CaO	0.05 ± 0.03	0.05 ± 0.03	<i>0.06 ± 0.01</i>	1.50 ± 1.41	1.39 ± 0.57	0.49 ± 0.05
Na ₂ O	2.03 ± 0.88	2.67 ± 1.61	<i>1.70 ± 0.77</i>	0.77 ± 0.50	0.75 ± 0.43	3.91 ± 1.21
K ₂ O	4.34 ± 0.46	4.52 ± 1.76	<i>6.08 ± 0.31</i>	2.42 ± 0.40	2.20 ± 0.36	4.72 ± 0.27
P ₂ O ₅	0.01 ± 0.01	0.01 ± 0.01	<i>0.01 ± 0.00</i>	0.01 ± 0.00	0.01 ± 0.02	0.02 ± 0.00
C	1.04 ± 0.88	-	-	-	-	-
ppm						
Ba	251 ± 168	390 ± 375	<i>702 ± 115</i>	470 ± 179	472 ± 42	420 ± 31
Cr	4.3 ± 1.6	1.2 ± 1.5	<i>1.0 ± 0.0</i>	7.2 ± 10.6	4.3 ± 0.5	1.0 ± 0.0
Cu	2.1 ± 1.3	2.8 ± 1.5	<i>4.0 ± 0.0</i>	2.5 ± 1.0	3.0 ± 0.8	2.3 ± 0.5
Ga	24.1 ± 4.5	19.4 ± 8.8	<i>19.7 ± 3.3</i>	20.3 ± 4.4	28.3 ± 2.6	14.7 ± 1.2
Nb	24.4 ± 3.5	31.9 ± 38.8	<i>15.7 ± 0.5</i>	16.0 ± 4.9	26.0 ± 2.2	11.0 ± 0.8
Ni	0.1 ± 0.3	0.6 ± 0.8	<i>1.0 ± 0.8</i>	0.8 ± 1.5	0.0 ± 0.0	1.0 ± 0.8
Pb	12.1 ± 7.5	18.2 ± 8.8	<i>27.7 ± 9.2</i>	12.2 ± 4.9	26.3 ± 4.1	16.7 ± 4.5
Rb	156 ± 42	173 ± 74	<i>256 ± 34</i>	91 ± 20	94 ± 9	126 ± 17
Sr	86.4 ± 34.3	27.9 ± 27.0	<i>31.3 ± 7.3</i>	105.0 ± 63.3	100.7 ± 8.7	91.0 ± 4.3
Th	17.8 ± 2.9	23.2 ± 6.2	<i>23.0 ± 2.2</i>	13.0 ± 2.8	20.0 ± 1.4	16.7 ± 1.2
U	3.7 ± 1.6	5.1 ± 3.1	<i>4.0 ± 0.0</i>	2.7 ± 1.2	3.0 ± 0.8	2.7 ± 0.5
V	7.1 ± 2.6	3.8 ± 2.7	<i>5.33 ± 0.47</i>	17.7 ± 16.3	9.7 ± 0.5	6.3 ± 0.9
Y	117 ± 29	82 ± 48	<i>65 ± 16</i>	65 ± 19	118 ± 11	22 ± 1
Zn	118 ± 67	61 ± 44	<i>44 ± 5</i>	70 ± 30	170 ± 50	37 ± 3
Zr	678 ± 110	453 ± 333	<i>415 ± 39</i>	456 ± 143	689 ± 73	180 ± 8

Analyses are presented on a hydrous basis. For details on individual samples see Appendix A. Because of the conspicuous free carbon in many samples of the Brisbane Tuff, CO₂ was calculated as free carbon (C) for the Brisbane Tuff samples. Values quoted in italics are for the Clarrie Hall Dam sub-suite of the Chillingham Volcanics. Data for the Chillingham Volcanics include the Clarrie Hall Dam sub-suite.

typically contains less than 0.3 wt% H₂O, whereas similar devitrified rocks usually contain more than 3 wt% H₂O. Furthermore, Friedman and Long (1984) suggest that the process of low temperature rhyolitic glass devitrification (as opposed to the initial high

temperature devitrification which dehydrates the glass) is intimately linked with re-hydration.

The granites of the South D'Aguilar block (Fig. 2.1) are similar in age and composition to the Brisbane Tuff. Because they have a modern surficial history similar to the Brisbane Tuff, I suggest that secondary alteration and weathering of the two groups of rocks should be similar. It follows that major differences in alteration between the Brisbane Tuff and the granites could reflect Late Triassic surface processes occurring during and immediately after emplacement of the Brisbane Tuff, or differences in the porosity of the Brisbane Tuff, or both. The granites typically have a water content much less than 2 wt%, therefore most of the > 3% water in the Brisbane Tuff is believed to be caused by vapour phase alteration during devitrification. The high normative corundum abundances of the Brisbane Tuff can likewise be largely attributed to post emplacement vapour phase hydrothermal alteration and fumarolic activity, of which there is extensive physical evidence in the form of fossil fumaroles (see Chapter 2). McPhie *et al.* (1993) suggest that normative corundum abundance is particularly sensitive to modification during devitrification. The altered character of the Brisbane Tuff, even if considered syn-depositional, still requires that the whole rock chemical data be interpreted cautiously.

5.2.1.1 Association of high Fe_2O_3 with welding and pumice

With the exception of iron, differences in the major elements of individual samples of the Brisbane Tuff show little systematic variation. As a broad generalization, pumice clast-rich samples and samples of more intensely welded ignimbrite have higher ferric iron contents ($\text{Fe}_2\text{O}_3 > 1.5$ wt %) than those samples dominated by dense lithic clasts or poorly welded. This is most noticeable in samples ARPHD0099-02 and ARPHD0099-04, which although < 10 m apart, show a great variation in iron contents. Sample ARPHD0099-02 is a highly welded pumice rich ignimbrite ($\text{Fe}_2\text{O}_3 = 2.96$ wt %), ARPHD0099-04 ($\text{Fe}_2\text{O}_3 = 0.58$ wt %) is a less welded (and compacted) pumice poor ignimbrite. It is likely that the vitric/pumice component of the ignimbrite was originally enriched in iron, or that the lower porosity of the more intensely welded (or glassy) rocks made them less susceptible to later stage iron re-mobilization than the more

porous less welded samples. A higher concentration of iron in glass was noted by Vanman *et al.* (1993) in the vitrophyre zone of the Topopah Spring Member of the Paintbrush Tuff, western USA.

5.2.2 Chillingham Volcanics

The analysed samples of the Chillingham Volcanics, with the exception of a dacitic air-fall tuff (ARPHD250-01), are rhyolitic in composition, whether lavas, air-fall tuffs, or ignimbrites. Most analyses are of the rhyolitic lavas, but representative samples of pyroclastic rocks are also presented. With the exception of the dacitic air-fall tuff, all samples have a fairly uniform whole rock chemistry, with only minor variations in some major elements from the northern to southern extent of the unit. All rocks analysed were devitrified, and some of the high volatile and normative corundum abundances are probably the result of this devitrification.

The dacitic sample predictably is the only specimen which shows any significant enrichment in normative ferro-magnesium minerals, having normative ferro-magnesium contents typically three to five times greater than the rhyolites of the unit. Additionally, as would be expected, it is the most silica depleted and titanium enriched sample of the Chillingham Volcanics, possessing 70 wt% SiO₂, and 0.53 wt% TiO₂.

Excluding the dacite, the most obvious variation amongst the samples of the Chillingham Volcanics occurs with the TiO₂ content of the rocks. Although Table 5.1 shows TiO₂ values similar to the Brisbane Tuff, this average has been greatly inflated by the dacitic sample (0.53 wt %), and in reality most specimens have considerably less TiO₂ than the Brisbane Tuff. This difference is reflected in Figure 5.1, as is the partitioned nature of TiO₂ content. Analyses of Chillingham Volcanics plot in three distinct fields - those samples with TiO₂ values < 0.1 wt%, those with TiO₂ values between 0.1 and 0.2 wt%, and those samples with TiO₂ values > 0.2 wt%. With the exception of the last group, the TiO₂ of the Chillingham Volcanics increases to the south. TiO₂ is the only element which reflects this change, and considering it is not mirrored by the SiO₂ content, it is suggested that the difference is not due to the differentiation of a common magma. An exception to this trend are the rocks in the Frogs Hollow - Clarrie Hall Dam - Terragon region, which show anomalously higher

TiO₂ contents for their latitude (greater than 0.2 wt%) and SiO₂ content, including the few Clarrie Hall Dam analyses in the average Chillingham Volcanics column of table 5.1 does not significantly affect the average.

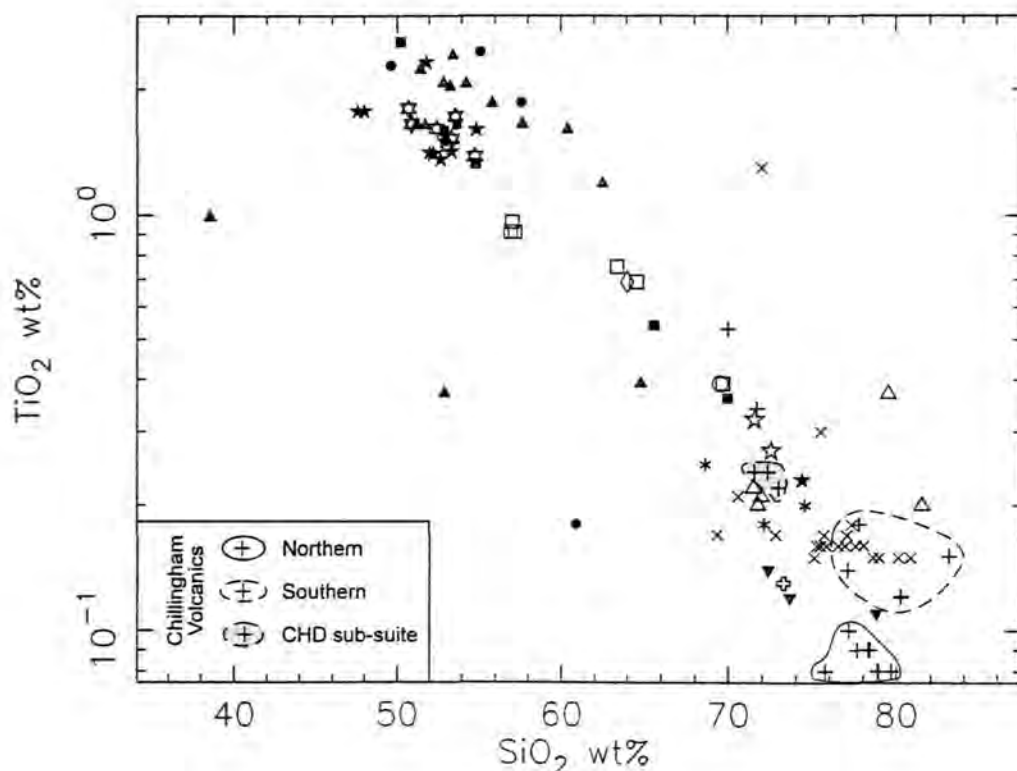


Figure 5.1 Variation diagram using TiO₂ and SiO₂. Symbols are as follows: X=Brisbane Tuff; + =Chillingham Volcanics; ☆=Weir Basalt; ★=Sugars Basalt; ▲=GSQ Ipswich 26 subunit F; ▼=GSQ Ipswich 26 subunit E; △=Hector Tuff; * =Mount Crosby Formation Tuff; ● =QA No1 “The Overflow”; ■=NS 93; +=Mount Byron Volcanics; ◇=Dayboro Tonalite; ☆=Enoggera Granite; □=Mt Samson Granodiorite; and ○=Samford Granodiorite. Shaded points are from previously published works.

As noted in Chapter 3, eruptive styles vary along the strike of the Chillingham Volcanics, with fissure type eruptions dominating over domal eruptions in the north. Rocks with TiO₂ < 0.1 wt% are commonly associated with fissure eruptions, whereas those rocks with TiO₂ > 0.1 wt% are formed by domal eruptions. Differences in TiO₂ along strike may reflect slight changes in magma composition through space and time, as different eruptive styles (fissure as opposed to domal) may reflect progressive changes in the gross eruptive mechanics through time or space. Therefore the

variation in TiO_2 may not be linked to the actual eruptive style.

5.2.2.1 Clarrie Hall Dam sub-suite of the Chillingham Volcanics

The lavas in the Frogs Hollow - Clarrie Hall Dam - Terragon area (Fig. 3.12) are chemically distinct from other Chillingham Volcanics, and are classified as the Clarrie Hall Dam (CHD) sub-suite. In addition to possessing higher TiO_2 and lower SiO_2 (71-72 wt%) relative to all other samples of Chillingham Volcanics (77-78 wt%), they are, as expected, slightly enriched in normative ferromagnesian minerals and elements (Table 5.1). CHD sub-suite rocks also show slight enrichment in Zr, Rb, Pb, V and Cu, and depletion in Nb relative to other Chillingham Volcanics rocks. It should be noted that unlike other formations of the Ipswich Basin, the SiO_2 contents of the Chillingham Volcanics are remarkably uniform, especially considering their large extent, and that no continuum between these two populations of SiO_2 was observed. Broadly speaking, samples of the Clarrie Hall Dam sub-suite are more altered and typically more porphyritic than other samples of the Chillingham Volcanics. Additionally, due to the proximity of the rocks to the Tertiary Mount Warning complex, this section of Chillingham Volcanics is intruded by numerous dykes of basaltic composition.

While the possibility exists that the differences observed in the whole rock composition of the CHD sub-suite were caused by metamorphic and/or hydrothermal effects of the Mount Warning Complex, every attempt was made during sampling to avoid obvious contact areoles associated with dyke activity. The volcanology of the rocks in CHD sub-suite is different from that elsewhere, in that the succession is dominated by an unusually vigorous, early phase of dome growth, with the thickest rhyolitic lava preserved in the Chillingham Volcanics. The possibility that these greater accumulations may be related to differing magma compositions cannot be precluded. The more fluid nature of the less silicic rocks near Clarrie Hill Dam may have enabled a greater volume of material to be passively effused. Additionally the reduction of volatiles that would accompany the less siliceous magma may also have led to effusion commencing at an earlier stage, due to an earlier degassing, which also would have resulted in a reduced volume of pre-effusive pyroclastic rocks, as noted in Chapter 3.

5.2.3 Hector Tuff and Mount Crosby Formation tuff

Sampling of the Hector Tuff and the Mount Crosby Formation tuff was restricted by the limited exposure of the highly weathered and altered rock so that most samples analysed were obtained from drill core, with only one outcropping sample of the Hector Tuff included. Despite this, alteration in the units was still extensive, as evident from both their normative and whole rock chemistry. Compared with the Chillingham Volcanics and Brisbane Tuff, both the Hector Tuff and Mount Crosby Formation tuff contain elevated iron, magnesium and titanium levels, reflecting the presence of biotite. This trend also reflects the dacitic character of both formations.

5.2.4 Mafic Rocks

The mafic rocks of the Ipswich Basin, although commonly referred to as basalts are, by and large, basaltic andesites and andesites. Few true basalts exist. According to Gill's (1981) classification of andesites based on their K_2O and SiO_2 levels (Fig. 5.2), most samples plot in the field of medium-K andesites. The trachyandesitic samples (as defined by the TAS diagram) of the Sugars Basalt all plot in the high-K andesite field, and display a linear variation not shown as clearly on other classification diagrams. All but a few samples from subunit F of GSQ Ipswich 26 also plot along a linear array in figure 5.2 as they do on the other Harker plots (Fig. 5.3, Fig. 5.7, Fig. 5.10), suggesting they may be derived from a common parental magma.

While the Weir Basalt and the Sugars Basalt are broadly similar in chemistry, several differences exist in both the whole rock and trace element chemistry. Other than the previously noted difference in K_2O between the formations, these differences are best reflected by the chalcophile elements typically associated with mafic rocks (Fig. 5.3). Of the major oxides, the greatest difference is in P_2O_5 , with most samples of the Weir Basalt having almost double the amount of that in the Sugars Basalt (see Table 5.2 and Fig. 5.3). Figure 5.3 also illustrates some subtle differences between these two formations. MgO in the Weir Basalt has a more restricted (yet overlapping) compositional range than the Sugars Basalt. The MgO values, while not serving to distinguish the Sugars Basalt from the Weir Basalt, distinguish the quite markedly MgO depleted rocks of GSQ Ipswich 26 subunit F from the other mafic rocks.

Table 5.2 Average compositions of mafic rocks of the Ipswich Basin.

Unit	Sugars Basalt	Weir Basalt	GSQ26 (F)	QAO No. 1 "The Overflow"	NS 93
wt %	n=7	n=5	n=15	n=4	n=3
SiO ₂	52.68 ± 1.15	52.91 ± 1.25	52.81 ± 5.83	52.90 ± 1.70	54.10 ± 3.34
TiO ₂	1.48 ± 0.10	1.52 ± 0.10	1.70 ± 0.59	1.79 ± 0.48	2.20 ± 0.25
Al ₂ O ₃	17.25 ± 0.49	16.78 ± 0.76	16.81 ± 2.23	17.80 ± 0.39	18.33 ± 0.47
Fe ₂ O ₃	3.93 ± 0.85	3.99 ± 0.69	2.58 ± 1.24	6.36 ± 0.94	5.93 ± 1.11
FeO	4.93 ± 0.30	4.04 ± 0.59	6.20 ± 1.94	2.72 ± 0.39	2.40 ± 0.28
MnO	0.14 ± 0.07	0.20 ± 0.06	0.22 ± 0.17	0.21 ± 0.05	0.19 ± 0.01
MgO	3.85 ± 0.78	4.58 ± 0.38	1.38 ± 0.41	3.76 ± 0.25	2.92 ± 1.47
CaO	6.03 ± 2.37	5.93 ± 1.31	4.90 ± 3.84	6.08 ± 1.29	4.07 ± 0.50
Na ₂ O	4.55 ± 1.37	4.55 ± 0.67	4.73 ± 1.53	3.70 ± 0.54	5.17 ± 0.26
K ₂ O	1.45 ± 0.50	0.63 ± 0.23	1.18 ± 0.70	1.33 ± 0.41	0.73 ± 0.36
P ₂ O ₅	0.33 ± 0.07	0.51 ± 0.02	0.54 ± 0.20	0.42 ± 0.22	0.51 ± 0.13
ppm					
Ba	516 ± 230	868 ± 462	268.5 ± 161		
Cr	100.1 ± 26.7	164.0 ± 13.9	9.77 ± 8		
Cu	25.3 ± 2.1	26.8 ± 2.6	20.38 ± 9.4		
Ga	18.1 ± 2.0	18.6 ± 0.5	21.31 ± 2.6		
Nb	7.6 ± 3.1	15.0 ± 0.6	17.77 ± 1.9		
Ni	36.6 ± 11.6	54.2 ± 2.6	7.62 ± 6.1		
Pb	9.6 ± 1.8	11.0 ± 0.6	13.85 ± 4.2		
Rb	39 ± 16	15 ± 9	42.08 ± 29.2		
Sr	516.4 ± 81.8	704.8 ± 60.8	200.4 ± 85.4		
Th	5.0 ± 0.5	6.4 ± 0.8	7.54 ± 2.7		
U	1.4 ± 0.9	0.2 ± 0.4	0.62 ± 0.7		
V	213.7 ± 19.5	183.6 ± 7.8	181.9 ± 81.1		
Y	39 ± 1	37 ± 1	54.23 ± 14.5		
Zn	87 ± 10	88 ± 8	109 ± 54		
Zr	212 ± 33	274 ± 15	369 ± 60		

Analyses are presented as hydrous data. For details of individual samples see Appendices A and C. Data for drillhole QA No. 1 "The Overflow" were obtained from Houston (1967a) and data for drillhole NS93 is from Houston (1965). The large range of values shown for GSQ Ipswich 26 subunit F reflects the presence of some low-silica dacites in the sample pool.

A similar trend of GSQ Ipswich 26 subunit F being depleted, and the Weir Basalt enriched, with respect to the Sugars Basalt is displayed by both Ni and Cr (Fig. 5.3) and to a lesser extent by Cu. As well as affecting chalcophile elements, this relative

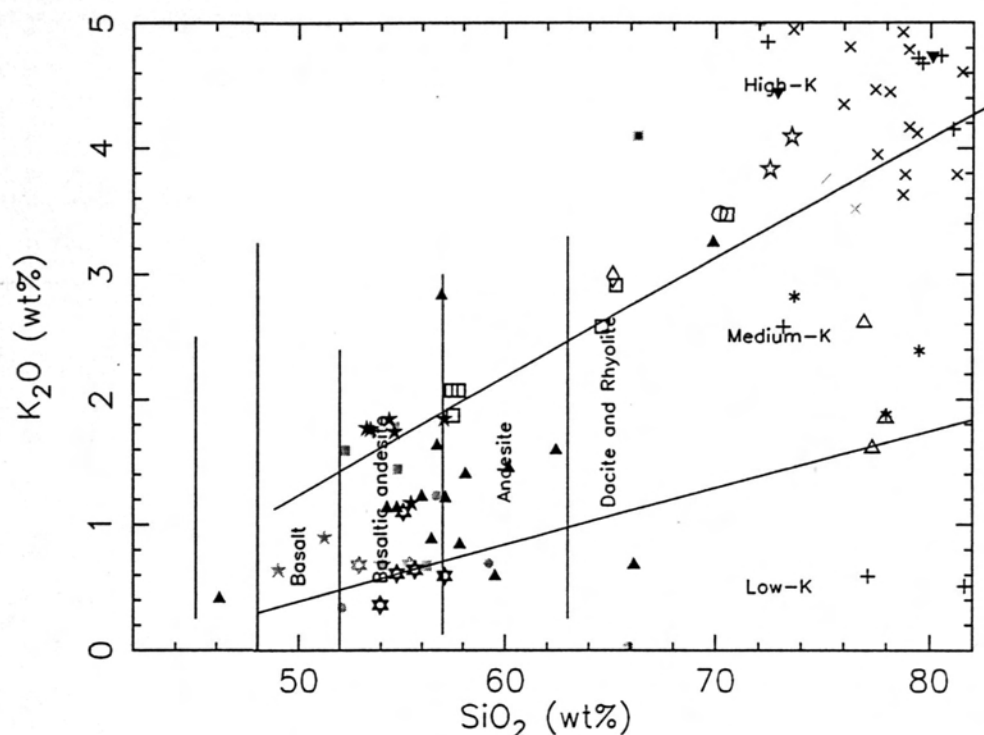


Figure 5.2 Subdivision of the volcanic rocks into High-K, Medium-K, and Low-K series (Le Maitre, 1989). The subdivisions for the andesites correspond with Gill's (1981) field of acidic andesites, and the field of basaltic andesites with Gill's (1981) basic andesites. The subdivisions into Low-K, Medium-K, and High-K are common to both classifications. (Symbols as in Fig 5.1).

enrichment/depletion pattern also occurs with Sr. These differences can be due in some extent to alteration effects, especially for GSQ Ipswich 26 whose large normative corundum levels compared with the other mafic formations (typically > 5%) suggest that this formation underwent more extensive alteration, but the differences between the Sugars Basalt and the Weirs Basalt would seem to be mainly primary.

Typical calc-alkaline andesites and basalts have TiO_2 values < 0.8 wt%, and the more enriched island-arc tholeiitic series, have TiO_2 up to 1.25 wt%. All mafic rocks of the Ipswich Basin have TiO_2 values significantly greater than those of typical island-arc basalts and andesites. The implications of this will be discussed in section 5.6. In the case of GSQ Ipswich 26 subunit F, two distinct groups exist - those with 1.5-1.7 wt% TiO_2 (in the upper part of the drill hole), and samples with 2.0-2.4 wt% TiO_2 (in the lower part). This upper interval is also the zone where the interbedded dacites occur, and the flows in this interval are, in general, thinner and lack well defined flow margins. Although the TiO_2 values for subunit F occur in two distinct ranges, excluding the differing chemistry of the more dacitic rocks interbedded in the subunit, no other

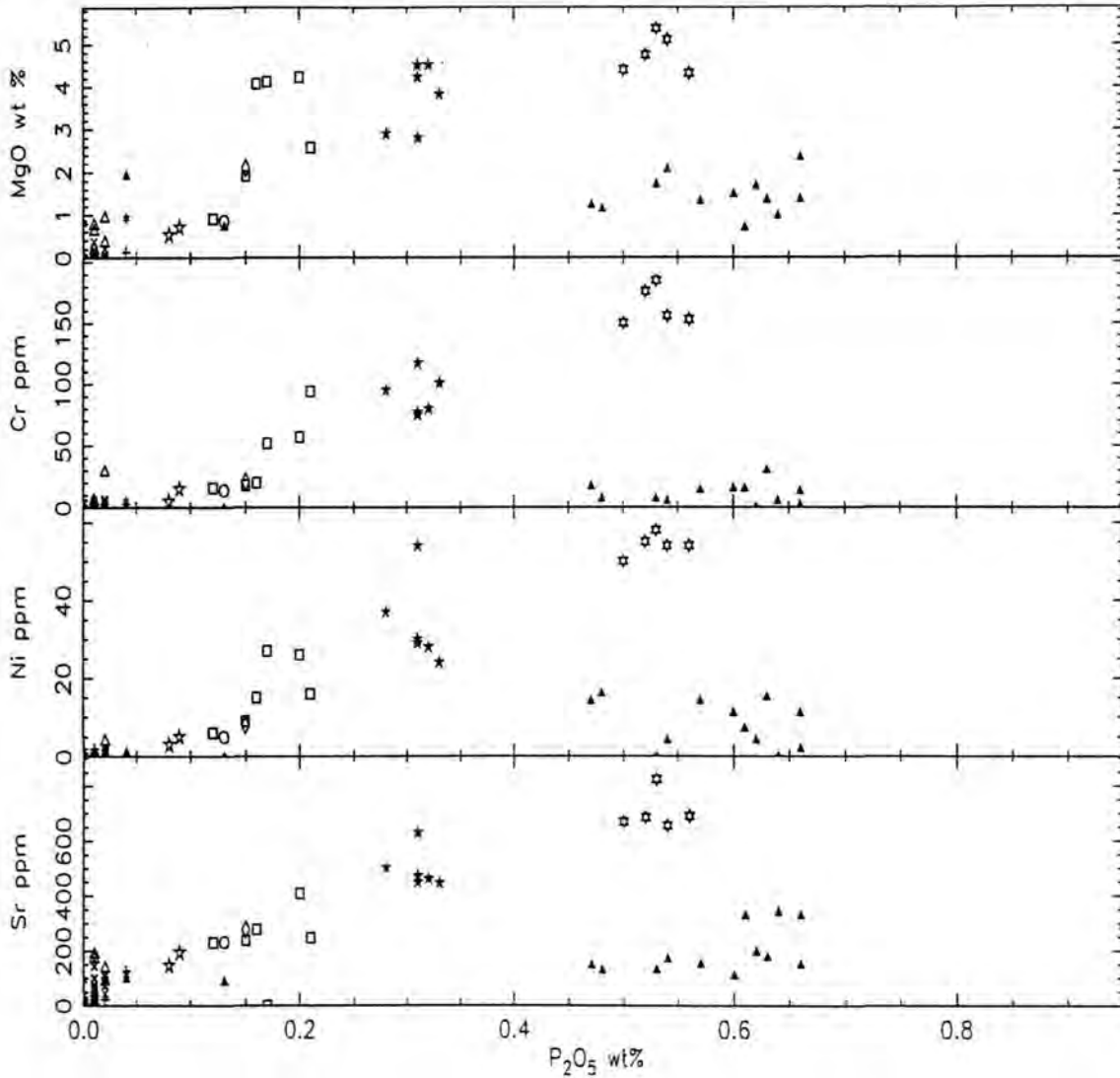


Figure 5.3 Composite Harker variation diagrams illustrating the differences between the mafic rocks based on their chalcophile elements, Sr, and MgO. This diagram illustrates the possible separation of the mafic rocks units (☆=Weir Basalt; ★=Sugars Basalt; ▲=GSQ Ipswich 26 subunit F) based on major element chemistry alone.

chemical differences are associated with the two different groups of lava flows.

5.2.4.1 Alteration of the Mafic Rocks

Altered mafic rocks are green with an earthy lustre. Calcic plagioclase phenocrysts are completely albitised, pyroxenes are fresh in all but the most altered rocks which have replacements of chlorite and less commonly carbonate. The least altered Sugars Basalt typically possess < 1% calcite, and the most altered (members of

GSQ Ipswich 26 sub-unit F) up to 5% calcite. Water content of most samples ranges from 2-4%, consistent with the presence of chlorite, and together with the high normative corundum levels (> 5%) in GSQ Ipswich 26, reflect clay minerals. Normative quartz is in many of the mafic samples, and the value of > 15% in most of GSQ Ipswich 26 sub-unit F suggests the loss of Ca and Mg. The least altered mafic rocks are in the Sugars Basalt and the most altered samples are from GSQ Ipswich 26. Major Element Tectonic Discrimination Schemes for Mafic Rocks Several schemes indicate the discrimination of the tectonic environment of basic volcanic rocks; most use trace element chemistry, while others use the major element chemistry (Pearce *et al.*, 1977; Irvine and Baragar, 1971; Mullen, 1983). Trace elements are preferred for discriminating the tectonic environment of volcanic rocks that show signs of alteration, as the more immobile trace element chemistry is less prone to modification through alteration. Major element discrimination schemes are, nevertheless, worthy of mention, if only to demonstrate their deficiencies.

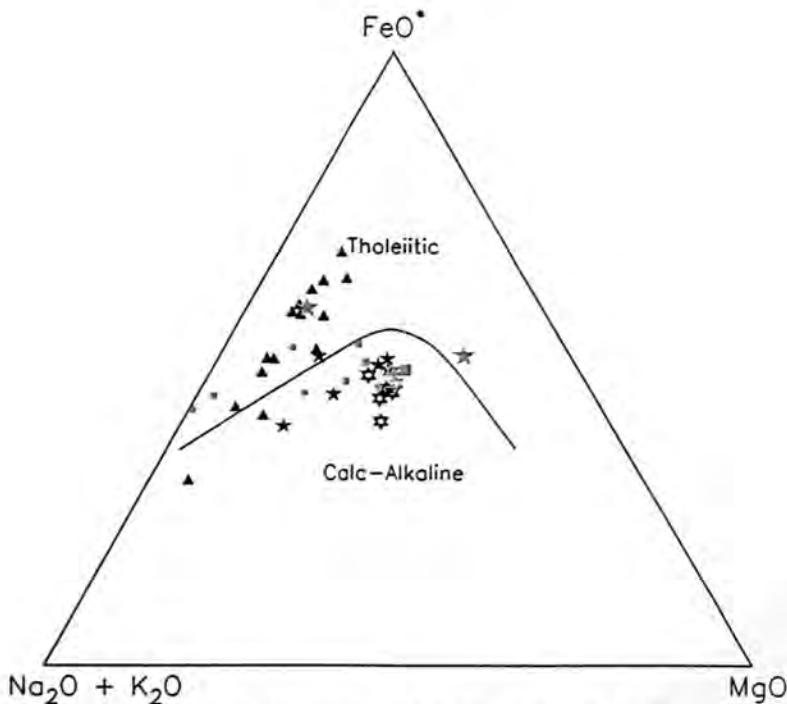


Figure 5.4 AFM diagram of Irvine and Baragar (1971). (☆=Weir Basalt; ★=Sugars Basalt; ▲=GSQ Ipswich 26 subunit F; ●=QA No1 "The Overflow"; ■=NS 93)

The AFM diagram of Irvine and Baragar (1971) (Fig. 5.4) attempts to classify

mafic volcanic rocks by using total alkali, and total iron as FeO and MgO. The subdivisions on the AFM diagram are intended to subdivide sub-alkaline rocks and do not always apply to alkaline rocks. All samples of the Weir Basalt and most of the Sugars Basalt plot in a tightly confined area in the calc-alkaline field of the AFM diagram. Departing radically from this tightly confined field, the samples from subunit F of GSQ Ipswich 26 plot in the field of tholeiites along a line of low and uniform MgO/MgO+FeO ratios. The rocks plotting in the field of tholeiites (samples from GSQ Ipswich 26) are alkaline, and are not validly identified on this plot. Although this diagram is useful for demonstrating the differing trends of the Weir and Sugars Basalts from those of GSQ Ipswich 26 subunit F, its usefulness as a tectonic discriminator is marginal.

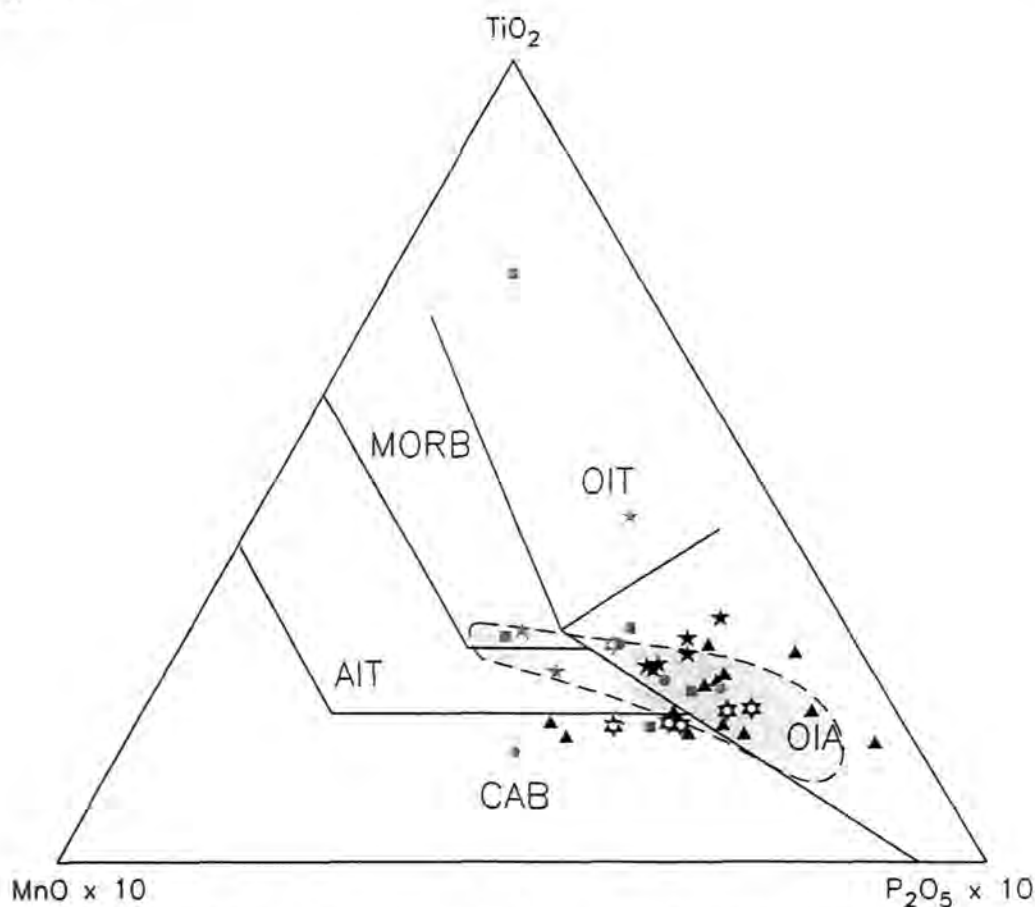


Figure 5.5 TiO_2 - MnO - P_2O_5 tectonic discrimination diagram of Mullen (1983). MORB = mid ocean ridge basalt; OIT = ocean island tholeiite; AIT = island arc tholeiite; CAB = calc-alkaline basalt; and OIA = ocean island alkaline. Shaded area is for typical Basin and Range rocks (data taken from Bradshaw *et al.*, 1993). (Symbols as used in Fig. 5.4)

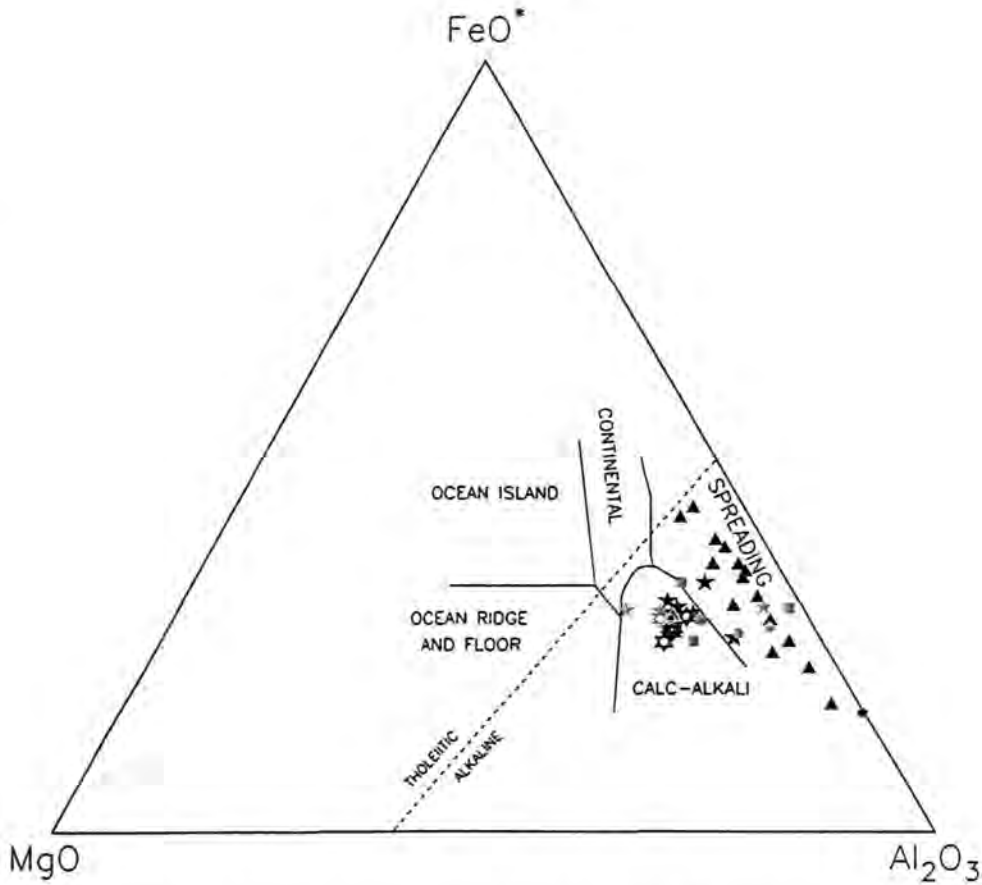


Figure 5.6 FeO-MgO-Al₂O₃ ternary tectonic discrimination diagram of Pearce *et al.*'s (1977). (Symbols as in Fig. 5.4)

Although Mullen's (1983) classification relies on major elements, only the MnO component of his diagram can be considered highly mobile, with the P₂O₅ being considered relatively stable, and TiO₂ (a high field strength element) generally immobile. As Figure 5.5 illustrates, the samples plot across the entire diagram probably reflecting some mobility in the elements although it should be pointed out that the majority of the samples contributing to this scatter are from Houston's analyses (shaded on plots), the accuracy of which could not be validated, and that samples analysed by XRF at Macquarie University are not scattered extensively. Despite this, the main concentration of samples plot in the ocean island rock fields (which Mullen, 1983, considers indistinguishable from continental rift lavas) with a few Weir Basalt samples extending into the calc-alkaline field. In Pearce *et al.*'s (1977) (Fig. 5.6) ternary diagram, using the somewhat more mobile elements of MgO, Al₂O₃, and FeO, most samples plot in the field of calc-alkaline rocks, with GSQ Ipswich 26 subunit F samples

plotting in the alkaline side of the spreading field, not unexpectedly reflecting a similar trend to the AMF diagram (Fig. 5.4).

5.2.5 Whole Rock Classification Diagrams

Most whole rock chemical classification diagrams for volcanic rocks have been created using unaltered volcanic rocks, and are commonly not considered suitable for ancient altered volcanic rocks. Although the majority of the volcanic rock samples from the Ipswich Basin are altered to varying degrees, it is believed that the chemistry of these rocks is not so extremely modified that some of the whole rock classifications cannot be applied to the rocks. The most universally accepted whole rock classification scheme for volcanic rocks is the Total Alkali Silica (TAS) diagram of Le Maitre (1984). Although Le Maitre (1984) warns against applying his TAS diagram to altered rocks with volatiles greater than 2 wt%, it was found that his classification (Fig. 5.7), by and large, agreed with both petrological assessments and trace element classification schemes for the volcanic rocks.

Volcanic rocks are also commonly arbitrarily subdivided based on their K_2O levels (Gill, 1981; Le Maitre, 1989). It is felt that especially for altered volcanic rocks, considering the highly mobile nature of K_2O during alteration, that the combination of both alkali elements together on the TAS diagram should more accurately reflect the original nature of the rock. However, the use of K_2O as a classification tool, especially for mafic rocks (Gill, 1981), is quite common in the literature, therefore such a classification system has also been included here. Gill (1981) proposed a classification for andesites based on a comparison of the K_2O vs SiO_2 plot. Le Maitre (1989) extended this classification to also include more acidic members, therefore this classification is used here (Fig. 5.2).

5.2.5.1 Brisbane Tuff

All analysed samples of the Brisbane Tuff are rhyolitic in composition, and the majority can be considered high-silica rhyolites. Additionally the samples plot in Le Maitre's (1989) field of High-K Rhyolites (Fig. 5.2). In the TAS diagram (Fig. 5.7), the samples plot in the field of rhyolites, but over a comparatively broad range of total

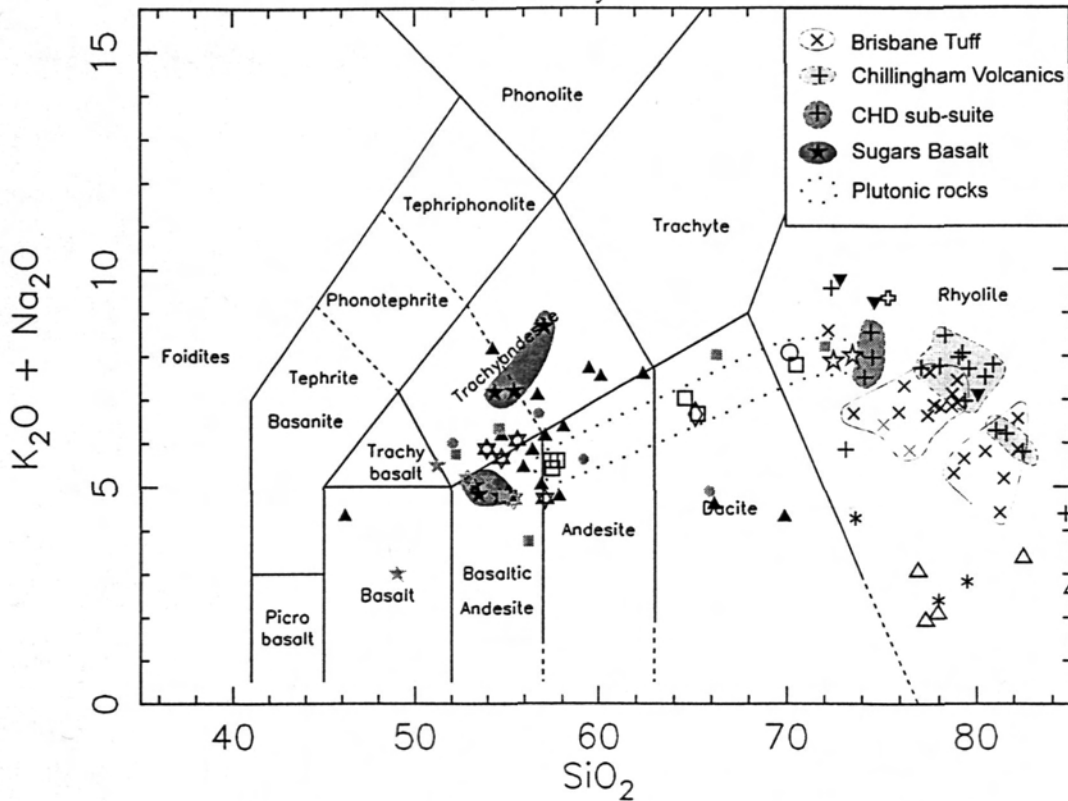


Figure 5.7 Total Alkali Silica (TAS) diagram for the volcanic rocks of the Ipswich Basin, and some plutonic rocks of the South D'Aguilar Block. Analyses were all recalculated to anhydrous state. (X=Brisbane Tuff; +=Chillingham Volcanics; ☆=Weir Basalt; ★=Sugars Basalt; ▲=GSQ Ipswich 26 Subunit F; ▼=GSQ Ipswich 26 subunit E; △=Hector Tuff; *=Mt. Crosby Formation Tuff; ●=QA No1 "The Overflow"; ■=NS 93; +=Mount Byron Volcanics; ◇=Dayboro Tonalite; ☆= Enoggera Granite; □=Mt Samson Granodiorite; and ○=Samford Granodiorite. Shaded points are from previously published works.)

alkalis, reflecting alteration rather than primary magmatic differences. As shown in Figure 5.7, two sub-populations exist, differentiated by a distinct break between the sub populations. This differentiation also most likely represents two differing degrees of alteration or slightly different alteration styles. The samples of the Brisbane Tuff with higher total alkalis overlap samples of the Chillingham Volcanics, although no genetic association is necessarily suggested.

5.2.5.2 Chillingham Volcanics

Samples of the Chillingham Volcanics plot in the field of rhyolites on the TAS diagram (analyses re-calculated to 100% anhydrous), in a broad field with higher alkalis for any given silica level than comparable Brisbane Tuff samples. One specimen (the dacite air-fall tuff) plots out of this broad field, close to the field of dacites and, when the data are plotted as a hydrous analysis, in the field of dacites.

The main body of Chillingham Volcanic samples plots in three poorly defined sub-populations. The “*low silica*” population corresponds with the Clarrie Hall Dam sub-suite of the Chillingham Volcanics. Though no genetic or geographic association could be found for the other two sub-populations, the boundary between these two sub-populations is virtually identical to the one which subdivides the Brisbane Tuff.

5.2.5.3 Hector Tuff and Mount Crosby Formation tuff

The Hector Tuff and the tuff from the Mount Crosby Formation, although plotting in the field of rhyolites, plot closer to the dacite field than either the Brisbane Tuff or the Chillingham Volcanics (Fig. 5.7). Although few analyses of these Formations are available, the Hector Tuff is divisible into a rhyodacite, and a low-alkali (Medium-K) high-silica rhyolite. Samples are highly altered and show evidence of alkali mobility, and this may be largely responsible for their unique position on the TAS diagram. Without more data it is impossible to say whether this represents two end-members in what would be a continuous range, or, if as preferred, it represents two different magmatic sources.

Two samples of the tuff in the Mount Crosby Formation plot in a similar position to the rhyo-dacitic Hector Tuff samples, although insufficient data exist to suggest any further correlations or similarities between the two formations other than broad composition.

5.2.5.4 Mafic Rocks

On the TAS diagram (Fig 5.7) most samples of the mafic rock units plot in an area covered by the fields of trachyandesite, andesite, and basaltic andesite. While Houston’s (1965, 1967a) data from NS 93 and QA No.1 “The Overflow” do not show any systematic trends, trends between the various other units are apparent. The Sugars Basalt and Weir Basalt have samples plotting in the basaltic andesite field and the trachyandesite field. The basaltic andesite/ andesite field is common to both formations, whereas the Sugars Basalt trachyandesite field is unique in being more alkali enriched than the trachyandesite members of the Weir Basalt. Additionally the Sugars Basalt has a sample that plots in the basalt field.

In addition to having basaltic andesite, andesite, and trachyandesite samples, subunit F of GSQ Ipswich 26 also has two dacitic samples (one at least of which was pyroclastic in origin) and one basaltic sample. Most samples overlap with the ranges of the Weir and Sugars Basalt and additionally GSQ Ipswich 26 subunit F has more siliceous members that extend into the andesite field.

5.2.5.5 Plutonic Rocks of the South D'Aguilar Block

The ten samples of plutonic rocks from the South D'Aguilar Block plotted on the TAS diagram (Fig 5.7) split into three populations that lie along a linear array, suggesting a possible genetic connection. The plutonic rocks show a progressive increase of total alkalis with increasing silica, unlike the volcanic rocks, which are scattered. Compared with the mafic rocks, which are alkaline to transitional alkaline, the plutonic rocks are calc-alkaline, and compared with the felsic rocks (except for the CHD of the Chillingham Volcanics), the plutonic rocks have higher total alkalis for any given silica content. These factors together suggest that little, if any, genetic association exists between the plutonic and volcanic rocks.

5.2.6 CIPW Normative Chemistry

Figure 5.8 uses various combinations of CIPW normative quartz, albite, anorthite, orthoclase, and corundum to assess the likely degree of alteration of the analysed rocks. Normative corundum is less than one percent in most unaltered igneous rocks (S-type granites and volcanics and very evolved muscovite-bearing I-type granites are examples of the exceptions). Thus values for these I-type volcanics should be less than about 1% if unaltered. Removal of alkalis during alteration or devitrification (McPhie *et al.*, 1993) produces and/or increases the normative corundum abundance. The large ranges in normative plagioclase/orthoclase ratio may also reflect alkali mobility.

Based on the normative compositions, the plutonic rocks show the least alteration of all samples on the various normative plots. All plutonic rocks have low normative corundum, and have quartz/feldspar ratios typical of mafic, intermediate, and felsic calc-alkaline rocks. Most mafic rocks, except for most of those from GSQ Ipswich

26 subunit F, similarly show little evidence of extensive alteration. Most samples from GSQ Ipswich 26 subunit F are strongly corundum normative (Fig. 5.8c) but do not plot abnormally on the other two plots.

The majority of the felsic rocks show signs of extensive alteration that has produced normative quartz enrichment, high normative corundum, and widely scattered normative plagioclase/orthoclase ratios (area II of Fig. 5.8c). Friedman and Long (1984) indicate that hydration of rocks accompanying devitrification can cause mobility of alkalis, and Wilkinson (1971) shows that alkali mobility can occur in hydrated glasses, both workers effectively linking hydration (either pre- or post-devitrification) with remobilising alkalis. As all the felsic volcanic rocks were originally glassy and have subsequently devitrified, the potential for alkali mobility is high.

For the samples of the Brisbane Tuff, the high normative quartz (30.41-60.21%) relative to most unaltered granites and rhyolite lavas (< 40%) is inferred to result from a combination of eruption-controlled crystal enrichment, post-emplacement silicification, alkali loss during vapour-phase alteration and devitrification, and local fumarolic activity. The Chillingham Volcanics samples (only a few of which are not lavas) show no evidence of crystal enrichment, therefore the enrichment in normative quartz can only be attributed to alkali remobilisation during devitrification or secondary silicification. The role of quartz phenocryst concentration in influencing the normative composition of the Brisbane Tuff is further supported by its slight enrichment in normative quartz relative to the Chillingham Volcanics, for which quartz phenocryst enrichment can play no significant role.

The samples most enriched in normative quartz and corundum belong to the Hector Tuff and Mount Crosby Formation tuff (field III of Fig. 5.8). All surface samples were visibly highly altered (both in hand specimen and thin section), and for this reason samples were collected from drill core. Surficial outcrops of both units contain rocks that are ignimbritic in origin, but (as discussed in Chapter 4) there is a strong possibility that some of the beds are re-worked. The combination of the samples being extensively weathered and altered, derived from an explosive eruption (and hence possible crystal concentration), and the possibility that they were re-worked in a fluvial environment are all factors which could have concentrated normative quartz in the samples.

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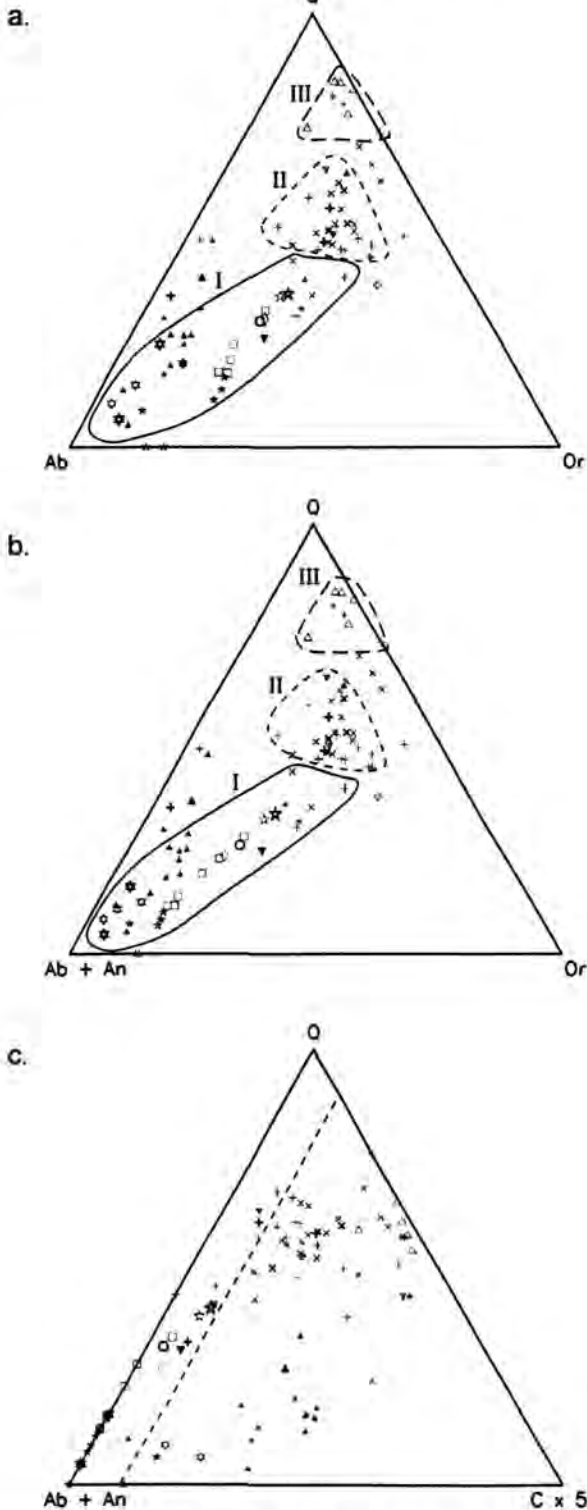


Figure 5.8 Normative plots used for assessing the likely degree of alteration. a) Plot of normative quartz (Q), albite (Ab), and normative orthoclase (Or); b) Plot of Q, Ab + normative anorthite (An), and OR; and c) Plot of Q, Ab + An, and normative corundum (C). Fields defined in (a) and (b) are as follows “I” refers to samples which can be considered minimally altered. “II” includes samples which have been enriched in normative quartz through either removal of alkalis or concentration of quartz. “III” refers to samples which have had extreme normative quartz enrichment, due either to alkali removal from extreme alteration or quartz enrichment from sedimentary re-working. The dashed line in figure (c) divides rocks which might be un-altered (on the left) from those which are altered. (Symbols as for Fig 5.1, however samples not used for isotopic studies have been rendered in grey).

5.3 Trace Element Analysis Results

Samples were analysed for Ba, Cr, Cu, Ga, Nb, Ni, Pb, Rb, Sr, Th, U, V, Y, Zn, and Zr. Complete results are given in Appendix A, and average results in Tables 5.1 and 5.2. The following discussion refers to Figure 5.10.

Ba shows little systematic variation, except samples from GSQ Ipswich 26 subunit F are uniformly depleted in Ba.

Cr, and Ni are, as expected, enriched in the mafic volcanic rocks, and the plutonic rocks from the D'Aguilar Block also show modest enrichment relative to volcanic rocks of similar SiO_2 content. Cu and V depart from this trend, showing enrichment in the mafic rocks, but no enrichment in the plutonic rocks. While some samples from the siliceous rocks have high Zn levels (most notably the Brisbane Tuff), the overall trend, although subtle, is for Zn to decrease with SiO_2 .

Ga values for all rocks are remarkably uniform, the only noticeable trends being slight enrichment, relative to other mafic rocks, in GSQ Ipswich 26 subunit F, and slight enrichment in the Brisbane Tuff relative to the Chillingham Volcanics.

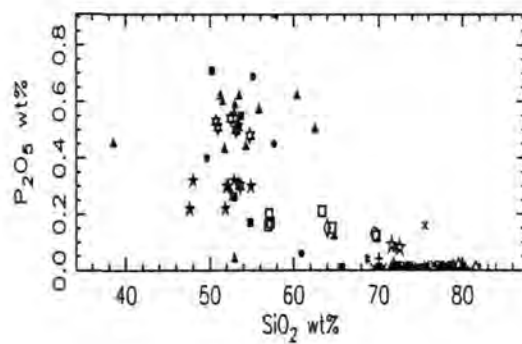
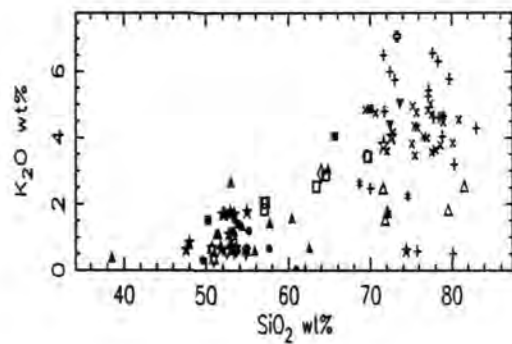
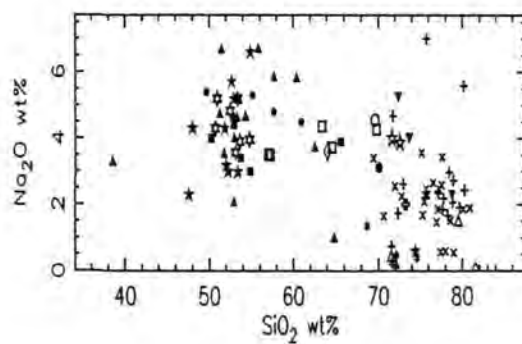
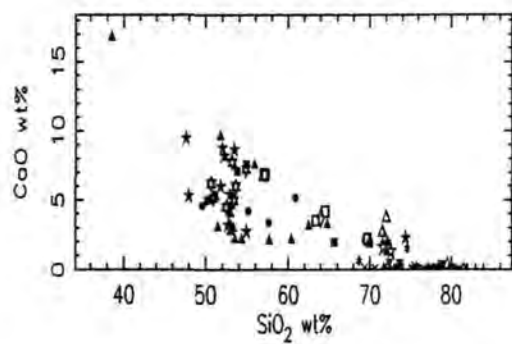
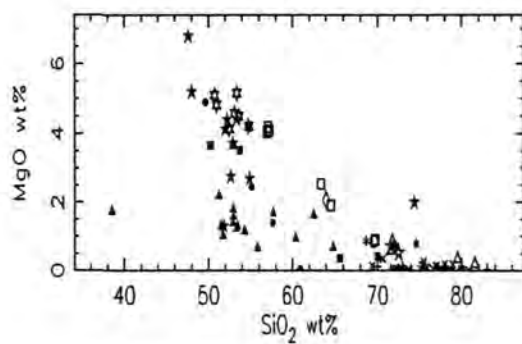
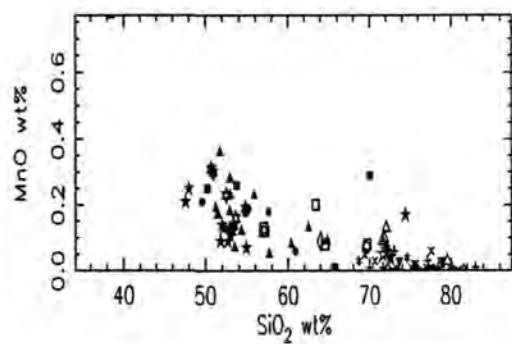
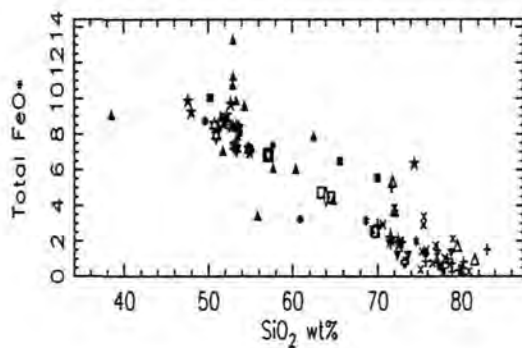
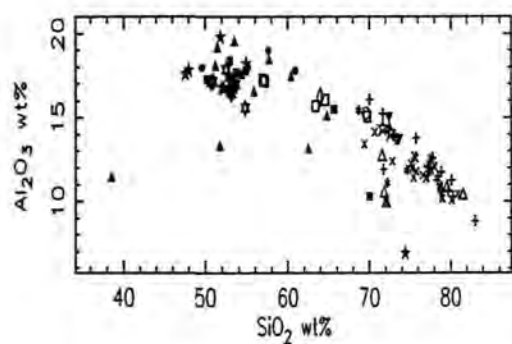
The Sugars Basalt is the most depleted in Nb reflecting its more arc-like nature, and its Y and Zr values are also the lowest of the mafic rocks. Nb and its scatter increases slightly with SiO_2 . The Nb content of the plutonic rocks of the D'Aguilar block, while also increasing with SiO_2 , does so along a different trend from the volcanic rocks. Departing from the trend of Nb increasing with SiO_2 , samples from GSQ Ipswich 26 subunit F show a modest decline.

With the exception of the plutonic rocks of the D'Aguilar Block, which decrease uniformly with increasing SiO_2 content, the most mafic rocks of the Ipswich Basin contain the least Rb, whereas the most siliceous rocks have both the greatest range in values and uniformly higher values of Rb than the mafic rocks. Sr shows a reverse from this trend, except for the plutonic rocks which decrease uniformly with increasing SiO_2 .

The range of values of both U and Th increases with SiO_2 . For Th, a trend of increasing Th with SiO_2 accompanies this, except for the plutonic rocks which have a uniform range of Th values across all SiO_2 ranges.

Plutonic rocks of the D'Aguilar block have the lowest values for both Y and Zr,

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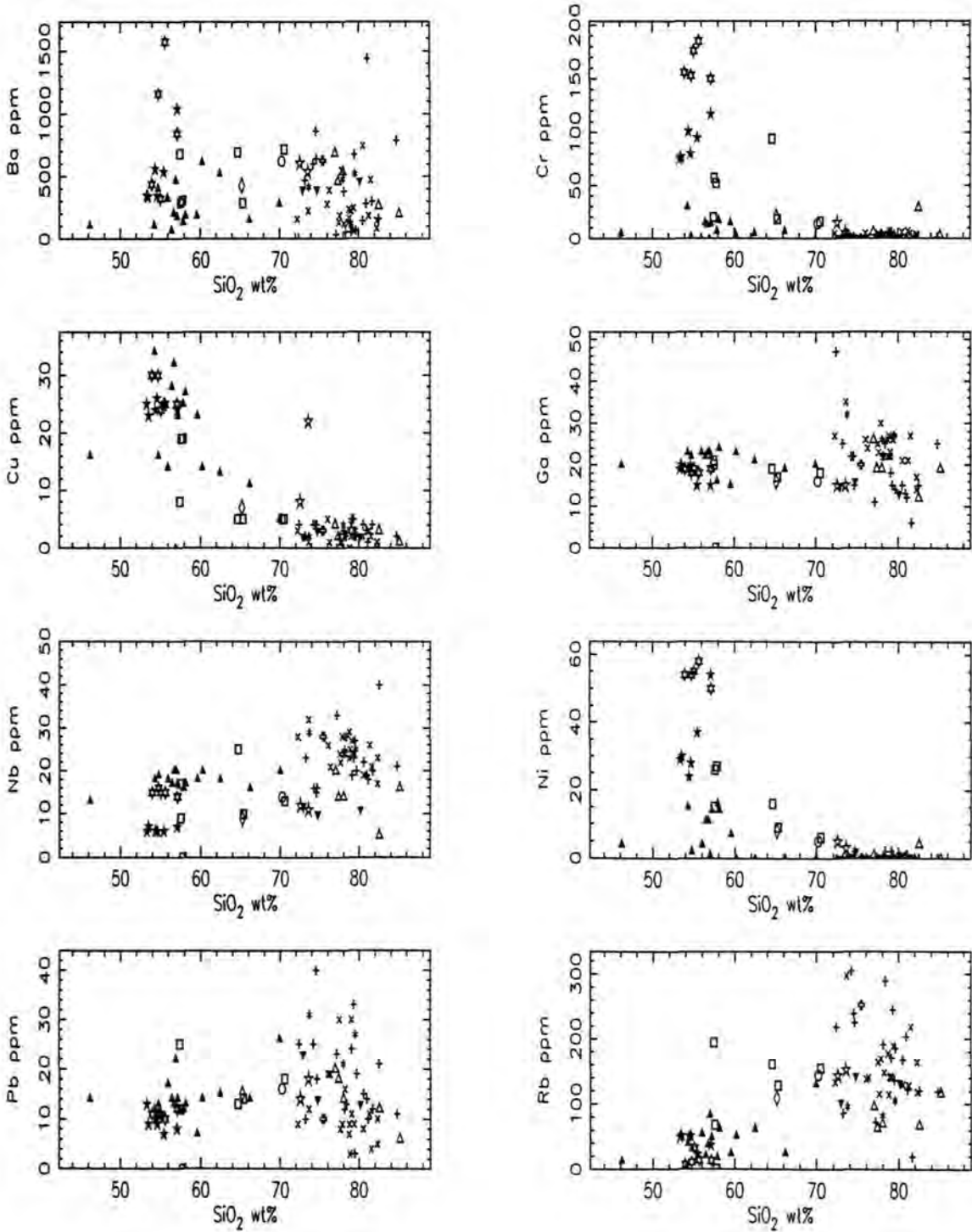


Figure 5.10 Harker variation diagrams for trace elements in volcanic and plutonic rocks.

showing little or no variation with SiO_2 . For both of these elements, the mafic volcanic rocks are lower and less dispersed than the felsic rocks. The Brisbane Tuff is typically more enriched than the other felsic rocks in both Y and Zr. Samples from GSQ Ipswich 26 subunit E and some anomalous samples from the Chillingham Volcanics are depleted in Zr, and plot along a similar trend to the plutonic rocks.

5.3.1 Trace Element Classification Diagrams

In view of the alteration of most samples analysed, some doubt exists on the validity of using only whole rock data for rock classification. Many trace elements, most notably the high field strength elements (HFSE) Ti, Zr, Y, Nb, and Ga, are believed to be largely immobile during alteration and low level metamorphism (Winchester & Floyd, 1977; Pearce & Norry, 1979), and therefore form the basis of several classification and tectonic discrimination schemes for volcanic rocks. These schemes fall into two categories, those which differentiate tectonic environment, and those which classify the rocks according to composition. The only trace element systems which classify rocks according to composition are those of Winchester and Floyd (1977). Systems for discriminating tectonic environments have been devised mainly for basaltic to intermediate rocks (Pearce *et al.*, 1977; Pearce & Norry, 1979; Pearce & Cann, 1973), with the exception of Pearce *et al.* (1984), which although designed for granites, has found application with volcanic rocks as well.

On the various classification diagrams of Winchester and Floyd (1977) (see Figs 5.11, 5.12, & 5.13), most samples classify in the same way as on whole rock TAS diagram. Samples of the Weir and Sugars Basalt plot in slightly different fields on all these diagrams, with samples from GSQ Ipswich 26 subunit F mostly plotting in a field similar to that of the Weir Basalt. Although plotting as two distinct populations, all samples always plot in the same field on the graphs, because differences between the trace elemental composition between the formations are minor. Of the felsic rocks, the Brisbane Tuff, Chillingham Volcanics, Mount Crosby Formation tuff, and GSQ Ipswich 26 subunit E rhyolite generally plot as rhyolite, and the Hector Tuff as a rhyodacite. One sample of the Chillingham Volcanics, probably a Tertiary comendite of the Mount Warning suite, constantly plots in the field of comendite on all diagrams.

5.3.1.1 SiO_2 v Zr/TiO_2

Zr/TiO_2 is a useful discrimination ratio as it indicates the differentiation of a magma. The decline of TiO_2 with increase in SiO_2 is accompanied by an increasing Zr/TiO_2 ratio. The Zr/TiO_2 ratio is also sensitive to alkalinity, as alkaline magmas typically concentrate Zr (Winchester & Floyd, 1977). On figure 5.11, which uses the SiO_2 v Zr/TiO_2 as a discriminator, samples of the Sugars Basalt plot in the fields of sub-alkaline to alkaline basalts and andesites, whereas the Weir Basalt plots in the field of alkaline basalts and trachyandesites. Most samples from GSQ Ipswich 26 subunit F plot in a broader field ranging from alkali basalts through trachyandesites to andesites. On this diagram, the difference in Zr between Sugars Basalt and the other mafic units is illustrated by its separation from both the Weir Basalt and the GSQ Ipswich 26 subunit F rocks. The “dacites” of GSQ Ipswich 26 subunit F plot in the fields of phonolite, trachyte, and dacite.

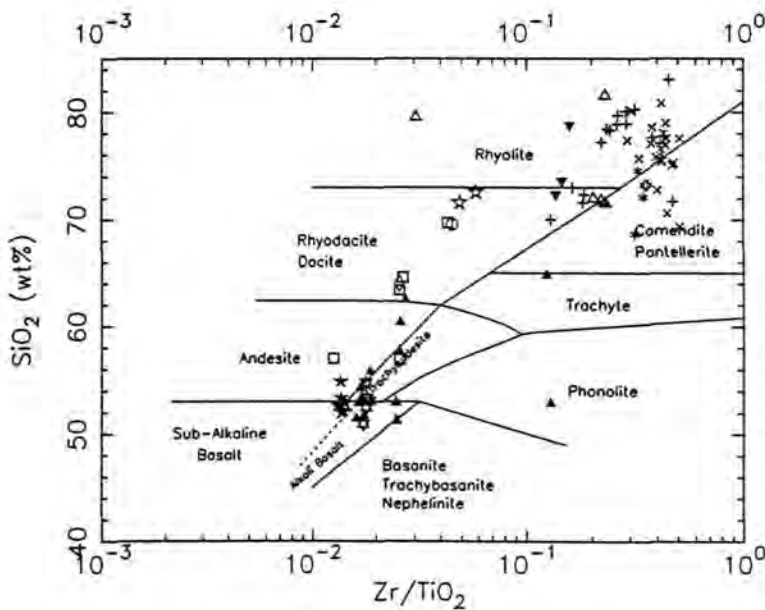


Figure 5.11 SiO_2 vs Zr/TiO_2 classification diagram of Winchester and Floyd (1977). (X=Brisbane Tuff; + =Chillingham Volcanics; ☆=Weir Basalt; ★=Sugars Basalt; ▲=GSQ Ipswich 26 subunit F; ▼=GSQ Ipswich 26 subunit E; △=Hector Tuff; * =Mount Crosby Formation Tuff; + =Mount Byron Volcanics; ◇=Dayboro Tonalite; ☆ = Enoggera Granite; □=Mt Samson Granodiorite; and ○=Samford Granodiorite)

Most samples of Brisbane Tuff plot in the rhyolite field. Three outlying samples plotting in the comendite field are the low-silica members of the Brisbane Tuff, and may reflect secondary leaching of silica rather than a magmatic difference. Two populations

of Chillingham Volcanics samples plot in the field of rhyolites, and a third in the rhyodacitic field. The samples plotting in the rhyodacitic field belong exclusively to the Clarrie Hall Dam sub-suite of the Chillingham Volcanics, distinguishable by their elevated TiO_2 and lower SiO_2 levels (discussed earlier). Similarly, the other two populations of Chillingham Volcanics on the plot correspond with specimens from the northern extent of the Chillingham Volcanics (lower TiO_2) and those to south. The sample of Chillingham Volcanics anomalously plotting in the comendite field is probably a misidentified sample from the Tertiary Mount Warning suite. Samples of the Hector Tuff plot tightly in the rhyodacite field, with two anomalous samples plotting in the field of rhyolites caused by silica enrichment. The Mount Crosby Formation tuff plots in a broad area over the fields of comendite and rhyolite, exhibiting a comparatively uniform HFSE chemistry, with variation entirely due to the SiO_2 content of the samples.

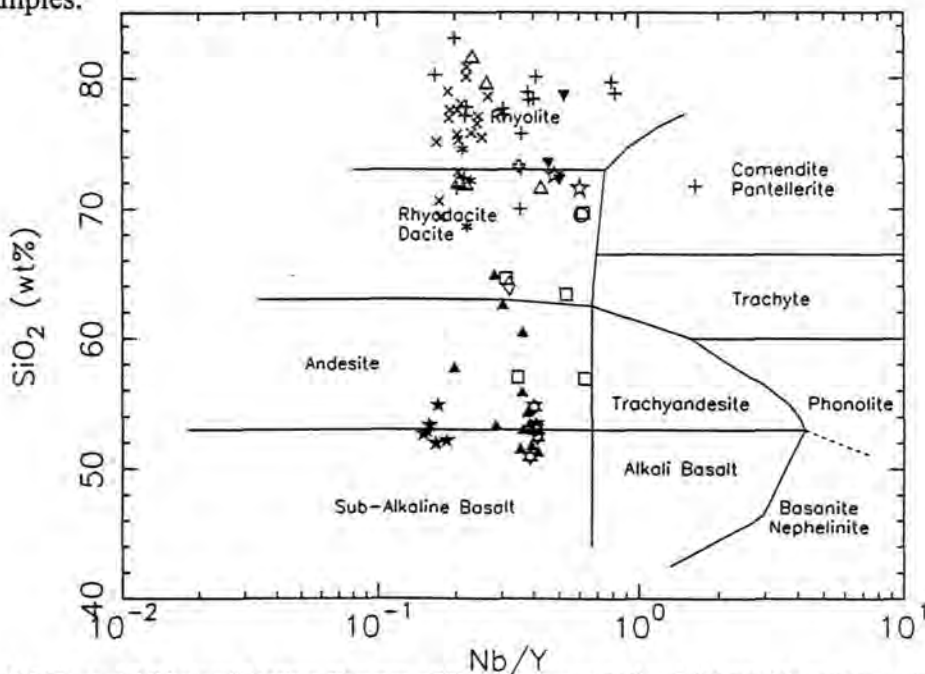


Figure 5.12 SiO_2 vs Nb/Y classification diagram of Winchester and Floyd (1977). (Symbols as in Fig. 5.11)

5.3.1.2 SiO_2 v Nb/Y

In addition to Zr being sensitive to alkalinity, the Nb/Y ratio is also systematically related to alkalinity (Winchester & Floyd, 1977; Pearce & Cann, 1973; Pearce & Norry, 1979). Figure 5.12 uses SiO_2 as a differentiation index, and the Nb/Y

ratio as an alkalinity index. The Nb/Y ratio produces a slightly different result than using the Zr/TiO₂ ratio as the alkalinity index, with samples by and large plotting in less alkaline fields. All mafic rocks plot in the fields of sub-alkaline basalts and andesites, and the pronounced separation of the Sugars Basalt from the other mafic rocks as was evident from the Zr/TiO₂ ratio (Fig. 5.11) is again present, this time shown by the relative depletion in Nb of the Sugars Basalt which has less than half that of the other mafic units.

As with Figure 5.11, the population distribution of the felsic rocks is largely controlled by their SiO₂ content. The Brisbane Tuff plots in a comparatively confined field as rhyolite, with the exception of the three outlying silica-depleted members in the rhyodacite field. The Mount Crosby Formation tuff, as in Figure 5.11, is dispersed via its SiO₂ content; however, its Nb/Y ratio confines it to a narrow field overlapping with that of the Brisbane Tuff. Subunit E of GSQ Ipswich 26 is similarly confined by its Nb/Y ratio, and widely dispersed by its SiO₂ content, and plots in a different field than either the Brisbane Tuff or Mount Crosby Formation tuff. The Hector Tuff departs dramatically from its pattern illustrated in all other discrimination diagrams, with all samples except for one having a similar Nb/Y ratio. Even the two outlying higher silica samples which usually plot independently of the main trend are confined in this zone.

Unlike the other felsic rocks, the Chillingham Volcanics plot in a broad field covering the compositions of rhyolite, rhyodacite, and comendite, unlike in Figure 5.11, where they plotted in TiO₂/geographically influenced populations. The large variations in the Nb/Y ratio (caused by Y) of the Chillingham Volcanics transcend the geographically constrained TiO₂ ratio, with not even the Clarrie Hall Dam sub-suite showing any systematic similarities to each other. As noted above, the lone sample plotting in the comendite field is probably from the Mount Warning suite.

5.3.1.3 Zr/TiO₂ v Nb/Y

The dependence of Figures 5.11 and 5.12 on SiO₂ on a differentiation index can be overcome using only the HFSE elements and plotting Zr/TiO₂ against Nb/Y (Fig. 5.13). In this system, the TiO₂ in the Zr/TiO₂ ratio is used as a differentiation index, and the Nb/Y ratio and Zr are used to measure alkalinity. Unlike the SiO₂ dependent graphs,

using the HFSE elements only results in a significantly different result, particularly for the mafic rocks. All of the mafic samples plot in the field of andesite, with the Sugars Basalt a separate population from the Weir Basalt and the bulk of GSQ Ipswich 26 subunit F. The dacitic samples of GSQ Ipswich 26 subunit F plot in the field of rhyolite, and plot close to GSQ Ipswich 26 subunit E. This supports other observed trends which indicate magmatic similarities between subunit E and F.

Of the felsic rocks, the Mount Crosby Formation tuff predictably plotted in an extremely narrow zone, occupying a position similar to but not overlapping with, the Brisbane Tuff, the differentiation between the formations caused by the relative depletion in TiO_2 of the Brisbane Tuff. The Brisbane Tuff plots as a single population in the rhyolite field. Similarly, most samples of the Hector Tuff plotted together in the rhyolite field, although one sample is so anomalously alkali-rich (for this graph) that it fails to plot in any of the recognised fields. The other outlying sample of Hector Tuff also plots in the rhyolite field, although well away from the main population.

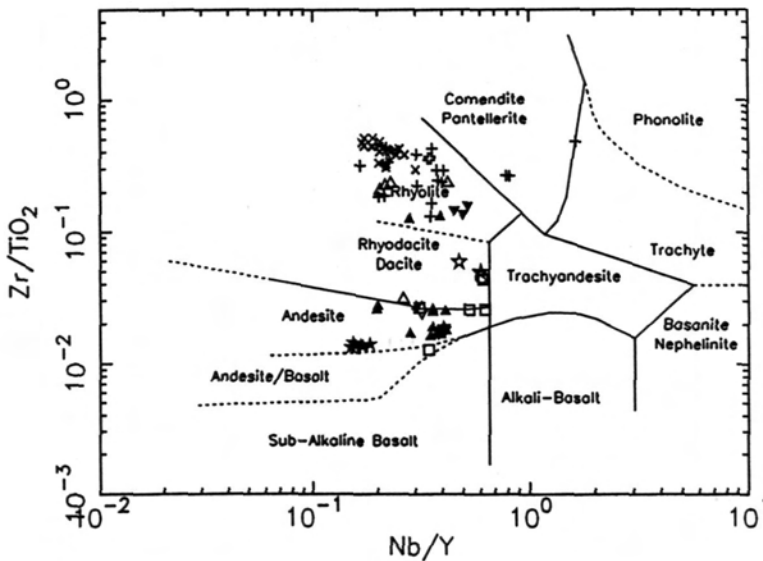


Figure 5.13 Zr/TiO_2 vs Nb/Y classification diagram of Winchester and Floyd (1977). (Symbols as in Fig. 5.11)

Due to the Chillingham Volcanics large range in values for the ratio of Nb/Y , samples plot across a broad area in both the rhyolite and comendite fields. The non-systematic nature of the variation in the Nb/Y ratio (outlined above) is exemplified in this diagram. The lone sample plotting on the comendite/trachyte boundary is again the

sample from the Mount Warning suite. The samples plotting in the comendite field are from the Clarrie Hall Dam sub-suite.

5.3.2 Tectonic Discrimination using High Field Strength Elements

Most tectonic discrimination diagrams have been optimised for rocks of basaltic to intermediate composition (Pearce *et al.*, 1977; Pearce & Norry, 1979; Pearce & Cann, 1973), with the exception of discrimination diagrams of Pearce *et al.* (1984) (Figs 5.16 & 5.17), which are applicable to more silicic rocks as well. The subtle differences in HFSE chemistry between basaltic-andesites and basalts enable diagrams designed originally only for basalts to be applied, at least approximately, to basaltic-andesites. The diagrams fall into two categories: those which use major elements for discrimination; and those which use trace elements. Most of the discrimination diagrams were designed with pristine volcanic rocks from modern environments, and their suitability with major oxides of altered rock data is questionable; however, those diagrams which use HFSE are thought to be suitable with moderately altered rocks in certain circumstances (Pearce & Norry, 1979; Pearce & Cann, 1973). Most of the discrimination schemes are derived from plotting data from known tectonic settings on the diagrams and defining fields around them. While mid-ocean ridge and volcanic-arc settings are well sampled, intra-plate rocks are poorly studied and under-represented in these studies, and are probably skewed by available modern study sites (Pearce & Norry, 1979; Pearce & Cann, 1973).

Comparisons between HFSE data for the Ipswich Basin and data compiled by Pearce and Cann (1973) for several tectonic environments reveal some interesting trends even without the assistance of discrimination diagrams. It should be noted that the all continental rocks which Pearce and Cann (1973) used for their data set were from flood basalt provinces of Africa and India. Comparisons were made using the Basin and Range Province HFSE concentrations (Carlson & Hart, 1987; Hoffer, 1988; Bradshaw *et al.*, 1993), largely confirming the ranges for the HFSE quoted for continental rocks by Pearce and Cann (1973), although Pearce and Cann's ranges are quoted subsequently without the Basin and Range data. Because of the similarities between ocean island basalts and the continental basalts, the two sets were merged by Pearce and Cann (1973)

and considered as one set which was termed “*within-plate basalts*”.

Nb values for volcanic arcs are typically less than 3 ppm, and continental (and non-MOR) rift-related rocks usually range from 20-25 ppm, with some as low as 10 ppm, and others as high as 90 ppm (Pearce and Cann, 1973). Rocks of the Ipswich Basin fall between, with Weir Basalt and GSQ Ipswich 26 subunit F rocks containing approximately 15-17 ppm, and the Sugars Basalt about 7 ppm. Volcanic arc samples usually contain less than 70 ppm Zr, continental rocks 130-330 ppm (Pearce and Cann, 1973), and Ipswich Basin rocks 200-350 ppm, within the bound of the continental rocks. Y is problematic as Gill (1981) suggests that andesites and basalts from the same tectonic setting should have similar Y values, whereas values recorded for the Ipswich Basin (35 - 50 ppm) exceed those of all tectonic settings as noted by Pearce and Cann (1973).

Various plots of Ipswich Basin volcanic rocks yield different, and apparently contradictory, results for tectonic environments, however this serves only to illustrate the complexities of both the chemistry of the Ipswich Basin rocks and their tectonic setting. Some tectonic discrimination diagrams suggest that the bulk of the rocks are calc-alkaline and arc related in their tectonic environment, other diagrams suggest that they are within-plate rift-related rocks.

On Meschede’s (1986) discrimination diagram (Fig. 5.14), which utilises HFSE elements only, the mafic rocks plot in three fields: within-plate alkaline rocks; within-plate tholeiites; and volcanic-arc (calc-alkali) basalts. It should however be noted that Meschede’s diagram contains overlap regions, and that some within-plate rocks are expected to plot in the field of calc-alkali basalts. Samples of the Sugars Basalt are confined as a separate population to the calc-alkaline field so for the purposes of Meschede’s classification, they can be considered to be strictly calc-alkaline.

Pearce and Norry’s (1979) classification diagram also exclusively utilizes the HFSE elements for discrimination, in this case Zr and Y (Fig. 5.15). This classification scheme is optimised towards differentiating between the gross tectonic settings, of mid-ocean ridge (MOR), volcanic-arc, and within-plate settings. Under this scheme, excluding some samples of GSQ Ipswich 26 subunit F containing anomalously high Y which plot out of the recognised field, all samples plot in the within-plate field, with

each unit forming a separate population.

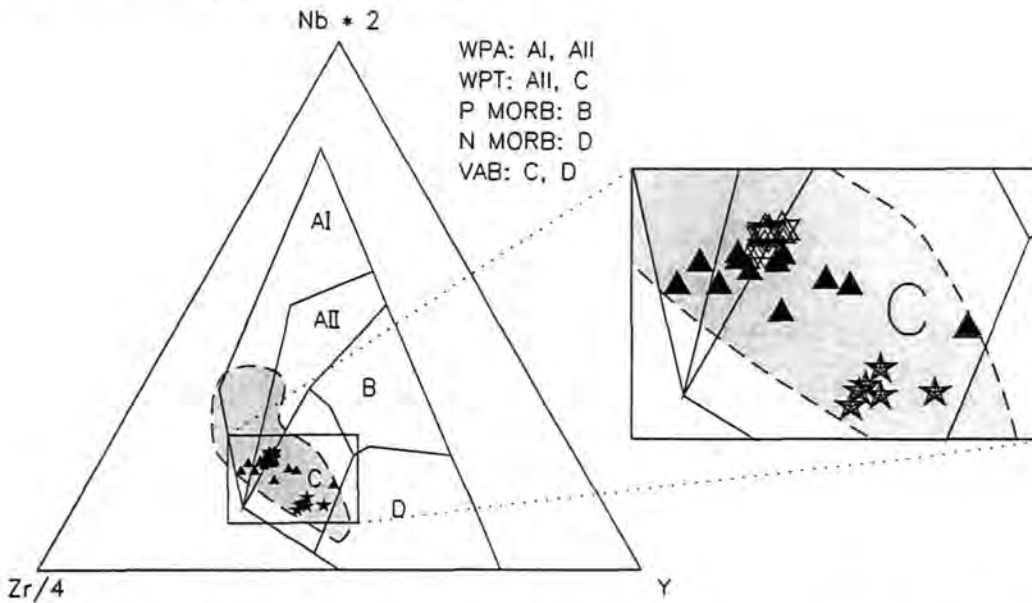


Figure 5.14 Nb, Y, and Zr ternary tectonic discrimination diagram of Meschede (1986). A certain amount of overlap is allowed between the fields, and the areas covered by populations as a whole should be considered rather than isolated samples. WPA = within-plate alkaline; WPT = within-plate tholeiites; VAB= volcanic arc basalts; PMORB = “P” type mid ocean ridge basalt; and NMORB = “N” type mid ocean ridge basalts. Shaded area is for typical Basin and Range rocks (data taken from Bradshaw *et al.*, (1993)). (☆=Weir Basalt; ★=Sugars Basalt; ▲=GSQ Ipswich 26 subunit F)

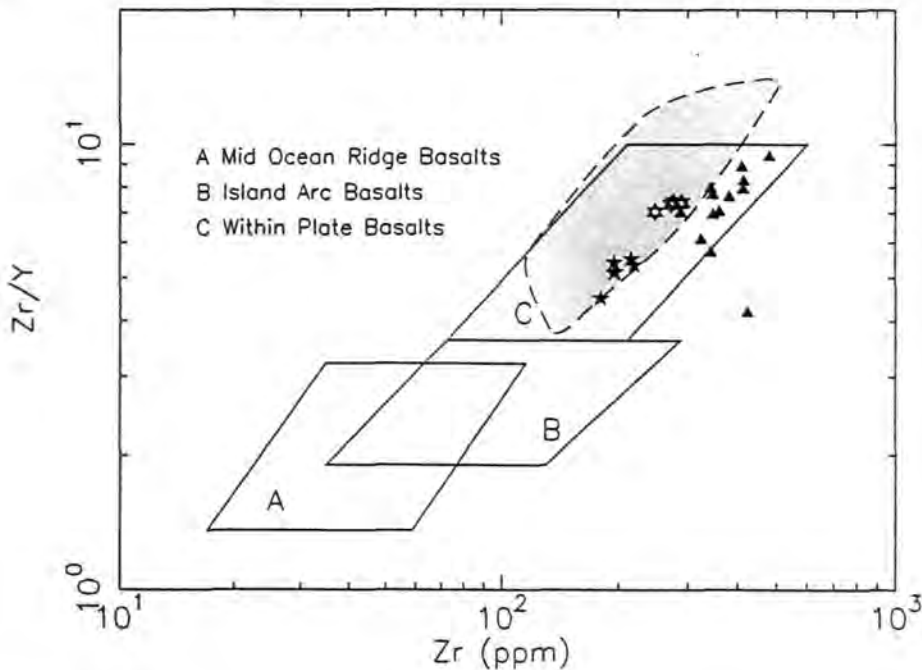


Figure 5.15 Zr vs Zr/Y tectonic discrimination diagram of Pearce and Norry (1979). Shaded area is for typical Basin and Range rocks (data taken from Bradshaw *et al.*, (1993)). (Symbols as in Fig. 5.14)

Pearce *et al.* (1984) produced tectonic discrimination diagrams for granites

which utilised the HFSE. The scheme adopted is less specific than those for mafic rocks, differentiating between volcanic arc, orogenic, and within-plate rocks. Derived from granites, the diagrams apply also to co-magmatic silicic volcanic rocks. Pearce *et al.* (1984) included diorites in their “granites”, so that the volcanic equivalents - basaltic-andesites - are also relevant. Hence I plot here the Sugars Basalt and Weir Basalt.

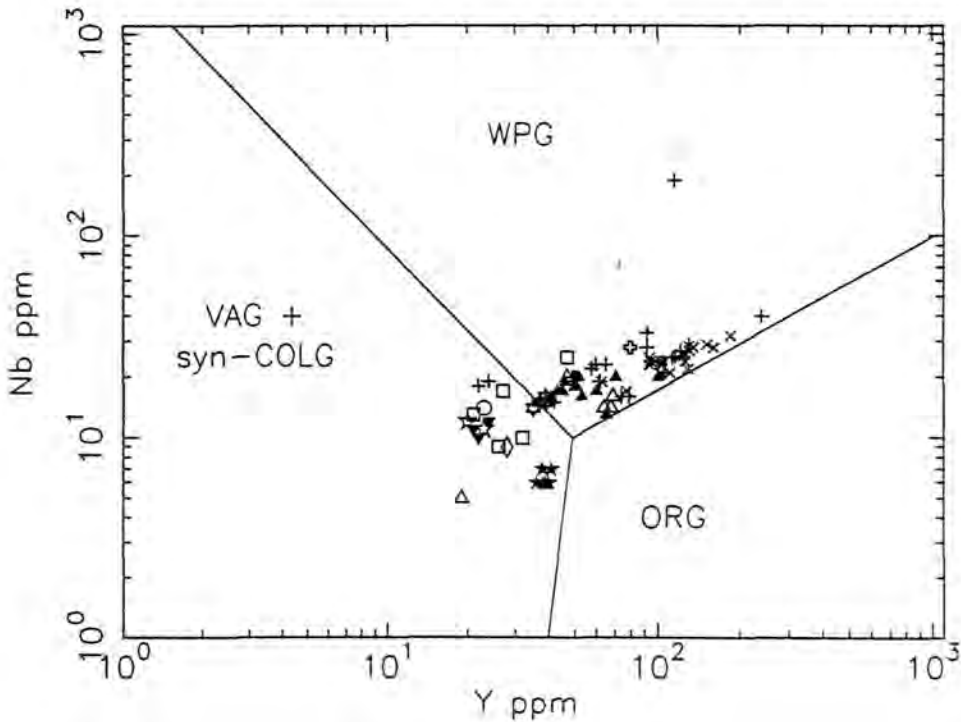


Figure 5.16 Nb v Y tectonic discrimination diagram for granites (Pearce *et al.*, 1984). Although designed for use with granites, the diagram can also be applied to volcanic rocks. (WPG = in plate granite; VAG = volcanic arc granite; ORG= orogenic granite)

The tectonic discrimination of granites is further complicated because erosion does not expose granites until well after their intrusion and cooling, during which time the tectonic setting may have changed, whereas volcanic rocks are directly observed being emplaced into active tectonic settings. Figure 5.16, which uses Nb and Y, implies that the granites, the Sugars Basalt, and GSQ Ipswich 26 subunit E rhyolites formed in a “volcanic-arc setting”, and the others in a “within-plate setting”. With the exception of the Chillingham Volcanics, which, as mentioned earlier, has a wide range of Nb/Y ratios (0.15-0.8), all formations plot in tightly confined fields. The lone sample from the Chillingham Volcanics plotting in the “within-plate granite” field is the sample thought

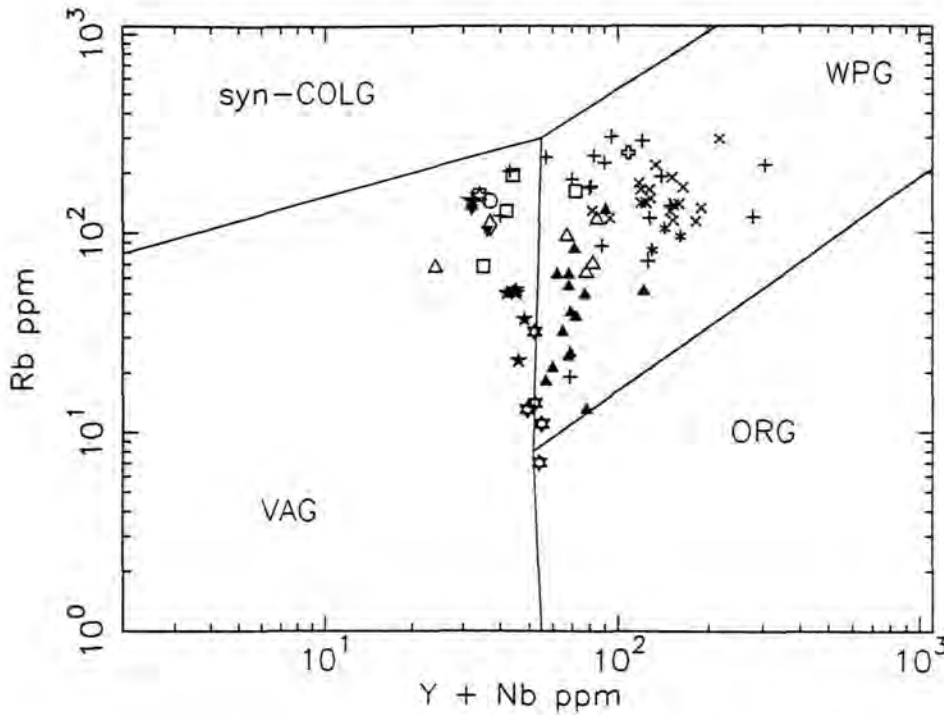


Figure 5.17 Rb vs Nb + Y tectonic discrimination diagram for granites (Pearce *et al.*, 1984).

to be from the Mount Warning suite. Figure 5.17 shows a similar classification using the slightly more mobile element Rb, but with a wider scatter of points. As with Figure 5.16, the granites, the Sugars Basalt, and GSQ Ipswich 26 subunit E rhyolites plot in the volcanic-arc field, with the balance of samples in the within-plate field, although the greater range of Rb values leads to more dispersed populations of samples. The interesting feature of these graphs is the separation of the GSQ Ipswich 26 subunit E rhyolites into the volcanic-arc field. These rhyolites represent the oldest known rhyolites of the Ipswich Basin (at least 230 Ma) and may reflect an arc.

Because samples plot in the “within-plate setting” for the volcanic rocks on most other discrimination diagrams reliant on the HFSE, it is surprising that Pearce and Cann’s (1973) ternary diagram utilizing Ti, Zr, and Y shows a significantly different result. As discussed earlier in this section, a comparison of the HFSE data on their own suggests a within-plate setting; however, on Pearce and Cann’s (1973) ternary diagram (Fig. 5.18) samples plot in the field of calc-alkaline rocks except for some samples of GSQ Ipswich 26 subunit F which plot outside all fields. As with most other

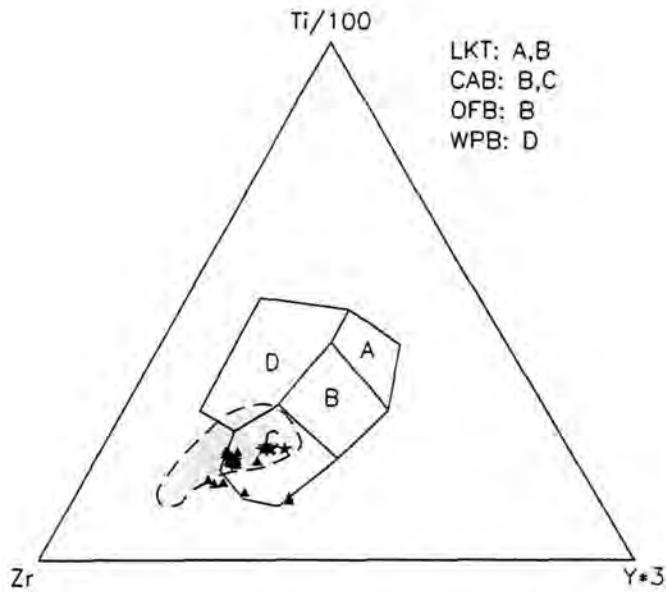


Figure 5.18 Ti- Zr-Y ternary tectonic discrimination diagram of Pearce and Cann (1973). Shaded field in for typical Basin and Range rocks (data taken from Bradshaw *et al.*, (1993)). LKT = low potassium tholeiites; CAB= calc-alkaline basalts; OFB= ocean floor basalts; and WPB = within-plate basalts.

discrimination diagrams, the Sugars Basalt plots apart from the other mafic rock units. Although the same HFSE elements (Zr and Y) in other diagrams have discriminated the samples as within-plate, on the Ti-Zr-Y diagram they plot as island-arc rocks. This may be due to the use of African flood basalts for defining the continental field. These basalts typically have in excess of 2.6 wt% TiO_2 , which has upwardly skewed the within-plate field of the diagram. Other continental provinces, such as the Basin and Range Province, have lower TiO_2 values (1.2-2.4 wt%) (Carlson & Hart, 1987; Hoffer, 1988; Bradshaw *et al.*, 1993), many of which when plotted on Pearce and Cann's (1973) diagram would also plot in the calc-alkaline field.

5.4 Isotope Analysis Results

In an attempt to characterise the source magmas for the volcanic rocks and to obtain a model age for some of the un-dated volcanic rocks of the Ipswich Basin, isotopic studies were carried out on 12 samples at the Centre for Isotope Studies at CSIRO North Ryde. Of the 12 samples, three were from the Brisbane Tuff, three from the Chillingham Volcanics, and two each from the Weir Basalt, GSQ Ipswich 26, and plutonic rocks of the South D'Aguilar Block. Details are listed in Table 5.3.

Table 5.3 Isotope data for Ipswich Basin volcanic rocks and South D'Aguilar Block plutonic rocks.

Formation	Sample	Rb ppm	Sr ppm	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	ϵNd	Initial $^{87}\text{Sr}/^{86}\text{Sr}$
Brisbane Tuff	088-01	183	45	11.2788	0.737464	0.13464	0.512754	2.26281	0.70153
	092-01	133	68	5.38308	0.72375	0.154908	0.512774	2.65294	0.70660
	099-04	114	98	3.21584	0.718858	0.143212	0.512772	2.61393	0.70861
Chillingham Volcanics	191-01	158	22	20.192	0.764278	0.0669862	0.512785	2.86752	0.69995
	240-20	71	22	8.84459	0.7544	0.17614	0.512771	2.59442	0.72622
	204-03	123	0	0	0	0.116471	0.512731	1.81415	-
Weir Basalt	260-03	13	824	0.0445028	0.705108	0.127238	0.512732	1.83365	0.70497
	260-06	13	679	0.0514514	0.70486	0.097118	0.512744	2.06774	0.70470
GSQ26	261-24	18	0	0.389608	0	0.132217	0.512781	2.78949	-
	261-15	104	95	2.99895	0.712202	0.370719	0.512828	3.70632	0.70239
Plutonic Rocks	269-01	149	0	2.07736	0	-	0.512652	0.27310	-
	270-01	150	150	2.76373	0.713734	0.161248	0.512628	-0.19507	0.70493*

Inferred initial ratios for all samples were calculated using an assumed age of 224 Ma, except for * which uses a measured age of 224 Ma (Cranfield *et al.*, 1976). Zero values are quoted for samples for which there was no data.

Although care was taken in the selection of representative and least altered samples, the $^{87}\text{Sr}/^{86}\text{Sr}$ data suggest that many samples are considerably altered, and cannot be considered to reflect primary values. In the case of the Brisbane Tuff and Chillingham Volcanics samples, for which the age is constrained by microfloral evidence, the anomalous abundance of Sr in the original sample was most likely caused by Rb/Sr leaching of the samples. Musselwhite *et al.* (1989) consider that hydration was a major factor influencing the $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios. They conclude that the degree and uncertainty of this hydration-related alteration was so significant that chemical modelling should be used cautiously in hydrated samples. They did not however notice any such correlation between the Sm-Nd isotopic system and hydration-related alkali remobilisation, and concluded that the Sm-Nd system was more reliable for magma characterization. The $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ (and hence ϵNd) values are consistent and do not seem to have been modified by the alteration.

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the rocks were calculated using an assumed age of 224 Ma based on published ages for plutonic rocks and similar late Triassic volcanic rocks of south-east Queensland outside the Ipswich Basin (Cranfield *et al.*, 1976). Data in

section 5.4.1 confirm that the ages selected from published data are appropriate.

The initial ratios calculated ranged from 0.69995 to 0.72622, extremes at either end of this range are discounted because of mobilization of Rb/Sr during alteration. Samples with discounted initial ratios come from the Brisbane Tuff, Chillingham Volcanics, and sample 261-15 from GSQ Ipswich 26 subunit E. They are rhyolitic in composition, and all were originally glassy (as evident from welding, perlitic cracks, spherulites etc.) and subsequently devitrified. Figure 5.8 shows that most felsic rocks analyses have undergone some alteration which has affected their alkali content, which in turn could be expected to affect the Rb/Sr ratio. A filtered range of initial ratios from the plutonic rocks and the Weir Basalt range from 0.70470 to 0.70497.

ϵNd data can in general be considered a more reliable measure of the initial isotopic composition of the magma for this particular data set than the Rb/Sr data. The results obtained show more continuity, and do not appear to have been so affected by alteration. Ranges in value for ϵNd are -0.19507 to +3.70632 in two groups, and if the data from sample ARPHD0261-15 are accepted, a third group. The most crustally influenced samples (+0.27310, and -0.19507), are the two plutonic rocks of the South D'Aguilar block. These samples are more negative than typical arc rocks, which commonly have $\epsilon\text{Nd} > +4$ (DePaolo, 1988).

Other samples have ϵNd in the range of +1.81415 to +2.86752 (Brisbane Tuff, Chillingham Volcanics, Weir Basalt, and GSQ Ipswich 26 subunit F), suggesting alteration has had a minimal affect on the ϵNd values. The values, while positive, are less than is generally accepted for uncontaminated mantle derived or island-arc rocks, and indicate a limited amount of crustal contamination.

Sample ARPHD0251-15, a rhyolite from GSQ Ipswich 26 subunit E, with an ϵNd value of +3.70632, is the least crustally contaminated sample, and closest to the lower cut off of +4 that is typical of island-arc rocks. As previously noted, the rhyolites from this subunit are distinct from other rhyolites of the Ipswich Basin in terms of stratigraphic position and chemistry, with HFSE discrimination diagrams indicating an arc environment for these rocks, differing markedly with the within-plate setting of the other rhyolites.

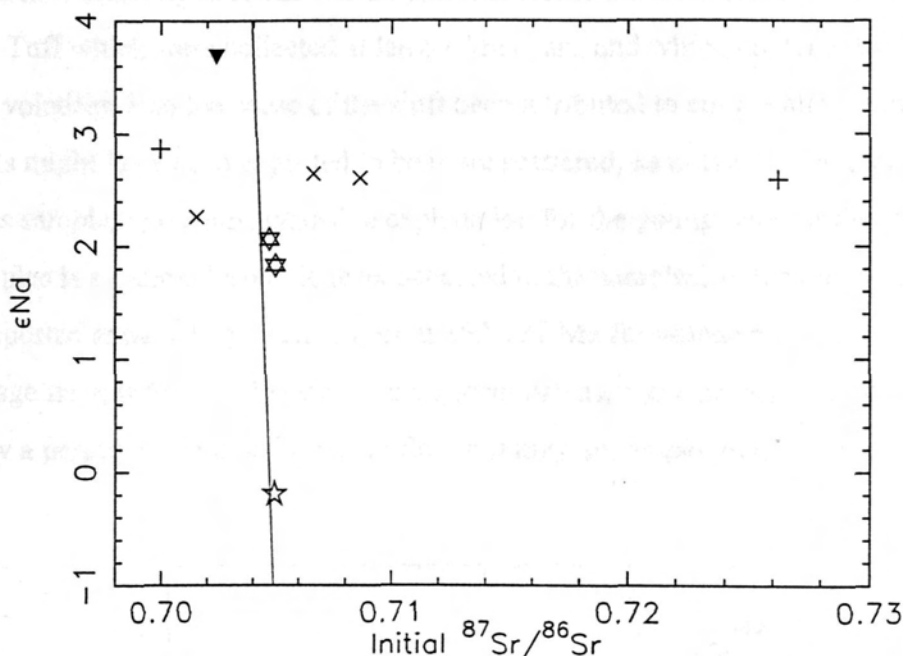


Figure 5.19 ϵNd v- $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the volcanic rocks of the Ipswich Basin and plutonic rocks of the D'Aguilar block. Line is the approximate location of the *mantle array* of DePaolo (1988). (Symbols as in Fig 5.1)

Bulk Rock Age Determinations

Volcanic rocks from the Ipswich Basin have not been extensively isotopically dated. Although most formations have reasonably well constrained faunal ages, the only formations which have been isotopically (K/Ar whole rock) dated at 229 and 232 Ma have been the Weir/Sugars Basalt by (Webb and McNaughton, 1978). In the absence of un-altered rocks with biotite, Rb/Sr dating of biotite mineral separates could not be undertaken. Instead it was hoped that the Rb/Sr data could be used to obtain a bulk rock age. Age dates were calculated using Mc Intyre *et al.*'s (1966) program.

As previously noted, some of the Sr samples did not run on the TIMS, and this combined with some altered samples reduced the usefulness of the data set for use in a bulk rock age determination. Only one formation, the Brisbane Tuff, had more than two usable data points from which to plot an isochron. The isochron obtained from the Brisbane Tuff data alone (Fig. 5.20), has a calculated regression date of 154.5 ± 29.4 Ma (initial ratio 0.71141 ± 0.00224), and the favoured model 3 date was 154.6 ± 29.9 Ma (initial ratio 0.71140 ± 0.00231). While modification of the Rb/Sr during hydration from groundwater or hydrothermal sources can cause a shift in the apparent age, it is difficult

to explain how leaching of Rb/Sr was so uniform across the three samples of the Brisbane Tuff which were collected at least 1 km apart, and which contained vastly different volatiles. Had the cause of the shift been attributed to simple alteration alone, the results might have been expected to be more scattered, as in the Chillingham Volcanics samples. The most plausible explanation for the young date for the Brisbane Tuff samples is a regional isotopic reset occurred in the samples. Ashley and Shaw (1993) reported apparent ages ranging from 152-187 Ma for volcanic rocks of Late Triassic age from within the Ipswich and adjacent basins, representing an isotopic reset caused by a period of regional high heat flow possibly accompanying Jurassic magmatic activity.

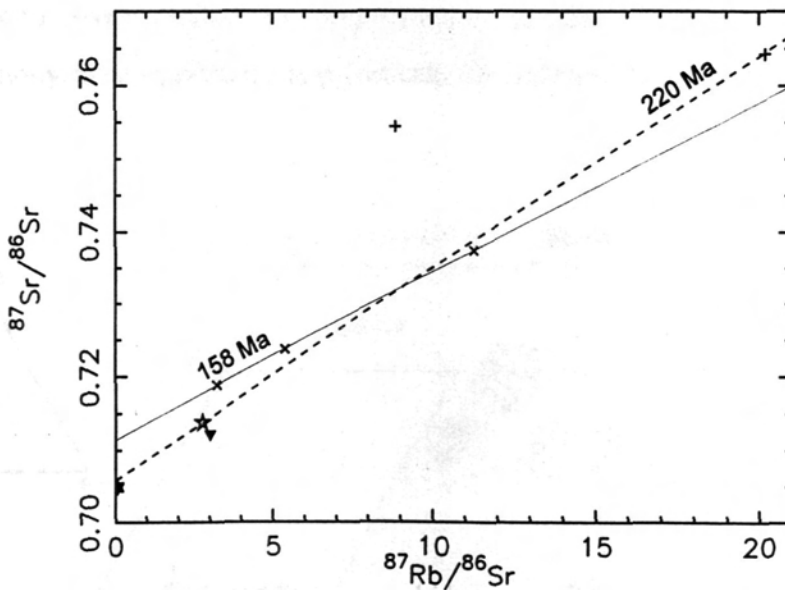


Figure 5.20 Rb/Sr whole rock radiometric age data.

The best estimated age for the volcanic rocks of the Ipswich Basin is based on specimens considered unaltered, using the assumption that the rocks were all formed at about the same time and with similar initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and using bulk rock data from several formations and granite. These data produce a regression “errorchron” date of 220.1 ± 3.1 Ma (initial ratio 0.70485 ± 0.00011) that has a large mean squares weighted deviate of 245, which at least compares favourably with the 230-218 Ma ages of Late Triassic magmatism in south-east Queensland (Cranfield *et al.*, 1976), although McIntyre *et al.*’s (1966) analyses gives a model 3 age of 196.8 ± 20.1 Ma (initial ratio

0.70576±0.00249).

5.5 Pyroxene Chemistry

The pyroxenes studied are clinopyroxenes. Sixty grains, 58 augites and 2 salites, from 10 rocks (5 from the Sugars Basalt, 4 from the Weir Basalt, and one from GSQ Ipswich 26 subunit F) were analysed on a Cameca Camebax SX50 electron microprobe. Clinopyroxenes were analysed to confirm geochemical conclusions from whole rock and trace element data because:

- 1) clinopyroxene phenocrysts are commonly fresh even in rocks with considerably altered feldspars;
- 2) clinopyroxenes reflect the composition of the original mafic magma; and
- 3) clinopyroxene chemistry may indicate the tectonic environment.

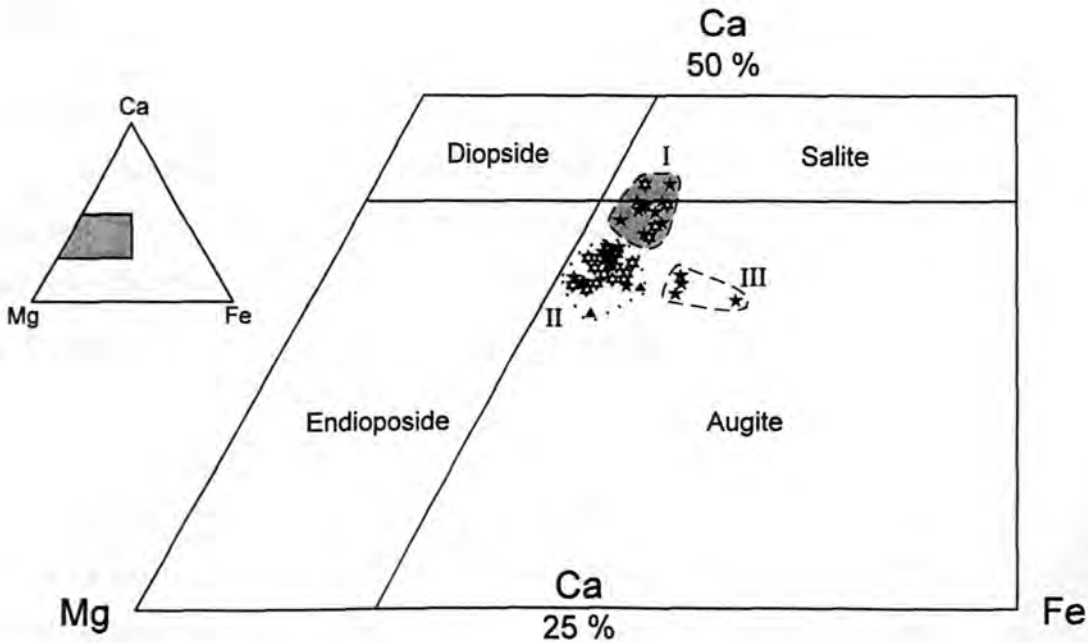


Figure 5.21 Pyroxene classification tetrahedra of Deer *et al.* (1978). (☆=Weir Basalt; ★=Sugars Basalt; ▲=GSQ Ipswich 26 Subunit F). Cluster III contains five analyses including an overlapping pair.

5.5.1 Ca-Mg-Fe diagram

On the Ca-Mg-Fe diagram of Deer *et al.* (1978) (Fig. 5.21), analyses cluster (II and III) in the high Ca and Mg part of the augite field, and I (the most calcic population)

overlaps into the salite field. The membership of the clusters is constant in figures 5.21 - 5.25. Each individual rock of the Weir Basalt and GSQ Ipswich 26 subunit F has a uniform Ca-Fe-Mg composition, whereas pyroxene analyses of individual samples of the Sugars Basalt plot in clusters I, II, and III.

Grains of GSQ Ipswich 26 subunit F (confined to cluster II) are the least calcic augites, consistent with their tholeiitic major-element chemistry. The Sugars Basalt dominates the high-calcic field (cluster I), consistent with their calc-alkaline major and trace element geochemistry of the three formations.

The more calcic augites (I) occur in the Sugars Basalt, representing analyses from five samples, and from a single sample (DDH NS 295) of the Weir Basalt, which is significantly more calcic than other Weir Basalt samples.

The analyses of the Sugars Basalt in cluster III may indicate a fractionation trend from II.

5.5.2 SiO_2 v Al_2O_3 diagram

In Figure 5.22, cluster I, the same analyses as in Figure 5.21, except for three analyses, lie in the alkaline field, the rest in the subalkaline field (Le Bas, 1962). Cluster I are from the NS 295 sample of the Weir Basalt and some grains of the Sugars Basalt. All formations are represented in the subalkaline field.

5.5.3 Al_Z v TiO_2 diagram

Le Bas (1962) pointed out that the proportion of the Z group occupied by Al (Al_Z) is in most circumstances in approximate proportion to the total Al_2O_3 in the rock. 70% of Al goes into the Z site, the rest into the Y site. Available Al fills the Z site after silica. On a 6 O model, $\text{Al}_Z = ([2\text{-Si}]/2) \times 100$. Because Al_Z varies inversely with Si in the Z group, Al_Z can be used as a measure of the differentiation index for the rock. Alkaline augites have > 1 % TiO_2 , so TiO_2 can be used as a guide to alkalinity.

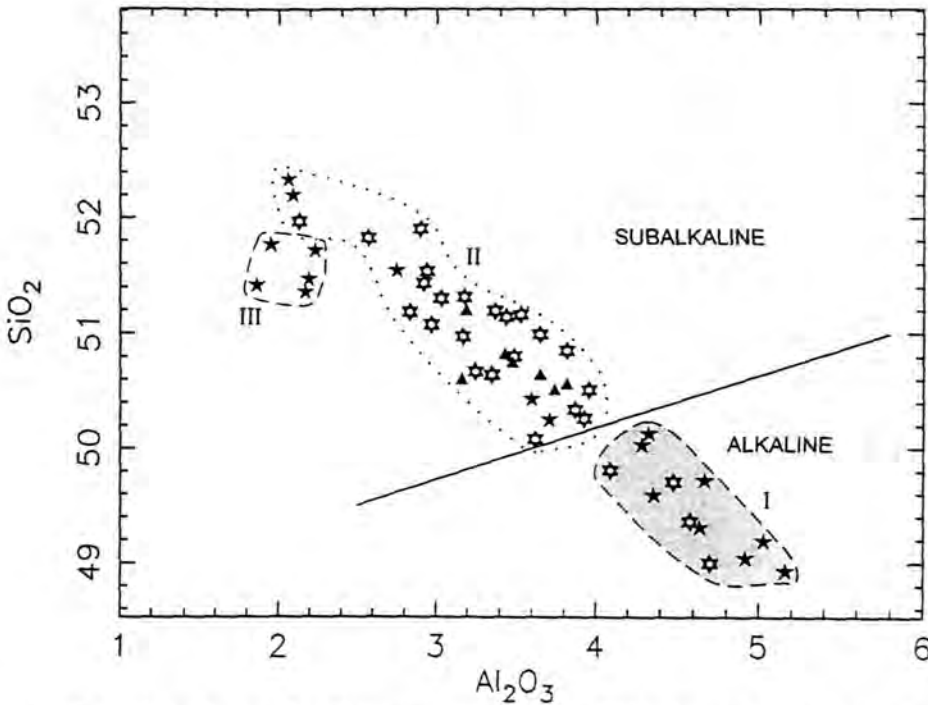


Figure 5.22 SiO_2 v Al_2O_3 diagram for clinopyroxenes (Le Bas, 1962), showing classification between sub-alkaline and alkaline pyroxenes. (\star =Weir Basalt; \star =Sugars Basalt; \blacktriangle =GSQ Ipswich 26 Subunit F).

On the Al_2 v TiO_2 diagram (Fig. 5.23), II and III are sub-alkaline, and I (except for one analysis) alkaline. Analyses in the alkaline field are the same as those in the alkaline field on the SiO_2 v Al_2O_3 diagram (Fig. 5.22). The Sugars Basalt contains both low TiO_2 (< 1.0 wt%) augites and higher TiO_2 (> 1.1 wt%) titaniferous augites (Table 5.4) within the same sample.

The analyses of Sugars Basalt (III), a possible fractionation trend on the Ca-Mg-Fe diagram (Fig. 5.21), again plot within their own cluster.

Table 5.4 Classification of augites on TiO_2 content (Deer *et al.* 1978)

Augite	$< 1\% \text{ TiO}_2$
Titaniferous augite	$1\% - 3\% \text{ TiO}_2$
Titanaugite	$> 3\% \text{ TiO}_2$

5.5.4 TiO_2 - MnO - Na_2O tectonic discriminator of Nisbet and Pearce (1977)

Figure 5.24 discriminates between different tectonic environments. Although a large central field (D) has no specific tectonic affinities, the diagram can still be useful

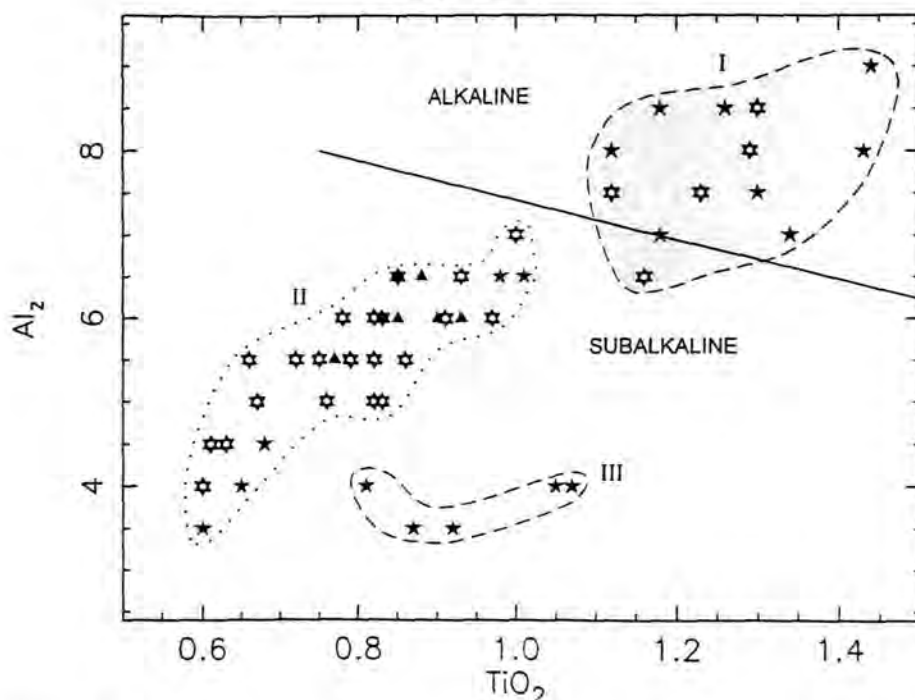


Figure 5.23 Al_2O_3 v TiO_2 diagram fields taken from Le Bas (1962). (☆=Weir Basalt; ★=Sugars Basalt; ▲=GSQ Ipswich 26 subunit F).

for determining overall trends.

All analyses plot in the higher TiO_2 area of the diagram. Samples straddle fields B (ocean floor basalts), C (within-plate alkaline), E (volcanic-arc basalts, within-plate tholeiites, and within-plate alkalis), with most in D (all). Although plotting in several small clusters, the more calcic population (I) is the only population cluster recognisable on previous diagrams.

The augites fall within fields D and E and at the margins of B and C, and do not indicate any specific environment.

5.5.5 Factor Analysis

Factor analysis of the pyroxene data using factors defined by Nisbet and Pearce (1977) was undertaken to determine the tectonic environment. Factors are defined as:

$$F_1 = -0.012 \times \text{SiO}_2 - 0.0807 \times \text{TiO}_2 + 0.0026 \times \text{Al}_2\text{O}_3 - 0.0012 \times \text{FeO}^* - 0.0026 \times \text{MnO} + 0.0087 \times \text{MgO} - 0.0128 \times \text{CaO} - 0.0419 \times \text{Na}_2\text{O}$$

$$F_2 = -0.469 \times \text{SiO}_2 - 0.0818 \times \text{TiO}_2 - 0.0212 \times \text{Al}_2\text{O}_3 - 0.0041 \times \text{FeO}^* - 0.1435 \times \text{MnO} - 0.0029 \times \text{MgO} + 0.00085 \times \text{CaO} + 0.01060 \times \text{Na}_2\text{O}$$

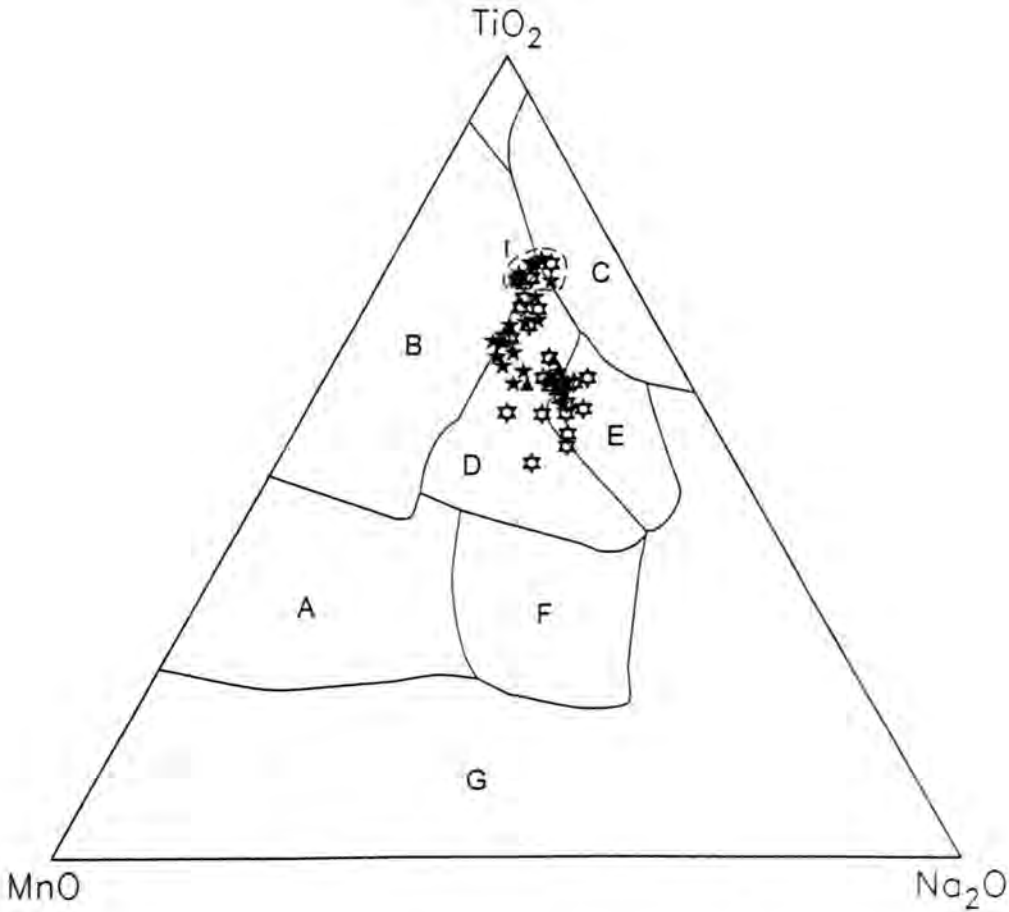


Figure 5.24 Pyroxene tectonic discriminator TiO_2 - MnO - Na_2O of Nisbet and Pearce (1977). A = Volcanic-arc basalts; B = ocean-floor basalts; C = within-plate alkaline; D = all; E = volcanic-arc basalts, within-plate tholeiites, and within-plate alkaline; F = volcanic-arc basalts and within-plate alkaline; and G = within-plate alkaline. (☆=Weir Basalt; ★=Sugars Basalt; ▲=GSQ Ipswich 26 subunit F).

Nisbet and Pearce (1977) found that up to 22% of within-plate tholeiites and volcanic-arc basalts could be misclassified; only 30% of within-plate tholeiites were correctly diagnosed.

In Figure 5.25, the more calcic population (I) plots across the fields of volcanic-arc basalts and volcanic-arc + ocean-floor basalts. All others plot in the volcanic-arc + ocean-floor basalt field. The possibly “fractionated” Sugars Basalt analyses (III) plot together. The “fractionated” field (III) together with some outlying Sugars Basalt analyses, which are not separated on other diagrams, plot close to the “ocean-floor + within-plate basalt” field.

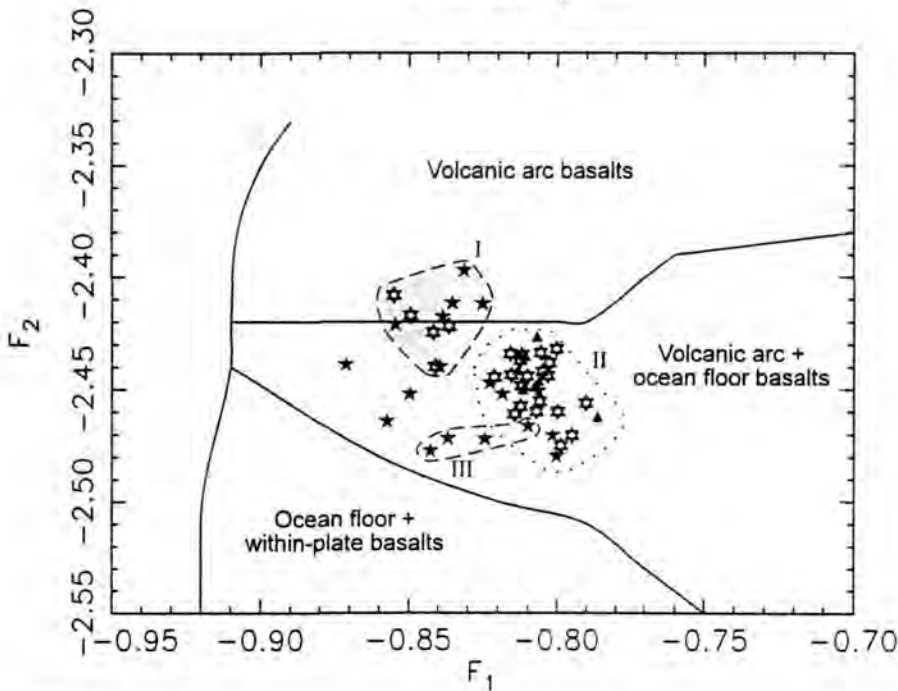


Figure 5.25 Plot of discrimination functions F_1 v F_2 for pyroxene analyses. Discrimination boundaries from Nisbet and Pearce, (1977). (☆=Weir Basalt; ★=Sugars Basalt; ▲=GSQ Ipswich 26 subunit F).

5.5.6 Conclusions

Most augites are subalkaline, with 20% of the analyses being more calcic augites that have an alkaline character. The differences in composition between the more and less calcic augites are slight, and within the range of variation of individual flows (Deer *et al.*, 1978).

The alkaline/more calcic analyses (I) were clustered on all diagrams, verifying the validity of the various classification schemes. As expected, the augites from the more alkaline rocks are more titaniferous than most of the sub-alkaline ones.

The silica undersaturation of the pyroxenes is reflected in the whole rock normative composition (Appendix B). The alkaline Weir Basalt sample from NS 295 is the least quartz-normative of all the Weir Basalt samples. A third of the Sugars Basalt samples analysed for normative compositions is not quartz normative, and the other two thirds are the least quartz normative of all the mafic rocks of the Ipswich Basin.

All samples of GSQ Ipswich 26 subunit F are subalkaline, and many diagrams indicate that they are the most tholeiitic of the samples, which confirms the trend from major element geochemistry.

All samples of the Sugars Basalt have two types of augite - an alkaline/more

calcic Ti-rich augite, and a subalkaline augite. There is no fractionation between the alkaline Sugars Basalt augites and the sub-alkaline ones. Some undersaturated analyses from the Sugars Basalt were anomalously high in TiO_2 for their Si number, so that analyses plot away from the main field of subalkaline rocks. Some diagrams imply that the augites may be a product of fractionation, others do not.

The whole rock TiO_2 content of the basaltic-andesites of the Ipswich Basin ranges from 1.4 to 2.06 wt%, and the fresh augites from them ranges from 0.6 to 1.4 wt% (average 0.9 wt%). According to Coleman and Walker (1990), titanomagnetites with up to 30% TiO_2 in some rocks suggests that the bulk of the TiO_2 is accommodated in oxides. The ranges of TiO_2 for both augites and whole rock samples from the Panamint Valley area of the Basin and Range Province are similar to those of the Ipswich Basin; TiO_2 in the whole rock was concentrated in rutile (TiO_2).

In some of the Sugars Basalt samples, the alkaline/ TiO_2 rich analyses are restricted to larger phenocrysts, and lower TiO_2 analyses to the groundmass. Some of the larger phenocrysts have TiO_2 depleted rims, but no zonation is visible in the phenocrysts.

Deer *et al.* (1978) reported that andesites from Tonga vary randomly in Al and Fe content of the augites, and suggest slow diffusion in the liquid relative to the pyroxene growth rate and the co-precipitation of plagioclase that led to irregular concentration gradients under the conditions of quench crystallization. A similar process may have been responsible for the variations in augite composition of the Sugars Basalt.

5.6 Implications for Tectonic Settings

Other geochemical studies of Late Triassic volcanic rocks in southeast Queensland gave similar results to those from the Ipswich Basin, showing either a stratigraphic alternation of a volcanic-arc and within-plate basalt (Cranfield and Murray, 1989), or a mixed signature which indicates a change from subduction-related to extensional volcanism (Stephens, 1992). Key features of the chemistry (trace element, whole rock, isotope, and pyroxene) can be used to suggest tectonic environments in which they formed. As discussed earlier, much work has been done in characterising mafic rocks and their tectonic settings, and little for felsic rocks, therefore most of the

following discussion will be related to the mafic rocks.

Most whole rock and trace element diagrams suggest a within-plate setting for the bulk of the volcanic rocks of the Ipswich Basin. Other diagrams suggest calc-alkaline or arc-settings for the rocks. While possibly illustrating the shortcomings of the various discrimination schemes, the mixed trend more realistically reflects the mixed-chemistry of these rocks, namely that of both calc-alkaline and within-plate rocks. It is therefore suggested that the Ipswich Basin mafic rocks formed in a back-arc rift environment after subduction had ceased or the angle of subduction increased. Modern rocks in similar tectonic settings should have similar chemistry. In order to locate rocks with similar compositions (and hence tectonic environment), key elements (TiO_2 , P_2O_5 , Nb, Y, and Zr) were compared with regions in which rifting has occurred after subduction.

5.6.1 Comparison of the Ipswich Basin mafic rocks with those of the South Shetland Islands

The South Shetland Islands (SSI) (Fig. 5.26) are believed to have formed in an environment where subduction ceased in geologically recent time (Ewart, 1982). Following the cessation of subduction, back-arc rifting commenced about 100 ka, and developed into its present configuration, which is considered to be transitional between a marginal back-arc basin and a mid-ocean ridge (Keller & Fisk, 1992; Keller *et al.*, 1992). No felsic rocks in this convergent margin are found.

Rocks within the SSI show chemistries ranging from arc to MOR, and while not possessing a strong within-plate signature, have anomalous levels of some elements typical of these settings. TiO_2 and Al_2O_3 levels (for given SiO_2) of the SSI (Ewart, 1982; Keller & Fisk, 1992; Keller *et al.*, 1992) are similar to the Ipswich Basin mafic rocks, but P_2O_5 and K_2O are considerably less in the SSI rocks. The trace element data are highly variable, perhaps reflecting the extreme tectonic range, immature back-arc rift to MOR. Most of the immobile HFSE are comparatively depleted in the SSI rocks, but some ratios are similar to those of the Ipswich Basin mafic rocks.

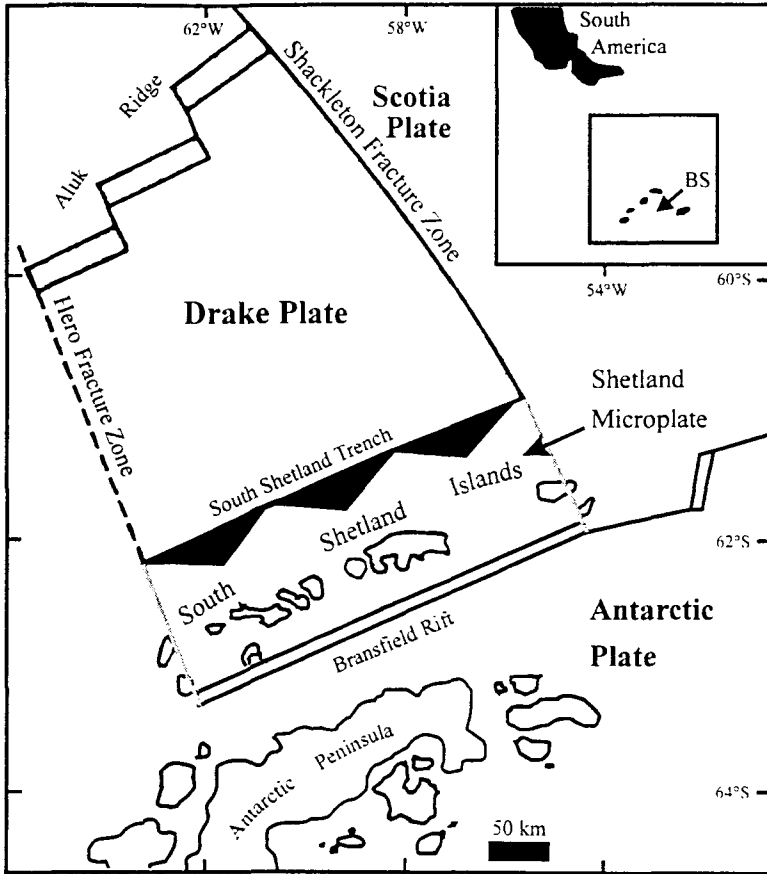


Figure 5.26 Plate tectonic setting of the South Shetland Islands (after Keller and Fisk, 1992).

5.6.2 Comparison with Basin and Range Province

Compared with arc-related rocks, the basaltic andesites/andesites of the Basin and Range Province are enriched in TiO_2 (Carlson & Hart, 1987; Hoffer, 1988; Bradshaw *et al.*, 1993; Ewart, 1982; Coleman & Walker, 1990), typically greater (between 1.7-2.5 wt%) than those of the Ipswich Basin. The province lacks geochemical details of the felsic rocks. The Basin and Range Province is divided into northern and southern provinces, with the transition zone near Las Vegas. The northern province is wider and of higher elevation than the southern province, and contains a thick miogeoclinal succession not exposed in the south (Wernicke, 1990). The northern Basin and Range Province (nBAR) is generally more tholeiitic in character and also more enriched in TiO_2 than the southern Basin and Range Province (Carlson & Hart, 1987; Bradshaw *et al.*, 1993). The lower levels of TiO_2 in the southern Basin and Range (sBAR) Province make them (chemically) more analogous to the Ipswich Basin rocks.

In the Colorado River Trough (CRT) of the sBAR, the youngest basalts (called

“Group 1” or “post extensional” by Bradshaw *et al.*, 1993) generally have the highest TiO_2 and P_2O_5 contents, the highest Nb/Y ratios, and lowest initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Bradshaw *et al.*, 1993). Hoffer (1988) used the term “Group I” to describe the youngest sBAR rocks in New Mexico, and indicated that they were the most alkaline of the sBAR. Compositions of the youngest sBAR mafic rocks are similar to those of QAO No. 1 “The Overflow” and NS 93, which are more enriched in TiO_2 than other mafic rocks of the Ipswich Basin.

The oldest of the sBAR rocks (“Group 2” or “pre/syn/post-extensional” of Bradshaw *et al.*, 1993; “Group II” of Hoffer, 1988) have compositions closest to those of most of the Ipswich Basin (IB) mafic rocks. Comparing the sBAR rocks of CRT with the IB mafic rocks: the TiO_2 values are similar (although slightly less); P_2O_5 values are similar (although slightly greater); and Al_2O_3 up to 1 wt% less in the sBAR (although the modal values for both are similar). The “Group II” rocks of New Mexico (Hoffer, 1988) are more TiO_2 enriched than either the IB rocks or the CRT rocks; however, within for the Rio Grande Rift, Gornitz (1982) noted a southward increase in the TiO_2 content from Colorado to New Mexico, so similar trends conceivably exist in the Basin and Range Province. Coleman and Walker (1990) report rocks of similar composition to Bradshaw *et al.* 's (1993) “Group 2” rocks around Panamint Valley (California); however, they do not relate them to either their position within the Basin and Range, or state if they are “post-extensional”. The radiometric ages quoted for the rocks suggest the same age as Bradshaw *et al.* 's. (1993) “Group 1” rocks, although it is possible that the onset of the post-extensional “Group 1” rocks was not uniform across the entire BAR.

Nb, Y, and Zr values for the sBAR are variable, and cannot be directly compared with the IB rocks; however, all values from the sBAR are greater than those for regular volcanic-arc rocks, and are within the ranges quoted by Pearce and Cann (1973) for continental/within-plate rocks. Y values in the sBAR (Hoffer, 1988; Bradshaw *et al.*, 1993; Coleman & Walker, 1990) are anomalously high for a within-plate setting (according to the criteria of Pearce and Cann, 1973) but values are similar to those of the IB rocks.

5.6.3 Discussion

The chemistry of the IB mafic rocks differs from either simple volcanic-arc mafic rocks or within-plate mafic rocks, although it shares more features of the latter. It is believed that this “mixed” signature reflects the tectonic environment into which the mafic rocks were erupted, and not alteration or other secondary effect. Rocks with similar compositions to the IB mafic rocks have been documented in early stages of rifting in both the Basin and Range Province and the South Shetland Islands. All of these rocks differ from advanced rift-related volcanic rocks (such as the East African Rift basalts) by possessing calc-alkaline overprints in their chemical signatures, possibly caused by their derivation in, or contamination by, recently accreted arc material. As the development of the rift system progresses, the rocks become more basaltic in a trend away from arc compositions towards intra-plate oceanic basalt compositions (Keller & Fisk, 1992; Keller *et al.*, 1992; Saunders & Tarney, 1978), probably reflecting the greater role of the mantle within the rifting system. In the BAR this later phase is marked by extensive flood basalts. The IB mafic rocks share more chemical similarities with the early BAR rocks, and with their individual small thickness (usually < 10 m), it is unlikely they formed in an extensive flood basalt province. It is therefore suggested that based on available chemical evidence, that the IB mafic rocks formed as a result of back-arc extension occurring in a within-plate setting, and that their eruption above a recently inactive volcanic-arc imparted a remnant calc-alkaline signature on the rocks.

All the felsic volcanic rocks of the Ipswich Basin, except for the subunit E of GSQ Ipswich 26, show affinities with within-plate rocks. Samples from GSQ Ipswich 26 subunit E, the oldest lava flow, show a distinctive volcanic-arc signature in its trace element chemistry, and its ϵNd content is the greatest, indicating minimal crustal contamination.

5.7 Conclusions

Felsic volcanic rocks show relative enrichment in normative quartz, caused in part by leaching of alkalis, concentration of quartz phenocrysts in the pyroclastic rocks, and original high-silica composition for the rocks.

Samples of the Hector Tuff and Mount Crosby Formation tuff are the most

leached felsic rocks analysed, perhaps indicating some reworking of the material and subsequent concentration of quartz. Even so, their chemistry is significantly different enough from the Brisbane Tuff to suggest that different eruptions produced each of the formations.

The Chillingham Volcanics vary slightly in composition with latitude, with the exception of a large rhyolitic dome at Clarrie Hall Dam, which has a uniquely less evolved chemistry.

Samples from GSQ Ipswich 26 subunit E, the stratigraphically oldest analysed lava flow, show a distinctive volcanic-arc signature in its trace element chemistry, and its ϵNd content is the greatest, indicating minimal crustal contamination.

Slight differences in the trace element and whole rock chemistries of the mafic rocks differentiate the studied formations, which have broadly similar chemistries. All mafic rocks of the Ipswich Basin are sub-alkaline to alkaline, a trend confirmed by their pyroxene chemistry. The Ti-Zr-Y ternary diagram of Pearce and Cann (1973) (Fig. 5.18) suggests a calc-alkaline island-arc origin for the mafic rocks. The Zr/Y vs Zr diagram of Pearce and Norry (1979) (Fig. 5.15) and the Nb, Zr, and Y ternary diagram of Meschede (1986) (Fig. 5.14) indicate a within-plate setting. The TiO_2 , MnO, and P_2O_5 ternary diagram of Mullen (1983) (Fig. 5.5) and Pearce *et al.*'s (1977) whole-rock ternary diagram of FeO, MgO, and Al_2O_3 (Fig. 5.6) suggest a within-plate setting but overlap with the calc-alkaline setting. Other diagrams suggest an associated subtle calc-alkaline character with the within-plate character for the rocks. This "mixed" calc-alkaline/within-plate character is consistent with early back-arc rift related rocks such as those developed in the early stages of the Basin and Range Province.

Microprobe analysis of pyroxenes from the mafic rocks does not conclusively define the tectonic environment, but a predominantly volcanic-arc signature was suggested for the samples based on Nisbet and Pearce's (1977) factor analysis (Fig. 5.25).

ϵNd values range from +1.8 to +3.7 for the volcanic rocks, while the granites of the South D' Aguilar Block are more negative (-0.2 to +0.3), indicating slightly more crustal involvement of the granites than the Ipswich Basin volcanic rocks.