Akaroa Volcano as a volcanic complex and the 'Daly Gap'

Anna Gerrits[1, 2]

[1]Department of Geological Sciences, University of Canterbury, Christchurch, New Zealand

[2]Oberlin College Geology Department, Oberlin College, Ohio, USA

Abstract

Controls on magmatic conditions and the effects these controls have on volcanic systems are important questions in the study of volcanics and are difficult to determine. Akaroa Volcano is a composite shield volcano on Bank's Peninsula, New Zealand, which has been the interest of many geologic studies dealing with the volcanoes relationship with the 'Daly Gap' and its magmatic evolution. By looking at Akaroa Volcano's lava sequences and accompanying major element geochemistry data from Okains Bay, View Hill, Panama Ridge, Pa Bay, Ducksfoot Bay, Stony Bay, Raupo Bay, Otepatotu Reserve, Goat Rock, Lavericks Bay, and Le Bons Bay, it was possible to attempt to answer some of these questions. Two observed compositional gaps in Akaroa's lava sequence suggest that crystal fractionation, which accounts for the 'Daly Gap', is not the only control on Akaroa's eruptives; this study proposes a connection between the smaller mid-range compositional gap in Akaroa's sequence and a physical control in the magmatic system. The major element geochemistry data was also used to map observed lava flows, scoria cones, dikes and domes on Banks Peninsula by rock type and wt% silica values, which resulted in observed cyclic trends in the eruption of similar sequences of evolved and less-evolved lavas. Reconstructing past vents and observing the 'Daly Gap' and the mid-range compositional gap, both apparent in the geochemical evolution of Akaroa's magmatic sequence, are important steps to understanding and thoroughly documenting the history of Akaroa Volcano, discovering additional vent location, and ultimately understanding mechanisms for the controls on eruptive packages.

Introduction

Akaroa Volcano has been the subject of many recent geochemistry focused studies attempting to discern the volcanoes relationship with the 'Daly Gap' and its magmatic evolution. The 'Daly Gap' is a bimodal distribution of rock compositions in the magmatic sequence (Daly 1925). This observation has been seen in tholeiitic and calc-alkaline volcanic provinces, oceanic hotspots and island arcs, and continental arcs. This composition gap has been attributed to different processes: first, to partial melting of the preexisting crust, second, to crystal fractionation of mafic magmas (Dufek et al. 2010 and all references there in), third, to a physical control: density or viscosity maximum restricts the ascent and eruption of some magma compositions, and finally, a phase equilibrium control: new liquidus material causes the fractionating magma to become unstable in certain compositions, reducing the likelihood that those compositions will be erupted (Brophy 1991). However, the first two processes proposed seem to be the most likely.

The 'Daly Gap' is seen worldwide and including Akaroa Volcano. Workers including Hartung (2011) and Johnson (2012) have concluded that fractional crystallization greatly influenced Akaroa's magma batches an may account for Akaroa's 'Daly Gap'. Hartung (2011) proposes that Akaroa exhibits the 'Daly Gap' based on a two-stage model. In the first stage, alkali basalt and hawaiite lavas are produced from a picritic source near the crust-mantle boundary (9 to 10 kbar). The second stage begins with magma trapped in the mid-crustal region fractionating an olivine-plagioclase assemblage to create the alkali basalt-hawaiite trend and results in the formation of trachyte melts from the crystal mush (hawaiite to mugearite in composition). This two-step process ultimately results in the observed 'Daly Gap' composition discontinuities observed in Akaroa's sequence.

By looking at a large pool of geochemistry data, major and trace element, that was collected from Okains Bay, View Hill, Panama Ridge, Pa Bay, Ducksfoot Bay, Stony Bay, Raupo Bay, Otepatotu Reserve, Goat Rock, Lavericks Bay, and Le Bons Bay on the eastern side of Banks Peninsula and samples from Dorsey (1988) from Onawe Peninsula, Petit Carenage Bay, Takamatua Bay, Haylocks Bay, and Les Bons

Bay, this study hopes to apply its findings more confidently to Akaroa Volcano as a whole to discern its relationship to the 'Daly Gap'. Through a detailed stratigraphic study of Akaroa's lava sequence through the interpretation of the geochemistry data collected from the eastern bays may also lead to further reconstruction of Akaroa's eruptive history, not as a composite shield volcano with a single vent (Timm's et al. 2009), but as a volcanic complex with multiple vent locations.

Background Geology

Akaroa Volcano is a composite shield volcano on Bank's Peninsula, New Zealand that has been the interest of many geologic studies since the 1800's. Akaroa has been previously mapped as a single deposit originating from one vent source, seen in Figure 1. The imprecise mapping of the volcano has let to limitations in understanding the complexities and history of Akaroa and the entire Banks Peninsula volcanic system. Akaroa is an intraplate volcano that occupies the eastern two-thirds of Banks Peninsula and has lavas dated to be 9.4 to 6.8 Ma (Timm et al. 2009). Intraplate volcanism is a form of volcanism that occurs away from plate boundaries and other tectonic features that are traditionally thought to facilitate volcanism; consequently, its cause is still a topic of much debate. Recently studies have attributed intraplate volcanism to interactions between upwelling asthenosphere and the lithosphere in those locations and further mantle convection (Timm et al. 2009; Conrad et al. 2011).

Akaroa volcanics are mainly lava flows and have rock compositions ranging from picrate basalts to trachytes (Hartung 2011; Price et al. 1980; Johnson 2012; Crystal 2013; Dorsey 1988). As previously mentioned, Akaroa displays a notable composition gap in its lava sequence known as the 'Daly Gap'. Johnson (2012) proposes a model for the notable composition gap in Akaroa's lava sequence that deals with Akaroa's magmatic controls: the eruption of small batches of magma from multiple eruptive centers all fed from the same mid-crustal source chamber. This model, seen in Figure 2, fits with the calculated eruptive depths found by Hartung (2011). Overall, Akaroa Volcano is an area of great interest that has yet to be accurately mapped and because of this much of Akaroa's history is still unknown.

Methods

240 samples were collected from Okains Bay, View Hill, Panama Ridge, Pa Bay, Ducksfoot Bay, Stony Bay, Raupo Bay, Otepatotu Reserve, Goat Rock, Lavericks Bay, and Le Bons Bay on Banks Peninsula, New Zealand in 2012 through 2014. Samples were selected in each location with the intent to fully represent the stratigraphic sequence of Akaroa's lavas using the most un-weathered samples available.

X-ray fluorescence spectroscopy (XRF) analysis was conducted at the University of Canterbury using a Philips PW2400 Sequential Wavelength Dispersive X-ray Fluorescence Spectrometer calibrated to international standards. The major element weight percents were calculated using glass fusion beads prepared by fusing 1.3 grams of the powdered sample and combining with 6.98 g of a Li2B4O7/ Li2O/La2O3 mixture and a few grains of NH4NO3 at 1030 °C for at least 15 minutes. Trace element weight percents were calculated using pressed powder pellets from eight-gram samples and polyvinyl alcohol binder solution that were combined and pressed into 32 mm diameter pellets within a hardened steel die for 10 seconds at 3000 psi. Both analyses were performed using a rhodium tube set, set at 50kV/55mA for major elements and 60kV/46mA for trace elements (Johnson 2012; Hartung 2011).

Results

Major Element Geochemistry

Major geochemistry data from Okains Bay, View Hill, Panama Ridge, Pa Bay, Ducksfoot Bay, Stony Bay, Raupo Bay, Otepatotu Reserve, Goat Rock, Lavericks Bay, and Le Bons Bay is shown in Table 1. The overall $Si0_2$ wt% of all of the samples ranges from low in Stony Bay (40.1 wt%) to high in Okains Bay (64.7 wt%); however, the majority of the samples have lower silica values (40 - 50 wt%). Variations in major elements verses silica diagrams can be seen in Figure 3 and shows consistent trends for all locations in FeO, MgO, P_2O_5, K_2O, Na_2O, Al_2O_3, CaO, TiO_2 verses SiO_2. Rock types according to Cox et al. (1979) classifications range from picric basalts to trachyte with a notable gap in the upper mid-range, seen in Figure 4. A combination of the locations from this study and of sampled xenoliths and domes from Dorsey (1988) show a complete trend in rock types plotted on the same diagram, see in Figure 5.

Individual Bay Geochemistry

Each bay location in this study shows two distinct composition gaps when plotted on Cox et al. (1979) rock type classification diagrams, one in mid-range values and one in upper mid-range values (the 'Daly Gap'). Using Stony Bay as an example this can be seen in Figure 6. When plotting xenoliths and dome compositions from Goat Rock and from Dorsey's 1988 study along with the lava flow sequence of each bay, the compositional gaps are filled. Goat Rock values fill the first mid-range gap and Dorsey's (1988) values fills the 'Daly Gap', seen in Figure 7. This trend can be seen in all of the eastern bays from this study.

Banks Peninsula Mapping

This study uses the major geochemistry data to map observed lava flows, scoria cones, and domes on Banks Peninsula by rock type and wt% silica values resulting in Figure 8. Additionally, an in depth study of individual bays on Banks Peninsula results in observed cyclic trends in the eruption of similar sequences of evolved and less-evolved lavas seen in Raupo Bay in Figure 9.

Discussion

Major Element Geochemistry

Major element diagrams show correlations with SiO_2, seen in Figure 3, and imply that fractional crystallization processes play a central role in the petrogenesis of Akaroa volcanics. Curved trends in MgO and P_2O_5 verses SiO_2 represent the onset of crystallization of modal phenocryst phases. The decline in MgO with increasing SiO_2 is attributed to the primary crystallization of magnesium-bearing minerals such as olivine and clinopyroxene. The trend in P_2O_5 verses SiO_2 shows a change in fractionation at 50 wt% SiO_2 that marks the beginning of apatite crystallization. MgO and CaO exhibit strong negative curvilinear trends providing further support for the importance of crystal fractionation (Johnson 2012).

Several previous workers have proposed fractional crystallization as a process that plays a central role in the magmatic evolution of Akaroa Volcano (Price and Taylor 1980; Dorsey 1988; Timm et al. 2009; Hartung 2011; Johnson 2012; Crystal 2013), and has been successfully tested using melt calculations by Hartung (2011). Samples from this study fit into the overall trend of previous studies on Akaroa shows that fractional crystallization processes greatly influence Akaroa volcanics.

Stratigraphic Analysis and Vent Locations

Using the geochemistry data, this study was able to map Akaroa's lava flows in the eastern bays based on rock types, seen in Figure 8. From this map it can be seen that specific bays follow the same cyclic pattern. The lava sequence on the southern side of Raupo Bay shows evolution from picrite basalt to hawaiite to benmorite then to picrite basalt again, Figure 9. This pattern of the eruption of evolved and less evolved magmas is also seen in Okains Bay (Johnson 2012) and Lavericks Bay (Crystal 2013). The observed cyclic pattern of less evolved to more evolved lavas forwards Johnson's (2012) model of a mid-crustal reservoir of picrite basalt that feeds or replenishes the upper-crustal magma chamber through multiple intrusion events (Timm 2009; Johnson 2012), seen in Figure 2.

The lava sequence on the north side of Raupo Bay dips east-southeast, different from the southern lava sequence, which dips northeast. The northern sequence also contians a massive lava flow with huge toe lobes, which mark the end of the flow as the northern side of Raupo Bay. Through Raupo Bay's lava sequence, it can be proposed that there is a possible vent location to the northwest of the bay and at least one other vent location to the west. Multiple vent locations would be highly probable for Akaroa Volcano based on Hampton and Cole's (2009) mapping of 15 eruptive centers on Akaroa's neighbor, Lyttlton Volcano, and has been suggested by many recent works (Ring and Hampton 2012).

Compositional Gaps

This large data set contains two compositional gaps: one in mid-range values and one in upper mid-range values known as the 'Daly Gap'. The observed 'Daly Gap, seen in Figure 4, is filled in by sampled xenoliths and domes from Dorsey (1988) collected from Onawe Peninsula, Petit Carenage Bay, Takamatua Bay, Haylocks Bay, and Les Bons Bay, Figure 5. The second compositional gap can be seen in the mid-range values of rock types from Okains Bay, View Hill, Panama Ridge, Pa Bay, Ducksfoot Bay, Stony Bay, Raupo Bay, Otepatotu Reserve, Lavericks Bay, and Le Bons Bay, seen in Figure 6 using Stony Bay as an example, and is filled in by Goat Rock xenoliths and dome compositions, Figure 7.

The completion of the rock type sequence by the non-eruptive packages from Goat Rock and other dome locations on Banks Peninsula suggests that in addition to Hartung's (2011) two-stage crystal fractionation model there is also a physical control on eruptive material and creates the mid-range compositional gap. This proposed physical control on Akaroa's eruptives seen in the mid-range compositional gap should be looked for in volcanic sequences including Lyttlton Volcano to attempt to connect Akaroa's volcanics to the larger understanding of volcanic processes.

Additionally, this study would benefit from a large-scale petrographic study of Akaroa's lava sequence. This further work would involve a detailed analysis of the mineral assemblages of each lava flow, dome, and xenolith to connect the geochemistry, stratigraphic, and physical data.

Conclusion

This study proposes a connection between the smaller mid-range compositional gap in Akaroa's sequence and a physical control in the magmatic system. This proposed additional control on Akaroa's eruptive packages is made in addition to the already observed crystal fractionation control, which accounts for the 'Daly Gap' and can be seen in major element verses silica diagrams. An in depth study of Akaroa Volcano's lava sequences was possible through major element geochemistry data from Okains Bay, View Hill, Panama Ridge, Pa Bay, Ducksfoot Bay, Stony Bay, Raupo Bay, Otepatotu Reserve, Goat Rock, Lavericks Bay, and Le Bons Bay.

Overall $Si0_2$ wt% of all of the samples ranges from 40.1 to 64.7 with the majority of the samples having lower silica values (40 - 50 wt%). Rock types according to Cox et al. (1979) classifications range from picric basalts to trachyte with a notable gap in the upper mid-range. The major geochemistry data was also used to map observed lava flows, scoria cones, dikes, and domes on Banks Peninsula by rock type and wt% silica values which results in observed cyclic trends in the eruption of similar sequences of evolved and less-evolved lavas. Reconstructing past vents and observing the 'Daly Gap' and the mid-range compositional gap, both apparent in the geochemical evolution of Akaroa's magmatic sequence, are important steps to understanding and thoroughly documenting the history of Akaroa Volcano, discovering additional vent location, and understanding mechanisms for the controls on eruptive packages.

Acknowledgements

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Figures

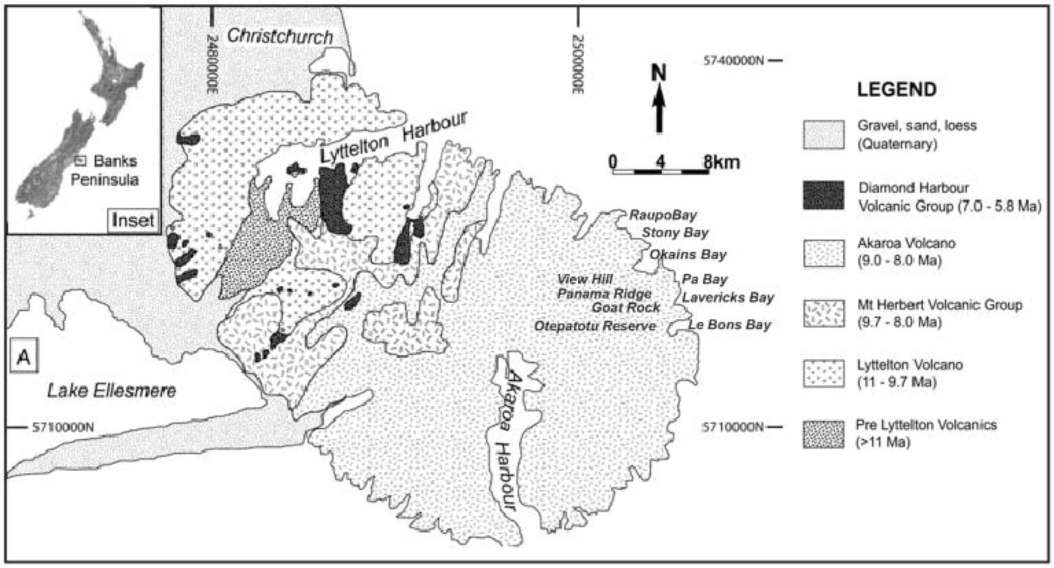


Figure 1

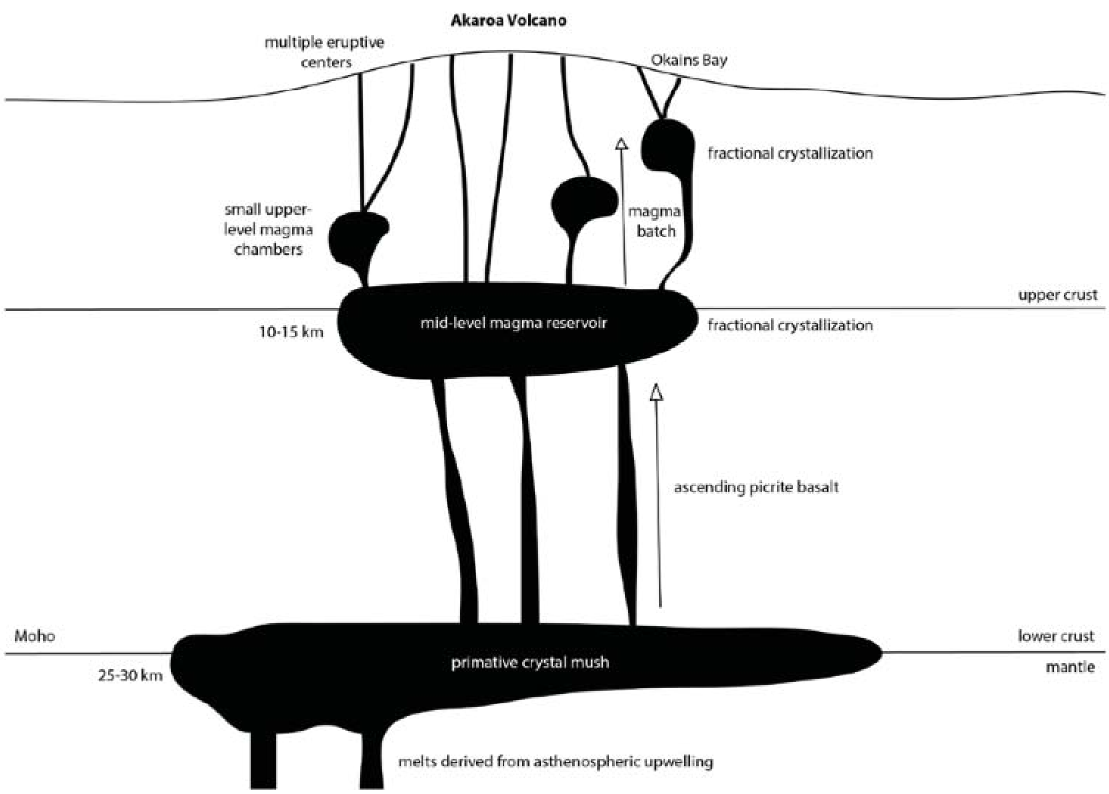


Figure 2

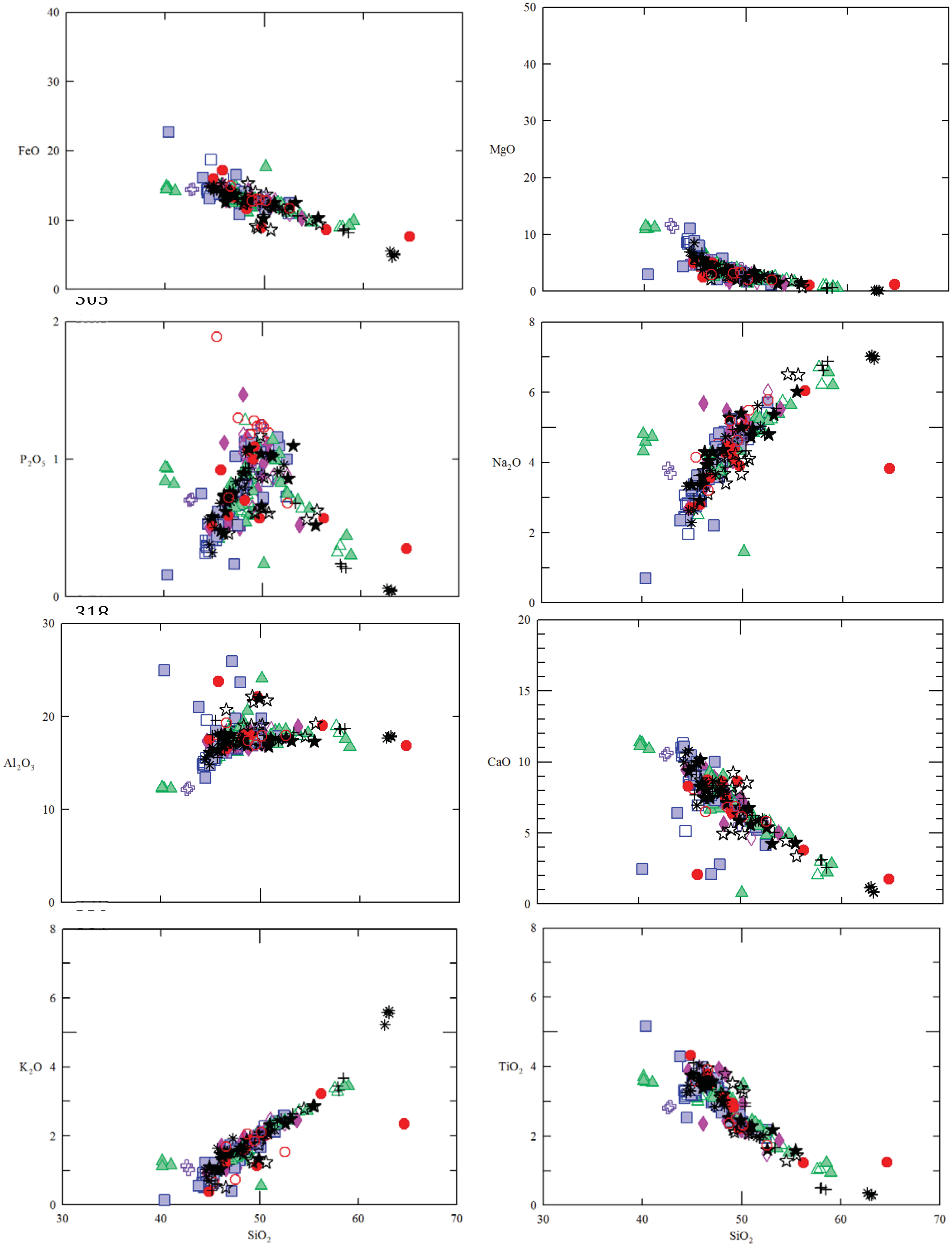
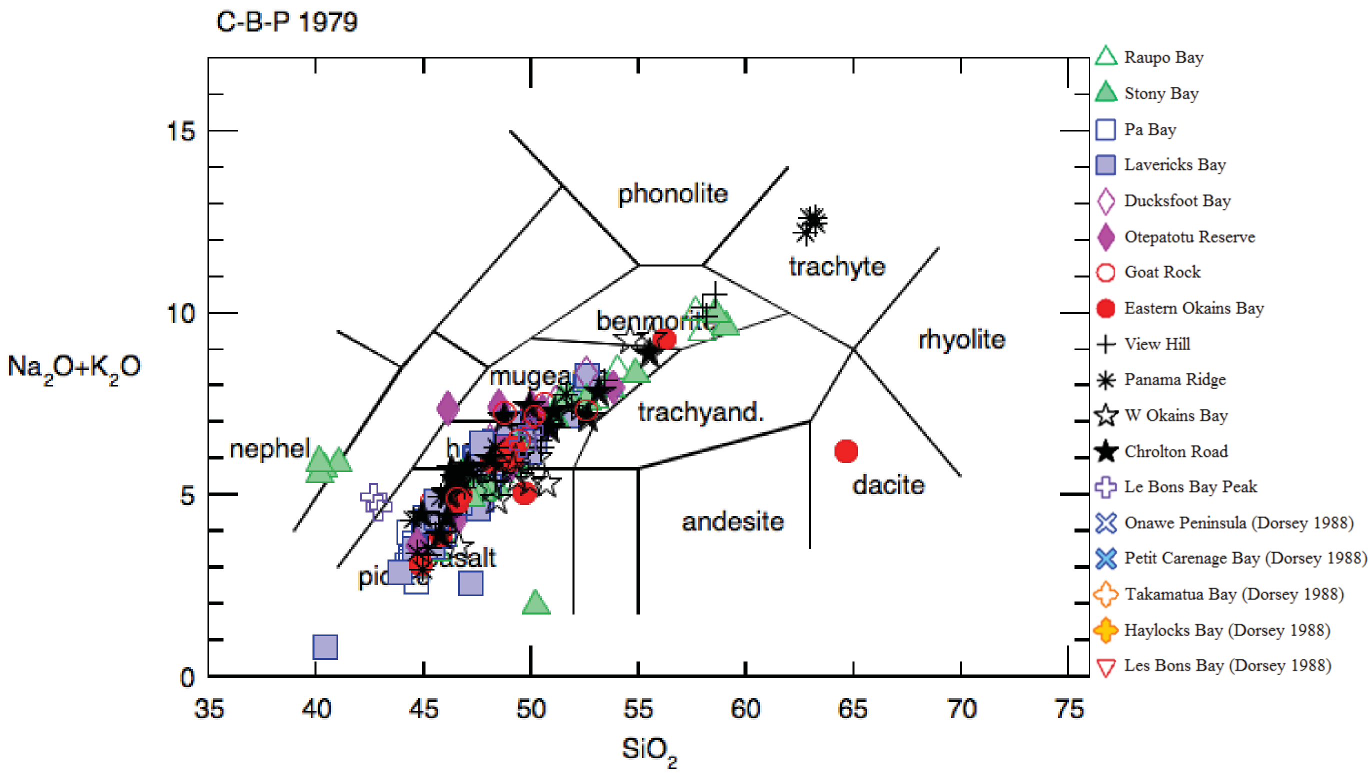


Figure 3


C-B-P 1979
Na2O+K2O
SiO2
phonolite
trachyte
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rhyolite
mugearite
trachyand.
nephel
dacite
andesite
basalt
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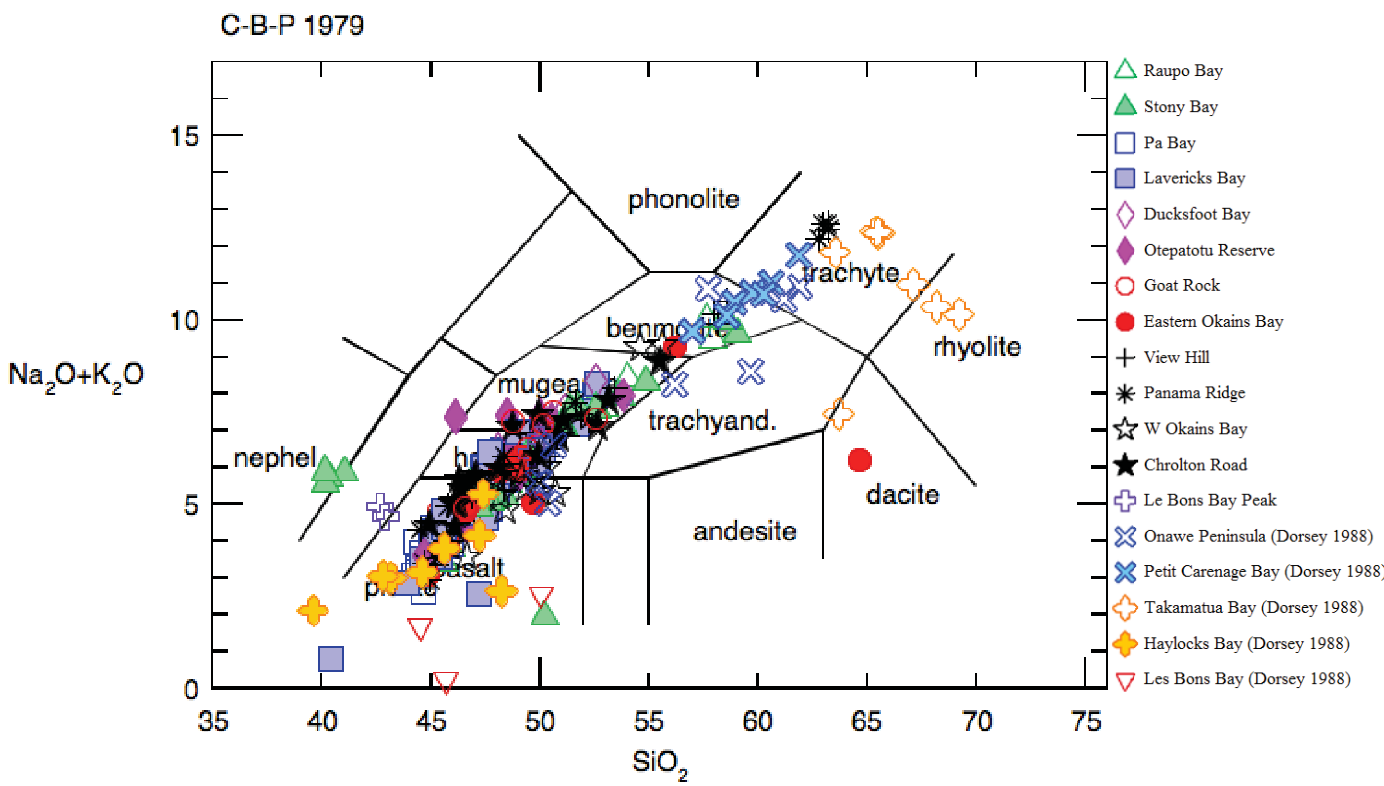
Raupo Bay
Stony Bay
Pa Bay
Lavericks Bay
Ducksfoot Bay
Otepatotu Reserve
Goat Rock
Eastern Okains Bay
View Hill
Panama Ridge
W Okains Bay
Chrolton Road
Le Bons Bay Peak
Onawe Peninsula (Dorsey 1988)
Petit Carenage Bay (Dorsey 1988)
Takamatua Bay (Dorsey 1988)
Haylocks Bay (Dorsey 1988)
Les Bons Bay (Dorsey 1988)

Figure 4


C-B-P 1979
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Raupo Bay
Stony Bay
Pa Bay
Lavericks Bay
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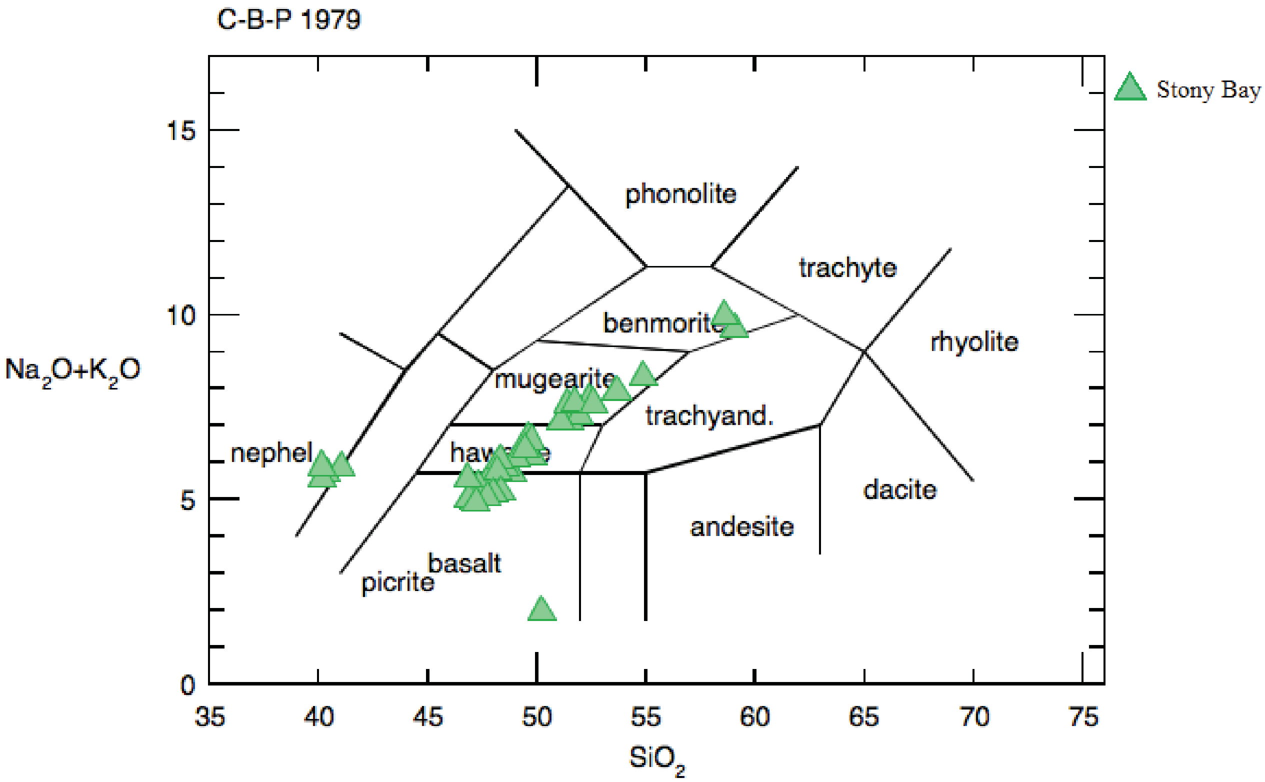
Otepatotu Reserve
Goat Rock
Eastern Okains Bay
View Hill
Panama Ridge
W Okains Bay
Chrolton Road
Le Bons Bay Peak
Onawe Peninsula (Dorsey 1988)
Petit Carenage Bay (Dorsey 1988)
Takamatua Bay (Dorsey 1988)
Haylocks Bay (Dorsey 1988)
Les Bons Bay (Dorsey 1988)

Figure 5


C-B-P 1979
Stony Bay
Na$_2$O+K$_2$O
SiO$_2$
0
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phonolite
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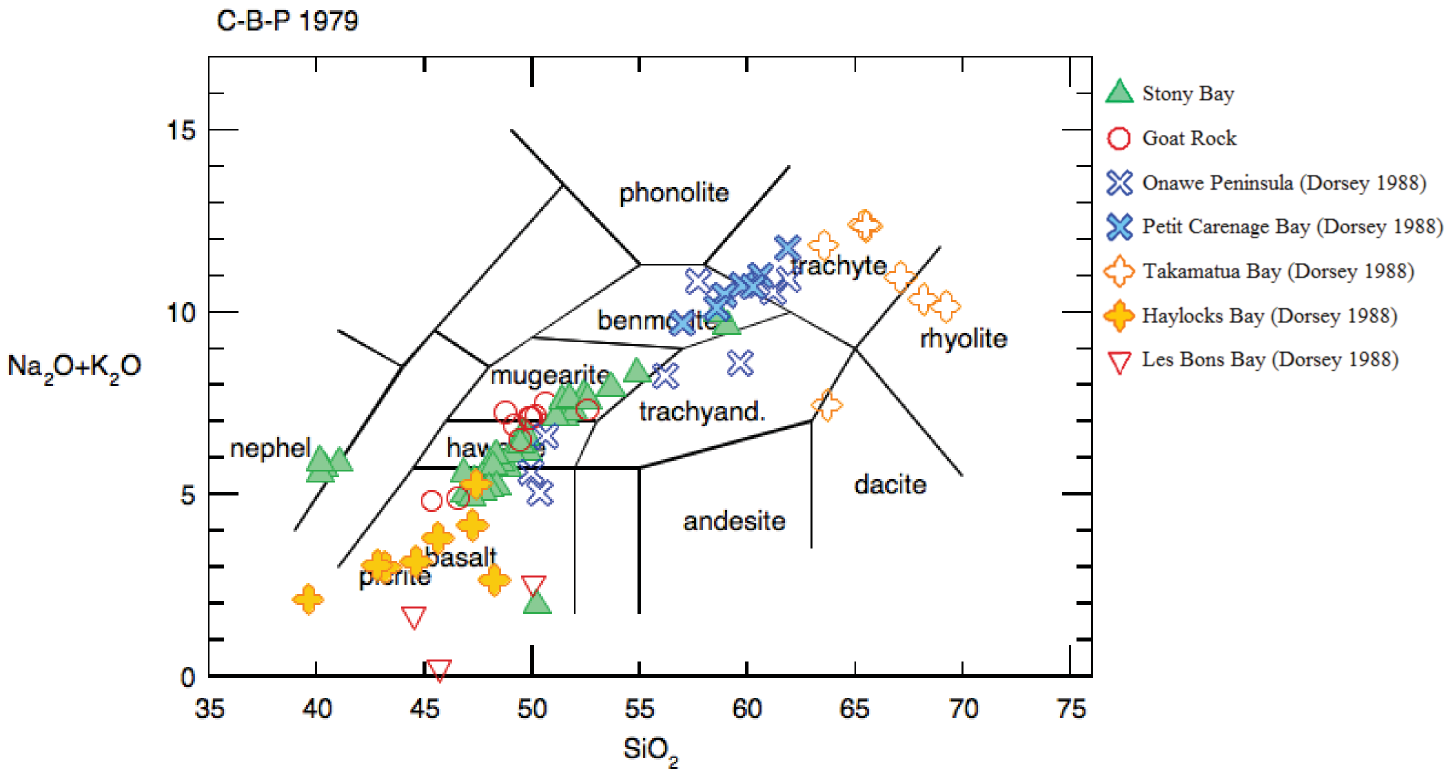
rhyolite
mugearite
trachyand.
nephel
dacite
andesite
basalt
picrite

Figure 6


C-B-P 1979
Na_2O+K_2O
SiO_2
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phonolite
trachyte
benmoreite
rhyolite
mugearite
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basalt
picrite
andesite
dacite
Stony Bay
Goat Rock
Onawe Peninsula (Dorsey 1988)
Petit Carenage Bay (Dorsey 1988)
Takamatua Bay (Dorsey 1988)
Haylocks Bay (Dorsey 1988)
Les Bons Bay (Dorsey 1988)

Figure 7

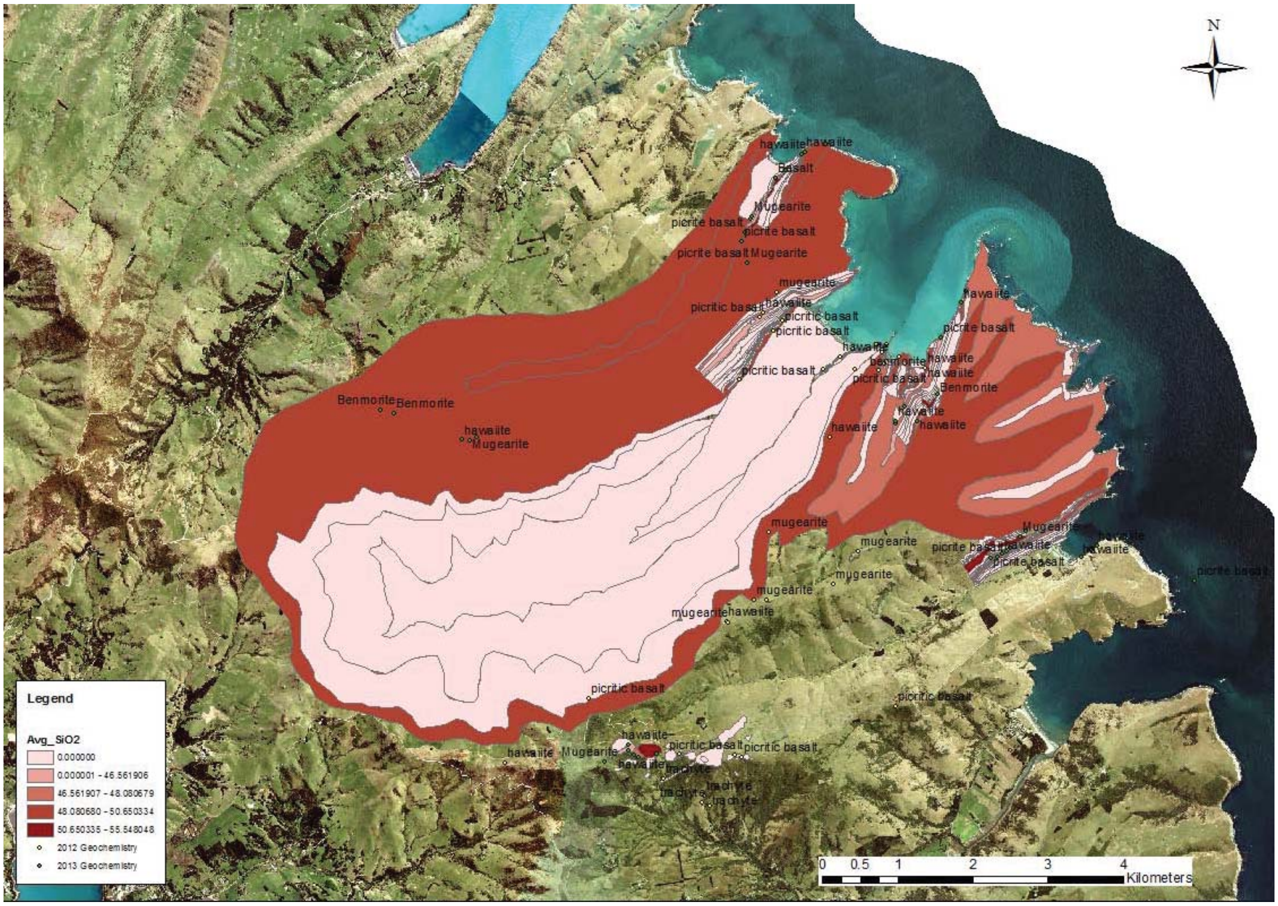
N
Benmorite Benmorite
hawaiite
Mugearite
Legend
Avg_SiO2
0.000000
0.000001 - 46.561906
46.561907 - 48.080679
48.080680 - 50.650334
50.650335 - 55.548048
2012 Geochemistry
2013 Geochemistry
0 0.5 1 2 3 4
Kilometers

Figure 8

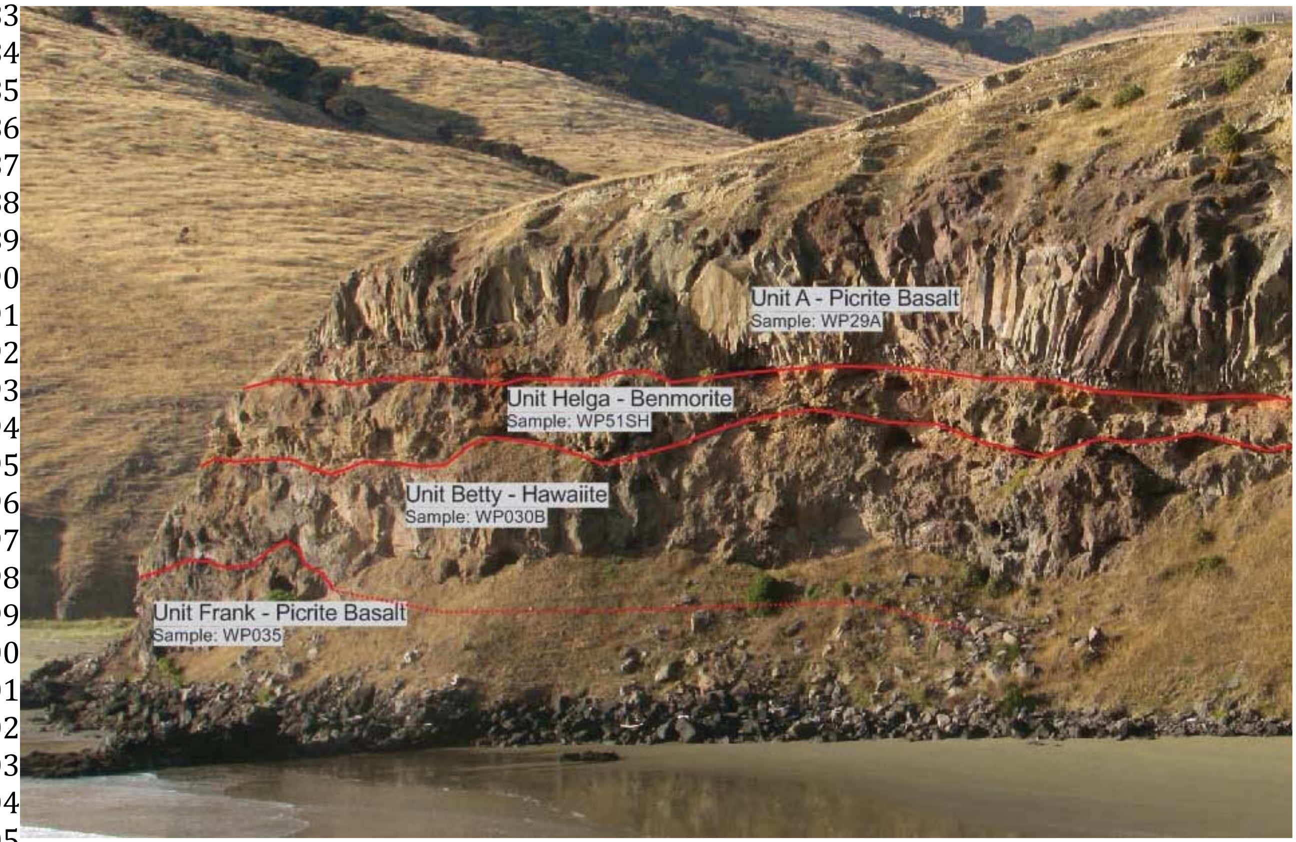
Unit A - Picrite Basalt
Sample: WP29A
Unit Helga - Benmorite
Sample: WP51SH
Unit Betty - Hawaiite
Sample: WP030B
Unit Frank - Picrite Basalt
Sample: WP035

Figure 9

Tables – see Appendix

Figure Captions

Figure 1- Banks Peninsula, New Zealand with labeled bays marking the locations sampled in this study. Adapted from Hampton and Cole 2009.

Figure 2- Akaroa Volcano's mid-crustal magma chamber. Adapted from Johnson 2012.

Figure 3 – Variation diagrams of major elements plotted against silica.

Figure 4 – Rock type diagrams after Cox et al. (1979). Rock types of the eastern bays of Banks Peninsula showing 'Daly Gap'

Figure 5 – Rock type diagrams after Cox et al. (1979). Rock types of the eastern bays of Banks Peninsula plotted with Dorsey (1988) filling the 'Daly Gap'.

Figure 6 - Rock type diagrams after Cox et al. (1979) of 40 samples from Stony Bay, Banks Peninsula showing a mid-range composition gap and the 'Daly Gap'.

Figure 7 - Rock type diagrams after Cox et al. (1979) of 40 samples from Stony Bay, Banks Peninsula plotted with dome and xenoliths from Goat Rock filling the mid-range gap and Dorsey's (1988) locations filling the 'Daly Gap'.

Figure 8 – ArcGIS map of the eastern bays of Banks Peninsula. Each lava flow and dome is mapped by silica content and when possible, labeled by rock type.

Figure 9 – The lava sequence on the southern side of Raupo Bay shows a cyclic evolution pattern, evolving from picrite basalt in Unit Frank to hawaiite in Unit Betty to benmorite in Unit Helga then devolving to picrite basalt again in Unit A.

Table Captions

Table 1 – Major element data collected from Okains Bay, View Hill, Panama Ridge, Pa Bay, Ducksfoot Bay, Stony Bay, Raupo Bay, Otepatotu Reserve, Goat Rock, Lavericks Bay, and Le Bons Bay on the eastern side of Banks Peninsula, New Zealand.

Table 2 – Major element data collected and published by Dorsey (1988) from Onawe Peninsula, Petit Carenage Bay, Takamatua Bay, Haylocks Bay, and Les Bons Bay Banks Peninsula, New Zealand.

Appendix

Table 1

UC ID	Sample ID	Site Name	Rock Type	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI
35713	RPB wp024	Raupo Bay	Hawaiite	48.23	2.87	17.17	13.42	0.19	3.37	7.48	4.36	1.62	1.28	1.41
35706	RPB WP026	Raupo Bay	Picrite Basalt	45.82	3.15	15.66	14.12	0.16	6.95	9.82	2.83	1.02	0.49	0.19
35718	RPBWP029A(upper)	Raupo Bay	Picrite Basalt	45.55	3.00	15.58	14.99	0.15	7.57	9.31	2.50	0.94	0.42	1.52
35705	RPB2WP030A: right at the end	Raupo Bay	Picrite Basalt	47.79	3.30	16.70	13.47	0.16	4.24	8.60	3.83	1.30	0.62	-0.09
35715	WP030A2	Raupo Bay	Mugearite	53.97	1.74	17.86	10.24	0.18	2.01	4.92	5.73	2.71	0.64	1.09
35719	RPBWP030B: Beach Betty	Raupo Bay	Hawaiite	48.60	3.06	16.82	13.10	0.17	3.89	7.91	4.23	1.54	0.68	0.61
35707	RPBWP030D: Rubble	Raupo Bay	Mugearite	52.84	1.91	17.62	10.75	0.18	2.55	5.77	5.22	2.43	0.72	-0.14
35717	RPB-WP035	Raupo Bay	Picrite Basalt	48.46	3.15	17.50	12.85	0.18	3.62	7.91	4.07	1.52	0.74	0.57
35709	RPBWP039Betty	Raupo Bay	Hawaiite	48.41	3.22	17.58	13.72	0.16	3.47	7.02	4.20	1.61	0.61	1.95
35710	RPBWP:044	Raupo Bay	Hawaiite	49.07	3.05	17.20	13.05	0.15	3.40	7.48	4.33	1.68	0.62	1.91
35708	RPBWP:047	Raupo Bay	Picrite Basalt	47.16	3.25	17.03	13.03	0.18	4.71	8.42	3.93	1.48	0.80	0.71
35714	RPBWP:049Lower	Raupo Bay	Hawaiite	49.10	2.95	16.85	12.78	0.17	4.00	7.83	4.14	1.60	0.59	0.17
35711	RPBWP:050 Upper	Raupo Bay	Picrite Basalt	45.52	3.09	15.36	13.72	0.17	7.52	9.93	3.16	1.07	0.47	-0.06
35712	WP 51 NS	Raupo Bay	Benmorite	57.61	1.02	18.94	8.99	0.12	0.90	2.02	6.70	3.37	0.32	2.15
35716	WP 51 SH	Raupo Bay	Benmorite	57.88	1.05	18.21	8.96	0.15	0.94	2.96	6.21	3.28	0.37	1.37
35790A	SB-1	Stony Bay	hawaiite	48.69	2.93	20.59	11.87	0.17	2.29	7.11	4.32	1.45	0.60	2.44
35791A	SB-2	Stony Bay	mugearite	52.37	2.01	17.93	11.04	0.16	2.19	5.78	5.30	2.46	0.75	1.36
35792A	SB-7	Stony Bay	nepheline	40.31	3.55	12.25	14.66	0.20	11.08	11.28	4.59	1.15	0.93	0.43
35793A	SB-11	Stony Bay	picrite basalt	47.91	3.01	16.85	12.89	0.19	4.56	8.34	4.06	1.46	0.74	0.82
35794A	SB-15	Stony Bay	benmorite	58.98	0.94	16.73	9.89	0.12	0.59	2.82	6.20	3.44	0.30	0.20
35795A	SB-16	Stony Bay	hawaiite	48.82	3.08	16.73	13.28	0.19	3.69	7.61	4.19	1.56	0.85	-0.09
35796A	SB-17	Stony Bay	hawaiite	49.75	2.76	17.22	12.74	0.20	3.34	6.90	4.33	1.86	0.91	0.65
35797A	SB-18	Stony Bay	picrite basalt	47.83	3.35	19.23	13.92	0.14	2.81	6.73	3.73	1.55	0.70	3.00
35798A	SB-20	Stony Bay	mugearite	54.79	1.52	18.19	9.70	0.27	1.61	4.89	5.64	2.73	0.64	1.74
35799A	SB-21	Stony Bay	hawaiite	49.53	2.32	18.18	12.39	0.21	2.99	6.59	4.68	1.99	1.11	2.08
35800A	SB-22	Stony Bay	mugearite	51.24	2.12	17.63	11.97	0.20	2.56	6.14	4.98	2.17	1.00	1.75
35801A	SB-25	Stony Bay	picrite basalt	47.00	3.52	16.56	13.77	0.19	4.66	8.58	3.79	1.31	0.61	-0.47
35802A	SB-26	Stony Bay	picrite basalt	47.65	3.47	16.18	13.85	0.20	4.12	8.23	4.05	1.47	0.77	-0.57