A Textural and Geochemical Analysis of Goat Rock Dome Enclaves

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I. Abstract

Enclaves found at Goat Rock dome on Banks Peninsula, New Zealand display a strong alignment of the plagioclase phase and on overall texture characteristic of a cumulate mush. The primary fabric of the enclaves contains large (up to 5 cm) subhedral, aligned plagioclase crystals and are intergrown with smaller feldspar, pyroxene, olivine, apatite, and iron oxide minerals that have undergone alteration. It is proposed that this primary fabric represents the initial cumulate material compacted by the extraction of fractionated melt in a shallow magma reservoir and the additional phases represent later pulses of magmatic injections from depth, the last stages of which entrained the enclaves in the eruption of Goat Rock dome. This study provides physical evidence to support previous models of Akaroa volcanism while applying electron backscatter analysis techniques to igneous fabrics.

II. Geologic Background

Banks Peninsula is the site of remnant composite volcanoes active in the Cenozoic. Volcanism on the peninsula is characterized by two main phases: the Lyttelton (12.4-9.7 Ma) and Akaroa (9.4-8.0 Ma) phases and the associated late-stage phases of the Mt. Herbert Volcanic group (9.7-8.30 Ma) and the Diamond Harbour volcanic group (8.1-5.8 Ma) (Ring and Hampton, 2012). Akaroa volcanism is distinct in its lower silica content compared to the Lyttelton group with products ranging from picritic to alkali basalt (Timm et al., 2009). The transition from more lithospherically influenced magmatism to more mafic products is modelled by lithospheric delamination and resultant asthenospheric upwelling between the two main volcanic phases (Timm et al., 2009). This model (figure 3) has been researched and refined by Hartung (2011) and Johnson (2012) who propose a parental, picritic basalt magma reservoir at 15-20 km depth that fed mid-crustal chambers that were fractionated during magma ascent to produce the picritic basalt to trachyte lava flows seen on the peninsula. These shallow chambers fed multiple eruptive centers and were often intruded by pulses of more mafic magma (Johnson, 2012). This fractionation and mafic remobilization of shallow reservoirs is reflected in the cyclic nature of the small, replenishing batches of magma that are represented in the lava flows of Banks Peninsula. While previously proposed models for Banks Peninsula volcanism cite a single, deep source, the distinct trace element composition of the lava flows but their overall similarity and repetitive pattern suggest that a large, deep magmatic reservoir fed shallow chambers that were fractionated, re-injected, and erupted at distinct eruptive centers (Johnson, 2012). The fractionation and extraction of these melts left behind cumulate material that constitutes the enclaves of Goat Rock.

The peninsula has multiple volcanic domes ranging in composition from basaltic to rhyolitic. Goat Rock is a mafic, pelean dome that intruded a basaltic scoria cone located on the northeast flank of Banks Peninsula (figure 1). Within the host, less evolved basalt to trachy-basalt enclaves are found and range in size from 5-25 cm. These enclaves display variable visible textures; some having aligned pyroxene and plagioclase minerals while others do not have a clear fabric. Specific schlieren samples were found at the dome and the strength of their fabric in hand sample provided evidence that these enclaves may have a texture that enlightens the magmatic structure of Banks Peninsula and the processes related to volcanism at Goat Rock. The geochemistry and texture of these enclaves are most similar to type B enclaves found at Le Bons Bay Peak which are proposed to have been entrained by intruding, rapidly ascending magma (Sewell et al., 1993).

III. Methods

Samples of the host material and enclaves were collected from rock fall debris at the base of Goat Rock where material was most accessible. Thin sections were made from a selection of these samples and major and trace element data were collected on a Philips PW 2400 Sequential Wavelength Dispersive X-ray Fluorescence 63 Spectrometer at the University of Canterbury. The five largest enclave samples selected were cut with three orthogonal sections. Of these cuts, those with the strongest apparent fabric from each xenolith were made in to thin sections and prepared for electron back scatter analysis. The thin sections were finished with a colloidal silica polish (LECO) and a carbon coating.

Five samples were analyzed on the Zeiss SEM fitted with Oxford Instruments at the OCEM lab at the University of Otago. An SEM scan was taken to determine the crystal chemistry to make EBSD analysis as accurate as possible. The enclaves were found to contain plagioclase on the Ca-rich end of the feldspar spectrum, augite, olivine, ilmenite, magnetite, and apatite. This data was collected specifically to determine the composition of the feldspar so that the correct lattice pattern could be recognized by the AZtech software that processes the EBSD data.

Each EBSD scan was taken at about a fifty step interval to produce a rough but robust scan. An additional, higher resolution scan at a 5.15 step interval was done on the sample with the strongest fabric. These scans were processed using the program Channel 5 and were cleaned of excess pixels to be further analyzed. This was done by growing the grain size of pixels so that only points with adjacent points of the same phase constituted a grain as opposed to many single pixels that represented errors in the scan. This data was processed with Mambo and Tango models in Channel 5 to produce phase identification maps, euler orientation maps, inverse pole frame images, and principal direction and principle plane point and contour images. To analyze individual grains for deformation, crystals were adjusted to be represented by a single pixel so that higher resolution could be achieved.

IV. Results

Goat Rock dome host material is basaltic trachy-andesite while the enclaves are less evolved trachy-basalt (figure 4) with 45-47 silica wt% with host silica ranging from 49-50 wt% (table 1). Dome enclaves exhibit intense alignment of the plagioclase phase. Principal directions of anorthite crystals were plotted with fifteen degree contours. The maximum density of the crystal directions range from 7.03 to 19.41 and those of the principal plane projection range from 6.38 to 19.48. In contrast, the other phases do not exhibit as strong or consistent of a crystal alignment though clustering was found. The principle direction density of the clinopyroxene crystals represented by diopside range from 8.30 to 17.25 and the principle plane densities of olivine, represented by forsterite, in the samples range from 6.33 to 15.95 per fifteen degree contour. The point densities of each phase are found in table 2. These maximum densities are significant and, from the plagioclase phase, represent a strong fabric in the enclaves. All the anorthite pole figures except one show the same pattern of crystal alignment with clustering around the {010} axis and linear spread about the {001} and {100} axes (figure 7). Sample 9B is the exception with only a linear alignment around the {010} axis as opposed to a strong clustering.

Crystals exhibit one to three degrees of deformation along their long axis. Elongation of the crystal projection in multiple samples reflects distortion within individual crystals. In the high resolution scan of GR8B smearing of multiple crystals on the {001} and {010} axes and clustering on the {100} axis seen in figure 10 reflect this deformation of the anorthite lattice. This configuration is characteristic of a dislocation slip with rotation around the {100} axis. This smearing along two planes and clustering around the third is seen in sample 7A as well, providing evidence of prevailing crystal distortion though the axis of rotation is variable.

V. Discussion

The strong fabric seen in the sampled enclaves reflects deformation in the magma chamber and is characteristic of cumulate material. There are multiple ways that igneous rocks may form an aligned texture; from natural sedimentation of crystals nucleating and falling out of the melt, compaction due to some stress and related fluid loss, and flow within the magma chamber. David Shelley (1993) describes the products of these processes and suggests that sedimentation alone is unlikely due to similarities in density between the crystals and melt and the high viscosity of magma, stating that many igneous fabrics will be due to some combination of compaction and flow. Due to its intensity as represented by the point and contour data of the plagioclase phase, it is likely that the enclave fabric at Goat Rock is a primary feature of the chamber and that the enclaves were later entrained in the rising magma of the dome. The consistent pattern of crystal alignment along the long axis point to primary compaction processes.

This is supported by the distortion of individual plagioclase grains that is seen in the high resolution scan (figure 8). The configuration of deformation in sample 8B discussed above is characteristic of a dislocation slip with rotation around the {100} axis. The deformation was produced in a high temperature environment with abundant interstitial melt. This melt was later extracted with the ascension of the fractionated portion of the magma. Evidence for this is found in the dihedral angles of the samples which have very fine material suggesting that primary melt extraction produced compaction of the crystal cumulate mush producing the strong alignment of the plagioclase phase (Holness et al., 2005). In addition, there is evidence of multiple possible magmatic intrusions including finer, more diverse phases overprinting larger, highly aligned plagioclase crystals, extensive alteration products and brittle deformation, and fine intercrystalline material.

While this pattern is strong in the plagioclase phase, such a consistent fabric is not found in the pyroxene and clinopyroxene phases, an example of which is represented by figure 9. This discrepancy, along with analysis of thin section textures, points to a scenario in which fractionization of a shallow magma chamber produced the strong, primary cumulate fabric found in the plagioclase phase while subsequent magmatic recharge events produced the additional phases. These phases, because they were not under conditions of compaction, do not have a strong alignment. This is supported by elongate plagioclase crystals overgrown by more randomly oriented pyroxene and clinopyroxene crystals in addition to smaller plagioclase crystals. These crystals have evidence of brittle deformation and high temperature alteration.

Further evidence to support a primary cumulate fabric can be found in a comparison with the geochemistry of lava flows in Ducksfoot Bay which, stratigraphically, lie directly below Goat Rock. Goat Rock enclaves and host, both from this study and the 2012 study by Tramantano, fit into gaps in the evolution of Ducksfoot Bay flows. Interestingly, the flows do not follow a pattern of fractionation with vertical stratigraphy, though other flow packages on Banks Peninsula do follow this pattern. The similarity of Goat Rock and these flows presents a likelihood of a single magma reservoir.

These findings are important for their physical evidence in support of previously proposed models based only on the geochemistry of the peninsula. They also show that EBSD can be applied to igneous rocks to explain magmatic processes. Additional analysis could further enlighten the subvolcanic processes of Akaroa volcanism. Such analysis may include a reconstruction of crystallization temperatures, magmatic processes and compaction timescales, and further textural and geochemical study at similar volcanic domes on Banks Peninsula.

VI. Conclusion

The mafic enclaves found at Goat Rock have a cumulate texture displaying strong alignment of the plagioclase phase. The cumulate material represented by the Goat Rock enclaves is physical evidence of the geochemical models researched and proposed by Hartung (2011) and Johnson (2012). The enclaves represent the cumulate material of shallow magmatic reservoirs that have been compacted with the extraction of the fractionated portion of the melt, further altered by magmatic recharge, and entrained and erupted in sequence with proximal lava flow packages on the peninsula. These shallow chambers are supported by physical and geochemical evidence of multiple eruption centers for Akaroa volcanism which are sourced from a deep, mantle derived magma reservoir and produce multiple fractionated packages.

Acknowledgements

This project was supported by Frontiers Abroad and the University of Canterbury and the support of Darren Gravley, Sam Hampton, and Chad Deering is greatly appreciated. EBSD analysis was conducted at the OCEM lab at the University of Otago under the knowledgeable guidance of David Prior. In addition, this project could not have been completed without the help of Rob Spiers and Stephan Brown in the lab as well as Anna Gerrits and Abra Atwood.

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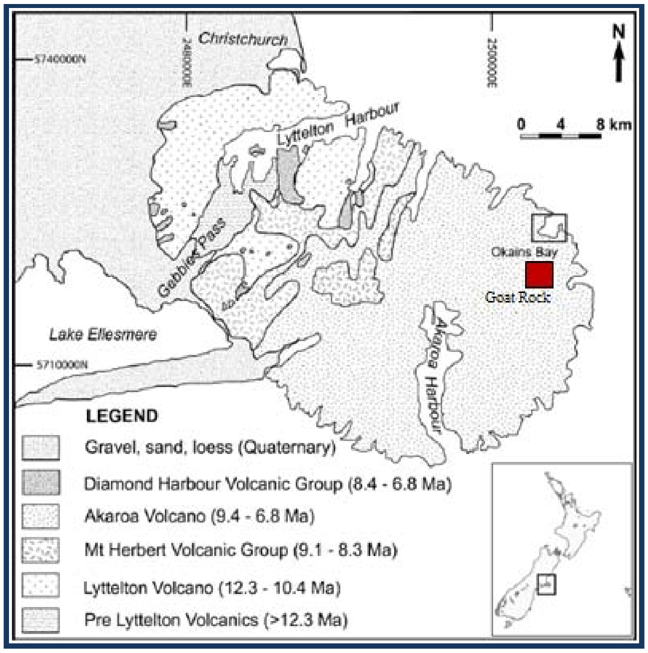
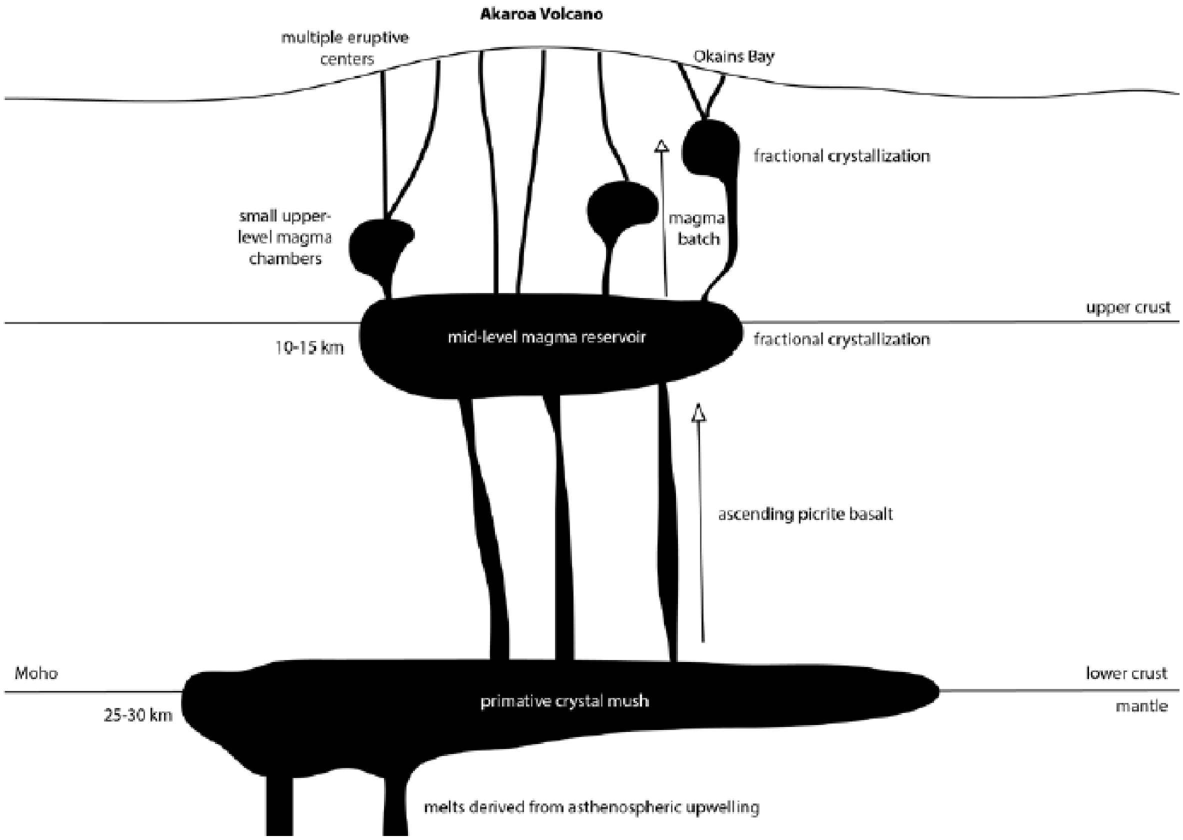


Figure 1.

Figure 2.



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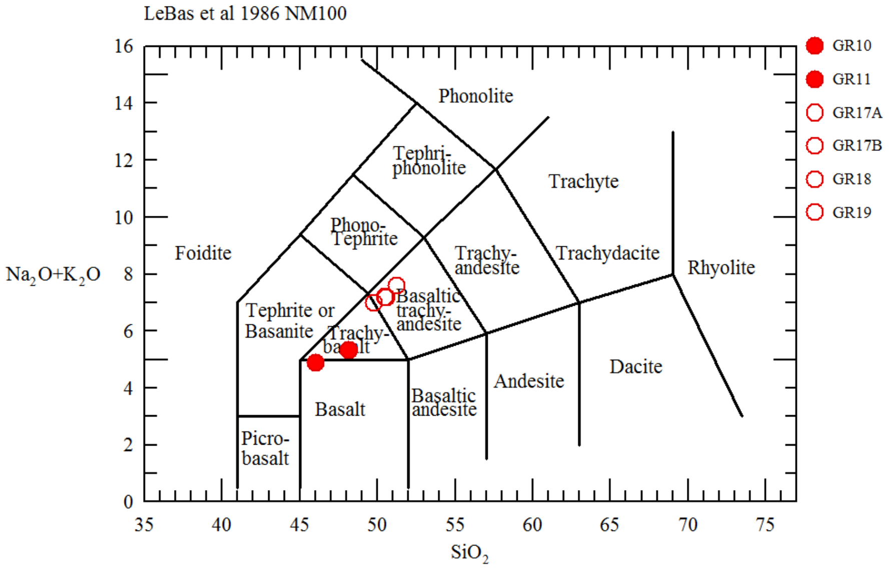
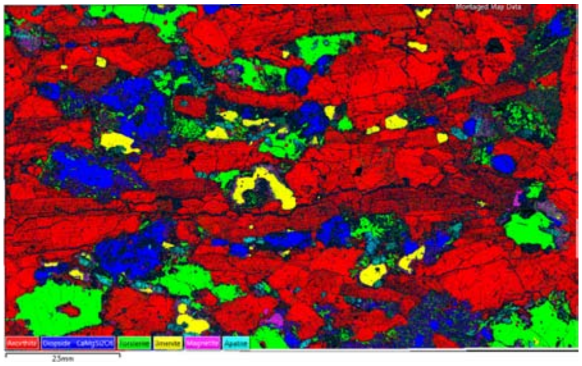


Figure 4.

	SiO2 (%)	TiO2 (%)	Al2O3 (%)	Fe2O3T (%)	FeO (%)	MnO (%)	MgO (%)	CaO (%)	Na2O (%)	K2O (%)	P2O5 (%)
GR10	45.36	3.58	17.03	14.59	13.12	0.25	4.42	8.08	4.15	0.66	1.89
GR11	47.52	2.95	16.95	13.61	12.25	0.23	4.10	8.08	4.52	0.74	1.30
GR17A	49.85	2.24	17.08	12.58	11.32	0.22	3.06	6.61	5.19	1.91	1.25
GR17B	49.94	2.24	17.05	12.56	11.30	0.22	3.05	6.60	5.20	1.89	1.25
GR18	50.64	2.17	17.34	12.19	10.97	0.21	2.48	6.28	5.48	2.02	1.19
GR19	49.17	2.38	16.81	12.77	11.49	0.21	3.42	7.05	5.03	1.87	1.28

Table 1.



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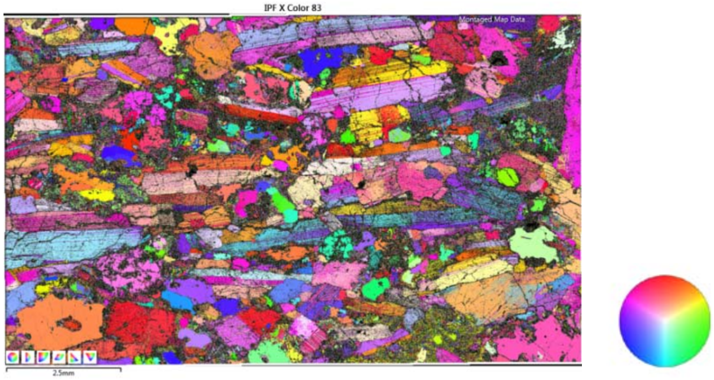

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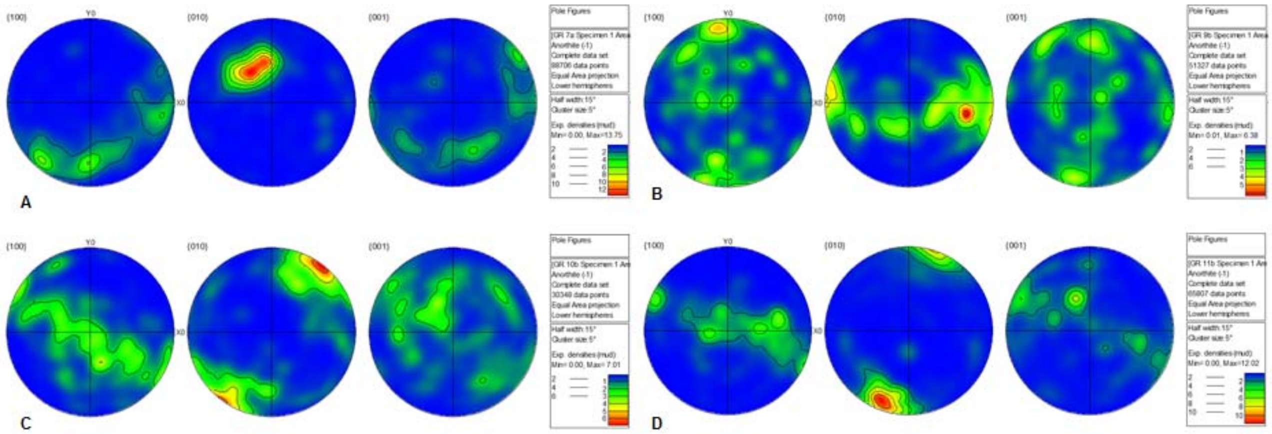
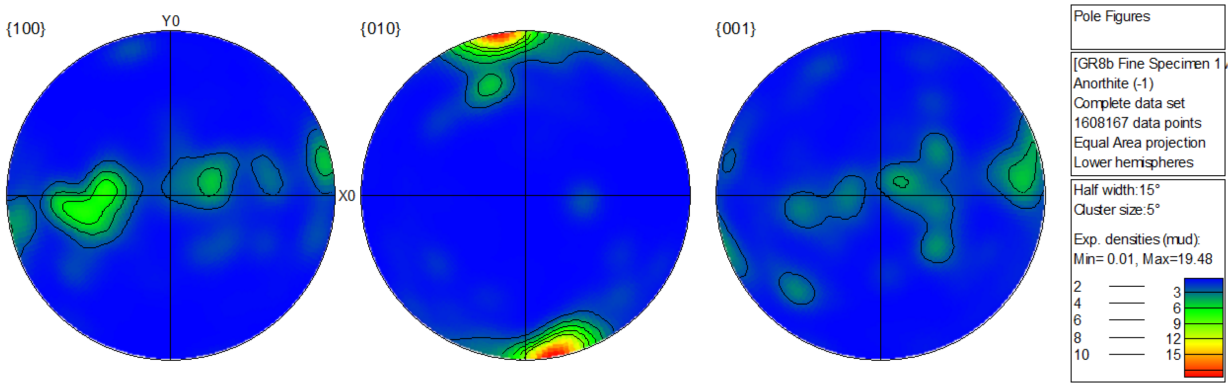


Figure 7.

Phase	Sample 7A	Sample 8B	Sample 9B	Sample 10B	Sample 11B	Sample 8B High Resolution
Anorthite: principle plane	13.75	12.28	6.38	7.01	12.02	19.48
Anorthite: principle direction	16.81	12.09	7.03	8.27	13.45	19.41
Diopside: principle direction	13.59	17.19	14.59	8.30	11.74	17.25
Forsterite: principle plane	14.47	13.23	13.54	7.80	6.33	15.95

Table 2.



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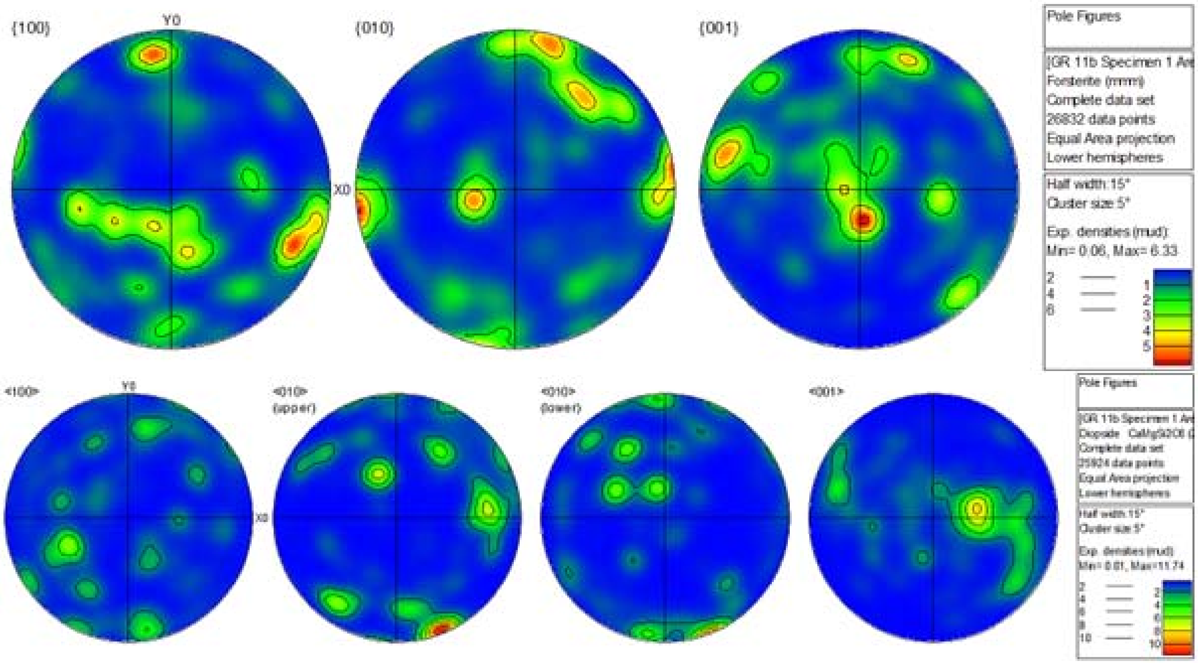

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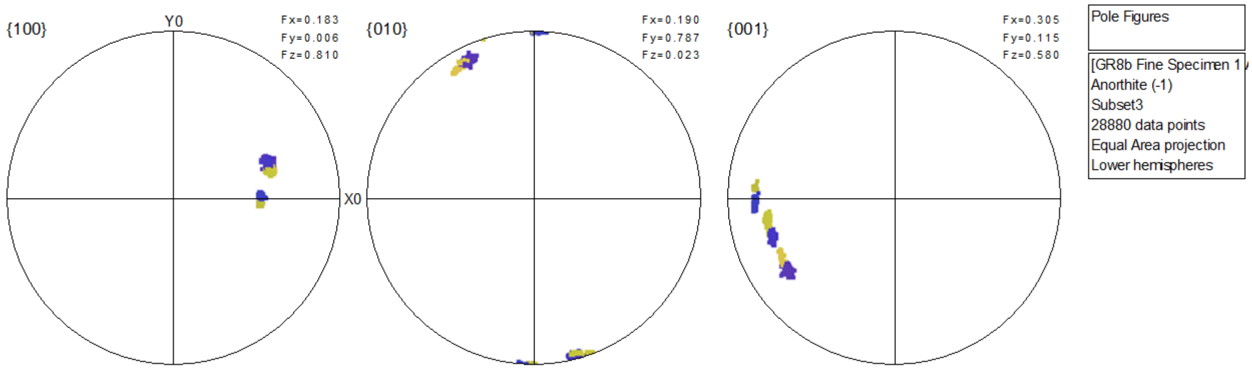

Figure 10.

Figure and Table Captions

Figure 1. Banks Peninsula. Location of Goat Rock represented by red box. Adapted from Hampton and Cole (2009).

Figure 2. Goat Rock (left) and enclaves (right).

Figure 3. The model for Akaroa volcanism proposed by Johnson (2012).

Figure 4. Rock type diagram for the 2014 geochemical work on Goat Rock.

Figure 5. Phase map of sample 8B.

Figure 6. Left: inverse pole figure with euler colors based on the orientation of the X axis. Right: color legend.

Figure 7. Principle plane and direction contour diagrams of A. sample 7A B. sample 9B, C. sample 10B, and D. sample 11B. Contours are drawn at intervals of 15 points.

Figure 8. Pole figure with contours of the principle plane orientations of anorthite in the fine resolution scan of sample 8B.

Figure 9. Principle plane contour diagram of the olivine phases (top) and principle direction contour diagram of the clinopyroxene phase (bottom) from sample 11B.

Figure 10. Pole figure of sample 8B showing individual grain distortion in the anorthite phase and rotation about the {100} axis.

Table 1. Major element Data for 2014 analysis of Goat Rock. GR10 and GR11 are xenoloths, GR17A, GR17B, GR18, and GR19 are dome host material.

Table 2. The maximum point densities of the (010) axis of the plagioclase phase when plotted as pole figures.