Reconstructing the Magmatic History of Goat Rock Intrusive, Banks Peninsula, New Zealand

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Abstract:

The incorporation of crustal xenoliths in a volcanic unit can be analyzed in conjunction with structural observations to provide details on crustal and mantle behaviour at the time of active volcanism. Volcanic domes of the Akaroa unit (~9.6-8.6 mya) (Timm, et al. 2009) of Banks Peninsula on the south island of New Zealand showcase a variety of mafic xenoliths in a trachytic groundmass. Recently exposed meta-gabbro xenoliths of the Goat Rock dome were petrographically and geochemically analysed and combined with structural measurements to reconstruct the formation of this particular intrusive. Structurally, Goat Rock is surrounded by a basaltic scoria unit and has vertical spiny joints. Its groundmass is trachy-andesitic and porphyritic with feldspar phenocrysts and large (5-25cm) meta-gabbro xenoliths. The structure implies Goat Rock was intruded through an old scoria conduit, and the absence of ultra-mafic xenoliths in Goat Rock indicates a transitional period between basaltic magmatism and late stage magmatism. Geochemical analysis and microscopic observations are consistent with samples used in studies that apply an intraplate volcanism theory to Banks Peninsula (Hoke, et al., 2000) (Timm, et al., 2009) (Hartung, 2011). The results from my study provide support for this theory of lower lithospheric detachment but yield different conditions of mantle upwelling than previous domes studied in the area.

Introduction:

The intraplate volcanic history of New Zealand and the surrounding oceanic plateaus during the Cenozoic exhibits sporadic and irregular data in terms of longevity, distribution, and plate motion progressions (Finn et al, 2005) & (Hoernle et al, 2006). This erratic data is later interpreted as a multi-stage detachment of the bottom part of the lithosphere during the separation of New Zealand from Antarctica in the break-up of Gondwana (Timm et al, 2009).

Banks Peninsula is an entirely volcanic unit closest to the city of Christchurch on the middle of the east coast of the South Island of New Zealand. It is comprised of two eruptive...
centers: the Lyttleton group (10.6-12.4 Ma) on the northwestern side and the Akaroa group
on the Northeastern corner of Banks Peninsula between Le Bons Bay and Okains Bay within
the Akaroa Group (Figure 1). A late-stage period of volcanism, known as the Diamond
Harbor Group (6.8-8.4 Ma) mostly appears on the eastern flanks of the Lyttleton group, but
small eruptive centers are observed to outcrop on the northeastern flanks of Akaroa group
(Timm et al, 2009). The eruptive centers have yet to be explicitly studied outside of one: Le
Bons Bay Peak Basanite, which contains similar metagabbro xenoliths to Goat Rock, but also
include ultramafic Iherzolites and nodules as well (Sewell et al, 1993).

Looking at elemental and isotopic compositions of the smaller units within the
Akaroa group is a way to piece together different stages of volcanism within one group. A
previous study theorized the isotopic ratios in Banks Peninsula are derived from carbonated
eglogite with peridotite in the form of enriched, recycled oceanic lithosphere that detached
and descended into the mantle (Timm et al, 2009). Throughout the Akaroa group, a Daly gap
is recognised between 50% and 60% weight in silica (wt. SiO₂), which is interpreted as a
distinct separation between basaltic and trachytic magmatism (Hartung, 2011). Although
the groundmass of Goat Rock plots just below 50% wt. SiO₂, the metagabbro xenoliths
contain 52%, which implies the start of a transitional period before trachytic and later-stage
magmatism.

**Sampling & Methods:**

Five samples of three rock types were taken along the outcrop of Goat Rock, and
from the underlying scoria (Figure 6). The main focus of sampling was to locate xenoliths
and make compositional and structural observations along the unit. Care was taken to
ensure that only the freshest samples would be taken for geochemical analysis. Oriented
surface samples that exhibited some weathering were only cut into thin sections to observe
flow orientations. Plunge and trend measurements focused mainly on the large sub-vertical
joints and were taken on a standard levelled compass.

Major and trace element geochemical analysis was conducted at the University of
Canterbury on a Philips PW 2400 Sequential Wavelength Dispersive X-ray Fluorescence
(XRF) Spectrometer calibrated to international standards. At least 1.3 grams of unweathered
rock powder of the three major rock types were analysed. The results of the three
groundmass samples, one xenolith sample, and one scoria sample were plotted and
presented in Tables 1 & 2 and Figures 2 & 3.

Field Data:

Structural Observations:

Goat Rock exhibits an elongate volcanic dome shape oriented northeast southwest,
and is broken into two distinct segments. The entire outcrop of the dome is approximately
500 meters long, with the smaller northeast segment about 75 meters in length and
separated from the main outcrop by about 30 meters (Figure 6). From the northeast, the
dome gently slopes upward, and has steep faces on the north and the northeast side. Large,
parallel, sub-vertical joints (Figure 11) are consistent between the two segments and exhibit
a bit of rotation in their orientation. Within these large joints, some meter-scale outcrops
show a jointing pattern indicating flow within the unit. There was only one sighting of
vesicle pockets in an outcrop. The vesicles showed no preferred orientation, and the
pockets were never larger than 5 cm. The scoria unit outcrops on the roadcut below Goat
Rock (Figure 6) as well as the south side of the intrusion. Oriented bombs point away from
the south-western side of the intrusive.

Petrographic Data:

Groundmass:

The groundmass is a porphyritic, microcrystalline trachy-andesite with plagioclase
phenocrysts up to 3cm long. The intergranular groundmass has larger plagioclase laths
intergrown with pyroxene crystals. In thin section, feldspar megacrysts (~1.5cm) show
poikilitic textures with intergrown clinopyroxene (cpx) and distinct mineral zoning (Figure 5).
Along the dome, the abundance of crystals large enough to see without a microscope ranges
from 2-6%. Smaller pyroxene crystals were noticed in a few outcrops and were never larger
than 2mm and never over 1% abundance. Flow direction is visible and trends northeast in
two oriented thin sections.

Xenoliths:
The only type of mafic xenolith found in the recent rock fall is a metagabbro. Radial cooling joints are present surrounding some large xenoliths (Figure 11). The major minerals present are orthopyroxene and cpx, and plagioclase feldspar. Feldspar laths are generally larger than the pyroxene and only slightly more abundant. Minor amounts of quartz and olivine are also present, and no amphibole is visible. Feldspar abundance is about 50%, pyroxenes appear 45%, with only 5% olivine. Intergrowth between orthopyroxene and clinopyroxene is present within the xenoliths, and the larger feldspar crystals are often zoned with microcrystalline borders also of feldspar (Figure 5E).

**Scoria:**

The red scoria unit is noticed at two outcrops. The first outcrop appears after a steep drop on the southwest side of the intrusive unit. It is apparently dipping southwest. The other outcrop follows the roadcut along the north-northwest side and contains numerous hypocrystalline bombs, with large (2cm) plagioclase phenocrysts and vesicle pockets ~ 4 cm diameters. The bombs show an intergranular matrix of larger plagioclase laths, smaller glass and mafic microcrystalline fill, and prismatic crystals that exhibit a large amount of weathering that was once likely biotite (Figure 5F).

**Geochemistry Results:**

The major element geochemical analysis of Goat Rock yielded 3 distinct compositional varieties, consistent with the three different rock types. The results are summed in Table 1 and plotted on Figures 1 and 2. The underlying scoria plots as picritic basalt, the groundmass lies on the border between hawaiite and mugearite, and the metagabbro xenoliths show a rare silica content of 52%, which lies within the Daly gap of the Akaroa group (Hartung, 2011). The xenoliths are most similar to the type “B” xenolith found on Le Bons Bay Peak (Sewell, et al., 1993). Major element analysis of the xenoliths from these two domes on Banks Peninsula is compared to an average of 10 mafic granulite xenoliths from eastern Australia (Rudnick et al., 1986) (Table 3).

Trace element geochemical trends show less enriched mantle source values than the values obtained for the Lyttleton group (Timm et al., 2009), and are plotted on Harker diagrams (Figure 4). Floyd and Winchester (1977) relationships between TiO$_2$ and Zr/P$_2$O$_5$
show alkali basaltic compositions, with a decreasing trend in TiO$_2$ from the basaltic scoria, through the groundmass, to the xenolith (Figure 9). The Pearce and Norry (1979) trace element plot between Zr and Zr/Y show a mantle source for the basalt and groundmass to be shallow and within the plate. (Figure 8).

Discussion:

Structural Reconstruction:

An older scoria cone of the Akaroa group (AGES) with an unevolved, picritic basaltic composition provides a conduit for the intrusion of Goat Rock. Primary vertical joints, steep sides, and a smooth surface (Figure 6) are indicative that this is the top of a Pelean (or spiny) dome (Fink & Griffiths 1998). The segmentation can be explained by a pulsing intrusion and the rotation of the vertical joints can be explained by post-emplacement deformation.

Geochemistry:

The picritic basaltic scoria is undersaturated (less silica) and older than the intruding hawaiite/mugearite groundmass of Goat Rock. As depicted in Figure 4, trace element harker diagrams show a depleted environment that plots in the middle of previous Akaroa group trends (Hartung, 2011) (Timm et al., 2009). Trace element trends in the Pearce and Norry (1983) plot (Figure 8) show that the magmatic origin of the scoria cone and Goat Rock groundmass is shallow and within the plate. The major element igneous classification scheme (Figure 2) of the groundmass samples show a silica content just under 50%, which has been previously interpreted as a margin of a Daly Gap in Banks Peninsula (Hartung, 2011). Their proximity to the Gap and the geochemistry of the xenoliths (which is explained in detail below) indicate the start of a small transitional period within Akaroa Group compositional trends. The scoria unit represents an earlier tendency of basaltic magmatism, and Panama Rock, another dome in the area, represents strictly trachytic magmatism. Goat Rock is significant because it plots closer to basaltic magmatism, but shows influence of a more trachytic tendency through metagabbro xenoliths (Figure 7B & C).
**Intraplate Volcanism:**

The combination of two magmatic theories are combined in Figure 7 (Hartung, 2011) and illustrate how Goat Rock petrogenetically fits into the context of Banks Peninsula. The older Lyttleton group (Figure 7A) shows an enriched composition due to more crustal interaction than Akaroa (Figure 10, Timm et al., 2009). However, my values plot unreasonably high in the same Nb/Th vs. Nb/La plot (figure 10), which could be the result of a small amount of samples or faulty readings. Helium isotope ratios (Hoke et al., 2000) and other isotope and rare earth element analysis (Timm et al, 2009) show that the upwelling mantle is comparable to that of ocean island basalts, with a lithosphere/mantle boundary at ~80km deep (Hoke et al., 2000). Late-stage volcanism, known as the Diamond Harbour Formation, erupts more alkaline basanite with metagabbro and other ultramafic xenoliths (Sewell et al., 1993)(Figure 7D).

**Summary and Interpretation of Xenolith data:**

The presence of mafic metagabbro xenoliths is significant because they are unique in that they exist without accompaniment of any ultramafic xenoliths (such as lherzolites or nodules seen on Le Bons Bay Peak) (Sewell et al., 1993). Radial cooling joints (Figure 11) and the large size of the xenoliths (<20cm) imply a rapid ascension. Ultramafic xenoliths in the area are theorised to originate from a depleted upper mantle/lithosphere boundary at about 60 km deep as well as from cumulates <30 km deep, while metagabbros are thought to be a direct result of magmatic underplating (Sewell et al., 1993). Evidence for magmatic underplating can be seen in the recrystalisation of pyroxenes and the zoning of feldspars under thin section (Hartung, 2011). Ultramafic xenoliths are also only seen in basanitic lavas, which are even more alkalic than Goat Rock lavas. This magmatic underplating would have differentiated a slightly more evolved yet still depleted mafic magma later in the time span of Akaroa volcano (Figure 7C). Depleted trace elements and evolved (higher wt.% SiO₂) magmatic trends are shown in the trace element variation diagrams, as well as in a silica content of 52%. This SiO₂ value plots within the Daly Gap of the Akaroa Group (Hartung 2011), which supports that Goat Rock intruded during a small transitional phase between basaltic and trachytic magmatism. Magmatic mixing from a recycled oceanic lithosphere
(Timm et al, 2009) also contributes to this composition, which is also shown in the trace element plot within the MORB region (upper mantle ~90km) of Figure 8.

Conclusion:

Goat Rock is a pelean spiny dome of the Akaroa group on Banks Peninsula, New Zealand that occurred at approximately 8 Ma. After the eruptive phase of the less enriched Lyttleton group, a period of basaltic magmatism occurs, where the underlying picritic scoria unit was erupted (Figure 7B). Convection and crystal fractionation condition belows the brittle/ductile boundary are evident in plagioclase zoning in scoria bombs under thin section. Next, during a transitional period towards trachytic magmatism, less convection and more crystal fractionation was happening due to magmatic underplating that occurs closer to the surface (Figure 7C). It is early in this period that Goat Rock intruded the Akaroa group through an older basaltic scoria conduit. In conclusion, the conditions of the upwelling magma for Goat Rock must be within 30km of the surface, a thin, depleted lithosphere, a fast ascension, and incorporation of upper mantle derived metagabbro cumulates from magmatic underplating. Testing of helium isotope ratios in the Northeastern region of Banks Peninsula, including trachytic magmatism and this transitional period, has yet to be sampled, and could be expanded on in further research.

Acknowledgements:

I’d like to thank Frontiers Abroad in conjunction with the University of Canterbury for this research opportunity on Banks Peninsula – specifically Darren Gravley and Samuel Hampton. I’d also like to thank Rob Spiers for thin section help, and Shane Cronin and Paul Ashwell for advice on volcanic domes.
**Goat Rock**: Basaltic Magmatism - Transitional Period

**Le Bons Bay Peak**: Diamond Harbor Late-Stage Volcanism (ultramafic xenoliths)

**Panama Rock**: Trachytic Magmatism

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**Figure 1**: Map of Banks Peninsula and the location of relevant domes and Volcanic groups:

- **Goat Rock**: Basaltic Magmatism - Transitional Period
- **Le Bons Bay Peak**: Diamond Harbor Late-Stage Volcanism (ultramafic xenoliths)
- **Panama Rock**: Trachytic Magmatism

**Figure 2**: Igneous Rock Classification

- Orange = Metagabbro Xenolith
- Blue = Goat Rock Groundmass
- Pink = Scoria
### Table 1:

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<th>Sample Number</th>
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<th>Type</th>
<th>SiO2 (%)</th>
<th>TiO2 (%)</th>
<th>Al2O3 (%)</th>
<th>Fe2O3T (%)</th>
<th>MnO (%)</th>
<th>MgO (%)</th>
<th>CaO (%)</th>
<th>Na2O (%)</th>
<th>K2O (%)</th>
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### Table 2:

#### Major Element Comparison between local Metagabbro Xenoliths

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<tr>
<th>Sample Number</th>
<th>Type</th>
<th>SiO2 (%)</th>
<th>TiO2 (%)</th>
<th>Al2O3 (%)</th>
<th>Fe2O3T (%)</th>
<th>MnO (%)</th>
<th>MgO (%)</th>
<th>CaO (%)</th>
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<th>P2O5 (%)</th>
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<th>Total (%)</th>
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<tr>
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<td>Xenoliths</td>
<td>Metagabbro</td>
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<td>1.75</td>
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**Table 3:**

- **BP-48:** Personal Xenolith sample
- **Type “B”:** Metagabbro Xenolith sample (Sewell et al., 1993)
- **East AU:** An average of ten mafic granulite xenoliths (Rudnick et al, 1986)
Figure 3:
Volcanic Classification Scheme
Orange: Xenolith
Blue: Groundmass
Pink: Scoria

Figure 4:
Harker Variation Diagrams
Figure 5:

a), b) Zoned Plagioclase, indicative of magmatic underplating. Clinopyroxene recrystalisation and poikilitic texture also an indicator. Flow apparent. (Sample 3, Figure 6)

c) Extreme replacement of plagioclase crystal within a clinopyroxene. Flow very visible, and small olivine crystal noted. (Sample 1, Figure 6)

d) Flow Direction is northwest-southeast. (Sample 5, Figure 6)

e) Xenolith Thin section: Large feldspar crystals with microcrystalline zoned rims. Pyroxenes are overgrowing one another. Olivine in trace amounts (Sample 3, Figure 6)

f) Scoria thin section with weathered biotite, large plagioclase crystals. (Sample 4, Figure 6)
Figure 6:

Bird’s eye view of Goat Rock (white):

Pink = Trend and plunge measurements of vertical joints in Figure 11

Yellow = Extrapolated lineation of spines

Blue Numbers = Thin Section & Geochemistry Samples

Green Number = Sample from Lynn Geiger

Purple = Microscopic flow orientations

Red = Scoria Outcrop

Aquamarine = Separate lava flow
Figure 7:

A) Lyttleton group: Crystal fractionation occurs at the mantle (~80km deep) and brittle/ductile boundaries. Composition is silica saturated and enriched with trace elements due to a delamination of the lower lithosphere (pink).

B) Akaroa Group – Basaltic Magmatism: Lithosphere is thinner here and upwelling asthenosphere is closer to Moho. Undersaturated basaltic magmatism occurs and produces a scoria cone on the Northeastern corner of Banks Peninsula (red). Fractionation and convection at the brittle/ductile boundary is shown through zoned plagioclases.

C) Akaroa Group – Transitional Period: Mantle mixing occurs in a zone of magmatic underplating, which is the origin of metagabbro xenoliths seen in the intrusive unit Goat Rock (yellow). This is pre-trachytic magmatism, where convection and zoning is still present, but further into the brittle zone of the lithosphere.

D) Diamond Harbour Group: This is the late-stage volcanism of the Akaroa Group where ultramafic xenoliths are brought to the surface due to a higher upwelling asthenosphere and a completely annealed lithosphere.
Figure 8:
Pearce and Norry (1979)
Trace Element Plot:

Figure 9:
Floyd and Winchester (1977)
Trace element Plot:
Figure 10:  
Taken from Timm et al, 2009: 
Personal Samples plotted in color, Trace element relationships of Nb, Th, and La show a trend of less crustal interaction as time progresses in Banks Peninsula volcanism.

Figure 11:  
Left: Goat Rock, with distinct underlying scoria bed and vertical joint set  
Right: Metagabbro Xenoliths displaying radial cooling joints


