Abstract

The Al-hornblende geobarometer is a widely applied tool for calculating the depth of a pluton's emplacement. Though its widespread use has been questioned, it is still often used with little investigation of its applicability, as there are few geobarometers available in these systems (Anderson and Smith 1995, Ague 1997).

To examine the applicability of the hornblende geobarometer within the Tuolumne Intrusive Suite within Yosemity National Park, California, samples of hornblende phenocrysts from the Half Dome Granodiorite were collected and analyzed. From them, maps of mineral inclusions and Al content were made using scanning electron microscopy and remote sensing techniques. Instead of the expected regular concentric zoning in Al content, zoning in Al is patchy and irregular. Furthermore, the crystals are riddled with inclusions of other minerals, some of them late crystallization products.

These features suggest that Al zoning within these crystals is not controlled by pressure and temperature, and that these crystals would be unsuitable for geobarometry. Because the included and zoned nature of these crystals is not obvious in hand sample, it is necessary that hornblende crystals be carefully examined before Al geobarometry is attempted. Furthermore, the inclusion of late-crystallizing minerals within hornblende strongly suggests that they could not have formed in a single crystallization event. This indicates that their origin must be more complicated than traditional models of pluton formation account for.

Introduction

The nature and formation of plutons has been a subject of fierce debate within the field of geology. While the dominant model has been one of single emplacement, a model of incremental emplacement has recently been proposed (Coleman et al, 2004). These models are important for the understanding not only of plutons but of their relationship to surrounding crustal rocks and to volcanic systems.

One important piece of information in understanding a pluton's history is its depth of emplacement. However, plutons have few mineral assemblages that give obvious indications of their pressure (and thus depth) of formation. It was not until Hammarstrom and Zen (1986) that a geobarometer based on a common plutonic mineral assemblage became available to researchers. They showed a positive relationship between depth of pluton emplacement inferred from other data and the overall Al content of hornblende crystals found in these rocks. This is the result of Al entering tetrahedral configuration within the crystal. This geobarometer has been applied to a number of plutons. Further calibrations by Anderson and Smith (1995) added additional terms to take temperature and f_{O2} into account.

However, hornblende phenocrysts from the Half Dome Granodiorite in the Sierra Nevada batholith, a pluton which has become particularly important to this debate (Coleman et al, 2004), show strong and irregularly zoned internal variation in Al content. Moreover, these crystals are heavily included by a wide variety of minerals, some of which indicate alteration and metamorphism. These features suggest a complicated history, and that factors other than pressure and temperature have controlled Al content within the hornblende crystals of this body. This in turn raises questions about the applicability of the Al geobarometer within this system, and possibly within other systems across the world.

Methods

Euhedral hornblende and biotite phenocrysts ranging from 1 to 2 cm in maximum dimension were collected by Dr. Allen Glazner in Yosemite National Park from grus developed on the Half Dome Granodiorite. Differential weathering releases intact hornblende phenocrysts with pieces of enclosing quartz and feldspars attached (see figure 1). Hornblende crystals were collected from 3 weathering pans on glacial pavement west of Tenaya Lake, and biotite crystals were collected from similar pans on the summit of Half Dome.

Five samples of hornblende were mounted in epoxy, sliced and polished. Three were cut perpendicular to the *c*-axis, one perpendicular to the *a*-axis and one perpendicular to the *b*-axis. All were cut through the center. Three samples of biotite were mounted and polished, two perpendicular to the *c*-axis and one parallel to the *c*-axis. The polished samples were then examined in a Tescan VEGA 5341 scanning electron microscope, and X-ray maps of four of them were generated using a Sirius Si-drift detector and 4pi Rev.ution software. Typical analytical conditions were 15 kV accelerating potential and 5 nA absorbed current. At minimum magnification of approximately 80x it is possible to create a map approximately of 2.7 x 2.0 mm. The elements selected for examination were Al, Si, Ca, Na, K, Mg, Fe, Ti, P and Zr. Because the Zr Kβ overlaps P Kα, the P map also includes Zr. These maps and the backscatter image were exported as image files, cropped, grayscaled and imported into ENVI.

In ENVI, the files were georeferenced to an arbitrary preexisting map file. The maps were then run through a Gaussian low-pass filter with a kernel size of 9x9 to reduce noise.

Regions of interest were placed on representative crystals of mineral inclusions within the hornblende crystals, which were readily identified by their spectral characteristics. These regions of interest were then used as the basis for a supervised classification using the minimum distance method. The Al map was then superimposed over the areas of hornblende to better show Al zoning.

A single hornblende phenocryst was mounted and polished perpendicular to its *a*-axis and point analyses were conducted by Dr. Allen Glazner using a JEOL JXA-8530 field emission microprobe at Fayetteville State University to more precisely establish ranges of Al content.

To assess the effects these compositional variations would have on the hornblende geobarometer, pressures and temperatures of formation were calculated based on the hornblende point analyses. This was accomplished using a combination hornblende geobarometer and plagioclase-hornblende geothermometer (Anderson et al., 2008). A plagioclase composition of An_{17} was measured on the scanning electron microscope and used for these calculations.

Results

Mineral maps were generated for seven of the nine available crystals. The mounted hornblende and biotite crystals and their mapped areas are pictured in Figure 1 below, and Figures 2-8 show the maps themselves.

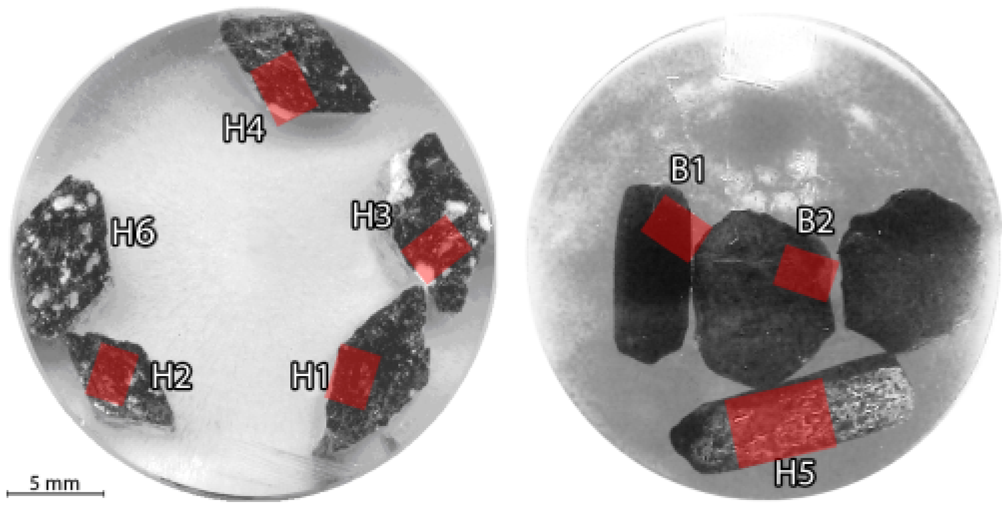

Figure 1: The hornblende and biotite phenocrysts in their epoxy pucks, with labels indicating which map they correspond to and red overlays over the mapped areas.

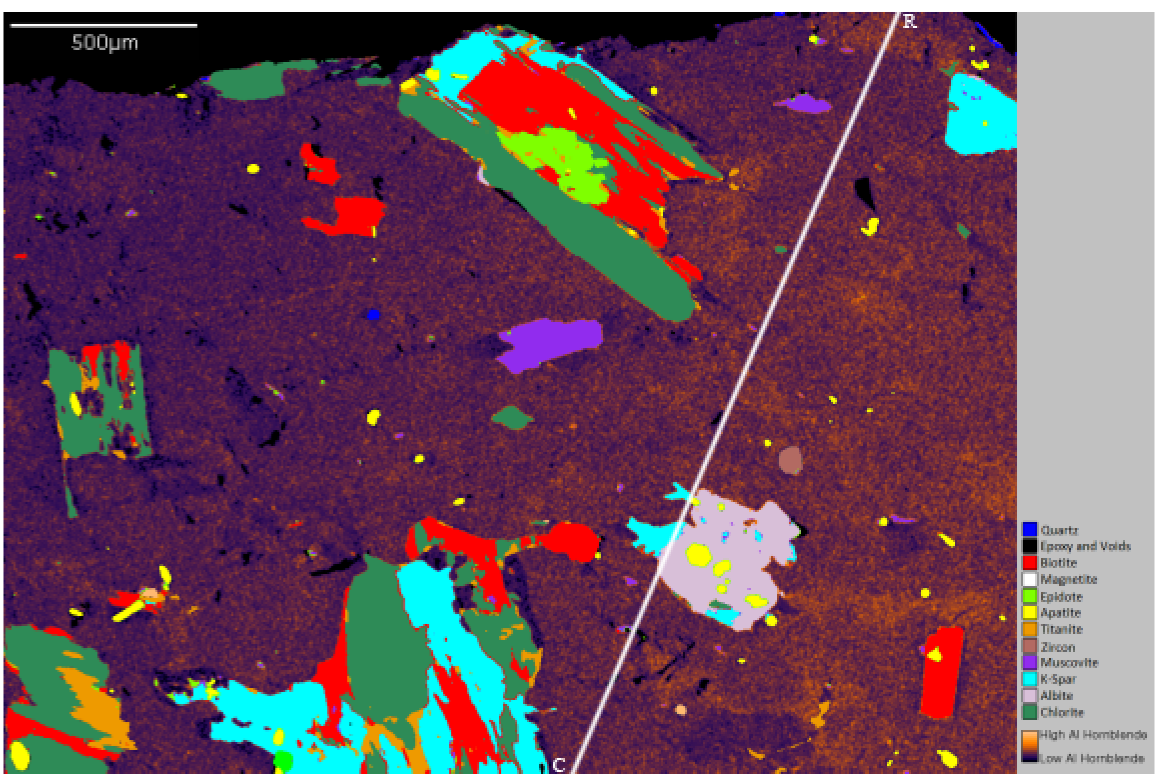

Figure 2: A mineral map of Hornblende H1, with line C-R extending from the rim towards the core.

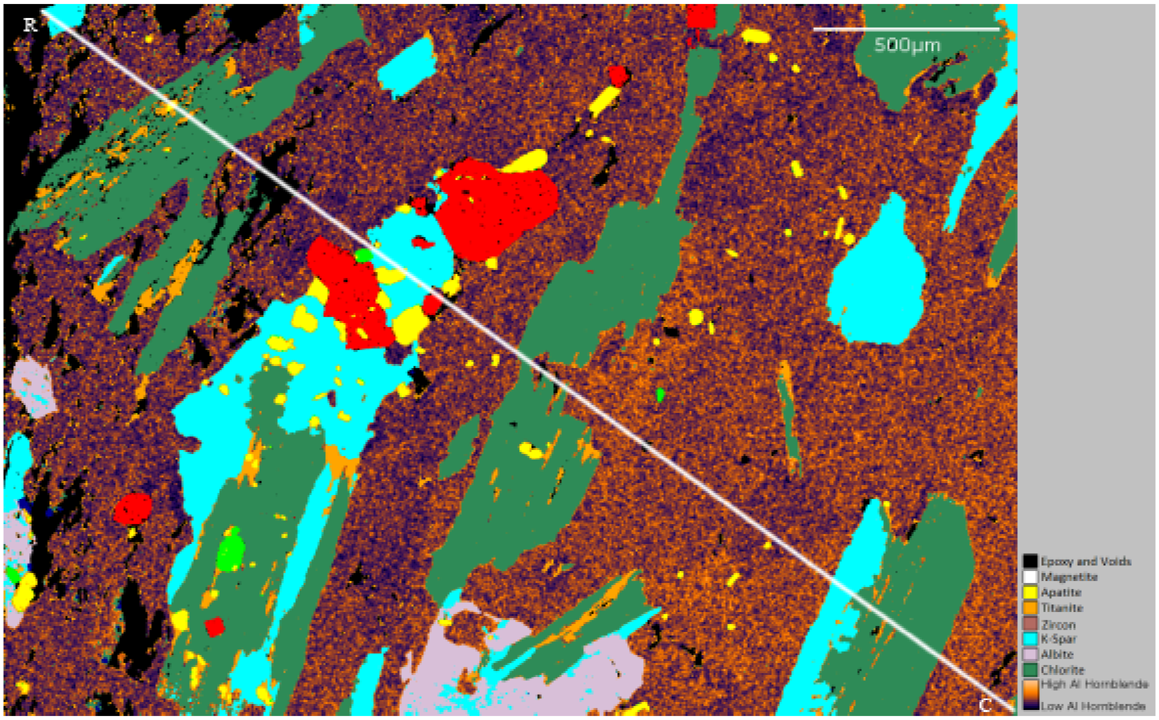

Figure 3: A map of Hornblende H2

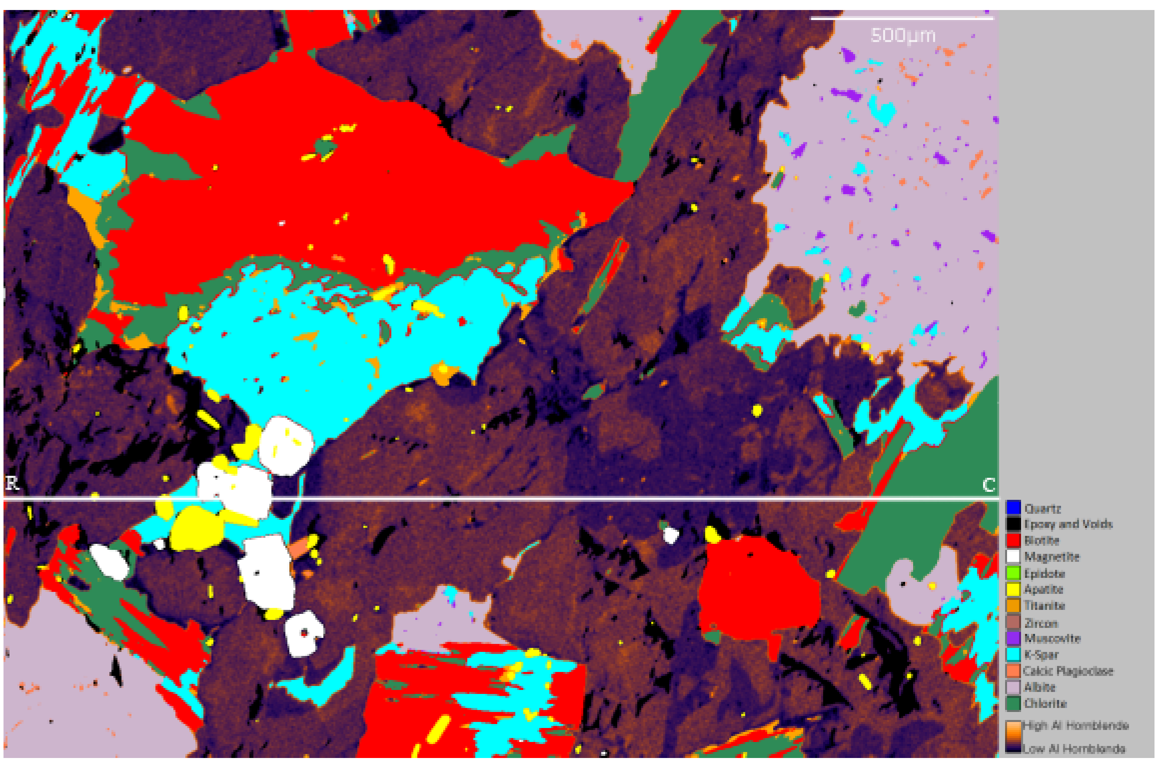

Figure 4: A map of Hornblende H3.

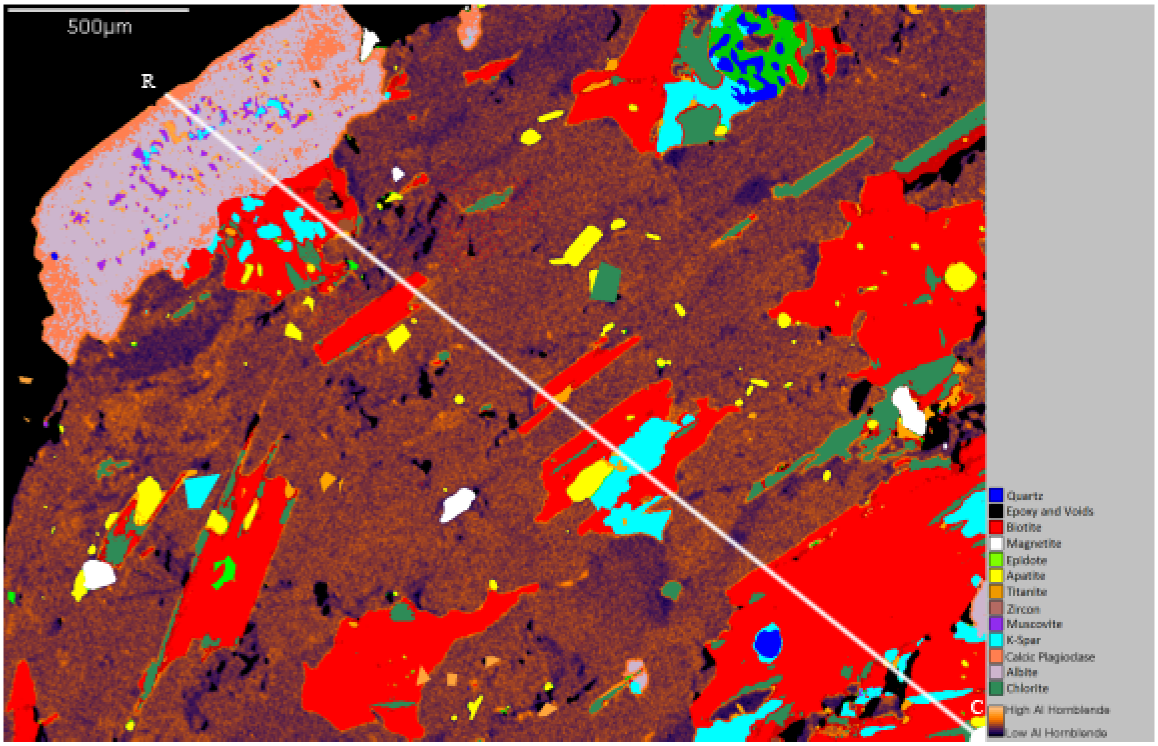

Figure 5: A map of hornblende H4.

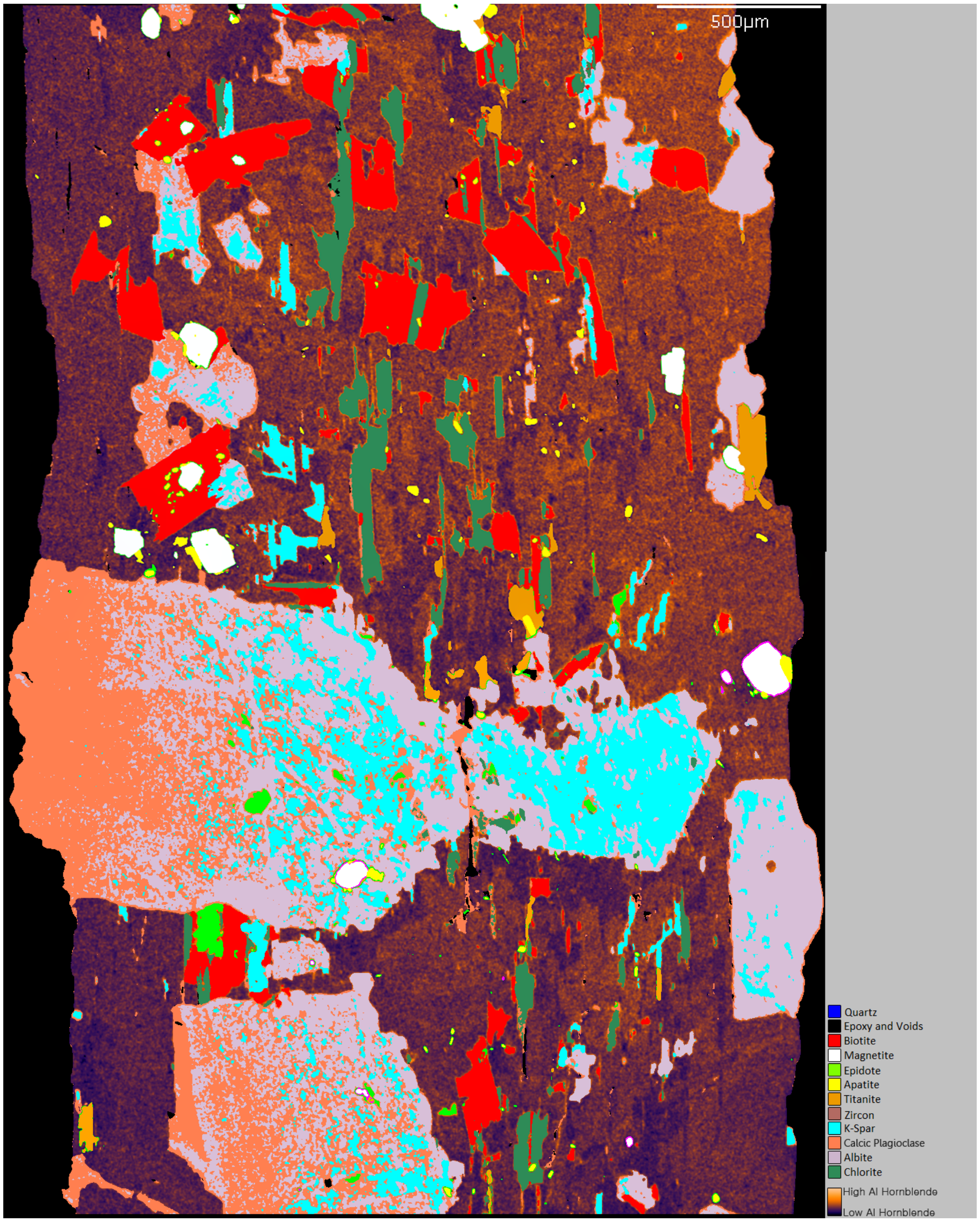

Figure 6: A composite of two maps from Hornblende H5.

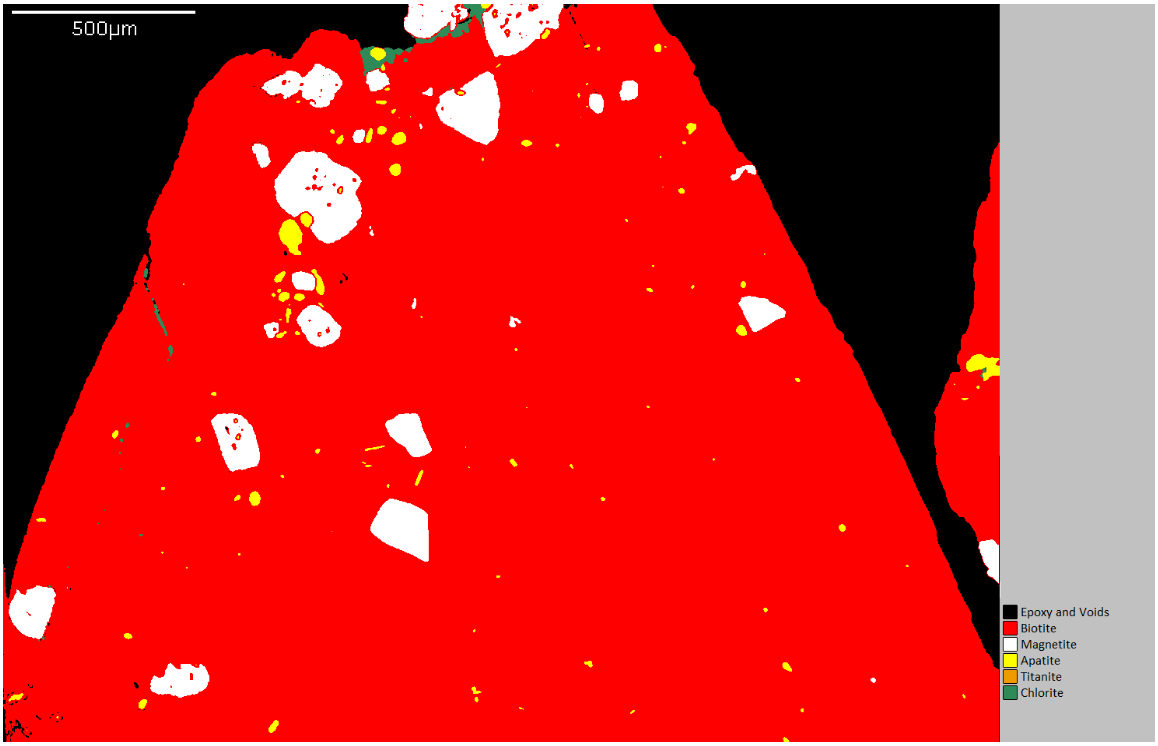

Figure 7:A map of biotite B1 showing the plane perpendicular to the *c*-axis

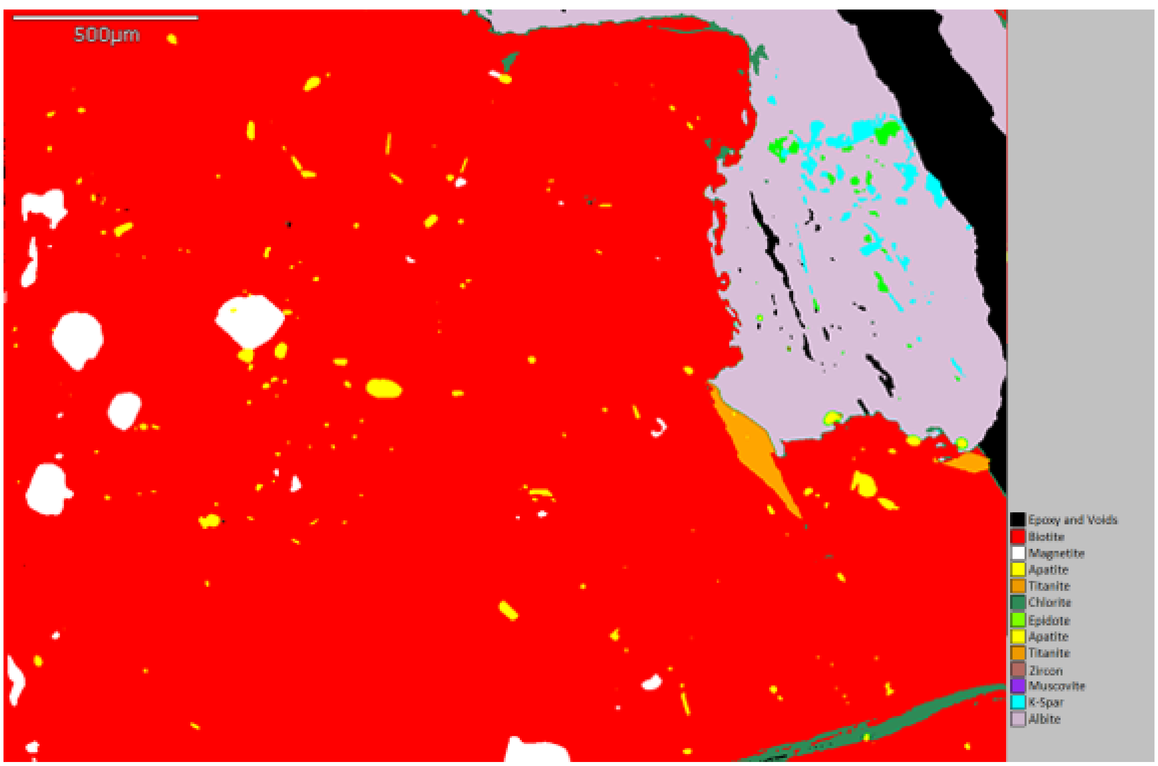

Figure 8:A map of biotite B2 showing the plane parallel to cleavage

The zoning of Al within the hornblende is patchy and irregular. Large variations in aluminum content occur within close proximity within the hornblende crystals. Spectra taken from two points less than a millimeter apart within hornblende H3 (see Figure 4) clearly show a large variation in Al content, and similar variation can be seen in Figures 9 and 10. One shows a significant Al peak while the other barely exceeds noise.

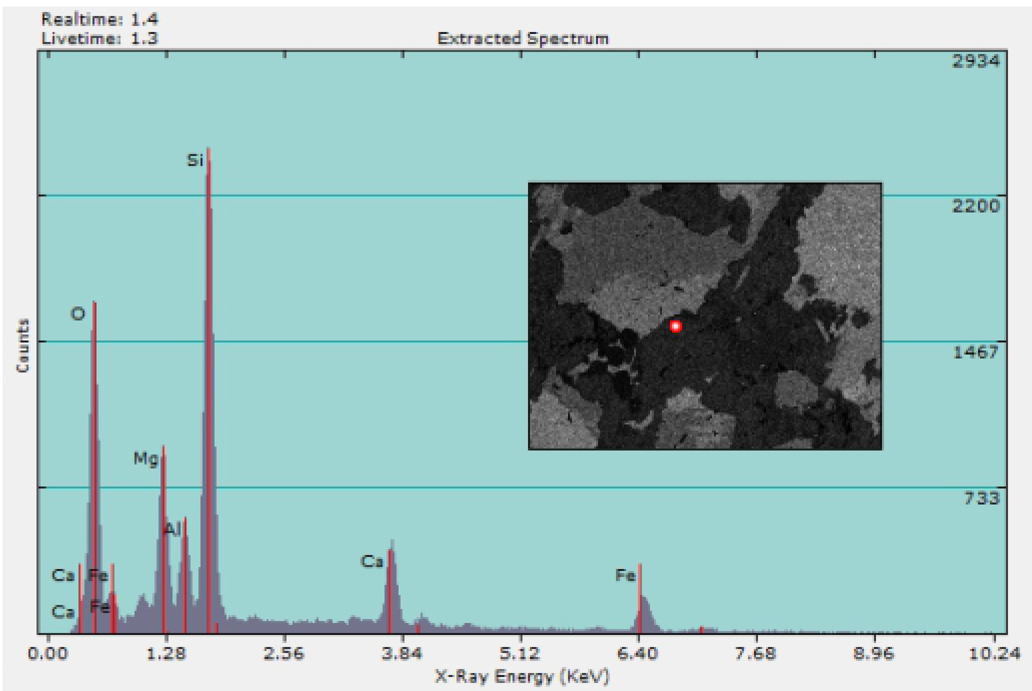

Figure 9: This spectrum shows high Al content in the sampled region of the hornblende

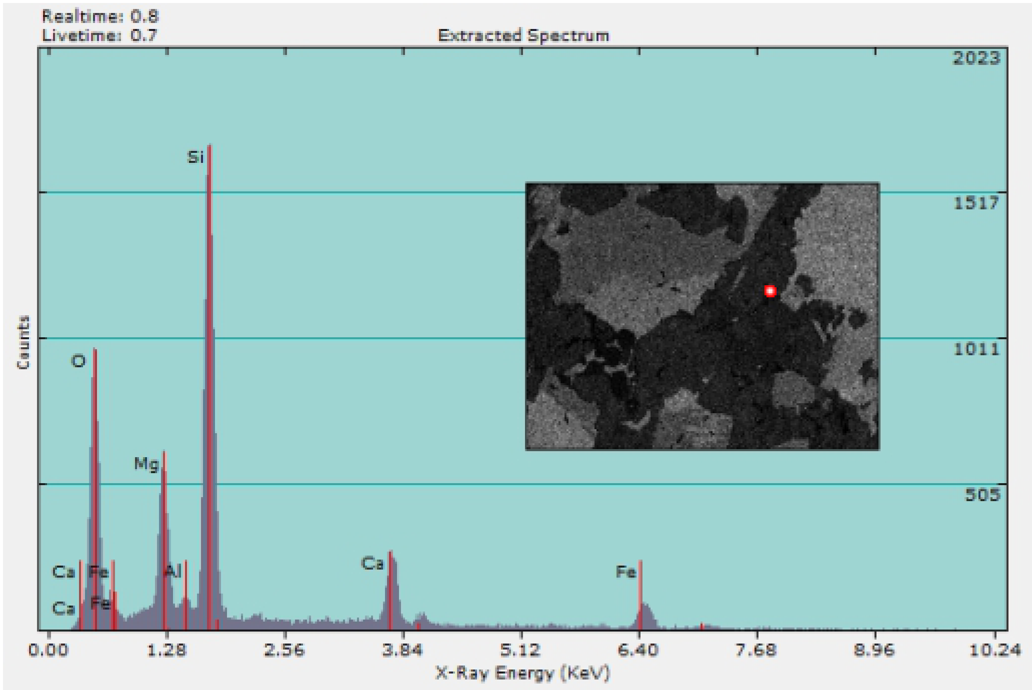

Figure 10: This spectrum shows very low levels of Al in the sampled area of the hornblende, with the Al peak barely exceeding noise.

A microprobe spot traverse across hornblende crystal H6 showed a range of Al content within the hornblende from 3.626 to 7.616 wt%, with no concentric pattern to the variations. The pressure values calculated from the point compositions showed a similarly wide range and lack of concentricity, ranging from -0.3 to 3.1 Mb (see Figures 11 and 12).

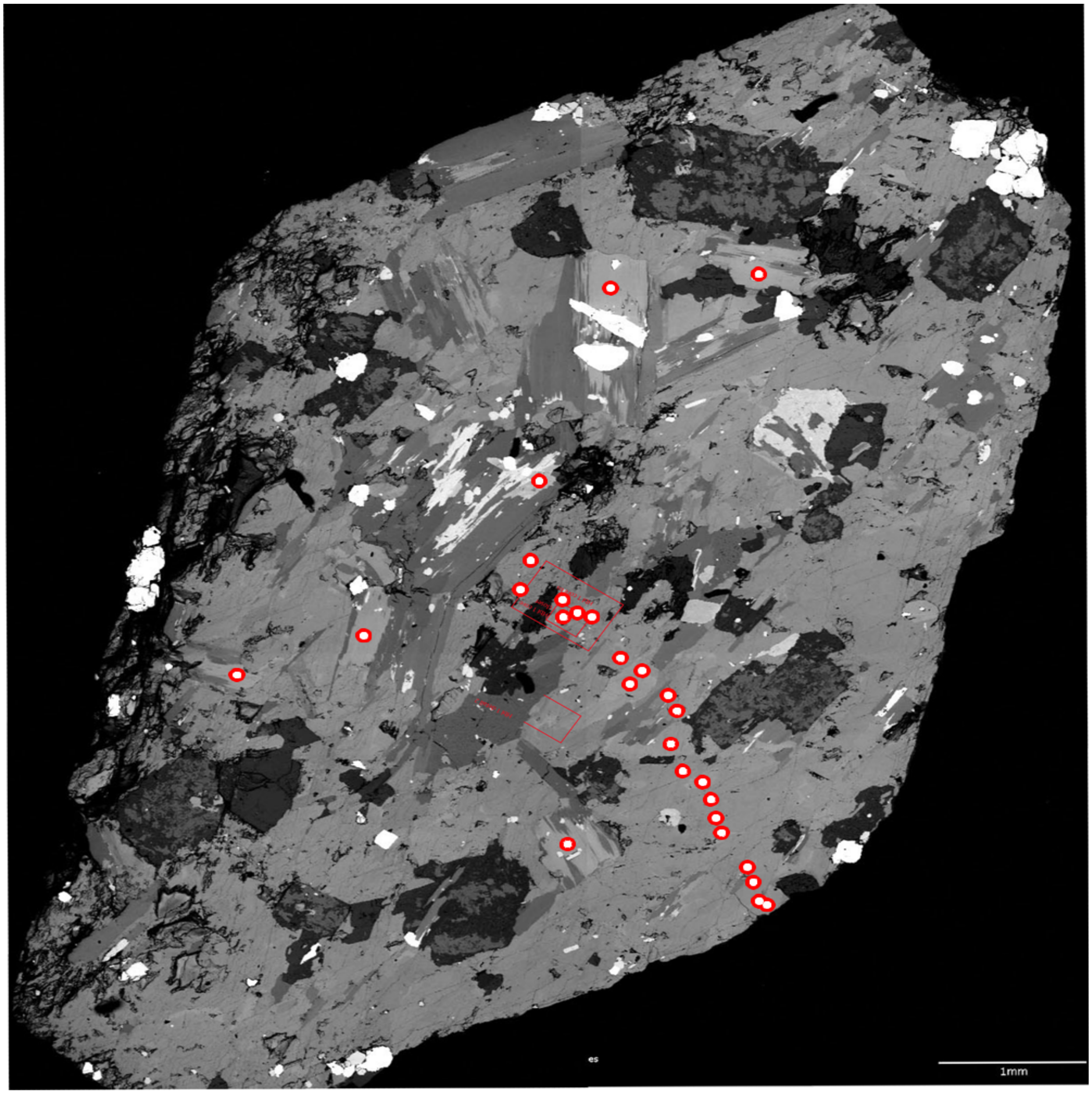

Figure 11: Image of hornblende H6 with probe points marked.

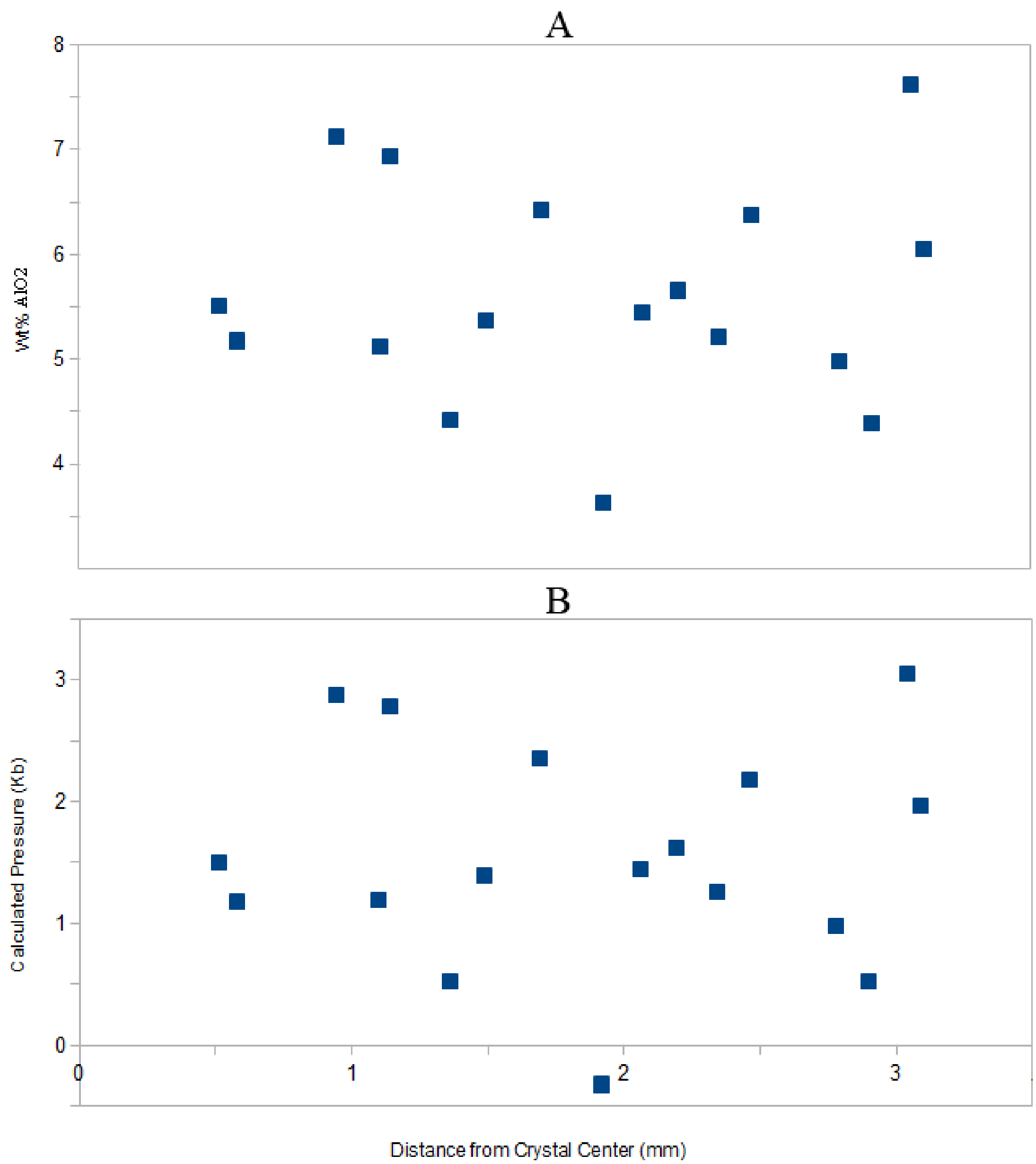

Figure 12: Wt% AlO2 and calculated pressure of formation by distance from crystal center

The maps of the hornblende crystals revealed numerous inclusions, with a total of 13 different identified minerals within the hornblende. Inclusions comprise k-feldspar, albite, calcic plagioclase, biotite, chlorite, muscovite (in the form of sericite), apatite, magnetite, epidote, quartz, zircon and titanite. These inclusions make up a significant portion of the crystal. In the examined section of hornblendes H3 and H5, hornblende makes up less than 50% of the mapped area. A summary of the area occupied by each mineral in hornblende crystals 1-4 is presented below in Table 1.

Table 1: Mineral composition of hornblende crystals

	Percent Area of Mineral				
Mineral	H1	H2	H3	H4	H5
Low Al Hornblende	23.08	9.80	7.54	27.47	27.99
Med Al Hornblende	15.52	11.50	28.55	18.32	13.65
High Al Hornblende	35.95	37.00	11.09	11.61	2.57
Total Hornblende	74.55	58.30	47.18	57.40	44.21
Biotite	4.50	0.00	16.08	17.82	4.02
Chlorite	7.17	19.25	6.67	1.41	5.81
Biotite + Chlorite	11.67	19.25	22.75	19.23	9.83
Feldspars	5.41	10.88	22.94	9.48	35.56
Other	8.35	11.40	7.08	11.05	10.40

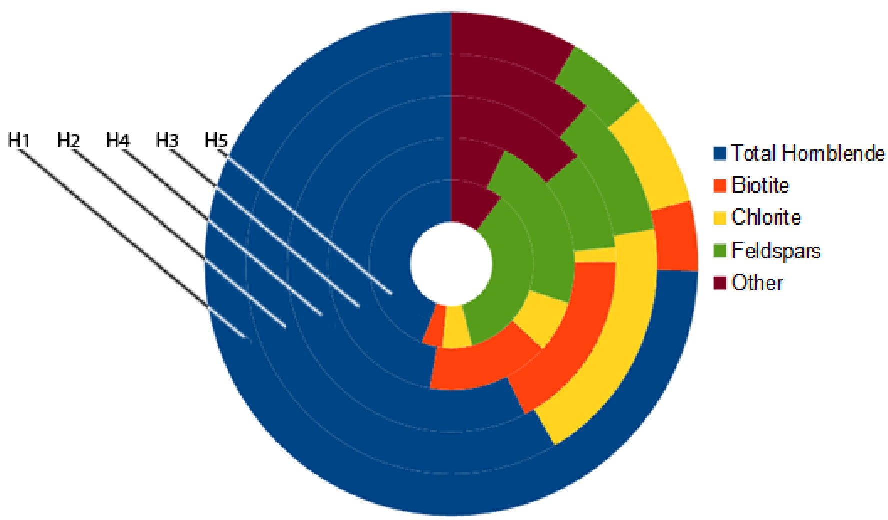

Figure 12: Mineral Areas by hornblende crystal, with increasing hornblende area from the center

The biotite crystals, however, showed very few inclusions with a smaller variety of including minerals. Although the map of biotite B1 does include a significant amount of albite, it is a crystal attached to the outside of the biotite rather than an inclusion.

Table 2: Mineral Composition of Biotite Crystals

	Percent Area of Minerals	
Mineral	Biotite B1	Biotite B2
Biotite	83.34	93.35
Chlorite	0.74	0.00
Albite	12.42	0.00
Magnetite	1.55	5.02
Other	1.95	1.63

Discussion

Because pressure and temperature are uniform for a crystal at a given time, if Al content in hornblende crystals were only controlled by these conditions upon crystallization they would show zones of uniform Al content parallel to planes of growth. The patchy and largely aconcentric Al zoning observed in these hornblende crystals does not match this prediction. It is thus unsurprising that, when pressures are calculated from the point analyses, they reveal a range and distribution of values which are clearly unreasonable. One important feature of the Al in hornblende barometer is that it is not intended to calculate pressures below 2 Kb, and that many of the pressures calculated fall below this mark (Anderson and Smith, 1995). However, independent of this limit it is clear that the aluminum content is not reflecting melt conditions on crystallization. Either pressure and temperature were not the dominant controlling factor in Al content when the crystal formed, or their effects were later masked by other processes.

Hammarstrom and Zen (1986) described hornblende crystals with internal variations but offered little elaboration, beyond their exclusion of crystals of "actinolite riddled with opaques" and which they considered to be "obviously altered." Similarly, Anderson and Smith (1995) described hornblende crystals with patchy zoning which they excluded, though these were universally low in aluminum. However, no criteria which would exclude crystals like those in the Half Dome Granodiorite are given.

The presence of other minerals within the hornblende is also rather unusual. There is very little overarching pattern to the placement of the inclusions. In hornblende crystals 2, 4 and 5 the chlorite/biotite crystals appear to be preferentially aligned parallel to the faces of the hornblende crystal, but this relationship is not seen in 1 or 3. Hornblende 6 seems to show some preferential orientation of biotites parallel to the *c*-axis, with the further detail that most biotites oriented this way are altered to chlorite, whereas non-oriented biotites are largely not. Another notable feature of the inclusions is the alteration which they have obviously undergone. Biotite in particular is widely altered to chlorite, with associated titanite which likely formed to accommodate Ti which chlorite could not. One proposed reaction for this transformation is Bi + 3.23H2O + $0.06H^{+}$ + 0.10Mg2* + $0.l6Fe2^{+}$+ 0.01Mn2+ 0.1ECa2+ = 0.58chl + 0.18Titanite + 0.96H4SiO2 + $0.96K^{+}$ + $0.01Na^{+}$ (Veblen, 1983). However, the examined euhedral biotite phenocrysts which dominate other areas of the Half Dome Granodiorite showed very little chloritization.

Another important feature of the crystals is the range of crystallization conditions that appear to be represented within them. Large euhedral crystals in plutons, including hornblende in the Halfdome Granodiorite, have been interpreted as early crystallization products (Glazner and Johnson, 2013, Bateman and Chappell, 1979). However, many of the hornblende crystals include crystals of potassium feldspar, which has been shown to be a late crystallization product in granodiorites (Glazner and Johnson, 2013). This provides strong evidence that at least some hornblende could not have crystallized early, and suggests that they did not form in a single crystallization event as has been previously modeled.

Hornblende crystals showing either weak or no concentric zoning in Al content as well as numerous mineral inclusions have been reported from the Fish Canyon Tuff in Colorado (Bachmann and Dungan, 2002). When the authors attempted to calculate depths of crystallization using Hammarstrom and Zen's Al barometer the results were deemed unreasonable (Bachmann and Dungan, 2002). However, when these hornblende crystals were reassessed using a modified thermodynamic hornblende geobarometer (Ague, 1997), the results were much more reasonable and consistent.

Conclusions

The results indicate that, in the samples studied, Al content within hornblende is not controlled by pressure and temperature of crystallization. This suggests that use of the Al-hornblende geobarometer on these crystals would yield erroneous results.

Furthermore, the zoning of Al and sheer volume of inclusions in these crystals is unusual. While hornblende crystals from the Half Dome Granodiorite have been briefly described in the literature before (Dodge et al., 1968), there is no published explanation for the heavily and irregularly included nature. The inclusion of traditionally late-crystallizing minerals like quartz and k-feldspar within the phenocrysts is puzzling, but may be explained by an alternate model of pluton formation. For instance, thermal cycling caused by incremental emplacement has been proposed as an alternative explanation for the formation of large K-feldspar phenocrysts elsewhere in the Tuolumne

Intrusive Suite (Glazner and Johnson, 2013). While the data do not require this model it may provide a viable solution.

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