Volatile transfer differentiation of the Gordon Butte magma
northern Crazy Mountains Montana

Laura A. Emmart
The University of Montana

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VOLATILE TRANSFER DIFFERENTIATION OF THE GORDON BUTTE MAGMA,
NORTHERN CRAZY MOUNTAINS, MONTANA

By

Laura A. Emmart
B. A., University of Montana, 1981

presented in partial fulfillment of the requirements
for the degree of

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Chairman, Board of Examiners

Dean, Graduate School

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ABSTRACT

Emmart, Laura A.
Geology

VOLATILE TRANSFER DIFFERENTIATION OF THE GORDON BUTTE MAGMA, NORTHERN CRAZY MOUNTAINS, MONTANA (83 pp.)

Director: Dave Alt

Gordon Butte is a Tertiary shonkinite laccolith in the Crazy Mountain basin of central Montana. The shonkinite is a homogeneous coarse-grained rock containing a high sodium content reflected in the presence of nepheline, primary faujasite and analcite, aegirine-augite, and aegirine. The shonkinite magma intruded the Paleocene Fort Union Formation fenitizing the silty-sandstones into dense, green aegirine-potassium feldspar rocks. The magma contained a high volatile content, rich in both carbon dioxide and water, which influenced the generation of carbon dioxide-rich fenitizing fluids and a magmatic fluid phase rich in water. Fenitization results from the exsolution of an acidic, low pH, carbon dioxide-rich fluid phase enriched in alkalies, ferric iron, and aluminum due to the release of pressure on an ascending magma from upper mantle depths. Carbon dioxide looses solubility and exsolves as a separate phase preceding intrusion of the alkaline rocks. Fenitization as well as the enrichment of select elements toward the top of the laccolith provide evidence for volatile transfer processes and their importance in alkaline magmatic differentiation.
Acknowledgements

I would like to gratefully acknowledge the steady encouragement and guidance my advisors, Dave Alt and Don Hyndman, have shown me. Without their patience and willingness to help, this project would still be at loose-ends. Wayne Van Meter and Keith Osterheld help keep the chemistry within realistic limits and their assistance is much appreciated. Funding for the chemical analyses came from Don Hyndman's University Grant and a grant from Sigma Xi. Ben Munger deserves a medal for putting up with me through the ordeal of this project. And finally, all the effort and concentration this thesis represents is dedicated to my brother Kyle Emmart (November 31, 1951-August 28, 1984), with love.
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INTRODUCTION

Volatile transfer is a process of magmatic differentiation whereby selected elements, typically alkalis, show an affinity for a mobile fluid phase (Rittmann, 1975). The migration of these fluids within the magma produce compositional variations in the resulting rock. Mobile fluids are also capable of exsolving out of the magma, carrying along dissolved alkalis, and producing a metasomatic aureole around the intrusion. Alkali metasomatism, or fenitization, commonly occurs around alkaline silicate intrusions (Lebas, 1977). Thus differentiation of a magma by volatile transfer involves the movement of fluids and associated elements within and possibly out of the magma.

Fluid inclusion studies indicate that carbon dioxide and water are the dominant volatiles active in magmatic fluids (Fyfe and others, 1978, p.35). Carbon dioxide is a major constituent of mantle derived magmas; it not only plays an important role in the petrogenesis of alkaline rocks (Rock, 1976) but has broad implications for the generation of fenitizing fluids from alkalic magmas (Schissel, 1983). Water, on the other hand, plays an important role in transporting the pneumatolytic elements toward the top of the intrusion thus, creating subtle geochemical variation in the rock composition (Rittmann, 1975, Hildreth, 1979).

The activity of the volatiles in the fluid phase depend directly on the specific volatiles' solubility and response to various
temperature and pressure conditions. For example, the solubility of carbon dioxide is only 10-20% that of water in alkaline silicate magmas. At upper mantle conditions a carbonated magma would be close to saturation with respect to carbon dioxide but nowhere near saturation with respect to water. If a mantle derived magma were to intrude near surface conditions, carbon dioxide would lose solubility and exsolve from the magma as a separate fluid phase (Mysen, 1975). This mobile phase would carry along dissolved alkalies and penetrate the surrounding host rock causing fenitization of the border zone. As the intruded magma equilibrates to lower pressure conditions carbon dioxide continues to exsolve from the magma. However, water remains soluble in the magmatic fluid phase. A differentiating magma influenced by a water-bearing fluid would not be very viscous as water would tend to depolymerize the silicate structures. Such a situation would allow fluids to migrate freely toward lower pressure conditions at the top of the intrusion, concentrating selected elements in the upper portions of the intrusion.

In summary, a magma differentiating by volatile transfer depends directly on the specific volatile involved and their response to imposing conditions of solubility, temperature, and pressure.

GENERAL STATEMENT

This is a petrologic and chemical study of the differentiation history of the alkaline magma which formed Gordon Butte, an outlier of the Crazy Mountain igneous complex in central Montana, and the
alteration the Gordon Butte magma imposed on the country rocks during intrusion. Other studies of the Crazy Mountain igneous complex mention the occurrence of alteration aureoles which surround the large Loco Mountain and Big Timber stocks (Weed, 1899, Tappe, 1966) but virtually ignore the implications these aureoles might have had on the evolution of these intrusions.

Although much smaller in size compared to the large stocks in the Crazy Mountains, Gordon Butte has an aureole of fenite. Fluids emanating from the alkaline magma fenitized the surrounding sedimentary rocks of the Fort Union Formation. These fenitizing solutions effectively removed selected elements from the magma.

Previous studies by Wolff (1938) and Larsen and Simms (1972) attribute differentiation of Gordon Butte to the process of crystal fractionation. However, fieldwork documents that neither the base of the laccolith contains an accumulation of 'heavier' mafic minerals, nor does the top of the laccolith contain a dominantly felsic layer. The lack of a felsic top, or syenite cap, would also eliminate the possibility of the Gordon Butte magma differentiating under the process of liquid immiscibility. The rock at Gordon Butte is extremely homogeneous in texture. This pervasive texture together with the presence of fenite cannot be explained by either crystal fractionation or liquid immiscibility differentiation. Other processes must be used to help explain these features observed at Gordon Butte. Both the homogeneous igneous rock and the fenite provide a worthwhile small-scale area for study of volatile transfer differentiation.
GEOLOGIC SETTING

The igneous rocks of the Crazy Mountains are part of a group of isolated igneous centers on the eastern flank of the northern Rocky Mountains (see figure 1). Pirrson (1905) first grouped these isolated igneous mountain ranges into the central Montana petrographic province.

Both Pirsson (1905) and Larsen (1940) consider the isolated igneous centers related with respect to time and space. The numerous igneous centers within the province are divided into subprovinces on the basis of chemical, mineral, and textural similarities. Each subprovince contains mafic and felsic rock types belonging to a chemical series ranging from alkaline to calc-alkaline (Larsen, 1940).

Figure 2 shows Gordon Butte in relation to the other Crazy Mountain intrusions. Wolff (1938), in his thorough study of the igneous rocks in the Crazy Mountain basin, divides the subprovince into two parts, a northern and southern area conveniently separated by the Shields River. The northern area, which includes Gordon Butte, contains numerous alkaline laccoliths, dikes, and sills. However, calc-alkaline rocks in the form of the Loco Mountain stock do occur as well in the northern area. A metamorphic aureole of adinole surrounds the Loco Mountain stock (Larsen and Simms, 1972, Wolff, 1938, Weed, 1899). According to Weed (1899), the adinole consists of a very dense, hard zone of new mineral growth, mostly shale-like, and ranging in color from white porcelain-like to green
Figure 1. The isolated igneous mountain ranges Pirsson (1905) grouped into the central Montana petrographic province.
Figure 2. Crazy Mountains igneous complex, central Montana, modified from Weed, 1899.
and lavender. Weed does not report the exact new minerals.

The southern area contains the calc-alkaline Big Timber stock and associated metamorphic aureole, a prominent radial dike swarm, and an alkaline laccolith called Ibex Mountain (Larsen and Simms, 1972). Tappe (1966) describes the Big Timber stock as cut by a series of dikes ranging in composition from basalt to aplite to andesite. Tappe (1966) also notes that the andesite dikes contain phenocrysts which show strong chemical affinities to the dikes and sills of the northern area.

NOMENCLATURE

The alkaline rocks at Gordon Butte are mafic and contain subequal modes of potassium feldspar and augite. However, nomenclature describing the rock types at Gordon Butte has been a problem. For instance, Pirrson (1905) and Wolff (1938) refer to the rocks at Gordon Butte as theralite, Simms (1966) uses the term malignite, and Dudas (1984) uses basanite.

Wolff (1938) chooses the term theralite from a strict chemical analysis point of view. Wolff's data finds the potash to soda ratio equal to 8/11, which in his opinion most closely approaches the alkali ratio of a theralite \( \frac{K_2O}{Na_2O} = 1/2 \). Wolff mentions the possibility of using the term shonkinite to reflect the presence of orthoclase in the rock. A shonkinite should have an alkali ratio of \( \frac{K_2O}{Na_2O} = 2/1 \), which according to Wolff does not fit his data.

Simms (1966) uses the term malignite, as he feels the term
theralite does not fit the mineralogy of the mafic alkaline rock. According to Simms (1966), a theralite should contain significant plagioclase. Simms uses the term malignite because malignites are half aegirine-augite and contain varying proportions of nepheline and orthoclase in subequal amounts.

The most misleading representation of the potassium feldspar-augite rock at Gordon Butte concerns the term basanite. Basanites are defined to contain calcic plagioclase, clinopyroxene, and a feldspathoid (Bates and Jackson, 1980). The rocks at Gordon Butte are free of calcic plagioclase.

The discrepancy over nomenclature centers around the percentage and ratio of the alkalies contained in the rocks of Gordon Butte. Clearly these rocks contain a high percentage of both sodium and potassium, see Table 1. Using the data from Table 1 to plot the following relationships: $K_2O$ vs $SiO_2$ and $K_2O + Na_2O$ vs $SiO_2$ on figure 3, the rocks at Gordon Butte are alkaline, and dominantly potassium-rich with $K_2O/Na_2O > 0.06$, and therefore shoshonitic according to the criteria of Morrison (1980). Figure 4 is a plot of the alkali data on a ternary An-Ab-Or diagram. This diagram by Irvine and Baragar (1971) confirms that the rocks at Gordon Butte belong to a potassic, and not a sodic, series. Therefore, these mafic potassium feldspar-augite rocks should be referred to as shonkinite. Shonkinite characterizes the mafic alkaline rocks of the other igneous centers within the Montana petrographic province, for instance: in the
TABLE 1. Chemical composition of the rock types of Gordon Butte in weight percent
(Note iron is reported as ferric iron)

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>Fe₂O₃</th>
<th>MnO</th>
<th>TiO₂</th>
<th>P₂O₅</th>
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<tr>
<td>GB-11 Fenitized Chill Zone</td>
<td>55.1</td>
<td>15.2</td>
<td>4.29</td>
<td>2.52</td>
<td>4.41</td>
<td>7.75</td>
<td>5.72</td>
<td>0.24</td>
<td>0.52</td>
<td>0.31</td>
</tr>
<tr>
<td>GB-10 Top Chill Zone</td>
<td>46.1</td>
<td>13.2</td>
<td>9.57</td>
<td>4.75</td>
<td>5.70</td>
<td>4.03</td>
<td>10.10</td>
<td>0.24</td>
<td>1.14</td>
<td>1.50</td>
</tr>
<tr>
<td>GB-9 Vertical Section #5</td>
<td>44.7</td>
<td>13.7</td>
<td>9.08</td>
<td>4.97</td>
<td>6.59</td>
<td>4.50</td>
<td>9.63</td>
<td>0.20</td>
<td>1.01</td>
<td>1.50</td>
</tr>
<tr>
<td>GB-8 #4</td>
<td>46.5</td>
<td>12.5</td>
<td>10.5</td>
<td>6.52</td>
<td>4.01</td>
<td>3.62</td>
<td>8.17</td>
<td>0.14</td>
<td>0.95</td>
<td>1.26</td>
</tr>
<tr>
<td>GB-7 #3</td>
<td>44.1</td>
<td>11.8</td>
<td>11.9</td>
<td>7.43</td>
<td>2.29</td>
<td>3.92</td>
<td>9.34</td>
<td>0.15</td>
<td>0.99</td>
<td>1.49</td>
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<tr>
<td>GB-6 #2</td>
<td>43.4</td>
<td>12.1</td>
<td>11.8</td>
<td>6.49</td>
<td>3.31</td>
<td>4.41</td>
<td>9.10</td>
<td>0.15</td>
<td>0.85</td>
<td>1.83</td>
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<td>GB-5 Vertical Section #1</td>
<td>44.7</td>
<td>13.8</td>
<td>10.8</td>
<td>5.38</td>
<td>4.64</td>
<td>3.35</td>
<td>9.27</td>
<td>0.18</td>
<td>0.92</td>
<td>1.48</td>
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<tr>
<td>GB-4 Bottom Chill Zone</td>
<td>44.8</td>
<td>13.1</td>
<td>9.57</td>
<td>4.80</td>
<td>6.04</td>
<td>3.95</td>
<td>10.45</td>
<td>0.24</td>
<td>1.22</td>
<td>1.56</td>
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<tr>
<td>GB-3 Basal Fort Union Fm.</td>
<td>63.8</td>
<td>15.9</td>
<td>1.29</td>
<td>2.42</td>
<td>2.08</td>
<td>7.42</td>
<td>4.01</td>
<td>3.02</td>
<td>0.53</td>
<td>0.21</td>
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<tr>
<td>GB-2 Unaltered Fort Union</td>
<td>39.2</td>
<td>6.19</td>
<td>26.0</td>
<td>0.71</td>
<td>0.55</td>
<td>2.25</td>
<td>1.51</td>
<td>1.31</td>
<td>0.29</td>
<td>0.14</td>
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<tr>
<td>GB-1 Shonkinite Dike</td>
<td>49.5</td>
<td>13.6</td>
<td>8.06</td>
<td>5.66</td>
<td>5.04</td>
<td>4.01</td>
<td>7.54</td>
<td>0.13</td>
<td>0.90</td>
<td>1.00</td>
</tr>
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X-ray Flourescence analyses by X-ray Assay Laboratories, Don Mills, Ontario
| Sample | Lc | Or | An | Ab | Na | Ac | Dl | Ns | Fo | Fa | En | Wd | Mt | Bl | Ap | No | Q  | C | Co |
|--------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| GB-11  | 38.00  | 0.13  | 12.03  | 17.09  | 12.47  | 7.11  | 0.05  | 2.07  | 0.76  | 0.83  |
| GB-10  | 26.04  | 2.36  | 26.27  | 2.56  | 16.05  | 15.70  | 2.13  | 2.51  | 2.71  | 2.26  | 3.63  |
| GB-9   | Vertical Section 03  | 16.09  | 6.30  | 23.79  | 7.62  | 16.35  | 14.00  | 3.18  | 3.60  | 2.01  | 3.65  | 0.52  |
| GB-8   | 04  | 22.35  | 5.75  | 8.90  | 14.70  | 21.92  | 11.31  | 3.96  | 2.22  | 3.77  | 1.92  | 3.10  |
| GB-7   | 03  | 24.90  | 11.08  | 0.59  | 10.94  | 22.09  | 11.94  | 5.29  | 3.42  | 3.07  | 2.02  | 3.71  |
| GB-6   | 02  | 0.57  | 17.05  | 5.50  | 16.27  | 22.50  | 13.70  | 3.56  | 2.75  | 3.66  | 1.73  | 6.55  |
| GB-5   | Vertical Section 04  | 21.03  | 7.35  | 4.70  | 19.96  | 10.44  | 13.04  | 2.76  | 2.82  | 3.72  | 1.85  | 3.64  |
| GB-4   | Bottom Chill Zone  | 0.05  | 13.14  | 25.50  | 7.51  | 15.90  | 15.60  | 2.70  | 3.45  | 4.75  | 0.50  | 2.71  | 2.82  |
| GB-3   | Basal Fort Union Fa.  | 44.03  | 5.13  | 17.90  | 2.01  | 1.03  | 0.50  | 17.36  | 2.65  | 2.50  |
| GB-2   | Unsterred Fort Union  | 5.60  | 9.04  | 9.93  | 3.22  | 3.10  | 3.73  | 60.69  | 2.79  | 0.70  | 0.61  |
| GB-1   | Shoshinite Dikes  | 26.85  | 2.76  | 17.95  | 14.40  | 17.13  | 9.16  | 3.44  | 2.34  | 3.65  | 1.79  | 2.63  |
Figure 3. Plots of alkalies versus silica for the rocks at Gordon Butte. Included on the diagrams for comparison are plots of alkaline and calc-alkaline series for island arc and continental margin shoshonitic rocks, from Morrison, 1980.
Figure 4. The ternary An-Ab-Or diagram of Irvine and Baragar (1971) shows the rocks at Gordon Butte to belong to a potassic series. Plots in percent cation equivalents.

STRUCTURE

The Crazy Mountain basin is in the southwest corner of the Montana petrographic province. The basin is not only a physiographic depression but a structural basin as well. Structural features to the north of the Crazy Mountain basin include the Castle Mountains, Shawmut Anticline, Battle Ridge Monocline, and the Huntly-Lake Basin Fault Zone, to the west the Bridger Mountains, to the south the Nye-Bowler lineament and Beartooth Range, and to the east the Pryor-Bighorn Uplift (Garrett, 1972) (see figure 5). Structures within the basin presumably result from Laramide compression of fragmented Precambrian crystalline basement. Dominant structural features in the Crazy Mountain basin consist of folds: anticlinal, drape, and en echelon (Garrett, 1972).

Tertiary intrusions occupy the deeper part of the basin (Garrett, 1972). Tappe (1966) suggests the Crazy Mountain intrusions may relate to movement at depth along Lewis and Clark megashears, principally the Lake Basin and Nye-Bowler lineaments. Tappe considers these lineaments as fundamental "master" faults and the
Figure 5. The structural features that bound the Crazy Mountain Basin, modified from Garrett, 1972.
surface expressions of deep seated shear zones. Smith (1965) suggests, like the other centers in the alkaline province, the Crazy Mountain igneous center occupies a region on a tectonically stable craton where the deep seated lineaments intersect.

Emplacement of the Crazy Mountain complex appears coaxial to the basin, the basin axis approximately parallels the Bridger Range (Tappe, 1966). The intrusions are a combination of stocks, laccoliths, dikes, and sills. Stocks and accompanying radial dike swarms typify the southern area of the basin whereas laccoliths and sills dominate the northern area.

In both the northern and southern areas, sills and laccolith intrusions conform to the folded sedimentary strata. Weed (1899) interprets the folding and intrusive events as synchronous. Wolff (1938) notes that the sedimentary strata commonly dip gently inward toward the intrusive bodies. Presumably in such cases the igneous rock intrudes the trough of a synclinal fold, indicating the intrusive events are post folding. The Big Timber and Loco Mountain stocks intrude an anticline in the Fort Union and Livingston formations (Tappe, 1966) and are associated with a strong Bouguer gravity anomaly (Kelly, 1966).

CONTACT RELATIONS

Gordon Butte, the largest and thickest laccolith in the Crazy Mountain complex, stands as a 105 meter thick saucer-like mass (Weed, 1899, Wolff, 1938). The distinctive shape of the butte may
simply involve compaction and dewatering of the softer sediments under the weight of the injected magma. The surrounding sedimentary rocks dip inward toward the center of Gordon Butte at approximately 5-8 degrees.

The feeder dike for Gordon Butte sporadically cropped out southwest of the laccolith. Approximately three kilometers away from Gordon Butte the dike is vertical. About one kilometer from the laccolith, the dip of the feeder dike changes from 90° to 30°, about 100 meters from Gordon Butte it flattens to a dip between 5 and 10 degrees, becoming a sill. Thus the dike rolled-over from a vertical to an almost horizontal orientation before terminating in the laccolith. This rolling-over of the feeder dike into a laccolith is common in other alkaline subprovinces. The Adel Mountains contain similar contact relations between numerous feeder dikes and laccoliths emanating from a central igneous stock (Whiting, 1977).

Topographically below the 105 meter circular laccolith are a series of shonkinite sills, which feather into the surrounding country rock (see figure 6). These sills are in actuality part of the laccolith, making the real thickness of shonkinite approximately 270 meters. However, due to their contact relations and exposure beneath the circular mass of shonkinite they are mapped and referred to as sills. Wolff (1938) describes this contact relation as lit-par-lit injection; Tappe (1966) finds similar contact relations around the Big Timber Stock, which he describes as a cedar tree-like injection.
Figure 6. Schematic diagram of feather-like sill injection. Top diagram may represent the contact relations at Gordon Butte, bottom diagram represents Tappe's (1966) description of cedar tree-like sill injection.
The sills give the appearance of a hummocky apron surrounding Gordon Butte, especially to the northeast where they concentrate. Weed (1899) interpreted the sills as a separate intrusion underneath the circular laccolith. However, the texture and mineralogy remain consistent between the circular mass of shonkinite and the shonkinite sills, indicating the injection of the Gordon Butte magma was one event.
PETROLOGY AT GORDON BUTTE

Three important rock types exist at Gordon Butte: shonkinite, fenite, and the surrounding sedimentary rock of the Fort Union Formation.

Shonkinite.

Table 2 shows the modal mineralogy from samples collected in a vertical section through the top 105 meters of the laccolith. In hand specimen, the shonkinite consistently occurs as a medium to coarse grained augite-potassium feldspar rock, green-black and gray colored respectively. The chill zones are much darker green than the main mass of shonkinite and contain a fine grained groundmass with coarse grained augite phenocrysts. The augite phenocrysts in the chill zones appear oriented in a flow lineation, roughly parallel to the intrusion's basal and top contacts. The bottom chill zone is approximately 1 meter thick, however, the top chill zone is only about 20 centimeters thick.

Approximately 40-45% of the shonkinite is the potassium feldspar sanidine with a low 2V, approximately 15-20° and a negative biaxial sign (Troger, 1979). In hand specimen the anhedral sanidine crystals appear bluish-gray. In thin section, secondary alteration of the sanidine produces natrolite that shows a low birefringence and radiating texture. Natrolite tends to occur in the interstices between other mineral grains enclosed in the anhedral sanidine. Exsolution of very fine grained (<1mm) albite also appears in the
TABLE 2. Modal mineralogy of the shonkinite

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<tr>
<td>Top Chill Zone</td>
<td>25</td>
<td>35</td>
<td>25</td>
<td>3</td>
<td>1-2</td>
<td>5</td>
<td>5</td>
<td>--</td>
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<tr>
<td>Vertical Section #5</td>
<td>40</td>
<td>(included in Au)</td>
<td>40</td>
<td>5</td>
<td>tr.</td>
<td>10</td>
<td>3-4'</td>
<td>1</td>
</tr>
<tr>
<td>#4</td>
<td>30</td>
<td>1</td>
<td>45</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>3</td>
<td>tr.</td>
</tr>
<tr>
<td>#3</td>
<td>25-30</td>
<td>tr.</td>
<td>50</td>
<td>3</td>
<td>15</td>
<td>2</td>
<td>2</td>
<td>tr.</td>
</tr>
<tr>
<td>#2</td>
<td>35</td>
<td>1</td>
<td>40</td>
<td>3</td>
<td>15</td>
<td>3</td>
<td>3</td>
<td>--</td>
</tr>
<tr>
<td>Vertical Section #1</td>
<td>30</td>
<td>(included in Au)</td>
<td>42</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>3</td>
<td>--</td>
</tr>
<tr>
<td>Bottom Chill Zone</td>
<td>20</td>
<td>35</td>
<td>25</td>
<td>5</td>
<td>tr.</td>
<td>10</td>
<td>5</td>
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sanidine, standing at a higher relief than the enclosing sanidine. Texturally the albite can be square-like euhedral grains or graphic intergrowths (see figure 7).

The shonkinite contains on average about 35% augite in euhedral grains that range in size from (1mm - 7mm. In thin section, the coarse augites (3mm - 7mm) generally appear pale green with Z^C measurements equal to 45°. A consistent 2V = 60° and positive biaxial sign indicate that these augites are specifically salite (Troger, 1979), which is the common pyroxene in the petrographic province (Larsen, 1940). The finer grained augites (<1mm - 3mm) are pleochroic with X=dark green and Z=light green. These pyroxenes are positive biaxial minerals that display near parallel extinction and are probably aegirine-augite. The mineralogic replacement of aegirine-augite for augite consists of NaFe^3 going to Ca(Mg,Fe^2+) (Hurlbut and Klein, 1977). Aegirine-augite commonly rims the coarser salite cores (see figure 8). Apart from the distinct color difference, the salite core and aegirine-augite alteration rim exhibit different extinction angles.

The total 35% pyroxene content in the shonkinite also includes aegirine in trace amounts up to about 1% in the main body of shonkinite. In the chill zones aegirine accounts for approximately 15-20% of the total pyroxene content. The aegirine grains occur as (1mm stubby or needle-like crystals. Texturally, all grain sizes of augite and aegirine-augite show strong zoning (see figure 9).
Figure 7. Square-like euhedral texture of albite.

Figure 8. Aegirine-augite rimming salite cores.
Both pyroxenes are commonly poikilitic enclosing very fine grains (<1mm) of biotite, apatite, magnetite, and sanidine. Locally the coarse pyroxene grains exhibit a zone of tiny inclusions surrounding the enclosed minerals mentioned above.

The amount of biotite throughout the laccolith, is approximately 5 percent. However, the size of the biotite grains as well as the degree of oxidation varies considerably from the base of Gordon Butte to the top.

In the chill zones, the biotite grains are very fine, (<1mm, with thick very rusty red oxidation rims. The pleochroic scheme of the unoxidized biotite cores is X=orange-brown and Z=dark red-brown. Many biotite grains are broken or fractured and some are bent (see figure 10). Biotite also commonly rims augite grains in the chill zones.

Adjacent to the chill zones the biotite grains range in size from (<1mm up to 3mm. Toward the center of the laccolith, biotite becomes less oxidized and coarser grained. The coarse biotites are euhedral and pleochroically similar to the unoxidized biotite cores in the chill zones. These coarse (3mm) grains of biotite are poikilitic and enclose sanidine, magnetite, apatite and rarely very fine grained augites.

Primary faujasite, a sodium-calcium zeolite, accounts for up to 15% of the shonkinite depending on position in the vertical section. The faujasite occurs primarily in the lower half of the laccolith and appears to have suffered severe secondary alteration to "grunge".
Figure 9. Strong zoning in an augite phenocryst.

Figure 10. Bent biotite grain in the chill zone.
Optical determination is confirmed by the distinct euhedral shape, fine grained nature (<1mm), and isotropic property in polarized light. Wolff (1938) described this isotropic mineral as sodalite but electron microprobe analysis reveals both calcium and sodium, thus the mineral can not be sodalite. Figure 11 is a photomicrograph of faujasite enclosed in anhedral sanidine.

Apatite makes up approximately 3-4% of the shonkinite. The grains are typically euhedral and occur individually as well as in aggregates. The apatite can range in size from <1mm to 5mm, some of the coarse grains could almost qualify as phenocrysts.

In addition to the common accessories magnetite and sphene, the shonkinite contains two sodium-rich minerals: nepheline and analcite. Nepheline makes up about 5% of the rock and analcite typically less than 1%. Both are anhedral, and commonly enclosed in larger sanidine grains. The nepheline grains are distinguished from the sanidine by a negative uniaxial sign and typical secondary alteration to natrolite. Analcite is isotropic and displays negative relief when compared to sanidine in plane light. Analcite appears relatively unaffected by secondary alteration. Very fine grains of hematite which presumably altered from primary magnetite are commonly enclosed in the analcite.

Figure 12 shows a textural feature of the shonkinite. These dominantly felsic patches in the shonkinite consist of approximately 80% potassium feldspar, 10% augite, 5% biotite, 2% faujasite, 1% each
Figure II. Faujasite enclosed in anhedral sanidine, faujasite altered to "grunge".
Figure 12. Felsic patches that locally occur in the shonkinite, note the mafic selvages at the felsic patch boundary.
Aegirine, apatite, and magnetite. The potassium feldspar is very coarse grained, locally almost pegmatitic, and shows a perthitic texture. The texture of the patches could represent areas of volatile accumulation during the final stages of crystallization, or may be evidence of incipient immiscible separations of syenite from shonkinite. These felsic segregations are commonly surrounded by mafic selvages of very coarse grained biotite and augite. Thus the argument for volatile accumulation appears more realistic.

The feeder dike for Gordon Butte is well exposed and contains mafic pyroxenite xenoliths, which range from 2 to 6 centimeters in maximum dimension and are subangular to well rounded. Elongate xenoliths have their long axes roughly parallel to a flow lineation defined by coarse grained augite phenocrysts (see figure 13).

The pyroxenite xenoliths contain ~87% diopsidic augite, 5-8% apatite, 3-5% biotite, and 1-2% magnetite. The xenoliths are rimmed by biotite and locally aegirine. The diopsidic augites have a 2V ~ 55-60°; they are anhedral and pleochroically very light green=X and tannish-green=Z. Aegirine alteration rims, as well as zoning, are absent in the xenolith clinopyroxenes. The apatite appears as sub to euhedral (1mm - 1mm grains interstitial to the augite. Biotite occurs as subhedral to euhedral grains with pleochroism as X=tan-brown and Z= dark brown. The biotite rarely encloses magnetite and pyroxene. The overall texture does not appear cumulate (see figure 14).
Figure 13. Pyroxenite xenoliths in the feeder dike.

Figure 14. Texture of a pyroxenite xenolith in the feeder dike, xenolith rimmed by biotite.
The shonkinite in the feeder dike is similar to that of the laccolith except in containing 2-3% olivine phenocrysts. The olivine has a 2V ~ 85-90°, a positive biaxial sign, and parallel extinction. The olivine in the dike shonkinite occurs without rims of pyroxene, whereas the trace amount of olivine observed in the basal chill zone of the laccolith shows olivine cores rimmed by pyroxene.

Figure 15 shows pyroxenite xenoliths within the laccolith; these xenoliths are the only pyroxenite found at Gordon Butte and most likely were included in the shonkinite magma during ascent from depth. This peculiar shonkinite spotted with xenoliths occurs mainly in the lower half of Gordon Butte and locally toward the top of the intrusion. The xenoliths in the laccolith lack the sharp boundaries and biotite rims that typify the dike xenoliths. They are mere augite-rich concentrations apparently caught by crystallization before they fully equilibrated with the magma. Mafic augite-rich concentrations nowhere accumulate within the laccolith, but remain separated.

**Fenite**

Two types of fenite exist at Gordon Butte: fenitized country rock and fenitized chill zone (top chill zone). Both are very dense aegirine-potassium feldspar rocks, green and whitish gray in color. The types differ in grain size, texture, and mineral composition.

The fenitized country rock previously belonged to the Fort Union Formation. The sediments are fenitized into extremely fine grained,
Figure 15. Pyroxenite xenoliths in the laccolith, biotite rims are lacking.
green fenites. Rarely these fenites show relict bedding (see figure 16). However, the majority of the fenitized country rocks have undergone complete metasomatism with recrystallization destroying any relict bedding features. The principal texture of these fenites include green and white layers around felsic segregations and individual felsic grains (see figure 16).

In thin section the fenitized country rock is so fine grained that optical determination of the minerals is difficult. However, individual and aggregates of euhedral stubby aegirine grains (<1mm) commonly occur with altered calcite and tiny patches (<.5mm) of anhedral potassium feldspar. In hand specimen, particularly in the fenite samples with the layered texture, an iron oxide weathering stain appears to be associated with the white felsic segregations. In thin section, the felsic areas are seen to contain 2-3% magnetite.

The fenitized chill zone contains 30% very fine grained aegirine, both stubby and needle-like grains, which show near parallel extinction and are biaxially negative. The needles appear as discrete grains, in bundles, or in radial mats (see figure 17). Stubby aegirine grains also appear as discrete grains or in aggregates.

Approximately 65% of the fenitized chill zone contains a medium to coarse (3mm - 7cm) grained potassium feldspar. Sanidine is the dominant feldspar, ranging in size from 3mm to 5mm. The sanidine grains are anhedral and commonly show sericitic alteration.
Figure 16. Relict bedding preserved in the fenite (top photograph), layered texture in the fenite (bottom photograph).
Figure 17. Radial mat of aegirine needles in fenite.
Orthoclase is the other potassium feldspar in the fenitized shonkinite, optically distinguished from the sanidine by a $2V \sim 70^\circ$. The orthoclase occurs as extremely coarse grains up to 7 cm across, and also in medium grains 3 mm - 5 mm across. The very coarse orthoclase is perthitic and commonly observed in comb structure; the orthoclase grains apparently grew perpendicular to fractures filled with fenitizing fluids (see figure 18). The medium grained orthoclase appears as intergrown laths that commonly show twinning.

The remaining 5% of the fenitized chill zone contains fine grained (<1 mm - 3 mm) euhedral magnetite (3-5%), and trace amounts of very coarse (5 mm) biotite and apatite grains. Augite rarely occurs, appearing as "skeleton" grains that retain no optical properties. The skeletal augites are replaced by magnetite with aegirine needles clustering around the crystal boundary of each augite. In addition to their ghost-like appearance, the augites are quite deformed (see figure 19).

In most of the fenitized chill zone sampled, the fenite appears to be bounded by shonkinite. In these adjacent shonkinite zones protoclasis of augite and biotite grains occur. The photomicrograph in figure 20 shows fractured augite grains annealed by aegirine-augite. Textures such as this as well as deformed biotites may attest to the movement of fluids within the laccolith.

**Fort Union Formation**

The Fort Union Formation surrounds and formerly enclosed Gordon Butte. Weed (1899) describes the Fort Union as predominantly clay-
Figure 18. Comb-structure produced by fenite veins (or fractures) within the shonkinite.
Figure 19. Deformed augite in contact with a radial mat of aegirine.

Figure 20. Fractured augite grains, annealed by aegirine-augite.
rich sediments interbedded with cross-bedded, crumbly sandstones and local impure limestone lenses. Wolff (1938) later commented that the Fort Union contains massive sandstone beds near the base of the formation with shales above. Wolff also noted the rare thin interbeds of limestone. Sims (1964) however, working specifically on the petrology of the Fort Union, described the type section of the formation as a series of drab, mostly thin bedded silty sandstones with occasional lenses of limestone. The average sandstone, according to Sims (1964), contains medium to fine-grained quartz and feldspar grains which are subangular to subrounded and cemented with carbonate. These silty sandstones contain very little clay sized material or clay minerals.

The Fort Union Formation surrounding Gordon Butte most closely resembles Sims' (1964) description. The sedimentary rock is a very silty sandstone: fine to medium grained quartz, feldspar, and magnetite, massive, light gray on a fresh surface but deep brown on a weathered surface, and cemented with carbonate. Rarely interbedded with the silty sandstones are 25-50 cm thick, medium grained, light tan, crumbly lenses quartzofeldspathic sandstone. These sandstones contain biotite, magnetite, and up to 25% lithic fragments.

In the drainage cutting Gordon Butte (section 27, T 8 N, R 11 E) the basal contact between the top 105 meters of the shonkinite and the Fort Union sediments is well exposed showing a bottom chill zone approximately one meter thick (see figure 21). The baked sedimentary
Figure 21. Basal contact between the top 105 meters of shonkinite and the Fort Union Formation sediments.
rock (.5m thick) is very hard and appears bleached or buff-tan in color on a weathered surface. On a fresh surface however, the rock is dominantly green with white feldspar grains (1mm). In thin section, approximately 30% of fine grained aegirine is visible giving the contact rock the green color. The rest of the rock is (1mm) grains of quartz, feldspar, and magnetite.

The presence of the Fort Union sandstones were important in mapping the sill contacts that surround the main laccolith body of Gordon Butte. Figure 22 shows in cross-section the contact relations observed when walking down and away from the cliffs of shonkinite, which form the laccolith rim, into a series of stairstep-like hummocks. As drawn in the figure, the rock types encountered are shonkinite (laccolith), sandstone, fenite, shonkinite (sill), sandstone, fenite, shonkinite (sill), and finally sandstone. (Note that, as described under the heading of Contact Relations, the sills of shonkinite should be considered as part of laccolith).
Figure 22. Schematic diagram of the stairstep-like hummocks surrounding Gordon Butte (not to scale).
CHEMISTRY

Eleven samples were collected at Gordon Butte for major element chemical analysis; analyses by X-ray Assay Laboratories, Don Mills, Ontario, see plate 1 for sample locations and Table 1 for the analyses. Ten of these samples were collected to represent a vertical section that begins in the unaltered country rock, passes up through the laccolith, and includes the fenite which caps the igneous rock.

Figure 23 represents the vertical section in major element cation percent for aluminum, sodium, potassium, ferric iron (not as total iron), calcium, and magnesium. Within the shonkinite, potassium, ferric iron, and aluminum remain relatively constant. Magnesium and calcium both increase to section #3 then gradually decrease to a lesser percent in section #5 and the top chill zone. Sodium is high in the bottom chill zone, drops to a low in section #3, sharply increases until section #5, only to decrease again in the top chill zone.

Several relationships may explain the patterns listed above. The magma was undersaturated, containing an average of 44% silicon in cation percent. Ionic substitution must have occurred with aluminum filling sites usually occupied by silicon in the silica tetrahedron. The substitution of aluminum for silicon generates a negative charge, compensated for by available potassium ions. The affinity of aluminum and potassium would not only aid the
Figure 23. Whole-rock chemical analyses in cation percent for the vertical section at Gordon Butte.
crystallization of sanidine but biotite as well. Note that in figure 24 these cations have similar patterns throughout the vertical section.

Aluminum and potassium both increase markedly across the contact between the top chill zone and the fenite zone. The fenite zone contains approximately 15% more potassium feldspar than the shonkinite. Metasomatic fenitizing solutions appear to have enriched the fenite in these two elements.

Another relationship exists in the shonkinite between the behavior of the divalent ions, calcium and magnesium, and the monovalent sodium ion. The alteration of augite to aegirine-augite along the rims of the phenocrysts presents a plausible explanation for the patterns of calcium, magnesium, and sodium. Aegirine-augite is part of the solid solution series between aegirine (NaFe+3) and augite (Ca(Mg,Fe+2)). Ionic substitution of sodium and ferric iron into the crystal lattice for calcium and magnesium would alter the chemical composition of the rock. Ferric iron would not necessarily have to be added to the crystal lattice from the melt because ferrous iron already in the lattice could be oxidized. However, electron microprobe data on five augite phenocrysts with aegirine-augite rims indicates the total iron content (in cation percent) increases from an average of 5% in the augite cores to as high as 18% in the altered rims. These data show iron was probably added to the crystal lattice during aegirine alteration.
Figure 24. Microprobe data in cation percent for an augite phenocryst in the dike shonkinite; included for comparison is the particular cation percent value for each element represented from the clinopyroxene in the xenolith, plotted as open triangle.
The degree of aegirine alteration corresponds nicely to the patterns observed for calcium, magnesium, and sodium, although not for ferric iron. The cation percent for calcium and magnesium are highest in section #3, which contains only trace amounts of aegirine alteration rims on the augite phenocrysts. Compare figure 23 to the modes reported for the vertical section in Table 2.

Six thin sections were selected for microprobe analysis: a sample of the dike shonkinite with a pyroxenite xenolith, the bottom chill zone, section #1, section #4, section #5, and a fenitized shonkinite. These six thin sections contain zoned augite phenocrysts. Appendix A contains the microprobe results.

Figure 24 graphs the percent of sodium, calcium, magnesium, total iron, aluminium, and titanium cations per 24 oxygens in a zoned augite phenocryst from the dike shonkinite. Probing of the augite phenocryst included the outer aegirine alteration rim, two successively concentric inner zones, and the augite core. Also plotted on figure 24 is the probe data for the clinopyroxene in the pyroxenite xenolith for comparison between the compositions of the xenolith clinopyroxene and the core of the augite in the shonkinite.

The core of the augite phenocryst shows a similar composition to that of the xenolith clinopyroxene for the elements magnesium, sodium, total iron, and calcium. Both aluminium and titanium are slightly higher in the core of the shonkinitic augite compared to the xenolith clinopyroxene. The aegirine alteration rim on the augite
phenocryst shows enrichment in sodium, total iron, and titanium. The aegirine rim is depleted in magnesium, calcium, and aluminium.

The data show that the augite phenocrysts in the shonkinite were in equilibrium with and probably originated from the same magma that crystallized the clinopyroxenes found in the xenolith. The cores of the augite phenocrysts are essentially the same composition as the clinopyroxene cores.

Figure 25 graphs the cation percent data obtained from probing five augite phenocrysts. The five augites represent phenocrysts in the dike shonkinite, the bottom chill zone, and vertical section #1, #4, and #5. Probe data was obtained from the aegirine alteration rim and the core of each of the five augite phenocrysts.

The following observations can be made from the graphs in figure 25. The sodium and total iron content in the aegirine alteration rims are greatest in the dike samples. The amount of sodium and iron decreases in the aegirine rims with increased height in the vertical section. Conversely, calcium and magnesium contents are greatest in the aegirine rims of section #5, which is close to the top of the laccolith. Aluminum behaves erratically and no general trends can be recognized. The cores of all the augites show low total iron and sodium contents, and high calcium and magnesium contents.

As in the whole-rock analyses, there exists a relationship between the behavior of the calcium and magnesium ions and the sodium and iron ions. The aegirine-augite rims in the upper part of the
Figure 25. Microprobe data from five augite phenocrysts, in cation percent. (D-dike, BCZ-bottom chill zone, VS-vertical section)
laccolith contain more calcium and magnesium than the successively lower vertical sections. While the alteration rim content of sodium and iron show the exact reverse trends, ie: much higher sodium and iron in the bottom sections and lower values for successively higher sections. The augite cores, regardless of position in the vertical section, contain similar compositions for each respective individual ion represented.

In summary, the chemical analyses of Gordon Butte show a variation in composition from the bottom of the laccolith to the top. Certain elements, most noticeably sodium, appear to have been quite mobile in the shonkinitic magma. The mobility of elements within a magma requires a medium, most likely an active volatile phase, to effectively transport the elements and penetrate the entire intrusive body.
NATURE OF VOLATILE TRANSFER

The preceding descriptions and chemical analyses of Gordon Butte indicate subtle differentiation. Previous studies (Wolff, 1938, Larsen and Simms, 1972) describe differentiation at Gordon Butte as resulting from crystal settling. However, the shonkinite lacks the distinctive textural features that accompany the differentiation process of crystal fractionation. Except for the occurrence of the felsic patches, described in the previous section, the shonkinite lacks the diagnostic syenite cap that may infer liquid immiscibility differentiation. Instead, the texturally uniform but compositionally varied shonkinite appears to have evolved through volatile transfer.

Differentiation of a magma by volatile transfer is not as well documented as the processes of crystal fractionation or liquid immiscibility because of a shortage of related experimental data. Empirical studies indicate gaseous transfer of volatiles commonly carrying alkali and other constituents upward in, and ultimately out of, the magma may be an important cause of the variation in chemical composition of igneous bodies (Hyndman, 1985, p.397). Although volatile transfer is considered an acceptable means of differentiation, this process is typically associated with late, highly evolved, residual magmatic events such as hydrothermal fluid generation or second boiling phenomena.

Numerous features at and around Gordon Butte suggest the magma contained a high volatile content. These features include fenite and
a uniformly coarse-grained shonkinite containing primary hydrous minerals, strongly zoned pyroxene phenocrysts, and pyroxenite xenoliths. The xenoliths may be the result of high vapor pressures; a high volatile content may act as a propellant for rapid ascent of an alkaline magma from upper mantle depths carrying with it ultramafic and pyroxenite nodules (Mysen, 1975). Clearly the features listed above indicate the activity of volatiles in the Gordon Butte magma was neither exclusively early nor late, but perhaps a combination of both.

Fenite capping the laccolith, feeder dike, and individual sills is the strongest field evidence of a parent magma rich in volatiles and an "early" volatile transfer event. Fenitization typically occurs around alkalic complexes. Lebas (1977) and Robins and Tysseland (1979) attribute it to a dense, penetrating fluid phase rich in carbon dioxide, alkalies, ferric iron, and aluminum that precedes intrusion of the alkaline magma.

A magma which crystallizes shonkinite contains essentially a basaltic composition. However, a shonkinite with up to 20% hydrous minerals must have remained high in volatiles even after generation of fenitizing solutions. In addition, the abundant zoned pyroxene phenocrysts indicate that the chemical composition of the magma was in a state of flux. Thus, a mental picture of differentiation by volatile transfer at Gordon Butte must include an "early" fenitization event accompanied by a "later" high volatile influence on mineral composition and texture.
Table 3 lists the mineral composition of the shonkinite and indicates the volatile phase contained water and phosphate. Although not obvious from the mineral composition, carbon dioxide was also presumably present. Carbon dioxide as a volatile component is inferred from the association of the mantle as a source for alkaline magma. Under mantle temperatures and pressures alkaline magmas are characteristically saturated with carbon dioxide (Rock, 1976). There is a general consensus in the current literature that carbon dioxide plays an important role in the origin and differentiation of alkaline intrusions.

The solubility of carbon dioxide in alkaline silicate melts increases with increasing pressure and temperature (Mysen, 1975). Mysen (1975) argued that a low degree of polymerization in the melt tends to increase the solubility of carbon dioxide. Mysen (1975) found that at upper mantle conditions carbon dioxide is stored in ultrabasic melts as carbon dioxide molecules and carbonate anions. Using quenched silicate liquids and infra-red spectrometric techniques Mysen (1975) observed that a diopsidic melt contains 34-44% more soluble carbon dioxide than a jadeitic melt; apparently because the diopsidic melt is much less polymerized than its jadeitic counterpart. Albite melts were found to dissolve only a minor carbonate anion component. However, the addition of water to the albite melt essentially depolymerized the silicate structure and
Table 3. Mineral composition of the Shonkinite

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<tr>
<td>Augite</td>
<td>$(\text{Ca,Na})(\text{Mg,Fe,Al})(\text{Si,Al})_2\text{O}_6$</td>
<td></td>
</tr>
<tr>
<td>Aegirine-augite</td>
<td>$(\text{Na,Ca})(\text{Fe}^{+3},\text{Fe}^{+2}\text{-Mg,Al})\text{Si}_2\text{O}_6$</td>
<td></td>
</tr>
<tr>
<td>Aegirine</td>
<td>$\text{NaFe}^{+3}\text{Si}_2\text{O}_6$</td>
<td></td>
</tr>
<tr>
<td>Sanidine</td>
<td>$\text{KAlSi}_3\text{O}_8$</td>
<td></td>
</tr>
<tr>
<td>Biotite</td>
<td>$\text{K(Mg,Fe)}_3(\text{Al, Si}<em>3\text{O}</em>{10})(\text{OH})_2$</td>
<td>$\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Nepheline</td>
<td>$(\text{Na,K})\text{AlSi}_2\text{O}_4$</td>
<td></td>
</tr>
<tr>
<td>Faujasite</td>
<td>$(\text{Na}<em>{2.1},\text{Ca})<em>1.75\text{Al}</em>{3.5}\text{Si}</em>{8.5}\text{O}_{24} \cdot 16\text{H}_2\text{O}$</td>
<td>$\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Analcite</td>
<td>$\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$</td>
<td>$\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Apatite</td>
<td>$\text{Ca}_5(\text{PO}_4)_3(\text{F,Cl,OH})$</td>
<td>$\text{PO}_4^{-3}$</td>
</tr>
<tr>
<td>Magnetite</td>
<td>$\text{Fe}_3\text{O}_4$</td>
<td></td>
</tr>
<tr>
<td>Sphene</td>
<td>$\text{CaTiO(Si}_4\text{)}$</td>
<td></td>
</tr>
</tbody>
</table>
promoted stabilization of the carbonate anion.

Solubility of water in alkaline silicate melts apparently does not depend on the bulk composition of the melt. Presumably then, water and carbon dioxide operate under different solubility mechanisms (Mysen, 1975). This difference in the solubility of carbon dioxide and water may provide the means to generate a separate super-critical fluid phase during intrusion of an alkaline magma.

Fyfe and others (1978, p.60) report that, above upper mantle pressures and temperatures carbon dioxide-water mixtures exist as a single-phase super-critical fluid. Apparently below these pressure and temperature conditions a density inversion of the single phase carbon dioxide-water occurs. Carbon dioxide inverts from a dense phase at high pressures to a lighter phase at low pressures. This inversion may also influence the phase separation of carbon dioxide and water.

Mysen's (1975) work on the solubility of carbon dioxide in separate studies of albite, nepheline, and jadeite melts found that at pressures of 20kb the weight percent of soluble carbon dioxide could be as high as 2-3 wt.% but as pressures drop to 5kb the solubility of carbon dioxide drops to less than 1 wt.% Mysen suggests that the relatively small solubility of carbon dioxide in silicate melts as compared with water provides the means of generating a separate fluid phase during magmatic evolution in the upper mantle. For instance, 0.2 wt.% soluble carbon dioxide in the
source region of a basaltic melt at 15-20kb can saturate 10% partial melt. Even if the initial melt is under-saturated in carbon dioxide, the strong positive pressure and temperature dependence of carbon dioxide may lead to saturation during cooling or decompression of the magma, or both (Mysen, 1975). Figure 26 schematically represents the generation of a separate carbon dioxide-rich fluid phase with magmatic ascent, assuming a melt saturated with carbon dioxide.

**COMPOSITION OF THE EARLY FLUID PHASE**

The composition of the early volatile fenitizing solutions is not well understood (Lebas, 1977). The solutions must consist primarily of carbon dioxide if fenitization is related to early exsolution of a carbon dioxide-rich fluid (Schissel, 1983). Since the shonkinite magma was basic in composition and contained water, as evidenced by hydrous minerals, presumably the exsolved fluid phase contained both carbon dioxide and carbonate anions. Although Mysen's (1975) experimental work does not report the presence of bicarbonate in the exsolved fluid phase, it seems reasonable to infer its presence, as

\[
\text{CO}_2 + \text{CO}_3^{-2} + \text{H}_2\text{O} \rightarrow 2\text{HCO}_3^{-1}.
\]

Fenitizing solutions carry metal ions such as ferric iron. Assuming ferric iron will be dissolved in these solutions, a slightly acidic pH is required.

Fenitizing solutions possess considerable solvent abilities, which, according to Krauskopf (1979, p.617) is characteristic of
Figure 26. Weight percent solubility of carbon dioxide in albite melt at 1450°C (Mysen, 1975), contrasted with water solubility in albite melt at 1000°C (Burnham, 1975) shows exsolution of carbon dioxide fluid phase with pressure decrease, from Schissel, 1983.
super-critical fluids at high confining pressures. Common elements soluble in these solutions include sodium, potassium, ferric iron, aluminum, and the minor element barium. Hildreth (1979) showed that dissolved volatiles in a fluid enhance cation mobility, both through complexing and increasing cation solubility.

Schissel (1983) looking at fenitization around an alkali-feldspar syenite in the Haines Point Alkaline Complex of northwestern Montana, suggests carbonate complexing is responsible for mobilization of the elements sodium, potassium, ferric iron, and aluminum in fenitizing solutions. Schissel explains that complexing between both aluminum and ferric iron with the carbonate anion would shift the equilibrium constant toward greater solubility of these metal ions in the fluid. These carbonate complexes would then require monovalent ions such as sodium and potassium to move with the solutions to maintain electrical neutrality. Dissociation of these complexes with precipitation of the metal ions in the fenite zone would result from decreasing partial pressures of carbon dioxide as the solutions penetrate the country rock.

Carbonate complexing implies specific conditions in the volatile phase that were not necessarily present in the Gordon Butte magma. Complexing requires a high concentration of the complexing agent be present in the fluid phase, that is, the carbonate anion, aluminum, and ferric iron cations. There will only be a high concentration of the carbonate anion in the fluid phase if conditions are quite basic such as pH equal to 8.3 at 25°C and 1 atm (Clifford, 1961, p.210).
However, as discussed above, if the magma contained both discrete carbon dioxide as well as water, the original super-critical carbon dioxide-water fluid phase was most likely slightly acidic because of the reaction:

\[ \text{CO}_2 + \text{CO}_3^{-2} + \text{H}_2\text{O} \rightarrow 2\text{HCO}_3^{-1} . \]

Solutions containing dissolved carbon dioxide alone are considered acidic.

Assuming that upon emplacement of a carbon dioxide-water rich magma from depth and subsequent pressure release, an acidic carbon dioxide fluid phase exsolves. Thus, the acidic conditions of the fluid are all that is necessary to mobilize elements like sodium, potassium, aluminum, and ferric iron; carbonate complexing is not a prerequisite for their mobilization. Once the fenitizing solutions lose the partial pressure required to keep carbon dioxide dissolved in the fluid, dissociation of the carbon dioxide-rich fluid follows.

The sediments of the Fort Union Formation in the fenite zone were originally quite calcareous. However, fenitization did not produce any metasomatic carbonate minerals. This observation favors slightly acidic fenitizing solutions. Bicarbonate would certainly inhibit the formation of metasomatic carbonate minerals.

Experimental work shows that at 25° and 1 atm bicarbonate solutions are quite basic (Clifford, 1961, p. 210). Such solutions would be expected to produce carbonate minerals. However, precipitation of carbonate minerals from bicarbonate solutions
requires water to be present in the system, such that the following reaction occurs:

\[ \text{HCO}_3^- + \text{H}_2\text{O} = \text{H}_2\text{CO}_3 + \text{OH}^- . \]

This hydration reaction develops a pH equal to 8.3. The carbonic acid product occurs essentially as water and carbon dioxide. Clifford (1961, p.150) explains that less than 1% of carbonic acid is actually present in an aqueous solution of carbon dioxide.

At Gordon Butte, metasomatic mineral growth in the fenite zone does not form any hydrous minerals. Perhaps the fenitizing solutions were either anhydrous or, more likely, contained a low concentration of water. Aqueous solutions of carbon dioxide do not crystallize carbonate minerals, because of the acidic pH of the solution (Clifford, 1961, p.151).

**COMPOSITION OF THE WATER-RICH FLUID PHASE**

Figure 26 indicates that the solubility of water in silicate melts remains fairly constant with changes in pressure. During intrusion, and after generation of the fenitizing solutions, a supercritical fluid phase containing water would have remained dissolved in the magma. Enough water remains to influence the mobility of certain elements toward the top of the laccolith, thus affecting the type of minerals crystallized and the texture of the resulting rock.

Texturally, fractures appear in the shonkinite near the top of the laccolith that are composed exclusively of fenite which suggests two inferences: (1) that some carbon dioxide remained dissolved in
the water-bearing magmatic fluid phase, and (2) that the generation of fenitizing solutions continues after emplacement of the magma (see figure 27).

Elements showing the greatest mobility in the magma include sodium, niobium, zirconium, and barium. These elements show enrichment toward the top of the laccolith, and for barium enrichment in the fenite cap rock. The water bearing volatile phase functions quite effectively as the means of transporting soluble elements within the laccolith.

Water is the dominant solvent, the dominant chemical transport agent, and the dominant silicate-reaction catalyst (Fyfe and others, 1978, p.47). Water is one of the best solvents for inorganic materials because the electrical charge on a water molecule is asymmetric. One side of the central oxygen carries the hydrogen atoms and a net positive charge, the other side carries the lone pair, or non-bonded, electrons of the oxygen thus generating a net negative charge. The asymmetrical arrangement of the charge explains the water molecules' ability to solvate both negative and positive ions in solution. The charge arrangement of the strong hydrogen bonds also explains the association of water molecules with each other in the fluid phase. Above the critical point for water the degree of association decreases.

Fyfe and others (1978, p.25) report that if water pressure equals lithostatic pressure, water may be expected to dissociate
Figure 27. Fractures in the upper part of the laccolith that contain fenite and comb-structure texture.
increasingly with depth. The dissociation constant for water ($10^{-14}$) at room temperature can change to values near $10^{-6}$ at temperatures occurring at the base of the crust, thus the 'neutral' pH will also change with depth. Krauskopf (1979) contends that regardless of temperature, pH depends on the amount of acid supplied to the system and the dissociation constants of the acids present.

The pH of the fluid phase becomes important in volatile transfer. The fluid phase should maintain a slightly acidic pH as the confining pressure keeps carbon dioxide in solution. During emplacement of the magma the confining pressure decreases which triggers the exsolution of the fenitizing solutions. However, not all of the carbon dioxide exsolves at once. The remaining carbon dioxide continues to exsolve as the magma equilibrates to the new, lower pressure conditions. As long as soluble carbon dioxide exists in the water phase in the magma, acidic conditions should persist.

Since related experimental work on both volatile transfer and fenitization is severely lacking, the conditions of pH can only be inferred from the mineral composition and textural relationships in the rock.

PRESSURE AND TEMPERATURE CONSTRAINTS OF VOLATILE TRANSFER

Although the exact pressure conditions that influenced the solidification of the Gordon Butte magma are difficult to ascertain, the magma probably solidified under very low pressures of less than 1kb. The magma that formed Gordon Butte apparently intruded the
lower part of the Tongue River Member of the Fort Union Formation (Simms, 1966). The Tongue River Member, also referred to as the Melville Formation of the Fort Union Group (Fields, 1957), is the youngest member of the Fort Union. Because the Tongue River Member is approximately 250 meters thick (Ballard and others, 1983), and no younger sediments were deposited before emplacement of the laccolith, the pressure imposed on the intruded magma was less than 1kb. (Using an average density of 2.2 g/cm³ and an average thickness of 250 meters the pressure imposed on the magma was approximately 863 bars.)

The temperature of volatile transfer in the Gordon Butte magma was presumably near molten magmatic temperatures, in order that fluid migration involving large amounts of constituents exist. The presence of certain minerals over others in both the fenite and shonkinite help delineate the temperature boundaries of volatile transfer. Not only are the stability limits of the individual minerals important but the presence of volatiles will also effect the temperature of differentiation.

\[ P_{total} = P_{water} + P_{carbon dioxide} + \text{the Por any other fluids} \]

so that when \( P_{total} \) is greater than the Por any one fluid constituent the reaction boundaries must be modified. Hyndman (1985, p.530) suggests when the mole fraction of water in a fluid phase is 0.5, or half the load pressure, the temperature of a reaction boundary is approximately that at half of load pressure. Extrapolating from this simple approximation and assuming the \( P_{water} \)
M E C H A N I C S  O F  V O L A T I L E  T R A N S F E R

The actual movement of volatiles and dissolved components is not well understood. Advocates of gaseous or volatile transfer describe the 'mechanics' of the process as simply the rise of a volatile phase toward the top of the intrusion or magma chamber. Rittmann (1975) favors the argument of the pneumatolytic elements (e.g.: sodium, iron, manganese, titanium, zirconium, niobium) dissolving into the gas phase at high pressures and rising toward the surface in bubbles. At lower pressures the bubbles become oversaturated and release the excess dissolved elements thus altering the composition of the surrounding melt. Hildreth (1979) instead notes that in the rhyolite–dacite rocks of the Bishop Tuff the light volatiles (water
with dissolved lithium, beryllium, sodium, niobium) follow silica toward the top of the magma chamber. The heavier elements (potassium, magnesium, calcium, iron, strontium, barium) concentrate in the lower part of the chamber.

At Gordon Butte, volatile transfer was the dominant differentiation process which caused the following enrichment patterns: sodium, zirconium, niobium, barium, and strontium show strong enrichment toward the top of the laccolith; ferric iron, aluminum, and potassium show only a slight upward enrichment, and calcium and magnesium are enriched in the center of the laccolith but show depletion at the top (see figure 28 and refer to figure 23). Apparently the enrichment patterns in the shonkinite do not correspond to either Rittmann or Hildreth’s predicted models. Perhaps the activity or interaction of both fenitizing carbon dioxide-rich fluids as well as magmatic water-rich fluids created the varied enrichment pattern observed in the shonkinite.

Orville’s (1963) studies of feldspars at 2kb and 400-800°C show sodium to be extremely soluble in water, much more so than potassium. This situation does not require large volumes of alkalies to be present in solution, but only that diffusion of sodium and potassium ions take place through a pervasive vapor phase. The reservoir of sodium and potassium ions necessary for volatile transfer may exist in the silicate phase (Orville, 1963).

The silicate phase, or melt structure, must be a reservoir for
Figure 26. Minor element concentration, in ppm.
all the elements involved in volatile transfer. To what extent a particular metal ion is present in the fluid phase is a function of its interaction with the fluid. Addition of any metal ion to the fluid phase will decrease the activity of water or carbon dioxide (Fyfe and others, 1978, p. 62), ie:

\[ \text{water} + \text{carbon dioxide} + \text{metal ions} = \text{fluid}. \]

However, the complexing of the metal ions with available hydroxyl carbonate, or phosphate anions will shift the equilibrium back toward greater solubility of the particular metal ion in question (K. Osterheld, pers. comm., 1985). Thus the composition of the fluid would appear in a constant state of flux; the transfer of specific ions requires a balance between the solubility of the ion and the availability of complexing anions. The availability of complexing anions would depend on the solubility of water and carbon dioxide in the magma.

The actual movement of the volatile phase is up and away from the crystallizing silicate structures as movement or diffusion takes place along the activity gradient and toward regions of lower pressures.
MODEL FOR THE EVOLUTION OF GORDON BUTTE

Any model describing the evolution of Gordon Butte must incorporate methods of altering the chemical composition of the magma without physically separating the crystalline phases from contact with the melt. The process of volatile transfer, including fenitization, can accomplish this. Differentiation by the transfer of volatiles produces subtle, cryptic changes in the chemical composition of an igneous intrusion.

The theory of volatile transfer is not new. In 1912 R.A. Daly (Shand, 1947) used the theory to explain the formation of feldspathoidal rocks through the escape of carbon dioxide carrying alkali toward the top of the magma chamber. A magma chamber subject to Daly's interpretation of volatile transfer would produce a rock richer in pyroxene in the lower part of the chamber and a melt richer in alkali in the upper part. At Gordon Butte this situation does not occur; the magma chamber contains a uniform rock type. The only pyroxenite present are the xenoliths in the dike and laccolith. Rock (1976) stresses the importance of a high volatile content, specifically carbon dioxide over water, to explain generation of a strongly alkaline magma with pyroxenite xenoliths. Rock argues that variations in gaseous composition of magmas at depth offer a simple explanation for the compositional variations in the intruded rock.

Because experimental work has concentrated on documenting the processes of crystal fractionation, gravitational settling, and more
recently on liquid immiscibility, the process of volatile transfer has mostly been ignored. Our knowledge about the distribution of major, minor, and trace elements is based on observations made in the field and during petrographic research (Rittmann, 1975). Experimental petrology needs to model research that will document gaseous behavior and transfer in magmas of varying compositions under varying pressure and temperature conditions.

According to the above descriptions and interpretation the following scenario suggests a plausible explanation for the evolution of Gordon Butte.

1. The Gordon Butte magma originated in a lower crust-upper mantle magma chamber, based on the presence of the pyroxenite xenoliths in the magma. The chemical composition of the clinopyroxenes in the xenolith and augite core in the shonkinite are the same indicating they probably crystallized from the same parental magma and under similar pressures. The super-critical fluid phase presumably contained both carbon dioxide and water.

2. Transfer of the fluid phase rich in alkalis toward the top of the chamber is synchronous with the crystallization of mafic minerals such as biotite and pyroxene producing a parental magma chamber with an alkaline-rich melt separating from a pyroxenite base; perhaps a situation similar to the model Daly proposed.

3. High volatile content of the magma at upper mantle conditions, thus high volatile pressures, would influence a rapid
ascent, carrying along pyroxenite inclusions (Mysen, 1975). If pyroxenite was forming in the lower portion of the parental magma chamber, then presumably a magma energetically exiting the chamber would bring along fragments of the lower part or walls of the chamber.

4. Decrease in pressure on an ascending carbonated magma causes exsolution of a carbon dioxide-rich phase which incorporates metal ions from the magma to form the fenitizing solutions. The fenitizing solutions are super-critical; they precede the final crystallization of magma and approximate molten magmatic temperatures.

5. After emplacement, the temperature of the magma remains high. The pressure conditions are high enough to keep the water and carbon dioxide in super-critical fluid phases. However, the pressure is low enough to continue forcing the generation of fenitizing solutions from the magma. Exsolution of the carbon dioxide continually concentrates water in the magma; thus the water-bearing volatile phase becomes progressively more important.

6. As the temperature drops and the magma begins to solidify, the water-bearing fluid actively migrates toward the top of the intrusion. Water carries dissolved elements that either may react with the silicate phase, as in the alteration of augite to aegirine-augite, accumulate at the top of the laccolith, or exsolve out of the water-bearing fluid with the carbon dioxide and become a constituent in the fenitizing solutions.
THE EFFECT OF FENITIZATION ON MAGMATIC DIFFERENTIATION

Magmas that exsolve fenitizing fluids should show depletion of certain mobile constituents from the igneous rock and presumably addition of these constituents into the fenite. Fenitization, as a process, operates during intrusion and crystallization modifying the chemistry of a magma by loss of material to the host rock (Rubie, 1982). Alkaline intrusions surrounded by fenitized border zones are commonly studied to document the process of fenitization by using quantitative techniques of mass transfer and volume change (Gresens, 1967, Appleyard and Woolley, 1979). Although fenitization is present at Gordon Butte, calculations of mass transfer and volume change are not possible as an incomplete section of fenite remains. Instead, semi-quantitative calculations can be made to approximate the original composition of the magma prior to fenitization, as well as, to estimate the original thickness of the fenite zone.

The average composition of the chill zones at Gordon Butte should reasonably represent the original composition of the magma just before intrusion. The average composition for the main mass of shonkinite, excluding the chill zones, represents the bulk chemical composition of the rock after fenitization has occurred. Assuming a closed system including the fenite, the difference between these two average compositions should represent the amount of constituents lost to the fenite; these figures are listed in Table 4.

Assuming elements are only added by fenitization, and not
### TABLE 4. Average chemical composition for the shonkinite, Fort Union Formation, and fenitized Fort Union Formation, in weight percent

<table>
<thead>
<tr>
<th>Average Composition for:</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>CaO</th>
<th>MgO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>Fe$_2$O$_3$</th>
<th>MnO</th>
<th>TiO$_2$</th>
<th>P$_2$O$_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Chill Zone</td>
<td>45.45</td>
<td>13.15</td>
<td>9.57</td>
<td>4.78</td>
<td>5.87</td>
<td>3.98</td>
<td>10.28</td>
<td>0.24</td>
<td>1.18</td>
<td>1.53</td>
</tr>
<tr>
<td>B. Vertical Sections #1-4</td>
<td>44.68</td>
<td>12.55</td>
<td>11.25</td>
<td>6.46</td>
<td>3.65</td>
<td>3.83</td>
<td>8.97</td>
<td>0.16</td>
<td>0.93</td>
<td>1.52</td>
</tr>
<tr>
<td>C. Difference of A-B for Na$_2$O</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.31</td>
</tr>
<tr>
<td>D. Fenitized Fort Union Fm.</td>
<td>55.12</td>
<td>6.85</td>
<td>4.67</td>
<td>1.82</td>
<td>6.61</td>
<td>5.04</td>
<td>15.23</td>
<td>0.21</td>
<td>1.30</td>
<td>--</td>
</tr>
<tr>
<td>E. Fort Union Fm.</td>
<td>39.2</td>
<td>6.19</td>
<td>26.0</td>
<td>0.71</td>
<td>0.55</td>
<td>2.25</td>
<td>1.51</td>
<td>1.31</td>
<td>0.29</td>
<td>0.14</td>
</tr>
<tr>
<td>F. Difference of D-E for Na$_2$O</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.06</td>
</tr>
</tbody>
</table>
removed from the fenitized rock, a calculation can be made to
determine the approximate thickness of the original fenite capping
Gordon Butte; that is, what proportion of elements must be added back
into the shonkinite from the fenite to achieve a composition similar
to the average chill zone. To keep the procedure simple only sodium,
a highly mobile element in fenitization, is considered. Sodium is
the dominant element involved in fenitization surrounding alkaline
intrusions (LeBas, 1977), sodium is extremely soluble in alkalic
metasomatic fluids (Orville, 1963), and of all the major elements
present in the Gordon Butte shonkinite sodium shows the greatest
changes (see figure 24).

The calculation assumes (1) that the 20 centimeter fenitized
chill zone be ignored, as proportionately the fenitized chill zone is
insignificant in volume to the laccolith below and that the weight
percent sodium in the fenite is actually less than in the top chill
zone (see figure 29). Perhaps the fenitized chill zone, as
shonkinite, initially contained high sodium values so that
fenitization failed to have any significant change in the weight
percent of sodium. Regardless, the fenite cap was probably much
thicker than 20 centimeters and proportionately contained fenitized
country rock, thus the fenitized chill zone is ignored. Continuing,
the calculation also assumes, (2) that the fenitizing solutions
originated from the lower to middle part of the laccolith,
Figure 29. Plot of the sodium content in the laccolith and associated fenite.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Na₂O Wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Chill zone</td>
<td>5.87</td>
</tr>
<tr>
<td>b. 'Depleted' shonkinite</td>
<td>3.65</td>
</tr>
<tr>
<td>a-b c-d</td>
<td>2.31</td>
</tr>
<tr>
<td>c. Fenitized Ft. Union</td>
<td>6.61</td>
</tr>
<tr>
<td>d. Unaltered Ft. Union</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Sodium Lost = Sodium Gained

Area under the curve: \(180.2 = 6.06 \times (X)\); Area of fenite cap \(29.7m = X\)
corresponding to vertical sections #1-4, a height of 78 meters. Vertical section #5 is not included as this section contains even a higher percent sodium than the top chill zone; this may reflect the differentiation process of upward concentration of select elements (as discussed in the chapter on the nature of volatile transfer).

The calculation is based on the proportion of fenite to shonkinite and the differences in weight percent of sodium between the two rock types. The calculation is as follows: the area that represents the weight percent sodium lost from the shonkinite equals 180.2 wt.%/m (shaded area on figure 29). The volume of a fenite cap that would represent the weight percent of sodium gained would then equal:

\[ \frac{180.2 \text{ wt.}%}{m} = 6.06 \text{ wt.}% \times m \]

\[ X = 29.7 \text{ m} \]

Thus the original fenitized cap (fenitized country rock) was approximately 30 meters thick. Figure 29 schematically shows the "balance" of sodium lost from the shonkinite to sodium gained by the fenite.

The calculation above represents the possible thickness of a fenite cap above a shonkinite mass 105 meters thick. If the laccolith was actually thicker, then presumably the original fenite cap would have been thicker. Considering the sills as part of the laccolith (as discussed in the section of Contact Relations) the actual thickness of shonkinite should be approximately 270 meters,
versus the 105 meter thickness used in the above calculation.
Recalculating with a shonkinite thickness of 270 meters, the fenite cap could have been approximately 77 meters thick.

Estimations of fenite thickness based on simple lost-gained assumptions are risky, as assumptions like the ones used above are too simple and do not truly represent the reactions occurring in nature. In addition, the data represents only a small number of analyses and thus should not be taken at face value. Rather, the numbers indicate a direction of change; they appear to indicate a significant amount of sodium was removed from the laccolith. The sodium most likely went to metasomatize the overlying country rock into a layer of fenite. Recall that fenite was also recognized above the feeder dike and sills at Gordon Butte. Volatile transfer appears to have dominated much of the differentiation of the Gordon Butte magma.

The transfer of volatiles definitively affected the evolution of the Gordon Butte magma. If fenitization did not occur and sodium remained confined to the magma then presumably the ratio of potash to soda would have been greater; thus the resulting composition of the rock may not have been shonkinitic. (Refer to Table 1 for the figures on potash and soda in the chill zones versus the main mass of shonkinite). In essence, the shonkinite composition may be a direct result of fenitization.

Magmatic differentiation influenced by volatile transfer and fenitization presents a system open to constant change, constituents
dissolving, migrating, exsolving, etc.. The reactions that occur during volatile transfer and fenitization presumably operate at temperatures and pressures difficult to experimentally work with. Until experimental work can accomodate such open-ended systems, simple approaches similar to the one used above to trace the movement of sodium may help clarify the geologic implications of processes like volatile transfer and fenitization.
REFERENCES


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Appendix A. Electron microprobe results of augite phenocrysts, in cation percent.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Na</th>
<th>Fe</th>
<th>K</th>
<th>Si</th>
<th>Ca</th>
<th>Al</th>
<th>Ti</th>
<th>Mg</th>
<th>Mn</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyroxenite xenolith (clinopyroxene)</td>
<td>0.77</td>
<td>5.34</td>
<td>0.01</td>
<td>24.54</td>
<td>15.98</td>
<td>1.14</td>
<td>0.27</td>
<td>8.36</td>
<td>0.09</td>
<td>42.86</td>
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