RAPAKIVI FORMATION OF O'LEARY PEAK PORPHYRY

by

Katherine Laing Bladh

A Dissertation Submitted to the Faculty of the
DEPARTMENT OF GEOSCIENCES
In Partial Fulfillment of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY
In the Graduate College
THE UNIVERSITY OF ARIZONA

1976
I hereby recommend that this dissertation prepared under my
direction by Katherine Laing Bladh
entitled Rapakivi Formation of O'Leary Peak Porphyry
be accepted as fulfilling the dissertation requirement for the
degree of Doctor of Philosophy

Dissertation Director  Date

As members of the Final Examination Committee, we certify
that we have read this dissertation and agree that it may be
presented for final defense.

Final approval and acceptance of this dissertation is contingent
on the candidate's adequate performance and defense thereof at the
final oral examination.
STATEMENT BY AUTHOR

This dissertation has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this dissertation are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: Katherine Lani Black
To the two Kens in my life: my husband, and my father who never had the chance to go to college but made it possible for me to go.
PREFACE

The porphyry of O'Leary Peak and Darton Dome (the O'Leary Peak porphyry herein called the O'Leary Porphyry for brevity) contains sanidine rimmed or mantled with oligoclase—a texture called rapakivi. The occurrence of sanidine in rapakivi is rare, there being only two other occurrences in the literature. How were the sanidines mantled with oligoclase? What changes caused the plagioclase rather than the sanidine to become the stable phase?

Embayed andesite xenoliths occur within the porphyry. Is the rapakivi related to the resorption of these xenoliths? The association of both mantled (rapakivi) and unmantled alkali feldspar is common at O'Leary Peak as well as elsewhere. This author believes that no completely satisfactory explanation of the association has yet been supplied.

O'Leary Peak and Darton Dome are Pleistocene in age and relatively unaltered. The rocks are obviously igneous, are accessible, and have well developed rapakivi texture. In short, they offer an excellent field location to study rapakivi of igneous origin. The purpose of this study was to acquire as much data as possible concerning the chemical and mineralogical nature of the O'Leary rock system in order to shed light on the formation of its rapakivi.

I wish to express my gratitude to my dissertation director, Dr. P. Damon, for his direction and encouragement. Thanks also go to Drs. T. Loomis, J. Anthony, W. Miller, and W. Saltzman (all of The University
of Arizona) for reading the dissertation. Drs. Loomis and Miller also
gave advice concerning the section on diffusion and Dr. Loomis gave
advice concerning the section on nucleation and growth rates. Thanks
to R. Wilcox (U.S.G.S., Denver) for discussions concerning the
basification.

The Laboratory of Isotope Geochemistry supplied the K/Ar date
and the rubidium and strontium analyses (x-ray fluorescence). Electron
microprobe time was supplied by The University of Arizona. The traverse
of one rapakivi and three coexisting plagioclases was done by Mr. E.
Mathez on the University of Washington microprobe. The Department of
Geosciences supplied glassware and chemicals necessary for the atomic
absorption analyses. Computer time for running Empadr VII to reduce the
microprobe data was supplied by The University of Arizona Computer Cen­
ter. Discussion with Mr. R. Scarborough concerning digestion procedure
for atomic absorption analyses was helpful. Mr. D. Lynch supplied the
analysis for the plagioclase xenocryst. Dr. D. Norton and Mr. J. Knight
helped debug the Empadr VII program. Special thanks to Mr. K. Bladh for
doing the single crystal work to determine the cell parameters of the
O'Leary sanidine.

My special thanks go to Mr. M. Mosesso for instruction in the
use and idiosyncrasies of hydrothermal experimental laboratory equipment.
Mr. Mosesso, like myself, experiences many frustrations due to inade­
quate equipment and repeated burglaries of the laboratory. Mr. Mosesso
kindly allowed me to use two of the four available furnaces, although
this caused the voltage to fluctuate in the two which he used. Thanks
must also go to The University of Arizona cattle at the Campbell Avenue farm for occasionally allowing me to use their water to run the x-ray generator.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xiii</td>
</tr>
<tr>
<td>DISCUSSION OF THE PROBLEM</td>
<td>1</td>
</tr>
<tr>
<td>Definition of Rapakivi</td>
<td>1</td>
</tr>
<tr>
<td>Occurrences of Rapakivi</td>
<td>1</td>
</tr>
<tr>
<td>Selection of O'Leary Porphyry</td>
<td>4</td>
</tr>
<tr>
<td>REGIONAL SETTING</td>
<td>5</td>
</tr>
<tr>
<td>Origin of the Field</td>
<td>5</td>
</tr>
<tr>
<td>Topography of the Domes</td>
<td>7</td>
</tr>
<tr>
<td>Petrography of the O'Leary Porphyry</td>
<td>7</td>
</tr>
<tr>
<td>Plagioclase Xenocrysts</td>
<td>8</td>
</tr>
<tr>
<td>&quot;Sponge&quot; Texture</td>
<td>9</td>
</tr>
<tr>
<td>Field Sampling and Observations</td>
<td>10</td>
</tr>
<tr>
<td>Feldspar Nomenclature</td>
<td>12</td>
</tr>
<tr>
<td>CHEMISTRY OF RAPAKIVI ROCKS</td>
<td>14</td>
</tr>
<tr>
<td>Major Elements</td>
<td>14</td>
</tr>
<tr>
<td>Trace Elements</td>
<td>19</td>
</tr>
<tr>
<td>Atomic Absorption Work</td>
<td>20</td>
</tr>
<tr>
<td>PETROLOGY OF THE O'LEARY PORPHYRY</td>
<td>29</td>
</tr>
<tr>
<td>Hydrothermal Experiments</td>
<td>29</td>
</tr>
<tr>
<td>Defocused Microprobe Scans</td>
<td>29</td>
</tr>
<tr>
<td>Composition of Xenoliths</td>
<td>32</td>
</tr>
<tr>
<td>DESCRIPTION OF RAPAKIVI</td>
<td>36</td>
</tr>
<tr>
<td>Shape of Rapakivi</td>
<td>36</td>
</tr>
<tr>
<td>Nature of Core</td>
<td>36</td>
</tr>
<tr>
<td>Nature of the Rim</td>
<td>38</td>
</tr>
<tr>
<td>Replacement Textures</td>
<td>39</td>
</tr>
<tr>
<td>Myrmekite</td>
<td>43</td>
</tr>
<tr>
<td>Summary</td>
<td>44</td>
</tr>
</tbody>
</table>
### TABLE OF CONTENTS—Continued

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPOSITION OF RAPAKIVI FELDSPARS</td>
<td>45</td>
</tr>
<tr>
<td>- Rapakivi Feldspars from the Literature</td>
<td>45</td>
</tr>
<tr>
<td>- O'Leary Feldspars</td>
<td>46</td>
</tr>
<tr>
<td>- Rubidium and Strontium Analyses</td>
<td>46</td>
</tr>
<tr>
<td>- Hydrothermal Seed Crystals</td>
<td>50</td>
</tr>
<tr>
<td>THE ORIGIN OF THE RAPAKIVI OF THE O'LEARY PORPHYRY</td>
<td>53</td>
</tr>
<tr>
<td>- Early Theories</td>
<td>53</td>
</tr>
<tr>
<td>- Major Theories</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>- Metamorphic-metasomatic (Feldspathization) Theories</td>
</tr>
<tr>
<td></td>
<td>- Exsolution</td>
</tr>
<tr>
<td></td>
<td>- Magmatic Theories</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>72</td>
</tr>
<tr>
<td>APPENDIX A: METHOD OF STUDY</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>- X-ray Work on Sanidines</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- X-ray Fluorescence Work</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Hydrothermal Work</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Atomic Absorption Work</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## TABLE OF CONTENTS—Continued

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Microprobe Work</td>
<td>98</td>
</tr>
<tr>
<td>Sample Preparation</td>
<td>98</td>
</tr>
<tr>
<td>Equipment and Working Conditions</td>
<td>100</td>
</tr>
<tr>
<td>Standards</td>
<td>101</td>
</tr>
<tr>
<td>Reduction of Data</td>
<td>103</td>
</tr>
<tr>
<td>Error Analysis</td>
<td>103</td>
</tr>
<tr>
<td>Results</td>
<td>105</td>
</tr>
<tr>
<td>APPENDIX B: DIFFUSION</td>
<td>106</td>
</tr>
<tr>
<td>APPENDIX C: APPLICATION OF FELDSPAR G EOTHERMOMETERS</td>
<td>110</td>
</tr>
<tr>
<td>APPENDIX D: ASSIMILATION OF XENOLITHS</td>
<td>113</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>114</td>
</tr>
</tbody>
</table>
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Map of O'Leary Peak from Bladh (1972)</td>
<td>6</td>
</tr>
<tr>
<td>2. Norms of Rapakivi Rocks Containing Mantled Alkali Feldspars</td>
<td>16</td>
</tr>
<tr>
<td>3. Norms of Rapakivi Rocks Plotted on Or-Ab-An Diagram</td>
<td>17</td>
</tr>
<tr>
<td>4. Norms of Rapakivi Rocks Containing Mantled Alkali Feldspars, Plotted on Diagram Modified after James and Hamilton (1969, figs. 3 to 6)</td>
<td>18</td>
</tr>
<tr>
<td>5. MgO Distribution (Weight Percent, Atomic Absorption Results) on O'Leary Peak and Darton Dome</td>
<td>22</td>
</tr>
<tr>
<td>6. CaO Distribution (Weight Percent, Atomic Absorption Results) on O'Leary Peak and Darton Dome</td>
<td>23</td>
</tr>
<tr>
<td>7. K2O Distribution (Weight Percent, Atomic Absorption Results) on O'Leary Peak and Darton Dome</td>
<td>24</td>
</tr>
<tr>
<td>8. Na2O Distribution (Weight Percent, Atomic Absorption Results) on O'Leary Peak and Darton Dome</td>
<td>25</td>
</tr>
<tr>
<td>9. Fe2O3 Distribution (Weight Percent, Atomic Absorption Results) on O'Leary Peak and Darton Dome</td>
<td>26</td>
</tr>
<tr>
<td>10. Hydrothermally Determined Melting Interval for O'Leary Porphyry with 5 Weight Percent Added Water</td>
<td>30</td>
</tr>
<tr>
<td>11. Hydrothermally Determined Melting Interval of O'Leary Porphyry with 15 Weight Percent Added Water</td>
<td>31</td>
</tr>
<tr>
<td>12. Defocused Microprobe Scans on PBl-y from Xenolith (Left) through O'Leary Porphyry to Mantled (Rimmed) Sanidine (rs)</td>
<td>33</td>
</tr>
<tr>
<td>13. Defocused Microprobe Scan on PBl-X from Mantled (Rimmed) Sanidine (Left) Xenolith (Right)</td>
<td>34</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>14.</td>
<td>Drawing of Multiple-Core Mantled (Rimmed) Sanidine from Thin Section P-21</td>
</tr>
<tr>
<td>15.</td>
<td>Polaroid Mosaic of Microprobe Thin Section &quot;URSX&quot;</td>
</tr>
<tr>
<td>16.</td>
<td>Drawing of Mantled (Rimmed) Sanidine from Thin Section P18b</td>
</tr>
<tr>
<td>17.</td>
<td>Drawing of Mantled (Rimmed) Sanidine from Thin Section P-24</td>
</tr>
<tr>
<td>18.</td>
<td>Microprobe Results on O’Leary Porphyry Feldspars Including Plagioclase and Mantled (Rimmed) and Unmantled (Unrimmed) Sanidines</td>
</tr>
<tr>
<td>Table</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>I. U. S. Geol. Survey Chemical Analyses and Partial Norms of O'Leary Porphyry</td>
<td>15</td>
</tr>
<tr>
<td>II. Atomic Absorption Values on Porphyry Samples</td>
<td>21</td>
</tr>
<tr>
<td>III. Chemical Analyses of Xenoliths and Their Minerals</td>
<td>35</td>
</tr>
<tr>
<td>IV. Chemistry of O'Leary Porphyry Sanidines</td>
<td>47</td>
</tr>
<tr>
<td>V. Partial Chemical Analyses and Norms of O'Leary Porphyry Plagioclases</td>
<td>48</td>
</tr>
<tr>
<td>VI. X-ray Peaks of O'Leary Sanidines</td>
<td>83</td>
</tr>
<tr>
<td>VII. Valid Hydrothermal Runs</td>
<td>86</td>
</tr>
<tr>
<td>VIII. Standard Solutions I, II, III, and IV for Porphyry Runs</td>
<td>92</td>
</tr>
<tr>
<td>IX. Standard Solutions I, II, III, and IV for Feldspar Runs</td>
<td>92</td>
</tr>
<tr>
<td>X. Atomic Absorption Settings for Elements</td>
<td>97</td>
</tr>
<tr>
<td>XI. Composition of Feldspar Standards</td>
<td>99</td>
</tr>
</tbody>
</table>
ABSTRACT

The rhyodacite O'Leary Porphyry which makes up the Pleistocene (0.233 ± 0.37 m.y.) volcanic domes of O'Leary Peak and Barton Dome in the San Francisco Volcanic Field (northern Arizona) contains oligoclase mantles on sanidine (rapakivi texture). Rapakivi occurs world-wide in rocks of various compositions and ages; it has been attributed both to igneous and metamorphic processes. The O'Leary Porphyry rapakivi are well-developed, accessible, unaltered, and obviously igneous.

The O'Leary Porphyry contains mantled and unmantled sanidine (both are Or$^{63-69} \cdot$Ab$^{30-36} \cdot$An$^1$), oligoclase (An$^{11-26} \cdot$Ab$^{70-80} \cdot$Or$^{4-10}$), quartz, labradorite xenocrysts (An$^{53} \cdot$Ab$^{45} \cdot$Or$^2$), and andesite xenoliths composed of kaersutite, andesine (An$^{44} \cdot$Ab$^{53} \cdot$Or$^2$), magnetite, hematite, and olivine. The average length of mantled sanidines is 14 mm, and of unmantled sanidines 13.5 mm. Mantles (An$^{12-23} \cdot$Ab$^{63-78} \cdot$Or$^{7-23}$) are generally discontinuous and are 0.5-5 mm in width. Plagioclases (An$^{14-21} \cdot$Ab$^{72-78} \cdot$Or$^{7-10}$) are also poikilitic within sanidines.

A chemical analysis of the porphyry from O'Leary Peak yields (in weight percent): 71.2 SiO$_2$, 14.4 Al$_2$O$_3$, 3.4 Fe$_2$O$_3$, 0.05 FeO, 0.4 MgO, 1.5 CaO, 5.0 Na$_2$O, 3.8 K$_2$O, 0.27 TiO$_2$, 0.13 P$_2$O$_5$, 0.09 MnO. The porphyry of O'Leary Peak is distinct from that of Barton Dome, being higher in K$_2$O and Na$_2$O and lower in CaO, Fe$_2$O$_3$, and MgO. The highest values of these five oxides were found at vents.
Hydrothermal melting experiments were run on the O'Leary Porphyry with 5 and 15 weight percent water at 1 kb water pressure. For those runs with 5% water, there was 95% melt at about 850°C, quartz began to crystallize at about 830°C, and the solidus was reached at about 770°C. In the runs with 15% water, sanidine began crystallizing at about 880°C (with about 98% melt), quartz began to crystallize at about 830°C, and the solidus was reached at about 725°C. Plagioclase was present throughout the runs. Sanidine seed crystals run (average of 825°C, 1 kb water pressure) with porphyry and 15 weight percent added water, produced mantles richer in sodium and calcium than were the seed crystals. This is interpreted as the beginning of plagioclase-mantle formation.

There is no evidence of any metamorphic or metasomatic mechanism of rapakivi formation in the O'Leary Porphyry. Exsolution of a ternary feldspar to form mantles is unlikely in this porphyry because the mantled sanidines and the cores of the unmantled sanidines have the same composition. It is also unlikely that a build-up of water caused rapakivi formation.

Two mechanisms remain viable for rapakivi formation in the O'Leary Porphyry. The first is basification—contamination of the melt by assimilation of basic xenoliths. The spatial relationship within the O'Leary Porphyry between mantled sanidines and andesite xenoliths lends no support to this theory; however, the association of rapakivi and basic xenoliths is common. The other mechanism is one of slow cooling where growth is faster than is nucleation. This could cause the use of
sanidine as nuclei for plagioclase growth. Such a situation would be expected in chemically-appropriate melts which were cooled slowly and are, thus, fairly coarse-grained. Rapakivi does commonly occur in plutonic and coarse-grained volcanic silicic rocks. It, apparently, is not present in chemically similar rocks which are finer grained.
DISCUSSION OF THE PROBLEM

Definition of Rapakivi

"Rapakivi" is a Finnish word for rotten or weathered stone (Sederholm 1928, p. 87). Among geologists of Scandinavia and the Soviet Union, rapakivi is "... an orogenic granite of the Late Precambrian." (Marmo 1971, p. 123). Some authors have suggested that a rapakivi is a granite with two generations of quartz and alkali feldspar. By this definition rapakivi do not necessarily have mantled alkali feldspar. Wahl (1925) distinguished two types of Scandinavian rapakivi granites—wiborgite which contains mantled alkali feldspar, and pyterlite which does not. Other authors, for example Sederholm (1928, p. 87), considered the anhedral "ovoidal" shape of the alkali feldspar necessary to the definition. Phillips (1972, pp. 92-3) distinguished the classical rapakivi discussed above from the one with euhedral feldspars having sporadic and not necessarily continuous mantles. The use of the term rapakivi in this paper, however, will follow the modern usage as described by Stewart (1959, p. 294): "... rapakivi texture or rapakivi means the occurrence of potassic feldspar with plagioclase arranged within or upon it in a crudely concentric mantle or mantles."

Occurrences of Rapakivi

The rapakivi is not as uncommon as many authors have suggested. The type locality, which is also the best known occurrence, is the Fennoscandinavian shield granite massifs. Here, rapakivi ovoids occur
within granites and within their associated rhyolites (Raguin 1965, p. 70). Other rapakivi granites occur in the Baltic area in the Soviet Union near Kiev, Leningrad, and Riga (Marmo 1971, p. 124) and in Poland (Borkowska 1963).

In Arizona, rapakivi occurs in quartz monzonites in the Dos Cabezas Mountains (Erickson 1969), in quartz monzonites in the Comobabi Mountains (Bryner 1959, p. 26), and in the O'Leary Peak and Darton Dome rhyodacite porphyries (Bladh 1972). This author has found rapakivi in the dacite porphyry of Bill Williams Mountain and in the silicic plugs in O'Neil and Strawberry Craters within the San Francisco Volcanic Field. The texture has also been found in Sitgreaves and Kendrick Peaks and in San Francisco Mountain (R. B. Moore, U. S. Geol. Survey, Flagstaff, Arizona, oral communication, 1976). Volborth (1962, p. 828) listed the texture in a granitoid rock from Clark County, Nevada. Ehrreich and Winchell (1969, pp. 905-6) cited rapakivi sanidine in a rhyolite flow from west of Death Valley, California. The Rattlesnake Mountain quartz monzonite of southern California contains microcline rapakivi (MacColl 1964, p. 809). Hutchinson (1956) described rapakivi in the Enchanted Rock Batholith of Texas. A biotite granite in the Salmon River Mountains of Idaho contains rapakivi (Goodspeed 1969), as do some granites from Wisconsin (Elders 1968). Lowell and Sides (1973) described a rapakivi granite from southeastern Missouri. Some charnockites from New York contain discontinuous rims of plagioclase on alkali feldspar (Crosby 1971, p. 1791). Granites from the Adirondacks contain rapakivi (Buddington and Leonard 1962). Several plutons from Maine and New
Brunswick which contain rapakivi are the Tunk Lake granite (Karner 1968, p. 196), Bottle Lake and Chiputneticook quartz monzonites (Larrabee, Spencer, and Swift 1965, pp. E21-24), the Deer Isle and Eastern Penobscot Bay plutons (Stewart 1959, pp. 295-6), the Head Harbor Island granite (Terzaghi 1940), the George batholith (Martin 1970, p. 310), and the Pokoik batholith (Martin 1970, p. 310).

Elsewhere rapakivi is reported in Brazil (Goni 1961), in augen schist in Scotland (Fernando 1941), in syenite in Turkey (Maucher 1938), in adamellite from New South Wales, Australia (Phillips 1972), and in granulite-gneiss, granites, and "mixed-diorite" in Germany (Riederer 1966). Occurrences in granite include Greenland (Dawes 1970), France (Thomas and Campbell-Smith 1932), Nigeria (Greenwood 1951), South Africa (Shand 1949), and Portugal (Schmermerhorn 1956).

Not all of the rapakivi occurrences in the literature have been dated. However, of those dated, rapakivi occurs in Precambrian rocks with dates of 1.0 (Volborth 1962, p. 828) and 1.645 billion years (Dawes 1970, p. 111), Paleozoic rocks with dates of 380-400 m.y. (Tupper and Hart 1961, p. 1286; Larrabee et al. 1965, pp. E21-24; Martin 1970, p. 310), in Mesozoic rocks dating 143 and 85 m.y. (Volborth 1973, p. 39), in Tertiary rocks date 16-18 and 8 m.y. (Volborth 1973, p. 39), and in Recent rocks date 0.2 m.y. (Bladh 1973).

It can be concluded that rapakivi is not uncommon, and occurs in rocks all over the world of differing ages and environments.
Selection of O'Leary Porphyry

The O'Leary Porphyry contains large sanidine rapakivi. The porphyry is generally well exposed and, except in the vent area, relatively unaltered. The volcanic domes are Pleistocene in age and are unmetamorphosed. Discussion of rapakivi has, in the past, centered on conflicting evidence of metamorphic versus igneous origin of the texture. Here is an obviously igneous occurrence which shows all the petrographic features seen in other rapakivi occurrences. The fact that the alkali feldspar of the O'Leary rapakivi is sanidine rather than orthoclase or microcline, makes this occurrence different from most other rapakivi. The O'Leary rapakivi thus reflect what is common--rapakivi in silicic rocks--and what is not--sanidine in rapakivi.

Since the formation of rapakivi depends upon the physio-chemical history of the magma in which it formed, study of the rapakivi help to unravel that history. O'Leary Peak and Darton Dome, because of their easy access, well-developed rapakivi, and relatively unaltered volcanic nature, provide a system without some of the complexities present in older, more altered, or metamorphosed rapakivi occurrences.
REGIONAL SETTING

O'Leary Peak and Darton Dome are volcanic domes which lie in the San Francisco Volcanic Field about 15 miles northeast of Flagstaff, Arizona. The domes were erupted through the earlier basalts of the field and contain xenoliths of the sedimentary rocks of the area. K/Ar dating on the sanidine from locality P31 (Figure 1) of O'Leary Peak (Laboratory of Isotope Geochemistry, The University of Arizona) gave a value of $0.233 \pm 0.037$ m.y.

Origin of the Field

Moore, Wolfe, and Ulrich (1974, pp. 492-3) stated "... If the parent magma for the entire volcanic field is considered to be alkali olivine basalt, the volume of erupted silicic rocks which Robinson (1913) estimated as about half the total volume of the volcanic field, is excessive for a simple differentiation model based on fractional crystallization." Alkali basalt is common within the field. Moore et al. therefore suggested repeated partial meltings of the mantle as the mechanism of magma generation for the field. It must be pointed out, however, that Robinson's estimate of silicic rocks may be too high. O'Leary Peak's Sr 87/86 ratio of 0.7050 suggests some crustal contamination of the O'Leary magma compared with the basalts of the field which show ratios of 0.7026-0.7042 (Moore et al. 1974, p. 492).
Figure 1. Map of O'Leary Peak from Bladh (1972). — North is towards top of page.
**Topography of the Domes**

O'Leary Peak rises 1800 ft and Darton Dome 1300 ft above the surrounding topography. Collapse and/or explosion has resulted in the loss of the northern part of the O'Leary Peak dome. Flow apparently took place out of the eastern side of O'Leary Peak forming the Eastern Flat (Figure 1) and out of the northeastern side of Darton Dome resulting in its asymmetry. The domes are bordered on the north by a series of later volcanic flows which are chemically similar to the domes. See Bladh (1972) and Figure 1 for further details.

**Petrography of the O'Leary Porphyry**

The domes are composed of the rhyodacitic O'Leary Porphyry (classified by the norms from chemical analyses given under "chemistry of the domes" according to the system of Williams, Turner, and Gilbert 1954) which contains oligoclase (11%), sanidine (8%), and quartz (3%) phenocrysts in a quartzo-feldspathic groundmass which includes kaersutite xenocrysts and andesite xenoliths (4%). These values were determined by placing a grid over a sample from locality P31. Thin section values are oligoclase 15-33%, sanidine trace-8%, quartz 3-9%, kaersutite trace-11%. Sporadic minor biotite, pyroxene, hornblende, and xenocrystic olivine occur in some parts of the porphyry (Bladh 1972, pp. 59-60). Allanite was found in the O'Leary Porphyry by Moore et al. (1974, p. 492) and was listed by Volborth (1962, p. 825; 1973, p. 34) as being present in the rapakivi rocks which he studied.
Plagioclase Xenocrysts

Three calcic plagioclase xenocrysts were found—two on the southern side of O'Leary Peak and one on the eastern side of Darton Dome. Preliminary identification was by x-ray powder films which resemble the pattern of labradorite. Measurements in oils gave indices of about 1.558, 1.561, and 1.567, a 2V of about 80°, and a (+) sign. This corresponds, according to J. V. Smith (1974, p. 397), to a composition of about An58. This composition corresponds to a 2V value (J. V. Smith 1974, p. 395) of a "low" structural plagioclase of 80°. Atomic absorption analysis of the mineral by Dan J. Lynch gave the following analysis (which corresponds approximately to An53Ab45O12):

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca0</td>
<td>10.84</td>
</tr>
<tr>
<td>Na2O</td>
<td>4.99</td>
</tr>
<tr>
<td>K2O</td>
<td>0.33</td>
</tr>
<tr>
<td>MgO</td>
<td>0.08</td>
</tr>
<tr>
<td>MnO</td>
<td>0.03</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>0.44</td>
</tr>
</tbody>
</table>

The method used for atomic absorption was a modified lithium metaborate fusion technique described by Medlin, Suhr, and Bodkin (1969) with a strontium nitrate releasing agent. The crystals are assumed to be xenocrysts, although they were not within xenoliths, two were euhedral, and they were unreacted with the rhyodacite. The third crystal was anhedral and surrounded by a wide reaction rim of pink material.
"Sponge" Texture

The oligoclase phenocrysts exhibit a "sponge" texture made up of areas of opaques and glass blebs which variously occurs in the core, the rim, or certain zones of the crystals. Similarly-appearing textures occur on the sanidine crystals. There is a variety of possible explanations of this texture (Bladh 1972, pp. 89-92) including fusion, corrosion, or pressure changes (De Fino, LaVolpe, and Lirer 1973). A similar texture, apparently the result of fusion, was developed on a sanidine seed crystal in one hydrothermal experiment done by this author.

Lofgren (1974, p. 251) described "... boxwork dendritic forms" illustrations of which resemble this "sponge" texture. Lofgren's texture was produced by the supercooling of 150-250°C (water pressure of 5 kb; water content of 10%) of a plagioclase of composition more basic than An$_{20}$. Although the water pressure and plagioclase composition do not correspond to that of the O'Leary Porphyry (Appendix A), supercooling may have occurred during eruption of the domes.

Orville (1972, pp. 252-3) showed photographs which also resemble the "sponge" texture of O'Leary. He described that texture as "... irregular channels and voids ..." on a crystal which was originally An$_{17}$ but after exchange with 2N CaCl$_2$ solution at 700°C and pressure of 2 kb for six days became anorthite (An$_{100}$). Cleavage surfaces and twin boundaries of the original crystal were preserved. This "replacement texture" was formed by diffusion outward of sodium and silica and diffusion inward of calcium following this equation:
Although the molar volumes of albite and anorthite are similar (Weast 1971), the loss of the quartz resulted in a decrease in volume, thus producing voids. This author does not envision this as a possible mechanism for the "sponge" texture of O'Leary for the following reasons:

1. Unlike altered rocks elsewhere, there is no evidence at O'Leary of strong chlorine solutions.
2. There is no quartz within the plagioclase or localization of it in the groundmass which would represent that produced by the cited equation.
3. The "sponge" texture appears to be related to certain zones within the crystals and this mechanism provides no reason why the entire crystal should not have reacted.

Eichelberger (personal communication, 1976) stated that a texture similar in appearance to the "sponge" texture occurs in plagioclase associated with basalt or andesite xenoliths in silicic volcanics. He attributes this texture to fusion resulting from heat supplied to the magma by molten basalt globules which were quenched in the magma-forming xenoliths.

Field Sampling and Observations

Previously, samples had been taken during mapping of the field area (Bladh 1972). Additional sampling was done to complete coverage on a grid of approximately 1000 ft. Sampling on a complete grid was
not possible, however, due to lack of outcrop, presence of weathered outcrops, or inaccessibility in certain areas. Extreme weathering is present on the western side of Darton Dome while the northern side of O'Leary Peak is fragmented and altered by vent activity.

Samples from the closest good exposure to the grid location were taken. Material was taken from talus slopes when necessary and when the material was fresh. All of the following were sampled if available: xenolith, porphyry near xenolith, xenolith-free porphyry, mantled and unmantled sanidines, and kaersutite. Lengths of sanidine phenocrysts, their mantle thicknesses, and distances to the nearest xenolith were measured. Further measurements of this type were taken on hand samples. The type of xenolith and its dimensions were recorded.

Three types of xenoliths were observed: fine- to medium-grained very-resorbed red xenoliths, less resorbed fine- to medium-grained gray xenoliths, and "salt-and-pepper" (containing light and dark minerals in about equal proportions) medium- to coarse-grained xenoliths.

The average length of mantled sanidines (563 crystals) is 14.0 mm, the average length of unmantled sanidines (212 crystals) is 13.5 mm, and the average width of mantles (118 crystals) is 1.5 mm. Mantle thickness is variable and the mantle is not necessarily present at both ends of the crystal; however, it appears that mantled sanidine cores are somewhat shorter than unmantled sanidines. This suggests that resorption of the sanidine of the rapakivi occurred during the mantling process. If it had occurred prior to mantling, the sanidines of the unmantled crystals would also have been resorbed and the two types of
crystals would be about the same length. If it had occurred after mantling, the total length of core plus mantle should still equal 15 mm—assuming an original 13.5 mm long sanidine and 1.5 mm wide mantle.

The average distance between xenoliths and, respectively, mantled and unmantled sanidines is 4.3 cm and 3.3 cm (95 and 34 crystals, respectively). Thus, there is no evidence that mantled sanidines are, on the average, closer to xenoliths than are the unmantled ones. There is no relationship between width of mantles or ratio of number of mantled to unmantled sanidines and area of the xenoliths. Mantles from the Eastern Flat (Figure 1) are wider and the ratio of mantled to unmantled sanidines is higher here. Since the Eastern Flat was extruded out of O'Leary Peak, this may indicate that mantling continued after emplacement of the O'Leary Peak dome.

**Feldspar Nomenclature**

The alkali feldspar from the O'Leary Porphyry is a glassy, high-temperature volcanic feldspar with an optical axial angle of about 20°. Its x-ray pattern (Appendix A) resembles that of other sanidines. Electron microprobe analyses give a composition of $\text{An}_{1}\text{Ab}_{30-36}\text{Or}_{63-69}$ which plots as "Na-sanidine" on figure 9-16 of J. V. Smith (1974, p. 447). Single crystal work done by Kenneth Bladh gave the following unit cell size: \( a = 8.56 \text{ Å}, b = 13.02 \text{ Å}, c = 7.18 \text{ Å} \). These \( b \) and \( c \) values plot on figure 7-14 of J. V. Smith (1974, p. 256) in the high albite-high sanidine series. Calculated \( b^* \) and \( c^* \) plot on figure 9-11 of J. V. Smith (1974, p. 434) near sanidine—the accuracy is not sufficient to determine whether "sodian high sanidine" or "K-high sanidine" is indicated.
The O-level Weisenberg photograph on b showed two sets of spots which resemble those due to cryptoperthite. The a dimension of the perthite is about 8 Å, which is about that of plagioclase.

The only minerals likely to be confused (as to nomenclature) with sanidine are anorthoclase and adularia. Adularia, whose x-ray pattern closely resembles this sanidine, is usually named on the basis of a low-temperature vein association. The range of composition for anorthoclase by various authors is Or₃₇Ab₆₃-Or₀Ab₁₀₀ (Marfunin 1962, p. 155); Or₅₋₄₀ (Wright and Stewart 1968, p. 66); Or₀₋₃₈ at An₀ to Or₁₄₋₃₉ at An₁₀ (J. V. Smith 1974, p. 444); Or₇₀Ab₃₀-Or₂₀Ab₈₀ (Alling 1936 cited in Laves 1952, p. 571). In the last case, Alling's figure 10B of page 72 is after Chudoba (1932) and the area on the Ab-An-Or diagram which appears to be from Or₇₀Ab₃₀ to Or₂₀Ab₈₀ is labelled "anorthoclase and perthite" and lies between albite and microcline. Therefore, the O'Leary alkali feldspar is named sanidine.

The previously assumed stability fields of sanidine, anorthoclase, and adularia are now under some scrutiny. Wyart and Sabatier (1956), when trying to exchange alkalis between microcline and low albite in an aqueous chloride solution, discovered that the feldspars became sanidine and high albite at a temperature as low as 350°C. J. V. Smith (1974, p. 423) stated that "meta-sanidine" may occur below the temperature at which microcline is stable (about 450°C) as a result of rapid growth, and these are probably the crystals which have been called adularia. Kastner (1971, p. 1424) listed a few occurrences of authigenic alkali feldspar which were monoclinic and disordered (thus possibly sanidine.
CHEMISTRY OF RAPAKIVI ROCKS

Major Elements

There is little agreement on the characteristic major element chemistry of rocks which contain rapakivi. Sahama (1945, pp. 63-4) stated that rapakivi granites have more SiO₂ and K₂O and less MgO, CaO, and Al₂O₃ than do other granites. This probably includes, however, both wiborgite and ptyerlite. Vorma (1971) agreed that Scandinavian rapakivi bulk compositions are low in Al₂O₃. Various papers have shown that Al₂O₃ is at least 12.3 weight percent in rapakivi. Wahl (1925), as cited in Holmquist (1939, p. 164), stated that rapakivi granites compared with other granites are low in MgO and high in iron oxides. The main rapakivi of Terzaghi (1940, p. 112) and the Eisenkappel rapakivi granite of Austria (Richter 1966, p. 445) have less K₂O than do the Scandinavian ones. There is no correlation between rapakivi and the ratio Na₂O/K₂O—the O'Leary Porphyry's ratio varies between 1.3 and 1.6 while that of the Scandinavian occurrences ranges from 0.4-0.5. The chemical composition of the O'Leary Porphyry varies from location to location on the two domes (Table I). A comparison of the O'Leary Porphyry with other rapakivi rocks is shown on the Q-Or-An+Ab plot of Figure 2 and the Or-Ab-An plot of Figure 3. Rapakivi generally plot within the plagioclase field (Figure 4) suggesting that in them plagioclase crystallizes before alkali feldspar or quartz.
Table I. U. S. Geol. Survey Chemical Analyses and Partial Norms of O'Leary Porphyry.

<table>
<thead>
<tr>
<th></th>
<th>1&lt;sup&gt;a&lt;/sup&gt;</th>
<th>2&lt;sup&gt;b&lt;/sup&gt;</th>
<th>3&lt;sup&gt;b&lt;/sup&gt;</th>
<th>4&lt;sup&gt;b&lt;/sup&gt;</th>
<th>5&lt;sup&gt;b&lt;/sup&gt;</th>
<th>6&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>71.2</td>
<td>70.2</td>
<td>69.6</td>
<td>69.0</td>
<td>66.0</td>
<td>65.4</td>
</tr>
<tr>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>14.4</td>
<td>14.1</td>
<td>14.9</td>
<td>14.8</td>
<td>15.4</td>
<td>15.0</td>
</tr>
<tr>
<td>FeO</td>
<td>3.4</td>
<td>3.1</td>
<td>3.15</td>
<td>1.68</td>
<td>2.42</td>
<td>2.63</td>
</tr>
<tr>
<td>FeO</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>2.03</td>
<td>1.98</td>
<td>1.94</td>
</tr>
<tr>
<td>(all Fe as FeO&lt;sub&gt;3&lt;/sub&gt;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.7</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>CaO</td>
<td>1.5</td>
<td>1.5</td>
<td>1.6</td>
<td>2.2</td>
<td>2.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Na&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>5.0</td>
<td>5.1</td>
<td>5.1</td>
<td>5.2</td>
<td>5.2</td>
<td>4.9</td>
</tr>
<tr>
<td>K&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>3.8</td>
<td>4.0</td>
<td>3.7</td>
<td>3.4</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.27</td>
<td>0.25</td>
<td>0.32</td>
<td>0.5</td>
<td>0.7</td>
<td>0.71</td>
</tr>
<tr>
<td>P&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td>0.15</td>
<td>0.11</td>
<td>0.14</td>
<td>0.17</td>
<td>0.22</td>
<td>0.24</td>
</tr>
<tr>
<td>MnO</td>
<td>0.09</td>
<td>0.12</td>
<td>0.08</td>
<td>0.1</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>tH&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>0.07</td>
<td>0.15</td>
<td>0.05</td>
<td>0.02</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>-H&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>0.07</td>
<td>0.17</td>
<td>0.25</td>
<td>0.13</td>
<td>0.12</td>
<td>0.33</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.05</td>
<td>0.07</td>
<td>0.07</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Total</td>
<td>100.43</td>
<td>99.22</td>
<td>99.31</td>
<td>100.02</td>
<td>99.59</td>
<td>99.19</td>
</tr>
</tbody>
</table>

1— P31 location on O'Leary road, south side O'Leary Peak
2— Western O'Leary Peak (mm821)
3— Eastern O'Leary Peak (mm820A)
4, 5, 6— Barton Dome (mm812, 811, 806)
<sup>a</sup> E. Wolfe, written communication, 1970
<sup>b</sup> R. Moore, written communication, 1976
Figure 2. Norms of Rapakivi Rocks Containing Mantled Alkali Feldspars. — Data is from Hutchinson (1956), Karner (1968), Larrabee, Spencer, and Swift (1965), Sahama (1945), Savolahti (1956), Sederholm (1967), Simonen and Vorma (1969), and Vorma (1971). OLP is the norm for the O'Leary Porphyry.
Figure 3. Norms of Rapakivi Rocks Plotted on Or-Ab-An Diagram. — See Figure 1 for sources of data. OLP is norm of O'Leary Porphyry.
Figure 4. Norms of Rapakivi Rocks Containing Mantled Alkali Feldspars, Plotted on Diagram Modified after James and Hamilton (1969, figs. 3 to 6). — See Figure 1 for sources of data. OLP is norm of O'Leary Porphyry.
Trace Elements

Sahama (1945, pp. 63-4) stated that the eastern Fennoscandian rapakivi granites compared with other granites are higher in F, Zr, Hf, Ba, Rb, Pb, Ta, and the rare earths and are depleted in Li and Cs.

\( \text{P}_2\text{O}_5 \) and fluorine appear to be higher in rapakivi rocks than in non-rapakivi rocks. Fluorite is common within rapakivi (Greenwood 1951, p. 1158; Hutchinson 1956; Lowell and Sides 1973; Riederer 1967; Schermerhorn 1956). Many rapakivi occurrences have no analyses for fluorine. A further difficulty is that it is difficult to distinguish magmatic from secondary fluorite, since fluorite may be hydrothermal. Addition of HF brings down the crystallization temperature (Savolahti 1962, p. 73) and decreases the orthoclase field (van Platen 1965, p. 352) which could result in plagioclase becoming stable rather than alkali feldspar. The fluorine content (total of six analyses) of the Scandinavian wiborgite rapakivi has the following range: 0.05-0.21 weight percent (Vorma 1971, p. 8; Simonen and Vorma 1969, p. 9; Yeshin, Obukhov, and Khrenov 1971, p. 83). Hutchinson (1956, p. 782) listed the fluorine content of the rapakivi Enchanted Rock Batholith of Texas as 0.24 weight percent.

Specific ion electrode analyses (sodium peroxide fusion) of five O'Leary Porphyry samples by Rocky Mountain Geochemical Corporation gave a range of fluorine of 0.069-2.20 weight percent. Two are from O'Leary Peak; one from the Eastern Flat (Figure 1) and two from Darton Dome. The high value is from the northwestern part of the rim surrounding
the Central Depression (Figure 1) of O'Leary Peak. This area shows bleaching and alteration and is near a likely vent area where fumarolic activity may have occurred. A 0.090 value (the highest value except for the bleached area) is from the Eastern Flat where rapakivi is best developed. Therefore, there appears to be a correlation between higher (but not alteration levels) fluorine contents and rapakivi development.

**Atomic Absorption Work**

Samples had been collected on a grid covering O'Leary Peak and Darton Dome in order to determine any inhomogeneities within each dome and the chemical differences between the two domes. Atomic absorption proved to be a quick, accurate method of analysis for calcium, sodium, potassium, iron, and magnesium. Table II shows the results from each run on the standards. P31 is the same as that of analysis #1, Table I. All runs show iron as Fe$_2$O$_3$.

Figures 5 to 9 show the oxide value maps of O'Leary Peak and Darton Dome constructed from the atomic absorption data on the O'Leary Porphyry. The contours seem to show linear features in a northwest-north-northwest direction on O'Leary Peak and east-northeast on Darton Dome. These linear features are also reflected in the topography.

On the basis of the atomic absorption analyses, the porphyry of O'Leary Peak is lower in MgO, CaO, and Fe$_2$O$_3$, and higher in Na$_2$O than is that of Darton Dome. This result is in agreement with the analyses of Table I except for Na$_2$O. The area of O'Leary Peak near the Eastern Flat shows the best developed rapakivi. The oxide maps show this area
<table>
<thead>
<tr>
<th>Sample Date</th>
<th>CaO</th>
<th>MgO</th>
<th>Fe as Fe₂O₃</th>
<th>Na₂O</th>
<th>K₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>P31 U.S.G.S. Analysis</td>
<td>1.50</td>
<td>0.40</td>
<td>3.50</td>
<td>5.00</td>
<td>3.80</td>
</tr>
<tr>
<td>10/24 run</td>
<td>1.43</td>
<td>0.30</td>
<td>1.85-1.90</td>
<td>5.20</td>
<td>3.80</td>
</tr>
<tr>
<td>11/1</td>
<td>1.50</td>
<td>0.34</td>
<td>2.65-2.70</td>
<td>5.00</td>
<td>4.10</td>
</tr>
<tr>
<td>11/7</td>
<td>1.46-1.49</td>
<td>0.39</td>
<td>3.40</td>
<td>5.40</td>
<td>4.20</td>
</tr>
<tr>
<td>11/14</td>
<td>1.50</td>
<td>0.41</td>
<td>3.60</td>
<td>5.40</td>
<td>4.35</td>
</tr>
<tr>
<td>11/21</td>
<td>1.50</td>
<td>0.40</td>
<td>3.60</td>
<td>5.00</td>
<td>4.20</td>
</tr>
<tr>
<td>12/5</td>
<td>1.50</td>
<td>0.40</td>
<td>3.40</td>
<td>5.50</td>
<td>3.90</td>
</tr>
<tr>
<td>Avg.</td>
<td>1.50</td>
<td>0.40</td>
<td>3.50</td>
<td>5.30</td>
<td>4.20</td>
</tr>
<tr>
<td>BF U.S.G.S. Analysis</td>
<td>1.80</td>
<td>0.40</td>
<td>3.90</td>
<td>5.60</td>
<td>3.10</td>
</tr>
<tr>
<td>10/24 run</td>
<td>1.86</td>
<td>0.36</td>
<td>3.75</td>
<td>6.2-6.6</td>
<td>3.10</td>
</tr>
<tr>
<td>11/1</td>
<td>1.73-1.77</td>
<td>0.36</td>
<td>3.90</td>
<td>6.20</td>
<td>2.80</td>
</tr>
<tr>
<td>11/7</td>
<td>1.80</td>
<td>0.37</td>
<td>4.10</td>
<td>6.20</td>
<td>3.00-3.30</td>
</tr>
<tr>
<td>11/14</td>
<td>1.83</td>
<td>0.37</td>
<td>4.25</td>
<td>6.20</td>
<td>3.35</td>
</tr>
<tr>
<td>11/21</td>
<td>1.80</td>
<td>0.40</td>
<td>4.30</td>
<td>6.20</td>
<td>3.20</td>
</tr>
<tr>
<td>12/5</td>
<td>1.80</td>
<td>0.40</td>
<td>3.90</td>
<td>6.20</td>
<td>3.10</td>
</tr>
<tr>
<td>Avg.</td>
<td>1.80</td>
<td>0.39</td>
<td>4.10</td>
<td>6.20</td>
<td>3.20</td>
</tr>
</tbody>
</table>
Figure 5. MgO Distribution (Weight Percent, Atomic Absorption Results) on O'Leary Peak and Darton Dome.
Figure 6. CaO Distribution (Weight Percent, Atomic Absorption Results) on O'Leary Peak and Darton Dome.
Figure 7. K$_2$O Distribution (Weight Percent, Atomic Absorption Results) on O'Leary Peak and Darton Dome.
Figure 8. Na$_2$O Distribution (Weight Percent, Atomic Absorption Results) on O'Leary Peak and Darton Dome.
Figure 9. Fe₂O₃ Distribution (Weight Percent, Atomic Absorption Results) on O'Leary Peak and Darton Dome.
to be higher in all oxides than other areas of O'Leary Peak and Darton Dome.

Lows of Na$_2$O, K$_2$O, CaO, and MgO coincide on the northwest side of O'Leary Peak in a location where field study has shown that a spine with vertical flow banding exists. Lows of the five oxides on the eastern side of O'Leary Peak have more scatter, but are located near the point of extrusion of the Eastern Flat flow from the eastern side of O'Leary Peak. Data on Barton Dome are less clear. The low of Na$_2$O coincides with the vent on the crest of the dome. Two other locations of lows occur—one (of CaO, Fe$_2$O$_3$, and MgO) on the southwestern side of the dome and one (CaO, K$_2$O, and MgO) on the northeastern side of the dome, where flow apparently has occurred.

A tentative conclusion is that "lows" in oxides nearly coincide with vents on the two domes. Vents probably contain the later erupted and thus the most differentiated magma. Crystallization is likely to have continued longer and xenoliths to have reacted more in this more differentiated magma. Crystallization of sanidine and oligoclase would remove sodium, potassium, and some calcium from the magma; resorption of the kaersutite-plagioclase xenoliths would add calcium, magnesium, iron, and sodium to the magma. "Lows" on the maps of sodium and potassium could, therefore, correspond to areas of crystallization while magnesium, iron, and calcium "lows" could correspond to areas of lower xenolith resorption or availability. Apparently, then, vent areas on O'Leary Peak and Barton Dome are areas of greater crystallization and less xenolith resorption (possibly resulting from lower availability of xenoliths). Perhaps the supply of xenoliths had been nearly exhausted by the time
of the last erupted material, or perhaps the temperature was too low to promote reaction.

If this relationship is accurate, it may prove useful in either locating vents which show no surface characteristics, or in helping to determine the magmatic history of an area.
PETROLOGY OF THE O'LEARY PORPHYRY

The melting interval of the porphyry was determined by hydrothermal experiments. Electron microprobe scans across the groundmass resulted in chemical data on the porphyry.

Hydrothermal Experiments

One object of hydrothermal experiments on ground O'Leary Porphyry was to determine two melting intervals for it—one with 5 and the other with 15 weight percent added water (OP series). In this way the actual melting interval of the rock could be bracketed, since the actual water content of the magma is thought to have been between 5 and 15%. The results of these experiments are given in Figures 10 and 11, which show that the order of crystallization with decreasing temperature of silicate crystals from the O'Leary Porphyry at 1 kb water pressure is plagioclase, sanidine, and quartz. The other object of this work was to place sanidine seed crystals with a mixture of ground porphyry and water under different conditions of temperature and pressure to see whether the sanidine would form plagioclase mantles (S and SX series).

Defocused Microprobe Scans

Microprobe scans with the beam defocused to approximately 100μ rather than the normal 2-5μ are thought to give a good rough estimate of the average composition of groundmass (Prinz, Bunch, and Keil 1971). The results of the defocused scans are given on the graphs of Figures
Figure 10. Hydrothermally Determined Melting Interval for O'Leary Porphyry with 5 Weight Percent Added Water.
Figure 11. Hydrothermally Determined Melting Interval of O'Leary Porphyry with 15 Weight Percent Added Water.
12 and 13. The sharp variation suggests that the inhomogeneity of the groundmass was such that mineralogical differences are being seen rather than any diffusion gradients.

**Composition of Xenoliths**

The compositions of andesite xenoliths are given in Table III. Comparison of these compositions with that of the P31 analysis of the O'Leary Porphyry makes calculations possible concerning the amount of assimilation of xenoliths.

The composition of the xenolithic plagioclase and kaersutite are also given in Table III. The kaersutite is classified according to Leake's (1968, p. 9) method. The kaersutite within the porphyry apparently came from the andesite xenoliths, which are composed mainly of kaersutite and plagioclase with minor magnetite and/or hematite and olivine.

Williams et al. (1954, p. 43) distinguished andesites from basalts in that the former have plagioclase with An<50 and SiO₂>52 weight percent. Manson (1967, p. 221) stated that basalts have <56% SiO₂ and >3.0% MgO (if FeO <10%). On the basis of these criteria, the xenoliths are not basalt but andesite. The xenoliths are, however, unusually high in TiO₂, P₂O₅, and Na₂O for andesites as compared with values given by Chayes (1969, p. 3). The xenoliths are strongly embayed and, on the eastern side of O'Leary Peak, form schlieren.
Figure 12. Defocused Microprobe Scans on Pb1-y from Xenolith (Left) through O'Leary Porphyry to Mantled (Rimmed) Sanidine (rs). — Beam diameter is about 100µ.
Figure 13. Defocused Microprobe Scan on PB1-X from Mantled (Rimmed) Sanidine (Left) Xenolith (Right). — Beam diameter is about 100μ.
Table III. Chemical Analyses of Xenoliths and Their Minerals.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>56.6</td>
<td>55.6</td>
<td>40.8-41.8</td>
<td>74.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>16.7</td>
<td>16.1</td>
<td>11.9-13.1</td>
<td>14.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>9.46</td>
<td>3.97ᵃ</td>
<td>12.6-15.8</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td>0.05</td>
<td>4.97ᵃ</td>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>2.5</td>
<td>3.4</td>
<td>12.3-13.7</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>5.0</td>
<td>6.6</td>
<td>10.5-11.2</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na₂O</td>
<td>4.7</td>
<td>4.6</td>
<td>2.7</td>
<td>5.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K₂O</td>
<td>2.2</td>
<td>1.5</td>
<td>0.7-0.8</td>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.76</td>
<td>1.9</td>
<td>4.8-5.7</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.53</td>
<td>0.56</td>
<td>-</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>0.18</td>
<td>0.17</td>
<td>-</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΣH₂O</td>
<td>0.46</td>
<td>0.72</td>
<td>-</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>0.07</td>
<td>0.15</td>
<td>-</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100.16</td>
<td>100.24</td>
<td>96.3-104.8</td>
<td>100.71</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An  44  45
Ab  53  53
Or  3   2
Total (E) 100 100

¹As FeO

1—U. S. Geol. Survey analysis of red xenoliths (R. Moore, written communication, 1976)
2—U. S. Geol. Survey analysis of black xenoliths (R. Moore, written communication, 1976)
3—University of Arizona microprobe analysis of kaersutite
4—University of Arizona microprobe analysis of xenolith plagioclase
5—Moore, Wolfe, and Ulrich (1974) analysis of xenolith plagioclase
6—Calculated original composition of O'Leary magma based on analysis of xenoliths and P31 analysis of porphyry (see Appendix for discussion of method)
DESCRIPTION OF RAPAKIVI

Shape of Rapakivi

The shape of rapakivi may be euhedral, taublar, and rectangular (Dawes 1966, p. 570; Erickson 1969, p. 77; Maucher 1938, p. 80; Sylvester 1962, pp. 600-1) or anhedral, called "ovoidal" (Dawes 1966, p. 570; Erickson 1969, p. 77; Terzaghi 1940, pp. 112-4; Vorma 1971). The O'Leary rapakivi vary from nearly euhedral to anhedral and embayed.

Nature of Core

Some rapakivi show Carlsbad twin planes which continue from the core through the mantle (Phillips 1972, p. 92; Riederer 1966, p. 34). Thus, the core and mantle would appear to be coherent. A two-individual (probably Carlsbad) twin can sometimes be seen to continue from the core into the mantle of O'Leary rapakivi. In one instance the core of an O'Leary rapakivi was made up of several sanidine crystals, apparently due to synneusis. Synneusis is a process described by Vance (1969) by which two or more crystals growing in a melt join along some favored crystallographic direction producing something which may resemble a twin or a mantle. The contact between crystals (twin plane?) of this O'Leary rapakivi continues into their common mantle (Figure 14).

Although some O'Leary sanidines—both mantled and unmantled—appear to be optically zoned, no chemical zonation was indicated by microprobe results. Subhedral plagioclase crystals are commonly poikilitic in cores and mantles of rapakivi. This is also true of O'Leary
Figure 14. Drawing of Multiple-Core Mantled (Rimmed) Sanidine from Thin Section P-21. Lines indicate polysynthetic twinning on discontinuous mantle (rim). Sponge texture is on sanidine.
where many show zoning. While poikilitic plagioclases in the O'Leary Porphyry are sometimes arranged along zones in the sanidine core, as is common in rapakivi (Savolahti 1962, p. 69), more often they are randomly oriented both in the core and mantle. Many are located on the mantle-core border extending into both the core and mantle; others are oriented parallel to the border. Mafics are also poikilitic in cores and mantles.

The mantle-core border of most rapakivi is irregular and may suggest resorption of the core (Gates 1953, p. 68; Terzaghi 1940, pp. 112-4). The mantle-core border of the O'Leary rapakivi is usually only slightly irregular but the core may be strongly embayed and channeled. The channeling varies in size and contains isotropic material, the composition of which is given under "Replacement Textures."

Nature of the Rim

The plagioclase mantles of rapakivi may be as thick as 5 mm (Sederholm 1928, p. 85); those in the O'Leary rapakivi range from 0.5 to 5 mm. The mantle may be continuous (Phillips 1972, p. 91; Vorma 1971; Wahl 1925), or discontinuous (Buddington and Leonard 1962, p. 53; Riederer 1967; Vorma 1971; Wahl 1925). When discontinuous, the mantle consists of many crystals oriented with their lengths and polysynthetic twins parallel to the contact with the alkali feldspar core (Maucher 1938, p. 80; Phillips 1972, p. 91; Sylvester 1962, pp. 600-1; Terzaghi 1940, pp. 112-4; Volborth 1973, p. 34). Because of this high degree of alignment, Riederer (1967, pp. 103-6) believed that the discontinuous mantles of the granulites which he studied were once continuous and were subsequently replaced by the alkali feldspar core.
Twenty-one O'Leary sanidine crystals with at least partial mantles were studied in thin section. The rapakivi are highly variable. In most cases the mantle is discontinuous. The polysynthetic twinning of the mantle, where visible through replacement textures, is parallel to the length of the rapakivi crystal; thus, it is parallel to the mantle-core border on the sides of the crystal and perpendicular to that border at the ends of the crystal (Figure 15). One crystal, seen in this photograph, has a continuous mantle. Some crystals suggest that originally they had multiple mantles (Figure 16), although this cannot be confirmed because of confusion due to replacement textures.

Replacement Textures

Perthite is commonly associated with rapakivi (Dawes 1966; Elders 1968; Gates 1953; Savolahti 1956, 1962; Schermerhorn 1956; Sylvester 1962; Vorma 1971).

The mantling on the O'Leary rapakivi is confused by sparse to dense "perthite" which obviously replaced both mantle and core. At least one discontinuous mantle consists of plagioclase crystals (which extinguish simultaneously) surrounded by "strong" perthite which is perpendicular to the length of the crystals (Figure 16). It appears that the replacement "perthite" altered a continuous mantle into a series of parallel plagioclase crystals. The replacement "perthite" varies from a typical "string" perthite, as in Figure 16, to a confused network of two-dimensional (and possibly the third dimension which is unseen in thin section) channeling leaving a "dusted" appearance (Figure 17). The isotropic material within this type of channeling has the following
Figure 15. Polaroid Mosaic of Microprobe Thin Section "URSX". — Note continuous plagioclase mantle with polysynthetic twinning. Crystal is about 3 mm wide.
Figure 16. Drawing of Mantled (Rimmed) Sanidine from Thin Section P18b. — Lines indicate direction of polysynthetic twinning.
Figure 17. Drawing of Mantled (Rimmed) Sanidine from Thin Section P-24. -- This rapakivi contains poikilitic plagioclase and a network "replacement texture."
composition in weight percent: CaO 0.8-1.7, Na₂O 0.9-3.8, K₂O 0.4-7.1. Larger channeling on one sanidine had the following composition: CaO 10.1-14.5, Na₂O 0.2-0.3, K₂O 0.4-0.8. Only the elements listed were analyzed. This network is usually small compared to the electron beam and thus some analyses may include small mafic minerals. The network texture resembles the "sponge" texture on the plagioclases (discussed in "Regional Setting").

It is possible that both the "perthite" and the channeling are late-stage replacement textures. It is impossible to distinguish the replacement "perthite" from what may be exsolution perthite. Only one analysis of "string" perthite was made because of the small size of the "string" (see "Electron Microprobe Results"). "String" perthite usually occurs at acute angles to the mantle edge. In one crystal it occurs in two directions at about 45° to one another, forming an "elbow" appearance. Two directions of perthite have been explained (Ohashi 1974, p. 402) as due to a double minimum of string energy consistent with (601) or (801) during exsolution. Evidence concerning exsolution perthite is discussed under the "Origin of the Rapakivi."

Myrmekite

One apparent difference between the O'Leary rapakivi and that of most other occurrences is the lack of myrmekite in O'Leary. There are only two possible blebs of myrmekite (Figure 14). Various irregularly shaped quartz blebs and myrmekite are described within rapakivi (Budanov 1964, p. 105; Buddington and Leonard 1962, p. 53; Dawes 1966, p. 570;
Summary

Although the O'Leary rapakivi consists of sanidine in a volcanic rock rather than orthoclase or microcline in a plutonic rock, the rapakivi is quite similar to all other world occurrences except for the apparent lack of myrmekite. The mantles are usually discontinuous, having been replaced by perthite or a network of isotropic material which also replaces the sanidine cores. Poikilitic plagioclases occur within the O'Leary rapakivi but are easily distinguished from mantle constituents by their lack of alignment and by their zoning.
COMPOSITION OF RAPAKIVI FELDSPARS

The cores of rapakivi reported in the literature may be microcline, orthoclase, or sanidine. These cores sometimes have the same composition as the coexisting unmantled alkali feldspars (Elders 1968, pp. 42-44; Stewart 1959, p. 300) and sometimes do not (Holmquist 1939, pp. 158-9). In most instances, chemical data are not available on both coexisting mantled and unmantled alkali feldspars.

**Rapakivi Feldspars from the Literature**

The composition of rapakivi cores ranges from An 0-7 Ab 20-36 Or 62-76 (Holmquist 1899; Larsen et al. 1938; Phillips 1972; Stewart 1959; Terzaghi 1940; Zavaritsky 1937). Holmquist (1939, pp. 158-9) listed mantled orthoclases from Wiborg of compositions ranging An^1^ Ab^4^ Or^4^ and unmantled orthoclase of An^4^ Ab^24^ Or^57^-73. Ehrreich and Winchell (1969, p. 905) gave the composition of rapakivi sanidine cores from a rhyolite flow as Ab^52^ Or^4^.


Plagioclase phenocrysts within rapakivi rocks have the following composition: An^3^-40 (Ehrreich and Winchell 1969, p. 905; Erickson 1969,
These analyses were by wet chemistry on mineral separates in the case of Holmquist, Sviridenko, and apparently Terzaghi. Those of Phillips are by optics and wet chemistry, of Ehrreich and Winchell by optics and x-ray, of Erickson and Volborth by optics, and of Elders by microprobe.

**O'Leary Feldspars**

Electron microprobe results and atomic absorption results on O'Leary feldspars are given in Tables IV and V. The microprobe results are plotted on an An-Ab-Or diagram in Figure 18.

**Rubidium and Strontium Analyses**

X-ray fluorescence work on sanidine separates from O'Leary Porphyry (P31) gave a value for rubidium of $123 \pm 1$ ppm and for strontium of $515 \pm 2$ ppm. Sanidines from tuffs and flows having $K_2O$ values less than those of O'Leary sanidines gave rubidium values ranging from 20-135 ppm (Noble and Hedge 1970, p. 235). Some Italian sanidines ($K_2O = 10.4-11.0$ weight percent) had rubidium contents from 285-620 ppm (Barbieri, Fornaseri, and Penta 1968, p. 192). Sanidine strontium values of less than 150 ppm indicate highly differentiated volcanics according to Noble and Hedge (1970, pp. 234-5). By this criterium the O'Leary Porphyry is not highly differentiated. Berlin and Henderson (1969, p. 240) listed strontium values of 1200-1500 ppm (three analyses) for sanidines from volcanic rocks in which plagioclase crystallized before sanidine and values of 240-1100 ppm (four analyses) for those sanidines from rocks in
Table IV. Chemistry of O'Leary Porphyry Sanidines.

<table>
<thead>
<tr>
<th>Ang of Several Crystals</th>
<th>Unmantled-Mantled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td><strong>Or</strong></td>
<td>60</td>
</tr>
<tr>
<td><strong>Ab</strong></td>
<td>36</td>
</tr>
<tr>
<td><strong>An</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Rb</strong></td>
<td>123±1ppm</td>
</tr>
<tr>
<td><strong>Sr</strong></td>
<td>515±2ppm</td>
</tr>
</tbody>
</table>

1—Average of many P31 crystals, x-ray fluorescence
2—Average of 45 runs P31 crystals
3—Average of 7 runs P13 (south side O'Leary Peak)
4—Average of 2 runs unmantled crystals 635 (southeast of Barton Dome)
5,6—University of Arizona microprobe on P31 crystals
7—Core of rapakivi University of Washington microprobe
8—Core of hydrothermal seed crystal, University of Arizona microprobe

*By Three Peak method x-ray diffractogram with KBrO₃ internal standard
<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>An</td>
<td>15</td>
<td>14-23</td>
<td>19</td>
<td>12-19</td>
<td>14-21</td>
<td>14-21</td>
<td>11-26</td>
<td>11-17</td>
<td>10-15</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Ab</td>
<td>76</td>
<td>63-76</td>
<td>72</td>
<td>65-78</td>
<td>72-78</td>
<td>72-78</td>
<td>70-80</td>
<td>40-55</td>
<td>37-49</td>
<td>69</td>
<td>75</td>
</tr>
<tr>
<td>Or</td>
<td>9</td>
<td>6-21</td>
<td>9</td>
<td>7-23</td>
<td>7-10</td>
<td>7-10</td>
<td>4-9</td>
<td>15-21</td>
<td>15-22</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Σ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>66-93</td>
<td></td>
<td>62-86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>63.8-67.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17.1-22.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.4-3.5</td>
<td>2.0-3.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na₂O</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.5-6.2</td>
<td>4.1-5.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K₂O</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.6-3.5</td>
<td>2.5-3.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Σ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>94.8-97.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1—Clear mantles on rapakivi, University of Arizona microprobe
2—"Spongy" or "perthitic" mantles, University of Arizona microprobe
3—String perthite
4—Rapakivi mantle, University of Washington microprobe
5—Poikilitic plagioclases in rapakivi, University of Arizona microprobe
6—Plagioclase phenocrysts, University of Arizona microprobe
7—Plagioclase phenocrysts, University of Washington microprobe
8,9—Mantles on hydrothermal seed crystals, University of Arizona microprobe
10—Plagioclase separate P31, atomic absorption
11—Ang. O'Leary plagioclase (Moore, Wolfe, and Ulrich 1974, p. 483)
Figure 18. Microprobe Results on O'Leary Porphyry Feldspars Including Plagioclase and Mantled (Rimmed) and Unmantled (Unrimmed) Sanidines.
which sanidine crystallized first or shortly after plagioclase. Even though its strontium value falls into the "sanidine first" group, the hydrothermal experimental work on the O'Leary Porphyry with 5 and 15% water shows plagioclase to have crystallized before sanidine.

**Hydrothermal Seed Crystals**

The seed crystals SX7 and S7, which were run in hydrothermal experiments (Appendix A), grew mantles which showed no polysynthetic twinning. One crystal was run with added xenolith material. Since both grew mantles, apparently there was already sufficient sodium and calcium in the porphyry to form the mantle—probably from earlier contamination.

The composition of the seed cores remained the same before and after the experiments, while the composition of the seed mantles varied across and along the mantle (Tables IV and V). The analyses show that the mantles are not stoichiometric plagioclase, although they are enriched in sodium and calcium relative to the seed crystal. The mantles contain too much Al$_2$O$_3$ and SiO$_2$ for stoichiometric plagioclase.

A discussion of stoichiometry of feldspars is not usually undertaken by most authors. Until recently analytical techniques were not always good enough and contamination problems were not resolved well enough to either support or reject the possibility of non-stoichiometry in the feldspars (Luth and Tuttle 1966, pp. 1360-1). However, some authors have considered the possibility (Chayes and Zies 1962, p. 116), who stated: "... it seems to us that the possibility of systematic departure from the assumed 1:1:6 ratio ... in alkali feldspars
deserves more than casual consideration." Holmquist (1939, p. 159) concluded "... dass die Gesteinfeldspate manchmal unrein oder gewissermassen chemisch fehlgebaut sind." This author has translated Holmquist's words as "... that the rock feldspars many times are impure or, to some degree, chemically non-stoichiometric." Luth and Tuttle (1966, p. 1360) and Sturt (1970, p. 824) indicated that plots of many alkali feldspar compositions have shown that most are not stoichiometric with respect to alumina and silica. Barth (1969, p. 13) cited an example where it was necessary to add the end member nepheline to complete a feldspar composition. Bhatty, Gard, and Glasser (1970, p. 787) stated that "anorthite" can take up to 10 mole percent excess alumina. Excess Al\textsuperscript{3+} may be included associated with twinning according to Bhatty et al. (1970, p. 780) or Al\textsubscript{6} octahedra may accidentally be included in growing feldspars as point defects along crystallographic shear planes or collapsed twin boundaries (Torske 1974, p. 79).

The seed mantles have too much alumina to be stoichiometric. This suggests that alumina from the seed crystal was used to form the mantle. Since aluminum diffusion "lags" in the melt (Bottinga, Kudo, and Weill 1966, p. 797), if diffused aluminum were the source for the aluminum in the mantle, a non-stoichiometric rim with excess alkalis would be expected rather than one with excess alumina, as is the case here. The sodium and calcium having no source in the sanidine must have diffused to the mantle but not in sufficient amounts. These mantles, then, are not crystallized around the seed but are replacements of the
seeds. This would account for rapakivi mantle-core borders being irregular and the smaller size of sanidine cores than of unmantled sanidines.

The seed mantles are not stoichiometric plagioclase; however, they are much richer in sodium and calcium than the seed cores. Thus, a process similar to that which formed the O'Leary rapakivi has occurred. The conditions under which these mantles were formed are not the same as those during which the rapakivi formed; the volatiles are probably different and assimilation of xenolith material has progressed farther in the first. Nonetheless, the conditions under which these seed mantles were formed must be examined in consideration of rapakivi formation.
THE ORIGIN OF THE
RAPAKIVI OF THE O'LEARY PORPHYRY

The literature concerning the origin of rapakivi is extensive. The presentation here will be a statement and discussion of the major theories in more-or-less chronological order. The author does not believe that there is a single mechanism which forms rapakivi. In this belief, the author is joined by Erickson (1969, p. 108), who stated "... not all rapakivis need have identical genesis."

Early Theories

Early theories include the following: Holmquist's (1901) liquation theory, Popoff's (1903) gravitative movement of ovoids theory, Vogt's (1906) and Harker's (1909) eutectic supersaturation theories, and Wahl's (1925) theory of the melting of the alkali feldspars as a result of an increase in temperature or decrease in pressure, adhesion of plagioclase phenocrysts, and subsequent fusion by decrease in temperature. None of these theories are supported today. Sederholm's (1928) theory that high melt viscosities hinder diffusion around a growing alkali feldspar is, however, still considered. A similar theory is that of Riederer (1967, p. 108), who suggested that fluctuation of the alkali concentration of pore solutions caused the growth of rapakivi in the German granulite-gneisses which he studied.
Major Theories

There are three major classes of theories of rapakivi formation: metamorphic-metasomatic, exsolution, and magmatic. The three can, naturally, overlap.

Metamorphic-metasomatic (Felspathization) Theories

The terminology and mechanism of rapakivi formation from metamorphic-metasomaticity theories are not well agreed upon by workers. Unfortunately, much of the literature is in French or Russian--languages which this author does not read. There are numerous cases where plagioclase crystals are oriented within alkali feldspars in granitic rocks (see especially Smithson 1965). In some of these cases there is no evidence that these crystals were once a continuous mantle. Often the crystals do not extinguish optically simultaneously, suggesting that they were incorporated during growth of the alkali feldspar. This incorporation could have been during the magmatic stage of rock formation or during metamorphism--the evidence is often contradictory, especially in granitic rocks. In either case, however, the texture is not properly called "rapakivi" and the numerous papers on the subject have not been discussed here, since at least one O'Leary rapakivi has a continuous mantle and the others appear to have once been continuous.

While the igneous theories have been described in great detail by their supporters and much evidence for them supplied, often very little evidence is given to support the metamorphic-metasomatic theories (Allaart, Bridgwater, and Henriksen 1967; Dawes 1970; Goni 1961; Raguin
1965; Sato 1961). Other authors have used evidence which is equivocal. Augustithis (1973, p. 57), for instance, stated that rapakivi is of "blastogenic" origin because of its association with myrmekite, perthite, and graphic texture—all of which he considered metasomatic in origin. Gradwell (1956, p. 7) attributed rapakivi to felspathization on the basis of "hornfelsic" texture and association with xenoliths. Wegmann (1938, pp. 98-121) cited the zone of rapakivi granite between a granite and the metamorphic country rock as evidence of metamorphic origin. This association is just as valuable evidence for a "basification" mechanism (discussed later). Backlund (1938) for some time considered some Scandinavian rapakivi the product of metasomatic granitization of the Jotnian Sandstone. This theory is no longer accepted (Didier 1973, p. 215).

According to Vorma (1971), the following workers were proponents of a felspathization mechanism: Hawkes (1967), Dimanche and Michot (1966; in French), Sobolev (1947; in Russian), and Velikoslavinskiy (1953; in Russian). The first three proposed replacement autometamatically or metasomatically of plagioclase by alkali feldspar and the last two autometamorphic replacement of alkali feldspar by plagioclase. Since autometamatism is defined as "Alteration of a recently crystallized igneous rock by its own last, water-rich liquid fraction . . ." by the A.G.I. Glossary (Gary, McAfee, and Wolf 1972), this mechanism might be considered deuteric. The mantle-core borders in the O'Leary rapakivi are irregular and appear, as discussed earlier, to be due to reaction of the melt with the sanidine at the time of mantling. The distinction between autometamorphic reaction and reaction of a melt with its crystal "mush" appear subtle to this author.
Several persuasive descriptions of "metasomatic rapakivi" do exist. Fernando (1941) found rapakivi in gneisses having no associated igneous rocks and called upon first a potassium and then a sodium solution to form the rapakivi. Anderson (1937, p. 62) described albitized and epidotized rocks of cataclastic nature which include rapakivi. Greenwood (1951, p. 1161) described sawtoothed edges of albite rims which replaced perthite. These occurrences seem to have evidence of metasomatism.

Perhaps the most persuasive evidence for metasomatic rapakivi, however, is the arrangement of rapakivi in zones in Wisconsin rocks which are otherwise devoid of rapakivi (Prucha 1946). However, Elders (1968, p. 39) has studied the field area in detail and stated that the rapakivi are not localized in zones but are simply more obvious in the zones of brecciated and altered rock.

The most commonly used piece of evidence for a metamorphic-metasomatic origin of rapakivi is that they occur within xenoliths and within wallrock near the rapakivi granite. Most metasomatic proponents have claimed that this is proof of a metasomatic origin of the texture in the granite. Rapakivi in xenoliths are cited as evidence for metamorphic-metasomatic origin of the texture in granites (Budanov 1964, p. 105; Dawes 1970, p. 94; Dickson 1966, p. 53; Read 1944, p. 76; Volborth 1973, p. 37; Vorma 1971, p. 60).

Budanov (1964, pp. 105-6) visualized the melt entering the softened xenoliths either before the melt was fully crystallized or in the "... early alkali stage of post-magmatic transformation ...".
Schermerhorn (1956, p. 343) suggested that the "... xenoliths were reduced to a plastic, part-fluid condition...". Rapakivi commonly occur within the andesite xenoliths at O'Leary Peak. The rapakivi within the O'Leary Porphyry appear to be magmatic in origin, since they occur in fresh igneous rock showing no evidence of metasomatism or metamorphism. Thus, O'Leary casts a doubt, this author believes, upon the use of the existence of rapakivi in xenoliths as evidence of the metamorphic-metasomatic origin of the rapakivi of the rock within which the xenoliths occur.

Phillips (1972, p. 92) noticed rapakivi crystals which were on the rock-xenolith contact and stated that this implied "... both inclusion and magma were close to equilibrium." Such an association occurs within O'Leary. This author, however, cannot believe that equilibrium was nearly reached within the O'Leary Porphyry in which xenoliths were being assimilated and mantled sanidines formed.

This author envisions the occurrence of rapakivi in the xenoliths of O'Leary as due to incorporation of the mantled sanidines from the melt into plastic xenoliths (much as described by Schermerhorn 1956) during the movement of the melt and assimilation of the xenoliths. It is also possible that the xenoliths were originally molten as previously described.

This author makes no judgment as to the validity of metamorphic-metasomatic theories in general. However, no metamorphism has affected the Pleistocene extrusive dome of O'Leary Peak. The rapakivi are not localized along any fractures which might have supplied metasomatic
fluids. It seems unlikely that a metasomatic process has occurred, unless one considers the "basification" contamination of xenoliths as such. One additional consideration is the hydrothermal formation of rapakivi. Mantles can easily be formed by exchange in the laboratory with aqueous alkali chloride solutions. This would be analogous to some hydrothermal solutions contacting the igneous rock. Although in some locations this consideration may be warranted, there is no evidence that the O'Leary Porphyry encountered such extreme alteration.

Exsolution

The formation of mantles by exsolution has been accomplished in the laboratory by Tuttle (Hutchinson 1956, p. 795) in a few hours when water vapor was present. Exsolution forming mantles within the kalsilite-nepheline system is well known (Sahama 1962, pp. 170-1).

Tuttle (1952, p. 115) believed that the fine-grained plagioclase around each perthite grain in the Quincy granite may have been due to exsolution. Volborth (1962, p. 827) considered exsolution as well as other theories, but Riederer (1967, pp. 107-8) rejected the exsolution theory for metamorphic rocks as well as for granites.

Mantles were considered the "... stable state of an exsolved feldspar crystal" during rock deformation by Christie (1968, p. 191). Exsolution during deformation was called upon by Crosby (1971, p. 1792) and Poldervaart and von Backstrom (1949, pp. 461-2). Migration of exsolved material into fracture zones was proposed by Gates (1953, pp. 67-8). Buddington and Leonard (1962, pp. 53-4) suggested exsolution during pulsation of physiochemical conditions during deuteric alteration.
Dawes (1966, p. 570) combined exsolution and metasomatic theories by suggesting a series of exsolutions during "... post-magmatic potash metasomatism."

Sylvester (1962, pp. 602-3) analyzed mantled and unmantled alkali feldspars and found that the cores of mantled ones were high in Or, while the unmantled ones had no gradient. This relationship is what would be expected if exsolution had occurred, since the Ab and An components would migrate toward the mantle area. Perthite in the O'Leary rapakivi, however, occurs at the mantle-core border. If Ab and An components from perthite strings had migrated to form the mantle, perthite would be more likely in the core since it is farther from the mantle site. It is possible, however, that exsolution was completed forming the mantles and replacement perthite was later formed. Chemical evidence discussed later suggests otherwise, however.

If both mantled and unmantled feldspars began with the same composition (which would be supposed for similarly sized crystals unless evidence to the contrary were present), then exsolution in some and not in other crystals would result in two compositional groups of alkali feldspars. Savolahti (1962, p. 78) found that mantled and unmantled alkali feldspars didn't vary sufficiently from one another to be due to exsolution. The mantled and unmantled O'Leary sanidines (which are of the same size range) have a composition of An$_1$Ab$_{30-36}$Or$_{63-69}$ (see "Electron Microprobe Results"). This is strong evidence against exsolution as the mechanism of rapakivi formation at O'Leary Peak.
Another test of this theory is a comparison of the volume of the core to that of the mantle of rapakivi. Elders (1968, p. 45) stated that the ratio of alkali feldspar to plagioclase was variable from crystal to crystal in the Wisconsin rapakivi area. This is not what would be expected from exsolution from crystals originally the same composition. Elders (1968, p. 45) plotted the bulk composition of a Wisconsin rapakivi on Barth's An-Ab-Or solid solubility field diagram (Barth 1962a, p. 8). The composition corresponded to a temperature of greater than 900°C, which Elders believed improbable. A volume calculation on one O'Leary rapakivi resulted in a bulk composition of An_{5}Ab_{44}Or_{51}. This value, plotted on Barth's diagram, corresponded to a temperature of 890°C. According to experimental work (Figures 10 and 11), sanidine would be crystallizing from the O'Leary Porphyry at this temperature.

Another problem with the exsolution theory is the need to explain multiple mantles which are found on some crystals (Elders 1968, p. 40). Multiple mantles are visible in hand samples of O'Leary rapakivi, one of which shows an outer pink mantle and two inner white opaque discontinuous mantles. Multiple mantles have not been definitely identified in thin section because of the replacement textures which obscure the mantles (see "Description of Rapakivi"). Figure 16 does, however, suggest more than one mantle.

Magmatic Theories

Magmatic theories include any mechanism by which the phase boundary between plagioclase and alkali feldspar may be changed (sometimes more than once) so that, for the composition of the melt, alkali
feldspar is no longer stable and plagioclase begins to crystallize. There are numerous ways of changing this boundary including changes in pressure, temperature, and chemistry of the melt. The latter may be accomplished by disequilibrium reactions in the melt during fractional crystallization, assimilation of xenoliths, or mixing of magmas. All of these means were considered by Elders (1968, pp. 46–7) as possibilities. The O'Leary xenoliths may have been globules of magma which were injected into the O'Leary magma in a manner similar to that described by Eichelberger, oral communication, 1976). If the xenoliths were molten, rapakivi crystals would have been more easily incorporated into them and chemical diffusion may have occurred more readily. There are three widely considered theories which incorporate these factors: Tuttle and Bowen's (1958) theory, Stewart's (1959) theory, and the "basification" theory.

**Tuttle and Bowen.** The Tuttle and Bowen (1958, pp. 96–7) theory is essentially one of changing water pressure. It required that the magma begin crystallizing in the orthoclase field. Their description was concerned with the Ab–Q–Or system, although they believed that since rapakivi do not contain much CaO (the average being 1.59%) that An may be neglected as a first approximation. Alkali feldspar crystallized at about 800°C from a melt containing 2% water, causing the melt composition to change. With 15% crystals, the melt composition reached the minimum on the quartz boundary at about 770°C. If no water were lost, the water content of the magma was about 2.4%. As the water increased
in the melt, the water pressure rose causing the minimum composition to move toward the Ab corner of the Ab-Q-Or diagram. This can be seen by examination of Tuttle and Bowen's figures 22-25 (1958, pp. 54-6) and of diagrams by Luth, Jahns, and Tuttle (1964). At 660°C and 78% crystallization, the melt contained 10% water and had a water pressure of about 4 kb. At this point, the solvus was intersected causing quartz and two feldspars to crystallize simultaneously. The two feldspars changed their compositions with decreasing temperature. Tuttle and Bowen suggested that since the process was a slow one, no plagioclase nucleated but, rather, the already present feldspars became zoned—one composition moved toward oligoclase, and the other toward orthoclase.

Some obvious considerations concerning this theory's validity are:

1. What happens if plagioclase crystallizes before alkali feldspar?
2. Does the Ab-Q-Or system portrayed by Tuttle and Bowen model and predict nature?
3. Is it realistic to consider a build-up of 4 kb of water pressure?

Tuttle and Bowen (1958, p. 95), Sederholm (1928, p. 85), and Sviridenko (1968, p. 517) suggested that it is necessary for alkali feldspar to crystallize before plagioclase in order to produce rapakivi. Indeed, the alkali feldspars are often much larger than the coexisting plagioclase crystals (Tuttle and Bowen 1958, p. 95), as is the case at O'Leary. However, this need not be due to crystallization of alkali feldspars first. Nucleation, cooling rates (Terzaghi 1940, pp. 119-20),
and growth rates (Stewart 1959, p. 311) must also be considered and these are not yet known. Richter (1966, p. 453) and Terzaghi (1940, p. 117) believed plagioclase crystallized first in rapakivi magmas. Stewart (1959), p. 304, 308) stated that plagioclase crystallized first in most rapakivi granites. Vorma (1971, p. 63) plotted wiborgites (rapakivi granites with mantled alkali feldspars) from Scandinavia and found that they all lie within the plagioclase field with one exception. Pyterlites (no mantle), on the other hand, plotted in the quartz or alkali feldspar field. The O'Leary Porphyry plots within the plagioclase field (Figure 4). Further, experimental melting of O'Leary Porphyry showed that plagioclase began crystallizing before sanidine (Figure 11), since plagioclase was still present at temperatures greater than that at which sanidine disappeared. And, further, small poikilitic plagioclases may be seen in the center of the cores of some O'Leary rapakivi. The crystallization of plagioclase prior to alkali feldspar is not present in Tuttle and Bowen's theory.

More detailed experimental work has been done since that of Tuttle and Bowen. Their work did not consider the An component nor many other components present in a silicic melt which either do not enter into the feldspar system or do so only as trace elements (such as iron). Sviridenko (1968, p. 507) objected to the Tuttle and Bowen theory on these grounds. This author feels that omitting An and those mafics (such as amphibole) which compete with feldspar for elements may be significant.
Another problem concerns Tuttle and Bowen's description of one set of feldspars zoning toward oligoclase and the other toward orthoclase. This suggests a gradual zoning in both mantled and unmantled sanidines which is not seen in O'Leary.

Perhaps the most serious objection to this theory is, however, the build-up of water pressure of almost 4 kb. It seems unlikely that 4 kb of pressure could have built up in the O'Leary magma chamber. O'Leary appears to have some multiple mantles on rapakivi which would require the pressure to build up, then be bled off repeatedly.

Several other authors have suggested that a change in water pressure may have resulted in rapakivi. They believed that it caused a change in the location of the phase boundary between plagioclase and alkali feldspar. Terzaghi (1935, p. 373) suggested that an increase in pressure would result in a decrease in the orthoclase field. As Erickson (1969, p. 111) has pointed out, however, the effect would appear to be just the opposite according to Tuttle and Bowen (1958, pp. 54-6). Thus, a decrease in water pressure would decrease the orthoclase field and, for certain melt compositions, result in plagioclase rather than alkali feldspar being the stable phase. Stewart (1959, p. 305) mentioned fluctuation of water pressure as a possible explanation for multiple mantling.

Stewart. Stewart (1959) has presented work on the Ab-An-Or-SiO₂-H₂O system in which composition of feldspars change so rapidly that reaction between the melt and crystals is incomplete. This disequilibrium would result in alkali feldspar being present when the magma composition
is within the plagioclase + liquid + vapor + quartz field. Stewart sug-
gested that the alkali feldspar would be resorbed and plagioclase pre-
cipitated either as nuclei or mantles on preexisting plagioclase or
alkali feldspar. Such disequilibrium, according to Stewart, would not
be expected to mantle every alkali feldspar. This theory has the advan-
tage of explaining mantled and unmantled alkali feldspars occurring to-
gether. Stewart's system is based on the assumption that quartz and an
aqueous fluid coexist with the other phases at a constant pressure of 2
kb. The mantling, as described by this theory, would have occurred at
about 675-680°C. Vorma (1971, p. 63) believed that rapakivi formation
is more complex than that suggested by Tuttle and Bowen and thus sup-
ported Stewart's theory.

The test of Stewart's theory is whether the above assumptions
are reasonable, and the resulting feldspar compositions and temperatures
correspond to those in natural systems.

As in the case of Tuttle and Bowen (1958), Stewart's work was
done prior to the vast amount of phase work now available on the feld-
spar system. For example, he used Bowen and Tuttle's (1950) value for
the crest of the feldspar solvus (at 1 kb) of 660°C and Or45. More re-
cent data give a similar temperature but the critical composition is
usually given as closer to Or35-38 (Luth, Martin, and Fenn 1974, p. 307).
What difference such refinements would make upon Stewart's 1959 theory,
this author cannot say. Stewart's assumptions of coexisting quartz and
an aqueous fluid at 2 kb water pressure would seem reasonable for O'Leary
although the hydrothermal experiments were carried out on the porphyry at 1 kb.

Referring to figure 11 of Stewart's (1959, p. 312), the area of plagioclase + quartz + liquid + vapor stability can be seen. Stewart's mechanism is such that, due to disequilibrium, alkali feldspar still remains when the composition of the melt lies within this stability region. The alkali feldspar thus reacts and plagioclase is formed. It would appear that the composition of that plagioclase, and thus of the mantles on rapakivi, should be of the composition within that stability region. As seen from the diagram, that composition is about An$_{0-10}$Ab$_{55-70}$Or$_{30-40}$, quite near the Ab-Or sideline. This high Or content does not agree with any mantle composition that this author has seen in the literature nor with that of O'Leary, which is Or$_9$. The temperature at which this mantling would occur is given as 675-680°C. This temperature is below the O'Leary Porphyry solidus as determined at 1 kb in the experimental work and, projected to 2 kb, would likely also be subsolidus. Although the specific crystallization sequence given by Stewart does not seem to fit for O'Leary, the general theory of disequilibrium resulting in unstable alkali feldspar crystals which are then mantled seems plausible to this author.

**Basification.** The topic of basification can be divided into two mechanisms:

1. reaction of hornblende to form biotite during normal crystallization resulting in reduced potassium and increased calcium and sodium in the melt (Erickson 1969).
2. contamination of the magma by assimilation of xenoliths or by close association with wallrock.

Erickson (1969, p. 91) suggested that the replacement of hornblende by biotite and epidote formed the rapakivi in the Dos Cabezos quartz monzonite. Karner (1968, p. 213) suggested that rising water pressure facilitated the replacement of the hornblende by biotite thus liberating calcium to form plagioclase rims on alkali feldspar.

This type of basification is unlikely at O'Leary. Although some trace amounts of biotite may be found in some portions of the porphyry, the amphibole present shows reaction to iron oxides rather than to biotite. The process could not be present at O'Leary in sufficient quantity to produce the large amount of rapakivi seen there.

Addition of sodium and calcium perthite may also be caused by contamination of the melt. Ramberg (1972, p. 302), in discussing formation, stated that sodium and calcium were added from "... external sources." Many authors have cited the association of rapakivi with xenoliths or wallrock (Dawes 1970, p. 96; Gradwell 1956, p. 5; Phillips 1972, p. 94; Shand 1949, p. 1214; Stewart 1959, p. 317; Volborth 1962, p. 824). Many more authors have cited this association and attributed to it the rapakivi formation (Elders 1968, pp. 46-7; Kirkegaard 1960; Richter 1966, pp. 445-6; Riederer 1967, p. 108; Sylvester 1962, p. 600; Thomas and Campbell-Smith 1932; Volborth 1973, p. 34, 38; Wells and Wooldridge 1931, p. 198).

Basification by means of contamination appears to be a reasonable explanation of the O'Leary rapakivi. Basic xenoliths occur in O'Leary
Peak and Darton Dome where evidence for their resorption abounds. Xenolith kaersutite is well distributed throughout the porphyry and forms "halos" around the xenoliths. Distribution of the xenolith andesine is impossible to determine, but it likely has reacted with the melt. If so, this is a reasonable source of the sodium and calcium with which to mantle the sanidine.

Mantled sanidines are more common and the mantles are thicker in areas of the domes where xenoliths show the most resorption. As stated under "Field Sampling and Observations", there is no evidence, however, for a spatial relationship between xenoliths and mantled sanidines. Indeed, unmantled sanidines can be seen to lie next to xenoliths.

Basification is a highly disequilibrated process in which relationships are vague. The magma may have been inhomogeneous in composition, temperature, or water pressure. These variations may have affected the degree of assimilation of the xenoliths and thus, in turn, the degree of rapakivi formation. The problem with this theory is that although at first it appears promising, the number of variables involved and the disequilibrium involved make testing of the theory difficult.

If basification has been operative in the O'Leary Porphyry, then some evidence of it may be found from chemical analyses of the groundmass. Diffusion fronts of sodium and calcium from the xenoliths may have been frozen into the rock. Diffusion is discussed in Appendix B; microprobe analyses of the groundmass are discussed under "Defocused Microprobe Scans."
Nucleation vs. Growth Rate. Plagioclase began to crystallize before sanidine in the O'Leary Porphyry according to experimental work done on the porphyry by the author. This is also indicated by the presence of poikilitic plagioclase crystals in the center of some sanidines. Plagioclase and sanidine probably continued to nucleate and grow simultaneously, however, over at least some of the cooling history of the porphyry.

The maximum nucleation rate of silicate minerals crystallizing from silicate melts occurs at a lower temperature (and thus great undercooling) than does the maximum growth rate (Winkler 1947; Kirkpatrick, written communication, 1976). A magma experiencing a small undercooling would experience fast growth of crystals but slow nucleation. In such a case, nucleation might not be able to keep up with growth if the melt were overwhelmed in the components of the growing minerals. In the case of the O'Leary Porphyry, it is possible that such a small undercooling would result in An and Ab not being used quickly enough by the growing plagioclase phenocrysts. Nucleation could not produce new crystals fast enough to use these components. Growing sanidine crystals may have provided nuclei upon which plagioclase crystallized.

A small undercooling is indicated for the slow cooling O'Leary volcanic dome (average length of rapakivi is 14 mm) and for granites (the most common rock type for rapakivi occurrences). Fine-grained (up to 8 mm) volcanic flows and domes of analogous composition which have coexisting sanidine and plagioclase do not show rapakivi (Fernandez and Enlows 1966; Fodor 1976; Rhodes 1976a, 1976b; E. I. Smith 1976). A
similar volcanic, the Sugarloaf Rhyolite near O'Leary Peak, is fine-grained and contains no rapakivi. Several other occurrences within the San Francisco Volcanic Field (previously mentioned) contain rapakivi; their grain size fall between that of Sugarloaf and O'Leary—the rapakivi phenocrysts being about 7-10 mm in length.

A magma, then, similar in composition to the O'Leary Porphyry might be expected to form rapakivi if it were cooled slowly enough so that crystallization occurred in the region where growth rate is much greater than nucleation rate. The melt must be oversaturated in An and Ab components. The normal oversaturation of these components due to undercooling may be sufficient to cause rapakivi formation. The author points out, however, that the diffusion of sodium and calcium from assimilated xenoliths would magnify this effect. The fine-grained rocks without rapakivi (mentioned previously) also have no basic xenoliths. The other occurrences of rapakivi rocks within the San Francisco Volcanic Field do have such xenoliths.

**Other Considerations.** Several other possibilities must be considered during the magmatic process. Maucher (1943) studied poikilitic plagioclases in sanidine, most of which were oriented to the zoning and cleavage of the sanidine host. He concluded that rapakivi was caused by coalescence of plagioclase nuclei and overgrowth by sanidine. These plagioclase were probably incorporated during growth of the sanidine and oriented epitaxially. Vance (1969) described, in some length, this process which he called synneusis. Synneusis should be considered when dealing with rapakivi with discontinuous mantles. Some poikilitic
plagioclase within sanidine cores and one multiple sanidine (Figure 14) appear to be due to synneusis. However, incorporation of plagioclase phenocrysts to form a mantle does not seem to have occurred within the O'Leary Porphyry. Some mantles are continuous, and those which are not continuous appear to have been broken by replacement perthite.
CONCLUSIONS

There probably are many ways in which rapakivi is formed, but several mechanisms can be eliminated for the O'Leary Porphyry.

Exsolution, although a mechanism of rapakivi formation elsewhere, apparently did not form the O'Leary rapakivi on the basis of the following evidence:

1. Mantled and unmantled sanidines are of the same size range and would therefore be expected to be of the same original composition. If one set of crystals exsolved mantles and the other set did not, two compositional groups should result. Mantled and unmantled O'Leary sanidines have the same composition, however.

2. Multiple mantles, as seen in hand sample (thin section evidence is controversial, would not likely be formed by exsolution.

3. If perthite broadened and formed mantles by diffusion, then the remaining perthite (if any) would be expected in locations farthest from the mantle sites—that is, the cores of crystals. Perthite in O'Leary rapakivi is present only at the mantle-core border.

Tuttle and Bowen's (1958) theory is unacceptable for the O'Leary rapakivi for the following reasons:

1. Plagioclase crystallized first in the O'Leary melt. Tuttle and Bowen's theory requires alkali feldspar to crystallize first.
2. Tuttle and Bowen described zoning of already present feldspars—one set toward oligoclase and one set toward orthoclase. This implies no sharp mantle-core boundary. The O'Leary rapakivi, however, have sharp mantle-core borders and are not zoned.

3. The build-up of high water pressure (almost 4 kb) required by Tuttle and Bowen is unlikely at O'Leary—an extrusive dome. Multiple mantles intensify this discrepancy.

Stewart's (1959) disequilibrium theory, although generally applicable to O'Leary, has several problems when applied literally to the O'Leary rapakivi:

1. The proposed compositions of the mantles from Stewart's phase diagram are quite different from the actual compositions of mantles, whether from the literature or from the O'Leary Porphyry.

2. The temperature at which mantling occurred, according to this theory, is about 680°C—a temperature which is subsolidus according to hydrothermal melting experiments on O'Leary Porphyry. Synneusis (as described by Vance 1969) has occurred in the O'Leary Porphyry but is not the cause of rapakivi formation. It cannot explain continuous mantles (at least one of which is present in O'Leary). The O'Leary discontinuous mantles appear to have once been continuous ones which were subsequently broken by replacement textures.

Evidence for metamorphic-metasomatic origin of rapakivi is vague. The O'Leary rapakivi are not localized along what might be considered fractures which might have allowed passage of metasomatic fluids.
occurrence of rapakivi within xenoliths is not considered evidence, by
this author, of the metasomatic origin of the texture.

After considering the O'Leary data, three mechanisms remain attrac-
tive:

1. a decrease or pulsation in water pressure during breaching of
   the dome's roof resulting in the alkali feldspar field being
diminished.

2. the addition of sodium and calcium "basification" by assimila-
tion of andesite xenoliths thus changing the bulk composition
   of the melt.

3. a small undercooling resulting in the growth rate being much
greater than the nucleation rate.

In the first case, the composition of the melt would be critical
in order for it to have fractionated to the plagioclase-alkali feldspar
phase boundary by the time of pressure release. In this way the compo-
sition of the melt would be within the plagioclase field as the boundary
was moved by decreasing pressure.

In the second case, after diffusion of sodium and calcium from
the xenoliths had formed the mantles, further crystallization would have
occurred, the magma would have changed in composition, and the rapakivi
would have been out of equilibrium with the melt. This probably would
have resulted in reaction with the melt forming the perthitic, boxwork,
and channeling replacement textures.

There is very little biotite in the porphyry and the kaersutite
present is altering to iron oxides, rather than biotite; therefore,
there is no evidence for Erickson's (1969) mechanism of hornblende altering to biotite to supply sodium and calcium.

Xenoliths within the porphyry are obviously assimilated, as seen in the field. These xenoliths are richer in sodium and calcium than is the porphyry and therefore offered a source of cations for rapakivi formation. The author in no way wishes to suggest that the rhyodacite O'Leary Porphyry melted the andesite xenoliths—it would not have had a high enough temperature to do this. Also, nucleation apparently did not proceed rapidly enough to produce much latent heat of crystallization.

Although mantled sanidines are more common and their mantles thicker in parts of the two domes where the xenoliths are the most resorbed, field measurements give no support for a spatial relationship between rapakivi and xenoliths (at least two-dimensionally as measured). No definite evidence of diffusion of sodium and calcium from the xenolith through the porphyry toward mantled sanidines was obtained by the two defocused microprobe scans made.

In conclusion, there is no positive evidence that diffusion of sodium and calcium from the xenoliths occurred within the O'Leary Porphyry forming the rapakivi. Mantles did form on seed sanidines run at temperatures where sanidine and plagioclase were crystallizing from the melt, but it is uncertain whether this was due to diffusion.

Perhaps the most favorable mechanism is that of a small undercooling resulting in a situation where the growth rate is near its maximum while the nucleation rate is much slower. This would likely result in growth of plagioclase on sanidine as well as on plagioclase
nuclei, since the rate of formation of new nuclei is insufficient for the amount of An and Ab components in the melt. This oversaturation of plagioclase components is a natural outcome of crystallization of a magma of a composition similar to that of the O'Leary Porphyry. A more rapid cooling (larger undercooling) would not result in a situation where growth rate was more rapid than nucleation, thus it would not result in the rapakivi. The author would like to suggest, however, that an oversaturation of plagioclase components in the melt would also occur because of assimilation of andesite xenoliths.

In conclusion, the author feels that one major mechanism—that of a small undercooling making growth dominant over nucleation—was operative in forming the rapakivi of the O'Leary Porphyry. This mechanism was quite possibly aided by the assimilation of andesite xenoliths which added to the oversaturation of the melt with respect to plagioclase components. It should be noted that rapakivi occurrences are usually coarse-grained (supporting the nucleation vs. growth mechanism) and usually contain basic xenoliths.

Further study is, naturally, suggested. Detailed hydrothermal experiments on homogenous O'Leary Porphyry could bracket the conditions (T, P, undercooling) under which mantles form on the sanidine seed crystals. An interesting problem which may or may not have bearing on the rapakivi problem is the non-stoichiometry of the seed mantles.

Detailed diffusion investigations could be done by microprobe studies on hydrothermal runs on homogeneous porphyry, seed sanidines, and xenolith fragments. Such a study could supply precise diffusion curves which could be treated with nonequilibrium thermodynamics.
Once these problems are solved, temperature gradients might be superimposed on the chemical ones. The study of the O'Leary Porphyry involves subjects upon which work has begun just recently—nonequilibrium geologic systems and diffusion in melts.

Another interesting subject is the crystallographic relationship between mantles and their sanidine cores. A detailed universal-stage study might shed light on the epitaxial relationship and apparent coherency between plagioclase and sanidine frameworks.

There are still many unanswered questions. Foremost in this author's mind is why mantled and unmantled sanidines occur together. Other than to call upon disequilibrium (upon which geologists have few quantitative holds), this author has no explanation.
APPENDIX A

METHOD OF STUDY

The volcanic geology of the O'Leary Peak area had previously been mapped (Bladh 1972). Further samples were taken on a grid of about 1000 ft.

About 75 thin sections were available to carefully study and describe the O'Leary Porphyry and the rapakivi texture (21 crystals present in thin sections had the texture). Extensive x-ray diffraction work was done on homogenized porphyry sanidines in an attempt to determine the Or content of various mantled and unmantled sanidines. X-ray fluorescence work to determine K₂O, CaO, Rb, and Sr was done on sanidine separates.

Hydrothermal experiments were done to determine the melting interval of the porphyry. These data supplied information on the order and temperature of crystallization of porphyry minerals. Sanidine seed crystals were placed in some runs along with ground porphyry and xenolith material in order to determine the conditions under which a mantle would form.

Atomic absorption analyses were done on porphyry samples, mantled and unmantled sanidines, and plagioclases from various locations on O'Leary Peak and Darton Dome. In this manner, any inhomogeneities within and between the two domes could be ascertained. Comparison of results with other techniques was made.
Electron microprobe analyses of mantled and unmantled sanidines, plagioclase rims and phenocrysts, plagioclases poikilitic within sanidines, and kaersutite were made. Defocused scans across the xenoliths and porphyry groundmass were made in order to detail any cation peaks. Such peaks would give evidence concerning diffusion through the porphyry.

**X-ray Work on Sanidines**

**Purpose of Study**

Since both mantled and unmantled sanidines occur together within the porphyry, any composition differences between them may be significant. Therefore, a method of measuring sanidine compositions was sought. X-ray diffraction requires only a small amount of sample (thus a single crystal may be done), is non-destructive, and sample preparation is generally simple.

**Discussion of Technique**

The Three Peak Method of Wright (1968) which related the 2θ of (201) with the Or content of sanidines was used. Wright's (1968, pp. 93-4) criteria for anomalous feldspar showed the O'Leary sanidines to be normal. Various temperatures and durations of heating for homogenization of the sanidine have been suggested (Wright and Stewart 1968, p. 55; Jones, Nesbitt, and Slade 1969, p. 490; Tuttle and Bowen 1958, p. 10). The O'Leary sanidine was heated for 24 hours in a furnace whose setting was 1050°C. A thermocouple reading indicated that this temperature was actually closer to 900°C. The position of the (201) peak of this sanidine was the same as for those sanidines run for 48 and 70
hours. Thus, 24 hours appeared to be sufficient to homogenize the sanidine. Reagent grade KBrO₃ was used as an internal standard and the location of its (101) peak was used to calibrate the location of sanidine's (201) peak as suggested by Wright and Stewart (1968).

Homogenization

Coarsely ground sanidine was put into ceramic crucibles (in almost all cases with lids) and placed into an electric furnace for 24 hours at a temperature of 900°C. Corrosion of the wiring by sulfur which volatilized from the furnace bricks resulted in the burning out of the furnace unless the door was left ajar during heating. No other furnace was available for use. Twenty-four hours was sufficient to homogenize the sanidine.

Sample Preparation

Different sample preparations were used including filling a circular hole in an aluminum holder backed with scotch tape, sieving material into such a hole, sprinkling material on double-stick tape on a glass slide, and sprinkling material onto a vaseline film on a glass slide. The aluminum holder method gave the best results.

The homogenized sanidine was ground and mixed with KBrO₃ and the resulting mixture poured into the hole in the aluminum holder. The sample was then run using settings which showed the most discernible (201) peak. Sometimes no (201) peak was present. Only runs with obvious (201) peaks were used to determine the Or percent from Wright's (1968, p. 93) curve using the distance between the (101) peak of the
standard and the (201) peak of sanidine. An average of five to ten good to excellent scans from 19-22° 2θ was used to calculate the Or content.

Machine Settings

A Phillips goniometer and x-ray machine and a Bowen (Honeywell) type 153 chart recorder were used. Slits on the x-ray machine were 1°, 0.006, and 1°. A 1°/min scan was found to be the most efficient. A warm-up period did not improve the results. Another x-ray machine was also used; however, an inadequate water supply made its use sporadic. Both goniometers were checked using rose quartz.

Results

The x-ray equipment available did not give reproducible results. The variation between the two runs on the same prepared sample was as much as 20 weight percent Or. One sample was allowed to run at a constant 2θ value. The variation on the recorder was up to 10 units in height, resulting in an apparent peak. Background noise was high. Erroneous peaks resulted from power pulses. No two consecutive scans from 15 to 60° 2θ on the same sample (all settings the same) gave the same results in intensity, peaks present, or location of those peaks relative to the standard. On some runs either (101) of the standard and/or (201) of sanidine were doublets. This did not occur consistently for any one sample. This technique was abandoned as no immediate solution of the technical problems was foreseen and there was hope of use of an electron microprobe.
Table VI shows the pattern of the O'Leary sanidines which have some but not all of the peaks of sanidine and adularia patterns listed in Borg and Smith (1969).

X-ray Fluorescence Work

Sample Preparation

Sanidine which was separated from the O'Leary Porphyry by magnetic separation and heavy liquids was ground to fine powder in a shatterbox. This material was pressed (without binder) with a pressure of 20,000 psi into a methyl cellulose backing.

Standards

The standards used for calcium and potassium analyses by the author were the following: G-1, G-2, GSP-1, NSB-99, and NSB-70. The first two are granites and the third a granodiorite; all three are from the U. S. Geol. Survey. The last two standards are National Bureau of Standards feldspars—an albite and a potassium feldspar, respectively. These are the same NBS feldspar standards which were used in the atomic absorption work. U. S. Geol. Survey standards such as G-1, W-1, and DTS-1 were used for rubidium and strontium which was done by the Laboratory of Isotope Geochemistry, University of Arizona.

Equipment

The standard Siemens unit x-ray fluorescence set-up was used for the analyses. For calcium and potassium, the chromium tube was used at 30 Kv and 14 mA. The gypsum crystal, vacuum path, and flow proportional
<table>
<thead>
<tr>
<th>(2\theta)</th>
<th>(I/I_{100})</th>
<th>(H\kappa l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.6</td>
<td>10</td>
<td>020</td>
</tr>
<tr>
<td>20.87-21.13</td>
<td>35-45</td>
<td>201</td>
</tr>
<tr>
<td>22.5-23.6</td>
<td>10-20</td>
<td>111</td>
</tr>
<tr>
<td>23.1</td>
<td>10-30</td>
<td>200</td>
</tr>
<tr>
<td>23.5-24.6</td>
<td>65-70</td>
<td>130</td>
</tr>
<tr>
<td>24.6</td>
<td>12-15</td>
<td>131</td>
</tr>
<tr>
<td>25.65-26.8</td>
<td>40-60</td>
<td>112</td>
</tr>
<tr>
<td>26.8-27.0</td>
<td>70</td>
<td>220</td>
</tr>
<tr>
<td>27.1</td>
<td>55</td>
<td>202</td>
</tr>
<tr>
<td>27.5</td>
<td>100</td>
<td>040</td>
</tr>
<tr>
<td>27.7-27.8</td>
<td>90</td>
<td>002, 012</td>
</tr>
<tr>
<td>29.8-30.9</td>
<td>35-50</td>
<td>131</td>
</tr>
<tr>
<td>30.5</td>
<td>15-25</td>
<td>222</td>
</tr>
<tr>
<td>30.8</td>
<td>25</td>
<td>041</td>
</tr>
<tr>
<td>32.3-33.4</td>
<td>20</td>
<td>132</td>
</tr>
<tr>
<td>34.4</td>
<td>15</td>
<td>312</td>
</tr>
<tr>
<td>34.8</td>
<td>30</td>
<td>241</td>
</tr>
<tr>
<td>35.1</td>
<td>15</td>
<td>112</td>
</tr>
<tr>
<td>37.5</td>
<td>6-10</td>
<td>331</td>
</tr>
<tr>
<td>41.6-42.0</td>
<td>14-30</td>
<td>060</td>
</tr>
<tr>
<td>45.8-46.9</td>
<td>8-15</td>
<td>222</td>
</tr>
<tr>
<td>50.6-51.8</td>
<td>20</td>
<td>062</td>
</tr>
<tr>
<td>51.0</td>
<td>25-30</td>
<td>204, 043</td>
</tr>
</tbody>
</table>
counter were used. Calibration for the unit was determined by comparison of the KKα peak of potassium dichromate with peak values in the standard tables.

A pulse height analysis was used to determine the window and baseline for the peaks used. Correction was made for interference between CaKα and KKβ by use of the ratio of KKβ to KKα determined from potassium dichromate. Two one-minute counts were taken on each sample for Ca Kα, KKα, and background (at θ = 22°). G-2 was used as a monitor for drift. All counts on G-2 were within three standard deviations so no drift correction was made.

For rubidium and strontium, the sanidine pellet was run at 55 Kv, 46 mA with air path, and a scintillation counter at 1050 v. LiF (220), a molybdenum tube, and a 0.4° collimator were used. The baseline was 8 v and the window 13 v; attenuation was 5. Kα peaks were used for rubidium and strontium; absorption corrections were made using the molybdenum Compton Kα peak as described by Livingston (1969, pp. 60-72). Two one-minute counts were taken on each peak. The θ values were: background 34.88°, Sr 35.86°, Rb 38.00°, and Mo Compton 29.98°.

Results

A plot of the net counts versus oxide values of standards was made. The net counts for Ca Kα were raw counts minus the KKβ counts and minus background. The net counts for KKα were raw counts minus background. The plot of both CaO and K₂O fit straight lines.
Hydrothermal Work

Sample Preparation

The OP series (Table VII) was run with porphyry from the P31 locality. It is a fresh porphyry from which the sanidines and xenoliths were hand picked; however, due to the extreme assimilation of xenoliths, some fragments and kaersutite from the xenoliths were undoubtedly retained in the matrix. The material was then ground in a shatterbox. The first material ground was not used, as it may have been contaminated.

Capsule Preparation

Gold tubing (2.5 mm outside diameter and 0.1 mm wall thickness) about 2.7 cm in length was welded at one end on a Temp-Press research model Ac-lla arc welder. All welding was checked with a binocular microscope to assure closure. It was then weighed on a Mettler H20T balance using an aluminum holder (into which the capsule fit sitting upright) as a reference weight to monitor drift of the machine. Accuracy of the balance was ± 0.00010 gms. About 1 ml of distilled water was then added to the capsule with a Hamilton microliter 701 syringe. Addition of water before porphyry proved the more successful method. The capsule was weighed to determine the exact weight of water and ground porphyry was added until the water was either 6 or 16% of the weight of the porphyry. About 1% water was always lost during welding shut of the capsule. Later runs contained sanidine seeds weighing 0.00131-0.00239 gms and ground xenolith material (23.3 to 48.5% of the weight of the porphyry). These were added after the porphyry. The
Table VII. Valid¹ Hydrothermal Runs.

<table>
<thead>
<tr>
<th>OP Sample Number</th>
<th>H₂O Loss or Gain (%)</th>
<th>Average T and T Range (°C)</th>
<th>Average P and P Range (psi)</th>
<th>Duration of Run (hrs)</th>
<th>Furnace</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-10.0</td>
<td>738 (735-45)</td>
<td>13200 (11500-13400)</td>
<td>68</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>-5.5</td>
<td>887 (883-92)</td>
<td>15100 (14800-15200)</td>
<td>165</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>&lt;10.0</td>
<td>793 (792-801)</td>
<td>15200 (15100-15400)</td>
<td>166</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>+3.8</td>
<td>759 (757-81)</td>
<td>14600 (14400-15300)</td>
<td>164</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>+11.7</td>
<td>759 (757-81)</td>
<td>14600 (14400-15300)</td>
<td>164</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>+3.8</td>
<td>732 (721-35)</td>
<td>16500 (16300-16900)</td>
<td>328</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>+7.7</td>
<td>732 (721-35)</td>
<td>16500 (16300-16900)</td>
<td>328</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>+2.6</td>
<td>838 (832-41)</td>
<td>14700 (14400-14950)</td>
<td>164</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>838 (832-41)</td>
<td>14700 (14400-14950)</td>
<td>164</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>-3.7</td>
<td>716 (711-18)</td>
<td>14750 (14000-15600)</td>
<td>331</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>+8.8</td>
<td>775 (767-79)</td>
<td>9470 (9200-9750)</td>
<td>428</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>+6.4</td>
<td>799 (780-806)</td>
<td>7740 (7200-8500)</td>
<td>406</td>
<td>2</td>
</tr>
<tr>
<td>19</td>
<td>+5.2</td>
<td>799 (780-806)</td>
<td>7740 (7200-8500)</td>
<td>406</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>774 (773-77)</td>
<td>12245 (12200-12500)</td>
<td>164</td>
<td>1</td>
</tr>
<tr>
<td>21</td>
<td>-9.5</td>
<td>774 (773-77)</td>
<td>12245 (12200-12500)</td>
<td>164</td>
<td>1</td>
</tr>
<tr>
<td>22</td>
<td>0</td>
<td>823 (818-25)</td>
<td>12230 (12000-12500)</td>
<td>161</td>
<td>2</td>
</tr>
<tr>
<td>23</td>
<td>+7.3</td>
<td>823 (818-25)</td>
<td>12230 (12000-12500)</td>
<td>161</td>
<td>2</td>
</tr>
<tr>
<td>24</td>
<td>0</td>
<td>853 (850-60)</td>
<td>12260 (11900-14300)</td>
<td>238</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>853 (850-60)</td>
<td>12260 (11900-14300)</td>
<td>238</td>
<td>1</td>
</tr>
<tr>
<td>34</td>
<td>0</td>
<td>822 (818-26)</td>
<td>15240 (14000-15500)</td>
<td>213</td>
<td>2</td>
</tr>
<tr>
<td>36</td>
<td>0</td>
<td>861 (856-65)</td>
<td>14860 (14500-15100)</td>
<td>191</td>
<td>1</td>
</tr>
<tr>
<td>37</td>
<td>0</td>
<td>861 (856-65)</td>
<td>14860 (14500-15100)</td>
<td>191</td>
<td>1</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>863 (861-69)</td>
<td>15600 (15500-15750)</td>
<td>118</td>
<td>3</td>
</tr>
<tr>
<td>41</td>
<td>+2.4</td>
<td>863 (816-69)</td>
<td>15600 (15500-15750)</td>
<td>118</td>
<td>3</td>
</tr>
</tbody>
</table>

¹Percent weight loss of water after run completed was less than ±10% except for run 7, which was +11.7%.
capsule was cleaned of sample around the mouth and on the outside and then pinched closed with tweezers. The top was examined under the binocular and usually some gold trimmed so that the closure was smooth. The weight removed was recorded. The closure was then welded shut while the capsule was sitting in a watersoaked sponge envelope. The height of the capsule in the vise during welding was critical. Enough height was necessary to allow a smooth weld but too much height resulted in gold loss by beads popping out. Once the weld was complete, the capsule was weighed. The weight loss, if any, was subtracted from the amount of water. If the water percentage was still close to that of 5 or 15%, the capsule was used. Two capsules were run together in the same vessel so one had an "x" scratched into the gold at its top.

Loading

Several cold seal Tuttle-type stellite vessels were used. The upper temperature limit for these vessels was about 900°C. They were approximately 8 inches in length and 1 inch in diameter with a 1/4 inch center hole drilled to within 1/4 inch of the bottom. The inside of the vessel was cleaned with distilled water and a small bottle brush. The capsules were put inside and the vessel filled with distilled water. The threads on the top of the vessel were coated with Keystone No-Weld #1 anti-seize compound. The stainless steel top was then threaded onto both the stellite rod and the high pressure fittings on a horizontal bar and tightened with a wrench. After the thermocouple was attached, the horizontal cross-bar which moved on two vertical pipes was lowered so that the assemblage fit into the furnace.
The thermocouple of #24 chromel and alumel enclosed in ceramic tubing was rewelded before each run. It was plugged in and fitted into the thermocouple well in the vessel. Some of the vessels had the thermocouple hole on the side about 7/8 inch from the bottom slanting inward at an angle of about 45° approximately 1/4 inch into the vessel. Other vessels had the thermocouple hole on the bottom about 3/16 inch from the edge and penetrating inward about an inch. Wire was used to fasten the thermocouple. The wire was attached around the ceramic envelope of the thermocouple as near the top of the vessel as possible so as to prevent contact with wire inside the furnace. Care was taken to insure that no contact occurred between the encircling wire and the wire of the thermocouple. The wires were untangled and attached to the back panel with scotch tape so that no contact between the wires themselves or between them and the other metal occurred.

The pressure fitting on the top of the vessel cap led to stainless steel capillary tubing which led to a pressure gauge (either 20,000 or 100,000 psi range Tempress Research or 50,000 psi range Ashcroft Maxisafe pressure gauge depending upon furnace used) and a Sprague model S-440-300 diaphragm pump. The pump was fed by one of two compressors. After the vessel was lowered into the furnace, the pressure was pumped up to the desired pressure. The Barber-Coleman Amplitrols Model 152P anticipatory controller, which regulated the temperature of the furnace to within ± 2°C was set. As the temperature rose, the pressure had to be periodically bled to retain the value at which it had been set. When the temperature was close to the desired temperature, the value on the
temperature controller was changed as necessary to maintain the desired temperature—a procedure requiring 4 hours. The temperature of the thermocouple within the vessel was read on a 7554 Type K-4 Leeds and Northrup universal guarded potentiometer using an ice bath. The measured temperature varied not only in response to the furnace temperature, but also in response to the fluctuation in voltage coming into the building. The temperature also changed when one or more other furnaces were used. The error in temperature is related to the error in the thermocouple, that in the potentiometer, and the difference in the temperature at the thermocouple well and inside the pressure vessel. Not all of these errors were systematic or predictable so the resulting work is not precise. Runs on the graphs (Figures 10 and 11) are given as points, which are the average, and bars indicating the range of temperature and pressure measured during the run.

Unloading

If the proper length of time for the run had been successfully completed without substantial pressure or temperature change, the vessel was raised from the furnace, the controller set to zero, and the vessel quenched. Quenching was completed by means of a system of copper coils (connected to the compressor) filled with cold circulating air which surrounded the vessel. Final quenching in a pan of water was used because the compressor was not large enough to maintain the flow of air for a sufficient time to completely cool the vessel. The vessel was unscrewed from the horizontal bar and opened. The capsules were removed,
dried, and weighed. If the weight loss or gain was within ±10 weight percent of the total water added to the capsule prior to the experiment, the run was considered valid. The sample was then removed from the capsule.

Examination of Results

The samples were sometimes x-rayed on a collodion film on aluminum holders, but this was not sensitive enough for small amounts of material. The identification of phases and estimate of percent of each was done optically after the sample had been ground and placed in oils. The glass produced by these experiments had an index slightly less than 1.500 which corresponds to an SiO₂ content of about 72% (George 1924, p. 365). This compares favorably with the SiO₂ value of 71.2% (Table I). Plagioclase was identified by polysynthetic twinning. One problem arose in that some polysynthetically twinned crystals had a biaxial (−) figure with a small 2V—a figure similar to that of sanidine. The melting intervals are given for 5% (Figure 10) and 15% (Figure 11) water.

Seeded Runs

Several runs were made with seed crystals but only the results of one run were examined on the electron microprobe. These were samples SX7 and S7, both of which were run for 504 hours at an average temperature of 825°C (range 818-31) and pressure of 14,420 psi (range 14,300-14,750). SX7 contained 15.5 weight percent water and S7 15.8%. After the run they together had gained weight equal to 3.2% of the water weight. SX7 contained, in addition to porphyry, seed sanidine and water,
ground xenolith equal to 34.3% of the weight of the porphyry. S7 contained no xenolith (see "Electron Microprobe Results").

Atomic Absorption Work

Porphyry Runs

Preparation of Standards I, II, III, IV. A stock solution "A" was made from elemental solutions of Na, K, Ca, Mg, Fe, Al, and Si. Solution "A" was prepared in such a manner that it contained the same ratio of these elements as does rock P31 according to its U. S. Geol. Survey analysis. Four 200 ml solutions (I, II, III, IV--see Tables VIII and IX) were then made from different amounts of solution "A". These solutions were thus consecutive dilutions of "A". As such, they contained the same ratio of elements as in "A" and therefore P31, but differing concentrations of each element. The dilutions were made so that their elemental amounts bracketed those in solutions made of porphyry samples. Enough HF was added to make a total of 14 ml and enough H\textsubscript{3}BO\textsubscript{3} to make 9.0 gm, the amount of both depending on the amount of "A" since both HF and H\textsubscript{3}BO\textsubscript{3} were present in "A". 4.0 ml of aqua regia (2HCL; 1HNO\textsubscript{3}) were added to each solution. Sufficient distilled water was then added to make the total volume 200 ml. In this way, the ratio of major elements is the same for the standards as for the 200 ml sample solutions (described later). Likewise, the amount of HF, H\textsubscript{3}BO\textsubscript{3}, and aqua regia are the same for standards and unknowns. For these reasons, matrix effects should be minimized.
Table VIII. Standard Solutions I, II, III, and IV for Porphyry Runs.

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ml of &quot;A&quot;</td>
<td>150</td>
<td>100</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>ml HF in &quot;A&quot;</td>
<td>12.4</td>
<td>8.3</td>
<td>4.1</td>
<td>0.8</td>
</tr>
<tr>
<td>ml HF added</td>
<td>1.6</td>
<td>5.7</td>
<td>9.9</td>
<td>13.2</td>
</tr>
<tr>
<td>$\text{H}_3\text{BO}_3$ in &quot;A&quot; (gm)</td>
<td>3.5</td>
<td>2.3</td>
<td>1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$\text{H}_3\text{BO}_3$ added (gm)</td>
<td>5.5</td>
<td>6.7</td>
<td>7.8</td>
<td>8.8</td>
</tr>
<tr>
<td>aqua regia (ml)</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Total ml after distilled water added volumetrically | 200.0 | 200.0 | 200.0 | 200.0

\(^1\)Includes HF required to dissolve SiO\textsubscript{2} to make Si solution and $\text{H}_3\text{BO}_3$ to neutralize solution.

Table IX. Standard Solutions I, II, III, and IV for Feldspar Runs.

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ml &quot;B&quot;</td>
<td>150</td>
<td>100</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>ml HF in &quot;B&quot; (^1)</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>ml HF added</td>
<td>1</td>
<td>6</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>$\text{H}_3\text{BO}_3$ in &quot;B&quot; (gm)</td>
<td>5.2</td>
<td>3.48</td>
<td>1.74</td>
<td>0.35</td>
</tr>
<tr>
<td>$\text{H}_3\text{BO}_3$ added (gm)</td>
<td>3.78</td>
<td>5.52</td>
<td>7.26</td>
<td>8.65</td>
</tr>
<tr>
<td>aqua regia (ml)</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Total ml after distilled water added volumetrically | 200.0 | 200.0 | 200.0 | 200.0

\(^1\)Eight ml of HF was added to each unknown feldspar powder.
Preparation of Elemental Standards. Stock solution "A" used in preparation of standards I, II, III, and IV was prepared by combining 100 ml of each of the elemental solutions described below of Na, K, Ca, Mg, Fe, Al, and Si. The concentration of these solutions was calculated so that about 70 ml of "A" in a 200 ml solution (i.e., intermediate between II and III of Tables VIII and IX) would produce a solution with concentrations equal to those of the P31 analysis.

SPEX chemicals were used because of their purity to make the elemental solutions. Aluminum rod (1.14326 gm) was put into a 150 ml pyrex beaker with about 90 ml of distilled water and 20 ml of HCl and 10 ml of HNO₃. This was heated and when all the aluminum had reacted, the solution was brought to 500 ml volumetrically by addition of distilled water.

CaCO₃ (0.40155 gm) was placed in a 150 ml pyrex beaker with 23 ml of distilled water and 23 ml of HCl. When the CaCO₃ was completely dissolved, the solution was brought to 500 ml volumetrically by addition of distilled water.

In a teflon crucible (or nalgene beaker) 4.27160 gm of SiO₂ was placed with about 107 ml of HF (48%) until the SiO₂ was dissolved (several hours in some cases). This was then neutralized with about 16.22 gm of boric acid or until no further gas was evolved upon addition of boric acid. These proportions may need to be modified depending upon the freshness of the HF and thus its ability to dissolve the SiO₂. This solution was brought to 200 ml volumetrically by the addition of distilled water.
NaCl (1.41500 gm) was added to a beaker and dissolved in distilled water and the solution increased to 500 ml volumetrically by the addition of distilled water. KCl (0.90155 gm) was dissolved in distilled water to make 500 ml. Mg metal (0.03650 gm) were added to a 150 ml pyrex beaker with about 3 ml of HCl and when dissolved, increased to 500 ml volumetrically by addition of distilled water.

The only chemical used to make elemental solutions which was not SPEX was that of AR grade Mallinckrodt iron wire. Wire (0.36456 gm) was added to a 150 ml pyrex beaker with 26 ml of distilled water and 26 ml of HCl and heated. When it had dissolved, the solution was increased to 500 ml volumetrically by addition of distilled water. The amounts of chemical dissolved depend upon the rock analysis to which the standards are modelled as explained previously.

Sample Solution Preparation. Two splits of 0.15 gm each of powdered unknown rock sample were weighed on a Mettler balance. A weight was used as reference to monitor drift on the balance. The samples were weighed in nalgene beakers so as to prevent loss during transfer.

After weighing, 2 ml of freshly made aqua regia were added to each sample. Each beaker was lightly swirled to wet the powder to aid digestion. Fresh HF (7 ml) was added to each beaker and the beakers covered with teflon lids. Fitted nalgene lids are preferable, if available, to prevent spillage. The samples were allowed to sit and were then heated on a hot plate and/or agitated on a magnetic stirring plate using a teflon-coated magnetic stir bar. These techniques are not preferable to allowing the solutions to sit since some solution may be
lost. The degree of agreement with the U. S. Geol. Survey analyses was best on those neither heated nor stirred. Sample solutions are stable for at least two weeks. Although allowing the beakers to sit is best, heavy use of the hood required quick digestion. Fresh HF is required for complete digestion.

When the sample was dissolved in the HF, boric acid solution was added until the solution equalled 100 ml volumetrically. The boric acid solution was a 90% saturated solution made from 900 ml of saturated solution and 100 ml of distilled, deionized water.

The solutions were then transferred to clean nalgene bottles. If residue remained in the volumetric flask, digestion was incomplete and another preparation was done.

**Equipment.** Extreme cleanliness was necessary. New glassware and plastic ware were used. They were soaked in chromerge, cleaned with Alconex, and thoroughly rinsed with distilled water before use. All equipment was locked up to prevent other use and therefore contamination. All ware was rinsed with distilled, deionized water four times after every use. Gloves were worn to prevent any contamination by fingers. All beakers and bottles were permanently numbered and records kept as to all use to which they were put.

**Running of Samples.** Sample solutions in nalgene bottles were run on the Perkin-Elmer model 403 atomic absorption spectrophotometer. Each split was run twice (not consecutively). Two 100-second counts per split were the minimum recorded. If sufficient fluctuation of
values was present, more counts were made. The aspirator was placed in distilled water between different solutions. Standards I, II, III, and IV were run sufficiently often to bracket concentrations and to monitor drift. A "zero" solution of boric acid, HF, and aqua regia in amounts equal to that in sample and standard solutions was used to zero the machine. Two rocks having U. S. Geol. Survey analyses were run each time to monitor precision and accuracy—one as a solution prepared in the beginning and run each time and one as a solution prepared with each set of sample solutions. For precision results, see Table II. For different machine settings for different elements, see Table X.

**Evaluation of Data.** Counts of splits were compared. If they did not compare within about 10 counts, the unknown was prepared again. Comparable results were plotted on a graph with the standards. Some judgment in drawing curves was involved since standards did not always form a straight line (solutions were not always within the linear limit of the machine). For this reason, data was plotted by hand. Errors in reading values from the curves and from variation between the two splits were calculated as ± values. Data was converted to oxides, listed, and when all fresh porphyry samples had been run, the values of each oxide plotted on a map. Contours were drawn. See Figures 11 through 15 for the results.

**Feldspar Runs**

The technique for running feldspars is analogous to that for the porphyry samples. As well as standard solutions prepared (analogous to
Table X. Atomic Absorption Settings for Elements.

<table>
<thead>
<tr>
<th></th>
<th>Ca</th>
<th>Mg</th>
<th>Fe</th>
<th>Na</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>burner head</td>
<td>N$_2$O$^1$</td>
<td>N$_2$O</td>
<td>N$_2$O</td>
<td>AcTFB$^4$</td>
<td>AcTFB$^4$</td>
</tr>
<tr>
<td>mode</td>
<td>Abs$^2$</td>
<td>Abs</td>
<td>Abs</td>
<td>Abs</td>
<td>Abs</td>
</tr>
<tr>
<td>wavelength</td>
<td>211.3</td>
<td>285.6</td>
<td>248.8</td>
<td>294.5</td>
<td>383.2</td>
</tr>
<tr>
<td>burner settings</td>
<td>4 1/2</td>
<td>4 1/2-5</td>
<td>4 1/2-5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>12 1/2</td>
<td>12 1/2</td>
<td>12 1/2</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>air mixture</td>
<td>Ac/N$_2$O$^3$</td>
<td>Ac/N$_2$O</td>
<td>Ac/N$_2$O</td>
<td>Ac/Air</td>
<td>Ac/Air</td>
</tr>
<tr>
<td>air ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ac/Air or</td>
<td>35/50</td>
<td>50/33</td>
<td>50/33</td>
<td>35/50</td>
<td>35/50</td>
</tr>
<tr>
<td>Ac/N$_2$O</td>
<td>50/33</td>
<td>50/33</td>
<td>50/33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^1$AcTFB used for feldspar analyses
$^2$Abs = absorbence; concentration 10.0 used for feldspar analyses
$^3$Ac/Air used for feldspar analyses
$^4$AcTFB = Acetylene triple head turned with length in front to back position on machine rather than left to right.
I, II, III, IV for porphyry), four feldspar standard solutions were prepared in the same way as samples. See Table XI for the compositions of these feldspar standards Or-1, Ab-1, NBS-70a, and NBS-99. The standards were obtained from the Laboratory of Isotope Geochemistry, University of Arizona. Or-1 and Ab-1 are Pennsylvania State University standards and NBS-70a and NBS-99 are National Bureau of Standards standards.

Feldspars were hand picked from porphyry samples, ground in a mortar and pestle, and again hand picked to remove the small amount of mafic minerals poikilitic in the feldspar. The results compare favorably with electron microprobe values on similar feldspars (see "Electron Microprobe Results"). The atomic absorption values are average of crystals while the electron microprobe values are point values. Atomic absorption results indicate no variation in sanidine composition between O'Leary Peak, Barton Dome, and the Eastern Flat.

Electron Microprobe Work

Sample Preparation

Polished thin section (1 3/4 x 1 inch slides) were made from P31 locality feldspar and were carbon coated in a Varian vacuum evaporator model VE 10. Silver conductive paint for printed circuits (GC Electronic no. 21-2 Walsco no. 36-1) was used to conduct current to all parts of the section.
## Table XI. Composition of Feldspar Standards.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>68.66</td>
<td>67.1</td>
<td>65.63</td>
<td>64.39</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>19.06</td>
<td>17.9</td>
<td>20.33</td>
<td>18.58</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>0.067</td>
<td>0.075</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>FeO</td>
<td>---</td>
<td>---</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>MgO</td>
<td>0.053</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>CaO</td>
<td>0.36</td>
<td>0.11</td>
<td>1.93</td>
<td>---</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>10.73</td>
<td>2.55</td>
<td>9.06</td>
<td>1.14</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.41</td>
<td>11.80</td>
<td>2.39</td>
<td>14.92</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.017</td>
<td>0.01</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.142</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>MnO</td>
<td>0.001</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>BaO</td>
<td>0.01</td>
<td>0.02</td>
<td>---</td>
<td>0.78</td>
</tr>
<tr>
<td>loss on ignition</td>
<td>0.52</td>
<td>0.40</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Rb$_2$O</td>
<td>---</td>
<td>0.06</td>
<td>---</td>
<td>0.03</td>
</tr>
<tr>
<td>SrO</td>
<td>---</td>
<td>---</td>
<td>0.005</td>
<td>0.035</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>---</td>
<td>---</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>BeO</td>
<td>---</td>
<td>---</td>
<td>0.015</td>
<td>---</td>
</tr>
</tbody>
</table>

1—NBA—National 99 National Bureau of Standards  
2—NBA—70 a National Bureau of Standards  
3—Albite Ab-1, Pennsylvania State University  
4—Orthoclase Or-1, Pennsylvania State University
Equipment and Working Conditions

An ARL-SEMQ electron microprobe of The University of Arizona with a 52.5° x-ray take-off angle was used. Some analyses done on the University of Washington microprobe are also available. Both machines were run at 15 Kv. Beam diameter on The University of Arizona microprobe was about 2μ for step scans and about 100μ for the defocused scans. Beam diameter on the University of Washington microprobe was 5μ. Reed (1972, p. 1551) has suggested that 10-15 Kv is the best acceleration voltage, since variation in carbon coat thickness doesn't affect accuracy as much at this value. Sample current on The University of Arizona microprobe was set on brass at 0.044-0.05μA depending upon the filament (the bias was set at 100 and the filament not above 450). Sample current on the University of Washington microprobe was 0.04μA. Sample current on both samples and standards ranged from 0.0475 to 0.0585μA. Beam current was 0.75-0.946μA. The distances between analyzed points in step scans of feldspars varied from 125 to 325μ. At most locations one analysis was taken of 100 seconds duration; some were for 20 seconds. A chart recorder monitored beam current and the sample current on brass was adjusted when necessary. Data was collected on a teletype.

The machine has three spectrometers which were set for three elements by means of pulse height analysis. Coordinates of locations on the sample were recorded and analyzed for the next set of three elements. Photographs were also used for location purposes. Kα peaks were used for all elements. The LiF crystal was used for calcium
and iron, the RAP crystal for sodium and magnesium, the PET crystal for potassium, silicon, and titanium, and the ADP crystal for aluminum. The elements were run in groups of two or three: calcium-sodium-potassium; aluminum-silicon; iron-magnesium-titanium.

Standards

Standards on the University of Washington microprobe include orthoclase Or-1, Tiburon albite, and anorthite glass. The following standards were used on The University of Arizona microprobe: for potassium, the Asbestos microcline; for sodium, the Amelia albite; for calcium, an anorthite from J. V. Smith; for iron, fayalite from Rockport, Massachusetts; for magnesium, a diopside glass from the Geophysical Laboratory of the Carnegie Institute of Washington (prepared by J. F. Schairer); for titanium, a sphene glass from Arizona State University. There is a considerable problem involved with the standards used in the Lunar Laboratory. Their source and analyses are poorly recorded; the analyst is not always given. Apparently, analyses have been taken from the literature and applied to material from the same locality but not actually collected by the authors from which the analyses were taken. Further, the anorthite, sphene, and apparently the diopside glass have analyses calculated from assumed stoichiometry. The analyses of the Amelia albite (listed as from Goldich et al. 1967) do not agree with that published in Ribbe and Smith (1966). Goldich et al. admitted that their analysis may have included microcline and muscovite impurities. The Asbestos microcline analysis is stated as being a revised analysis from the University of Chicago. This analysis does not agree with that
published in Smith and Ribbe (1966). While working with the sphene "standard" this author analyzed it for CaO and SiO₂ using the anorthite standard and assumed the remaining material was TiO₂; this value was used for sphene as a titanium standard. Work has been done by others who analyzed material with both these standards and with other standards (Welber, personal communication, 1976). The two sets of standards do not agree and suggest that the Na₂O value listed for the Amelia albite is too low for the actual value (this agrees with the higher Na₂O value given by Smith and Ribbe over that of Goldich et al.), that the Al₂O₃ and CaO values of the anorthite are too high and the SiO₂ value too low, that the K₂O value of the Asbestos microcline is too high, and that the MgO value of the forsterite is too low (Welber, personal communication, 1976). Al₂O₃ and SiO₂ values determined for the O'Leary feldspars are stoichiometrically too high in some cases. This is probably related to problems with standards; therefore, alkali values were used to determine An, Ab, and Or values. These problems have not yet been resolved. However, the errors involved should be consistent throughout the work on O'Leary material and therefore insignificant when comparing one O'Leary analysis from this probe to another. Comparison of these results with results on another crystal done at the University of Washington (see "Electron Microprobe Results") suggest that the resulting values compare favorably. The xenolith plagioclase value from this probe is essentially identical to that from Moore, Wolfe, and Ulrich (1974) which was done on the University of New Mexico probe (Wolfe, personal communication, 1970).
Reduction of Data

Reduction of data was done by means of the computer program Empadr VII (Rucklidge and Gasparrini 1969). For most of the feldspar scans the stoichiometric subroutine was employed since only calcium, sodium, and potassium were analyzed. The program corrects for dead time, characteristic fluorescence, atomic number, absorption, background, and drift. Beaman and Isasi (1970, p. 1564) stated that the correction procedure of this program was an accurate one.

Error Analysis

Most studies which have employed electron microprobe work have had standards which had been analyzed by wet chemical techniques. In this way accuracy could be estimated by comparison of wet chemistry and microprobe values. Accuracy is usually 2% for major elements and 5-10% for minor elements. No such standards were available for this work.

During operation of the machine a certain amount of drift in x and y coordinates were noticed as well as in z, which is the focus. One area of error for microprobe data is the variability of the carbon coat between samples and standards. Kerrick, Eminhizer, and Villaume (1973, p. 921) stated that film thickness differences up to 200 Å between a standard and a sample cause ± 1% error for iron, silicon, and sodium and up to ± 2% for lighter elements such as fluorine. The error in variable thickness is minimized by running at 15 Kv as described previously.

A special problem with feldspars is the possibility of volatilization of the sodium. Some workers have minimized sodium loss in minerals
by enlarging the beam diameter to about 10μ and lowering the sample current (Cheney and Guidotti 1973, p. 1078). However, Pringle, Trembath, and Pajari (1973, p. 88) using a beam diameter of 5μ and a sample current of 0.024μA stated that sodium, silicon, and calcium counts for plagioclase were stable for periods of up to 300 seconds. Several pertinent conclusions are drawn by Siivola (1969). One is that higher acceleration voltage results in alkali intensities remaining stable longer.

Potassium was stable in alkali feldspar at 15 K( for 160 seconds using a sample current of 0.040μA and a beam diameter of 2μ (Siivola 1969, p. 89). Siivola (1969, p. 89) also stated concerning the fact that the sodium intensity in oligoclase remained constant for 400 seconds, that the calcium content of the oligoclase made the oligoclase resistant to sodium volatilization.

A test of the volatilization of sodium was performed on O'Leary feldspars. At three locations sodium counts for 20 seconds were followed by 100 second counts on the same spot. At three other locations long counts followed shorter counts (the shortest being 12.76 seconds). At all the locations, sodium values for longer counting periods were within 1% of the shorter periods when compared on a counts/second basis.

Counting error was estimated by three standard deviations divided by the number of counts. Three standard deviations give over 99% of the counts. In the scans of plagioclase, the error in calcium ranges from 2 to 4% and in sanidine it was up to 7%. Sodium error was up to 2% in plagioclases and less than 1% in sanidines and their rims. Potassium error was less than 1% in sanidines and was 2-4% in the
plagioclases. Defocused run errors were: calcium 8-9%, sodium 3%, potassium 2-3%, aluminum 3-4%, and silicon 1-1.5%.

Results

O'Leary Feldspar. Data is available not only from analyses done on The University of Arizona microprobe but also that done by Ed Mathez on the University of Washington microprobe on one rapakivi and three co-existing plagioclase phenocrysts. In the latter work, acceleration voltage was 15 Kv, sample current 0.04μA, beam diameter 5μ. Standards used were orthoclase Or-1, Tiburon albite, anorthite glass. Information concerning the data reduction is lacking. Analyses on The University of Arizona microprobe were not done on the same sample as were those from the University of Washington. Results are shown in Figure 18 and Tables IV and V.

Hydrothermal Seed Crystals. Results of microprobe analyses of seed crystals SX7 and X7 are given in Table V.
APPENDIX B

DIFFUSION

Sederholm (1928) suggested that viscosity of the magma prevented the resupply of potassium around the growing alkali feldspar thus causing crystallization of plagioclase. Such a mechanism would involve diffusion, some evidence of which might be found by defocused electron microprobe scans across porphyry.

The defocused scans across xenolith and porphyry done on the microprobe are shown in Figures 12 and 13 where points represent the location of the center of a beam of diameter of 100μ. The distance between points (centers of beam) was usually about 600μ. The sources of error were discussed under "Electron Microprobe" and due to their uncertainty no error bars were placed on the figures. The plots suggest large inhomogeneities in the porphyry groundmass which the large beam area could not minimize. The porphyry was observed optically during such scans and the proportion of minerals appeared similar. However, it is quite likely that the peaks on the graphs represent inhomogeneities rather than diffusion peaks. There are, however, two peaks (locations 9 and 11 of Figure 12) which may represent diffusion. This area is just inside a xenolith. Sodium and calcium are slightly higher at locations 9 and 11 than would be expected and are separated by a low concentration of these elements.
The following assumptions are made for the purpose of a few calculations: one diffusion peak of calcium and sodium reached the mantled sanidine of location 18 of Figure 12 forming the mantle, another diffusion peak of calcium and sodium is present either at location 9 or 11, the resulting distance between the two peaks is either 0.54 cm or 0.42 cm. This distance may be substituted into the following equation (Medford 1973, pp. 396-7) if some assumption is made for time:

\[
D = \frac{x^2}{2t}
\]

where \(D\) is the diffusion coefficient, \(x\) is distance, and \(t\) is time.

The resulting \(D\) values for times of 10, 50, and 100 years are:

<table>
<thead>
<tr>
<th>Location 9 peak</th>
<th>Location 11 peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4.6 \times 10^{-10})</td>
<td>(2.8 \times 10^{-10})</td>
</tr>
<tr>
<td>(9.2 \times 10^{-11})</td>
<td>(5.6 \times 10^{-11})</td>
</tr>
<tr>
<td>(4.6 \times 10^{-11})</td>
<td>(2.8 \times 10^{-11})</td>
</tr>
</tbody>
</table>

\(D\) for sodium in orthoclase (2 kb; 800°C) is \(10^{-10}\) (Poland 1974, p. 82) and in low albite (600°C) also is about \(10^{-10}\) (Lin and Yund 1972, p. 179).

The relationship between time and temperature may be determined by means of the Arrhenius equation:

\[
D = D_0 \exp \left(\frac{-Q}{RT}\right)
\]

where \(D_0\) is the pre-exponential constant, \(Q\) is the activation energy, \(R\) is the gas constant, and \(T\) is the temperature. The temperature may
be estimated from the melting interval determined experimentally for the O'Leary Porphyry. Between about 800 and 850°C sanidine and plagioclase coexist according to that experimental data. The seeded crystals which grew mantles were run at 818-831°C. Therefore, 800 and 850°C are used. 

$D_0$ and $Q$ values of sodium in orthoclase and in low albite are quite different. $D_0$ for orthoclase is 8.9 cm$^2$/sec (Foland 1974, p. 77) and for low albite $2 \times 10^{-6}$ cm$^2$/sec. $Q$ for sodium in orthoclase is 52.7 kcal/mole (Folan 1974, p. 77) and for low albite 19 kcal/mole (Lin and Yund 1972, p. 177). Relating the two equations:

$$x^2/2t = D_0 \exp (-Q/RT)$$

for $x = 0.42$ cm, $D_0 = 9$ cm$^2$/sec, and $Q = 53$ kcal/mole, at 800°C:

$$t = \frac{0.1764 \, \text{cm}^2}{(9 \, \text{cm}^2/\text{sec}) \, \exp (-25)} = \frac{0.1764 \, \text{cm}^2}{(9) \, \frac{1}{(7.2 \times 10^{10})} \, \text{cm}^2/\text{sec}}$$

$$= 1.41 \times 10^9 \, \text{sec} = 44.7 \, \text{yrs.}$$

at 850°C:

$$t = \frac{0.1764 \, \text{cm}^2}{(9 \, \text{cm}^2/\text{sec}) \, \exp (-23.8)} = \frac{0.1764 \, \text{cm}^2}{(9) \, \frac{1}{(2.17 \times 10^{10})} \, \text{cm}^2/\text{sec}}$$

$$= 4.25 \times 10^8 \, \text{sec} = 13.5 \, \text{yrs.}$$

for $x = 0.42$ cm, $D_0 = 2 \times 10^{-6}$ cm$^2$/sec, and $Q = 19$ kcal/mole, at 800°C:
\[
t = \frac{0.1764 \text{ cm}^2}{(2 \times 10^{-6} \text{ cm}^2/\text{sec}) \exp (-8.9)}
\]
\[
= \frac{0.1764 \text{ cm}^2}{(2 \times 10^{-6})} = 6.5 \times 10^8 \text{ sec} = 20.6 \text{ yrs.}
\]
\[t = 0.1764 \text{ cm}^2\]
\[\frac{1}{(1.36) \times 10^{-10} \text{ cm}^2/\text{sec}}\]

at 850°C:

\[
t = \frac{0.1764 \text{ cm}^2}{(2 \times 10^{-6} \text{ cm}^2/\text{sec}) \exp (-8.5)}
\]
\[
= \frac{0.1764 \text{ cm}^2}{(2 \times 10^{-6})} = 4.3 \times 10^8 \text{ sec} = 13.7 \text{ yrs.}
\]

Thus, if temperature were held constant at 800°C, less than 50 years would be required to form peaks as observed. Of course, temperature is not held constant, but these values suggest that during cooling of a volcanic dome it might be possible to produce diffusion peaks on the order of 0.5 cm apart.
APPENDIX C

APPLICATION OF FELDSPAR GEOTHERMOMETERS

The feldspar geothermometers should indicate the temperature at which the plagioclase and alkali feldspar coexisted in the melt. This temperature will only correspond to the actual temperature within the O'Leary Porphyry if the assumptions are valid for the O'Leary melt.

Barth (1962b, pp. 332-3) used the ratio of the mole fraction of albite in alkali feldspar to that in coexisting plagioclase ($An_{5-40}$) to determine the temperature. This is valid only if the solutions are nearly ideal (Saxena 1973, p. 141) which is not true of sanidine. Stormer (1975, p. 669) rejected this method because of this, because the coefficients in the equation were determined by comparison to natural feldspars whose temperatures were determined from another method, and because pressure was not considered.

In Kudo and Weill's (1970) geothermometer the plagioclase was assumed ideal. Ab and An contents of the outer zones of plagioclase phenocrysts were related to the mole fraction of soda, lime, silica, and alumina in the groundmass near the plagioclase. This latter value may be approximated by those values in the whole rock if phenocrysts comprise 20% or less of the rock (Stormer and Carmichael 1970, p. 306).

The O'Leary phenocryst content is about 22%. The O'Leary groundmass is highly inhomogeneous and the microprobe values of it vary widely. The technique was used with both an average microprobe analysis of groundmass
and whole rock values. In the first case, a range of temperatures were obtained depending upon the average groundmass composition used. The values were higher than in other techniques (described below) where the values were subsolidus (according to hydrothermal experiments). Using the whole rock compositions, an imaginary number resulted.

Saxena (1973, pp. 142-4) presented the following equation:

\[
K_D = \frac{X_{Ab-s} X_{Or-pl}}{X_{Ab-pl} X_{Or-s}}
\]

In this equation the distribution coefficient \( K_D \) was related to the mole fractions of Ab and Or in sanidine \((s)\) and plagioclase \((pl)\). Sanidine and plagioclase were assumed to be binary solid solutions. Determinative curves were based on Seck (1971). Using the O'Leary sanidine composition variously with the clear mantle, plagioclase phenocrysts, and poikilitic plagioclase compositions, the temperatures derived were 690-700°C—values which are subsolidus. Since O'Leary plagioclase has 7-9 mole percent Or, the assumption of a plagioclase binary may be the cause of the obvious discrepancy.

Stormer (1975, p. 672) used a method similar to that of Saxena (1973). He assumed binary solid solutions and that the activity coefficient of Ab in plagioclase was 1. He used a regular solution model (Waldbaum and Thompson 1968). Values derived from the O'Leary compositions were 650-690°C—values similar to those derived from Saxena's method. Again, these values are subsolidus as determined from hydrothermal experiments.
Assuming that the hydrothermal melting interval adequately models the actual crystallization interval of the O'Leary Porphyry, these geothermometers are either inadequate, or there was subsolidus equilibration. The problem may lie in that they have assumptions, such as binary solid solutions, which are not valid for the O'Leary Porphyry.
APPENDIX D

ASSIMILATION OF XENOLITHS

Using the U. S. Geol. Survey chemical analyses of the two types of xenoliths (Table III) and of the O'Leary Porphyry (Table I), a calculation may be made of the composition of the O'Leary magma before assimilation of xenoliths. The MgO content of the O'Leary Porphyry (0.4 weight percent) limits the amount of assimilation to between 11.8 and 16% of the original melt (by weight). This amount of assimilation of xenolith containing, respectively, 3.4 and 2.5 weight percent MgO in a magma with no MgO would result in a rock containing 0.4 weight percent MgO. Assuming that the present porphyry is made up of a minimum of 84% original magma and a maximum of 16% assimilated xenoliths, the most silicic composition possible for the original magma has been calculated (Table III).
REFERENCES


Chudoba, K., 1932, Die Feldspäte und ihre praktische Bestimmung: Schweizerbarthsche Verlagsbuchhandlung Stuttgart, 54 S., 4 Taf., 46 Abb. Pr. 5, ---, geb. 6, R. M.


Eichelberger, J. C., 1976, personal communication, Los Alamos Scientific Laboratory, Los Alamos, N. M.


James, R. S. and Hamilton, D. L., 1969, Phase relations in the system NaAlSi$_3$O$_8$-KAlSi$_3$O$_8$-CaAl$_2$Si$_2$O$_8$ at 1 kilobar water vapour pressure: Contr. Mineralog. Petrol., v. 21, pp. 111-41.


________, 1976, written communication to Dr. T. Loomis of The University of Arizona.


Maucher, A., 1938, Über die Erzvorkommen von Keban-maden (Turkei): Z. prakt. Geol., v. 46, pp. 79-84


Rucklidge, J. C. and Gasparrini, E. L., 1969, EMPADR VII, a computer program for processing electron microprobe analytical data: Dept. of Geology, Univ. of Toronto, Toronto, Canada.


Sobolev, V. V., 1947, Petrologiya vostochnoy chast'i sloznogo Korosten skogo plutona (Petrology of Eastern Part of Korosten Complex Plutonic Body): Uchen. zap. Lvovsk. univ., v. VI, no. 5.


Wahl, W., 1925, Die Gesteine des Wiborger Rapakiwigebietes: Fennia, v. 45, pp. 105-26


Welber, P., 1976, personal communication, Department of Geosciences, The University of Arizona.


