RICE UNIVERSITY

ANORTHOSITE-GABBRO-GRANOPHYRE RELATIONSHIPS,
MOUNT SHERIDAN AREA, OKLAHOMA

by

EDWARD C. THORNTON

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF ARTS

Thesis Director's Signature:

Houston, Texas
May, 1975
ABSTRACT

ANORTHOSITE-GABBRO-GRANOPHYRE RELATIONSHIPS
MOUNT SHERIDAN AREA, OKLAHOMA

Edward C. Thornton

Field work, phase analysis by microprobe, petrography, and oxygen isotope analysis have been undertaken in an effort to establish the relationships among the anorthositic, gabbroic, and granophyric rocks of the Mount Sheridan area in southwestern Oklahoma.

The gabbro has been found to be somewhat finer-grained when in contact with the anorthosite. Petrographically, the gabbro is quite different from the anorthosite. The anorthosite is essentially a one-pyroxene rock (clinopyroxene) while the gabbro contains both augite and hypersthene. Quartz, micropegmatite, and biotite are present in the gabbro but essentially absent in the anorthosite. The anorthosite is a cumulate rock with well-developed igneous lamination whereas the gabbro is generally not laminated. The above information established that the anorthosite is the older unit and that the gabbro was subsequently intruded into it.

The gabbro is transitional into the overlying granophyre through a zone of intermediate rock. The zone of transition has been found to extend into the gabbro itself as has been determined by phase analysis. In addition,
diabasic inclusions are present in the granophyre — evidence of possible mixing of basaltic and granophytic magma. These observations suggest that gabbroic and granophytic magmas were emplaced simultaneously at Mount Sheridan and that the intermediate rock between the gabbro and granophyre may have been generated by mixing of the two magma types.

The granophyre has a $\delta^{18}O$ value of $+4.7 \pm 0.7$ (this study) while Johnson and Denison (1973) report that the initial value for the Sr87/Sr86 ratio is $0.707 \pm 0.001$. The granophyre has a minor amount of ferroaugite (this study). Chemical and mineralogical data suggest that the granophyre may have been derived, in part, from a basaltic parent but volume relationships indicate that melting of crustal or upper mantle material was also important.

A tectonic-magmatic model is presented to demonstrate the possible genetic relationships of the magma types.
ACKNOWLEDGEMENTS

This study is part of an investigation of the Wichita Mountain complex of Oklahoma in progress at Rice University under the direction of Dr. Powell, the writer's chief advisor. He has provided the advice and encouragement necessary for completing the study.

Dr. J. A. S. Adams and Dr. D. R. Baker, who have been on the thesis committee, have reviewed the manuscript and provided stimulating comments and criticisms. Recognition is made of the financial aid received from the Welch Science Foundation under the administration of Drs. J. A. S. Adams and J. J. W. Rogers.

Special thanks are due Michael L. Johnson for his guidance in obtaining the oxygen isotope data. He has also provided much stimulating discussion and advice during the course of the work.

The author has had the good fortune to be able to communicate either directly or by correspondence with many of the people who have performed important studies in the Wichita Mountains. Drs. R. E. Denison and J. F. Fischer have provided important information during our discussions. Drs. H. E. Hunter and A. B. Spencer have guided the author in recognizing critical field relationships. Dr. Warren Hamilton has corresponded with the author - many of the ideas presented in this paper are clearly a product of
the influence he has had.

David Phelps, a fellow graduate student working in the Wichitas, has provided stimulating discussion concerning crucial problems and has forced the author to continually reevaluate his observations and conclusions. Finally, thanks are extended to the many other student and faculty members who have provided much needed aid during the study.
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INTRODUCTION

Regional and Tectonic Setting

Mount Sheridan is located on the northern boundary of the Wichita Mountains Wildlife Refuge about 20 miles northeast of Lawton, Oklahoma (Figures 1, 2, and 5). The Wichita Mountains, a range trending northwest-southeast, are a group of granite and gabbro hills and, although relatively modest in terms of elevation, rise dramatically above the surrounding Permian plains of southwestern Oklahoma.

It has been suggested by recent workers that the Paleozoic trough extending from the Ouachita foldbelt northwest across the foreland platform of Southern Oklahoma is an aulacogen (Hoffman, Dewey, and Burke, 1974; Ham 1964, 1967, 1969). The igneous rocks may represent the products of magmatism associated with rifting of continental crust that began in the Early to Middle Cambrian. Downwarping of a broad trough occurred from Late Cambrian to Late Ordovician with sedimentation changing from clastics to carbonates. This trough was tectonically deformed in the late Paleozoic, accompanied by the development of vertical and trancurrent faults. Thick accumulations of Mississippian to Permian clastics were deposited in the Anadarko and Arbuckle Basins while, simultaneously, the Wichita and Arbuckle Mountains were uplifted (Figure 1).
Figure 1. Index Maps.

A. Structural Provinces of Southern Oklahoma.

Area within rectangle is shown in Illustration B. From Ham et al. (1964).

B. Wichita Mountains.

Index map showing principal towns and roads.

Area within rectangle is shown in Figure 2.
Figure 2. Geologic map of the eastern portion of the Wichita Mountains, Oklahoma

References: Merritt (1967), Miser (1954)
Personal field work, summer 1974

- Sedimentary rocks, mainly Permian in age

- Middle Cambrian(?)
  Approximately 525 m.y.

- Mt. Scott granite

- Carlton Rhyolite Group

- Mt. Sheridan biotite gabbro

- Lower Cambrian(?)
  Approximately 535 m.y.

- Gabbroic anorthosite of the Raggedy Mountain Gabbro Group
The geology of the Wichita Mountains was described early in the century by workers such as Taylor (1915) and Hoffman (1930). They believed that the igneous rocks were Precambrian in age and were time equivalents of those rocks exposed to the east in the Arbuckle Mountains. Hamilton (1956, 1959) pointed out that the two are not correlative, the granites in the Arbuckles being Precambrian in age while those in the Wichitas are Cambrian. Furthermore, he emphasized that their tectonic settings are different, pointing out that the Arbuckle granites are probably of the calc-alkaline variety, a type commonly produced in orogenic provinces, while the anorthosite and granite of the Wichitas are components of a large lopolith. The granites associated with lopoliths are somewhat alkalic and are more commonly present in anorogenic magmatic provinces.

More recent petrographic and mapping work was undertaken by Hunter (1962) and his students (unpublished M.A. theses, University of Oklahoma). Ham, Denison, and Merritt (1964) have effectively summarized the work of previous investigators and their own studies, outlined below.

The Raggedy Mountain Gabbro Group, a portion of the basement rock of the Wichita area, is now thought to be Early to Middle Cambrian in age (535 ± 30 m.y.) as determined by isotopic dating methods (U238/Pb206, U235/Pb207,
Table 1. Major Rock Units of the Wichita Province  
Data from Merritt (1967) and Ham et al. (1964).

<table>
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<th>Isotopic age (million years)</th>
<th>Extrusive Rocks</th>
<th>Intrusive Rocks</th>
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<td>525±25</td>
<td>granite and granophyre of the Wichita Granite Group</td>
<td>Carlton Rhyolite Group</td>
</tr>
<tr>
<td>535±30</td>
<td>Intrusive Group: granite-aplite, microdiorite composite dikes, Mt. Sheridan biotite gabbro</td>
<td>Navajoe Mountain Basalt-spilite Group</td>
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<tr>
<td></td>
<td>Raggedy Mountain Gabbro Group-principally layered gabbroic anorthosite</td>
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</table>
Pb207/Pb206, Th232/Pb208, Rb87/Sr87, K40/Ar40: Ham, Denison and Merritt, 1964). This group consists of 1) anorthosite with minor tructolite and gabbro exhibiting rhythmic layering and igneous lamination and 2) various rock types that intrude the layered rocks. Hunter (1967) has named these two groups the layered series and the intrusive group, respectively. Ham et al. concluded that the Wichita Granite Group, which appears to be slightly younger (525 ± 25 m.y.), cuts and overlies the Raggedy Mountain Gabbro Group (Table 1). The granite group consists of perthitic leucogranitic and granophyric sills and irregular plutons.

Most previous studies have thus separated the crystalline rocks of the Wichita Mountains into two distinct groups. A sizeable mass of biotite gabbro (here called the Mount Sheridan gabbro) in the eastern portion of the Wichita Mountains, however, has received very little attention. It was apparently recognized as younger than the gabbroic anorthosite in 1954 when the Geologic Map of Oklahoma was prepared (Miser, 1954), but little was known of the areal distribution and detailed relationships of the gabbro and the anorthosite. Hunter (1967) recognized that the Mount Sheridan gabbro is younger than the layered series and probably a member of the intrusive group but questioned its status relative to the granites and the anorthosites. He noted that age-wise the gabbro might be closer to the granophyre than to the anorthosite and
emphasized the need for more work in this area.

Statement of the Problem

The purpose of this study is to investigate the relationships among the basic, intermediate, and granitic igneous rocks which are temporally and spatially associated in the eastern Wichita Mountains. The elucidation of these relationships is necessary in order to attain an understanding of the magmatic and tectonic evolution of the Wichita complex.

Two distinct but possibly related problems explored are:

1) The relationships between the layered anorthosite, the biotite gabbro, and the granophyre.

2) The origin of the granophyre (Mount Scott granite of Merritt, 1965).

As mentioned above, Hunter (1967) recognized the distinction between the "diorite" (biotite gabbro) of Mount Sheridan and the layered series (gabbroic anorthosite) to the north. The biotite gabbro (Mount Sheridan gabbro) is younger and is probably related to the microdiorite and other members of the intrusive group present in the Roosevelt area to the west (Hunter, 1967; Figure 1). Thus, the Raggedy Mountain Gabbro Group consists of an older layered series and a group of younger dioritic and gabbroic rocks
intrusive into the layered series. The relationship between the layered anorthosite and the biotite gabbro is investigated in this study and, in addition, their relationship to the granophyre.

The second problem was suggested partly by a disagreement between Ham & Hon (1959) and Ham et al. (1964) that has arisen concerning the origin of the granophyre. Ham et al. have expressed the belief that the granites are younger than the anorthosites, being separated from them by a short, but distinct, pause in magmatic activity. They postulated that the magma which produced the anorthosites was intruded into a Precambrian metasedimentary terrain (the Tillman Group) while volcanics of the Navajo Mountain Basalt Group were simultaneously extruded on the surface of the metasediments. They suggested that the Wichita block was uplifted after the formation of the anorthosite with the subsequent removal by erosion of the basaltic and metasedimentary roof. Thus, the anorthosites were subaerially exposed. Rhyolites of the Carlton Group were then extruded on the erosional surface and shallow sills and plutons of granophyric (micrographic) and hypautomorphic-granular granite were intruded into the rhyolites. Thus Ham et al. concluded that the granite and anorthosite are completely unrelated genetically. This model is plausible with regard to what is presently known concerning the relative ages of the rock types but several
points are worth noting. The correlation of the Navajoe Mountain Basalt Group with the Raggedy Mountain Gabbro is tenuous as the basalt is present only in the subsurface. Furthermore, the basalt has not been dated (pers. comm. R. E. Denison). Also, recent isotopic dating has failed to clearly separate the anorthosite, members of the intrusive group, and granite (Denison, Hetherington, and Kenny, 1966). Hamilton (1959, 1960) has compared the chemistry of the granites associated with the Wichita, Duluth, Sudbury, and Bushveld intrusions and concluded that chemical trends and characteristics imply that granophyre forms a genetically related and integral part of such intrusions. In each instance, the rhyolite and granophyre appear to be incorporated into the roof of the intrusion with large masses of anorthosite and gabbro present below the granophyric roof. Hamilton suggested that the granophyre is a differentiate of the same parental magma that produced the basic portions of the intrusions. Although such a concept may be too simplistic, especially in a province as complicated as the Bushveld, it does present a correlation among the examples mentioned that could hardly be coincidental. Thus, Hamilton and Ham et al. are clearly at variance in their concepts of the origin of the granites of the Wichita complex.

The problems discussed above have been approached in this study by the following methods:
1) Field observation

2) Petrography by transmitted and reflected light microscopy

3) Phase chemistry by microprobe analysis

4) Oxygen isotope analysis

In addition, bulk chemical data from the literature have been utilized.
FIELD OBSERVATIONS AND MAPPING

Previous Work

Several geologic mapping projects have been conducted in the eastern Wichita Mountains, among the first being Taylor (1915) and Hoffman (1930). Chase (1950) and Ham et al. (1964) performed reconnaissance mapping and established the relative age relationships of the granite, rhyolite, and basic rock. Miser (1954) incorporated much of this information into the Geologic Map of Oklahoma. Merritt (1967) has prepared the most recent map, including his own study of the age relationships of the various granites and rhyolites. Hunter (1967), in a reconnaissance study, noted that the diorite (biotite gabbro) is intrusive into the layered series but did not define the extent or relationship of the two units. Figure 2 is a compilation of these studies with additional field work to define the extent of the biotite gabbro. It should be emphasized, however, that Figure 2 is only a general map. Figure 3 is a map of the Mount Sheridan area, the location of primary interest to this study and the area towards which detailed field and laboratory investigation has been directed.

The Present Study

The anorthosite north of Mount Sheridan dips slightly
toward the north as determined by the igneous lamination and stratigraphic sequence (see below and Figures 2 and 3). A biotite gabbro of more intermediate character is present along Medicine Creek and extends up the side of Mount Sheridan. This unit is designated the Mount Sheridan gabbro. A sill-like body of granophyre (Mount Scott granite of Merritt, 1965, 1967) occurs along the crest of Mount Sheridan and dips slightly to the south (about 5°). Stratigraphically above this is the Carlton Rhyolite Group, here removed by erosion, but exposed further south in the Fort Sill Military Reservation (Figure 2). Thus the relationships are basically simple, though somewhat complicated by poor exposure of the base of the granophyre and by possible movement along faults and joints in the area.

The anorthosite north of Medicine Creek is characterized by igneous lamination of the plagioclase and contains oikocrysts of pyroxene, magnetite, and olivine. The nature of these oikocrysts allows a two-fold field classification of anorthosite into the L- and M-zone types (Hunter, 1962, 1967). The plagioclase within the oikocrysts of the L-zone type are generally the same size as the plagioclase outside of the oikocrysts but tend to be somewhat finer-grained within the oikocrysts of the M-zone type. Also, the average length of the plagioclase of the L-zone is usually about 1 to 2 mm while the plagioclase in the M-zone is
about 1 mm in length. The anorthosite is usually fresh but appears to become somewhat altered or prehnitized near the contact with the gabbro. The L-zone lies directly above the gabbro whereas the M-zone, which is stratigraphically higher than the L-zone, lies a short distance further to the north and hence indicates that the layered series dips slightly towards the north. The L-zone, due to its proximity to the gabro, is more altered than the M-zone.

The gabbro is usually medium-grained and generally displays little or no igneous lamination. It has a grain-size of about 1 mm but is slightly finer (½ - 1 mm) near the contact with the anorthosite where the plagioclase laths also show flowage alignment. Pods and veins of a coarse pegmatite are present throughout the gabbro. The pegmatite may be recognized by its rather high content of mafic minerals (20 - 30% hornblende, biotite, and uralitized pyroxene) in addition to quartz, alkali feldspar, and altered plagioclase.

The exact location of the contact between the gabbro and granophyre is generally difficult because it is usually covered with granitic talus. Anorthosite has been found to occur immediately beneath the granophyre and above the gabbro, however, along the north side of Mount Sheridan and Mount Scott. The cross-section in Figure 3 illustrates that this may be an extension of the anorthosite exposed north of Medicine Creek. Another explanation, however,
might involve faulting along Medicine Creek. One could also interpret the anorthosite high on the northern slope of Mount Sheridan to be a xenolith of the layered series within the gabbro.

Exposure on the eastern slope of Little Mount Sheridan permit closer examination of the variation within the gabbro (Figure 4). The gabbro is fairly homogeneous near the base of the section although cut by veins and pods of pegmatite. The gabbro takes on a more heterogeneous appearance towards the top of Little Mount Sheridan, eventually assuming the composition of an intermediate rock due to the modal increase of quartz and alkali feldspar. The contact zone between the gabbro and the granophyre often comprises an intermediate rock (i.e. granogabbro, Huang, 1955). It is variable in texture and composition, sometimes approaching a granodiorite or diorite in character and at other times occurring as a fine-grain gabbro or diabase mixed with granophyre and intermediate rock. No anorthosite was seen along the gabbro-granophyre contact on Little Mount Sheridan.

The granophyre is generally homogeneous, but inclusions of diabase or fine-grained gabbro have been found in the granophyre a short distance above the contact with the gabbro.
Figure 4. Cryptic Variation—Little Mt. Sheridan (Traverse on the east side of Little Mt. Sheridan.}

<table>
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<tr>
<th>Feet</th>
<th>T-32</th>
<th>T-39</th>
<th>T-43</th>
<th>T-47</th>
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<td>Granophyre</td>
<td>Intermediate Rock</td>
<td>Quarry C</td>
<td>Quarry B</td>
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</table>

- Observed variations in mineralogy and composition along the traverse.
- Quartz and muscovite deplete at higher elevations.
- Pyroxene content varies from 0.34 to 0.52.
-顽toplase content ranges from An40 to An55.
Figure 5. View of Mt. Sheridan from the north. Granophyre forms the cap of the hill, gabbro the slope, and anorthosite underlies the valley. The small peak to the left is Little Mt. Sheridan.

Figure 6. Sample T-61: gabbroic anorthosite of the layered series. Collected north of Rowe's Quarry. Crossed polars
Field: 2x3 mm
pl=plagioclase, au=augite
PETROGRAPHY OF ROCK TYPES

Layered Series (Gabbroic Anorthosite of the Raggedy Mountain Gabbro Group)

Cumulus bytownite (An 70-75) is the principal phase (> 90%), occurring as subhedral interlocking grains, thus evidencing adcumulus growth (Figure 6). Interstitial augite often occurs (about 5%). Thus the rock may be designated a plagioclase-augite heteradcumulate (Wager and Brown, 1967). Accessory olivine and magnetite are present. Orthopyroxene forms coronas around the olivine; it also occasionally occurs as discrete grains.

Diopsidic augite is present as large oikocrysts (up to 5 cm in diameter) in the L- and M-zones of the anorthosite. The anorthosite of the L-zone has a grain size of about 1 to 2 mm while the M-zone is slightly finer. The oikocrysts of the M-zone are distinctive in that the plagioclase entrapped in the oikocrysts is subhedral to anhedral and is finer-grained and more sodic than the plagioclase outside of the oikocryst (Hunter, 1962, and personal comm.).

The anorthosite is generally fresh but is sometimes altered or prehnitized (Huang, 1955). In these instances, the plagioclase is also sericitized and the augite is uralitized. Augite often exsolves large quantities of opaques (magnetite and ilmenite) and coronas of orthopyroxene and spinel form around the olivine. Zoning of plagi-
oclase also occurs.

**Mount Sheridan Gabbro**

The principal rock unit on the north slope of Mounts Sheridan and Scott is composed of intermediate plagioclase, augite, hypersthene, magnetite, and ilmenite with interstitial quartz, micropegmatite, and biotite (Figure 7). The examination of a series of samples collected at Little Mount Sheridan has revealed that the unit varies systematically with respect to the quantity and composition of mineral phases (Figure 4). Olivine is present in minor amounts at the base of the exposed sequence (Figure 8). Plagioclase becomes more sodic towards the top and augite and hypersthene become more iron-rich. (See phase chemistry section.) Biotite, quartz, micropegmatite, primary and secondary chlorite and hornblende, and apatite also increases in abundance towards the contact with the granophyre at the top of Little Mount Sheridan (Figure 9).

The contact zone between the gabbro and granophyre is an intermediate rock composed of a mixture of partially altered pyroxene and plagioclase with micropegmatite, biotite, chlorite, hornblende, opaques, apatite, and accessories (Figure 10).

Pegmatite and diabase dikes occur in the gabbro. The pegmatite consists principally of quartz, perthite, micro-
Figure 7. Sample T-68: Mt. Sheridan biotite gabbro. Collected on north side of Mt. Scott. 
Crossed polars
Field: 2x3 mm
hy=hypersthenes, qt=quartz, pl=plagioclase, op=opales, au=augite

Figure 8. Sample T-49: Mt. Sheridan biotite gabbro. Collected on east side of Little Mt. Sheridan. 
Crossed polars
Field: 2x3 mm
ol=olivine, hy=hypersthene, pl=plagioclase
Figure 9. Sample T-39: Mt. Sheridan biotite gabbro. Collected on east side of Little Mt. Sheridan. Crossed polars Field: 2x3 mm
au=augite, qt=quartz, pl=plagioclase, ap=apatite, al=alkali feldspar

Figure 10. Sample T-35: intermediate rock. Collected below granophyre of Little Mt. Sheridan. Crossed polars Field: 2x3 mm
pl=plagioclase, qt=quartz, mc=microperthite, hd=hornblende
pegmatite, biotite, hornblende, opaques, and altered pyroxene and plagioclase (Figure 11). The pegmatite often occurs as dikes cutting the gabbro. The diabase is fine-grained and is composed of plagioclase, pyroxene, opaques, quartz, hornblende, and biotite. The larger diabasic dikes generally have a fine-grained intergranular texture composed of plagioclase laths (about 0.2 mm) with interstitial pyroxene and opaques.

Granophyre (Mount Scott Granite)

The granophyre sill which caps Mount Sheridan consists of perthite phenocrysts approximately 2 mm in diameter in a micrographic to hypantomorphic granular groundmass of quartz and microperthite (Figure 12). Opaques make up about 5% of the rock. Hastingsite (about 5%) occurs as subhedral grains about ½ mm in diameter which often have cores of ferroaugite. Sphene, zircon, and allanite occur as minor and accessory phases. Neither foyalite nor orthopyroxene have been identified among the minerals present. Hematite (?) dust is scattered through the perthite and occurs along grain boundaries. The opaques, amphibole, and sphene often occur in clots.
Figure 11. Sample T-50: pegmatite. Collected on east east side of Little Mt. Sheridan. Crossed polars
Field: 2x3 mm
qt=quartz, mp=micropegmatite, py=pyroxene

Figure 12. Sample T-32: granophyre (Mt. Scott granite). Collected on top of Little Mt. Sheridan. Plane-polarized light
Field: 2x3 mm
qt=quartz, mc=microlithoclast, hd=hornblende, fr=ferroaugite, pr=perthite phenocryst
PHASE CHEMISTRY

Mineral compositions were quantitatively analyzed by electron microprobe (ETEC Autoprobe). Natural mineral standards with compositions similar to those of the unknowns were used when available. The raw data were reduced by computer using an iterative process comparing the standard and unknown with corrections made for matrix effects. (See Appendix I for further details)

Pyroxene analyses from the anorthosite, gabbro, and granophyre are presented in Table 2 and Figure 13. The augite has been useful in comparing the rock types. The augite of the anorthosite is diopsidic, that of the gabbro is a more intermediate type, and that of the granophyre is ferroaugite. Table 2 demonstrates some of the variations in their minor element contents. The pyroxene of the anorthosite contains significant amounts of $\text{Al}_2\text{O}_3$ (2-3%) and $\text{TiO}_2$ (0.5%). The augite of the gabbro, in contrast, has lower values for both $\text{Al}_2\text{O}_3$ and $\text{TiO}_2$ (0.5 and 0.1%, respectively). The Ti/Al ratio for the anorthosite and the granophyre is about 0.18 and 0.17, respectively. The ratio for the augite of the gabbro is variable but averages about 0.12. These values suggest that feldspar fractionation may have been more important for the anorthosite and the granophyre than for the gabbro. The ferroaugite of the granophyre is interesting in that the MnO content is
Table 2. Representative Pyroxene and Amphibole Analyses

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<td>99.98</td>
<td>98.84</td>
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Z \{Si} IV 1.921 1.995 1.996 2.003 1.988 Z \{Si} IV 7.080
\{Al} IV 0.079 0.005 0.004 0.012 \{Al} IV 0.920
\{Al} VI 0.017 0.033 0.016 0.017 0.013 \{Al} VI 0.540
Ti 0.017 0.009 0.003 0.003 0.005 Ti 0.149
Fe 0.391 0.681 0.368 0.434 0.579 Y Fe 3.399
Mn 0.011 0.018 0.011 0.010 0.049 Mn 0.153
Mg 0.770 1.149 0.710 0.816 0.482 Mg 1.661
Ca 0.803 0.084 0.930 0.465 0.842 Ca 0.003 0.005 0.003 0.020 0.051 Ca 1.849
Na 0.003 0.005 0.003 0.020 0.051 Na 0.482
K n.d.
Mg 39.2 60.0 35.4 47.6 25.3 100Mg:(Mg+Fe+Mn)=31.8
Fe 19.9 35.6 18.3 25.2 30.4
Ca 40.9 4.4 46.3 27.1 44.2

Analyses 1-5: Pyroxene formulae on basis of 6 oxygens.
Analysis 6: Amphibole formulae on basis of 24 oxygens.

1. Augite from anorthosite taken north of Rowe's Quarry (sample T-61).
2. Hypersthene from Mt. Sheridan gabbro collected on north slope of Mt. Scott (T-68).
3. Augite of above sample.
4. Subcalcic augite from chilled (?) gabbro on north side of Mt. Scott (T-67B).
5. Ferroaugite from granophyre (Mt. Scott granite) collected near top of Little Mt. Sheridan (T-32).
Figure 13. Pyroxene Quadrilateral

- Skaergaard trend
- Anorthosite (T-61)
- Mt. Sheridan gabbro:
  - T-68 Mt. Scott
  - T-39
  - T-43 Little Mt. Sheridan
  - T-47
- Chilled(?) gabbro from Mt. Scott (T-67B)
- Granophyre:
  - T-88 Mt. Sheridan
  - T-32 Little Mt. Sheridan

![Figure 13: Pyroxene Quadrilateral](image-url)
significant (1.5%).

Figure 13 illustrates another characteristic of the ferroaugite: it consistently plots in an area above the Skaergaard curve (i.e. is more calcic.) Carmichael et al. (1974) have noted this in a number of pyroxene analyses from rhyolites and granophyres. This phenomena may be related to the position of the pyroxene solidus and hence its intersection with the limbs of the solvus.

An analysis of the hastingsite rim of the ferroaugite and of a subcalcic augite from a chilled (?) gabbro is also presented in Table 2. The poor stoichiometry and high Al₂O₃ of the subcalcic augite suggest that the pyroxene may have been somewhat uralitized, however. The low total may be due to the presence of H₂O in the lattice.

The hypersthene of the gabbro is rather iron-rich in some cases (e.g. T-39, Figure 5), being stable to a higher ferrosilite content than that of the Skaergaard. Most were obviously primary orthopyroxene and not inverted pigeonite. Naldrett (1967, 1970) has also reported iron-rich hypersthene in the sudbury Nickel Irruptive.

Microprobe analysis has revealed cryptic variation in the gabbro sequence at Little Mount Sheridan (Figure 4). Analysis indicates that a relative iron-enrichment of the pyroxene occurs vertically in the section with a complementary increase in the sodium content of the plagioclase.
OXYGEN ISOTOPIC ANALYSIS

Twenty-six whole rock oxygen isotope analyses were performed using the bromine pentafluoride technique (Clayton and Mayeda, 1963). The analytical apparatus and techniques used resulted in a precision of ± 0.2 ‰. (See Appendix II for details.)

Table 3 is a compilation of the oxygen isotope data. All values are positive.

Four of the anorthosites sampled just north of Medicine Creek were analyzed. Their isotopic values were found to vary significantly (+ 4.6, + 4.8, + 6.2, + 8.5). Samples T-61 (+ 4.6) and T-63 (+ 4.8), however, show some signs of alteration (prehnitization). T-60 (+ 8.5) was collected near the contact with the gabbro (+ 8) and thus may have been affected by the intrusion of the latter. T-62 (+ 6.2) was collected further to the north and appears to be unaffected. Additional samples of anorthosite from the Raggedy Mountains (T-12, T-23; GM55R, GM86R, GM97R, and GM188R collected by David Phelps) were analyzed and yielded values of about + 6. The average value for the anorthosite is + 6.2 with an average deviation of ± 0.3, omitting samples T-61, T-63, and T-60.

The gabbros were divided into two groups on the basis of grain size. The finer-grained variety appears to be chilled gabbro or diabase with a value of about 6.9. (Note:
Table 3. Oxygen Isotope Data ($\delta^{18}O$)
Performed by Edward C. Thornton and Michael Johnson
Analytical precision: $\pm 0.2\%$
Whole rock analyses using SMOW standard (James, 1974).

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<td>Mt. Sheridan</td>
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<td>sample $\delta^{18}O$</td>
<td>sample $\delta^{18}O$</td>
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<td>Granite</td>
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<td>GM188R(M) +5.5</td>
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Letter in parentheses refers to zone type
Figure 10 is of an intermediate rock while the analysis in Table 3 is of a diabase inclusion in the same sample.) This is within the normal basaltic range (Taylor, 1968). The coarse-grained gabbro has an average value of $8.0 \pm 0.7$ (uncertainty as average deviation from the mean), significantly higher than the finer-grained variety. The zone of intermediate rock between the gabbro and granophyre is about $+4$ and overlaps the range of the granophyre.

The granophyre isotope values range from $+3.3$ to $+5.9$ (6 analyses) and average $4.7 \pm 0.7$. Most of these fall below the L-Group (5.5 to 6.9), the range for rocks derived from a normal basaltic magma (Taylor, 1968).
CHEMISTRY OF THE GRANOPHYRES AND GRANITES
OF THE WICHITA COMPLEX

Several chemical analyses for the Mount Scott granite and the Quanah granite have been obtained from the literature (Table 4). Outcrops of the Quanah are found in the Wichita Mountains slightly to the southwest of the mapped area (Figure 2). Refer to Merritt's map (1967) for the specific location of the unit.

Examination of the bulk chemistry of the granites of the area reveals a regional characteristic: there is an association of peralkaline and nonperalkaline granite. Table 4 illustrates the chemical differences of these two types. Bowden and Turner (1974) point out that peralkaline granites have sodic pyroxene or amphibole in the mode and normative acmite or sodium silicate. The Quanah is a peralkaline granite with model riebeckite and normative acmite. A nonperalkaline or metaluminous granite generally has modal hastingsite, hedenbergite, or fayalite and has normative anorthite or corundum. The Mount Scott granite has modal ferroaugite with hastingsite rims and normative anorthite. The biotite granite of the Lake Altus area (Lugert granite) is a peraluminous variety.

This fundamental division of the granites is a reflection of the ratio of alkalis to alumins and is measured by a parameter called the agpaitic coefficient which is the

2. Quanah granite: medium-grained riebeckite-bearing granite, Buford Lake SE 21-3N-14W (Ham et al., 1964).

3. Carlton Rhyolite prophyry: abundant quartz and feldspar phenocysts, Little Medicine Creek, NE NE SE15-3N-13W (Ham et al., 1964).


Table 4. Chemistry of Various Peralkaline and Nonperalkaline Granites and Granophyres

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molecular ratio of the sum of Na$_2$O plus K$_2$O to Al$_2$O$_3$ (Bowden and Turner, 1974). A slight variation in this parameter leads to the distinct changes in the mafic mineral composition of the granites discussed above.

As of this time, no analyses are available on the biotite gabbro or intermediate rock of the eastern Wichita Mountains.
DISCUSSION

Age Relationships of the Rock Units

Field examination and mapping of the Mount Sheridan area has revealed several features which indicate that the Mount Sheridan gabbro and the granophyre are younger than the anorthosite. Examination of the contact of the gabbro with the anorthosite, for example, indicated that the gabbro is somewhat finer-grained than normal and hence chilled. The granophyre is closely associated with extrusive rhyolite and cuts the anorthosite or layered series as a discordant sill (Figure 3).

It is somewhat more difficult, however, to ascertain the age relationships between the granophyre and the gabbro. The contact zone between the gabbro and the granophyre is often an intermediate rock consisting of a mixture of altered pyroxene and plagioclase with perthite, quartz, biotite, chlorite, hornblende, opaques, apatite, and accessories. The apparent disequilibrium of the assemblage suggests that either magma mixing or metasomatism (if the granophyre followed the gabbro) occurred.

Several lines of evidence suggest that a mixing hypothesis is plausible. The presence of pegmatite dikes in the gabbro and diabase inclusions (chilled gabbro?) in the granophyre suggests that the two units were intruded either at the same time or within a very short period of time so
that a mixing of magmas could occur (Didier, 1973, p. 116). The case for simultaneous intrusion of the two magmas is somewhat strengthened by the presence of composite dikes (Yoder, 1972; Didier, 1973, p. 103-111; Wiebe, 1973; J. F. Fischer, pers. comm.) in the Roosevelt area. In most of the composite dikes, it appears that a microdiorite (andesitic) magma filled a fracture initially but was immediately followed by an aplitic magma. The margins of the andesitic magma were chilled against the country rock (layered series) to produce microdiorite whereas the portion of the andesitic magma towards the center of the dike remained fluid. The aplitic magma moved up the center of the dike, displacing the andesitic magma, but fracturing the crystallized microdiorite at the margins. The aplitic magma chilled the andesitic magma and thus the andesite formed "pillows" of microdiorite floating in the aplite. Walper (1951) considered the Cold Springs granite to be the product of assimilation of andesite by a granitic magma. It seems more reasonable to regard it merely as a mixture of andesitic and aplitic magmas, however. Merritt (1967), in a summary of the age relationships of the granites of the Wichita Group, expressed the belief that the aplitic magma was emplaced contemporaneous to the emplacement of the Mount Scott granite. Furthermore, Hunter (1967) suggested that the age of the microdiorite may be similar to that of the gabbro of
Mount Sheridan. This correlation suggests that simultaneous intrusion of granitic and gabbroic magmas may also have occurred at Mount Sheridan.

**Petrographic and Phase Chemistry Study**

Petrography and phase chemistry, in general, strengthen the conclusions drawn from field study. The differences in phase chemistry between the gabbro and anorthosite supports the conclusion that the gabbro is not part of the layered series. The anorthosite generally has a calcic plagioclase (An 70) while the gabbro has an intermediate plagioclase (An 45-55). Likewise the augite of the two units is different. The augite of the anorthosite contains larger amounts of Al₂O₃ and TiO₂ than that of the gabbro, suggesting that the magma which produced the anorthosite had a lower silica activity (Carmichael *et al.*, 1974, p. 274). The magma that produced the anorthosite may have been a high-alumina tholeiite (Carmichael *et al.*, 1974, p. 483), while a saturated tholeiitic magma produced the gabbro. The compositional break between the anorthosite and gabbro indicates that they were intruded as discrete magma types rather than being separated in place by differentiation. It is possible, however, that a fractionation relationship may have existed in a magma chamber at depth before the actual emplacement of the magmas.
Petrography and phase chemistry (Figures 4 and 13) both indicate a consistent vertical compositional variation in the gabbro of Little Mount Sheridan. Petrography has revealed an increase in modal quartz and alkali feldspar and associated phases in the section while phase chemistry indicates iron-enrichment of the pyroxene as well as an increase in the sodium content of the plagioclase. Compositional variation appears to changes drastically through the intermediate rock and into the overlying granophyre, however. The compositional variation in the gabbro can be explained in at least two ways: 1) differentiation of the gabbro, or 2) mixing of gabbroic and granitic magma (i.e. introduction of granophyre into the gabbroic magma).

A certain amount of differentiation of the gabbro probably did take place but probably not to the extent of actually generating the large quantity of granophyre present (i.e. granophyre comprises only about 1% of the Skaergaard intrusion). The introduction of granophyre into the gabbroic magma, however, might lead to the compositional variation within the gabbro. If the content of silica, for instance, is greatest in the upper portion of the gabbro, it is possible that it would crystallize at a lower temperature than the uncontaminated portions of the gabbro and hence contain a more iron-rich pyroxene and sodic plagioclase. This systematic variation
in phase chemistry would not be expected, on the other hand, if the granite were intruded subsequent to crystallization of the gabbro.

Finally, an alternative not mentioned thus far needs to be considered. It is possible that the granophyre is older than the gabbro. Some of the observed phenomena might be explained by the incorporation and remelting of the granophyre upon intrusion of the gabbro (e.g. the presence of the pegmatite in the gabbro and the compositional variation within the gabbro). This hypothesis, in part, would also involve magmamixing (i.e. primary gabbroic magma mixing with remobilized granophyre). It fails to account for the presence of the diabasic inclusions within the granophyre, however. Neither does the granophyre above the gabbro appear to have been recrystallized nor have inclusions of granophyre or granite been found in the gabbro.

The occurrence of augite in the granophyre has been noted by several workers. Merritt (1965) found a small amount of pyroxene in the Mount Scott granite but suggested that it was the remnants of a xenolith. Hamilton (1959) also noted the presence of augite in the granophyre but had no data regarding its composition. Phase analysis by microprobe has identified it as ferroaugite. It is thus probably a primary liquidus phase rather than a xenolith because it is distinctively more iron-rich than the
pyroxene of the associated basic rock. It is commonly surrounded by a rim of hastingsite. The presence of the ferroaugite is not surprising as the granophyre is rather iron rich \((\text{FeO} + \text{Fe}_2\text{O}_3 \sim 4\%\), Table 4\). Neither foyalite nor orthopyroxene has been identified.

The occurrence of pyroxene, olivine, and associated iron-titanium oxides in rhyolite and granophyre has been investigated in some detail by Carmichael (1967). As the opaque minerals of the granophyre do not appear to be highly oxidized, it may be possible to obtain an estimate of the liquidus temperature and oxygen fugacity by the methods he has outlined. The opaque minerals of the gabbro, on the other hand, are frequently oxidized and hence would not be amenable to such study.

**Oxygen Isotope Analysis**

The data obtained by oxygen isotope analysis has several interesting implications. The value for the granophyre is \(4.7 \pm 0.7\) per mil \((^\circ\text{O}^{18})\). This appears to be a fairly typical value (Taylor, 1968) and is similar to that reported for the Skaergaard granophyre. Originally, Taylor and Epstein (1963) had proposed that this value was consistent with the iron-enrichment trend observed in the Skaergaard magma series. The typical basaltic magma lies in the range 5.5 to 7.0 per mil and an iron-enrichment trend should produce derivatives with values somewhat lower than
a basalt. More recently (Taylor, 1968), however, it has become increasingly obvious that exchange with meteoric water may affect the isotopic values of shallow intrusive bodies. Thus, the value obtained for the Mount Scott granite does not necessarily mean that it has been derived from a basaltic parent. The relatively small variation in the values (compare with Taylor and Forrester, 1971) does suggest, however, that meteoric contamination has not been too severe.

The rather large isotopic differences between the gabbro and granophyre (8.0 and 4.7, respectively) suggests that the latter has not been derived directly from the former. It is interesting, however, that the diabase is about 6.9 and hence not unusual for a basic magma. It is possible that the isotopic values were initially much closer but were changed, perhaps by meteoric contamination or assimilation of country rock during crystallization.

Chemistry, Relative Ages, and Origin of the Granites and Granophyres

Hamilton (1959, 1960) and Didier (1973) have noted the alkaline traits of the granites and granophyres in the Wichitas and similar complexes. Didier has also pointed out that the textural characteristics and associations with rhyolite is an indication of a subvolcanic or shallow level of emplacement. Merritt (1967) has determined the
relative ages of the granites. He suggests that the extrusive rhyolite spans the entire history of all phases of granite intrusion. The Mount Scott granite was probably one of the earliest granite types to appear, being emplaced only shortly after the earliest rhyolite extrusions (Figure 14). This granite may be classified as a metaluminous granite (Table 4) as was pointed out earlier. Somewhat later, the Quanah was intruded (a peralkaline variety) with riebeckite pegmatite dikes following shortly thereafter. Finally, biotite granite (peraluminous) appeared towards the end of the period of granitic magmatism. These relationships are broadly similar to those reported for both the Nigeria-Niger province and the White Mountain magma series (Bowden and Turner, 1974; Billings, 1956). This appears to indicate that subvolcanic granite complexes commonly evolve through the stages described above.

One of the main questions pursued in this project concerns the origin of the granophyre. It is interesting, in this regard, that the initial Sr87/Sr86 value for the Mount Scott granite has been reported as 0.707 ± 0.001 (Johnson and Denison, 1973). This value is within the range of continental tholeiitic magma (0.704 - 0.708) and is definitely lower than that which would be expected from the melting of basement (> 0.710; Carmichael et al., 1974, p. 436). The relatively large volume of the Mount Scott granite, however, and the paucity of intermediate
rock makes it unlikely that the granophyre was produced purely by differentiation of a basaltic magma. Perhaps the most reasonable model for the production of the granophyre involves the mixing of granitic magma generated in the lower crust or upper mantle with differentiates of basaltic magma crystallizing at depth.
CONCLUSIONS

Petrogenetic Relationships

The following specific conclusions are presented on the basis of the data discussed above:

1) The anorthosite is the oldest unit. The gabbro and granophyre discordantly cut the anorthosite, with the gabbro being somewhat chilled along its contact with the layered series. Textural evidence and association with rhyolite indicate the subvolcanic emplacement of the granophyre.

2) It is proposed that gabbroic and granophyric magmas were emplaced simultaneously. The following specific considerations have been investigated in testing this hypothesis:

   a The presence of composite dikes in the Roosevelt area.
   b Inclusions of diabase within the granophyre.
   c The cryptic variation observed in the upper part of the gabbro may be due to the introduction of granophyric magma into gabbroic magma.
   d The intermediate rock between the gabbro and granophyre may have been generated by the mixing of magmas.

-43-
3) It is proposed that the granophyre may have been derived in part from a basaltic parent. The oxygen isotopic value of $4.7 \pm 0.7$, Sr$^{87}$/Sr$^{86}$ value of $0.707 \pm 0.001$ (Johnson and Denison, 1973), and the presence of ferroaugite in the granophyre make this suggestion plausible. Volumetric considerations and the paucity of intermediate rock types indicate that a considerable portion of the granophyre may have also been derived by partial melting of the lower crust or upper mantle, however. Thus, it is proposed that the granophyre is a mixture of melts of different origin.

Magmatic-tectonic Development of the Wichita Complex

A study of the regional relationships among the rock groups present in the Wichita Mountains together with the general information available in the literature regarding the evolution of similar areas in other parts of the world (e.g. the Duluth Complex, British-Arctic Province, etc.) suggests that perhaps a general model might be applicable to many of them. Admittedly, it is highly conjectural, but it does serve to illustrate the general events commonly involved. It is proposed that the following events may have occurred during the development of the Wichita complex:

I) Rifting and/or doming associated with the Southern Oklahoma Aulacogen (Hoffman, Dewey, and Burke, 1974) began
Figure 14. Time Relationships of the Principal Rock Types. Data from Merritt (1967) and Ham et al. (1964).
in the early Cambrian. The initial magmatic activity may have consisted of the eruption or emplacement of an olivine basaltic magma generated at depths in excess of 30 km by partial melting of the upper mantle. Such magmatism is commonly associated with early rifting and the eruption of plateau basalt (e.g. Keeweenawan: Green, 1972; British-Arctic Province: Turner and Verhoogen, 1960; Carmichael et al., 1974).

II) Continued rifting and thinning of crust often leads to the generation of high-alumina tholeiitic basalt. This may be generated either by the fractionation of olivine and augite from olivine basalt at depths of 15 to 30 km or by partial melting of mantle material at that depth (Green, 1972). This magma, upon rising to shallow depths in the crust (< 15 km), could precipitate plagioclase and aluminous augite to produce the anorthosite of the layered series. The residuum could either have crystallized as intermediate rock types (e.g. syenite, gabbro, etc.) or may have been extruded.

III) As the crust thinned to less than 15 km, it is possible that tholeiitic magma was generated in the upper mantle or, alternatively, developed as the residuum from the layered series. Granophyre was produced also at this time by the differentiation of the basaltic magmas and by partial melting of lower crust. The granophyre and tho-
I. Initial doming and rifting-
Eruption of olivine of the
plateau type.

II. Generation of high-alumina tholeiite
with fractional crystallization at
shallow depths to produce gabbroic
anorthosite.

III. Emplacement of saturated tholeiite
and granophyre in central complexes.

IV. Emplacement of plutons of biotite
granite.

Figure 15. Development of the Wichita Complex.
(From Green, 1972, and Carmichael et al., 1974.)
A. A magma chamber containing both granitic and basaltic magma rises to shallow depths. Gabbroic magma is injected up fractures towards the surface.

B. Ring-fractures and subsidence with rhyolitic extrusion and emplacement of granophyre. Fragments of roof rock sink into the chamber.

Figure 16. Emplacement of Central Complexes. (From Chapman, 1968.)
OLIVINE BASALT MAGMA (plateau type)  
Generated at about 30km.

(By removal of olivine and diopside at 30km)  
HIGH-ALUMINA THOLEIITIC MAGMA

(By accumulation of plagioclase and augite at less than 15km)

? ??

SAT'D OR OVERSAT'D THOLEITITE  
MAGMA 15km

GRANOPHYRE  
PERALKALINE GRANITE

Partial melting of SIALIC CRUST

BIOTITE GRANITE

Figure 17. Evolution of Magma Types.  
(From Green, 1972.)
 leiitic magma were subsequently intruded simultaneously into the upper parts of the crust as shallow central complexes similar to the ring-complexes of the British Hebrides (Carmichael et al., 1974) or the White Mountain magma series of New Hampshire (Billings, 1956; Chapman, 1968). The roof of the complex may have been previously removed by erosion during doming or may have subsided or collapsed into the central complexes as they were emplaced. It is interesting to note, in this regard, that Merritt (1965) suggested that the blocks of Meers quartzite present in the gabbro and the granophyre may be roof pendants.

IV) The final period of magmatism consisted of the emplacement of plutons of biotite granite (e.g. Lugert granite). This probably was produced primarily by the melting of sial.

The steps outlined above are intended to be very general and probably not entirely applicable to any one complex. In the Wichita complex, for example, little is known concerning the nature of early basaltic eruption because no surface outcrops exist.

It seems that as our knowledge of petrology increases, it becomes more apparent that several magma types are involved in the evolution of provinces. The Hebridean province is an excellent example. As Carmichael et al. (1974, p. 460) have noted, the Hebridean magma types may not have a common parent. They probably represent varieties of magma
whose general composition is a reflection of their source and conditions of fusion. Furthermore, the granites of Skye are probably derived from several sources - the melting of basement and the differentiation of basaltic magma. Thus, the model proposed for the Wichita complex is a compound one: several basaltic and granitic magma types have been successively generated as the province evolved.
APPENDIX I:

ANALYTICAL TECHNIQUE - MICROPROBE ANALYSIS

Analyses were obtained with the ETEC Autoprobe of the Department of Geology at Rice University. An acceleration potential of 20 kv with a spot diameter of 0.1 - 1 microns and specimen current of 0.025 microamperes were employed. Three wavelength dispersive spectrometers utilizing LiF, ADP, and KAP crystals were used simultaneously, with 30 second counting times. Beam current drift was minimized by an automatic beam regulation system.

Analyses were made on carbon coated and polished thin sections. Background intensities were determined by calculation for major elements and by offsetting the spectrometers for minor elements with peak to background ratios 7:1.

A computer program developed by J. A. Wood ("Probeg IV", 1969) was used to reduce the data. The program compares the elemental X-ray intensity of the unknown with that of the standard to compute the composition, making corrections for instrumental drift, background, dead-time, absorption, atomic number, and fluorescence. Two to three iterations are generally performed before obtaining the final composition. Oxygen is calculated by stoichiometry; iron is calculated as FeO.

-52-
The accompanying table is an example of the computer output. Results are expressed as element and oxide weight percents. Also tabulated are the mineral identification, stoichiometry calculations, and various elemental atomic ratios.

The output also provides an estimate of the uncertainty involved. The corrections made for the analysis (beam current drift, background, absorption, fluorescence, and atomic number) are individually weighted to produce an estimation of the error contributed by each. These may then be substituted into the following equation to obtain an estimation of the total uncertainty:

$$\text{total uncertainty} = \sqrt{\sum_{i=1}^{6} U_i^2}$$

where

- $U_1 = \text{uncertainty due to counting statistics}$
- $U_2 = 50\%$ of beam current drift
- $U_3 = 200\%$ of uncertainty due to counting statistics on the background (whether counted or calculated)
- $U_4 = 25\%$ of the absorption correction
- $U_5 = 50\%$ of the fluorescence correction
- $U_6 = 15\%$ of the atomic number correction

In the accompanying example, the value for magnesium has been reported as $8.24 \pm 0.11\%$. 
<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>PERCENT OXIDE</th>
<th>ANALYSIS N</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>42.27</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>NA</td>
<td>0.37</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>MG</td>
<td>8.24</td>
<td>13.66</td>
<td>0.08</td>
</tr>
<tr>
<td>AL</td>
<td>1.14</td>
<td>2.15</td>
<td>0.04</td>
</tr>
<tr>
<td>SI</td>
<td>23.76</td>
<td>50.84</td>
<td>0.02</td>
</tr>
<tr>
<td>CA</td>
<td>14.16</td>
<td>19.82</td>
<td>0.04</td>
</tr>
<tr>
<td>TI</td>
<td>0.37</td>
<td>0.51</td>
<td>0.00</td>
</tr>
<tr>
<td>CR</td>
<td>0.06</td>
<td>0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>MN</td>
<td>0.20</td>
<td>0.33</td>
<td>0.00</td>
</tr>
<tr>
<td>FE</td>
<td>9.61</td>
<td>12.37</td>
<td>0.03</td>
</tr>
<tr>
<td>SUM</td>
<td>99.91</td>
<td>13.35</td>
<td>2.00</td>
</tr>
</tbody>
</table>

**CLINOPOYROXENE, AUGITE**

\[ \text{FE/CA/MG} = 19.91/40.88/39.20 \quad (\text{SUM} = 100.0) \]

\[ \text{FE/(FE+MN+MG)} = 0.334 \]

\[ \text{MG/CA/TI/MN/FE/NI} = 0.387/0.403/0.009/0.005/0.196/0.0 \quad (\text{SUM} = 1.0) \]

\[ \text{AL/CR/SI} = 0.047/0.001/0.951 \quad (\text{SUM} = 1.0) \]

\[ \frac{(\text{MG+CA+TI+MN+FE+NI})}{(\text{AL+CR+SI})} = 0.936 \]

\[ \text{TI/AL} = 0.183 \]
APPENDIX II:

ANALYTICAL TECHNIQUE - OXYGEN ISOTOPE ANALYSIS

The technique employed was that of Clayton and Mayeda (1963) where a bromine pentafluoride sample preparation system is used to extract oxygen from the sample. A brief discussion of the system will be presented; further information can be found in James (1974).

Selection of samples involved consideration of size and homogeneity. Each was cleaned thoroughly and all weathered portions were removed. The size was reduced in a jaw crusher and the sample was split. Size was finally reduced to a fine powder and homogenization ensured by spec-mixing for 20 to 30 minutes.

Samples were weighed (~ 6 mg) and allowed to sit overnight in a dry box to remove moisture. Each was then placed in a reaction vessel and placed on the sample line for degassing under vacuum for about 8 hours. BrF$_4$ was transferred to each reaction vessel and allowed to react for about 12 hours. Removal of the oxygen and conversion to CO$_2$ completed the extraction procedure.

Measurement of the $\delta^{18}O$-value was made by mass spectrometry.

James (1974) and Johnson (1975) have run triplicate samples on the line and report a precision of $\pm 0.2 \%$. This is taken to be a reasonable value for this study.
APPENDIX III: PETROGRAPHIC REPORTS OF REPRESENTATIVE SAMPLES

Petrographic Report

Specimen: T-34. Sample of intermediate rock collected above gabbro and below granophyre of Little Mt. Sheridan. Specimen is fine-grained, brownish-gray and consisting of dark minerals with pink alkali feldspar.

Texture: 1) Holocrystalline
2) Grain-size: 0.1-1 mm
3) Hypautomorphic-granular

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Est. %</th>
<th>Mineral characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>plagioclase</td>
<td>15</td>
<td>0.5-1mm, zoned and surrounded by k-spar and microperthite</td>
</tr>
<tr>
<td>microperthite</td>
<td>25</td>
<td>As rims around plagioclase and as component of micropegmatite</td>
</tr>
<tr>
<td>quartz</td>
<td>25</td>
<td>Component of micropegmatite</td>
</tr>
<tr>
<td>pyroxene</td>
<td>15</td>
<td>0.2-0.3mm, subhedral, altered and rimmed by hornblende</td>
</tr>
<tr>
<td>opaques</td>
<td>10</td>
<td>0.25mm, subhedral granules</td>
</tr>
<tr>
<td>apatite</td>
<td>10</td>
<td>Up to 1mm, long needles</td>
</tr>
</tbody>
</table>

Paragenetic sequence and comments:

Paragenetic relationships are complex as is typical of the hybrid rock.
Crystallization sequence:
1) plagioclase, pyroxene, opaques
2) interstitial granophyre, hornblende, and apatite; alteration of plagioclase and pyroxene
Petrographic Report

Specimen: T-50. Sample of pegmatite collected near base of Little Mt. Sheridan. Specimen is a mixture of crystals of hornblende with a groundmass of quartz and k-spar.

Texture: 1) Holocrystalline
2) Grain size: $\frac{1}{2}$-5mm
3) Hypautomorphic-granular

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Est. %</th>
<th>Mineral characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>micropegmatite</td>
<td>20</td>
<td>interstitial</td>
</tr>
<tr>
<td>microperthite</td>
<td>10</td>
<td>1-5mm, subhedral</td>
</tr>
<tr>
<td>quartz</td>
<td>20</td>
<td>anhedral patches</td>
</tr>
<tr>
<td>uralitized pyroxene</td>
<td>20</td>
<td>2-3mm, subhedral</td>
</tr>
<tr>
<td>hornblende, biotite</td>
<td>20</td>
<td>anhedral to subhedral, interstitial</td>
</tr>
<tr>
<td>opaques</td>
<td>5</td>
<td>$\frac{1}{2}$-1mm, subhedral</td>
</tr>
<tr>
<td>zircon</td>
<td>tr</td>
<td>$\frac{1}{2}$-1mm, subhedral to euhedral</td>
</tr>
</tbody>
</table>

Paragenetic sequence and comments:

Pyroxene appears to have crystallized initially but was later partly to wholly uralitized.
Petrographic Report

**Specimen**: T-61. Sample of anorthosite collected north of Rowe's Quarry. Specimen is a gray plagioclase-augite heteradcumulate with igneous lamination (i.e. oriented plagioclase lathes).

**Texture**: 1) Holocrystalline
2) Grain size: 1-2mm
3) Heteradcumulate

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Est. %</th>
<th>Mineral characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>plagioclase An70</td>
<td>90</td>
<td>1-3mm, subhedral lathes, adcumulus</td>
</tr>
<tr>
<td>augite</td>
<td>.7</td>
<td>anhedral (intercumulus), subophitic, exsolution lamellae of opaques</td>
</tr>
<tr>
<td>opaques</td>
<td>1</td>
<td>anhedral, associated with augite</td>
</tr>
<tr>
<td>prehnite &amp; epidote, chlorite</td>
<td>2</td>
<td>alteration product, moderate birefringence, chlorite has v. low to anomalous birefringence</td>
</tr>
</tbody>
</table>

**Paragenetic sequence and comments:**

**Crystallization sequence:**
1) plagioclase
2) intercumulus augite and opaques
3) late prehnite, epidote, chlorite, etc.
Petrographic Report

Specimen: T-64. Sample of fine-grained gabbro collected north of Rowe's Quarry. It appears to be a portion of the Mt. Sheridan gabbro that was chilled against the layered series (i.e. anorthosite of the Raggedy Mountain Gabbro Group). Specimen is gray and finer-grained than the normal gabbro. Plagioclase lathes are aligned, perhaps by flow.

Texture: 1) Holocrystalline
2) Grain-size: $\frac{1}{2}$-1mm
3) Hypautomorphic-granular, plagioclase lathes are aligned.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Est. %</th>
<th>Mineral characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>plagioclase</td>
<td>70</td>
<td>$\frac{1}{2}$-2mm, subhedral lathes, aligned</td>
</tr>
<tr>
<td>augite</td>
<td>20</td>
<td>$\frac{1}{2}$-1mm, subhedral</td>
</tr>
<tr>
<td>hypersthene</td>
<td>tr</td>
<td>interstitial</td>
</tr>
<tr>
<td>opaques</td>
<td>10</td>
<td>$\frac{1}{2}$-1mm, subhedral</td>
</tr>
<tr>
<td>biotite, quartz</td>
<td>tr</td>
<td>interstitial</td>
</tr>
</tbody>
</table>

Paragenetic sequence and comments:

Crystallization sequence:
1) plagioclase
2) augite
3) opaques, hypersthene
4) biotite, quartz
Petrographic Report

Specimen: T-68. Sample of Mt. Sheridan gabbro collected on the north side of Mt. Scott. Specimen is a dark gray, medium-grained gabbro or diorite.

Texture: 1) Holocrystalline
2) Grain size: $\frac{1}{2}$-1mm
3) Hypautomorphic-granular

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Est. %</th>
<th>Mineral characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>plagioclase An50</td>
<td>50</td>
<td>1-2mm, subhedral, somewhat zoned</td>
</tr>
<tr>
<td>albite(?)</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>augite</td>
<td>15</td>
<td>1mm, anhedral, interstitial, no exsolution features</td>
</tr>
<tr>
<td>hypersthene</td>
<td>5</td>
<td>1-2mm, subhedral &amp; lath-shaped or ophitic around plagioclase and opaques; pleochroic, oriented opaque lamellae exsolved within the hypersthene</td>
</tr>
<tr>
<td>biotite</td>
<td>5</td>
<td>$\frac{1}{2}$-1mm, anhedral, appears to be reaction of magnetite with late fluids</td>
</tr>
<tr>
<td>opaques</td>
<td>10</td>
<td>$\frac{1}{2}$-1mm, anhedral, primarily magnetite with some exsolved ilmenite</td>
</tr>
<tr>
<td>quartz, k-spar,</td>
<td>10</td>
<td>late interstitial and alteration products</td>
</tr>
<tr>
<td>hornblende, etc.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Paragenetic sequence and comments:

Crystallization sequence: plagioclase, hypersthene, opaques, augite, late opaques(?), biotite, quartz
Petrographic Report

Specimen: T-88. Sample of granophyre collected near base of granophyre cap of Mt. Sheridan. Specimen is reddish-orange and consists of perthite phenocrysts with a groundmass of micropegmatite and clots of dark minerals.

Texture: 1) Holocrystalline
2) Grain size: perthite phenocrysts 2mm micrographic and microgranular groundmass

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Est. %</th>
<th>Mineral characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>microperthite</td>
<td>20</td>
<td>2mm phenocrysts, subhedral, turbid</td>
</tr>
<tr>
<td>quartz, perthite, and micropegmatite</td>
<td>70</td>
<td>½²mm, quartz often anhedral and surrounded by poikilitic microperthite</td>
</tr>
<tr>
<td>opaques</td>
<td>5</td>
<td>½²mm, subhedral</td>
</tr>
<tr>
<td>hornblende with minor augite</td>
<td>3</td>
<td>½²mm, subhedral</td>
</tr>
<tr>
<td>sphene</td>
<td>tr</td>
<td>some is primary; other appears to be a reaction between opaques and feldspar or quartz</td>
</tr>
<tr>
<td>hematite</td>
<td></td>
<td>alteration product</td>
</tr>
</tbody>
</table>

Paragenetic sequence and comments:

Crystallization sequence:
1) perthite phenocrysts
2) micropegmatite, opaques, etc.
3) late stage alteration of microperthite and augite

Opasques, hornblende, and sphene often appear in clots.
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