Abstract:
Archean exposures of the Spanish Peaks area of southwest Montana can be divided into at least two distinct high-grade metamorphic terranes which are characterized by differences in lithology, metamorphic grade, and structural style. The Gallatin Peak Terrane (GPT) consists of tonalitic paragneisses, kyanite-bearing metapelites and intercalated amphibolites. This supracrustal package was intruded by gabbroic dikes and sills and by a previously unrecognized suite of granitoids. The gabbroic intrusions form two distinct series: one series recrystallized into nematoblastic amphibolites, while the other series recrystallized into transitional granulites with complex corona textures. The granitic suite consists of older hornblende monzodiorite and tonalite, biotite quartz diorite and tonalite, porphyritic granodiorite, and younger trondhjemite and granodiorite to granite.

The Jerome Rock Lakes Terrane (JRLT) consists of K-feldspar paragneisses with locally extensive development of anatectic migmatite, sillimanite-bearing metapelites, and intercalated transitional granulites. The JRLT does not share the early granitic intrusive history of the GPT, but was intruded by the youngest granitoids and by the two series of gabbroic dikes and sills.

The two terranes are juxtaposed along a previously unrecognized ductile shear zone which is parallel to the regional foliation, which strikes northeast and dips steeply to the southeast. Field and textural evidence indicates that juxtaposition occurred during or just prior to high-grade metamorphism and injection of the youngest granitoids and the two series of gabbros. Textural evidence further suggests that rapid uplift along the shear zone followed juxtaposition, perhaps facilitated by the presence of anatectic and intrusive melt phases within the system.

The plutonic, metamorphic and structural styles in the Spanish Peaks are strikingly similar to the Phanerozoic Cordilleran configuration of southeastern Alaska and northern British Columbia. The emerging pattern in the Archean basement of southwest Montana of juxtaposition of discrete crustal blocks in a Cordilleran-type setting may reflect 'a period of rapid growth of the Archean continent through the accretion of possibly genetically unrelated terranes.'
ARCHEAN GEOLOGY OF THE SPANISH PEAKS AREA,
SOUTHWESTERN MONTANA.

by
Kenneth Julian Salt

A thesis submitted in partial fulfillment of the requirements for the degree
of
Master of Science
in
Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana
March, 1987
APPROVAL

of a thesis submitted by

Kenneth Julian Salt

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

3/24/87

Date

Chairperson, Graduate Committee

Approved for the Major Department

20 March 1987

Date

Head, Major Department

Approved for the College of Graduate Studies

April 3, 1987

Date

Graduate Dean
STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his/her absence, by the Director of Libraries when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature

[Signature]

Date 2004-07
ACKNOWLEDGEMENTS

The author would like to thank Professors David Mogk, David Lageson, and John Childs of the thesis committee for their encouragement and invaluable advice throughout the course of the project.

Partial funding for the research was provided by a grant from NASA through Dr. Mogk. Dr. Mogk also supplied microprobe analyses used in this study. Travel grants were provided to the author from the Research Creativity fund of Montana State University which enabled the author to present the results of this research at professional meetings.

Able field assistance was provided by Paul Anderson, who tolerated everything from mosquitoes to ridge-top lightning storms during the course of the research. Will Gavin provided the use of his llamas to pack samples out of the study area. Reggie Clark and Mike Clow of the U. S. Forest Service provided assistance when base camp facilities were discovered to be missing after a long day in the field. Susan Marsh, also of the U. S. Forest Service, found the missing equipment several weeks later.

Finally, the author indebted to his wife, Vickie, who provided financial support for the family of the author, acted as surrogate father to his children while the author was away in the field and at meetings, and provided moral support to the author during the compilation of this report.
### TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF PLATES</td>
<td>x</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xi</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>GALLATIN PEAK TERRANE</td>
<td>6</td>
</tr>
<tr>
<td>Tonalitic Paragneisses</td>
<td>6</td>
</tr>
<tr>
<td>Heterogeneous Metasupracrustal Suite</td>
<td>11</td>
</tr>
<tr>
<td>Granitoids</td>
<td>12</td>
</tr>
<tr>
<td>Biotite Tonalite Gneiss</td>
<td>15</td>
</tr>
<tr>
<td>Hornblende Granitoid Gneisses</td>
<td>16</td>
</tr>
<tr>
<td>Porphyritic Granodiorite</td>
<td>18</td>
</tr>
<tr>
<td>Granite</td>
<td>19</td>
</tr>
<tr>
<td>Pegmatites</td>
<td>22</td>
</tr>
<tr>
<td>Summary</td>
<td>22</td>
</tr>
<tr>
<td>Ultramafic and Mafic Rocks</td>
<td>23</td>
</tr>
<tr>
<td>Ultramafites</td>
<td>23</td>
</tr>
<tr>
<td>Amphibolites</td>
<td>26</td>
</tr>
<tr>
<td>Transitional Granulites</td>
<td>27</td>
</tr>
<tr>
<td>JEROME ROCK LAKES TERRANE</td>
<td>35</td>
</tr>
<tr>
<td>Quartzofeldspathic Gneisses</td>
<td>35</td>
</tr>
<tr>
<td>Granitic Paragneisses (KQFG)</td>
<td>35</td>
</tr>
<tr>
<td>Leucogneisses</td>
<td>37</td>
</tr>
<tr>
<td>Metapelites and Quartzites</td>
<td>40</td>
</tr>
<tr>
<td>Transitional Granulites</td>
<td>42</td>
</tr>
<tr>
<td>Intercalated Granulites</td>
<td>42</td>
</tr>
<tr>
<td>Leucogranulite</td>
<td>43</td>
</tr>
<tr>
<td>Amphibolites and Ultramafites</td>
<td>45</td>
</tr>
<tr>
<td>Granitoids</td>
<td>45</td>
</tr>
<tr>
<td>Summary</td>
<td>47</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS—Continued

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUCTILE SHEAR ZONE</td>
<td>49</td>
</tr>
<tr>
<td>PHYSICAL CONDITIONS OF METAMORPHISM</td>
<td>53</td>
</tr>
<tr>
<td>Petrogenetic Associations</td>
<td>53</td>
</tr>
<tr>
<td>Geothermobarometry</td>
<td>55</td>
</tr>
<tr>
<td>Garnet-Biotite</td>
<td>55</td>
</tr>
<tr>
<td>Garnet-Clinopyroxene</td>
<td>57</td>
</tr>
<tr>
<td>Geobarometry</td>
<td>58</td>
</tr>
<tr>
<td>Summary</td>
<td>60</td>
</tr>
<tr>
<td>STRUCTURE</td>
<td>63</td>
</tr>
<tr>
<td>CONCLUSION</td>
<td>69</td>
</tr>
<tr>
<td>Tectonic Evolution of the Spanish Peaks</td>
<td>69</td>
</tr>
<tr>
<td>Discussion</td>
<td>73</td>
</tr>
<tr>
<td>REFERENCES CITED</td>
<td>76</td>
</tr>
</tbody>
</table>
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mineral assemblages of the Gallatin Peak Terrane</td>
<td>8</td>
</tr>
<tr>
<td>2. Modal mineralogy of the granitoids</td>
<td>14</td>
</tr>
<tr>
<td>3. Summary of mineral assemblages in the JRLT</td>
<td>36</td>
</tr>
<tr>
<td>4. Comparison of lithologies, metamorphic and plutonic histories of GPT and the JRLT</td>
<td>48</td>
</tr>
<tr>
<td>5. Summary of P-T calculations</td>
<td>56</td>
</tr>
<tr>
<td>6. Proposed sequence of geologic events for the GPT and the JRLT</td>
<td>71</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Archean exposures of the Spanish Peaks and other ranges in southwestern Montana</td>
<td>2</td>
</tr>
<tr>
<td>2.</td>
<td>Index map of the Spanish Peaks area</td>
<td>2</td>
</tr>
<tr>
<td>3.</td>
<td>Schematic cross-section through Spanish Peaks area</td>
<td>4</td>
</tr>
<tr>
<td>4.</td>
<td>Modal quartz (QTZ), plagioclase (PLAG), K-feldspar (KSP) ratios of paragneisses, central Spanish Peaks area</td>
<td>7</td>
</tr>
<tr>
<td>5.</td>
<td>Modal proportions of quartz (QTZ), plagioclase (PLAG), K-feldspar (KSP) of granitoids</td>
<td>13</td>
</tr>
<tr>
<td>6.</td>
<td>Cross-cutting relationships in granitoids near Gallatin Peak</td>
<td>17</td>
</tr>
<tr>
<td>7.</td>
<td>Magmatic epidote (E) cored by allanite (A), surrounded by biotite in porphyritic granodiorite</td>
<td>20</td>
</tr>
<tr>
<td>8.</td>
<td>Transitional granulite corona texture in metabasite near Deer Lake</td>
<td>29</td>
</tr>
<tr>
<td>9.</td>
<td>Detail of corona texture from sample DC-6</td>
<td>29</td>
</tr>
<tr>
<td>10.</td>
<td>Intermediate stages of development of corona textures in cross-cutting transitional granulite metagabbro MG-GP near Mirror Lake</td>
<td>30</td>
</tr>
<tr>
<td>11.</td>
<td>Preservation of igneous exsolution in pyroxenes from transitional granulite metagabbro DC-9 near Deer Lake</td>
<td>32</td>
</tr>
<tr>
<td>12.</td>
<td>Relict pigeonite (Pi) mantled by subcalcic augite (SA) in cross-cutting transitional granulite metagabbro DC-9</td>
<td>32</td>
</tr>
<tr>
<td>13.</td>
<td>Incipient development of garnet (G) coronas around opaque oxide (O) and cpx (C) in metagabbro DC-9</td>
<td>33</td>
</tr>
<tr>
<td>14.</td>
<td>Ksp-bearing leucogneisses near the Spanish Lakes</td>
<td>38</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES—Continued

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>15. Leucogneiss along trail to Mirror Lake</td>
<td>38</td>
</tr>
<tr>
<td>16. Fibrolite (S) and biotite (B) embayments into garnet (G) in metapelitic sample CM-17 from JRLT near ductile shear zone</td>
<td>41</td>
</tr>
<tr>
<td>17. Successive retrograde symplectite coronas in leucogranulite near DSZ</td>
<td>44</td>
</tr>
<tr>
<td>18. Youngest granite injected along mylonitized amphibolite</td>
<td>46</td>
</tr>
<tr>
<td>19. Petrogenetic grids for the GPT and the JRLT</td>
<td>54</td>
</tr>
<tr>
<td>20. Graphic summary of P-T calculations</td>
<td>61</td>
</tr>
<tr>
<td>21. Orientations of structures in the GPT and the DSZ</td>
<td>65</td>
</tr>
<tr>
<td>Plate</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>1.</td>
<td>Geologic map of the central Spanish Peaks (in pocket)</td>
</tr>
</tbody>
</table>
Archean exposures of the Spanish Peaks area of southwest Montana can be divided into at least two distinct high-grade metamorphic terranes which are characterized by differences in lithology, metamorphic grade, and structural style. The Gallatin Peak Terrane (GPT) consists of tonalitic paragneisses, kyanite-bearing metapelites and intercalated amphibolites. This supracrustal package was intruded by gabbroic dikes and sills and by a previously unrecognized suite of granitoids. The gabbroic intrusions form two distinct series: one series recrystallized into nematoblastic amphibolites, while the other series recrystallized into transitional granulites with complex corona textures. The granitic suite consists of older hornblende monzodiorite and tonalite, biotite quartz diorite and tonalite, porphyritic granodiorite, and younger trondhjemite and granodiorite to granite.

The Jerome Rock Lakes Terrane (JRLT) consists of K-feldspar paragneisses with locally extensive development of anatectic migmatite, sillimanite-bearing metapelites, and intercalated transitional granulites. The JRLT does not share the early granitic intrusive history of the GPT, but was intruded by the youngest granitoids and by the two series of gabbroic dikes and sills.

The two terranes are juxtaposed along a previously unrecognized ductile shear zone which is parallel to the regional foliation, which strikes northeast and dips steeply to the southeast. Field and textural evidence indicates that juxtaposition occurred during or just prior to high-grade metamorphism and injection of the youngest granitoids and the two series of gabbros. Textural evidence further suggests that rapid uplift along the shear zone followed juxtaposition, perhaps facilitated by the presence of anatectic and intrusive melt phases within the system.

The plutonic, metamorphic and structural styles in the Spanish Peaks are strikingly similar to the Phanerozoic Cordilleran configuration of southeastern Alaska and northern British Columbia. The emerging pattern in the Archean basement of southwest Montana of juxtaposition of discrete crustal blocks in a Cordilleran-type setting may reflect a period of rapid growth of the Archean continent through the accretion of possibly genetically unrelated terranes.
INTRODUCTION

Archean exposures in the Spanish Peaks area of the northern Madison Range, southwestern Montana, occupy a transition zone between two distinct Archean terranes. To the east, the Beartooth Mountains (Fig. 1) are comprised predominantly of granitoids which were emplaced at approximately 2.7 to 2.8 Ga and contain inclusions of metasupracrustal assemblages as old as 3.4 Ga (Warner and others, 1982; Wooden and others, 1982; Mueller and others, 1982; Mueller and others, 1985; Richmond and Mogk, 1985). West of the Beartooth Mountains, Archean lithologies are dominated by several metasupracrustal suites (Peale, 1896; Tansley and others, 1933; Reid, 1957; Heinrich and Rabbitt, 1960; Garihan, 1979; Vitaliano and others, 1979; Erslev, 1983; Clark and Mogk, 1985). Reconnaissance geochronological studies of these rocks yield a composite Rb-Sr model age of 2.7 Ga with thermal resetting occurring at 1.9 and 1.6 Ga (Giletti, 1966, 1971; James and Hedge, 1980).

Archean exposures in the Spanish Peaks were originally described by Spencer and Kozak (1975) as a single metasupracrustal suite, dominated by tonalitic and granitic paragneisses with minor metabasite, metapelite, quartzite, marble, and ultramafite. Their study emphasized the overall structural trends and attempted to correlate the deformational features to the initial geochronologic studies of Giletti (1966, 1971). The generalized nature of the previous study, however, does not allow adequate constraints to be placed on the tectonic
Figure 1. Archean exposures of the Spanish Peaks and other ranges in southwestern Montana.

Figure 2. Index map of Spanish Peaks area. Labelled are locations of sites discussed in text, with pack trail access into the study area shown as dashed lines. Outline is area of Plate 1. Heavy waved line is mapped extent of ductile shear zone.
history of the Spanish Peaks, nor have these pivotal exposures been placed in a regional context. Therefore, this paper presents detailed lithologic and petrographic descriptions in order to place more precise constraints on the timing and conditions of metamorphism. This study should provide a more complete basis for the development of an integrated tectonic model for Archean crustal evolution in southwestern Montana.

The results of this investigation suggest a much higher degree of complexity than was previously recognized. Archean rocks of the central Spanish Peaks area can be divided into two distinct terranes based on differences in lithology, metamorphic grade, and structural style. The Gallatin Peak Terrane (GPT; Fig. 2) is a metasupracrustal suite of predominantly tonalitic paragneisses intercalated with kyanite-bearing metapelites and amphibolites, which is intruded by a previously unrecognized suite of concordant granitoids (Plate I). The Jerome Rock Lakes Terrane (JRLT; Fig. 2) is also a metasupracrustal suite, but is composed primarily of K-feldspar-bearing paragneisses intercalated with sillimanite-kyanite-bearing metapelites and transitional granulites (Plate I). The two terranes are juxtaposed along a northeast-striking, southeast-dipping ductile shear zone, with the GPT structurally overlying the JRLT (Figure 3). This paper describes the lithologic and petrologic characteristics of these terranes and serves to illustrate their different geologic histories.

Previous models of the tectonic evolution of the Archean rocks of this region have proposed the collapse of a basin marginal to an easterly continental source (Spencer and Kozak, 1975; Vitaliano and
Figure 3. Schematic cross section through central Spanish Peaks area. The GPT structurally overlies the JRLT along the northeast-striking, steeply southeast-dipping ductile shear zone (DSZ). Line of cross section shown on Plate 1. Abbreviations of lithologic units as for Plate 1.
others, 1979). However, the results of this study suggest that the Archean basement of southwestern Montana may be a collage of genetically unrelated terranes, and that accretionary tectonics may have been an important process in the Archean history of southwestern Montana.
GALLATIN PEAK TERRANE

Tonalitic Paragneisses

Grey, well-foliated quartzofeldspathic gneisses with an overall tonalitic composition occur between the ductile shear zone and Gallatin Peak (Plate 1). In contrast to the paragneisses of the JRLT, K-feldspar is absent or present in trace amounts only (Fig. 4). These gneisses have centimeter-scale biotite-rich and hornblende-rich compositional layering and are interspersed with centimeter- to meter-scale amphibolite layers and boudins. Although these gneisses do not contain intercalated rock types of more clearly sedimentary origin, the even, small-scale compositional layering and lack of igneous features suggest a supracrustal origin for these gneisses. Therefore, these gneisses are referred to as tonalitic paragneisses, while noting that further study is necessary to confirm a supracrustal origin for these gneisses.

The main mineral constituents of the tonalitic paragneisses in order of decreasing abundance are plagioclase (An 20-30), quartz, olive-green biotite, and green (Z) hornblende (Table 1). Accessory minerals include sphene, apatite, opaque oxides, and zircon. Garnet occurs rarely in the more mafic compositional layers. Secondary epidote and chlorite occur in some samples. Grain size is heterogenous, ranging from 0.1 to 3.0 millimeters. Plagioclase and quartz generally form a mosaic texture with straight grain boundaries, but xenoblastic
Figure 4. Modal quartz (QTZ), plagioclase (PLAG) and K-feldspar (KSP) ratios of paragneisses, central Spanish Peaks area. Ternary fields after Streckeisen (1976).
### MINERAL ASSEMBLAGES OF THE GPT

<table>
<thead>
<tr>
<th>Paragneisses</th>
<th>Quartzites</th>
</tr>
</thead>
<tbody>
<tr>
<td>plag-qtz-biot-hbld-sph-ksp-apat-op-zir-chl-epid</td>
<td>qtz-epid-mag-hbld</td>
</tr>
<tr>
<td>plag-qtz-biot-hbld-gt-sph-apat-op-zir-epid</td>
<td>qtz-musc-gt-mag</td>
</tr>
<tr>
<td>plag-qtz-biot-gt-cumm-apat-op-zir</td>
<td>qtz-biot-zir</td>
</tr>
<tr>
<td>Metapelites</td>
<td></td>
</tr>
<tr>
<td>plag-biot-qtz-ky-gt-zir-apat-rut</td>
<td></td>
</tr>
<tr>
<td>plag-biot-qtz-ky-musc-apat-op-zir</td>
<td></td>
</tr>
<tr>
<td>plag-biot-qtz-ged-musc-apat-op-zir</td>
<td></td>
</tr>
<tr>
<td>plag-biot-qtz-ged-gnt-(st-chl)-apat-op-zir</td>
<td></td>
</tr>
<tr>
<td>plag-biot-qtz-ged-gnt-ky-(st)</td>
<td></td>
</tr>
<tr>
<td>ged-ky-biot-op-zir</td>
<td></td>
</tr>
<tr>
<td>biot-ky-qtz-musc-sill</td>
<td></td>
</tr>
<tr>
<td>Amphibolites</td>
<td>Ultramafites</td>
</tr>
<tr>
<td>hbld-plag-qtz-op-chl-epid-all</td>
<td>mg hb-ol-opx-phl-chl-op-tc</td>
</tr>
<tr>
<td>hbld-plag-qtz-biot-gnt-op-epid</td>
<td>mg hb-opx-sp-phl-op-chl</td>
</tr>
<tr>
<td>hbld-plag-qtz-cpx-op</td>
<td>mg hb-anth-plag-apat-op-zir</td>
</tr>
<tr>
<td>hbld-oa-plag</td>
<td>mg hb-anth-mal</td>
</tr>
<tr>
<td></td>
<td>mg hb-cumm-plag-phl-op</td>
</tr>
<tr>
<td></td>
<td>mg hb-op</td>
</tr>
<tr>
<td>Transitional Granulites</td>
<td></td>
</tr>
<tr>
<td>plag-cpx-gt-hbld-op-qtz-scap</td>
<td></td>
</tr>
<tr>
<td>plag-cpx-gt-hbld-biot-op-qtz</td>
<td></td>
</tr>
<tr>
<td>plag-igneous cpx-igneous opx-gt-hbld-op</td>
<td></td>
</tr>
<tr>
<td>hbld-plag-cpx-sph-op</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Mineral assemblages of the Gallatin Peak Terrane. Abbreviations are as follows, to be used throughout the study: plag (plagioclase), biot (biotite), musc (muscovite), qtz (quartz), ky (kyanite), sill (sillimanite), hbld (hornblende), ged (gedrite), anth (anthophyllite), mg hb (magnesian hornblende), cumm (cummingtonite), gt (garnet), zir (zircon), epid (epidote), chl (chlorite), apat (apatite), op (opaque oxides), mag (magnetite), ol (olivine), cpx (clinopyroxene), scap (scapolite), sph (sphene), mal (malachite), all (allanite), rut (rutile), ksp (K-feldspar), opx (orthopyroxene), oa (orthoamphibole). Minerals in parentheses are relict inclusions.
textures are not uncommon. Biotite is aligned parallel to compositional layering and hornblende commonly forms nematoblastic aggregates.

The centimeter- to meter-scale amphibolite layers are composed of green (Z) hornblende, plagioclase (An 35-40), and lesser amounts of quartz, olive-green biotite, and sphene. Accessory minerals include apatite, opaque oxides, and zircon. Diopside occurs in one sample. Plagioclase and quartz form mosaic textures with straight grain boundaries, and hornblende exhibits nematoblastic textures. While there is no evidence of relict higher grade assemblages in any of the amphibolites, some show signs of retrogression, especially near the shear zone. In retrograded amphibolites, green hornblende is mantled by blue-green (Z) amphibole and locally replaced by epidote, and plagioclase exhibits locally extensive sericitization.

Two distinct migmatite styles occur within the tonalitic paragneisses. Semi-concordant interlayers of black amphibolite and white trondhjemite occur as distinct packages that range in thickness up to 30 meters. Interlayering of the two rock types occurs on a centimeter- to meter-scale. Within these sequences, small trondhjemite dikes which cross-cut the amphibolite have been flattened into the regional foliation. The composition and textures of amphibolite in these packages are very similar to the layers described above, with no evidence of granulite-forming reactions. No mafic selvages occur in the amphibolites. Trondhjemitic layers consist of optically unzoned plagioclase with composition varying from An 20-40 in different layers, quartz, and minor hornblende and biotite. Interstitial microcline is present in accessory amounts. Plagioclase and quartz form mosaic
textures and biotite is generally aligned parallel to surrounding foliation. The lack of selvages and the presence of cross-cutting relationships suggest that these migmatites are of the injection type (Yardley, 1978). The deformational features and microtextures suggest that injection occurred prior to or during peak orogenic activity.

Migmatites with a layered structure, or stromatic migmatites (Johannes and Gupta, 1982), are characterized by leucosome layers which vary in thickness from a few millimeters to several centimeters. Leucosome layers grade into granitic pegmatite which is commonly concentrated in the pressure shadows of mafic boudins and in the fold hinges of both isoclinal and open folds. The leucosome layers have overall granodioritic compositions and hypidiomorphic-granular textures. Bordering melanosomes as seen in other migmatite terranes (e.g. Johannes and Gupta, 1982) are not well-developed in these migmatites, but in tonalitic gneiss adjacent to leucosomes, garnet and magnetite concentrations indicate that biotite has broken down in a melt-forming reaction. This relationship has been described in Archean rocks of the Superior Province (Harris and Goodwin, 1976) and was specifically related to the generation of a melt phase by the reaction

\[ \text{biotite} = \text{garnet} + \text{magnetite} + (\text{quartz} + \text{H}_2\text{O} + K^+)\text{melt}. \]

Therefore, while some of the leucosomes may be related to injection of the youngest granitoids, at least some of the stromatic layers may be the result of \textit{in situ} partial melting of the tonalitic paragneisses.
Heterogeneous Metasupracrustal Suite

Tonalitic paragneisses on Gallatin Peak and southward into the Bear Basin area (Fig. 2) have numerous intercalations of pelitic schists and quartzites in addition to amphibolite layers and boudins, in contrast to the tonalitic paragneisses described above. These rocks are therefore mapped as a heterogeneous metasupracrustal suite (Plate 1). East of Wilson Peak and in the Gallatin River Canyon (Fig. 2), pelitic assemblages again become rare to absent.

Metapelites of this suite are characterized by the common occurrence of kyanite and gedrite. Garnet is also a common constituent of many of the pelitic rocks (Table 1). A contact aureole developed in metapelites intruded by a large granitic sill in Bear Basin contains mats of coarse grained gedrite-kyanite with gedrite crystals up to 15 cm long. In the same vicinity, an important limiting assemblage of gedrite-garnet-kyanite-biotite-plagioclase occurs which can be used to place tight brackets on the metamorphic conditions (Hudson and Harte, 1985) (see below). Gedrite and garnet both contain inclusions of staurolite and chlorite, indicating that this assemblage is superimposed on lower-grade assemblages. This finding contrasts with the southern Madison Range, where gedrite has been interpreted to be retrograde after granulite-facies assemblages (Erslev, 1983).

Three types of quartzite occur in the GPT. The most common is green micaceous quartzite with traces of garnet and opaque oxides. Quartzite with millimeter-scale foliation defined by layers of granoblastic epidote occurs in Bear Basin and proximal to the shear zone near the Chilled Lakes. Trace amounts of garnet and magnetite
are visible in hand sample in both occurrences. Blue, kyanite-rich quartzite with tiny (.05mm) anhedral staurolite and scattered garnets occurs west of Wilson Peak.

The tonalitic paragneisses, metapelites, and quartzites described above comprise a metasupracrustal suite which is compositionally distinct from the K-feldspar bearing suite of the JRLT. Mineral assemblages and textures in these rocks indicate that peak metamorphism reached upper amphibolite facies conditions. There is no textural or mineralogical evidence of any earlier, high-grade metamorphism in the GPT, in contrast to previous interpretations involving two or more high-grade events in the Spanish Peaks area (Spencer and Kozak, 1975). Instead, the relict staurolite and chlorite inclusions in pelitic schists indicate that any earlier metamorphism occurred at lower grades. These relics may be remnants of a separate, lower-grade event or may represent the early stages of a single, prograde event.

Granitoids

The metasupracrustal rocks described above were intruded by a previously unrecognized suite of largely concordant granitoids, which comprises roughly 1/4 to 1/3 of the total volume of Archean exposures in the Gallatin Peak area. Modal plagioclase-quartz-K-feldspar ratios are plotted in Figure 5 and a summary of the total modal mineralogy is presented in Table 2.

The oldest granitoids are hornblende monzodiorite and hornblende tonalite granitoid gneisses, and porphyritic biotite tonalite to quartz diorite granitoid gneiss. These granitoids are well-foliated,
Figure 5. Modal proportions of quartz (QTZ), plagioclase (PLAG), and K-feldspar (KSP) of granitoids. Field names for the granitoids as discussed in text. Ternary fields after Streckeisen (1976).
### Table 2. Modal mineralogy of the granitoids. 1000 points/sample. Mineral abbreviations as in Table 1. *Recalculated modal proportions of quartz, plagioclase and K-feldspar, as summarized in Figure 5.*

<table>
<thead>
<tr>
<th>Plag</th>
<th>Qtz</th>
<th>Ksp</th>
<th>Biot</th>
<th>Hbld</th>
<th>Sph</th>
<th>Musc</th>
<th>Epid</th>
<th>All</th>
<th>Op</th>
<th>Apat</th>
<th>Rut</th>
<th>Zir</th>
<th>Plag*</th>
<th>Qtz*</th>
<th>Ksp*</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>45</td>
<td>50</td>
<td>51</td>
<td>44</td>
<td>51</td>
<td>71</td>
<td>42</td>
<td>43</td>
<td>45</td>
<td>30</td>
<td>20</td>
<td>29</td>
<td>26</td>
<td>30</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>20</td>
<td>2</td>
<td>tr</td>
<td>1</td>
<td>2</td>
<td>13</td>
<td>19</td>
<td>19</td>
<td>12</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>19</td>
<td>17</td>
<td>18</td>
<td>11</td>
<td>1</td>
<td>2</td>
<td>11</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>32</td>
<td>23</td>
<td>17</td>
<td>18</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>7</td>
<td>11</td>
<td>1</td>
<td>--</td>
<td>--</td>
<td>1</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>tr</td>
<td>1</td>
<td>--</td>
<td>tr</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2</td>
<td>tr</td>
<td>1</td>
<td>--</td>
<td>--</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>tr</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>tr</td>
<td>1</td>
<td>2</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>1</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>77</td>
<td>62</td>
<td>71</td>
<td>75</td>
<td>61</td>
<td>66</td>
<td>83</td>
<td>49</td>
<td>51</td>
<td>49</td>
<td>54</td>
<td>44</td>
<td>54</td>
<td>35</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>26</td>
<td>25</td>
<td>39</td>
<td>32</td>
<td>17</td>
<td>35</td>
<td>24</td>
<td>32</td>
<td>32</td>
<td>28</td>
<td>31</td>
<td>15</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>27</td>
<td>3</td>
<td>tr</td>
<td>2</td>
<td>16</td>
<td>25</td>
<td>19</td>
<td>17</td>
<td>19</td>
<td>17</td>
<td>25</td>
<td>31</td>
<td>35</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Modal mineralogy of the granitoids. 1000 points/sample. Mineral abbreviations as in Table 1. *Recalculated modal proportions of quartz, plagioclase and K-feldspar, as summarized in Figure 5.*
and the hornblende granitoids have a moderate hornblende lineation. The two types of hornblende granitoid are very similar in outcrop and are virtually indistinguishable in hand sample. Because samples of both types have been obtained along strike of the same body, they are mapped as a single unit of hornblende granitoids until further study can resolve the relationships between the two types. The biotite tonalite–quartz diorite is distinguished from the tonalitic country rock paragneisses described above by higher mafic content and by the presence of relict plagioclase phenocrysts and xenoliths.

Porphyritic granodiorite contains xenoliths of both the hornblende and biotite granitoids and is therefore younger than these two rock types. The porphyritic granodiorite is moderately to weakly foliated and is locally deformed by open to isoclinal folding.

The youngest granitoids range in composition from granodiorite to quartz monzonite (Fig. 5), and are referred to collectively as granite. The granite intrudes all other granitoids and supracrustal rocks. The number and size of intrusions increases with proximity to the ductile shear zone. Individual intrusions may lack foliation or may have weakly to moderately developed foliation. Many of the granite intrusions are highly deformed by open to isoclinal folding.

**Biotite Tonalite Gneiss**

Biotite tonalite granitoid gneiss occurs only in Bear Basin (Plate 1). Biotite imparts a color index in the range of 10–20. Relict plagioclase phenocrysts up to 2 cm long are found within the unit and xenoliths of plagioclase–orthoamphibole rock occur rarely at the margins.
The mineralogy consists of optically homogenous plagioclase (An 25-30), quartz, biotite, and muscovite, with accessory apatite, opaque oxides, zircon, and rutile (Table 2). Interstitial microcline is present in trace quantities in some samples. Grain size is heterogenous, ranging from 0.05mm to 2.0mm. Plagioclase generally forms mosaic textures with straight grain boundaries, while quartz grain boundaries are more curved and irregular. Foliation is defined by parallel alignment of biotite. Euhedral muscovite often cross-cuts biotite and is rimmed by opaque oxide material, suggesting that muscovite formed after biotite and is not of igneous origin.

Hornblende Granitoid Gneisses

Mafic hornblende gneisses (Cl 25-40) occur in thick concordant layers in Bear Basin, on Gallatin Peak, and in the Mirror Lake area (Plate 1). These units are interpreted to be of plutonic origin because they contain scattered xenoliths of amphibolite and diopsidic hornblendite. The hornblende granitoids have well-developed foliation defined by alignments of hornblende and biotite and have a well-developed hornblende lineation. Early, cross-cutting pegmatites that are flattened into the regional foliation (Fig. 6) are commonly associated with the hornblende granitoids.

Based on petrographic analysis, these granitoid gneisses can be divided into hornblende monzodiorite and hornblende tonalite gneiss. However, as noted above, they are mapped as a single unit because of their similar outcrop appearance. The mineralogy of the hornblende monzodiorite consists of plagioclase, microcline, and blue-green (Z) hornblende (2Vx = 60-70) with variable amounts of quartz and olive-
Figure 6. Cross-cutting relationships in granitoids near Gallatin Peak. Granitoids, from oldest to youngest, are labelled as follows: HG = Hornblende monzodiorite; P1 = early pegmatite; G = granite; P2 = younger pegmatites.

green biotite (Table 2). Minor and accessory mineralogy consists of sphene, epidote, apatite, allanite, chlorite, zircon, and opaque oxides. Plagioclase has an average core composition of An 25, with slightly more calcic rims. Minor myrmekite occurs in contact with microcline. Plagioclase, microcline and quartz generally form mosaic textures. Hornblende ranges in modal abundance from 23% to 32% and occurs in nematoblastic aggregates, with polygonal grain boundary textures, suggesting that the hornblende has undergone metamorphic recrystallization. Biotite is cross-cutting with respect to hornblende and exhibits minor replacement by chlorite. Euhedral epidote commonly occurs within biotite grains, but it is not clear whether the epidote is coeval with biotite or secondary. Some epidote has symplectic
intergrowths of quartz and in rare instances is associated with the formation of actinolitic rims on hornblende. Since the euhedral epidote is associated with biotite that postdates metamorphic hornblende, it is probably not of magmatic origin (e.g. Zen and Hammarstrom, 1984). Opaque oxides do not occur in the matrix, but occur as thin rims around sphene or biotite.

Hornblende tonalite gneiss consists primarily of plagioclase (An 25-30), quartz, hornblende, and biotite. Microcline occurs only in trace amounts. Minor and accessory minerals include sphene, apatite, epidote, chlorite, opaque oxides, and zircon. Quartz and biotite are more abundant than in monzodiorite samples, and hornblende is less abundant (Table 2). The grain size is less heterogeneous than the biotite tonalite gneiss and averages 1.0mm. Plagioclase is unzoned and forms mosaic textures with quartz. Hornblende aggregates such as those found in the monzodiorite are lacking in the tonalite where hornblende occurs more commonly as single nematoblastic grains. Biotite, epidote, and chlorite form secondary textures as described in the monzodiorite.

Porphyritic Granodiorite

Moderately to weakly foliated porphyritic granodiorite gneiss with relict K-feldspar phenocrysts occurs in Bear Basin and on Indian Ridge (Fig. 2, Plate 1). Relict phenocrysts impart an augen texture to the Indian Ridge body. Inclusions of monzodiorite gneiss and biotite tonalite gneiss occur in the Bear Basin outcrops, demonstrating that the granodiorite is younger than both of these rock types.

The mineralogy of the porphyritic granodiorite consists of plagioclase, quartz, microcline, biotite, and blue-green
ferrohastingsite-rich hornblende (2Wx = 40-50). Minor and accessory mineralogy includes sphene, epidote, allanite, opaque oxides, apatite, and zircon (Table 2). Textures in thin section are sub-granoblastic, with limited preservation of original lobate, xenomorphic texture. Groundmass grain size is heterogeneous, ranging from 0.05mm to 3.0mm. Plagioclase composition averages An 25, but individual grains have more calcic rims (An 30) and myrmekitic texture in contact with microcline. Relict phenocrysts of potassic feldspar average 2-3 cm, but in thin section are found to be recrystallized to smaller, perthitic subgrains. Hornblende is not lineated, in contrast to the older granitoids, but instead occurs in optically continuous segments separated by intervening quartz, plagioclase, or K-feldspar. The individual segments have curved and embayed grain boundaries, which is interpreted as a relict, igneous resorption texture. The resorbed hornblende segments commonly have reacted to form platy biotite, sphene, and euhedral epidote which is commonly cored by allanite (Fig. 7). These textures suggest that epidote is a relict igneous mineral (e. g. Zen and Hammarstrom, 1984), in contrast to the retrograde epidote of the older hornblende granitoids.

**Granite**

Unfoliated to moderately foliated granite to granodiorite is ubiquitous throughout the GPT. Map-scale intrusions (Plate 1) are subconcordant with the regional foliation; smaller veins occur as both dikes and sills and range in thickness from tens of centimeters to tens of meters. The degree of deformation of granite intrusions varies greatly. Many of the intrusions are isoclinally folded, while other
intrusions are apparently undeformed. The number and size of intrusions increase toward the ductile shear zone. Although some intrusions of granite are moderately foliated, thin section textures are hypidiomorphic-granular, indicating that the foliation is a primary igneous feature. Forceful injection of granite along a contact between biotite schist and monzodiorite gneiss in Bear Basin created an agmatitic complex of cliff-scale proportions. The granite contains scattered ultramafic xenoliths, including diopsidic hornblende and metaultramafite composed of Mg-hornblende, orthopyroxene, and olivine. No other types of xenoliths were found.

The Q-Or-Pl ratios of the granite lie close to the granite-granodiorite boundary on the IUGS diagram (Fig. 5), overlapping the
field of the older porphyritic granodiorite. The mineralogy is very similar to the latter but is finer grained (ave. grain size of 0.5 mm) and has no relict K-feldspar phenocrysts. Euhedral grains of ilmenite up to 2 cm in diameter commonly occur along the margins of larger sills near Gallatin Peak. Hornblende occurs in trace amounts and is blue (Z) with a low 2Vx of 10-15, indicating a high ferrohastingsite content (Griffen and Phillips, 1980). Where present, hornblende displays the same segmented habit as in the porphyritic granodiorite with similar embayment and replacement by biotite and epidote. Biotite is also associated with euhedral epidote where hornblende is absent and is partially altered to chlorite.

The textural relationships between hornblende, biotite and epidote in granitoids are similar to those described in Phanerozoic granitoids of the North American Cordillera, where the formation of euhedral epidote has been interpreted as a late-stage product of hornblende resorption at moderate to high pressures (Zen and Hammarstrom, 1984). In both the porphyritic granodiorite and in the granite, the resorption textures of the hornblende suggest that similar processes occurred and that the epidote is of magmatic origin. However, in the foliated hornblende granitoids, the euhedral epidote is formed from metamorphic hornblende and, in rare instances, is associated with formation of actinolitic rims, and is probably of secondary, retrograde origin. Therefore, it is suggested that in the youngest granitoids, epidote is probably of magmatic origin, but epidote in older granitoids is probably metamorphic or secondary in origin.
Pegmatites

At least two generations of intrusive pegmatites are present in the GPT. This fact was noted by Spencer and Kozak (1975), but no descriptions of their occurrences or mineralogies have been made. The oldest intrusive pegmatites are restricted in occurrence to flattened veins within the hornblende granitoid gneisses. These pegmatites are hornblende-rich and have an average grain size of 0.5 to 1.0 cm. The mineralogy consists primarily of microcline, quartz and hornblende, with accessory apatite and opaque oxides.

The younger pegmatites are ubiquitous throughout the GPT and intrude foliated and unfoliated granite (Fig. 6). These pegmatites are, in general, coarser-grained than the older pegmatites, with an average grain size of 2-3 cm. The mineralogy of these pegmatites consists of microcline, plagioclase, and quartz, with accessory apatite and ilmenite.

Summary

The relative ages and timing of emplacement of the granitoids can be roughly determined from cross-cutting relationships and by the degree of development of metamorphic textures in the different phases. The oldest granitoids are hornblende and biotite tonalite, and hornblende monzodiorite granitoid gneisses. The high degree of foliation and lineation and the development of metamorphic mosaic textures in these phases suggest their emplacement prior to or during the early stages of high-grade tectonism of the GPT. The porphyritic granodiorite contains xenoliths of the hornblende granitoids and the biotite tonalite, demonstrating that it is younger than these two
granitoids. The partial development of metamorphic textures indicate that this phase was also emplaced prior to or during the early stages of orogenesis. At least some of the granite, however, was emplaced during the peak of tectonic activity in the GPT. The evidence for this interpretation comes from the development of primary, igneous foliation and from contact aureoles in metapelites with the same assemblages as metapelites away from intrusions. The formation of magmatic epidote in the granite further suggests that emplacement, and therefore high-grade tectonism, occurred at minimum pressures of 7-8 kbars.

**Ultramafic and Mafic Rocks**

Mafic and ultramafic boudins, dikes, and sills comprise between 10 and 20 percent of total outcrops in the GPT, with mafic bodies greatly outnumbering ultramafic occurrences. Most possess upper-amphibolite facies assemblages, with no evidence of any higher-grade relict metamorphism (Table 1). The only exception is a series of synkinematic metagabbros with transitional granulite assemblages. Northwest-trending diabase and basalt dikes are unmetamorphosed and are not considered to be part of the Archean suite.

**Ultramafites**

The largest ultramafic body is located near Wilson Peak (Fig. 2; Plate 1). The Wilson Peak ultramafite is about 100 meters thick and is continuous over at least 2 kilometers. The surrounding schists are increasingly muscovite-rich in a 20 meter thick zone approaching the ultramafite. The ultramafite is mantled by a thin outer margin of
garnetiferous amphibolite. Garnets in this margin are typically large, up to 3 cm in diameter, with plagioclase-depleted haloes. Amphibolite rapidly grades into an inner ultramafic zone which consists almost entirely of nematoblastic anthophyllite and Mg-hornblende, in which crude gneissic banding is defined by limited segregation of the two amphiboles. A weak schistosity is imparted by anhedral, flattened malachite grains which may be secondary mineralization along pre-existing partings.

An ultramafic body at Summit Lake (Fig. 2, Plate 1) is roughly 20 meters thick and occurs near the contact between hornblende granitoid gneiss and weakly foliated granite. This ultramafite has an outer mantle of garnetiferous amphibolite similar to the Wilson Peak ultramafite. The core of the Summit Lake ultramafite is essentially hornblendite, with minor mm-scale bands of cummingtonite and opaque oxides. Plagioclase comprises up to 5 modal percent in some samples. In the central core of the body, patchy remnants of orthopyroxenite are preserved. These remnants consist of aggregates of large (2.0 mm) orthopyroxene grains that exhibit extensive exsolution of opaque oxides. The large orthopyroxene grains have heavily corroded, embayed grain margins, recrystallizing to form a fine-grained mosaic of Mg-hornblende, inclusion-free orthopyroxene, and green spinel.

A zoned ultramafite about 100 meters long occurs in the ridge above the Chilled Lakes (Fig. 2, Plate 1). The ends of the body are tapered and folded, indicative of post-emplacement tectonic disruption. The ultramafite is texturally and mineralogically zoned, with an outer amphibolite margin, an outer core of magnesian-hornblendite, and a core
of megacryst-bearing rock of harzburgite composition. The outer amphibolite consists of subequal amounts of blue-green (Z) hornblende and plagioclase with minor sphene and opaque minerals. In contrast to the amphibolite mantles of the ultramafites described above, garnet is absent. The outer core of the body consists of pale green Mg-hornblende and phlogopite, with minor cummingtonite and opaque minerals. Foliation is defined by planar alignments of phlogopite. The Mg-hornblende is riddled with crystallographically oriented opaque inclusions. Grain size of 1 mm is nearly uniform, but some hornblende megacrysts are up to 4 mm long. The inner core consists of a matrix of equigranular Mg-hornblende, olivine, orthopyroxene, and opaque oxides, with megacrysts of orthopyroxene up to one centimeter long. The orthopyroxene megacrysts have numerous inclusions of opaque oxides, Mg-hornblende, and phlogopite which appear to have grown along fractures in the orthopyroxene. Some fractures in the megacrysts are filled with talc that surrounds a core of opaque minerals.

Ultramafites also occur as xenoliths in the monzodiorite gneiss and in the granite. The most common type of inclusion is diopsidic hornblendite, which consists of light blue-green (Z) hornblende, diopside, and biotite with accessory apatite, allanite, and opaque oxides. In late-stage granite in the Spanish Lakes area (Fig. 2), xenoliths with mineralogy and texture similar to the inner core of the Chilled Lakes ultramafite were found.

The following points should be noted regarding the ultramafites of the GPT. First, the assemblages described above are representative of upper amphibolite-facies metamorphic conditions (Evans, 1977;
Desmarais, 1981). There is no evidence that these assemblages are superimposed on any relict, higher-grade metamorphic assemblages. Second, many of the textures described above are similar to those found in ultramafites of the nearby Ruby Range (Desmarais, 1981) which were interpreted to be pre-tectonic emplacements that had been serpentinized prior to metamorphism. An important difference in the Spanish Peaks ultramafites is that opaque oxide inclusions do not define relict S-surfaces. Furthermore, the presence of chill-margins in the Summit Lake ultramafite and the long-range continuity of the Wilson Peak ultramafite, together with the formation of L- and S-textures, suggest that these may be syntectonic intrusions.

Amphibolites

Amphibolitized metabasites are ubiquitous throughout the GPT and form a sequence ranging from older, isolated meter-scale mafic pods to younger, more continuous metamorphosed dikes and sills. The isolated mafic pods are formed by boudinage or by disruption of mafic layering by nappe-style folding. Foliation and lineation are quite variable in degree of development and orientation within these bodies, as noted in earlier studies (Spencer and Kozak, 1975). Coarse-grained granitic pegmatite is commonly concentrated at the margins of the isolated pods. It is not clear whether the isolated mafic pods are of intrusive origin; many may be part of the original supracrustal suite. However, other amphibolite boudins form more continuously aligned sets and are more clearly disrupted intrusions. A swarm of amphibolitized sills and dikes with low discordance angles on Gallatin Peak were interpreted in a previous study to be undeformed (Spencer and Kozak, 1975). However,
closer inspection shows that many of these intrusions are locally disrupted by small-scale nappe style folds. Hornblendes in these intrusions generally are strongly lineated roughly parallel with fold axes. The youngest amphibolitized dikes intrude moderately foliated granite near Summit Lake and exhibit diabasic textures in outcrop.

The mineralogy of the amphibolites consists primarily of green hornblende (Z) and plagioclase (An 35-45) with lesser quartz and variable amounts of sphene. Accessory minerals include apatite, opaque oxides and zircon. Olive-green biotite occurs in many of the amphibolites. Garnet is most commonly found in the isolated boudins, although it occurs in some younger, cross-cutting bodies. The isolated boudins are commonly zoned with respect to garnet, with overall garnet content decreasing from core to rim.

Textures are primarily nematoblastic, with no evidence that the amphibolite-facies assemblages have been superimposed over relict higher-grade assemblages. Only minor retrogression was found in the amphibolites. Examination of fold hinges shows that both open and isoclinal fold types were accompanied by synkinematic growth of nematoblastic hornblende. The youngest amphibolitized metabasites exhibit static recrystallization of mafic minerals to hornblende and symplectic intergrowths of quartz, with plagioclase retaining its original lath-shaped igneous habit.

Transitional Granulites

The assemblage garnet-clinopyroxene-plagioclase-hornblende-quartz occurs only in widely scattered mafic boudins and intrusions. Distinctive corona textures are developed in these bodies which vary
systematically from total recrystallization in isolated boudins to incipient recrystallization of otherwise well-preserved igneous textures in more continuous mafic intrusions. De Waard (1965) has classified this assemblage as a high-pressure granulite, but other workers have more recently shown that this assemblage is transitional between amphibolite and granulite facies (Turner, 1981; Percival, 1983), an interpretation adopted in this study.

Outcrops of boudins with well-developed corona textures are dark reddish-brown, massive, and are generally several meters in diameter. Most have no apparent tectonite fabric in outcrop, but one boudin in the Deer Creek area exhibits millimeter-scale shearing. The mineralogy consists primarily of plagioclase (An 40-60), blue-green (Z) hornblende (2Vx = 70-80), diopside, garnet, and opaque oxides. Quartz occurs only as symplectic intergrowths with hornblende. Domains of diopside and ilmenite are separated from a mosaic of fine-grained (0.01 - 0.1 mm) granoblastic plagioclase by coronas of garnet or hornblende (Fig. 8). In some instances, hornblende coronas with symplectic intergrowths of quartz are also mantled by a garnet corona. Diopside occurs in two modes. Larger (1-2 mm) grains occur that have myriad opaque oxide inclusions and rare patches of sub-calcic augite and/or orthopyroxene. These larger diopside grains are recrystallized into mosaics of smaller (0.05 mm), inclusion-free grains. Garnet is inclusion-free in contact with plagioclase, but proximal to cpx or hornblende, garnet is highly poikiloblastic with inclusions of both hornblende and diopside (Fig. 9). Scapolite occurs within the mosaic of recrystallized plagioclase in boudins of the Gallatin River Canyon area, but not in the Gallatin Peak
Figure 8. Transitional granulite corona texture in metabasite near Deer Lake. Coronas of garnet (G) and hornblende (H) around cpx (C). Matrix consists of plagioclase (P) and minor scapolite (S). Mm-scale shear zone (SZ) also contains the transitional granulite assemblage.

Figure 9. Detail of corona texture from sample DC-6. Large cpx grain (C) recrystallized to fine-grained mosaic of smaller, inclusion-free cpx (c). Garnet (G) forms corona around both hornblende (H) and cpx.
area. The transitional granulite-facies mineral assemblage is present in mm-scale shears, but corona textures have been obliterated (Fig. 8).

An intermediate stage of development of the corona texture is exhibited in two metabasites near Mirror Lake. One of these is a continuous dike south of Mirror Lake (Fig. 2) which clearly postdates monzodiorite gneiss and tonalitic gneisses with amphibolitic mafic layers. The other, east of Mirror Lake (Fig. 2), is disrupted into a linear series of boudins. Both metagabbros have amphibolitized margins, but in the core, diabasic texture is moderately well-preserved. In thin section, diabasic textures are modified by coronas of hornblende and garnet around all clinopyroxene and opaque oxides, as described above (Fig. 10). The clinopyroxene is diopside with patchy remnants of

Figure 10. Intermediate development of corona textures in cross-cutting transitional granulite metagabbro MG-GP near Mirror Lake. Plagioclase (P) has undergone little recrystallization while coronas of garnet (G) and hornblende (H) form around all clinopyroxene (C).
subcalcic augite that retains complex exsolation textures. Plagioclase (An 50) occurs as relict laths with only moderate recrystallization (Fig. 10). Red biotite is part of the equilibrium assemblage, but is not present. The mineralogy of the amphibolitized margins consists primarily of hornblende and plagioclase with minor diopside and sphene. Corona textures and garnet are absent from the margins.

The most complete preservation of igneous features occurs in one metabasite near Deer Lake (Fig. 2). This metabasite forms discontinuous bodies separated by covered intervals but appears to truncate granitic pegmatite. A thin (1 meter) margin of amphibolite grades into an interior with well preserved diabasic texture. In thin section, plagioclase and pyroxene form sub-ophitic textures which are only slightly modified by incipient development of metamorphic corona textures. Pyroxene exhibits complex exsolution features resulting from the inversion of pigeonite, producing intergrowths of subcalcic augite, orthopyroxene, and exsolved opaque oxides (Fig. 11). Orthopyroxene domains have a strongly pleochroic center (eulite) with an outer mantle of nonpleochroic orthopyroxene. In some instances, subcalcic augite contains a core of relict pigeonite (Fig. 12). Igneous textures are only slightly modified by the metamorphic development of discontinuous rims of greenish-brown hornblende around pyroxene, and, in isolated cases, garnet coronas around pyroxene and opaque oxides (Fig. 13). Plagioclase (An 55) laths have undergone minor recrystallization to smaller ( < .01mm) granoblastic aggregates along grain boundaries.

Similar corona textures with transitional granulite-facies
Figure 11. Preservation of igneous exsolution in pyroxenes from transitional granulite metagabbro DC-9 near Deer Lake (Fig. 2). Intergrowths of subcalcic augite (SA) and opx (O).

Figure 12. Relict pigeonite (Pi) mantled by subcalcic augite (SA) in cross-cutting transitional granulite metagabbro DC-9.
Figure 13. Incipient development of garnet (G) coronas around opaque oxide (O) and cpx (C) in metagabbro DC-9.

Assemblages have been described in metagabbros from the Precambrian basement of Quebec (Barink, 1984). Barink modelled the formation of the corona textures as a direct response to cooling of synmetamorphic gabbroic intrusions by the following reaction:

$$H_2O + cpx' + hbl'd' + plag' + Fe-Ti oxides' = gnt + cpx'' + plag'' + Fe-Ti oxides'' + qtz.$$

Crosscutting relationships described above support this model and indicate that the transitional granulites are not relics of older metamorphic events. Instead, these rocks form a continuum of syntectonic gabbroic intrusions, with the oldest intrusions being structurally disrupted into isolated boudins and completely
recrystallized into metamorphic assemblages; progressively younger intrusions are more continuous and preserve more of the original igneous mineralogy and textures. The presence of relict pigeonite, which is unstable in slowly cooled intrusive rocks (Huebner, 1982; Lindsley, 1982), suggests that intrusion of this series of metagabbros may have been accompanied by rapid uplift, resulting in the "quenching" of this high-temperature pyroxene.

Of further interest is the formation of the transitional granulite facies assemblage in the syntectonic metagabbros while other mafic rocks formed typical amphibolite facies assemblages. In Barink's model, H₂O is consumed to form the corona texture assemblage. However, in the Spanish Peaks, it is possible that any water associated with this series of metagabbros may have been driven off into the country rock, promoting the formation of the transitional granulite facies assemblage. Water driven off into the country rock, combined with the heat added to the system by the intrusion of the high-temperature metagabbros, may have been a significant factor in the formation of the in situ partial melts described above (Mogk and Salt, 1986).
The ductile shear zone marks an abrupt change in composition of quartzofeldspathic paragneisses from tonalitic in the GPT to granitic and granodioritic in the JRLT (Fig. 4). A higher grade of metamorphism in the JRLT is indicated by the presence of sillimanite-bearing metapelites and centimeter-scale intercalations of transitional granulite. K-feldspar-bearing quartzofeldspathic gneisses are the predominant lithology of the JRLT, with subordinate amounts of metapelite, metabasite, quartzite, and ultramafite. Granitoids occur in minor amounts near the shear zone.

Quartzofeldspathic Gneisses

Two distinct types of K-feldspar-bearing quartzofeldspathic paragneisses have been recognized in the JRLT. In the Jerome Rock Lakes area (Fig. 2), paragneisses with an overall granitic composition (KQFG) predominate (Fig. 4). Near the shear zone, lighter colored paragneisses (leucogneiss) with an overall granodioritic composition (Fig. 4) form a roughly continuous unit from the Spanish Lakes to Diamond Lake (Fig. 2, Plate 1).

Granitic paragneisses (KQFG)

The KQFG has well-developed foliation defined by lepidoblastic biotite and by centimeter-scale mafic compositional layering. Lineations of hornblende and biotite impart a distinct streaky
appearance to the gneisses. Mafic layers consist of biotite schist, amphibolite and transitional granulite. Metapelitic and quartzite layers are also intercalated within the gneisses on a centimeter- to meter-scale, indicating a supracrustal origin for these gneisses.

**MINERAL ASSEMBLAGES, JRLT**

**Leucogneiss**
plag-ksp-qtz-biot-apat-epid-op-zir
plag-ksp-qtz-biot-hbld-apat-epid-op-zir

**Granitic Gneiss**
ksp-plag-qtz-biot-hbld-zir-apat-op
ksp-plag-qtz-biot-hbld-cpx-gt-zir-apat-op

**Transitional Granulites**
cpx-hbld-gt-op
plag-qtz-cpx-gt-hbld-op-apat
plag-qtz-cpx-gt-hbld-biot-epid-sph-op-apat

**Metapelites**
qtz-plag-biot-musc-sill-ky-gt-apat-rut-op
qtz-biot-sill-(ky-musc-gt)-apat-op

Table 3. Summary of mineral assemblages in the JRLT. Abbreviations as in Table 1.

The principal mineralogy of these gneisses consists of K-feldspar, quartz, plagioclase, biotite, and blue-green (Z) ferrohastingsite-rich hornblende (Table 3). Garnet and/or diopside occur in some samples. Accessory minerals include apatite, allanite, and zircon. The K-feldspar is mostly microcline, but in some samples, the 2V varies from 80 to a low of 15-20, which falls into the range of sanidine (Stewart
Sanidine forms straight grain boundaries with K-feldspar grains having higher 2V, and appears to be in textural equilibrium. A possible explanation for this occurrence is that the sanidine formed under high-temperature metamorphic conditions, followed by rapid post-metamorphic cooling, resulting in the "quenching" of sanidine in various stages of inversion to microcline. K-feldspar, plagioclase, and quartz form a polygonal mosaic with straight grain boundaries. Lepidoblastic biotite and nematoblastic hornblende form aggregates with associated allanite and euhedral zircon. Zircon in these clusters is typically large (up to 1.0mm) and often contains inclusions of hornblende, quartz or apatite. Zircon also occurs as large rounded grains in the quartzofeldspathic mosaic.

**Leucogneisses**

Leucogneisses have a highly deformed and heterogeneous outcrop appearance and exhibit many features indicative of partial melting. Outcrops are composed of leucocratic felsic layers (CI < 5), interspersed with irregular, centimeter- to meter-scale quartzite and mafic compositional layering that is disrupted by shearing and nappe-style displacements (Fig. 14). Disrupted mafic layers are often mantled by white, granitic pegmatite. Foliation in the leucocratic layers is highly variable and gradational, passing from well-developed centimeter-scale mafic compositional layering into a "ghost" foliation defined by mm-scale "wispy" mafic compositional layers which exhibit an extreme degree of deformation (Fig. 15). These nebulitic gneisses locally grade into massive, unfoliated rock.
Figure 14. Ksp-bearing leucogneisses of the JRLT near the Spanish Lakes. These gneisses generally exhibit a much higher degree of deformation than those of the GPT. The field of view is approximately 10 meters.

Figure 15. Leucogneiss along trail to Mirror Lake. The nebulitic aspect of the leucogneiss is the result of extensive partial melting. The formation of a melt phase probably facilitated the extreme degree of deformation observed in the leucogneisses (as in Figure 14).
The main mineral constituents of the leucocratic layers are plagioclase, quartz, microcline, and biotite (Table 3). Blue-green (Z) ferrohastingsite-rich hornblende (2V<sub>x</sub> = 25-30) is present in the thin mafic layers. Accessory minerals include apatite, zircon, allanite, epidote, and opaque oxides. While felsic minerals generally exhibit random distribution, some samples exhibit mm-scale microcline- and plagioclase-rich layering separated by mafic rich banding. Textures of the leucogneiss are hypidiomorphic granular, with complex intergrowths of microcline and plagioclase. Microcline embayments into plagioclase are often in optical continuity with microcline inclusions within the plagioclase. Plagioclase is frequently myrmekitic in contact with microcline. Idiomorphic epidote cored by allanite occurs in the center of biotite grains in a similar manner to epidote in the youngest granitoids. Allanite also occurs as isolated, zoned grains up to 1 mm long in the leucocratic matrix.

While the textures described above are very similar to those in the granite of the GPT, the millimeter- to meter-scale compositional interlayering and lack of cross-cutting relationships suggests a non-intrusive origin for the leucogneisses. Instead, the textural and outcrop similarities to migmatite terranes (e.g., Johannes and Gupta, 1982) suggest that this unit is a heterogenous metasupracrustal sequence that has undergone extensive in situ partial melting, with quartzite and mafic layers representing refractory remnants of the original sequence.
A sequence of reddish, garnet-rich, pelitic schists, with thin layers of quartzite and amphibolitic schist occurs between the leucogneiss and the shear zone. The pelitic schists are composed of quartz, plagioclase (An 25-30), biotite, muscovite, garnet, kyanite, and sillimanite, with accessory apatite, rutile, and zircon (Table 3). Plagioclase is absent in some samples. Biotite is reddish brown, indicative of higher titanium content than the green biotite in metapelites of the GPT.

Textures in one plagioclase-absent sample from this unit indicate that sillimanite (fibrolite) is formed through a complex series of replacement reactions involving garnet, muscovite, and biotite, as well as kyanite. The following replacement textures were observed: 1) lepidoblastic biotite replaces lepidoblastic muscovite; 2) garnet is embayed by both biotite and fibrolite, with excess Fe and Ti released from the breakdown of garnet forming opaque oxides within the sillimanite (Fig. 16); and 3) kyanite is directly replaced by fibrolite. However, direct replacement of kyanite does not occur in regions of the thin section where garnet is absent, suggesting that the breakdown of garnet is a requisite step in the breakdown of kyanite. Based on these replacement textures, the generalized sillimanite-forming reaction in these rocks is

\[ \text{ky + gar + mus} = \text{sill + biot + op ox +/- qtz}, \]

which is similar to sillimanite-forming reactions proposed by Yardley (1977). In contrast to the GPT, staurolite does not appear to have.
been part of the prograde metamorphic path in the metapelites of the JRLT. The stability of coexisting muscovite and quartz indicates that the reaction occurred below the second sillimanite isograd. Fibrolite in this sample is tightly folded and is partially replaced by late, sericitic muscovite. This suggests that deformation outlasted growth of sillimanite and occurred under retrogressive conditions, possibly related to late movements along the shear zone.

Figure 16. Fibrolite (S) and biotite (B) embayments into garnet (G) in metapelite sample CM-17 from JRLT near ductile shear zone. Note concentration of opaque minerals in fibrolite: Fe-Ti from breakdown of garnet not absorbed by sillimanite formed separate Fe-Ti oxide phases.

Metapelites in the Jerome Rock Lakes area are similar to those near the shear zone, but have more plagioclase and are less deformed. Sillimanite-forming reactions in these rocks are more ambiguous, but the presence of biotite-embayed garnet suggests similar processes.
Replacement of aluminosilicates by sericitic muscovite is less pronounced in the Jerome Rock Lakes area, perhaps related to increased distance from the shear zone.

Quartzite lenses are intercalated in both the KQFG and leucogneiss sequences and in the pelitic schists near the shear zone. In most cases, quartzites are composed of quartz, emerald green mica, and opaque oxides. No epidote-quartzites of the type occurring in the GPT were found north of the shear zone.

**Transitional Granulites**

Three distinct varieties of transitional (cpx-gnt) granulites were found in the JRLT. First, fine-grained mafic granulites form centimeter-scale intercalations within the KQFG gneisses and within a thick (50 m) mafic zone near the DSZ (Plate I). Second, a distinctive unit of leucocratic, coarse-grained plagioclase-garnet-diopside rock (referred to as leucogranulite) which varies in thickness from 2-3 meters occurs between the mafic zone and the metapelites described above. Finally, some isolated mafic bodies with total development of the corona textures described in the GPT are widely scattered throughout the JRLT, indicating that although the two terranes were juxtaposed by the time the high-temperature metagabbros were injected. The textural descriptions of these metagabbros were presented in the previous chapter and are not repeated in this section.

**Intercalated granulites**

Fine-grained transitional granulites intercalated with the KQFG gneisses are similar to those described from the Ruby Range (Dahl,
1979) and the Blacktail Range (Clark, 1986). The mineralogy consists of plagioclase, olive-green hornblende, garnet, diopside, and minor biotite (Table 3). Accessory minerals include apatite, opaque oxide, rutile, and zircon. Plagioclase generally forms a mosaic texture but includes some relict larger (1–2 mm) grains that exhibit continuous normal compositional zonation, from core composition of An 45 to rim compositions of An 30. Hornblende grains are in granoblastic contact with each other but are replaced by garnet and diopside. Garnet engulfs and has numerous inclusions of hornblende. Diopside is in grain boundary contact with garnet and commonly intervenes between hornblende and garnet. These textures indicate that hornblende is either a reactant in the formation of the granulite facies assemblage or part of the stable assemblage, but that it is not a product of retrogression from earlier metamorphic assemblages.

The thin bands of granulite in the mafic body near the shear zone are composed entirely of garnet, diopside, and hornblende (Table 3), giving the bands an ultramafic appearance. Grain boundaries form a granoblastic mosaic texture. The borders of the ribbons are composed of granoblastic hornblende and diopside with minor interstitial plagioclase, which grade outward into diopside-bearing amphibolite.

Leucogranulite

The coarse-grained leucogranulite near the shear zone has an assemblage of plagioclase, quartz, diopside, and garnet, with coronas of retrograde blue-green hornblende and epidote (Table 3). Sphene is present in minor amounts. Accessory minerals include apatite, opaque oxides, and calcite. Garnets reach a maximum size of 5 cm in diameter.
and are intensely fractured. Diopside tends to be smaller, with a maximum size of about 1 cm and is generally less fractured than the garnet. Plagioclase is nearly totally altered to sericite except where mantled by garnet. Both diopside and garnet have coronas of greenish-blue hornblende with symplectic intergrowths of quartz. The hornblende is subsequently mantled by coronas of epidote with similar symplectic intergrowths (Fig. 17). Epidote and hornblende also occur along fractures in diopside and garnet. Sphene occurs mostly along contacts between diopside and hornblende and within the garnet. Inclusions of hornblende commonly occur within the sphene, indicating that growth of sphene outlasted that of hornblende.

Figure 17. Successive retrograde coronas in leucogranulite near DSZ. Cpx (C) is mantled by hornblende (H), which in turn is mantled by epidote (E).
Amphibolites and Ultramafites

Amphibolites occur as centimeter- to meter-scale intercalations within gneisses, as isolated boudins, and as amphibolitized intrusions. Intercalations and boudins consist of plagioclase, hornblende, and sphene, with accessory apatite, allanite, and opaque oxides. Garnet or diopside is present in some samples. Numerous amphibolitized intrusions postdate both gneissic units and are commonly rich in garnet.

Pods of coarse-grained pyroxenite occur near the shear zone within the white gneiss and in outcrop show no signs of metamorphic zonation such as found in the ultramafites of the GPT. Spencer and Kozak (1975) also report the occurrence of a large ultramafic body north of the shear zone consisting of augite, olivine, and plagioclase.

Granitoids

Clearly intrusive granitoids form only a minor portion of the JRLT and are largely associated with the shear zone. In the Spanish Lakes area (Fig. 2), centimeter- to meter-scale intrusions of granite commonly occur along planes of mylonitization (Fig. 18). The composition is identical to the leucogneiss and youngest granitoids from the GPT and exhibits the same textural relationships involving "magmatic" epidote. This spatial association suggests that mylonitization was in part coeval with the injection of the youngest granite.

An agmatitic complex of trondhjemite and amphibolite occurs on the ridge south of Lake Solitude (Fig. 2). Amphibolites within the agmatite complex exhibit shearing, and injection of the trondhjemite
appears to be partly controlled by the orientation of the shear planes. The agmatitic fabric passes into concordant interlayers of trondhjemite and amphibolite, similar to occurrences in the tonalitic country rock gneisses of the GPT.

Pegmatites are also common in the JRLT, but the early pegmatites associated with the hornblende granitoids of the GPT were not found in the JRLT. The pegmatites of the JRLT are of granitic composition, and often contain xenoliths of supracrustal assemblages, including metapelite and marble.

Figure 18. Youngest granite injected into mylonitized amphibolite. Sigmoidal fold is disrupted by mylonitization (M), with injection of granite along shear plane.
The JRLT is a supracrustal terrane dominated by K-feldspar-bearing paragneisses, some of which have undergone extensive partial melting. Mineral assemblages in mafic compositional layers and in metapelites are indicative of transitional granulite facies, sillimanite-grade metamorphism.

The compositional, mineralogical, and textural evidence presented above demonstrates that the JRLT records a different geologic history than the GPT (Table 4). The K-feldspar-bearing paragneisses represent an entirely different source of supracrustal material than that of the tonalitic paragneisses of the GPT. The intercalated transitional granulites and sillimanite-bearing assemblages indicate that the JRLT experienced a different, higher-grade path of metamorphism. This change in metamorphic grade from the GPT to the JRLT is not continuous, with recognizable isograds, but is abrupt across the shear zone. Finally, the absence of the older granitoids of the GPT in the JRLT suggests that the two terranes were not juxtaposed during the early epoch of granitic plutonism. However, juxtaposition of the two terranes occurred prior to emplacement of the corona texture metagabbros, the youngest granite, and the trondhjemite-amphibolite sequences, as evidenced by the presence of these rock types in both terranes.
## COMPARISON OF THE GEOLOGIC HISTORIES OF THE GPT AND JRLT

<table>
<thead>
<tr>
<th>GALLATIN PEAK TERRANE</th>
<th>JEROME ROCK LAKES TERRANE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tonalitic paragneisses</td>
<td>Granitic paragneisses</td>
</tr>
<tr>
<td>Kyanite-gedrite metapelites, with early staurolite</td>
<td>Sillimanite metapelites with no evidence of early staurolite; early kyanite + muscovite</td>
</tr>
<tr>
<td>Transitional granulites only in corona-texture metagabbros</td>
<td>Transitional granulites intercalated with gneisses in addition to corona-texture metagabbros</td>
</tr>
<tr>
<td>Older foliated granitoids, and youngest granite and trondhjemite-amphibolite</td>
<td>Youngest granite and trondhjemite-amphibolite only</td>
</tr>
</tbody>
</table>

Table 4. Comparison of lithologies, metamorphic and plutonic histories of the GPT and the JRLT.
DUCTILE SHEAR ZONE

The ductile shear zone (DSZ) is roughly 500 meters thick and is coincident with the break in lithologies and metamorphic grade between the two terranes described above. This zone is continuous from the Spanish Lakes into the Diamond Lake area (Fig. 2), trending northeast and parallel to the regional foliation. The DSZ is characterized by anastomosing mylonite bands that are interleaved with meter-scale macrolithons of relatively less deformed gneiss and amphibolite. The mylonite bands are developed predominantly within tonalitic gneisses of the GPT, but some mylonite bands also occur within the sillimanite-bearing metapelites and leucogneiss of the JRLT. As described in previous sections, injection of the youngest granite occurs along shear planes bordered by mylonite (Fig. 18). The mylonite bands are generally parallel to the foliation of the surrounding gneisses, but they also form planes oblique to regional foliation. Individual mylonite bands are locally discontinuous and are highly variable in thickness, ranging from one centimeter to one meter. The mylonite bands have a dense, black, blastomylonitic fabric which varies from aphanitic to highly porphyroclastic.

Microstructures of samples from within and near the DSZ exhibit a progression of deformational textures in a manner similar to that described by Bell and Etheridge (1973), from incipient mylonitization in gneisses which shows little deformation in hand sample to development of blastomylonitic fabric in the mylonite bands. Initial
deformation in gneiss is characterized by development of subgrains and deformation bands within quartz grains and by incipient ductile grain size reduction at quartz grain boundaries. Boundaries between quartz grains commonly are seriate. Feldspars are bent and fractured and have undulose extinction. Biotite exhibits extensive kinking.

Intermediate deformational textures occur in augen gneisses and in isoclinally folded amphibolites. Microstructures in the augen gneisses are characterized by the development of quartz ribbons and millimeter-scale seams of fine-grained biotite. Plagioclase (and garnet, where present) becomes more rounded and forms asymmetrical augen structures with tails of mixed quartz and plagioclase (e.g. Simpson and Schmid, 1983). Quartz-feldspar microlithons also form augen textures. In amphibolite, hornblende and plagioclase are bent and broken around the hinges of isoclinal folds and show signs of mechanical grain-size reduction. A new, weak planar fabric, defined by bands of fine-grained material, is developed at an oblique angle to the axial plane of the isoclinal fold.

The most intense deformation results in the formation of a submicroscopic, mafic-rich matrix with no apparent internal foliation. In some instances, biotite grains are rotated into the edge of the bands where extreme reduction in grain size takes place, suggesting that the mafic matrix is biotite-rich. Porphyroclasts of plagioclase and epidote occur in all samples of mylonite bands. Hornblende, microcline, sphene, garnet, and apatite are variably present as porphyroclasts. Mylonite bands rich in hornblende porphyroclasts often have associated garnet porphyroclasts. Rarely, quartz-plagioclase-
garnet microlithons occur in association with mafic bands rich in hornblende porphyroclasts. Porphyroclasts are subrounded to ovoid and do not exhibit the asymmetric augen microstructures found in less deformed zones. Most plagioclase grains exhibit mechanical grain size reduction, but rarely, plagioclase grains which exhibit dynamic recrystallization textures at the margins are preserved. Composite planar fabrics (S-C surfaces), however, are common within the mafic bands. Quartz forms ribbons one or two grains thick which commonly have "teardrop" (Simpson, 1983) or fishhook microstructures. The quartz grains within the ribbons have mosaic or seriate grain boundaries, indicative of dynamic recrystallization and recovery (Bell and Etheridge, 1973).

The preservation of plagioclase with dynamic recrystallization textures indicates that early development of the shear zone occurred under at least amphibolite facies conditions (White and others, 1980). However, the dominance of generally brittle textures in the feldspars indicates that the latest deformation in the shear zone occurred at lower grades. Mineral assemblages within the shear zone exhibit variable degrees of retrogression. Hornblende is generally mantled by blue-green (Z) rims and plagioclase exhibits locally extensive sericitization. Tiny (0.05) euhedral tourmaline occurs in the fine-grained matrix of one mylonite sample. The formation of tourmaline, which is absent in either terrane, may be the result of concentration of late-stage fluids in the shear zone. Most epidote in the mylonites has been brittly deformed and may have been derived from the late, epidote-bearing granite, but it is also possible that some epidote may
be a product of retrogression. Locally, biotite is replaced by chlorite and in rare instances, actinolite forms homoaxial replacements of hornblende.

Therefore, while there is evidence for at least one stage of shearing under high-grade conditions, the latest deformation in the shear zone occurred under lower-grade conditions than seen in the two terranes. However, the intimate association of shear bands with the injection of the youngest granite, which has been shown to be equivalent at least in part to high-grade metamorphism in the GPT, suggests that the final stages of mylonitization occurred during progressively cooler stages of the same orogenic event, as opposed to being the product of a separate green schist facies event.
PHYSICAL CONDITIONS OF METAMORPHISM

Petrogenetic Associations

Metapelites in the GPT containing relict staurolite provide useful petrogenetic information for bracketing the minimum metamorphic conditions of this terrane. Various reactions involving the breakdown of staurolite to form orthoamphibole assemblages (Fig. 19a) have recently been modelled by Hudson and Harte (1985) for K₂O-poor systems in the FeO-MgO-Al₂O₃-SiO₂-H₂O (FMASH) field for P glitter = P total and ideal mineral compositions. The reaction of staurolite to form the assemblage orthoamphibole-kyanite-garnet observed in the metapelites of Bear Basin indicates metamorphism occurred at minimum conditions of 680-690 C and 7.5 kbars (Fig. 19a). This estimate is consistent with minimum conditions necessary to form the anatectic, stromatic migmatites in the tonalitic paragneisses (Fig. 19a; Johannes, 1985). Furthermore, the formation of coarse-grained orthoamphibole-kyanite-garnet assemblages in contact aureoles adjacent to intrusions of the granite indicates that granite emplacement occurred at least in part under the same conditions. This interpretation is consistent with the presence of magmatic epidote in the granite, which has been modelled as forming at minimum pressures of 7 to 8 kbars (Zen and Hammarstrom, 1984).

Petrogenetic associations in the JRLT do not allow the same precision in bracketing metamorphic conditions as do those from the
GPT. Qualitatively, however, the occurrence of transitional granulite assemblages intercalated within the gneisses and the reaction of kyanite, garnet, and muscovite to form sillimanite and biotite suggest that the JRLT experienced higher-grade metamorphic conditions. The stability of muscovite and quartz indicates that metamorphic conditions were below those required to form partial melts in pelitic rocks (Fig. 19b; Storre and Karotke, 1972). However, the locally extensive development of anatectic migmatites in the leucogneiss units indicates that conditions extended beyond the minimum-melting curve for rocks of granitic compositions (Fig. 19b; Johannes, 1985).

**Geothermobarometry**

Suitable assemblages for P-T studies in the Spanish Peaks area are garnet-biotite (GT-BT) and clinopyroxene-garnet (CPX-GT) for thermometry, and garnet-aluminosilicate-quartz-plagioclase (GASP) and clinopyroxene-garnet-plagioclase-quartz (CPX-GT-PLAG) for barometry (Table 5). The results indicate that at one time, the JRLT experienced higher peak temperatures than did the GPT, but later shared a common thermal history with the GPT at lower temperatures. Pressure estimates are more ambiguous, however, and it is not yet clear which terrane records the highest pressures; the GPT has a minimum pressure of 7.5 kbars, whereas mineral assemblages of the JRLT allow somewhat lower pressures.

**Garnet-biotite**

Garnet-biotite temperature estimates were obtained for two samples from each terrane. While several currently available models were used
### Calculated Temperatures and Pressures for the GPT and the JRLT

#### Temperatures (°C)

<table>
<thead>
<tr>
<th></th>
<th>GPT</th>
<th>JRLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT-BT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak:</td>
<td>BBE-7</td>
<td>BBE-32C</td>
</tr>
<tr>
<td>(range)</td>
<td>683-728</td>
<td>689-740</td>
</tr>
<tr>
<td></td>
<td>665-707</td>
<td>674-726</td>
</tr>
<tr>
<td></td>
<td>587-630</td>
<td>530-561</td>
</tr>
<tr>
<td></td>
<td>638-690</td>
<td>634-682</td>
</tr>
<tr>
<td>Peak</td>
<td>690</td>
<td>699</td>
</tr>
<tr>
<td>(average)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retrograde:</td>
<td>583-617</td>
<td>585-605</td>
</tr>
<tr>
<td>(range)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retrograde:</td>
<td>599</td>
<td>595</td>
</tr>
<tr>
<td>(average)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPX-GT</td>
<td>DC-6</td>
<td>DL-33B</td>
</tr>
<tr>
<td>5)</td>
<td>675-711</td>
<td>678-713</td>
</tr>
<tr>
<td>6)</td>
<td>580-637</td>
<td>610-673</td>
</tr>
</tbody>
</table>

#### Pressures (kbars)

<table>
<thead>
<tr>
<th></th>
<th>GPT</th>
<th>JRLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GASP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak:</td>
<td>BBE-7</td>
<td>BBE-MP</td>
</tr>
<tr>
<td>A)</td>
<td>6.8-7.7</td>
<td>7.5-8.3</td>
</tr>
<tr>
<td>B)</td>
<td>4.2-5.3</td>
<td>6.2-7.1</td>
</tr>
<tr>
<td>Retrograde:</td>
<td>4.5-5.3</td>
<td>4.8-6.0</td>
</tr>
<tr>
<td>CPX-GT-PLAG</td>
<td>DC-6</td>
<td>DL-33B</td>
</tr>
<tr>
<td>C)</td>
<td>5.4-7.2</td>
<td>5.2-7.0</td>
</tr>
</tbody>
</table>

Table 5. Summary of P-T calculations. The following models were used: 1) Hodges and Spear (1982); 2) Ferry and Spear (1978); 3) Ganguly and Saxena (1984); 4) Indares and Martignole (1985); 5) Ellis and Green (1979); 6) Dahl (1980); A) Newton and Haselton (1981); B) Ganguly and Saxena (1984); C) Newton and Perkins (1982). Samples BBE-7, BBE-32C, and BBE-MP are metapelites from the GPT. Samples CM-17 and SP-12 are metapelites from the JRLT. Sample CM-20 is an intercalated transitional granulite from the JRLT. Samples DC-6 and DL-33B are corona-texture mtsagabbros from the GPT and the JRLT, respectively.
for temperature calculations (Ferry and Spear, 1978; Hodges and Spear, 1978) model because of the uncertain effects of the various Margule's parameters used in the other models (Table 5).

Peak temperatures for the GPT range from 665-726 °C (Table 5). In sample BBE-7, garnet inner rim and adjacent biotite generally yield peak temperatures. However, in sample BBE-32C, garnet core and interior biotites give peak temperatures of 674-726 °C; garnet inner rim and both adjacent and matrix biotites give temperatures in the range of 604-670, which are interpreted to be partial re-equilibration temperatures. Garnet rim compositions of samples from the GPT consistently yield a lower temperature range of 583-617 °C; this range is reported in Table 5 as retrograde temperatures.

Peak garnet-biotite temperatures for the JRLT range from 745-784 °C (Table 5). Garnet inner rim compositions yield the highest temperatures in both the JRLT samples. However, in sample CM-17, matrix biotites give the highest temperatures, while in sample SP-12, adjacent biotites yield the highest temperatures. Garnet rims in samples from the JRLT yield a range of retrograde temperatures from 644-715 °C, which fall within the range of peak temperatures of the GPT.

**Garnet-clinopyroxene**

Temperature estimates for the assemblage clinopyroxene-garnet were obtained using the models of Ellis and Green (1979) and Dahl (1980). The formulation of Dahl (1980), which was empirically calibrated from transitional granulites from the nearby Ruby Range, yields temperatures
about 100 °C lower than those calculated from the Ellis and Green model, and are probably too low to represent peak conditions.

One corona-texture metagabbro from each terrane and one intercalated transitional granulite from the JRLT were used to obtain temperature estimates (Table 5). DC-6 is a metagabbro from south of the shear zone near Deer Lake (Fig. 2) and DL-33B is a metagabbro from just north of the shear zone near Diamond Lake. CM-20 is a transitional granulite intercalated within the mafic gneisses and schists on the ridge above Chilled Lakes (Fig. 2; Plate 1).

The model of Ellis and Green (1979) yields a temperature range of 675-713 °C for metagabbros from both terranes (Table 5) using both core and rim compositions. For the intercalated transitional granulite, core compositions yield temperatures of 751-763 °C, while rim compositions yield temperatures of 719-726 °C (Table 5). The core temperature estimate from the intercalated granulite is consistent with peak garnet-biotite temperature estimates for the JRLT. The temperature estimates from the metagabbros, however, are the same for samples from either terrane and correspond to peak temperatures of the GPT.

Geobarometry

Pressure estimates for both terranes were obtained using garnet-aluminosilicate-quartz-plagioclase (GASP) and clinopyroxene-garnet-plagioclase-quartz (CPX-GT-PLAG) assemblages (Table 5). The models of Newton and Haselton (1981) and Ganguly and Saxena (1984) were used for the GASP geobarometer. However, since the model of Ganguly and Saxena (1984) does not yield pressures consistent with the stability of kyanite in the GPT, the model of Newton and Haselton (1981) is
preferred in this study. Pressure estimates for the CPX-GT-PLAG system were calculated using the formulation of Newton and Perkins (1982).

For the GASP geobarometer, two samples, one from the GPT and one from the JRLT, were used (Table 5). Core and inner rim garnet compositions combined with plagioclase core compositions yield pressures of 6.8-8.3 kbars for the GPT using a peak temperature of 700°C, consistent with estimates using petrogenetic grids. Pressure estimates for the JRLT are somewhat ambiguous, ranging from 6.0 to 8.3 kbars, using a peak temperature of 770°C (Table 5). The large range of values for the sample from the JRLT is the result of variation in core anorthite mole fraction of individual grains from 0.22 to 0.28. Pressures calculated using the lower value range from 7.5-8.3 kbars; use of the higher anorthite content gives pressures of 6.0-6.8 kbars. For the assumed temperature of 770°C, both ranges fall within the stability field of sillimanite.

Pressure estimates using the empirical calibration of Newton and Perkins (1982) for the clinopyroxene-plagioclase-garnet-quartz (GPC) assemblages of the corona-texture metagabbros range from 5.0-7.2 kbars for the two samples from both terranes (Table 5). However, Newton and Perkins note that their formulation using this assemblage, in comparison with the formulation using assemblages containing orthopyroxene, yields pressure estimates on the order of 1-2 kbar too low. However, other studies have noted that the development of corona textures suggests disequilibrium conditions related to uplift (Dahl, 1979; Newton and Perkins, 1982) and the lower pressure estimates may be more realistic. The interpretation that these textures represent
uplift conditions is consistent with the preservation of relict pigeonite in the metagabbros, which is not likely to be preserved under slow cooling conditions.

Summary

Petrogenetic associations of the GPT constrain minimum peak conditions of metamorphism of this terrane to 680-690 C and 7.5 kbars and also constrain the timing of emplacement of the youngest granite to be coeval with high-grade metamorphism of the GPT. However, peak conditions of the JRLT can only be roughly bracketed by petrogenetic associations to be above minimum melting in quartzofeldspathic gneisses of granitic composition, but below melting reactions in muscovite-bearing metapelites.

Geothermobarometry calculations, summarized in Figure 21, indicate that the two terranes have different early metamorphic histories, but indicate that they may have shared a later history (Fig. 21). The GPT experienced peak metamorphism under amphibolite-facies conditions at temperatures of 665-726 C and pressures of 6.8-8.3 kbars (Box 1, Fig. 20). Temperature estimates from intercalated metapelites and transitional granulites immediately north of the shear zone confirm that the JRLT experienced early higher peak temperatures of 745-782 C, either at lower pressures or at roughly the same pressures (Box 2, Fig. 20).

Temperature and pressure estimates for the metagabbros which occur in both terranes, however, are the same for samples from either side
of the shear zone (Box 3, Fig. 20) and coincide with the peak temperature estimates of the GPT from garnet-biotite pairs. This finding constrains the timing and conditions of juxtaposition of the two terranes to prior to or during the injection and synmetamorphic recrystallization of the corona texture metagabbros at the prevailing peak temperatures recorded in the GPT. This shared thermal history may in part be reflected by the lower temperature range of 644-715 °C recorded in garnet rims from metapelite samples of the JRLT; pressures

Figure 20. Graphic summary of P-T calculations. 1) Peak estimates for GPT. 2) Peak estimates for JRLT. 3) P-T estimates using CPX-GT for metagabbros of both terranes. 4) Estimated retrograde re-equilibration of the JRLT (Dashed box). 5) Estimated retrograde re-equilibration of GPT (Dashed box). Dashed arrows are hypothetical post-peak paths for both terranes, suggesting that the two terranes shared a common thermal history during the synkinematic recrystallization of the corona-texture metagabbros.
calculated at these lower temperatures range from 5.6 to 7.3 kbars (Box 4, Fig. 20), coincident with the temperature and pressure ranges of the corona texture metagabbros. Since the corona texture metagabbros preserve relicts of high-temperature parageneses, it is suggested that the shared thermal history is associated with a pulse of rapid uplift of the two terranes. The mineral assemblages of the GPT continued to re-equilibrate during this uplift phase, with final re-equilibration at roughly 590-617 °C and 4.5-6.0 kbars (Box 5, Fig. 20).
STRUCTURE

While a comprehensive structural comparison between the GPT and the JRLT is beyond the scope of this study, the structural aspects of the GPT and the DSZ were examined in order to establish timing relationships between deformation, high-grade metamorphism, and juxtaposition. The deformational patterns of the GPT and the DSZ suggest that juxtaposition occurred during a single, high-grade orogenic event, with subsequent, continued deformation under progressively waning, post-peak conditions.

The megascopic fabric of the Spanish Peaks area is dominated by northeast-striking foliation that is folded into kilometer-scale open to tight folds with shallow northeast plunge (Spencer and Kozak, 1975). Within the study area, southeast-dipping foliation predominates, but poles to foliation define a diffuse great circle pattern on an equal area projection (Fig. 21a). The structural data of Spencer and Kozak (1975) indicate that this pattern is only present in this part of the Spanish Peaks area, proximal to the shear zone, which contains a high percentage of injected and anatectic melts; other domains away from the shear zone exhibit a clustering of poles to foliation.

Units in the south end of Bear Basin are deformed into a kilometer-scale synform. On the west ridge of Bear Basin this synform is overturned with both limbs dipping to the southeast, but on the east ridge, the synform is asymmetric with northwest-dipping foliation in the southern limb (Plate 1). Lithologic contacts in Bear Basin show
apparent offset between the two ridges, suggesting the presence of a northwest-trending fault (Plate 1).

On a mesoscopic scale, the rocks are deformed by isoclinal to open fold styles. In the GPT, isoclinal folds occur in centimeter- to meter-scale wavelengths and generally possess axial-planar foliation that is roughly parallel to the regional foliation. Isoclinal folds commonly occur as isolated, intrafolial, fishhook-shaped folds, and as meter-scale folding of the compositional layering. In addition, isoclinal folds with nappe-style attenuation and apparent offset in the overturned limb occur in both gneissic and amphibolitic layers. These nappe-style folds often verge toward the crest of larger open folds.

Many of what appear to be mafic boudins are actually amphibolite layers which have been disrupted by mesoscopic-scale nappe-style folding. The folds in these mafic bodies are often difficult to see, however, being defined only by millimeter-scale plagioclase-rich layers. It is suggested that nappe-style folding may be more pervasive throughout the Spanish Peaks area than previously recognized.

Open-style folds occur on centimeter- to kilometer-scale wavelengths. Open folding is superimposed coaxially on some isoclinal folds, but in some instances, Class 1A (Ramsey, 1967) open folds develop into coeval Class 2 similar fold geometries within the cores of the folds. Open fold styles include gentle flexures, kink folds, and meter-scale non-coaxial dome-and-basin structures. Kink folds most often form parasitic structures on the limbs of larger open folds. The dome-and-basin structures are the result of non-coaxial interference between northeast- and southeast- to southwest-plunging open folds; it
Figure 21. Orientations of structures in the GPT and DSZ. Lower hemisphere equal area projections. a) 185 poles to foliation, GPT. CI = 2%/1% area. Warping of foliation along the girdle shown may be due to the high percentage of melt phase near the shear zone. b) SW to NE trends of 30 open (spiked open circles) and 19 isoclinal (solid dots) fold axes, GPT. Similarity of open and isoclinal axial trends suggests coeval development of the two fold styles. c) SW to NE trends of 15 open and 26 isoclinal fold axes, DSZ. Similar deformation patterns of the GPT and the DSZ suggest a single, protracted orogenic event related to the juxtaposition of the JRLT and the GPT.
has not yet been determined whether the fold sets are diachronous or coeval.

Spencer and Kozak (1975) postulated that the isoclinal and open fold styles formed during separate, high-grade orogenic events. However, several lines of evidence suggest that the two fold styles were formed during the same orogenic event. As noted above, although some isoclinal folds are refolded by open folds, many open folds grade into isoclinal fold geometries. Also, the vergence of isoclinal nappe-style folds toward the crests of larger open structures suggests coeval development. On an equal area projection (Fig. 21b), axial orientations of the two fold styles from the GPT show similar patterns of dispersal along a great circle. Finally, in thin section, both isoclinal and open fold hinges generally possess granoblastic or nematoblastic textures with upper amphibolite facies assemblages, indicative of synkinematic recrystallization. In the isoclinal fold hinges, there is no evidence that the amphibolite facies assemblages are overprinted on any earlier, higher-grade assemblages. This indicates formation of the two fold styles under the same metamorphic conditions.

Both isoclinal and open fold styles occur within the DSZ. Hingeline orientation patterns of the two fold styles are similar to those of the GPT (Fig. 21c), as are foliation trends, suggesting that initial development of the ductile shear zone at the same time as high-grade metamorphism of the GPT. This is supported by the presence of some plagioclase grains which exhibit dynamic recrystallization at the margins, indicative of minimum upper amphibolite facies conditions.
(White and others, 1980), and by the presence of millimeter-scale shears within the corona-texture metagabbros which preserve high-grade assemblages (Fig. 8). Within the DSZ, however, some isoclinal folds disrupt amphibolite facies assemblages under brittle, retrogressive conditions, with plagioclase being frequently altered to sericitic muscovite. This indicates that isoclinal folding under post-peak conditions in the DSZ outlasted open folding under high-grade conditions in the GPT.

Recent studies support the premise that isoclinal and open fold styles can occur during the same orogenic event (e.g. Jacobson, 1983; Platt, 1983). The coeval development of the two fold styles may be attributable in part to the large percentage of melt in this area, which may have caused local differences in stress distributions arising from contrasts in competency of the rocks (McLellan, 1983). The large percentage of melt may also explain the warping of foliation (Fig. 21a) which is not present in other domains of the Spanish Peaks area (Spencer and Kozak, 1975), where large amounts of melt do not appear to have been present. It is therefore suggested that the deformational patterns of the GPT and DSZ developed during a single, protracted orogenic event which is related to juxtaposition of the GPT and the JRLT along the shear zone.

It will be necessary to determine the structure of the JRLT as it relates to this event. It was noted in this study, however, that in a qualitative sense, the structural style of the JRLT differs from the GPT. The KQFG gneisses possess a lineation defined by alignments of hornblende and biotite which is much more pronounced than in tonalitic
gneisses of the GPT. Also, the style of folding in the leucogneiss unit is much more chaotic than in gneisses of the GPT, with isoclinal and open refolding of earlier folds much more commonly encountered (Fig. 15).
CONCLUSION

Tectonic Evolution of the Spanish Peaks

Spencer and Kozak (1975) interpreted the Archean rocks of the Spanish Peaks area to represent a single metasupracrustal sequence with a common metamorphic and deformational history. However, the results of this study demonstrate that the present configuration of Archean exposures in the Spanish Peaks area is the result of tectonic juxtaposition of terranes with fundamentally different geologic histories. This conclusion requires the Archean tectonic evolution of the Spanish Peaks area to be modelled in terms of the different geologic histories of the individual terranes, as outlined in Table 6.

The supracrustal suite of the GPT consists primarily of tonalitic paragneisses, with minor metapelite, amphibolite, and quartzite. This sequence may be a volcanic arc suite, consisting of dacitic metavolcanic flows and/or metagreywacke sediments, or may be metasediments shed from pre-existing sialic crust of tonalitic composition. As the simplest model for the tectonic evolution of this terrane, relict staurolite assemblages represent the early stages of a single prograde tectonic event, culminating in upper amphibolite facies metamorphism. The oldest granitoids (hornblende granitoids, biotite tonalite and porphyritic granodiorite) would have been injected during the early stages of this event (Table 6). Alternatively, the formation of low-grade assemblages and injection of the oldest granitoids may have
occurred during an earlier event unrelated to upper amphibolite facies metamorphism. It is also possible that the older granitoids were emplaced prior to the onset of metamorphism. In any case, later upper amphibolite facies assemblages occurred at peak metamorphic conditions of 665-726 °C and 7-9 kbars. This suggests that the supracrustal package of the GPT was buried to minimum depths of 20-25 kilometers. The presence of nappe-style folding suggests that tectonic thickening through stacking of nappes was an important mechanism for transporting this package to mid-crustal levels. A similar mechanism has also been proposed for Archean supracrustal sequences in the nearby Ruby Range (Okuma, 1971; Karasevich and others, 1981). Peak metamorphism was accompanied in part by the emplacement of younger granitoids (granite and trondhjemite/amphibolite packages) and metagabbros (both corona-texture and amphibolitized). The injection of the granite and amphibolitized metagabbros may have outlasted peak metamorphic conditions.

In contrast to the GPT, the metasupracrustal suite of the JRLT is dominated by paragneisses of granitic composition, representative of a more highly evolved supracrustal setting (Engel and others, 1974; Condie, 1982) than that of the GPT. At present, there is no evidence that the JRLT shared the early plutonic history of the GPT (Table 6). The JRLT experienced a different path of metamorphism than did the GPT. Kyanite-muscovite assemblages formed early in the metamorphic history of the JRLT, while peak metamorphism produced transitional granulite facies assemblages at temperatures and pressures of 745-784 °C and 6.0-8.3 kbars, and resulted in the locally extensive development of
Table 6. Proposed sequence of geologic events for the GPT and the JRLT. The GPT and the JRLT have different geologic histories prior to juxtaposition and a shared history following juxtaposition.
anatetic migmatites. The JRLT shared the later plutonic history of the GPT, as indicated by the presence of the youngest granitoids near the zone and the corona-texture metagabbros throughout the JRLT. Pressures and temperatures calculated from the corona-texture metagabbros indicate that re-equilibration occurred in the JRLT at the roughly the same conditions as the peak conditions of the GPT.

Therefore, the relative timing of juxtaposition of the two terranes can be narrowed to prior to or during the injection of the youngest granitoids and the corona texture metagabbros, which are present in both terranes (Table 6). Furthermore, since there is no evidence for high-grade metamorphism after Archean time in southwestern Montana (Giletti, 1966, 1971; James and Hedge, 1980), the presence of the unique, high-grade, corona-texture metagabbros in both terranes indicates that amalgamation occurred during Archean orogenesis.

The preservation of relict, unstable, high temperature phases in the paragneisses of the JRLT and in the corona texture metagabbros suggests that a pulse of rapid uplift of the amalgamated terranes may have occurred during or shortly after juxtaposition. Rapid uplift may have been facilitated in part by the presence of anatetic melts in the JRLT and by the injection of mafic and granitic magmas, resulting in accelerated deformation along melt-lubricated shear planes, in a style similar to that described from the Coast Plutonic and Metamorphic Complex of northern British Columbia (Hollister and Crawford, 1986). The formation of retrogressive symplectite textures in granulites near the shear zone and retrogressive assemblages within the shear zone indicate that uplift continued through progressively cooler conditions,
possibly accompanied and facilitated by the continued injection of granite.

The Archean tectonic evolution of the Spanish Peaks area bears many striking similarities to Phanerozoic Cordilleran-style tectonic processes. First, pressures and temperatures of metamorphism for the Spanish Peaks area indicate a metamorphic gradient of 25-35 C/km, which is roughly equivalent to that reported from high-grade terranes of southeast Alaska and northern British Columbia (Hollister and Crawford, 1982). Second, the structural style suggests that these rocks were transported to mid-crustal levels by tectonic thickening through stacking of nappes. Finally, the compositional range of the granitoids from early hornblende monzodiorite and tonalite to younger trondhjemite and granite, the generally concordant style of intrusion, and the formation of melt-lubricated shears are nearly identical to descriptions of the Coast Plutonic and Metamorphic Complex of northern British Columbia, (Barker and others, 1981; Crawford and Hollister, 1982; Hollister and Crawford, 1986). These similarities indicate that the present configuration of Archean exposures of the Spanish Peaks area is the result of Cordilleran-style collisional processes involving the amalgamation of terranes with divergent geologic histories.

Discussion

Accretionary, or microplate tectonics is an important mechanism in the Phanerozoic growth of the North American continent (e.g. Coney and others, 1980; Iverson and Smithson, 1982; Jones and others, 1983). This mechanism has also been successfully applied in modelling early
and middle Proterozoic growth of North America (Karlstrom and Houston, 1984). However, while it has been suggested that Phanerozoic plate tectonic processes were operating in the Archean (Dewey and Windley, 1981), and that the Archean continents may have been stabilized through microplate accretion (Dickenson, 1981; Condie, 1982), few studies are available which adequately document the occurrence of Archean accretionary processes.

The results of this study form part of an emerging pattern in the Archean basement of southwestern Montana, in which discrete crustal blocks with widely differing geologic histories are juxtaposed along known or postulated Precambrian structural discontinuities in the Beartooth Mountains (Mogk, 1981, 1982; Thurston, 1986), and in the southern Madison Range (Erslev, 1983). Use of the word "terranes", which is defined by Jones and others (1983) as

"fault-bound entities of regional extent, each characterized by a geologic history that is different from the histories of contiguous terranes."

is particularly applicable in the Spanish Peaks for the GPT and the JRLT, where 1) the two terranes represent much different supracrustal settings, 2) the GPT records an early plutonic history not shared by the JRLT, and 3) the two terranes record different metamorphic histories (Table 6). Furthermore, Mueller and others (1985) have documented distinct geochemical and isotopic differences between metasupracrustal suites of the Beartooth region and suggest that they may be genetically unrelated terranes. Therefore, application of the terrane concept to the Archean basement of southwestern Montana
suggests that previous models which invoke a single depositional basin proximal to a stabilized continental source (Spencer and Kozak, 1975; Garihan, 1979; Vitaliano and others, 1979) may not be sufficient to explain the lithologic, metamorphic, and plutonic diversities which occur in the Archean basement of southwestern Montana.

Instead, the demonstrated tectonic juxtaposition of terranes with different geologic histories in the Spanish Peaks and other ranges of southwestern Montana strongly suggests that growth of the Archean craton of the northern Wyoming Province occurred through the horizontal accretion of discrete crustal blocks, which may be genetically unrelated, during a Cordilleran-style collisional event in the late Archean. This premise is supported by the close similarities in metamorphic, structural, and plutonic styles of the Spanish Peaks area to the Coast Plutonic and Metamorphic Complex of northern British Columbia, which is a major "tectonic welt" resulting from the Phanerozoic accretion of allochthonous terranes to the western margin of North America (Monger and others, 1982). Therefore, future studies should regard the various Archean lithotectonic suites of southwestern Montana as "suspect terranes" (Coney and others, 1980) until their genetic correlations can be demonstrated by detailed field, structural, petrologic, geochemical, and geochronological studies.
REFERENCES CITED


Storre, B., and Karotke, E., 1972, Experimental data on melting reactions of muscovite + quartz in the system K₂O-Al₂O₃-SiO₂-H₂O to 20 kb pressure: Contributions to Mineralogy and Petrology, v. 36, p. 343-345.


LEGEND

A Ig — Leucogneiss, granodioritic composition. Intercalated mafic and quartzite layers. Extensive migmatization.
Amg — Mafic gneiss and schist. Intercalated cpx-gt granulite.
Ams — Sillimanite-metapelite, quartzite.
DSZ — Ductile shear zone. Semi-continuous cm- to m-scale mylonite bands.
Atg — Grey para (?) gneiss, tonalitic composition. Local development of stromatic migmatite.
Ata — Trondhjemite-amphibolite injective migmatite.
Amk — Heterogeneous metasupracrustal suite. Tonalitic paragneiss, kyanite-metapelile, quartzite.
Aum — Ultramafite.
Ag — Granite.
Apgl — Porphyritic granodiorite.
Abt — Biotite tonalite granitoid gneiss.
Ahg — Hornblende gneiss: includes hornblende monzodiorite and hornblende tonalite gneisses.

Amphibolitized intrusions and boudins.
Corona-texture metagabbro intrusions and boudins.
Inferred Laramide fault.
Strike and dip of foliation.