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**LOW-PRESSURE HIGH-TEMPERATURE METAMORPHIC
RELATIONSHIPS BETWEEN THE ANIALIK RIVER VOLCANIC BELT
AND THE KANGGUYAK GNEISS BELT, NORTHWESTERN SLAVE
PROVINCE**

by

Annick Chouinard, B.Sc.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Science

Department of Earth Sciences
Carleton University
Ottawa-Carleton Geoscience Centre
Ottawa, Ontario
March, 1995

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**Low-pressure high-temperature metamorphic relationships between the
Anialik River volcanic belt
and the Kangguyak gneiss belt, northwestern Slave Province**

submitted by
Annick Chouinard, B.Sc.
in partial fulfilment of the requirements
for the degree of Master of Science

Chairman,
Department of Earth Sciences

Thesis Supervisor

Carleton University
March, 1995

Abstract

This study focuses on two low-pressure high-temperature belts located in the northwestern Slave Province: the *ca.* 3.0 Ga Kangguyak gneiss belt on the west side of the map area and the *ca.* 2668 Ma Anialik River volcanic belt on the east. The two belts are separated by an Archean tectonic boundary named the Tokhokatak fault.

Hornblende-in and actinolite-out isograds occurring along the margins of the volcanic belt were mapped. These separate three mineral zones, an actinolite, actinolite + hornblende and hornblende zone. Evidence for two distinct metamorphic events have been found. The older metamorphic event, occurred west of the volcanic belt at *ca.* 2656 Ma, is syn-to post-D₃ with temperatures ranging from 664°C to 714°C. Based on the width of the actinolite + hornblende zone, the isograds are thought to be shallow in the western part. The youngest metamorphic imprint occurs along the eastern boundary of the belt, is post-D₃ (*ca.* 2613 Ma) and has a temperature range from 573°C to 692°C. In addition, the two isograds occur within 50 meters, parallel to the steep contact between rocks of the volcanic belt and late Archean granites. Therefore, the isograds are thought to be steep in the eastern part. Qualitative barometry in the volcanic belt, based on classification of amphiboles and using petrogenetic grids, indicated pressures below 4 kb and as low as 2.3 kb.

Mineral assemblages and equilibria in the Kangguyak gneiss belt are similar to those of the volcanic belt. Porphyroblast growth associated with peak metamorphism is post-D₃. Samples analysed for thermobarometry indicate temperatures averaging 700° and pressures between 3.5 and 4.7 kb.

Rotated garnets found east of the Tokhokatak fault are possibly related to the fault. If so, kinematics of these rotated garnets indicate a sinistral shear sense with an oblique component, which would place the gneiss belt in a thrust contact with the volcanic belt. This is compatible with the NNE-SSW trending F₃ folds, and with the geochemistry data of both belts.

Data in the eastern part of the map area are compatible with metamorphism caused by the emplacement of late Archean granites. The high temperature values in the western part of the map area, along with geochronology and timing of metamorphism, suggest that the metamorphism is associated with the juxtaposition of the two terranes with the isotherms rising after the peak of deformation. Furthermore, most of the samples do not show reequilibration, suggesting rapid uplift rates.

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List of Symbols

R	universal gas constant
T	temperature, either Kelvin or Celsius as indicated
P	pressure
K	equilibrium constant
K_D	distribution coefficient
n	moles of substance
X	mole fraction

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CHAPTER I

INTRODUCTION

The Anialik River volcanic belt and the Kangguyak gneiss belt are located in the Hepburn Island map area (NTS 76M, see fig. 2.1). The present study was a contribution to a three year mapping project by the Canada-Northwest Territories Mineral Initiatives Office (Yellowknife), with additional financial support by the Geological Survey of Canada's Slave Province NATMAP Project. The project was headed by Carolyn Relf of the Government of Northwest Territories and the reader can find additional geological descriptions of the Anialik River volcanic belt and the Kangguyak gneiss belt in Relf (1992;1994), Relf *et al.* (1994a) and Chouinard and Relf (1994).

The study area covers over two thousand km², and this thesis combines regional mapping with petrographic studies and geothermobarometry in order to define the overall metamorphic history of the area.

The objectives of this study are fourfold:

a) to determine the metamorphic history of the Anialik River volcanic belt and the Kangguyak gneiss belt, using detailed petrographic observations, mineral equilibria and geothermobarometric data ;

b) to determine the timing of metamorphism relative to deformation within and between the two belts;

c) to place constraints on the Archean movement along the tectonic boundary that separates the two belts, the Tokhokatak fault, using rotated porphyroblasts;

d) to consider the tectonic significance of the study area in light of current models on the evolution of the Slave Province.

CHAPTER II

REGIONAL GEOLOGY

The Slave Province (fig. 2.1) formed over a period of more than a billion years and comprises several granite-greenstone and granite-gneiss terranes (Card and King, 1992). This chapter is a brief introduction to its evolution and presents the main lithotectonic subdivisions, a short description of metamorphic conditions, and an overview of the tectonic models that have been proposed for the evolution of the Slave Province.

Lithotectonic Subdivisions

Supracrustal rocks of the Slave Province have been subdivided into three major sequences, informally named the pre-, syn- and post-Yellowknife Supergroup sequences. The Yellowknife Supergroup comprised originally all the Archean supracrustal rocks of the Slave Province (Henderson, 1970), but has recently been informally narrowed to include only *ca.* 2.7-2.65 Ga volcanic rocks and related turbidites (Hrabi *et al.*, 1993). Intrusive rocks associated with these sequences are pre-Yellowknife Supergroup granitoids and gneisses, syn-Yellowknife Supergroup gabbro to tonalitic rocks and post-Yellowknife Supergroup tonalitic and granitic rocks. The three lithotectonic subdivisions and their regional distribution are summarized below.

• Pre-Yellowknife Supergroup rocks

Pre-Yellowknife Supergroup rocks, discontinuously exposed throughout the western and central parts of the Slave Province (Easton, 1985), include gneisses, intrusive rocks and

Figure 2.1. Geology of the Slave Province, modified from Fyson and Padham (1992). The study area is defined by the rectangle in the northwestern Slave Province; the numbers correspond to some pre-Yellowknife Supergroup occurrences. 1- Dwyer group; 2- Sleepy Dragon complex; 3- Benish Lake; 4- Acasta gneiss; 5- Point Lake; 6- Napaktulik area; 7- Kangguyak gneiss belt.

>2.9 Ga metasedimentary rocks. Kusky (1989) designated these rocks as part of the Anton Terrane, a term now broadly used for basement aged (> 2.9 Ga) rocks in the western Slave Province. Gneisses range in age from the *ca.* 3.96 Acasta gneisses (fig. 2.1; Bowring *et al.*, 1989), the oldest dated rocks in the world, to *ca.* 2.8 Ga (Card and King, 1992). Numerous dated Pre-Yellowknife Supergroup occurrences are presently documented (fig. 2.1); of these, the area around Point Lake-Ichen Lake has been well studied (Easton, 1985; King and Helmstaedt, 1989 and Kusky, 1991). This area (approximately 600 km²) is underlain by a variety of orthogneisses, migmatites, and granodiorites. The Kangguyak gneiss belt in the northwestern Slave Province may be part of the Anton terrane, as it has *ca.* 3.1 Ga detrital zircons (Relf *et al.*, 1994).

• Syn-Yellowknife Supergroup rocks

The second lithotectonic subdivision contains *ca.* 2.7-2.65 Ga Archean rocks consisting mainly of Yellowknife Supergroup rocks and syn-volcanic plutons that form the main granite-greenstone belts of the Slave Province (Card and King, 1992). Volcanic sequences have been divided into two types on the basis of mafic/felsic rock ratios (Padgham (1985): 1) the Yellowknife-type characterized by bimodal volcanism, and 2) the Hackett River-type dominated by felsic volcanism. Yellowknife-type volcanic belts are more abundant in the western and southern parts of the Slave Province whereas Hackett River-type volcanic belts occur throughout the province, but are most common in the northeastern part.

Sedimentary rocks associated with the Yellowknife Supergroup are dominated by turbidites. In the central Slave Province detrital zircons in turbidites have been dated at *ca.* 2.66 Ga (King *et al.*, 1992). Other sedimentary rocks associated with the Yellowknife Supergroup are minor carbonates and iron formations.

Syn-Yellowknife Supergroup plutonic rocks are spatially associated with volcanic belts. They range in age from *ca.* 2.7 Ga (the Aniak River Igneous Complex; Abraham *et al.*, 1994) to *ca.* 2.65 Ga (van Breemen *et al.*, 1992).

- Post-Yellowknife Supergroup rocks

The third lithotectonic subdivision includes post-Yellowknife Supergroup (< 2.6 Ga) conglomerates and quartz arenites that unconformably overlie many of the volcanic belts across the province, and late Archean plutons ranging from *ca.* 2.62 Ga metaluminous tonalites to *ca.* 2.58 Ga peraluminous granites (King *et al.*, 1992; van Breemen *et al.*, 1992).

- Distribution of lithotectonic units

Rocks of the pre-Yellowknife Supergroup are restricted to the western part of the Slave Province (Fig. 2.1). Late Archean conglomerates also appear to be restricted to the west of the province, with one exception (the James Falls conglomerate in the Hood River belt; Jefferson *et al.*, 1990).

Where basement/cover contacts are exposed in the Slave Province, they are characterized by mylonite zones, strongly schistose rocks and locally, straight gneisses. Based on Nd isotopic data, Davis and Hegner (1992) suggested that > 2.8 Ga rocks underlie the western part of the Slave Province but that young intrusive rocks in the eastern part of the province were formed from a juvenile source. Lead isotopic data obtained by Thorpe *et al.* (1992) are compatible with this idea. Thorpe *et al.* (1992) defined a boundary dividing the Slave

Province into a zone of high $^{206}/^{204}\text{Pb}$ in the west, and a zone of low $^{206}/^{204}\text{Pb}$ to the east; this isotopic boundary corresponds approximately to the division of Davis and Hegner (1992).

Metamorphism

The Slave Province is characterized by low-pressure- high-temperature metamorphism that occurred at *ca.* 2.6 Ga (Thompson, 1978). Turbidites throughout most of the Slave province record a prograde andalusite-sillimanite transition, implying pressures below the aluminosilicate triple point (*ca.* 4 Kb; Holdaway, 1971). Kyanite has been found as local relics in sillimanite-cordierite schist in the Hackett River area (Frith, 1987). In the Contwoyto Lake, in the central Slave Province, timing of metamorphism has been constrained with respect to plutonism and is bracketed between *ca.* 2610 Ma and *ca.* 2600 Ma (Relf and King, 1989). The metamorphic history of the Slave Province is intimately related to its tectonic evolution and will be considered in a further section.

Three hypotheses have been proposed to explain this particular thermobarometric condition; 1) crustal extension and thinning caused isotherms to rise in the crust, producing high temperature conditions at shallow structural levels (Thompson, 1978); 2) late Archean plutonism associated with crustal thickening, heating and melting, caused regional contact metamorphism (Relf and King, 1989) and; 3) crustal thickening caused delamination of the lithosphere, with underplating of the hot asthenosphere against the crust (Davis, 1991).

Tectonic Evolution

Two tectonic models have been proposed for the development of the Slave Province: 1) an intracratonic rifting model as supported by Henderson (1981), Easton (1985) and Thompson (1989) and; 2) a collision-accretion model. The latter can be divided into two subtypes: a) a collision between an island arc and a microcontinent (Hoffman, 1986; Kusky, 1989, 1991); and b) collision of two previously-rifted continental blocks, followed by underplating and Andean-type magmatism (Fyson and Helmstaedt, 1988). Each of these models are described briefly below.

- **Intracratonic model**

Henderson (1981) and Easton (1985) interpreted the Slave supracrustal basins as representing sites of grabens or half-grabens formed by ensialic rifting. Thus the volcanic belts outline margins of former basins which are underlain by sialic crust; turbidites that fill the basins were derived from the adjacent uplifted basement blocks. This model accounts for the formation of aligned volcanic belts bounding supracrustal basins, and explains the two types of volcanism (calc-alkaline and tholeiitic). Furthermore, rifting would have caused crustal thinning resulting in low-pressure regional metamorphism across the province at *ca.* 2600 Ma (Thompson, 1978).

However, some problems are related to this model, such as: 1) the rifting model requires that basement underlies all basins, but basement in the Slave Province appears to be restricted to the west (see above); 2) according to this model metamorphism occurred about 100 Ma after extension, which is an unrealistic duration for a thermal anomaly (Loosveld

and Etheridge (1990); and 3) the Slave Province lacks the typical alkaline volcanic rocks, alluvian-fan deposits and evaporites typical of a continental rift environment.

• Collision-accretion model

The Slave Province has some similarities with modern environments that suggest a collision-accretion model. Among them, the Hackett River-type calc-alkaline volcanic belts are lithologically and chemically similar to modern island arcs (Folinsbee *et al.*, 1968; Hoffman, 1986; Fyson and Helmsteadt, 1988; Kusky, 1989; 1991). The base of the Yellowknife belt has been compared to an ophiolite (Helmsteadt *et al.* 1986). Turbidites of the Slave Province are similar to accretionary prism sediments in modern settings (Hoffman, 1986). In addition, most of the contacts between basement-aged rocks and cover are sheared (Kusky, 1989) and finally, late Archean plutons (*ca.* 2.62 Ga) are similar to modern arc-type plutonic complexes (King *et al.*, 1992). These characteristics have led to several accretion-collision models for the Slave Province. The models are subdivided below into two types.

• Island arc-continent collision model

Kusky (1989) subdivided the Slave Province into four terranes, shown on figure 2.2. The Anton terrane includes the part of the western Slave Province that is underlain by >2.8 Ga gneisses. Kusky (1989) suggested that the Anton terrane represents an ancient microcontinent. The Sleepy Dragon terrane corresponds to the Sleepy Dragon Complex which is a basement-cored structural culmination. Based on structural features and similarities between lithologies and ages, Kusky (1989) suggested that the Sleepy Dragon Complex represents a basement nappe which was transported westward during the main

orogenic event. The Contwoyto terrane is similar in structure and lithology to forearc accretionary complexes (Hoffman, 1986; Kusky, 1989; King *et al.*, 1990). Kusky (1989) reported west-verging folds and thrusts in the Contwoyto terrane compatible with east-dipping subduction. Finally, the Hackett River arc terrane is interpreted as an island arc which formed above an east-dipping subduction zone at *ca.* 2.7-2.67 Ga.

- Andean-type collision model

Fyson and Helmstaedt (1988) proposed a different collisional model for the tectonic evolution of the Slave Province. Based on similarities between Yellowknife-type volcanic belts and oceanic crust, Fyson and Helmstaedt (1988) suggested that collision followed a period of crustal extension. Like Kusky's model, they proposed east-directed subduction during accretion, based on westerly vergence of structures in supracrustal domains. Following closure of the basin, shallow subduction shifted westward, causing the entire province to be underplated and intruded by Andean-type calc-alkaline plutons.

Figure 2.2. Location of terranes proposed by Kusky (1989); the Anton terrane, the Sleepy Dragon complex, the Contwoyto terrane, the Hackett River arc. AR: Anialik River; BeL: Beechy Lake; YK: Yellowknife; PT: Point Lake.

Summary

The Slave Province is a complex greenstone-granite terrane. It has many similarities to modern collision environments and may be a collage of island arc remnants, accretionary prisms, ocean crust, and older continental crust. The entire province is extensively intruded by syn- and post-collision granitoids. However, the Slave Province lacks some of the features of modern collision zones, such as high pressure metamorphism, a diachroneity in metamorphism or plutonism and structural evidence for regional structural vergence. No currently existing model fully answers these questions.

Recent work by Davis and Hegner (1992) clarified an important part of the debate by suggesting, based on Nd isotopic compositions of late Archean granites, that basement-aged rocks are restricted to the western part of the Slave Province. Further studies are underway in the northern Slave Province to trace this isotopic boundary northward (A. Davis, in progress).

CHAPTER III

LOCAL GEOLOGY

The map area in the northwestern Slave Province, is underlain by two belts (see fig. 3.1) distinguished by different lithologies and ages (Relf *et al.*, 1994). The eastern belt which underlies most of the map area is the Anialik River volcanic belt, dominated by *ca.* 2.68 Ga mafic to felsic calc-alkaline rocks. The western belt is the Kangguyak gneiss belt, made up of mixed ortho- and paragneisses that are at least in part older than the volcanic belt. Both belts are intruded by late Archean plutons. The Anialik River volcanic belt is approximately 30 km wide and 60 km long and is bordered on the west side by the Kangguyak gneiss belt. The area underlain by the gneiss belt has not been completely described in the present study as the western boundary of the belt is outside the map area. Recent mapping in the Hephurn Island area as part of the present study revealed a major fault, the Tokhokatak fault, separating the two belts. The fault appears to have a complex displacement spanning the late Archean to early Proterozoic. The Archean movement is characterized by a ductile deformation whereas the Proterozoic movement was brittle to ductile. The Archean sense of fault displacement is ambiguous and is discussed in chapter 5.

Previous Work

The area was first mapped by Fraser (1964) during a reconnaissance study at a ~1:500 000 scale. Between 1964 and 1991 several geological investigations were conducted by governments and mining companies. Among them, Tirrul and Bell (1980) as well as Yeo *et al.* (1983) mapped the Anialik River volcanic belt at 1:50 000. The mapping by Yeo *et al.* (1983) included part of the present Kangguyak gneiss belt. The geology of the Hephurn

Figure 3.1. Simplified geology of the Aniak River volcanic belt and the eastern part of the Kanguyak gneiss belt, modified from Relf (1993,1994). Abbreviations are: sc-String Lake conglomerate; kc-Kaycee conglomerate; JL-Joy Lake ML-Mistake Lake; RL-Rhino Lake; TL-Turtle Lake.

Island area has been compiled at a 1:125 000 scale by Jackson (1989) summarizing previous work mentioned above .

Rocks of the Anialik River volcanic belt

Table 3.1 shows stratigraphic relations in the Anialik River volcanic and the Kangguyak gneiss belts (Relf 1992; 1994a). Expanded descriptions are included in the text where applicable to this study. For detailed description of each map unit, the reader is referred to Relf (1992; 1994a) for the Anialik River volcanic belt and Relf *et al.* (1994) for the Kangguyak gneiss belt.

The Anialik River volcanic belt consists mainly of Archean felsic to mafic volcanic rocks and their intrusive equivalents (fig. 3.1). Other units include volcanoclastic, metasedimentary rocks as well as minor metacarbonates and iron formations. Archean conglomerates, part of the post-Yellowknife Supergroup lithotectonic unit, are also present.

Syn-volcanic intrusive rocks that cut the volcanic belt include gabbro dykes, sills and small plutons, and the large, composite quartz-diorite to granodiorite intrusive complex (the Anialik River Igneous Complex) at the north end of the belt. Numerous post-volcanic plutons surround and intrude the belt as well, and they range in composition from *ca.* 2613 Ma tonalite (Villeneuve and van Breemen, 1994) to *ca.* 2601 Ma monzogranite (Abraham *et al.*, 1994). Syn-to-post volcanic plutonic rocks range in composition from gabbro to tonalite. Sedimentary and intrusive Proterozoic rocks also occur in the area and have been described by Relf (1994a; see table 3.1).

	Kangguyak gneiss belt	Anialik River volcanic belt
Proterozoic	<p><u>Sedimentary rocks</u>: ca. 1077 Ma⁸ argilites and sandstones belonging to the mid-Proterozoic Rae Group</p> <p><u>Intrusive rocks</u>: 1) ca. 1267 Ma⁶ Mackenzie diabase dykes; 2) ca. 723 Ma⁷ Franklin gabbro sills and 3) syenite dykes of probable Proterozoic age.</p>	
		<p><u>Conglomerate</u> (< 2600 Ma¹) with granitoid, volcanic and sedimentary clasts.</p> <p><u>Post-tectonic granite</u>: ca. 2601 Ma² Leucocratic plutons ranging in composition from syenogranite to granodiorite</p> <p><u>Syn-tectonic granitoids</u>: ca. 2613 Ma³, range in composition from biotite tonalite to monzogranite</p> <p><u>Metasedimentary rocks</u>: psammites, semipelites, marbles, calc-silicates, chert and iron formations.</p> <p><u>Volcanic rocks</u> ca. 2678-2689 Ma^{4, 3}. Mafic, intermediate and felsic volcanic rocks (see text).</p> <p><u>Syn-volcanic igneous complex</u> (Anialik River Igneous Complex) ca. 2682-2703 Ma², range in composition from hornblende diorite to biotite monzogranite. Many phases of intrusion event?</p>
Archean	<p><u>Intrusive rocks and veins</u> of various generations, with cross-cutting relationships, are found throughout the belt and intrude the gneisses</p> <p><u>Tonalitic gneiss</u> with biotite ± hornblende (tonalite orthogneiss of McEachern, 1993),</p> <p><u>Granitic gneiss</u> with biotite ± hornblende ± muscovite, its origin is unknown,</p> <p><u>Mafic gneiss</u> is a hornblende amphibolite ± garnet. It may have a supracrustal origin</p> <p>All three are not presently dated</p> <p><u>Paragneiss</u></p> <p><u>Conglomerate</u> (<2880 Ma⁵): containing pebbles of granite, quartzite and amphibolite.</p> <p><u>Quartzite</u> (<3130 Ma⁵): up to 10m wide, layered</p>	

Table 3.1. Main rock types in the Anialik River volcanic belt and the Kangguyak gneiss belt (Relf 1992; 1994a). 1- Villeneuve *et al.*, 1993, 2- Abraham *et al.*, 1994; 3- M. Villeneuve, unpublished data; 4- Abraham, 1990; 5- Relf *et al.*, 1994; 6- LeCheminant and Heaman, 1989, 7- Heaman *et al.*, 1992 ; 8- Rambird and Jefferson, 1993.

- Felsic and felsic to intermediate volcanic rocks

Felsic to intermediate volcanic rocks are the predominant rock type in the northern part of the belt. They consist of massive rhyolite flows (locally plagioclase $\pm$ quartz porphyritic) finely-bedded tuffs and volcanoclastic rocks. Rocks shown on fig. 3.1 as intermediate to felsic volcanic rocks are commonly volcanoclastic with felsic fragments in a chloritic matrix. This unit also contains minor thin mafic flows and gabbro sills and dykes.

- Mafic volcanic rocks

Mafic volcanic rocks dominate the southern part of the belt (see fig. 3.1). Massive and pillowed mafic flows are predominant and may include quartz $\pm$ plagioclase-filled amygdules. Pillows are up to two metres in diameter but as they are generally flattened, the younging direction is not always preserved. Further south where the belt narrows, mafic volcanic rocks become mostly chloritic schist and appear as thin and discontinuous layers. Mafic volcanic rocks elsewhere in the belt are generally very fine grained, equigranular or locally plagioclase porphyritic, with a variable degree of chloritisation of the matrix. Although most mafic volcanic rocks are thought to be flows, some are thinly layered, from 0.5 to 2 cm, and are interpreted to be either mafic tuffs or sediments derived from mafic flows.

Dykes and sills ranging in composition from hornblende and/or actinolite gabbro to lesser quartz diorite have been included in the mafic volcanic map unit as they occur in lenses within it and in places have diffuse boundaries with flows. Furthermore, they locally appear to feed the mafic flows. Based on these observations, they are interpreted to be syn-volcanic (Relf, 1992).

Major element and geochemical data were obtained by Relf (1994a), Yeo *et al.* (unpublished data) and Barrie (unpublished data), and were evaluated by Relf (1994a). Based on the Irvine and Baragar (1971) classification using $\text{Na}_2\text{O}+\text{K}_2\text{O}$ vs SiO_2 and $\text{Na}_2\text{O}+\text{K}_2\text{O}$, FeO and MgO discriminations, the mafic volcanic rocks are subalkaline and span the calc-alkaline and tholeiitic fields. The tectonic classification of the rocks on the basis of $\text{MnO}-\text{P}_2\text{O}_5-\text{TiO}_2$ (Mullen, 1983) shows that volcanic rocks of the Anialik River belt have compositions similar to modern island arc type volcanic rocks. Relf (1994a) suggested that at least part of the belt may represent a continental arc based on 1) the abundance of rhyolite and rhyodacite at the north end of the belt and, 2) the presence of a large intrusive complex (Anialik River igneous complex, see fig. 3.1) of calc-alkaline composition occupying the core of the belt.

• Metasedimentary rocks

Metasedimentary rocks are largely low-Al semi pelites and psammites. Rock types within the sedimentary unit range in composition from biotite-quartz schist $\pm$ feldspar $\pm$ hornblende to biotite-garnet schist. Andalusite was found only in one locality in the study area and muscovite is rare. The thickest package of sedimentary rocks occurs along the eastern edge of the Anialik River volcanic belt, where it can be traced along strike for 12 km (Relf, 1992). These sediments have a minimum thickness of 200 m and give way to mafic volcanic rocks on the west and are intruded to the east by granitic rocks. This sedimentary package is too thin to appear on figure 3.1 due to the scale of the map. Relf (1992) mentioned the presence of a scoured bed top showing younging toward the east, suggesting that the sediments stratigraphically, as well as structurally, overlie the volcanic belt. In the rest of the belt, sedimentary rocks are of the same composition and modal

distribution but they appear as discontinuous and thin layers within the volcanic rocks, often too thin to map at a scale of a 1:50 000 . Minor carbonate (calcite $\pm$ dolomite $\pm$ phlogopite), calc-silicate (calcite, quartz $\pm$ diopside $\pm$ garnet $\pm$ phlogopite) and iron formation (quartz, grunerite, hornblende and magnetite) are found throughout the volcanic belt. The abundance of iron formations increases further south where the belt narrows.

Conglomerates in the volcanic belt occur as thin lenses, and contain volcanic, sedimentary and granitoid clasts. Zircons from a granitoid boulder from the String Lake conglomerate (fig. 3.1) yielded an age of ca. 2600 Ma (Villeneuve *et al.*, 1993) which means that the conglomerate is younger than 2600 Ma. Although no angular discordance is preserved between the volcanic rocks and the conglomerate, the time gap between the deposition of the volcanic rocks of the Anialik River volcanic belt and the conglomerate indicates that the latter sits unconformably above the volcanic belt.

Rocks of the Kangguyak gneiss belt

The Kangguyak gneiss belt consists of mixed ortho- and paragneisses that are in faulted contact with the west side of the Anialik River volcanic belt. Based on the differences in ages of rocks of the two belts (see Table 3.1), their different structural histories, and the faulted nature of the contact, Relf *et al.* (1994) suggested that the two belts may represent separate terranes.

The northern part of the gneiss belt includes paragneisses as well as tonalitic, granitic, and mafic gneisses. Gneisses are intruded by 2 sets of intrusive rocks (Relf, 1994a). The earlier intrusive suite transects gneissosity and includes variably foliated hornblende gabbro to tonalite. The younger intrusive suite ranges from monzogranite to granodiorite, and is

generally massive to moderately foliated. Further south, granitic and tonalitic gneisses dominate the belt with only minor paragneisses. The proportion of granitoid intrusions increases southward, so that locally in the southern part of the belt, the gneiss terrane is dominated by granitoid rocks with rafts of gneiss.

- Paragneiss

Paragneisses occur throughout the Kangguyak gneiss belt. The most voluminous type of paragneiss is a biotite $\pm$ garnet rich schist, with irregular lenses of coarse-grained to pegmatitic granite. In addition, two thinly-bedded quartzite lenses up to ten metres wide, and a polymictic meta-conglomerate containing granite, quartzite and amphibolite pebbles have been found in the north part of the belt. U-Pb geochronology studies of detrital zircons in these units have yielded ages ranging from *ca.* 3.27 to 3.13 Ga (Villeneuve *et al.*, 1993) for the quartzite and *ca.* 3.03 to 2.88 Ga for the conglomerate (Villeneuve and van Breemen, 1994). Metamorphic hornblende in the matrix of the conglomerate yielded a $^{40}\text{Ar}/^{40}\text{Ar}$ age, thought to be metamorphic, of 2644 ± 7.4 Ma (H. Sandeman, personal communication, 1994). Finally, a cross-cutting pegmatite dyke yielded two U/Pb titanite ages of *ca.* 2610 Ma and 2650 Ma (Villeneuve and van Breemen, 1994). These are interpreted as minimum and maximum ages for the dyke, and they put a lower limit on the age of the gneisses.

Based on the part of gneiss belt mapped in this study, it appears that the proportion of paragneisses is at least three times greater than that of sedimentary rocks in the Anialik River volcanic belt. This feature is consistent with an independent origin for the two belts prior to their juxtaposition.

- Other gneisses

Other gneisses consist of biotite $\pm$ hornblende $\pm$ muscovite granitic gneiss, biotite $\pm$ hornblende tonalitic gneiss, and hornblende mafic gneiss. Granitic gneiss are found everywhere throughout the belt. However, their origin and contact relationships are not well defined. Tonalitic and mafic gneisses also have an uncertain origin although the abundance of hornblende in the matrix of the conglomerate suggests that these mafic rocks were exposed during the sedimentation of the latter.

Regional structural geology

Structural analysis of the area has been carried out by Relf (1992,1994a) and Relf *et al.* (1994). Detailed mapping by Relf and co-workers (1993;1994b) identified five phases of structures in the Anialik River volcanic belt and the Kangguyak gneiss belt (fig. 3.2). Early structural elements (pre- D₃) in the Kangguyak gneiss belt are thought to be unrelated to the pre-D₃ structures of the Anialik River volcanic belt. D₃ structures are considered to coexist on both sides of the Tokhokatak fault, which separates the Anialik River volcanic belt from the Kangguyak gneiss belt (see fig. 3.2). This correlation is based on the parallelism of F₃ folds on each side of the fault. Both belts share a common D₄ and D₅ (Proterozoic) deformation (Relf *et al.* 1994).

- Archean deformation history

Anialik River volcanic belt

Three phases of Archean structures have been recognized in the Anialik River volcanic belt (Relf 1992; 1994a). An early and rare foliation (S₁) is defined by chlorite $\pm$ biotite and

Figure 3.2. Map summarizing the dominant structural elements and geochronological data of the map area. Detailed descriptions are in the text and abbreviations are the same as figure 3.1.

appears as microlithons between S_2 . It is overprinted by a penetrative, bedding-parallel foliation (S_2) with associated isoclinal (F_2) folds of the bedding. S_2 is defined by aligned chlorite and either actinolite or hornblende depending on metamorphic grade. NNE upright folds (F_3) and associated foliation (S_3) overprint S_2 , and form the kilometer scale antiform that exposes the Anialik River igneous complex in its core (see fig. 3.1 and 3.2).

This antiform was interpreted by Relf (1992) as a regional doubly-plunging fold since south of the Anialik River igneous complex, outcrop-scale F_3 folds plunge shallowly SSW whereas in the northern part of the belt they plunge NNE. Parallelism of S_2 and S_3 on the limbs of the antiform and local transposition of S_2 along S_3 makes these fabrics difficult to distinguish in many outcrops.

Kangguyak gneiss belt

Three phases of Archean structures have also been identified by Relf *et al.* (1994) in the Kangguyak gneiss belt. The oldest fabric in the area is an early gneissosity (S_1) defined by biotite $\pm$ hornblende-rich and quartzofeldspathic layers, overprinted by a southwest-dipping gneissosity (S_2) associated with folding of S_1 (F_2 folds). The S_2 gneissosity locally defines zones (5 to 10 meters wide) of straight gneiss transposing S_1 . The contact between these zones is gradational with gently to tightly folded gneisses of the same composition. The straight gneisses have been interpreted as recrystallised mylonites by McEachern (1993).

S_2 in the gneisses is folded into NE-striking F_3 folds parallel to F_3 folds in the Anialik River volcanic belt. These folds plunge dominantly towards the SW, and increase in intensity towards the Tokhokatak fault along the east side of the gneiss belt. Near the fault,

F₃ limbs are locally sheared off along shear surfaces parallel to both S₃ and the Tokhokatak fault (Relf *et al.*, 1994). Based on the parallelism of D₃ structure sets in the Anialik River volcanic belt and the Kangguyak gneiss belt, D₃ fabrics are thought to be correlative across the entire map area. In contrast, as early (pre-D₃) Archean fabrics in the two belts have different orientations, they are thought to have formed independently (Relf *et al.*, 1994).

Tokhokatak fault

The S₃ gneissosity within the Kangguyak gneiss belt contains a strong down-dip stretching lineation and increases in intensity eastward toward the Tokhokatak fault, thus defining a strain gradient (Relf *et al.*, 1994). In the northern part of the gneiss belt, S₃ becomes an intense, straight gneissosity (straight gneiss) within about 200 m or less of the gneiss-volcanic contact. Further south the Tokhokatak fault is narrower (as little as 10 m wide), and is characterized by refolded mylonites in a chlorite-rich matrix, with variably-plunging mineral lineations. Archean ductile fault fabrics are overprinted along the length of the fault by evidence of brittle-ductile Proterozoic reactivation. Chapter 5 focuses on the Archean movement history of the Tokhokatak fault, while fabrics associated with Proterozoic faulting are described below.

• Proterozoic deformation history

Proterozoic deformation in the map area consisted of two events; 1) an east-west shortening that produced east-dipping, west-vergent faults in the east part of the Anialik River volcanic belt, and oblique west-side-up reactivation of the Tokhokatak fault; and 2) an east-west shortening that produced conjugate NE trending-dextral and NW trending-sinistral transcurrent faults.

Kangguyak gneiss belt	Anialik River volcanic belt
Structural features and relative timing of deformation	
D5 NE, NW transcurent faults.	D5 NE, NW transcurent faults.
D4 oblique west-over-east reactivation of the Tokhokatak fault.	D4 oblique east-over-west faults. Ca. 2601 Ma: from the Chin Lake pluton, cuts D3.
D3 NNE upright folds, gneissosity, shearing along the Tokhokatak fault.	D3 NNE upright folds, cleavage. Ca. 2613 Ma: syn-D3 tonalite dyke (A4)
D2 SW-dipping gneissosity, folds.	D2 dominant bedding parallel cleavage, isoclinal folds.
D1 early gneissosity	D1 rare cleavage. Ca. 2678 Ma: crystallisation age on a qtz-fels porphyry

Table 3.2. Structural features and timing of deformation for the Anialik River volcanic belt and the Kangguyak gneiss belt (Relf, 1992; Relf *et al.*, 1994). 1- H.Sandeman (personnal communication, 1994). references to other ages can be found in table 3.1.

The former event was interpreted by Relf (1992) to be correlative to the Tree River deformation event (Hoffman *et al.*, 1984), and the latter to Early Proterozoic transcurrent faulting in the Wopmay Orogen (Hoffman, 1989).

- Timing of deformation

Many samples have been dated using the U-Pb system on zircons (Villeneuve and van Breemen, 1994). The relative timing of deformation events is shown in table 3.2. The geochronology studies provide a schematic chronological framework for the Anialik River volcanic belt even though no absolute ages were determined for specific fabric elements mentioned above. To date, there are no radiometric ages to bracket the timing of each deformation events in the Kangguyak gneiss belt.

Summary

The geology of the Anialik River volcanic belt is dominated by *ca.* 2.68 Ga calc-alkaline volcanic rocks with minor sediments, which are overlain in the northern part of the belt by young conglomerates. In contrast, the Kangguyak gneiss belt is dominated by mixed gneisses, some of which may be as old as *ca.* 3.0 Ga. The two belts are separated by an Archean tectonic boundary, the Tokhokatak fault.

While late Archean (D₃) and Proterozoic (D₄, D₅) deformation affected the entire map area, early fabrics in the belts have different characteristics, suggesting that they represent separate structural histories.

CHAPTER IV

THE METAMORPHISM OF THE ANIALIK RIVER VOLCANIC BELT

Introduction

This chapter describes the metamorphic history of the Anialik River volcanic belt which is characterized by low-pressure high-temperature metamorphism, like much of the Slave Province (Thompson, 1978). It includes a summary of the petrographic observations, geothermometric data and relative geobarometry that were used to constrain the relative timing relationships of metamorphism, deformation and plutonism.

Petrography and Petrology of Supracrustal Rocks

One hundred and fifty-three samples were collected and prepared as thin sections. Most of these (about 100) were collected to delineate the isograds (see fig. 3.1) and for hornblende-plagioclase thermometry. The rest are from sedimentary rocks that occur sparsely throughout the belt.

- **Bulk composition of metasedimentary rocks**

Metasedimentary rocks in the Anialik River volcanic belt include mafic volcanoclastic rocks, semi pelite and psammite. Semi pelites and psammites are generally garnet and biotite-rich, indicating high Fe/Fe+Mg ratios, but devoid of muscovite and aluminosilicate. The latter has been found at only one locality, northeast of the volcanic belt, as a retrograded porphyroblast almost totally altered to muscovite and chlorite (see below). The use of an

AFM diagram and petrogenetic grids are therefore limited by the bulk composition of the rocks as the metasedimentary rocks lack the major phases required by those ternary diagrams and grids.

- Petrography of metasedimentary rocks

Petrographic study of semi pelite and psammite showed a typical assemblage consisting of biotite, quartz, garnet, plagioclase, with traces of apatite, ilmenite and zircon. Chlorite is rarely part of the assemblage but occurs rather as an alteration of biotite or relict in garnet. This assemblage suggests a lithic sandstone protolith.

Garnet is abundant in metasedimentary rocks and commonly occurs as subhedral to euhedral porphyroblasts up to 1 cm in diameter. It generally contains quartz inclusions in the core, and rarely biotite and chlorite inclusions. Some garnets have inclusion-free rims while others are entirely poikiloblastic (see plate 4.1). Garnet porphyroblasts in the Anialik River volcanic belt are rarely or only weakly zoned (see chapter 5, fig. 5.3 for a compositional zoning profile of a garnet from the west side of the volcanic belt).

Biotite occurs either as elongated laths or subequant crystals and exhibits a red-brown pleochroism as well as frequent zircon inclusions which produce radiogenic halos. Crystals are up to 5 mm in length.

Chlorite is rarely in equilibrium with the assemblage. It is frequently found as a retrograde product, either replacing biotite or locally garnet porphyroblasts. It has been found as inclusions in garnet and locally as laths up to 2 mm.

Andalusite (sample 7142) was found in only one locality northeast of Mistake Lake (see fig. 3.1) with garnet, biotite, quartz and plagioclase. Porphyroblasts of andalusite are up to 6 mm with quartz inclusions. They are now almost totally retrograded to muscovite and chlorite (see plate 4.2). Andalusite is recognizable near the rim only through electron microprobe analysis. The porphyroblasts appear to have been in equilibrium with garnet and biotite (see plate 4.3).

• Petrology of metasedimentary rocks

Mineral reactions

Presence of chlorite inclusions within garnet suggests the following equilibrium during progressive metamorphism of sedimentary rocks:

Andalusite, garnet and biotite coexisting together in sample 7142 can provide a qualitative constraint on pressure for the rocks of the eastern volcanic belt using a petrogenetic grid. Several grids exist for pelitic rocks, such as in Carmichael *et al.* (1987), Spear (1993) and Powell and Holland (1990). Out of these, the grid of Carmichael *et al.* (1987) appears the most appropriate for this study, as the reaction curve:

allows the coexistence of andalusite and garnet for rocks containing biotite, quartz and plagioclase (see fig. 4.1).

The lower pressure limit is defined by the absence of the assemblage garnet, cordierite and muscovite, and the absence of Kfeldspar (see fig. 4.1) whereas the upper pressure is limited by the andalusite = sillimanite curve, as sillimanite does not occur in the area. Therefore, the pressure range for sample 7142 is between 2.3 and 3.6 Kb as indicated by shading on figure 4.1. In addition, the stability field of the assemblage is consistent with temperature obtained from thermometry in the area (573°C and 633°C; see further).

Finally, the textural relationships mentioned above suggest a retrograde reaction for andalusite (see plate 4.2):

• Petrography of mafic rocks

The typical mineral assemblage observed in thin sections of metabasites is actinolite and/or hornblende (40-60%), plagioclase (30-40%), quartz (0-10%), epidote (5%), $\pm$ chlorite, calcite, biotite, apatite, titanite and zircon. Hornblende and plagioclase occur as porphyroblasts. Chlorite, epidote, plagioclase and carbonate are the main minerals in the matrix. The mineral assemblage in metagabbroic rocks is similar to that in mafic volcanic rocks but has a higher proportion of plagioclase and generally less than 5% quartz; groundmass and alteration are similar in metagabbro and metabasalt. A table of mineral assemblages in mafic rocks used to establish the location of the isograds and amphibole-plagioclase thermometry is given in appendix A.

Figure 4.1. Petrogenetic grid for part of the modal system KNFMASH for pelitic schists and gneisses that contain biotite, quartz and plagioclase from Camichael *et al.* (1987). The stability field of garnet + andalusite is indicated by the shaded area and the upper and lower pressure limits by the dashed lines.

Greenschist facies mafic rocks contain the assemblage:

actinolite + plagioclase (An_{04}) + epidote (zoisite and clinozoisite) + chlorite $\pm$ calcite

Plagioclase in greenschist facies rocks near the first appearance of hornblende has an anorthite content averaging An_{04} (determined with the electron microprobe on 2 samples; AC93-6203 and 6448). At the hornblende isograd, plagioclase has anorthite contents of An_{04} and An_{20-32} within a single thin section (from microprobe analysis on sample AC93-6199). Epidote, sericite and calcite are the main alteration products of plagioclase.

Pale green actinolite occurs mainly as equant porphyroblasts up to 6 mm, or less commonly as radiating laths up to 4 mm in length, depending on its timing relative to deformation (see plate 4.4). Actinolite locally contains plagioclase and apatite inclusions. Where actinolite is altered, it is typically chloritized.

Amphibolite facies assemblages in mafic rocks of the volcanic belt include:

1) hornblende + actinolite + plagioclase (An_{40}) + quartz + epidote $\pm$ chlorite, calcite

2) hornblende + plagioclase (An_{40}) + quartz + epidote $\pm$ calcite

The assemblage (1) corresponds to the first appearance of hornblende in mafic rocks whereas the assemblage (2) occurs at higher grade, and corresponds to the disappearance of actinolite.

Hornblende appears as a prograde mineral that replaces actinolite. It occurs with different morphologies: as rims around actinolite porphyroblasts with a diffuse boundary between the two; as aggregates of small (less than 1 mm) euhedral crystals; as subhedral to euhedral porphyroblasts; and as elongated, subhedral laths up to 6 mm in length (see plate 4.4, 4.5 and 4.6). Hornblende crystals display dark green to blue-green pleochroism and locally include plagioclase and/or apatite crystals.

• Petrology of mafic rocks

Three mineral zones have been recorded in mafic rocks: an actinolite zone, an actinolite + hornblende zone and, a hornblende zone; these are separated by the hornblende-in and actinolite-out isograds (see fig. 3.1). In the Cape Smith belt, Bégin (1992) recorded an oligoclase isograd at higher temperature than the first appearance of hornblende and considered the oligoclase isograd as typical of medium pressure terranes. However, in the Anialik River volcanic belt oligoclase coexists with albite at the first appearance of hornblende, suggesting that the hornblende and oligoclase isograds occur at the same temperature (see above, under plagioclase).

Mineral reactions

The following section describes progressive reactions found in common mafic rocks. These reactions are based on both thin section observations and published equilibria. According to Laird and Albee (1981), the first appearance of actinolite is controlled by a reaction involving:

and by the bulk composition of the rock: in Fe-rich rocks, actinolite appears at lower temperatures than in Mg-rich rocks (Laird and Albee, 1981).

Plate 4.1. Garnet and biotite-rich schist with sub- to euhedral garnets. Note the inclusion-rich cores and the inclusion-free rims. The assemblage is garnet-biotite-quartz-plagioclase. Plane polarized light. Field of view is 5 millimetres. (AC93-6121)

Plate 4.2. Relict andalusite porphyroblast almost totally replaced by fine-grained muscovite and chlorite. Note the matrix foliation, defined by biotite, wrapping around the porphyroblast. Crossed polars. Field of view is 5 millimetres. (KP93-7142)

Plate 4.3. Relict andalusite (indicated as muscovite + chlorite) porphyroblast in contact with subhedral garnet. Plane polarized light. Field of view is 2.5 millimetres. (KP93-7142)

Plate 4.4. Equant hornblende surrounding actinolite aggregates. Mineral assemblage is hornblende-actinolite-plagioclase-quartz-epidote. Plane polarized light. Field of view is 5 millimetres. (AC93-6133)

Plate 4.5. Equant hornblende crystals in a mafic schist. Mineral assemblage is hornblende-plagioclase-quartz-epidote. Crossed polars. Field of view is 5 millimetres. (HS93-5278)

Plate 4.6. Amphibole porphyroblast from a hornblende gabbro, with actinolite relic (pale yellow) preserved in surrounding hornblende (dark yellow). Crossed polars. Field of view is 2.5 millimetres. (AC93-6450)

At the transition between the greenschist facies and amphibolite facies, mafic rocks of the volcanic belt contain both albite and oligoclase. The coexistence of both plagioclases has been found only in two samples: oligoclase being the main plagioclase present in rocks above the hornblende-in isograd. In addition, the zoisite/clinozoisite ratio generally decreases with the appearance of oligoclase and hornblende; this can be explained by a reaction implying the dehydration of epidote and the calcification of plagioclase (Spear, 1993):

Across the actinolite-out isograd, epidote persists in the assemblage whereas chlorite is not present due to bulk composition. Based on the experimental results of Liou (1973), Liou *et al.* (1974) and Apter and Liou (1982), it appears that at about 3.3 kb, the chlorite-out reaction intersects the epidote-out reaction (see fig. 4.2). Above 3.3 kb, epidote persists after the breakdown of chlorite, giving rise to the assemblage (2):

The pressure of the intersection depends on the oxygen fugacity due to ferric iron in epidote and hornblende. The pressure of the intersection (see fig. 4.2) of the chlorite-out and the epidote-out equilibria is at 3.3 kb for the reduced environment of the quartz-fayalite-magnetite assemblage, and decreases to lower pressures as the oxidation state of the rock increases upwards to the nickel-nickel-oxide assemblage.

Relative barometry based on classification of amphiboles

No assemblage suitable for quantitative barometry was found in the Anialik River volcanic belt. However, the diagram of Laird and Albee (1981) comparing amphibole compositions with five terranes of different pressure was applied to this study in order to obtain a qualitative estimate of the overall pressure (see fig. 4.2).

Laird and Albee (1981) compared amphiboles in rocks with a variety of bulk compositions and metamorphic grades. They classified these in four diagrams in order to show the pressure dependency of amphibole compositions. Diagrams 4.2 a) and d) are plots of Na(M4) over Na(A-site)+K (a) and over $Al^{VI}+Fe^{3+}+Ti$ (d). These plots reflect the glaucophane component in amphibole, which increases with metamorphic grade. Plot b), $Al^{VI}+Fe^{3+}+Ti$ over Al^{IV} , represents the edenite ($Na(A)Al^{IV}=oSi^{IV}$; o =vacancy) and Tschermakite ($Al^{VI}+Al^{IV}=Mg^{VI}+Si^{IV}$) exchanges (for the $Al^{VI}+Fe^{3+}+Ti$ term) and the Tschermakite and glaucophane ($Na(M4)Al^{VI}=Ca(M4)Si^{VI}$ exchanges (Al^{IV} term). Plot b) is based on the presumption that at low pressure, Al^{IV} is favored in the tetrahedral site. All exchanges increase with metamorphic grade.

Hornblende calculations accounting for Fe^{3+} were performed using Holland and Blundy's method (1994), through a Microsoft Excel spreadsheet made by Frederick Ford (personal communication, 1994). The Fe^{3+} values obtained are compared with those calculated with a formula based on a maximum Fe^{2+} (i.e. $Fe^{3+}=0$) in order to show the difference. Calculations with a formula based on a maximum Fe^{2+} give values of 0 for plots a) and d) and are therefore not shown in order to simplify the plots. These calculations do not affect plot c) but are shown on plot b).

Figure 4.2. P-T diagram showing the experimental results of Liou (1973), Liou *et al.* (1974) and Apter and Liou (1982) relevant to the greenschist to amphibolite transition (from Spear, 1993). Black curves represent experiments performed with oxygen fugacity defined by the quartz-fayalite-magnetite (QFM) buffer whereas grey curves are experiments performed with oxygen fugacity defined by the nickel-nickel oxide (NNO) buffer.

Figure 4.3. Composition plots for amphiboles from 5 different metamorphic series (Laird and Albee, 1981; from Spear, 1993). The Sanbagawa and Franciscan terranes are high pressure facies series, the Dalradian and Haast River terranes are intermediate pressure facies series and the Abukuma terrane is a low pressure terrane series. Amphiboles from each terrane have been collected over a range of metamorphic grades and from a variety of bulk compositions. Orange dots are amphiboles from the Anialik River volcanic belt. The amphibole calculations have been made through the Holland and Blundy method (1994) whereas dashed lines on plot b) relate to two amphibole calculations; 1) based on a maximum Fe^{2+} and 2) according to Holland and Blundy method (see text).

Although the amphibole classification made by Laird and Albee (1981) is based on modern metamorphic terranes and has not been tested for Archean metamorphic belts, the six amphiboles from the Aniak River volcanic belt (fig. 4.2) show remarkably consistent results which are independent of the amphibole calculation formulae. They all fall in the field of the Abukuma terrane which is a low pressure metamorphic belt (< 4 kb; Banno, 1986).

Geothermometry

Temperatures at which mineral assemblages equilibrated have been determined based on mineral equilibria calculated from thermodynamic data. The garnet-biotite exchange (Ferry and Spear, 1978; Hodges and Spear, 1982) and the amphibole-plagioclase thermometers (Plyusnina, 1982; Blundy and Holland, 1990; Holland and Blundy, 1994) have been applied in this study.

Minerals were analysed by energy-dispersive spectrometry (EDS) on a Cambridge Microscan 5 electron microprobe at Carleton University under the supervision of Peter C. Jones. Standards used were the Kakanui hornblende (U.S.N.M. standard 143965) and the Ingamells almandine garnet (R1598) and the average live counting time varied from 100 to 120 seconds. Representative analyses are given in appendix B. Temperature calculations were performed using a Microsoft Excel spreadsheet created by Frederic Ford (personal communication, 1994) for the garnet-biotite data, and the hornblende-plagioclase program of Holland and Blundy (1994).

Uncertainties on P-T data are numerous and span from the analytical error itself, to the choice of the activity model and temperature dependence of cation disorder (Hodges and

Crowley, 1985). However, accurate uncertainties of temperature values obtained in this study have not been calculated. Uncertainty in temperature data is estimated to be the same as that of Hodges and Spear (1982) for the garnet-biotite thermometer ($\pm 50^\circ \text{C}$). For the amphibole-plagioclase thermometer, Holland and Blundy (1994) suggested an uncertainty of $\pm 40^\circ \text{C}$; however, as the uncertainty may increase for iron-rich amphiboles, it is assumed to be the same as for garnet-biotite exchange (i.e. $\pm 50^\circ \text{C}$). This corresponds to the minimum error on thermometry data proposed by Hodges and Crowley (1985).

Samples that were analysed exhibit good equilibrium textures and plagioclases are generally unaltered. Garnet is rarely zoned in the Anialik River volcanic belt. Average values are used except where mentioned.

- Garnet-biotite thermometer

The garnet-biotite exchange thermometer uses the Fe^{2+} and Mg partitioning in these two minerals:

The free energy change of the equilibrium varies with temperature which is relatively insensitive to pressure variations.

The distribution coefficient is :

$$K_D = \frac{(X_{\text{Mg}}^{\text{py}})^3 (X_{\text{Fe}}^{\text{an}})^3}{(X_{\text{Fe}}^{\text{alm}})^3 (X_{\text{Mg}}^{\text{phl}})^3} \quad \text{where } X = \text{mole fraction} \quad (4.6)$$

Table 4.1 defines all mole fraction formulae used for the present study. Based on Ferry and Spear (1978), the equilibrium constant, for reaction 4.6, is given by:

$$\ln K = -2109/T(K) + 0.782 \quad (4.7)$$

at $P = 2.07 \text{ Kb}$. The Ferry and Spear (1978) thermometer has been subsequently modified, among others, by Hodges and Spear (1982) who used a non-ideal solution model for garnet and an ideal solution model for biotite. This approach is recommended by the authors where the grossular component in garnet becomes significant. Although garnets in the area have minor grossular component and the use of one or the other thermometer does not yield significantly different results, some samples in the Kangguyak gneiss belt showed zonation and a $\text{Ca+Mn}/\text{Ca+Mn+Fe+Mg}$ ratio up to 0.26 (see chapter 6). Therefore the Hodges and Spear (1982) method has been used systematically in order to facilitate comparisons.

- Amphibole-plagioclase thermometer

Holland and Blundy (1994) recently revised previous amphibole-plagioclase thermometers (Plyusnina, 1982; Blundy and Holland, 1990). The amphibole-plagioclase thermometer of Holland and Blundy (1994) uses the free energy of mixing in a regular solution model for within-site non-ideality, and a reciprocal solution model for cross-site-terms in order to account for the composition-dependence of the distribution coefficients for the equilibria:

Phase	Component	Mole fraction formulae	
Garnet	almandine	$\text{Fe}/\text{Fe}+\text{Mg}+\text{Mn}+\text{Ca}$	$=X_{\text{alm}} = X_{\text{Fe}}^{\text{Grt}}$
Garnet	pyrope	$\text{Mg}/\text{Fe}+\text{Mg}+\text{Mn}+\text{Ca}$	$=X_{\text{prp}} = X_{\text{Mg}}^{\text{Grt}}$
Garnet	spessartine	$\text{Mn}/\text{Fe}+\text{Mg}+\text{Mn}+\text{Ca}$	$=X_{\text{sps}} = X_{\text{Mn}}^{\text{Grt}}$
Garnet	grossular	$\text{Ca}/\text{Fe}+\text{Mg}+\text{Mn}+\text{Ca}$	$=X_{\text{grs}} = X_{\text{Ca}}^{\text{Grt}}$
Biotite	annite	$\text{Fe}/\text{Fe}+\text{Mg}+\text{Ti}+\text{Al}^{\text{VI}}$	$=X_{\text{ann}} = X_{\text{Fe}}^{\text{Bt}}$
Biotite	phlogopite	$\text{Mg}/\text{Fe}+\text{Mg}+\text{Ti}+\text{Al}^{\text{VI}}$	$=X_{\text{phl}} = X_{\text{Mg}}^{\text{Bt}}$
Muscovite	muscovite	$\text{K}/\text{K}+\text{Na}+\text{Ca}$	$=X_{\text{K}}^{\text{Mc}}$
		$\text{Al}/\text{sum of octahedral atoms}$	$=X_{\text{Al}}^{\text{Mc}}$
Plagioclase	anorthite	$\text{Ca}/\text{Ca}+\text{Na}+\text{K}$	$=X_{\text{an}} = X_{\text{Ca}}^{\text{Pl}}$
Plagioclase	albite	$\text{Na}/\text{Ca}+\text{Na}+\text{K}$	$=X_{\text{ab}} = X_{\text{Na}}^{\text{Pl}}$

Table 4.1: Expressions used to calculate mole fraction formulae. Mineral abbreviations are from Kretz (1983).

The reader is referred to Holland and Blundy (1994) for detailed descriptions of the activity coefficient calculations. As equation 4.9 involves anorthite in the reaction and the activity coefficient of anorthite is less constrained than that for albite (Holland and Blundy, 1994), temperatures presented in the present work refer to the first thermometer (4.8).

• Results

Results obtained from two samples using garnet-biotite and 6 samples using amphibole-plagioclase thermometers are summarized in table 4.2; figure 4.3 is a map showing the location of each sample analysed.

Crystals selected for analysis were the largest grains that showed an equilibrium texture with surrounding minerals of the matrix. In thin sections containing garnets, the biotite-garnet ratio is high limiting the need for a compositional adjustment of the biotite during cooling. All garnets were traversed to test for compositional zoning.

In order to avoid repetition in the text, the assemblage present in the thin section as well as a brief description of the analysis are described in table 4.2. Based on the petrological observations and on the amphibole classifications (see above), a maximum pressure of 4 kb has been chosen for temperature calculations.

Figure 4.4. Simplified geology of the Anialik River volcanic belt, modified from Relf (1993; 1994a), with location of samples used for thermometry.

Sample #	Thermo-meter	Mineral assemblage	Description of analysis	Results
6118	Grt -Bt	Grt-Bt-Qtz-Pl-Chl	One Grt up to 1cm, not zoned. 12 analyses of Grt, 6 in Bt including matrix Bt. The later has the same composition throughout the thin section. The average composition for the two minerals has been used.	573°C ± 50°C
6121	Grt-Bt	Grt-Bt-Qtz-Pl	Same as 6118. Two Grt unzoned with homogeneous Bt. 10 Grt and 8 Bt analyses (see plate 4.1).	633°C ± 50°C
3349	Am-Pl	Hbl-Pl-Qtz-Ep	Two pairs Hbl-Pl have been done with 3 analyses at the rim of each mineral within each pair.	714°C ± 50°C
5139	Am-Pl	Hbl-Act-Pl-Qtz-Ep	Small grains ≤ 1 mm. 8 Hbl and Pl analyses have been done at the rim of 4 different grains and the average composition has been used to calculate the temperature.	760°C ± 50°C
5278	Am-Pl	Hbl-Pl-Qtz-Ep	3 Hbl-Pl pairs with 3 analyses at the rim of each mineral within each pair. See plate 4.5.	664°C ± 50°C
5384	Am-Pl	Hbl-Act-Pl-Qtz-Ep	Same as 5278 plus 2 pairs Hbl-Pl taken in the core of Hbl with Pl inclusion. There are 3 analysis for each mineral. rim->	Core 676°C, 711°C ± 50°C
6133	Am-Pl	Hbl-Act-Pl-Qtz-Ep	Same as 5278 (see plate 4.4).	692°C ± 50°C
7936	Am-Pl	Hbl-Pl-Ep-Qtz(tr)	Same as 3349 with 2 pairs and 3 analyses of each mineral.	686°C ± 50°C

Table 4.2. Thermometry results obtained in the Anialik River volcanic belt: the pressure used is **4 kb** (see petrology of mafic rocks); mineral abbreviations are from Kretz (1983), (tr) is for trace amount. Temperatures presented are the average of the thin section. References for geothermometers are in the text.

Timing of Metamorphism with respect to Deformation

Greenschist facies metamorphism accompanied D₁ and D₂ in the Anialik River volcanic belt (see chapter 3) and the main metamorphic imprint is related to D₃ fabrics which represent the last Archean deformation event. Until more geochronological information on the metamorphism of the Anialik River volcanic belt is gathered, the belt will be separated into an eastern and western zone based on different styles of metamorphism.

•Eastern Anialik River volcanic belt

Garnet and hornblende porphyroblasts in samples of this area overgrow, and therefore post-date, S₃ (see plate 4.1 and 4.4). Hornblende crystals in the eastern volcanic belt are small, equant and locally weakly aligned. This alignment is attributed to primary bedding features rather than deformation, as hornblende crystals are concentrated in layers (see plate 4.7). In the eastern part of the Anialik River volcanic belt, D₃ has been shown to have overlapped with the emplacement of a folded tonalite dyke. It gave a zircon age of *ca.* 2613 Ma (Villeneuve and van Breemen, 1994).

Figure 3.1 shows that in the northeast part of the volcanic belt, the hornblende and actinolite isograds are closely spaced within 50 metres of each other, suggesting they dip steeply. In addition, the contact between volcanic rocks and late Archean granites, where observed, is subvertical. The steep dips of both the isograds and the intrusive contacts are consistent with a regional metamorphism caused by the emplacement of late Archean granitoids (*ca.* 2601 Ma; see chapter 3) occurring along the eastern margin of the belt.

- Western Anialik River volcanic belt

In the western, and possibly the southern, part of the Anialik River volcanic belt, porphyroblasts of hornblende and garnet are syn- to post-D₃ (see plate 4.5, 4.9 and 4.10). Syn or post deformation porphyroblasts cannot be separated into specific zones as both can occur within 20 metres of each other. Their relationship is therefore interpreted to be a function of bulk composition and/or to the heterogeneity of the deformation rather than distinct episodes of deformation. The coexistence of hornblende and actinolite over an area more than 8 km wide in the northwest part of the belt suggests that the hornblende and the actinolite-out isograds have relatively shallow dips in the area.

Abraham *et al.* (1994) dated epigenetic gold mineralisation, west of the Anialik River Igneous Complex, at 2656 ± 2 Ma from hydrothermal titanite. The gold itself is interpreted to be post peak metamorphism which gives a possible metamorphic age of >2656 Ma.

Plate 4.7. Sample 3569, located NE of Mistake Lake, shows fine-grained hornblende interpreted to be aligned along bedding. Note that the ellipsoidal form in the bottom left is an actinolite aggregate. Plane polarized light. Field of view is 5 millimetres.

Plate 4.8. Randomly oriented post-D₃ hornblende. Located in the western part of the Anialik River volcanic belt, north of Turtle Lake. Note that the thin section is not polished and has a variable thickness giving a variable color to the hornblende. Plane polarized light. Field of view is 5 millimetres. (AC94-8185)

Plate 4.9. Syn-deformation (D₃) garnet. The internal foliation, defined by quartz and ilmenite, is curved and continuous with the external foliation defined by biotite. Crossed polars. Photo length is 5 millimetres. (AC93-6248)

Conclusions

Three mineral zones in mafic rocks of the Anialik River volcanic belt have been mapped; the zones are separated by two isograds, the hornblende-in and the actinolite-out isograds. These isograds occur along the margins of the volcanic belt, thus the centre of the Anialik River volcanic belt is at greenschist facies.

The metamorphism of the Anialik River volcanic belt has been divided in two distinct events. The older one estimated at > 2656 Ma in the western part of the belt, was syn-to post- D_3 and reached upper-amphibolite facies grade with temperatures ranging from 664°C to $714^\circ\text{C} \pm 50^\circ\text{C}$.

The younger metamorphic event occurred along the eastern margin of the Anialik River volcanic belt, and related mineral growth is post D_3 and therefore post 2613 Ma, the age of a dyke folded by D_3 . Temperatures range from 573°C to $692^\circ\text{C} \pm 50^\circ\text{C}$ and increase eastward toward the contact with late Archean granitoids. The parallelism of the isograds and the granite-volcanic contact, and the timing of late Archean plutonism are consistent with a regional metamorphism caused by the late Archean plutons.

Although no assemblage has been found to obtain quantitative data on the pressure in the volcanic belt, petrological observations and mineralogical data suggest regional pressures below 4 kb and as low as 2.3 kb, which are consistent with the overall low pressure metamorphism of the Slave Province. The tectonic significance of these interpretations is discussed in chapter 7.

CHAPTER V

EVIDENCE FOR ARCHEAN DISPLACEMENT ALONG THE TOKHOKATAK FAULT

Introduction

The Tokhokatak fault has been traced for more than 50 km from Arcadia Bay to the James River area (fig. 3.1). This ductile, high strain fault separating both terranes represents an important tectonic boundary in the northern Slave Province and therefore much effort has been made to characterize its Archean movement history (McEachern, 1993; Relf *et al.*, 1994, Chouinard and Relf, 1994). The Kangguyak gneiss belt and the Anialik River volcanic belt are thought to have been juxtaposed during D₃, based on sheared F₃ fold limbs in the gneiss belt, adjacent to the Tokhokatak fault (Relf *et al.*, 1994). Shear planes are parallel to F₃ axial surfaces, in both the gneiss belt and volcanic belt, and to the Tokhokatak fault (Relf *et al.*, 1994).

The appearance of the Tokhokatak fault differs along its length. In the northern part of the Kangguyak gneiss belt, a vergence and increasing intensity of the D₃ structures was observed toward the fault, which is defined by a zone up to 200 meters wide of straight gneisses. These straight gneisses dip steeply west and have an associated steep down-dip mineral lineation, and they crystallized under amphibolite facies conditions (Relf *et al.* 1994; see plate 5.1). The straight gneisses have been interpreted as recrystallised mylonites by McEachern (1993). In the south of the Kangguyak gneiss belt, the gneissosity defines tight, upright folds which become overturned toward the Tokhokatak fault (Chouinard and Relf, 1994). The Tokhokatak fault itself is marked by a ~10 m wide zone with folded mylonite in a chloritic matrix (see plate 5.2).

Plate 5.1. Typical outcrop of the northern part of the Tokhokatak fault which is defined by a zone of amphibolite facies straight gneisses. These straight gneisses have a west-dipping gneissosity as well as an associated steep down-dip lineation. Pencil is 12 cm long.

Plate 5.2. The Tokhokatak fault in the southern part of the map area is characterized generally by folded felsic mylonite in a chloritic schist. These mylonitic zones are generally ~10 m wide.

Subsequent fracturing caused a curving of these folded mylonites suggesting a progressive transition between a ductile to brittle style of deformation (S. Hammer, personal communication, 1994).

Archean intrusive rocks appear along the fault and cut the gneisses in many areas, obscuring the Archean kinematic indicators. These rocks range in composition from gabbro to monzogranite and are themselves variably deformed along the fault implying a syn- to post-tectonic emplacement. There are presently no geochronological data on these units and kinematic indicators along the fault show various senses of movement. In addition, granitic intrusions as well as a brittle-ductile Proterozoic reactivation of the fault further obscure its Archean displacement history.

Existing isotopic geochemical data from the map area suggest that the Anialik River volcanic belt might be derived from a juvenile source. Indeed, a quartz-feldspar porphyry unit west of the Anialik River igneous complex was analysed for Nd by M. Villeneuve (personal communication, 1993) and yielded a juvenile E_{Nd} signature. A. Davis analysed two samples of the Kangguyak gneiss belt and obtained E_{Nd} values consistent with an old crustal source (Davis and Krogstad, 1995). In addition, 3 samples of late Archean granitoids yielded E_{Nd} signatures that suggest derivation from juvenile crust. Three of these granites are from the volcanic belt, but one intrudes the Kangguyak gneiss belt (A. Davis, personal communication, 1994). The granite must therefore have been derived from source rocks similar to the volcanic belt, suggesting that the gneisses are underlain at depth by rocks similar to those of the Anialik River volcanic belt.

Six samples of semi-pelitic schists along the eastern side of Rhino Lake (fig. 3.1) exhibit rotated garnet porphyroblasts. The samples are from few hundred meters east of the

Tokhokatak fault and are tentatively used to define the Archean history of the fault (see plate 5.3). Indeed, they occur in within sedimentary units surrounded by homogeneous mafic flows and are likely to have concentrated shearing during displacement on the Tokhokatak fault.

Theory on Rotating Porphyroblasts

Two points of view exist in the literature about the behavior of garnet porphyroblasts during deformation. Rotation of porphyroblasts has been advocated by a number of authors including, for example, Rosenfeld (1970), Schoneveld (1977), Powell and Vernon (1979) and Passchier *et al.* (1992). A second possibility has been pointed out by Bell (1985, Bell *et al.*, 1986, 1992), who suggested that porphyroblasts remain static during deformation, while the matrix rotates around them.

For S-shape inclusion trails, the traditional interpretation was proposed by Spry (1963) and later on modified by Rosenfeld (1968) and Schoneveld (1977). They considered garnet as a sphere rotating during growth under the effect of a non-coaxial (simple shear) deformation of the matrix. Figure 5.1a shows Spry's model (1963) for a rotating porphyroblast for rotations of more than 400° , whereas figure 5.1b summarizes basic concepts of Bell and co-workers (from Bell, 1985). Bell and others started from the premise that deformation in rocks is heterogeneous and it is possible to partition this deformation into different strain fields. Basically, an ellipsoidal zone occupied by a porphyroblast (especially in the middle of microlithons) exists, and is protected from any shearing. A porphyroblast will then neither deform nor rotate. Furthermore, Bell *et al.* (1992) tried to explain smoothly curving inclusion trails and complex snowball textures by truncation of the trails instead of deflection. Note that for the same final texture, the shear sense in figure 5.1a is sinistral

whereas that of figure 5.1b is dextral. The model of rotated porphyroblast has been applied in this study, based on the tectonic evolution of the area.

Application to the Tokhokatak Fault

Out of the six samples examined, the 3 southernmost samples exhibit rotated garnet porphyroblasts with inclusion trails defined by quartz and ilmenite, and the rest of the samples show a core with either an S-shape form or a "snowball" texture and an inclusion free rim defining euhedral garnet crystals (see plates 5.3 and 5.4). This indicates a syn-to-post deformation (i.e. late Archean) growth for the garnet porphyroblasts. Four samples have mineral lineations plunging northwest at 45° - 60° . No lineation has been clearly identified for the two others, and therefore they were cut perpendicular to the steep foliation, vertically and horizontally.

Given the development of such snowball textures and considering the structural evolution of the area, it is assumed that garnet porphyroblasts belong to one progressive deformation phase. Sample 5228 has been traversed from core to rim in order to support the hypothesis of a single growing period associated with a single progressive deformation (see fig. 5.2 and plate 5.3 and 5.5). Indeed, the compositional profile of manganese shows a "bell-shaped" pattern typical of growth during prograde metamorphism with a slight reequilibration at the margin of the crystal (Tracy, 1982). Appendix C shows the microprobe data for garnet 5228.

Based on the rotating porphyroblast hypothesis, the six samples along the Tokhokatak fault show an oblique west-side-up movement with a sinistral component. However, the outer rim part of a porphyroblast grown in a syn-tectonic environment should display continuity

between internal and external foliations (Spry, 1963). Plate 5.6 shows a rotated garnet (sample 5228) with an ellipsoidal shape and a rounded core. Inclusion trails near the edge of the garnet show an angular discordance with the matrix foliation defined by biotite, and newly grown quartz grains at the boundary of the garnet. This texture suggests that during its growth, the rotated porphyroblast was equant and that a subsequent or progressive ductile phase of deformation (i.e. D₃) affected this crystal, causing dissolution of the garnet along faces perpendicular to the ellipsoid and resulting in growth of new quartz grains (S. Hammer, personal communication, 1994). It also suggests that these small lenses of sedimentary rocks were originally the locus of high non-coaxial strain, and that progressive strain transposed shear fabrics in the matrix.

Conclusion

Further work on the geometry of the fault has to be done in order to determine the origin of these rotated garnets, i.e. are they formed by movement along the fault and if so, are they representative of the entire fault or are they produced by shearing along F₃ fold limbs during compression?

These questions are relevant for the Archean history of the Tokhokatak fault because if these rotated garnets are associated with the fault it would signify that the Kangguyak gneiss belt was thrust (reverse fault?) obliquely over the Anialik River volcanic belt, with a sinistral component to movement. The stress field required to produce sinistral east-vergent thrusting has the same orientation as that required for D₃ structures in the two belts. West-over-east thrusting is also compatible with Nd isotopic data, which suggest that the Kangguyak gneiss belt is underlain by juvenile rocks.

Figure 5.1 a) shows the rotating porphyroblasts model of Spry (1963) . Note the sinistral sense of movement. b) Model for the development of S-shaped inclusion fabric in porphyroblasts by transposition of the external foliation through 90° during incremental porphyroblast growth. The porphyroblast does not rotate and note the dextral sense of movement (Bell, 1985).

Plate 5.3. Rotated garnet porphyroblasts in sample 5228, near Rhino Lake, indicate syn-deformation growth. These garnets are from small lenses less than 60 m wide of semi-pelitic schists. Crossed polars. Field of view is 5 mm.

Plate 5.4. Syn-to-post deformation garnet in a semi-pelitic schist east of Rhino Lake. Crossed polars. Field of view is 5 mm.

Plate 5.5. Back-scattered electron image of garnet in sample 5228 showing the traverse that has been done to test the compositional zoning. Small, grey crystals defining the inclusion trails are ilmenite, quartz appears in black. Scale bar is 1mm.

Rotated garnet 5228

The molar fractions are

$$\text{grs} = \frac{\text{Ca}}{\text{Fe} + \text{Mg} + \text{Mn} + \text{Ca}}$$

$$\text{sps} = \frac{\text{Mn}}{\text{Fe} + \text{Mg} + \text{Mn} + \text{Ca}}$$

$$\text{alm} = \frac{\text{Fe}}{\text{Fe} + \text{Mg} + \text{Mn} + \text{Ca}}$$

$$\text{prp} = \frac{\text{Mg}}{\text{Fe} + \text{Mg} + \text{Mn} + \text{Ca}}$$

Figure 5.2 shows the compositional zoning of garnet in sample 5228. Note the spessartine component that shows a good "bell-shaped" pattern typical of growth zoning during prograde metamorphism (Tracy, 1982). Note also the reverse pattern for the last 0.2 mm at the rim indicating a slight reequilibration.

Plate 5.6. Ellipsoidal rotated garnet with rounded core and recrystallised quartz at the boundary in continuity with inclusion trails within the garnet indicating a subsequent or progressive deformation phase after the garnet growth. The ellipsoidal shape is oriented along the schistosity in the matrix. Crossed polars. Photo length is 5 mm. (AC93-5228)

The appearance of a relict small high strain zone in the footwall of the Tokhokatak fault could suggest that the fault moved laterally, possibly by break-back sequence of thrusting (Morley, 1988) toward the gneiss belt. Hanmer (1988) recorded a transcurrent dextral mylonite zone for the Great Slave Lake shear zone, northwestern Canadian Shield, and defined the evolution of this crustal-scale fault zone with 3 major observations. The first one is that with time the metamorphic grade decreased from granulite to greenschist facies. Secondly, the locus of the high strain narrowed and jumped laterally, abandoning relatively older mylonites during cooling and uplift, and following these events the deformation evolved progressively through the brittle-ductile transition.

The Tokhokatak fault and the Great Slave Lake shear zone might share some similarities. Indeed, the occurrence of rotated garnet porphyroblasts in small schist lenses probably represent an older shear zone later on annealed and abandoned. The main difference between the Great Slave Lake shear zone and the Tokhokatak fault is that metamorphism outlasted movement on the Tokhokatak fault the collision resulting in mylonites that were recrystallised under amphibolite conditions (see chapter 4 and 6). This difference would explain why the present fault zone is defined by a straight gneiss zone up to 200 m wide, i.e. the wider zone represents a deeper structural level and higher temperature.

CHAPTER VI

METAMORPHISM OF THE KANGGUYAK GNEISS BELT

Introduction

As mentioned previously, recent mapping by Relf and co-workers showed that the *ca.* 3.0 Ga Kangguyak gneiss belt is a distinct terrane with respect to the Anialik River volcanic belt (see Fig. 6.1). The gneiss belt is dominated by mixed ortho- and paragneisses and this chapter describes its metamorphic evolution. Petrographic and petrological observations as well as geothermobarometry results are presented here in order to relate the metamorphic history of the gneiss belt to the evolution of the Anialik River volcanic belt.

Petrography and Petrology of the Paragneisses

Neither metamorphic zones nor isograds have been mapped in the Kangguyak gneiss belt due to the paucity of mineral variation and the lack of mineralogical indicators of metamorphic change. Several aspects of the metamorphism of the gneiss belt are similar to those of the Anialik River volcanic belt, and therefore, the reader will often be referred to Chapter 4 in order to avoid repetition in the text. For the Kangguyak gneiss belt, 60 samples were collected for petrological observations.

- Bulk composition of paragneisses

Like the psammites and semi pelites of the Anialik River volcanic belt, the paragneisses are garnet and biotite-rich; i.e. iron-rich. They have rare muscovite and lack aluminosilicates.

Figure 6.1. Simplified geology of the Kangguyak gneiss belt and the western boundary of the Aniak River volcanic belt, modified from Relf (1993; 1994). The map also shows location of samples used for geothermobarometry. RL-Rhino Lake; TL-Turtle Lake.

Only two samples were found with muscovite large enough to be analysed; these were used for geobarometry (see below).

- **Petrography of paragneisses**

Petrographic study of paragneisses showed a typical assemblage consisting of biotite, quartz, plagioclase, garnet, often as porphyroblasts, $\pm$ muscovite, with traces of zircon, titanite and epidote. As in the Anialik River volcanic belt, chlorite is found as an alteration product of biotite and/or garnet. Furthermore, minerals have the same habit as described in Chapter 4, with the following few exceptions.

Garnet is rarely euhedral but rather subhedral to anhedral. It is locally compositionally zoned and more frequently includes biotite inclusions in contrast to garnets in the volcanic belt (see plate 6.5 and 6.6). Biotite locally has a brown-greenish pleochroism. Trace amounts of muscovite generally appear only as very tiny crystals in rare thin sections. The latter occurs, in one thin section, as laths up to 2 mm (see plate 6.1 and 6.2).

Petrography of Mafic Gneisses

The typical mineral assemblage observed in thin sections for mafic gneisses is:

Hornblende + plagioclase + quartz + epidote

$\pm$ calcite, biotite, apatite, titanite and zircon. Mafic gneisses are generally equigranular and the proportion of hornblende is up to 60%. The amount of quartz varies from < 5 % to 10 %.

Hornblende is mostly equant (see plate 6.4). It displays a dark green to blue-green pleochroism and it locally includes plagioclase and/or quartz inclusions. Chlorite is a typical alteration product of hornblende. Plagioclases have an An content varying from An₂₀ to An₅₃ (from microprobe analysis of 5 samples). As in the Anialik River volcanic belt, epidote, sericite and calcite are the main alteration products of plagioclase.

- Relative barometry based on classification of amphiboles

The diagram of Laird and Albee (1981) which compares amphibole compositions with five terranes of different pressure has been used in order to compare results from the Kangguyak gneiss belt with the Anialik River volcanic belt (see fig. 4.6 and fig. 6.2). The reader is referred to the section on relative barometry of mafic rocks of the Anialik River volcanic belt for details on the classification and on the diagram.

Although there are only three samples plotted on the diagrams, they all have a signature similar to the Abukuma terrane; the same result was obtained for amphiboles of the volcanic belt (in orange, fig. 6.2). As mentioned in Chapter 4, the Abukuma is a low pressure terrane, i.e. below 4 kb (Banno, 1986).

2

of/de

2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

Figure 6.2. Composition plots for amphiboles from 5 different metamorphic series (Laird and Albee, 1981; from Spear, 1993). The Sanbagawa and Franciscan terranes are high pressure facies series, the Dalradian and Haast River terranes are intermediate pressure facies series and the Abukuma terrane is a low pressure terrane series. Amphiboles from each terrane have been collected over a range of metamorphic grades and from a variety of bulk compositions. Orange dots are amphiboles from the Kangguyak gneiss belt. The amphibole calculations have been made through the Holland and Blundy method (1994) whereas dashed lines on plot b) relate to two amphibole calculations; 1) based on a maximum Fe^{2+} and 2) according to Holland and Blundy method (see text in chapter 4).

Plate 6.1. Assemblage garnet + biotite + retrograde muscovite + quartz + plagioclase used for geobarometry to obtain a minimum pressure for the gneiss belt. Note that plagioclase does not appear on this photo. Crossed polars. Field of view is 2.5 millimetres. (AC93-6354)

Plate 6.2. Same as plate 6.1 but plane polarized light. Field of view is 2.5 millimetres. (AC93-6354)

Plate 6.3. Typical garnet and biotite-rich paragneiss. Garnet porphyroblasts are anhedral and are late with respect to the deformation. Plane polarized light. Field of view is 2.5 millimetres. (AC93-6322)

Plate 6.4. Typical hornblende plagioclase mafic/gabbroic gneiss used for amphibole-plagioclase thermometry. Hornblende is anhedral to subhedral with a dark green to blue-green pleochroism in plane polarized light. The assemblage is hornblende-plagioclase-quartz-epidote. Crossed polars. Field of view is 2.5 millimetres. (AC94-8307)

Plate 6.5. Garnet 6552. Assemblage in thin section is garnet-biotite-quartz-plagioclase. The slight difference in biotite color is due to the carbon coating used for microprobe analysis. This garnet shows a complex zonation pattern (see text). Plane polarized light. Field of view is 5 millimetres. (AC93-6552)

Plate 6.6. Garnet and biotite-rich paragneiss. Biotite has a dark brown to locally greenish pleochroism. The assemblage is garnet - biotite - quartz - plagioclase. Plane polarized light. Field of view is 5 millimetres. (AC93-6355)

Thermobarometry

Analytical conditions are the same as those described in chapter 4. The thermometers used are the garnet-biotite exchange thermometer (Ferry and Spear, 1978; Hodges and Spear, 1982) and the amphibole-plagioclase thermometer (Holland and Blundy, 1994). Only the results will be presented in this chapter. The reader can refer to Chapter 4 for details on each thermometer.

• Geobarometry

Pressure calculations of these reaction curves were made using PTAX, a GEO-CALC software, which uses an internally consistent thermodynamic database (Berman, 1991). For pressures calculated from PTAX, the following mixing models were applied: Berman's (1988) non-ideal mixing model for garnet; Furrman and Lindsley (1988) model for plagioclase; McMullin *et al.* (1991) for biotite; and Chatterjee and Froese (1975) model for muscovite. The uncertainty shown is derived by Hodges and Crowley (1985), i.e. ± 1 kb. Figure 6.3 and 6.4 show PTAX results with mineral equilibria and the aluminosilicate stability field of Holdaway (1971).

Results

Sample locations used for thermobarometry are shown in figure 6.1; table 6.1 presents a synthesis of the results. Five samples with petrographical features as described in the petrography section were used for garnet-biotite and amphibole-plagioclase thermometry. Of the four other samples: sample AC93-6552 showed a complex zoning of garnet; AC93-6355 had higher temperature than the average and; AC93-6354 and 6536 have muscovite, allowing a pressure estimate (see fig. 6.3 and 6.4).

Figure 6.3. Reaction curves calculated using PTAX for sample 6354. Dashed lines show the aluminosilicate field.

Figure 6.4. Reaction curves calculated using PTAX for sample 6536. Dashed lines show the aluminosilicate field.

Sample #	Thermo- barometer	Mineral assemblage	Description of analysis	Results
4557	Am-Pl	Hbl-Pl-Qtz-Ep	Two pairs Hbl-Pl have been done with 3 analyses at the rim of each mineral within each pair.	680 °C ± 50 °C
6322	Grt-Bt	Grt-Bt-Qtz-Pl	2 Grt up to 2mm. 6 analyses in each to test for compositional zoning: not zoned. 6 Bt in the matrix (see plate 6.3).	721 °C ± 50 °C
6354	• Grt-Bt • Grt-Bt- Ms-Pl	Grt-Bt-Ms-Qtz-Pl	3 analyses of Grt at the rim as well as 3 of Bt and Ms. Pl was not in contact with Grt and is from the matrix: 8 analyses at the rim of two Pl (see plate 6.1 and 6.2)	610 °C ± 50 °C 4.7 kb ± 1 kb
6355	Grt-Bt	Grt-Bt-Qtz	Two Grt up to 3.2 mm. Very slightly zoned. Analyses in the the core, mantle and at the rim with matching Bt : 2 analyses of each mineral (see plate 6.6)	795°(c) 764°(m) 700°(r) ± 50 °C
6409	Grt-Bt	Grt-Bt-Qtz-Pl	2 homogeneous Grt and Bt. 6 analyses within each Grt and 6 of matrix Bt.	650 °C ± 50 °C
6526	Am-Pl	Hbl-Pl-Qtz-Pl	Fine-grained Hbl. 8 Hbl and Pl analysis have been done in 4 grains.	744 °C ± 50 °C
6536	• Grt-Bt • Grt-Bt- Ms-Pl	Grt-Bt-Ms-Qtz-Pl	Same as 6354 except that there was no Bt in the Grt.	582 °C ± 50 °C 3.5 kb ± 1 kb
6552	Grt-Bt	Grt-Bt-Qtz-Pl	2 Grt have been tested for zoning and the larger one has been kept. More than 150 analyses defines a complex zonation pattern of reequilibration (see plate 6.5 and following discussion).	relic high T:714 °C down to 468 °C ± 50 °C
8307	Am-Pl	Hbl-Pl-Qtz-Pl	Same as 4557 with 2 pairs and 3 analyses of each mineral (see plate 6.4).	683 °C ± 50 °C

Table 6.1. Thermobarometry results obtained in the Kangguyak gneiss belt: mineral abbreviations are from Kretz (1983). (c) is for core; (m) for mantle and; (r) for rim. Temperatures and pressures presented are generally the average of the thin section except when mentioned. References for the geothermobarometers are in the text.

- Discussion of results

Sample 6552

Garnets in sample AC93-6552 present a complex zonation pattern (see plate 6.5, fig. 6.5). Over 150 points were analysed in order to define this zonation. Figure 6.5 gives concentration contours; note the concentration lines locally cross the biotite inclusions. An X-ray map of the garnet (see plates 6.7 and 6.8) supports the pattern shown on the concentration map in figure 6.5 (see plate 6.5). Both maps indicate an enrichment of manganese near the rim of the garnet as well as biotite inclusions. The concentric zoning of Mn and almandine component around biotite suggests a reequilibration of garnet with biotite (see fig. 6.5). As diffusion in biotite is rapid relative to geologic cooling rates, the interior of biotite crystals reequilibrate quickly with the rim and the biotite composition appears homogeneous (Tracy, 1982). Note that biotite is homogeneous throughout the thin section.

Plots of compositional profiles along traverses A-A' and B-B' are presented in figure 6.6. Both plots show a $\text{Fe}/\text{Fe}+\text{Mg}$ and X_{sp} s defining an "error function" shape generally associated with diffusion as opposed to a "bell-shaped" profile typical of growth zoning (Tracy, 1982). As the trend of $\text{Fe}/\text{Fe}+\text{Mg}$ is independent of the addition of other components such as Mn and Ca, it is useful to evaluate zoning in garnet regardless of the complexity of the chemical system (Spear, 1993). Therefore the increase of the $\text{Fe}/\text{Fe}+\text{Mg}$ ratio in the vicinity of biotite suggests that diffusion occurred in response to Fe-Mg exchange between garnet and biotite, whereas zoning of Mn in garnet could be explained by the influence of fluids during diffusion (Yardley, 1977).

The effect of diffusion on temperature calculations is that the apparent reequilibration temperature might be lower than peak metamorphic temperature. Figure 6.7 presents apparent temperature versus distance profiles. In figure 6.7a, the highest temperature represents relict high temperature garnet and further reequilibration occurred on each side with time. Note that reequilibration of the garnet at the rim, in contact with quartz, gave a temperature of about 580 °C whereas temperatures obtained where the garnet is in contact with biotite are as low as 470°C. Spear (1993) mentioned that at lower temperature, diffusion occurs over very small distances and ceases around 450-500°C which is consistent with the temperature observed at the contact with biotite.

Sample 6355

Sample 6355 is a paragneiss with an assemblage similar to sample 6552 but with homogeneous garnets. It yielded a temperature of $795^{\circ}\text{C} \pm 50^{\circ}\text{C}$. This sample may be an equivalent of the relict high temperature garnet in 6552 that has not reequilibrated (see plate 6.6). In addition, the compositions of garnet and biotite are similar to those of other samples analysed. As reequilibration is a diffusion related process, either sample 6355 did not have the time to reequilibrate during cooling and/or diffusion in sample 6552 was facilitated by fluids.

Although no assemblage was found recording granulite facies metamorphism in the Kangguyak gneiss belt, the temperature indicated by the core of sample 6355 indicates metamorphic temperatures approached the granulite facies or at least at the upper limit of the amphibolite facies.

Figure 6.5. Complex reequilibration pattern of garnet (AC93-6552). In order to describe this pattern, this figure is accompanied with a X-ray map (see plate 6.7 and 6.8). Note the concentric zoning of Mn adjacent to biotite crystals. Stippled pattern represents biotite.

1 millimetre

Berman, R.G., 1988, Internally-consistent thermodynamic data for minerals in the system $\text{Na}_2\text{O}-\text{K}_2\text{O}-\text{CaO}-\text{MgO}-\text{FeO}-\text{Fe}_2\text{O}_3-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{TiO}_2-\text{H}_2\text{O}-\text{CO}_2$. *Journal of Petrology*, **29**: 445-522.

Berman, R.G., 1991, Thermobarometry using multi-equilibrium calculations: a new technique, with petrological applications. *Canadian Mineralogist*, **29**: 833-855.

Blundy, J.D. and Holland, T.J.B., 1990, Calcic amphibole equilibria and a new amphibole-plagioclase geothermometer. *Contributions to Mineralogy and Petrology*, **104**: 208-224.

Bowring, S.A., Williams, I.S., and Compston, W., 1989, 3.96 Ga gneisses from the Slave Province, Northwest Territories, Canada. *Geology*, **17**: 971-975.

Card, K.D. and King, J.E., 1992, The tectonic evolution of the Superior and Slave provinces of the Canadian Shield: introduction. *Canadian Journal of Earth Sciences*, **29**: 2059-2065.

Carmichael, D.M., Helmstaedt, H.H. and Thomas, N., 1987, A field trip guide in the Frontenac Arch with emphasis on stratigraphy, structure and metamorphism. Meeting of friends of Grenville, 23 p.

Chatterjee, N.D. and Froese, E., 1975, A thermodynamic study of the pseudo-binary join muscovite-paragonite in the system $\text{KAlSi}_3\text{O}_8-\text{NaAlSi}_3\text{O}_8-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$. *American Mineralogist*, **60**: 985-993.

Chouinard, A. and Relf, C., 1994, Recent advances in the geology of the Anialik River volcanic belt and Kangguyak gneiss belt. *in* Exploration Overview 1993, NWT Geology Division, CIM, DIAND, Yellowknife.

Davis, A.M. and Krogstad, E.J., 1995, Neodymium isotopic evidence for sources of granites, northern slave Province, NWT. Geological Survey of Canada Forum 1995, Program with Abstracts, p.32.

Figure 6.6. Compositional zoning profiles of traverse A-A' and B-B' (see fig. 6.5). Note the $Fe/Fe+Mg$ ratio and the X_{sps} profile shows an "error function" profile due to diffusion as opposed to a "bell-shaped" profile typical of growth zoning (Tracy, 1982). Traverse B-B' shows this type of profile on both sides of the biotite crystal.

Plate 6.7. X-Ray map of Mn, Mg, Fe and Ca. Area with higher concentration appears brighter. Note the Mn profile in the top left corner. (AC93- 6552)

Plate 6.8. Close-up of the Mn profile showing high concentration at the rim of the crystal as well as around biotite. (AC93- 6552)

Timing of Metamorphism with respect to Deformation

Porphyroblasts in the Kangguyak gneiss belt overgrow all fabrics suggesting that the timing of metamorphism with respect to deformation is post-D₃ (D₂?). A few samples from near the Tokhokatak fault exhibit syn-D₃ textures but this feature is thought to be unique and due to their location adjacent to the fault. Metamorphism has been dated in the Kangguyak gneiss belt, from titanite in the quartzite unit and from hornblende in the conglomerate, at *ca.* 2660 Ma and *ca.* 2640 Ma respectively (Villeneuve and van Breemen, 1994 and H. Sandeman, personal communication, 1994; see also chapter 3). This age indicates a minimum age for D₃.

Conclusions

Mineral assemblages and equilibria in the Kangguyak gneiss belt are similar to those of the Anialik River volcanic belt. In addition, thermobarometry data are consistent with a low-pressure high-temperature metamorphism. Of the nine samples analysed, two were used for geobarometry and gave pressures of 3.5 and 4.7 kb $\pm$ 1 kb.

As most samples in the Kangguyak gneiss belt preserve temperatures around 700°C, they probably did not have the time to reequilibrate during cooling, which suggests rapid uplift rates. Based on these observations, the timing of the juxtaposition of the two terranes (syn-D₃), the timing of metamorphism with respect to deformation and similarities with the western part of the volcanic belt (i.e. syn- to post D₃ mineral growth, high temperature and metamorphism dated at *ca.* 2.65 Ga), it is proposed that the metamorphism was associated with the juxtaposition of the Kangguyak gneiss belt and the Anialik River volcanic belt. Therefore the western margin of the Anialik River volcanic belt and the Kangguyak gneiss have undergone the same metamorphic event.

CHAPTER VII

DISCUSSION AND CONCLUSIONS

The following chapter is divided into two parts. The first presents the regional tectonic implications of the metamorphic and structural data presented in Chapters 4, 5 and 6; and possible causes of the metamorphism are discussed in the second section. General conclusions and observations made in chapters 4, 5 and 6 are summarized in table 7.1.

Regional Tectonic Implications

The following part summarizes the main ideas concerning the juxtaposition and the relationship of the Kangguyak gneiss belt and the Anialik River volcanic belt.

- a) Prior to their juxtaposition, the two belts had distinct histories as indicated by their different structural style, lithologies, isotopic signatures, and different metamorphic grade at which pre-peak temperature fabrics formed.
- b) Juxtaposition of the two terranes was accompanied and/or followed by folding during D₃. Indeed, the NNE-SSW trending regional-scale fold, cored by the Anialik River Igneous Complex, is compatible with a compressional phase accompanying oblique (sinistral) reverse shearing along the Tokhokatak fault.
- c) The rotated garnets, east of the Tokhokatak fault, suggest sinistral, west-over-east displacement. If the garnets formed in a shear zone that was related to the Tokhokatak fault (rather than shearing along a D₃ fold limb), then the Kangguyak gneiss belt lies in thrust contact with the Anialik River volcanic belt.

<p>Metamorphism of the Anialik River volcanic belt</p> <p>Chapter IV</p>	<ul style="list-style-type: none"> • 3 mineral zones separated by 2 isograds along both margins of the belt. <div style="margin-left: 40px;"> actinolite — — — — — hornblende isograd actinolite + hornblende — — — — — actinolite-out isograd hornblende </div> • 2 distinct metamorphic events: <div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> 1) - western margin of the belt <ul style="list-style-type: none"> - at about 2650 Ma - syn- to post-D₃ - fault related - T ranging from 664°C to 714°C ± 50°C - shallow isograds. </div> <div style="width: 45%;"> 2) - eastern margin of the belt <ul style="list-style-type: none"> - post ca. 2613 Ma - T ranging from 573°C to 692°C ± 50°C, P(kb) from 2.3-3.6. - steep isograds - prob. related to late Archean plutons. </div> </div> • Relative barometry on amphiboles indicates pressures below 4 kb for both metamorphic events.
<p>Archean movement of the Tokhokatak fault</p> <p>Chapter V</p>	<ul style="list-style-type: none"> • Rotated garnets found in foliated, semi-pelitic schist, in the footwall of the Tokhokatak fault suggest a relic shear zone possibly caused by movement along the fault . • Rotated garnets indicate a relative shear sense of sinistral, west-over-east, consistent with Nd data. • Shear sense and orientation of F3 folds are consistent with WNW-ESE shortening, implying continuous shearing and folding. • If garnets rotated during Tokhokatak faulting, the fault may have moved laterally toward the gneiss belt, in a break back sequence of thrusting.
<p>Metamorphism of the Kangguyak gneiss belt</p> <p>Chapter VI</p>	<ul style="list-style-type: none"> • Assemblages are similar to those in the Anialik River volcanic belt. • Mineral growth west of the fault is post-deformation (D₃?), except for few samples near the fault which are syn-deformation. • Metamorphism has bracketted between <i>ca.</i> 2640 Ma and <i>ca.</i> 2660 Ma suggesting a minimum age for D₃ in the gneisses and an association with the metamorphism west of the Anialik River volcanic belt. • Temperatures range from 582°C to 795°C ± 50°C and pressures from 3.5 to 4.7 Kb.

Table 7.1. Summary of the general conclusions made in chapter 4, 5 and 6.

d) Ductile deformation along the fault was accompanied by shearing along the limbs of F₃ folds in the gneisses adjacent to the Tokhokatak fault.

e) Displacement along the fault was coeval with, and outlasted by metamorphism in a low-pressure environment along the western margin of the volcanic belt as well as in the Kangguyak gneiss belt (see chapter 4 and 6). The metamorphism has been dated at around 2.65 Ga in the two belts. In addition, the high temperature values obtained in the western part of the area and their lack of reequilibration during cooling suggest possible rapid uplift rates.

f) Later on at *ca.* 2.60 Ga, emplacement of late Archean granites along the eastern margin of the volcanic belt produced a distinct low-pressure/high temperature metamorphic event.

Considering that the Tokhokatak fault has been traced for more than 50 km in the present study area, it is thought to be an important tectonic boundary for the northern Slave Province (Chouinard and Relf, 1994). Furthermore, the Tokhokatak fault represents a contact between a granite-greenstone belt and an older granite-gneiss belt that may be a northern part of the Anton terrane. It is proposed in this study that rocks of the Kangguyak gneiss belt are possibly in thrust contact (or reverse fault) with rocks of the Anialik River volcanic belt. However, according to Kusky's model (1989; see fig. 2.2) supracrustal rocks of the Slave Province are thrust westward over the Anton terrane. It is therefore possible that the tectonic boundary separating basement-aged rocks from other rocks of the Slave Province does not have a similar geometry throughout its length.

Cause of Metamorphism

As mentioned in chapter 2, there are 3 possible causes that have been proposed for low-pressure high-temperature metamorphism of the Slave Province: 1) crustal extension; 2) regional contact metamorphism and; 3) lithosphere detachment. These three models are based on the assumption that within a given region, metamorphic assemblages equilibrated during a single metamorphic event. However, in the present study area, evidence has been found for two distinct metamorphic events, each temporally related to different geologic events. Each of these models is considered below, in light of the conclusions presented above.

- **Crustal extension**

There is no evidence for an early extensional event in the map area. In addition, based on textural relations in the Kangguyak gneiss belt and the western Anialik River volcanic belt, metamorphism is thought to have accompanied compression, not extension of the crust.

- **Regional contact metamorphism**

In the eastern part of the Anialik River volcanic belt, the contact of supracrustal rocks with late Archean granitoids is steep (C. Relf, personal communication, 1995) and isograds are also thought to be relatively steep, since the hornblende and actinolite-out isograds are close to each other. Metamorphism is late with respect to D₃, which has been dated at *ca.* 2613 Ma (Villeneuve, unpublished data). These features are consistent with regional contact metamorphism caused by intrusion of late Archean plutons, around 2.60 Ga.

The origin of syn-thrusting plutons in the western part of the study area is not presently known. Although their abundance may increase downward, they are not interpreted to be the major cause of metamorphism in the western part of the map area, since metamorphism accompanied and outlasted thrusting, plutonism and folding. Plutonism was probably caused by crustal thickening related to the juxtaposition of the two terranes (see below).

- Lithosphere detachment

Houseman *et al.* (1981), Loosveld (1989) and Loosveld and Etheridge (1990) have suggested a model implying lithosphere detachment from the base of the crust producing high heat flow. The principle is the following: the underlying lithosphere thickens during shortening and is depressed downwards into the asthenosphere. As the lithosphere is dense and relatively cool, the convection in the asthenosphere may cause a detachment, total or partial, of the lithosphere from the base of the crust. Therefore, the cold crust will be in contact with the hot asthenosphere.

Davis (1991) proposed, for the Contwoyto Lake area that heating at the base of the crust by lithosphere detachment could have caused partial melting of the upper mantle or lower crust and would be responsible of the emplacement of syn-thermal peak *ca.* 2608 Ma calc-alkaline plutons of the Concession suite. Although a continental arc-setting has also been proposed for the calc-alkaline plutons (Fyson and Helmstaedt, 1988; Davis *et al.*, 1990 and; Kusky, 1991), Davis (1991) favoured the lithosphere detachment model for calc-alkaline plutonism across most of the Slave Province at *ca.* 2.61 Ga. Furthermore, this model accounts for areas where syn-thermal peak granitoid rocks are rare or absent.

Although it is generally impossible to test the lithospheric detachment model, there are some factors favouring this model. Indeed, crustal thickening due to compression causing D₃ folding and possibly thrusting occurred during the syn to post-D₃ peak of metamorphism. In addition, the average high temperature observed in the western part of the map area suggests that most of the rocks did not have the time to reequilibrate during cooling, possibly due to rapid uplift rates. These factors are consistent with tectonism resulting from lithospheric detachment (Loosveld and Etheridge, 1990). Although it is suggested that the Tokhokatak fault may have been the locus of granitic intrusion (Chouinard and Relf, 1994), the extension and volume of these granites do not appear to be significant enough to produce a wide contact metamorphism on both sides of the fault. Therefore, regional contact metamorphism does not provide a likely explanation for the metamorphism of the area.

Although the lithospheric detachment model is hard to prove, it seems to provide a feasible explanation for the metamorphism of the western boundary of the Anialik River volcanic belt and the studied portion of the Kangguyak gneiss belt.

Summary

To summarize, the metamorphic and tectonic history of the study area is more complex than previously thought, and consisted of three parts: 1) early (pre-D₃), separate deformation and metamorphism of the two terranes, the Anialik River volcanic belt and the Kangguyak gneiss belt; 2) Juxtaposition of the two belts along a possible oblique (sinistral) thrust fault, accompanied and followed by folding, high-temperature/ low-pressure metamorphism, and, possibly, lithosphere delamination; 3) emplacement of late Archean granites along the eastern margin of the volcanic belt causing a later, high-temperature/low-pressure metamorphic event related to heat imposed by the granites.

REFERENCES

- Abraham, A.P.G., 1990, Geological and geochronological constraints on magmatic evolution, deformation and gold mineralization of the Anialik River batholith and its relationship to the Anialik River greenstone belt, Slave Province, (76M/11). *in* Exploration Overview 1990, NWT Geology Division, DIAND, Yellowknife, p.18.
- Abraham, A.P.G., Davis, D.W., Kamo, S.L. and Spooner, E.T.C., 1994, Geochronological constraints on late Archean magmatism deformation and gold-quartz vein mineralization in the northwestern Anialik River greenstone belt and igneous complex, Slave Province, N.W.T. Canadian Journal of Earth Sciences, **31**: 1365-1383.
- Apted, M.J. and Liou, J.G., 1983. Phase relations among greenschist, epidote-amphibolite, and amphibolite in a basaltic system. American Journal of Science, **283**: 328-354.
- Banno, S., 1986, The high temperature metamorphic belts in Japan: a review. Geological Society of America, Memoir 164, p. 365-374.
- Bégin, N.J., 1992, Contrasting mineral isograd sequences in metabasites of the Cape Smith Belt, northern Québec, Canada: three new bathograds for mafic rocks. Journal of Metamorphic Geology, **10**: 685-704.
- Bell, T.H., 1985, Deformation partitioning and porphyroblast rotation in metamorphic rocks: a radical reinterpretation. Journal of Metamorphic Geology, **3**: 109-118.
- Bell, T.H., Fleming, P.D., and Rubenach, M.J., 1986, Porphyroblast nucleation, growth and dissolution in regional metamorphic rocks as a function of deformation partitioning during foliation development. Journal of Metamorphic Geology, **4**: 37-67.
- Bell, T.H., Forde, A., and Hayward, N., 1992, Can smoothly curving spiral-shaped inclusion trails form without rotation of the porphyroblast. Geology, **20**: 59-62.

- Berman, R.G., 1988, Internally-consistent thermodynamic data for minerals in the system $\text{Na}_2\text{O}-\text{K}_2\text{O}-\text{CaO}-\text{MgO}-\text{FeO}-\text{Fe}_2\text{O}_3-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{TiO}_2-\text{H}_2\text{O}-\text{CO}_2$. *Journal of Petrology*, **29**: 445-522.
- Berman, R.G., 1991, Thermobarometry using multi-equilibrium calculations: a new technique, with petrological applications. *Canadian Mineralogist*, **29**: 833-855.
- Blundy, J.D. and Holland, T.J.B., 1990, Calcic amphibole equilibria and a new amphibole-plagioclase geothermometer. *Contributions to Mineralogy and Petrology*, **104**: 208-224.
- Bowring, S.A., Williams, I.S., and Compston, W., 1989, 3.96 Ga gneisses from the Slave Province, Northwest Territories, Canada. *Geology*, **17** : 971-975.
- Card, K.D. and King, J.E., 1992, The tectonic evolution of the Superior and Slave provinces of the Canadian Shield: introduction. *Canadian Journal of Earth Sciences*, **29** : 2059-2065.
- Carmichael, D.M., Helmstaedt, H.H. and Thomas, N., 1987, A field trip guide in the Frontenac Arch with emphasis on stratigraphy, structure and metamorphism. Meeting of friends of Grenville, 23 p.
- Chatterjee, N.D. and Froese, E., 1975, A thermodynamic study of the pseudo-binary join muscovite-paragonite in the system $\text{KAlSi}_3\text{O}_8-\text{NaAlSi}_3\text{O}_8-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$. *American Mineralogist*, **60**: 985-993.
- Chouinard, A. and Relf, C., 1994, Recent advances in the geology of the Aniak River volcanic belt and Kangguyak gneiss belt. *in* Exploration Overview 1993, NWT Geology Division, CIM, DIAND, Yellowknife.
- Davis, A.M. and Krogstad, E.J., 1995, Neodymium isotopic evidence for sources of granites, northern slave Province, NWT. Geological Survey of Canada Forum 1995, Program with Abstracts, p.32.

Davis, W.J., 1991, Granitoid geochemistry and Late Archean crustal evolution in the central Slave Province. Ph.D. thesis, Memorial University of Newfoundland, St-John's, Nfld.

Davis, W.A. and Hegner, E., 1992, Neodymium isotopic evidence for the tectonic assembly of Late Archean crust in the Slave Province, northwest Canada. *Contributions to Mineralogy and Petrology*, **111**: 493-504.

Davis, W.A., King, J.E., Fryer, B.J. and van Breenan, O., 1990, Petrogenesis and evolution of late Archean granitoids in the central Slave Province: implications for the tectonic development of the Slave Province, Canada. 3rd International Archean Symposium, Perth, Extended Abstracts Volume, p.185-188.

Easton, R. M., 1985, The nature and significance of pre-Yellowknife Supergroup rocks in the Point Lake area, Slave Structural Province, Canada. In *Evolution of Archean Supracrustal Sequences*, Ed. by L.D. Ayres, K.D. Card, and W. Weber, Geological Association of Canada, p. 153-167.

Ferry, J.M. and Spear, F.S., 1978, Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. *Contributions to Mineralogy and Petrology*, **66**: 113-117.

Folinsbee, R.E., Baadsgaard, H., Cumming, G.L., and Green, D.C., 1968, A very ancient island arc. *in* The crust and upper mantle of the Pacific area. Ed. by L. Knopoff, C.L. Drake, and P.J. Hart. American Geophysical Union, Geophysical Monograph 12, p. 441-448.

Fraser, J.A., 1964, Geological notes on northeastern District of Mackenzie, Northwest Territories. Geological Survey of Canada, Paper 63-40.

Frith, R.A., 1987, Precambrian geology of the Hackett River area, District of Mackenzie, N.W.T.. Geological Survey of Canada, Memoir 417.

Fuhrman, M.L. and Lindsley, D.H., 1988, Ternary-feldspar modeling and thermometry. *American Mineralogist*, **73**: 201-215.

Fyson, W.K. and Helmsteadt, H., 1988, Structural patterns and tectonic evolution of supracrustal domains in the Archean Slave Province, Canada. *Canadian Journal of Earth Sciences*, **25** : 301-315.

Heaman, L.M., LeCheminant, A.N. and Rainbird, R.H., 1992, Nature and timing of Franklin igneous events, Canada: Implications for a Late Proterozoic mantle plume and the break-up of Laurentia. *Earth and Planetary Science Letters*, **109**: 117-131.

Helmsteadt, H., Padgham, W.A. and Brophy, J.A., 1986, Multiple dikes in lower Kam Group, Yellowknife belt: evidence for Archean sea-floor spreading? *Geology*, **14**: 562-566.

Henderson, J.B., 1970, Stratigraphy of the Archean Yellowknife Supergroup, Yellowknife Bay-Prosperous Lake area, District of Mackenzie. Geological Survey of Canada, Paper 70-26.

Henderson, J.B., 1981, Archean basins evolution in the Slave Province, Canada. *in* Precambrian plate tectonics. Ed. by A. Kroner, Elsevier, Amsterdam, p. 213-236.

Henderson, J.B., and Easton, R.M., 1977, Archean supracrustal-basement rock relationships in the Keskarrh Bay map area, Slave Structural Province, District of Mackenzie. Geological Survey of Canada, Paper 77-1A, p. 217-221.

Hodges, K.V. and Crowley, P.D., 1985, Error estimation and empirical geothermobarometry for pelitic systems. *American Mineralogist*, **70**: 702-709.

Hodges, K.V. and Spear, F.S., 1982, Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt Moosilauke, New Hampshire. *American Mineralogist*, **67**: 1118- 1134.

Hoffman, P.F., 1986, Crustal accretion in a 2.7-2.5 Ga granite-greenstone terrane, Slave Province, N.W.T.: a prograding trench-arc system?. Geological Association of Canada-Mineralogical Association of Canada, Program with abstracts, **11**: 82.

Hoffman, P.F., 1989, Precambrian geology and tectonic history of North America- an overview. in *The geology of North America*, Ed. by A.W. Bally and A.R. Palmer, Geological Society of America, p. 447-512.

Hoffman, P.F., Tirrul, R., Grotzinger, J.P., Lucas, S.B. and Eriksson, K.A., 1984, The externides of Wopmay orogen, Takijuk Lake and Kikerk Lake map areas, District of Mackenzie. in *Current Research, Part A*, Geological Survey of Canada, Paper 84-1A, p. 383-395.

Holdaway, M.J., 1971, Stability of andalusite and the aluminium silicate phase diagrams. *American Journal of Science*, **271**: 97-131.

Holland, T.J.B. and Blundy, J.D., 1994, Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry. *Contributions to Mineralogy and Petrology*, **116**: 433-447.

Houseman, G.A., McKenzie, D.P. and Molnar, P., 1981, Convective instability of a thickened boundary layer and its relevance for the thermal evolution of convergent continental belts. *Journal of Geophysical Research*, **86**: 6115-6132.

Hrabi, R.B., Grant, J.W. Godin, P.D., Helmsteadt, H., and King, J.E., 1993, Geology of the Winter Lake supra crustal belt, central Slave Province, District of Mackenzie, Northwest Territories. Geological Survey of Canada, Paper 93-1C, p. 71-81.

Irvine, T.N. and Baragar, W.R.A., 1971, A guide to the chemical classification of common volcanic rocks. *Canadian Journal of Earth Sciences*, **8**: 523-548.

Jackson, V.A., 1989, Preliminary geological compilation of the Hepburn Island map area (76M). EGS 1989-11, NWT Geology Division, DIAND, Yellowknife.

Jefferson, C.W., Henderson, M.M., Henderson, J.R and Schaan, S., 1990, Geological setting of stratabound gold occurrences in the Archean Fish-Hook-Turner lakes belt, Bathurst Inlet area, District of Mackenzie, N.W.T. in *Current Research, Part C*, Geological Survey of Canada, Paper 90-1C, p. 349-361.

King, J.E. and Helmsteadt, H., 1989, Deformation history of an Archean fold belt, eastern Point Lake area, Slave Structural Province, NWT. *Canadian Journal of Earth Sciences*, **26**: 106-118.

King J.E., Davis, W.J. and Relf C., 1990, Late Archean tectono-magmatic evolution of the central Slave Province, Canada. 3rd International Archean Symposium, Perth, Extended Abstracts Volume, p.75-76.

King J.E., Davis, W.J. and Relf C., 1992, Late Archean tectono-magmatic evolution of the central Slave Province, Northwest Territories. *Canadian Journal of Earth Sciences*, **29**: 2156-2170.

Kretz, R., 1983, Symbols for rock forming minerals. *American Mineralogist*, **68**: 277-279.

Kusky, T.M., 1989, Accretion of the Archean Slave Province. *Geology*, **17** : 63-67.

Kusky, T.M., 1991, Structural development of an Archean orogen, western Point Lake, Northwest Territories. *Tectonics*, **10** : 820-841.

Laird, J. and Albee, A.L., 1981, Pressure, temperature and time indicators in mafic schists: their application to reconstructing the polymetamorphic history of Vermont. *American Journal of Science*. **281**: 127-175.

LeCheminant, A.N. and Heaman, L.H., 1989, Mackenzie igneous events, Canada: Middle Proterozoic hot spot magmatism associated with ocean opening, *Earth and Planetary Science Letters*, **96**: 38-48.

Liou, J.G., 1973, Synthesis and stability relations of epidote, $\text{Ca}_2\text{Al}_2\text{FeSiO}_{12}(\text{OH})$. *Journal of Petrology*, **14**: 381-413.

Liou, J.G., Kuniyoshi, S. and Ito, K., 1974, Experimental studies of the phase relations between greenschist and amphibolite in a basaltic system. *American Journal of Science*, **274**: 613-632.

- Loosveld, R.J.H. and Etheridge, M.A., 1990, A model for low-pressure metamorphism during crustal thickening, *Journal of Metamorphic Geology*, **8**: 257-267.
- McEachern, S.J., 1993, Structural reconnaissance of gneissic tectonites in the western Hepburn Island map sheet, northernmost Slave Province, Northwest Territories. *in* Current Research, Part C, Geological Survey of Canada, Paper, 93-1C, p. 103-113.
- McMullin, D.W., Berman, R.G. and Greenwood, H.J., 1991, Calibration of the SGAM thermobarometer for pelitic rocks using data from phase-equilibrium experiments and natural assemblages. *Canadian Mineralogist*, **29**: 889-908.
- Morley, C.K., 1988, Out-of-sequence thrusts. *Tectonics*, vol.7, **3**: 539-561.
- Mullen, E.D., 1983, MnO/TiO₂/P₂O₅: a minor element discriminant for basaltic rocks of oceanic environment and its implications for petrogenesis, *Earth and Planetary Science Letters*, **62**: 52-62.
- Padgham, W.A., 1985, Observations and speculations on supracrustal successions in the Slave Structural Province. In *Evolution of Archean Supracrustal Sequences*. Ed. by L.D. Ayres K.D. Card, and W. Weber, Geological Association of Canada, p. 133-151.
- Padgham, W.A. and Fyson, W.K., 1992, The Slave Province: a distinct Archean craton. *Canadian Journal of Earth Sciences*, **29** : 2072-2086.
- Passchier, C.W., Trouw, A.J., Zwart, H.J. and Vissers, R.L.M., 1992, Porphyroblast rotation: *eppur si muove?*. *Journal of Metamorphic Geology*, **10**: 283-294.
- Plyusnina, L.P., 1982, Geothermometry and geobarometry of the plagioclase-hornblende bearing assemblages. *Contributions to Mineralogy and Petrology*, **80**: 140-146.
- Powell, C.McA and Vernon, R.H., 1979, Growth history of garnet porphyroblasts with inclusion spirals in a Karakorum schist. *Tectonophysics*, **54**: 25-43.
- Powell, R. and Holland, T., 1990, Calculated mineral equilibria in the pelite system, KFMASH (K₂O-FeO-MgO-Al₂SiO₃-SiO₂-H₂O). *American Mineralogist*, **75**: 367-380.

Rainbird, R.H. and Jefferson, C.W., 1993, Geology and resource potential of the Neoproterozoic Minto Inlier, Victoria Island, NWT. *in* Exploration Overview 1993, NWT Geology Division, DIAND, Yellowknife, p. 48.

Relf, C., 1992, Geology, structural history and economic potential of the northwestern Anialik River Volcanic belt. EGS 1992-19.

Relf, C., 1993, Preliminary geological map of the northern Anialik River volcanic belt and the northeastern Kangguyak gneiss belt, NWT, Parts of NTS 76M/5,6,10,11,12,14 and 15. EGS-1993-10, Mineral Initiatives, DIAND.

Relf, C., 1994, Preliminary geological map of the southern Anialik River volcanic belt and the northeastern Kangguyak gneiss belt, NWT. Parts of NTS 76M/4, 5, and 6. EGS-1994, Mineral Initiatives, DIAND.

Relf, C., 1994, Progress Report on the Geology of the Anialik River volcanic belt mapping project, EGS 1994-4, DIAND, Geology Division, Yellowknife, 32 p.

Relf, C. and King, J.E., 1989, Distribution of High-T/Low-P metamorphic mineral zones in the central Archean Slave Province: thermal and tectonic controls. Geological Association of Canada- Mineralogical Association of Canada, Program with abstracts, 14, p. A24.

Relf, C., Chouinard, A., Sandeman, H. and Villeneuve, M., 1994, Contact relationships between the Anialik River Volcanic belt and the Kangguyak Gneiss belt, northwestern Slave Province, Northwest Territories. *in* Current Research, Part C, Geological Survey of Canada, Paper 94-1C, p. 49-59..

Rosenfeld, J.L., 1970, Rotated garnets in metamorphic rocks. Geological Society Special Paper 129, 105 p.

Schoneveld, Chr., 1977, A study of typical inclusion patterns in strongly paracrystalline-rotated garnets. *Tectonophysics*, **39**: 453-471.

- Spear, F.S., 1993, Metamorphic phase equilibria and pressure-temperature-time paths. Mineralogical Society of America-Monograph series, 799 p.
- Spry, A., 1963, Origin and significance of snowball structure in garnet. *Journal of Petrology*, **4**: 211-222.
- Tirrul, R., and Bell, I., 1980, Geology of the Anialik River greenstone belt, Hepburn Island map-area, District of Mackenzie. *in* Current Research, part A, Geological Survey of Canada, Paper 80-1A, p. 157-164.
- Thompson, P.H., 1978, Archean regional metamorphism in the Slave Structural Province-a new perspective on some old rocks. *in* Metamorphism in the Canadian Shield. Ed by J.A. Fraser and W.W. Heywood, Geological Survey of Canada, Paper 78-10, p. 85-105.
- Thompson, P.H., 1989, An empirical model for metamorphic evolution of the Archaean Slave Province and adjacent Thelon Tectonic Zone, northwestern Canadian Shield. *in* Evolution of metamorphic belts, Ed. by J.S. Daly, R.A. Cliff, and B.W.D. Yardley, Geological Society Special Publication (London), no. 43, p. 245-263.
- Tracy, R.J., 1982, Compositional zoning and inclusions in metamorphic minerals. *Review of Mineralogy*, **10**: 355-397.
- van Breeman, O., Davis, W.J., and King, J.E., 1992, Temporal distribution of granitoid plutonic rocks in the Archean Slave Province, northwest Canadian Shield. *Canadian Journal of Earth Sciences*, **29**, p. 2186-2199.
- Villeneuve, M.E. and van Breeman, O., 1994, A compilation of U-Pb data from the Slave Province. Geological Survey of Canada, Open File, 53 p.
- Villeneuve, M.E., Hrabi, B., Jackson, V. and Relf, C., 1993, Geochronology of supracrustal sequences in the central and northern Slave Province. *in* Exploration Overview 1993, NWT Geology Division, DIAND, Yellowknife, p.53.
- Yardley, B.W.D., 1977, An empirical study of diffusion in garnet. *American Mineralogist*, **62**: 793-800.

Yeo, G.M., Bailey, G., Crux, J., Fischer, B., Jackson, V.A., Relf, C. and Wahlroth, J., 1983, Preliminary geology of the western Hepburn Island map area, NWT. NTS 76M/3-6, 11-14, EGS 1983-8, NWT Geology Division, DIAND, Yellowknife.

Appendix A. Simplified geology of the map area, modified from Relf (1993; 1994) with location of samples used to pin the isograds and amphibole-plagioclase thermometry (in bold). Assemblages for each of them are in the following table.

Appendix A- Mineral assemblages for the isograds: A-alteration; v-vein; tr-trace amount.										
Bold samples are those analysed for amphibole-plagioclase thermometry or An content.										
Sample #	Act	Hbl	Bt	Qtz	Pl	Chl	Ep	cc	Other/Comments	
3038	X			X	X	X	X	X		
3083	X				X	X	X			
3097	X	X		X	X	X	X			
3171	X	X		X	X					
3349		X	X	X	X	A	X	X	zircon, am-pl	
3350		X		X	X		X		zircon	
3358	X		X	X		A	X			
3569										
3633	X	X		X	X		X			
3651		X		X	X				grunerite	
3655		X		X	X	X	X		apatite	
3660	X	X			X	X				
3673	X	X								
3674	X	X		X		A	X	X	zircon	
4500	X	X		tr	X	A	X		sphene, apatite	
4510	X	X		tr	X		X		sphene, apatite	
4793a		X	X	X	X		X			
4793b	X	X	X	X	X		X			
4794	X	X	X	tr, v	X	X	X	X		
4797	X	X		tr	X	X				
4798	X	X		X	X					
4805	X				X	A				
5139	tr	X		X	X		X		zircon, am-pl	
5278		X		X	X	A	X		sphene, am-pl	

Sample #	Act	Hbl	Bt	Qtz	Pl	Chl	Ep	cc	Other/Comments
5384	X	X		X	X		X		sphene, am-pl
5601	X	X		tr	X	A	X		sphene
5602		X	X	tr	X		X		
5606		X	X	X	X				
5611	X	X	tr	X	X	X	X		
5620b	X	X		X	X		X		
5661	X	X		tr	X		X		
5835		X	tr		X	X	X		sphene
5898	X	X	X	tr	X		tr		relic of igneous texture
6017	X			X	X	A	X	X	zoisite
6130	tr	X		X	X	X	X		
6133	X	X	tr	X	X		tr		am-pl
6134		X	X	X	X		X		
6191	X			X	X		X	X	apatite
6199	X	X		X	X		X	X	n-pl: An04, An20
6200				X	X		X	X	
6203	X			X	X		X	X	An-pl: An04
6442	X	X		X	X	X			
6443	X	X	X	X	X	X			
6446	X			X	X	X			
6448	X			X		X	X	X	An-pl: An04
6449	X	X		X	X		X		apatite
6450	X	X		X	X				
6513	X	X	X	X	X	X	X		zircon
6527		X		X	X				
7301	X	X			X				
7308	X	X		tr	X	X			retrograded hornblende?
7421	X	X		X	X		X	X	titanite

Sample #	Act	Hbl	Bt	Qtz	Pl	Chl	Ep	cc	Other/Comments
7424	X	X		tr	X				
7427	X	X	tr	X	X	A	X		
7443	X	X		X	X	X	X		epidotisation
7452	X	X		X	X		X		
7482		X		X	X		X		
7485		X		tr	X	X	X		
7871a	X	X	X	v	X		X	X	titanite
7871b		X	tr	v	X	A		X	
7881a		X			X	X	X		chlorite and epidote alteration
7888	X	X		tr	X		X		titanite
7893	X	X		X	X		X		sphene, trace of muscovite?
7901	X			X	65%	X,A	X		
7903	X			tr	X		X		
7909	X	X			X	X	X		
7929	X		tr	tr	X		X		am-pl
7936b		X		tr	X				
9091	X			tr	X	A			chlorite alteration
8178	X				X	X	X	X	zoisite
8179	X	X		tr	X	X	X	X	
8180		X			X	X	X	X	
8181	tr	X		tr,v	X		X		biotite rich (20%)
8182		X	X	tr	X	X	X		
8183		X	tr	tr	X	X	X	X	
8184		X		tr	X	X		X	titanite
8185		X		X	X	A	tr		titanite
8186	X	X	tr	X	X	A	X		apatite
8187		X		X	X		X	X	
8188		X	tr	tr	X	X	X	X	

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	41.19	0.86	12.62	0.00	5.06	19.45	0.52	5.41	12.05	1.19	1.23
cats	6.261	0.098	2.261	0.000	0.578	2.473	0.067	1.226	1.963	0.351	0.239

x(ab) in plag: 0.60

x(an) in plag: 0.40

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	747	746	744	743	741	740	736	degC
T (ed-ri)	650	664	679	693	707	721	756	degC

amph.1 8307

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	43.90	1.08	10.40	0.00	3.52	16.13	0.37	8.89	11.97	1.34	0.91
cats	6.576	0.122	1.837	0.000	0.397	2.021	0.047	1.985	1.921	0.389	0.174

x(ab) in plag: 0.72

x(an) in plag: 0.27

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	717	710	703	696	688	681	663	degC
T (ed-ri)	630	641	653	664	675	686	714	degC

amph.2 8307

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	44.48	0.87	9.65	0.06	5.06	15.30	0.32	8.87	11.98	0.70	0.82
cats	6.667	0.098	1.705	0.007	0.571	1.918	0.041	1.981	1.924	0.203	0.157

x(ab) in plag: 0.70

x(an) in plag: 0.29

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	677	669	662	654	646	638	619	degC
T (ed-ri)	619	629	639	649	660	670	695	degC

Note that the analyses are presented as an output from program hb-plag (Holland and Blundy, 1994) and the weight percent includes FeO and Fe₂O₃, the FeO total from the probe analysis being the sum of the two. ed-tr: edenite-tremolite; ed-ri: edenite-richterite.

amph.1 4557

oxide	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
wt %	46.34	0.57	8.91	0.00	4.93	11.12	0.40	12.28	12.18	1.11	0.81
cats	6.770	0.063	1.535	0.000	0.542	1.358	0.049	2.674	1.907	0.314	0.151

x(ab) in plag: 0.73

x(an) in plag: 0.27

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	715	704	692	680	668	657	627	degC
T (ed-ri)	638	646	655	663	672	680	701	degC

amph.2 4557

oxide	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
wt %	46.20	0.59	8.72	0.00	4.86	10.91	0.35	12.20	12.12	0.89	0.82
cats	6.804	0.065	1.514	0.000	0.539	1.343	0.044	2.678	1.913	0.254	0.154

x(ab) in plag: 0.73

x(an) in plag: 0.27

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	689	678	668	657	647	636	610	degC
T (ed-ri)	623	632	640	649	658	667	689	degC

5228# 6	5228# 7	2DEC.33	5228# 8	2DEC.30	5228# 9	5228#10	5228#11
36.42	36.04	36.49	35.94	36.23	35.92	35.95	35.22
21.05	20.94	20.61	20.74	20.41	20.89	20.69	20.7
0	0.12	0.16	0	0.14	0	0	0
0	0	0	0	0	0	0	0
35.73	36.03	36.07	35.93	36.29	35.65	34.81	35.09
0.9	1.13	1.25	1.33	1.56	1.56	1.77	2.05
2.45	2.5	2.5	2.46	2.23	2.26	2.28	2.32
3.34	2.76	2.7	2.55	2.65	2.72	2.55	2.39
99.89	99.52	99.78	98.95	99.51	99	98.05	97.77
FORMULA (BASIS 24 OXYGENS)							
5.908	5.881	5.937	5.903	5.931	5.896	5.942	5.864
0.092	0.119	0.063	0.097	0.069	0.104	0.058	0.136
6	6	6	5	6	6	6	6
3.933	3.909	3.89	3.917	3.871	3.939	3.972	3.926
0	0.015	0.02	0	0.017	0	0	0
0	0	0	0	0	0	0	0
3.933	3.924	3.91	3.917	3.888	3.939	3.972	3.926
4.848	4.918	4.908	4.935	4.97	4.895	4.811	4.887
0.124	0.157	0.172	0.185	0.217	0.217	0.247	0.289
0.593	0.609	0.605	0.603	0.544	0.553	0.561	0.575
0.581	0.483	0.472	0.448	0.464	0.478	0.452	0.426
6.146	6.167	6.157	6.171	6.195	6.143	6.071	6.177
0.891	0.890	0.890	0.891	0.901	0.898	0.896	0.895
0.789	0.797	0.797	0.800	0.802	0.797	0.792	0.791
0.020	0.025	0.028	0.030	0.035	0.035	0.041	0.047
0.095	0.078	0.098	0.073	0.088	0.078	0.074	0.069
0.096	0.099	0.077	0.098	0.075	0.090	0.092	0.093

Appendix C-Microrobe analysis of zoned garnet, sample 5228.

	5228#1	5228# 2	5228# 3	2DEC.36	5228# 4	5228# 5	2DEC.35
SiO2	36.46	36.34	36.33	36.49	36.02	36.57	36.78 SiO2
Al2O3	21.17	20.9	21.18	20.86	21.02	21.5	20.94 Al2O3
TiO2	0	0	0	0	0	0	0.38 TiO2
CR2O3	0	0	0	0.15	0	0	0 CR2O3
FeO	36.69	35.9	35.52	35.73	35.89	35.74	36.58 FeO
MnO	0.56	0.53	0.61	0.76	0.76	0.88	1.05 MnO
MgO	2.75	2.63	2.79	2.74	2.62	2.6	2.14 MgO
CaO	2.06	3.1	3.22	3.1	2.92	3.23	2.85 CaO
TOTAL	99.69	99.4	99.65	99.83	99.23	100.52	100.72 TOTAL
FORMULA (BASIS 24 OXYGENS)							
Si	5.92	5.92	5.893	5.919	5.885	5.886	5.929 Si
Al	0.08	0.08	0.107	0.081	0.115	0.114	0.071 Al
sum	6	6	6	6	6	6	6 sum
Al	3.971	3.932	3.943	3.908	3.932	3.964	3.908 Al
Ti	0	0	0	0	0	0	0.046 Ti
Cr	0	0	0	0.019	0	0	0 Cr
sum	3.971	3.932	3.943	3.927	3.932	3.964	3.954 sum
Fe	4.982	4.89	4.819	4.847	4.904	4.811	4.933 Fe
Mn	0.077	0.073	0.084	0.104	0.105	0.12	0.143 Mn
Mg	0.666	0.638	0.675	0.662	0.639	0.623	0.514 Mg
Ca	0.358	0.541	0.56	0.538	0.511	0.556	0.492 Ca
sum	6.083	6.142	6.138	6.151	6.159	6.11	6.082 sum
Fe/Fe+Mg	0.882	0.885	0.877	0.880	0.885	0.885	0.906 Fe/Fe+Mg
Fe/FeMnMgCa	0.819	0.796	0.785	0.788	0.796	0.787	0.811 Fe/FeMnMgCa
Mn/FeMnMgCa	0.013	0.012	0.014	0.017	0.017	0.020	0.024 Mn/FeMnMgCa
Ca/FeMnMgCa	0.059	0.088	0.091	0.108	0.083	0.091	0.085 Ca/FeMnMgCa
Mg/MgFeCaM	0.109	0.104	0.110	0.087	0.104	0.102	0.081 Mg/MgFeCaM

Appendix B- Average compositions, from microprobe analysis, of selected samples from the volcanic belt.

garnet 6118		garnet 6121	biotite 6118		biotite 6121
SiO2	37.13	36.45	SiO2	35.40	33.73
Al2O3	20.95	20.50	Al2O3	18.65	16.80
TiO2	0.00	0.00	TiO2	0.12	1.74
FeO	35.72	37.83	Cr2O3	1.59	0.00
MnO	1.48	1.88	FeO	18.60	26.84
MgO	3.63	1.79	MnO	0.00	0.00
CaO	1.49	1.35	MgO	11.22	6.66
			CaO	0.00	0.00
			K2O	8.70	9.31
			Na2O	0.19	0.00
			Cl	0.00	0.00
TOTAL	100.40	99.80			
FORMULA (BASIS 24 OXYGENS)			FORMULA (BASIS 22 OXYGENS)		
Si	5.962	5.970	TOTAL	94.50	95.30
Al	0.019	0.030	Si	2.698	5.366
			Al	2.604	2.634
Al	3.920	3.928		8.000	8.000
Ti	0.000	0.000			
			Al	0.748	0.518
			Ti	0.014	0.208
			Cr	0.726	0.000
Fe	4.978	5.182	Fe	2.372	3.572
Mn	0.200	0.246	Mn	0.000	0.000
Mg	0.868	0.460	Mg	0.550	1.580
Ca	0.256	0.236			
				5.860	5.876
			Ca	0.000	0.000
			K	1.698	1.890
			Na	0.058	0.000
				1.750	1.890
					122

amph.1 7936

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	46.70	0.60	9.30	0.00	4.13	12.44	0.32	11.20	11.76	0.76	0.26
cats	6.873	0.066	1.614	0.000	0.458	1.531	0.040	2.456	1.854	0.217	0.049

x(ab) in plag: 0.44 x(an) in plag: 0.56

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	672	669	667	664	661	658	652	degC
T (ed-ri)	641	656	671	686	701	717	755	degC

amph.2 7936

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	45.34	0.42	10.72	0.00	4.87	12.02	0.30	10.70	11.92	1.10	0.30
cats	6.683	0.047	1.863	0.000	0.540	1.481	0.037	2.350	1.883	0.314	0.056

x(ab) in plag: 0.52 x(an) in plag: 0.48

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	706	706	706	706	706	705	705	degC
T (ed-ri)	643	659	675	692	708	725	765	degC

amph.1 6133

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	43.21	1.08	10.56	0.00	5.78	15.26	0.29	8.35	11.85	0.82	0.93
cats	6.505	0.122	1.874	0.000	0.655	1.921	0.037	1.873	1.911	0.239	0.179

x(ab) in plag: 0.66 x(an) in plag: 0.33

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	714	706	698	690	682	674	654	degC
T (ed-ri)	658	669	679	690	700	711	737	degC

amph.2 6133

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	45.25	0.95	9.26	0.00	4.58	15.40	0.27	9.22	12.01	0.80	0.70
cats	6.740	0.106	1.626	0.000	0.514	1.919	0.034	2.047	1.917	0.231	0.133

x(ab) in plag: 0.66 x(an) in plag: 0.34

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	690	682	673	665	657	649	628	degC
T (ed-ri)	635	645	656	666	676	687	713	degC

amph.3 6133

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	45.79	1.15	8.02	0.00	5.03	15.11	0.39	9.72	11.55	1.00	0.54
cats	6.825	0.129	1.409	0.000	0.564	1.884	0.049	2.159	1.845	0.289	0.103

x(ab) in plag: 0.66 x(an) in plag: 0.33

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	734	720	706	692	677	663	627	degC
T (ed-ri)	693	700	707	714	721	728	745	degC

amph.3 (rim) 5384

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	46.70	0.62	8.71	0.00	6.36	9.72	0.26	12.64	12.33	0.58	0.52
cats	6.789	0.068	1.493	0.000	0.696	1.182	0.032	2.739	1.921	0.164	0.096

x(ab) in plag: 0.41 x(an) in plag: 0.57

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	720	708	697	685	673	661	632	degC
T (ed-ri)	700	709	717	726	734	743	765	degC

amph.4 (core) 5384

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	47.30	0.53	8.92	0.00	5.19	10.14	0.18	12.71	12.32	0.54	0.38
cats	6.861	0.058	1.525	0.000	0.567	1.230	0.022	2.747	1.915	0.152	0.070

x(ab) in plag: 0.41 x(an) in plag: 0.57

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	676	669	662	655	648	641	623	degC
T (ed-ri)	651	663	674	686	698	710	739	degC

amph. 5 (rim) 5384

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	47.83	0.52	8.70	0.00	6.09	9.33	0.23	13.35	12.47	0.92	0.32
cats	6.831	0.056	1.465	0.000	0.654	1.115	0.028	2.841	1.908	0.255	0.058

x(ab) in plag: 0.47 x(an) in plag: 0.46

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	761	749	737	726	714	702	672	degC
T (ed-ri)	700	718	727	736	745	754	777	degC

amph.3 5278

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	43.61	0.57	11.27	0.00	4.00	16.43	0.55	7.91	12.08	1.00	1.00
cats	6.553	0.064	1.996	0.000	0.452	2.065	0.070	1.771	1.945	0.291	0.192

x(ab) in plag: 0.66 x(an) in plag: 0.33

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	673	668	669	669	669	669	669	degC
T (ed-ri)	593	608	623	638	653	668	706	degC

amph.1 (rim) 5384

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	47.33	0.49	8.46	0.00	6.19	9.14	0.24	13.07	12.29	0.68	0.27
cats	6.861	0.053	1.446	0.000	0.675	1.108	0.029	2.824	1.909	0.191	0.050

x(ab) in plag: 0.47 x(an) in plag: 0.48

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	719	709	698	687	677	666	640	degC
T (ed-ri)	691	701	710	719	729	738	761	degC

amph.2 (core) 5384

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	47.10	0.47	9.57	0.00	6.11	9.57	0.28	12.59	12.25	0.79	0.29
cats	6.779	0.051	1.624	0.000	0.661	1.151	0.034	2.701	1.889	0.220	0.053

x(ab) in plag: 0.53 x(an) in plag: 0.46

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	702	696	689	683	676	670	654	degC
T (ed-ri)	665	678	690	702	714	726	756	degC

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	44.66	0.62	11.20	0.00	7.32	10.84	0.23	10.98	11.45	1.49	0.11
cats	6.512	0.068	1.925	0.000	0.804	1.322	0.028	2.386	1.789	0.421	0.020

x(ab) in plag: 0.59 x(an) in plag: 0.40

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	771	765	760	754	748	742	728	degC
T (ed-ri)	706	719	732	745	758	771	804	degC

amph.1 5278

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	45.13	0.57	9.70	0.00	2.57	17.11	0.50	8.56	12.29	1.09	0.78
cats	6.767	0.064	1.715	0.000	0.290	2.145	0.064	1.913	1.975	0.317	0.149

x(ab) in plag: 0.70 x(an) in plag: 0.29

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	664	661	658	655	651	648	640	degC
T (ed-ri)	570	583	596	609	622	635	668	degC

amph.2 5278

oxide	SiO2	TiO2	Al2O3	Cr2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O
wt %	43.80	0.43	11.36	0.00	4.57	16.43	0.56	7.86	12.31	0.87	1.13
cats	6.534	0.048	1.998	0.000	0.513	2.050	0.071	1.747	1.968	0.252	0.215

x(ab) in plag: 0.67 x(an) in plag: 0.33

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	665	664	664	663	662	661	659	degC
T (ed-ri)	586	600	615	629	643	658	693	degC

Note that the analyses are presented as an output from the hb-plag program (Holland and Blundy, 1994) and the weight percent includes FeO and Fe₂O₃, the FeO total from the probe analysis being the sum of the two. ed-tr: edenite-tremolite; ed-ri: edenite-richterite.

amph 1-3349

oxide	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
wt %	43.57	0.54	11.39	0.00	6.49	13.24	0.20	9.53	12.08	1.13	0.76
cats	6.449	0.060	1.988	0.000	0.723	1.639	0.025	2.102	1.916	0.324	0.144

x(ab) in plag: 0.66 x(an) in plag: 0.34

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	738	732	726	721	715	709	695	degC
T (ed-ri)	652	664	676	688	700	712	743	degC

amph 2-3349

oxide	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
wt %	40.53	0.74	12.23	0.00	5.50	19.63	0.48	4.69	11.53	1.02	1.07
cats	6.305	0.087	2.243	0.000	0.644	2.554	0.063	1.087	1.922	0.308	0.212

x(ab) in plag: 0.67 x(an) in plag: 0.33

P	0	2	4	6	8	10	15	kbar
T (ed-tr)	702	702	702	702	702	702	702	degC
T (ed-ri)	627	642	656	671	686	701	738	degC

Appendix D (cont'd): average analysis for sample 6322 and 6409

	Grt 6322	Grt 6409		Bt 6322	Bt 6409
SiO2	36.52	36.82	SiO2	34.285	35.365
Al2O3	20.34	21.17	Al2O3	17.225	20.2
TiO2	0.045	0	TiO2	3.025	1.545
Cr2O3	0	0	Cr2O3	0.06	0.195
FeO	31.405	27.505	FeO	24.15	17.63
MnO	2.115	8.485	MnO	0.14	0.2
MgO	2.255	3.205	MgO	7.92	10.7
CaO	6.44	2.025	CaO	0.21	0.06
			K2O	8.39	9.365
TOTAL	99.12	99.21	Na2O	0	0.005
			CL	0.03	0.005
Si	5.9475	5.9625	TOTAL	95.435	95.27
Al	0.0525	0.0375	Si	5.336	5.332
	6	6	Al	2.664	2.668
Al	3.851	4.0025		8	0
Ti	0.005	0			8
Cr	3.856	4.0025	Al	0.4965	0.923
			Ti	0.3545	0.1755
Fe	4.2775	3.725	Cr	0.0075	0.023
Mn	0.2915	1.164	Fe	3.1435	2.223
Mg	0.5475	0.7735	Mn	0.0185	0.0255
Ca	1.1235	0.3515	Mg	1.838	2.4045
				0	0
	6.24	6.014		5.8585	5.7745
			Ca	0.035	0.0095
			K	1.666	1.802
			Na	0	0.002
				1.701	1.8135
			Cl	0.009	0.0015

Note that in appendix D, Grt is for garnet and Bt for biotite

Appendix D (cont'd). Average microprobe analysis for sample 6354

	Grt 6354		Bt 6354		Ms 6354		Pl 6354
SIO2	36.540	SIO2	34.710	SIO2	45.830	SIO2	62.905
AL2O3	0.750	AL2O3	18.710	AL2O3	34.678	AL2O3	23.265
TIO2	0.000	TIO2	0.660	TIO2	0.205	K2O	0.153
CR2O3	0.000	CR2O3	0.110	CR2O3	0.143	CAO	4.363
FE0	30.570	FE0	21.760	FE0	2.010	NA2O	9.582
MNO	7.985	MNO	0.300	MNO	0.028	FE0	0.000
MGO	2.430	MGO	8.670	MGO	0.788		
CAO	1.220	K2O	9.630	CAO	0.000	TOTAL	100.268
		CAO	0.000	K2O	10.578		
TOTAL	99.495	NA2O	0.000	NA2O	0.585		
		CL	0.080	BAO	0.000	Si	5.561
Si	5.965	TOTAL	94.630	CL	0.000	AL	2.424
AL	0.035			TOTAL	94.843		
		Si	5.410	Si	6.161		
		AL	2.590	AL	1.839	K	0.017
					8.000	CA	0.413
AL	3.958					NA	1.642
Ti	0.000						
CR	0.000	AL	0.848	AL	3.656		
		Ti	0.077	Ti	0.021		
		CR	0.014	CR	0.015		
	3.958	FE	2.837	FE	0.226	FE	2.072
FE	4.173	MN	0.040	MN	0.003		
MN	1.105	MG	2.014	MG	0.158		
MG	0.592				4.080		
CA	0.214						
			5.830				
		K	1.915	CA	0.000		
	6.083	CA	0.000	K	1.814		
		NA	0.000	NA	0.152		
			1.915	BA	0.000		
		CL	0.020		1.967		
				CL	0.000		

Appendix D (cont'd): average microprobe analysis for sample 6355

	Grt 1 (core)	Grt 2 (mantle)	Grt 3 (rim)		Bt 1	Bt 2	Bt 3
SiO2	36.843	37.140	37.980	SiO2	34.19	34.525	33.95
Al2O3	20.713	20.718	21.049	Al2O3	18.085	17.7	17.34
TiO2	0.000	0.000	0.000	TiO2	0.35	0.96	0.675
Cr2O3	0.005	0.023	0.008	Cr2O3	0.01	0.06	0.06
FeO	31.935	31.988	30.943	FeO	28.55	27.89	28.82
MnO	3.150	3.355	3.928	MnO	0.335	0.325	0.37
MgO	1.750	1.588	1.343	MgO	5.895	5.59	5.645
CaO	4.928	5.263	6.274	CaO	0	0.005	0
TOTAL	99.323	100.073	101.524	K2O	8.295	9.055	8.515
Si	5.992	6.000	6.032	Na2O	0.27	0.085	0.07
Al	0.015	0.012	0.004	Cl	0.13	0.135	0.145
				TOTAL	96.11	96.33	95.59
Al	6.006	6.012	6.036	Si	5.396	5.4385	5.4135
Ti	3.956	3.934	3.936	Al	2.604	2.5615	2.5865
Cr	0.000	0.000	0.000		8	8	8
	0.001	0.003	0.001				
	3.956	3.937	3.937	Al	0.76	0.725	0.6725
Fe	4.343	4.323	4.112	Ti	0.0415	0.1135	0.081
Mn	0.434	0.460	0.528	Cr	0.001	0.0075	0.0075
Mg	0.4	0.383	0.318	Fe	3.7685	3.6745	3.843
Ca	0.8	0.911	1.066	Mn	0.045	0.043	0.0495
				Mg	1.3865	1.313	1.342
	6.060	6.077	6.024		6.0025	5.8765	5.9955
				Ca	0	0.001	0
				K	1.67	1.8205	1.7315
				Na	0.0825	0.026	0.0225
					1.7525	1.8475	1.754
				Cl	0.035	0.0355	0.0395

Appendix D (cont'd). Microprobe analysis for traverse A-A', sample 6552.

	Grt1#1	Grt1#2	Grt1#3	Grt1#4	Grt1#5	Grt22-23-50	G6552.55	Grt1.7	Grt1#6	G6552.41
SiO2	37.15	37.14	37.54	37.44	36.48	36.757	36.92	36.75		36.43
Al2O3	20.9	20.87	20.54	20.68	20.42	20.673	21.13	20.79	36.97	20.48
TiO2	0	0	0	0	0	0.030	0	0.01	20.52	0
FeO	26.33	29.97	31.54	32.07	29.56	28.060	28.23	27.63	0	25.73
MnO	11.66	8.01	6.27	5.39	8.67	9.027	9.22	9.64	27.19	11.28
MgO	1.48	2.01	2.48	2.67	1.68	1.783	1.67	1.34	10.84	0.97
CaO	4.12	3.11	2.87	2.76	2.94	2.900	2.73	3.06	1.39	3.48
									3.48	
TOTAL	101.64	101.11	101.23	101.02	99.75	99.230	99.9	99.22	100.39	98.37
Si	2.977	2.984	3.006	3	2.982	6.002	5.986	6.007		6.017
Al	0.023	0.016	0	0	0.018	0.012	0.014	0		0
	3	3	3.006	3	3	6.014	6	6.007	2.999	6.017
									0.001	
Al	1.951	1.961	1.939	1.953	1.95	3.967	4.024	4.006	3	3.986
Ti	0	0	0	0	0	0.004	0	0.002		0
									1.961	
	1.951	1.961	1.939	1.953	1.95	3.971	4.024	4.008	0	3.986
									1.961	
Fe	1.764	2.014	2.113	2.149	2.021	3.831	3.827	3.777		3.554
Mn	0.791	0.545	0.425	0.366	0.6	1.250	1.266	1.334	1.845	1.578
Mg	0.177	0.24	0.296	0.319	0.205	0.433	0.404	0.327	0.745	0.239
Ca	0.353	0.267	0.246	0.237	0.258	0.508	0.474	0.537	0.167	0.616
									0.302	
	3.086	3.066	3.079	3.071	3.084	6.021	5.971	5.975	3.059	5.987

END

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