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Stratigraphy and Alteration of Gabbroic Rocks near the San
Antonio Gold Mine in the Rice Lake Area, Southeastern
Manitoba.

by

Doreen E. Ames

Thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment
of the requirements for the degree
Master of Science

Department of Geology
Carleton University
Ottawa, Ontario, Canada.

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Stratigraphy and Alteration of Gabbroic Rocks near the San
Antonio Gold Mine in the Rice Lake Area, Southeastern
Manitoba.

submitted by Doreen E. Ames

in partial fulfilment of the requirements for
the degree of Master of Science

Thesis Supervisor

Chairman, Department of Geology

Carleton University
September 8, 1988

Abstract

The San Antonio Mine, a vein-type gold deposit in the Rice Lake area, is localized in the leucogabbroic portion of the San Antonio Sill, a layered mafic intrusion in the western part of the Uchi subprovince of the Archean Superior province. The mafic sill consists of melagabbro, leucogabbro and gabbro with local granophyric leucogabbro. The compositional variations, distribution of rock types and preserved igneous textures in the San Antonio Sill are explained better by in situ differentiation than either immiscibility or multiple intrusions.

Regional metamorphism to greenschist facies is postdated by gold-associated hydrothermal alteration dominated by carbonatization. Carbonatization occurred syn- to late-deformation. Alteration isograds are characterized by changes of alteration mineral assemblages in the leucogabbro:

- 1) actinolite + epidote + CO_2 = chlorite + calcite + quartz
- 2) titanite + CO_2 = rutile + calcite + quartz
- 3) chlorite + calcite + albite + CO_2 = paragonite + ankerite + quartz + H_2O
- 4) chlorite + calcite + CO_2 + K^+ = muscovite + ankerite + quartz + H_2O .

Mapping these isograds indicates that the zonation varies from isograd 1 to 4 towards the gold-bearing structures. Adjacent to the veins, there is the assemblage albite, paragonite and muscovite which restricts log a (Na^+/K^+) of the fluid to approximately 0.7 at that point. Similar alteration assemblages and zonation adjacent to three vein sets of differing ages in the leucogabbro indicate that the composition of the fluid in the hydrothermal system remained constant over the time span required to form the veins. In contrast, alteration assemblages in the melagabbro reflect only isograds 1 and 2 and, with increasing alteration, chlorite and ankerite were formed. This reflects an increase in XCO_2 with a different starting composition.

Mass balance calculations showed that CO_2 , S and K were added to the leucogabbro from the hydrothermal fluid, with a change in oxidation state of the iron to reducing conditions. Metasomatic albite and tourmaline at the contact of the veins indicate that sodium and boron were also added locally. Pyrite, spatially and temporally related to gold, formed late in the alteration sequence, postdating the precipitation of muscovite and ankerite. Late chlorite-calcite-quartz veins crosscut and replace earlier formed alteration minerals.

Reactions involving alteration minerals and CO_2 and K^+ identified as mobile components in mass balance calculations, demonstrate that during isothermal isobaric metasomatism, isograds (1-3) can form during an increase in XCO_2 only. Mineral assemblages restrict the maximum temperature to approximately 440°C . Isograd (4) requires an

activity gradient of K^+ . The alteration path from isograd (1) to (4) can be modelled utilizing activity gradients of the mobile components CO_2 and K^+ .

The recognition of systematic changes in hydrothermal alteration assemblages towards gold-bearing structures provides a method of locating ore within carbonate haloes of any scale.

Acknowledgements

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CHAPTER 1

INTRODUCTION

1.1 Purpose of the Study

A relationship between gold mineralization and carbonate alteration has been recognized in many Precambrian gold camps (Robert and Kelly, 1987; Dube et al., 1987, 1986b; Clark et al., 1986; Melling et al., 1986; Phillips, 1986; Fyon and Crocket, 1982 and MacGeehan et al., 1982). Most alteration studies have emphasized vein-scale alteration, although a few have examined more pervasive alteration further from the deposits (Clark et al., 1986, Fyon and Crockett, 1982).

In the Rice Lake area, Manitoba, Bragg (1943) described five general types of alteration in a "sill-like body of basic rock", "classified as a meta-diorite" at the San Antonio Mine and wallrock alteration adjacent to gold-bearing stockwork veins. Economic quantities of gold have been found to date only within the San Antonio Sill. The San Antonio Mine is a vein-type gold deposit that occurs within a layered mafic intrusion, in the Uchi subprovince of the Canadian Shield, in Manitoba (Figure 1), (Ames et al., 1987).

This study is concerned with the nature and distribution of three mafic intrusions and hydrothermal alteration. Due to the grain size difference between the sills and extrusive basaltic sequence and the presence of

Figure 1: Location of the Rice Lake area, Bissett southeastern Manitoba.

carbonate-free mineral assemblages within the sills, the sills were selected for the alteration study. The homogeneity of the host rock enables the investigation of variations in alteration assemblage relative to the mineralized zone and the mineralogical data provide an opportunity to possibly reconstruct changes in the composition of the fluid with time.

The objectives of the present study are to:

- 1) Document the variations in composition of the mafic intrusive rocks and map their spatial distribution.
- 2) Document the composition and distribution of alteration assemblages and to examine the relationships between alteration and primary compositional variations within the mafic intrusions.
- 3) Evaluate the spatial and temporal relationship of hydrothermal alteration to gold deposition and to igneous, metamorphic and structural events in the area.
- 4) Discuss the constraints placed on the physical and chemical conditions of the hydrothermal fluid by the wallrock assemblages.

1.2 Location and Access

The town of Bissett, near the San Antonio Mine, is situated on the north shore of Rice Lake 160 km northeast of Winnipeg, Manitoba (Figure 1). The area is accessible by highway from Pine Falls and Lac du Bonnet. There is a private air service for float planes on Rice Lake.

1.3 Exploration History

The first gold discovered in Manitoba was found on the north shore of Rice Lake in 1911 on what is now the Gabrielle claim. Further activity in the region led to the discovery of the showing on which the San Antonio shaft was sunk in 1932. Between 1932 and 1968 the mine produced 45 million grams of gold. Sporadic production through to 1985 added another 3 million grams (Table 1).

1.4 Previous and Current Work

Mapping of the Rice Lake area was initiated in 1912 by E. Moore of the Geological Survey of Canada (GSC), in order to document the gold occurrences and to assess the economic potential of the area. This reconnaissance program was continued by Cooke (1922) and Wright (1932). Stockwell (1938) produced detailed maps of the area in and around the San Antonio Mine and in 1945 published a 1:63,380 scale map of the volcanic belt containing the gold deposits.

Other studies of the area include that of Davies (1963), who mapped the geology and gold deposits in the Rice

YEARS OF PRODUCTION.	COMPANY	GRADE g/tonne	PRODUCTION kg Au
1932-1968	SAN ANTONIO GOLD MINES LTD.	8.1	41,519 6,301 Ag
1972	CHEMALLOY MINERALS (60 day option)	---	-----
1982	LATHWELL RESOURCES (BRINCO MINING LTD.	6.51	344
1983	NEW FOURTY FOUR MINES LTD.)		137
1985	SAN ANTONIO RESOURCES (INCO LTD., QUEST RESOURCES Private Investors)	CALCULATED RESERVES	13,063 kg Au
(Compiled from Richardson & Ostry, 1987; Hogan, 1981)			

Table 1: Production History of the San Antonio Mine

Lake - Wanipigow area and Stephenson (1972), who classified the gold deposits. Whiting (1986) is presently undertaking a lithogeochemical study of the host rocks of the San Antonio Mine.

The Manitoba Mines Branch completed an integrated study of the Rice Lake region, (McRitchie and Weber, 1971) and a number of annual summary reports on mineral occurrences, geochronology and fluid inclusion studies (Theyer, 1983, 1984; Stewart, 1985; Turek et al., 1985; Strong and Gale, 1985).

In 1984 the GSC began a five year study centred on the San Antonio Mine. An area, 8 km by 12 km, was mapped at a scale of 1:10,000 with emphasis on the structural history of the region (Poulsen et al., 1986). Tirschmann (1986) completed a B.Sc. thesis on the volcanic stratigraphy in the Rice Lake area. Lau (1988) completed a structural study of the San Antonio Mine and a fluid inclusion study of the veins is in progress (L. Diamond, Carleton University).

Various aspects of alteration associated with gold mineralization at the San Antonio Mine were described by Stockwell (1938), Bragg (1943) and Davies (1963).

1.5 Methods and Sample Distribution

Subsurface structural studies and sampling were carried out for three weeks in December 1985 and for one week in March 1986 when Inco Ltd. reopened the mine for underground exploration. Surficial mapping of the mine stratigraphy (6

km X 0.7 km), was completed in three weeks during August 1987. Samples labelled with 84- were collected by K.H. Poulsen in 1984 in the San Antonio Mine. Sample location maps are in the pocket (Figures 2b-d). A simplified sketch of the geology is included (Figure 2) and a surface geology map at 1:5000 scale is contained in the pocket (Figure 2a). Due to the distribution of drill holes and the lack of outcrop, the dip of the gabbro east of Transect III, was calculated by projecting drillholes, adjacent and offset along strike, into a cross-section. Utilizing drillholes 74-4 and 86-3 and 74-4 and 86-4 the dip was calculated to be 62°N and utilizing 86-6, 87-1 and 87-2 the dip further along strike to the northeast was determined to be 75°N (Figure 2a).

Petrographic descriptions of 211 thin sections, 42 polished thin sections and 45 polished sections were completed with the results summarized in Appendix 1. X-ray diffraction and semi-quantitative modal estimates were performed by G. LeCheminant of the GSC for paragonite and muscovite and the results are included in Appendix 1. Carbonate-bearing slabs were stained utilizing a solution described by Evamy (1963), to determine the distribution, texture and habit of carbonate species. Electron microprobe analyses were performed by G. LeCheminant. Appendix 2 contains microprobe analyses for vein, alteration and host rock minerals from 12 polished thin sections and 4 polished sections.

Figure 2: Simplified geology of the Rice Lake area

Chemical analyses of 185 samples for major and minor elements were done by the Analytical Chemistry Section under the supervision of G. LaChance, Mineral Resource Division of the GSC. These data are listed in Appendix 3 (Tables 14,15). Sample densities for mass balance calculations were determined utilizing a Mettler balance and an air picnometer; data are presented in Appendix 3.

CHAPTER 2

GENERAL GEOLOGY

The San Antonio Mine is located in the Uchi Subprovince of the Archean Superior Province within the Rice Lake - Beresford Lake greenstone belt (Figure 3) which is 150 km long and attains a maximum width of 22 km. The belt is bounded to the north by the Wanipigow River Plutonic Complex and to the south by the Manigotagan gneissic belt.

2.1 Stratigraphy

The supracrustal rocks in the Rice Lake - Beresford Lake greenstone belt have been divided into the metavolcanic rocks of the Rice Lake Group and the subaerial metasedimentary rocks of the San Antonio Formation (Stockwell, 1938). The Rice Lake Group was further subdivided into three subgroups based on mapping in the eastern part of the belt in Manitoba (Table 16), (Campbell, 1971; Weber, 1971 and Seneshen and Owens, 1985.)

In the Rice Lake area, the Rice Lake Group consists of a northeast-dipping homoclinal, dominantly subaerial sequence of metamorphosed felsic to intermediate volcaniclastic rocks (the prefix "meta" will be inferred since all rocks are metamorphosed). Basaltic sheet flows constitute an apparent width of 80 metres of the 4.5 kilometre-wide succession. A preliminary age determination of a feldspar porphyritic dacite unit yields a U/Pb zircon

Figure 3: Geology of the Rice Lake-Beresford Lake greenstone belt (modified from Poulsen and Robert, 1988).

PRE-CAMBRIAN	CUMMINGS LAKE FORMATION		
	RICE LAKE GROUP	CUMMINGS LAKE FORMATION	WAGNER
		SEM LAKE SUB GROUP	LAKE
		HILL	SHORE

Table 16: Generalized stratigraphic units in the Rice Lake-Beresford Lake area (Richardson et al., 1987).

age of 2525 to $2718 \pm 2\text{Ma}$ and a Pb isochron age of 2808 . A felsic tuff unit, stratigraphically lower than the dacite yielded a Pb isochron age of $2739 \pm 2\text{Ma}$ with an estimated concordia age of $2732 \pm 2\text{Ma}$ (Turek et al., 1987).

The San Antonio Formation consists of trough- and planar-crossbedded arkose and polymictic conglomerate which unconformably overlies the Rice Lake Group.

2.2 Intrusive Rocks

The Rice Lake Group contains numerous synvolcanic intrusions (Figure 3). Gabbroic and diabasic sills and dykes show compositional characteristics similar to those of the tholeiitic mafic extrusive rocks, and are believed to be synvolcanic (Weber, 1971; Poulsen et al., 1986). In the eastern part of the Rice Lake area, there is a large synvolcanic gabbroic body, bounded by two faults on the north and south. Three parallel narrow mafic bodies at Rice

Lake are sub-concordant. One of the sills, the host to the San Antonio Mine, has historically been called a "diabase" (Stockwell, 1938; Bragg, 1941; Davies, 1963; Stephenson, 1972; Poulsen et al., 1986). In some recent work it has been proposed that the sill is a sequence of mafic flow and tuffaceous rocks (Theyer, 1984; Whiting and Sinclair, 1986). However, Ames et al (1987) have shown that the host rock to the San Antonio Mine, the San Antonio Sill is a layered mafic intrusion, consisting of melagabbro and leucogabbro.

The Ross River tonalite (17.7 km by 12.9 km), intruded the core of the Rice Lake - Beresford Lake greenstone belt. The Ross River pluton is 2712 - 2765 Ma old (U-Pb determination) and is coeval with the volcanic rocks of the Rice Lake Group (Turek et al., 1987). Compositionally similar plugs, sills and dykes intrude the Rice Lake volcanoclastic rocks.

Swarms of quartz-feldspar porphyry dykes crosscut both volcanic rocks and mafic intrusions. These dykes may be related to the same igneous event as the Ross River Pluton. Alkalic and diabasic dykes also crosscut the volcanic and gabbroic rocks but their relationship to the feldspar porphyry dykes is not known.

2.3 Regional Structure

The margins of the Rice Lake - Beresford Lake belt are the sites of two large-scale structures, the Wanipigow and Manigotogan faults (Figure 3). The Rice Lake area has been

divided into three domains. In the north, a one km-wide deformation zone is bounded to the south by the Wanipigow Fault and to the north by the Wanipigow River Complex (Figure 4). Rocks within the zone have undergone several periods of deformation and have been transposed into the strike of the Wanipigow Fault. On the outcrop scale, compositional layering indicates the presence of mafic and felsic volcanic rocks and felsic plutonic rocks.

South of Rice Lake is a relatively massive sequence of steeply dipping intermediate and felsic volcanic rocks. The rocks are cut by discrete northerly to northwesterly trending shear zones. The intensity of foliation development increased in the proximity of the Manigotogan Fault.

The central Rice Lake structural domain, which contains the San Antonio Mine, forms a wedge bounded by the dextral transcurrent Wanipigow Fault in the north, the Normandy Creek Shear Zone in the east and the San Antonio Formation in the west (Poulsen et al., 1986). The Rice Lake Group within this wedge forms a north-dipping monoclinial succession and the overlying San Antonio sedimentary rocks are deformed into upright folds (Stockwell, 1938).

Beds strike east - west and dip approximately 50° to the north. Facing indicators in the rocks north of Rice Lake, including fragments of a lower unit at the base of a higher unit, pillow morphology, concentrations of amygdales along flow tops and graded bedding within the volcanoclastic rocks, indicate a north-facing succession.

Figure 4: General geology of the Rice Lake area
(modified from Poulsen et al., 1986)

The rocks have a strong penetrative foliation (S_1), that has a more northerly strike and steeper dip than the bedding (S_0). A mineral stretch lineation trends northeast; due to deformation by later structures the plunge is variable (Figure 5). Near the Wanipigow Fault a second foliation (S_2) is characterized by an east-northeast crenulation of the S_1 foliation. The third foliation (S_3) is a local phenomenon defined by north-northwesterly trending kink bands accompanied by spaced crenulation cleavage.

S_1 and S_0 strike more northerly and dip more steeply near the Normandy Creek Shear Zone; also the mineral lineation plunges more steeply (Figure 5). Southeast of the Normandy Creek Shear Zone, the rocks are dominantly massive. This shear zone may be a high-angle ductile reverse fault (Poulsen et. al., 1986). The trend of the lineation becomes subparallel to the strike of the Wanipigow Fault and the plunge of the lineation is shallower.

The dextral transcurrent movement of the Wanipigow Fault postdates the development of the high-angle reverse Normandy Creek Shear Zone. Markers such as feldspar porphyry dykes have been shortened and sheared, possibly indicative of transpressive deformation (Sanderson and Marchinin, 1984).

2.4 Metamorphism and Alteration

All rocks in the Rice Lake area have been affected by lower greenschist facies metamorphism. Characteristic

—+— STRIKE OF FOLIATION
 —>— TREND OF LINEATION
 ● SAN ANTONIO MINE

PLUNGE VALUES OF LINEATION

[Pattern] < 30
 [Pattern] 30-45
 [Pattern] 45-60
 [Pattern] > 60

Figure 5: Structural trend map of the Rice Lake area
(Poulsen et al., 1986).

minerals are sericite, chlorite, albite, epidote and quartz in the felsic rocks and chlorite, actinolite, hornblende, albite, epidote and quartz in the mafic rocks.

At the northern margin of the belt the metamorphic grade corresponds to the amphibolite facies (Poulsen, 1987), due to the emplacement of the Wanipigow River Plutonic Complex. In the domain south of Rice Lake, Bailes (1971) reported local amphibolite-facies metamorphism. The metamorphic grade increases towards the southern margin of the belt.

Carbonate alteration is found in rocks other than the mafic intrusion hosting the San Antonio Gold Mine. The epiclastic rocks at Rice Lake contain abundant calcite and rare ankerite (Stockwell, 1938; Tirschmann, 1986 and Poulsen et al., 1986). The porphyritic dacite and the basaltic succession display ankerite and calcite alteration spatially associated with shear zones.

CHAPTER 3

MINE STRATIGRAPHY

3.1 Volcanic Rocks

The map area surrounding the San Antonio gold mine is underlain dominantly by volcanoclastic rocks with minor basalt flows, all intruded by gabbroic dykes and sills (Figure 2).

3.1.1 Rhyodacite

Rhyodacitic epiclastic rocks constitute a sequence, 1150 metres thick, of breccia, tuff breccia and tuff which is bounded to the south by the Gold Creek and Normandy Creek shear zones. The sequence is thickest in the centre of Rice Lake and thins to less than 100 metres along Normandy Creek. These quartz-plagioclase rocks weather light orange-beige to white and are pale green on the fresh surface.

Heterolithic tuff breccia, poorly sorted, and weakly bedded, dominates. The clasts are generally subrounded, consisting of mafic, felsic and quartzose clasts. At 51°01'06" latitude and 95°38'45" longitude angular fragments of andesite and basalt, with chilled margins, are found within a felsic matrix (Plate 1a). Volcanism was contemporaneous with reworking and the source of the fragments may be local. Fine pyritic seams are parallel to bedding and disseminated pyrite occurs locally within beds. There is an absence of plutonic, sedimentary or metamorphic

Plate 1: Volcanic strata in the Rice Lake area.

- A: Unit 1 (Rhyodacite):** Outcrop with angular heterolithic volcanic fragments, dominantly mafic with chilled margins in a felsic matrix. Lens cap 6 cm for scale.
- B: Unit 2 (Andesite):** Outcrop with clast-supported breccia with angular, epidotized clasts. Lens cap 6 cm for scale.
- C: Unit 2 (Andesite):** Massive amygdaloidal flow with millimeter-sized discontinuous laminations. Amygdales are 4 mm and filled with quartz and calcite. Lens cap is 6 cm for scale.
- D: Unit 3 (Basalt):** Brown weathering irregularly shaped basaltic pillow toes. Scale card 9 cm.
- E: Unit 3 (Basalt):** Strongly epidotized pillow toes with cooling cracks at top of flow indicating stratigraphic tops to the north. Pencil magnet is 12.5 cm.
- F: Unit 4 (Dacite):** Plagioclase-phyric monolithic breccia with compositionally similar matrix. Scale card 9 cm.

lithic grains (Tirschmann, 1986). Well bedded units are located along the northeast shoreline of Rice Lake and south of the sill along the 26th level in the San Antonio Mine.

The sequence is dominantly epiclastic, consisting of reworked felsic pyroclastic flows and minor mafic volcanic rocks.

3.1.2 Andesite

A unit of andesitic pyroclastic rocks is 850 metres long and 85 metres thick, forming a wedge that thins to the east. Limited exposure precluded detailed mapping of the andesite.

The gradational, irregular lower contact is defined by interlayered quartz-feldspar tuff, part of the the underlying epiclastic unit, and a very fine-grained andesitic tuff. In the centre of the study area, the andesite is in contact with rhyodacitic epiclastic rocks whereas, to the east and west, it is in contact with basalts. One exposed contact with basalt is faulted. The andesite has a sharp contact with the northern gabbro.

The fine-grained andesite weathers light orange-green and is light greenish grey on the fresh surface. Above the tuffaceous base, the andesite is a matrix-supported monolithic breccia with angular fragments up to 28 X 7 cm, progressing upwards to clast-supported breccia (Plate 1b). To the east, the andesite is locally heterolithic containing andesitic and minor felsic fragments.

The andesite is feldspar-phyric and the fragments tend to be more strongly epidotized than the matrix. It is overlain by massive, amygdaloidal, andesitic flows with fine regularly spaced, quartz-filled fractures (Plate 1c). Amygdales constitute approximately 5% of the rock, are composed of quartz and calcite, and have cusped boundaries. The matrix is composed of fine-grained plagioclase, epidote, chlorite, titanite and a trace of quartz.

3.1.3 Basalt

Basalt flows form two discontinuous lenses, trending 075° and 285° separated by rhyodacitic epiclastic rocks. The basaltic sequence is at least 80 metres thick, weathers orange-green and has a medium green fresh surface. The lower contact between rhyodacitic epiclastic rocks and the basalt is sharp, and the basalt contains fragments of the underlying epiclastic rocks.

The unit is composed of amygdaloidal pillowed basalt, pillow breccia and massive sheet flows. Quartz- and calcite-filled amygdales are most abundant at the top of a massive flow in contact with pillowed flow rocks, indicating stratigraphic top to the north-northwest. Chlorite-filled amygdales also occur within the massive flows. The basalt flows are scoriaceous at the eastern extremity of the western basaltic lens ($51^{\circ}01'11''$ latitude and $95^{\circ}39'41''$ longitude). In the upper part of the sequence, basaltic breccias contain scoriaceous fragments.

The pillowed lavas consist of irregularly shaped pillow toes. Rare well-formed pillows indicate stratigraphic top to the north (Plate 1d). The average pillow size is 45 X 20 cm. The aspect ratio of pillows in plan view is 3:1 and greater than 5:1 in vertical section. Pillow cores are intensely epidotized and fine-grained pillow rims are one cm thick (Plate 1e). Pyrite occurs in the pillow selvages and defines a lineation.

The basaltic sequence marking the southern extent of the map area consists of mafic schists and massive and pillowed basalts.

3.1.4 Plagioclase-Phyric Dacite

Dacite forms a 450 m thick sequence of plagioclase-phyric, monolithic breccia and massive dacite (Plate 1f). This unit weathers light green and on the fresh surface is also green. The base of the unit marks the northern limit of the study area.

The heterolithic base of this unit is variable in apparent width from 5 to 15 m. In the middle of the study area the contact is not observed but 25 m to the southwest basaltic flows are exposed. The base of the porphyritic dacite consists of a heterolithic breccia unit with fragments of dacite in a basaltic matrix (51°01'15" latitude, 95°39'52" longitude).

Eight hundred metres to the east, the base of the dacite is gradational with rhyodacitic epiclastic rocks.

There, the heterolithic breccia consists of dacitic fragments in a rhyodacitic matrix. At 51°01'35" latitude and 95°40'59" longitude, the base of the unit is in sheared contact with a basaltic breccia to the south.

Plagioclase constitutes 30-50% of the rock and occurs as euhedral to subhedral grains in a fine-grained groundmass. The monolithic fragments in the brecciated units are compositionally similar to the matrix. Breccias make up 60% of the unit. Tirschmann (1986) suggested a pyroclastic flow origin for the plagioclase-phyric dacite.

3.2 Plutonic Rocks

Three gabbroic sill-like bodies intrude the felsic volcanoclastic unit, with the central one being the host to the San Antonio gold mine and the San Norm gold occurrence. Gabbroic dykes cut the volcanic strata and one merges with the extrusive basaltic sequence in the northeast (51°01'14" latitude and 95°38'12" longitude). Fine-grained diabasic dykes cut the sequence. The gabbros are crosscut by feldspar porphyry dykes and alkalic dykes.

3.3 Gabbroic Intrusions

Three subconcordant gabbros intrude the volcanic strata (Figure 2). The three sills are separated stratigraphically; their macroscopic characteristics are similar. The sills intrude a felsic volcanoclastic unit and occur at the upper contact with andesite. The field observations of the three

sills are presented in this section and the petrographic and geochemical data for the unaltered sill in chapter 4.

3.3.1 Stratigraphy of the San Antonio Sill.

The central sill, is a layered mafic intrusion consisting of melagabbro, locally granophyric leucogabbro and gabbro (Plate 2a-h). Three stratigraphic sections across the sill show the variation in thickness and morphology along strike (Figure 6). The sill is exposed for a length of 4.85 km and, based on drillhole information it is at least 7 km in length, with the eastern contact open (Figure 2). The contacts are very sharp; at 51°00'49" latitude and 95°38'59" longitude, a layered fragment of rhyodacite was observed in the base of the intrusion. An intrusive contact with the rhyodacite is indicated by 0.5 m wide fine grained gabbroic margins at the top of the sill in contact with cherty sediments, found only at the upper contact and by fine grained basalt and gabbro dykes at the upper contact of the gabbro, which are compositionally similar to the fine grained margins. These dykes within rhyodacite strike towards the sill without crosscutting the intrusion. The contact itself is not exposed. There is also a local discordance of the gabbro with the sedimentary strata.

The melagabbro is a medium-grained, dark greenish brown-weathering rock with 2 mm amphibole euhedra within a fine-grained groundmass of epidotized feldspar and oxides including white-weathering leucoxene (Plate 2a). Irregular

Figure 6: Schematic representation of measured stratigraphic sections in the San Antonio Sill (see Figure 2 for section locations).

Plate 2: Characteristics of the San Antonio Sill

- A: San Antonio Sill: dark greenish-brown weathering melagabbro with resistant amphibole euhedra in a finer groundmass of dominantly chlorite and feldspar. Lens cap 6 cm for scale.
- B: San Antonio Sill: fresh melagabbro with scattered, 2mm amphibole pseudomorphs after pyroxene, in a groundmass of dominantly chlorite and white feldspar. (Sample 85-427)
- C: San Antonio Sill: leucogabbro exposed at the mine shaft is a fine- to medium-grained, greenish-beige weathering phanerite with discontinuous concentrations of feldspar. Lens cap 6 cm for scale.
- D: San Antonio Sill: fresh leucogabbro with saussuritized light green feldspar laths, medium green chloritized actinolite and black, ilmenomagnetite and quartz. (Sample 85-149)
- E: San Antonio Sill: internal leucogabbroic sills within melagabbro from the east shore of Rice Lake. These sills average 20 cm wide and at the top of the San Antonio Sill are 50 cm wide. Extensional fractures strike 325° and segment the sill. The foliation is $250/65N$ and the sills are boudinaged with an aspect ratio of 6:1. Pencil magnet 12.5 cm for scale.
- F: San Antonio Sill: sharp contact between melagabbro (right) and internal leucogabbroic sill (left). Greenish-white laths are saussuritized feldspar in a medium green groundmass of chlorite and quartz. The amphiboles are dark and equant in the leucogabbroic sill and occur as large 1 cm grains in the melagabbro which enclose feldspar. The fine grey mineral is ilmenomagnetite. (Sample 87-298a)
- G: San Antonio Sill: granophyric leucogabbro from the mine shaft outcrop displaying 1 cm diameter quartz, feldspar and epidote patches representing granophyric intergrowths.
- H: Lower chilled margin of the San Antonio Sill. The foliation is defined by elongated chlorite (after amphibole) in discontinuous dark green wisps. White weathering leucoxene is finely disseminated. (Sample 85

epidote knots and pods are randomly distributed constituting less than five percent of the unit.

Melagabbro is exposed on two islands in Rice Lake and on the northeast shore of Rice Lake (Figure 2a). At the base of the sill in the San Antonio Mine, the melagabbro is 18 m thick on average (Figure 6). On the east shore, the entire sill is melagabbro, consisting of an amphibole-phyric homogeneous base overlain by approximately 45 m of melagabbro with discontinuous feldspar-rich wisps less than 1 cm wide, subparallel to the sill contacts. The "wispy" melagabbro is present in an area less than 200 m long and is not present in other exposures of melagabbro. A feature similar to the "wispy" melagabbro was noted by Stephenson (1972) in the Wadhope Gabbro in the Beresford Lake area.

The leucogabbro occurs as 1) large discontinuous bodies within the upper portions of the sill, where it has gradational boundaries one to two m wide, with the melagabbro (Plate 2c,d), 2) sill-like segregations, 50 cm wide, and greater than 10 m long, with very sharp contacts (Plate 2e,f), and 3) irregular pods with sharp contacts within the melagabbro. The leucogabbro is exposed along the northwest shore at the mine shaft, and in the northeast near Transect III (Figure 2).

The leucogabbro sill-like segregations, within the melagabbro, are parallel to the upper contact of the sill. On the east shore of Rice Lake, nine of these sills occur within 5 m of the upper contact of the 50 m wide

melagabbroic sill (Figure 6). The sills bifurcate forming dyke-like apophyses.

The leucogabbro is medium-grained, and greenish-beige weathering. It consists of 40-65% leucocratic minerals and lesser amounts of amphibole, chlorite and magnetite (Plate 2c,d). The rock is locally inhomogeneous with discontinuous concentrations of feldspar. Macroscopically, granophyric intergrowths of quartz, plagioclase and epidote, one cm in diameter, are present (Plate 2g).

The gabbro forms the basal and upper fine-grained margin of the intrusion. This unit is 50 cm wide, fine-grained and weathers dark green to black with finely disseminated leucoxene producing a speckled texture (Plate 2h). The gabbro is well foliated, calcite-bearing and on the fresh surface is blackish-green. Gabbro also occurs on the 16th level for at least the upper 15 m of the 120 m wide sill. At transect III, gabbro is the gradational rock type between melagabbro at the base and leucogabbro at the top of the sill.

3.3.2 Northern Gabbro

The northern gabbro is discontinuous, weathers greenish-beige with resistant amphibole and is greyish green on the fresh surface. In this gabbro, the amphibole grains are smaller and less abundant than those in the melagabbro and the rock has a subophitic texture. One centimetre wide chlorite and actinolite-bearing fractures weathering reddish

brown occur within the northern gabbro (Plate 3a).

3.3.3 Southern Gabbro

The southern gabbro was examined on the 26 level in the San Antonio Mine, on two small islands and a submerged shoal in Rice Lake (Figure 2). The southern gabbro has gabbroic and leucogabbroic affinities. The leucogabbro has 20% disseminated, black quartz and ilmenomagnetite grains or contains coarse, light brown weathering leucoxene.

3.3.4 Internal Structure of the San Antonio Sill and Gold Deposit

Dykes which cut the intrusion provide useful indicators of deformation, as they were emplaced prior to foliation and shear zone development. On the east shore of Rice Lake, feldspar porphyry dykes are folded, with fold axes trending roughly east-west. They are also sheared compatible with a roughly north-south compression and east-northeast shearing. These features are most pronounced in dykes with an orientation at a high angle to the intrusion. The dykes oriented east-west are boudinaged.

The Normandy Creek Shear Zone is a 100 m wide zone of deformation with rocks inhomogeneously strained. Locally sheared contacts of the intrusion are at an angle to the bedding (Plate 3b) and the contacts are locally transposed (Transect III, Figure 2). Discrete zones of ductile shear

Plate 3: Structures within the sills in the Rice Lake area.

- A: Northern gabbro: discontinuous chlorite- and actinolite-bearing fractures occur within the gabbro. Lens cap 6 cm for scale.
- B: San Antonio Sill: sheared contact of the gabbro cross-cuts the bedding (parallel to the hammer handle) of the rhyodacitic host rocks in the Normandy Creek Shear Zone.
- C: San Antonio Sill: Shear-type (16-type) auriferous vein in the San Antonio Mine (93 vein, 33 Level). Well developed foliation parallel to the vein contact and minor bleached wallrock alteration. Rule 15 cm for scale.
- D: San Antonio Sill: Stockwork-type auriferous vein in the San Antonio Mine (7 Level). Bleached wallrock alteration prominent adjacent to the vein in the undeformed leucogabbro host rock. Central breccia core and marginal zone with relatively flat ladder veins. Scale card 9 cm.
- E: San Antonio Sill, "Southeast dippers" (NE/SE veins) in the San Antonio Mine (7 Level). Displacement and attenuation of the carbonate stringers indicate hangingwall up. Bleached alteration developed adjacent to the vein and stringers. Scale card is 9 cm for scale.
- F: San Antonio Sill: "130- vein" (NW/SW veins) in the San Antonio Mine, (6 Level). Visibly bleached alteration zone adjacent to the vein (bl). Brecciated core with vein parallel chlorite-quartz veins at the contact between the breccia vein and bleached alteration. Hammer is 33.5 cm for scale.

cut the sill at angles ranging from 020° to 070° . Brittle fractures at a high angle to the foliation are developed within epidote-quartz pods.

In the San Antonio mine, there are two types of auriferous structures which are crosscut and offset by two sets of faults containing quartz veins that were not mined (Plate 3c,d). Surface exposures reveal the two auriferous structures: veins with foliated margins (shear-type), and a set of randomly-oriented fractures without any shearing (stockwork veins). Shear-type veins strike 240 to 255° , dipping 50 to 60° northwest. Lineations in the shear-type veins plunge 45° to the northeast. The zone of fracturing marked by the stockwork type veins strikes 205 to 240° . An extensive study of the mine plans revealed average attitudes, stress orientation and kinematic data for the fracture sets these are listed in Table 17 (Lau, 1988).

In the vicinity of the mine the sill strikes 300° and dips 48° to the north. Although the shear zones associated with the gold-bearing veins crosscut the entire sill, the shear-type veins and stockwork-type veins, constituting the mineralization, occur in the upper $2/3$ of the sill (Ames et al., 1987). The restriction of the mineralization corresponds to the leucogabbroic portion of the sill.

The two unmined sets are 1) veins in shear zones that strike parallel to the northeast trending shear-type veins and dipping vertically to steeply southeast, or, "southeast dippers" (Plate 3e),

STRUCTURES		ATTITUDE	FRACTURE TYPE	KINEMATIC ANALYSES		PRINCIPAL STRESS ORIENTATION			Notes
				PITCH OF SLIP	SENSE OF SLIP	σ_1	σ_2	σ_3	
DIKES		N40°E/66°NW	Brittle hydraulic tension fractures						
STOCKWORKS	LADDER-VEINS	N83°W/50°NE	Brittle hydraulic tension fractures						
	CENTRAL BRECCIA ZONES	N40°W/78°NE	Shear ? Hydraulic ? Brecciation	RANGE OF SLIP DIRECTIONS FROM 45°NW TO 69°NW	THRUST RIGHT-HANDED	40°/114°E TO 44°/136°E	44°/115°E TO 47°/144°E	47°/131°E TO 51°/137°E	SHEARING 30
	CENTRAL VEINS	N40°W/78°NE	Shear ? Tension ? brittle fractures						
16-TYPE VEINS		N75°E/68°NW	Ductile shear fractures	41°NE	THRUST LEFT-HANDED	21°/117°E	41°/103°E	41°/103°E	30
NE, SE VEINS		N36°E/70°SE	Ductile shear fractures	39°NE	THRUST RIGHT-HANDED	20°/178°E	47°/113°W	37°/126°E	30
NW, SW VEINS		N50°W/75°SW	Shear ? Tension ? brittle fractures	45°SE	THRUST RIGHT-HANDED	18°/111°E	44°/117°W	37°/126°E	30

Table 17: Summary of structural data for all fracture sets in the San Antonio Mine (Lau, 1988).

2) veins in faults oriented subparallel to the strike of the gabbro in the mine dipping to the south (130/ 65), the "130" faults (plate 3f).

The mineral stretch lineation in the surrounding volcanic units is parallel to the line of intersection of the contact of the host rock and shear zones, of extensional veins and shear zones, and of the shear zones and southeast dippers (Poulsen, 1987; Lau, 1988). The sense of movement on the shear-type veins is west side up, subparallel to the contact of the intrusion with the volcanoclastic rocks. Lau (1988) reported a 30 m displacement in plan view of the contact. Substantial movement has occurred along these slip planes.

The shear type veins are in shear zones that represent high angle reverse faults similar in strike and sense of movement to the Normandy Creek shear zone. The southeast dippers are high angle reverse faults (Plate 3e). Poulsen et al. (1986) suggested that the extensional stockwork zones link en echelon shear zones, thus coeval. The "130" faults crosscut the structural fabric of the shear zones and have developed after the northeast striking shear zones (Lau, 1988).

The San Norm gold prospect within the central sill is poorly exposed but a drill program in 1986 and 1987 traced the gabbroic body to the northeast (Figure 2a). Shearing has obliterated most of the primary textures. The gabbro dips 60° to the north-northwest. Numerous shear zones trend

subparallel to strata. Two fairly continuous structures bound the "mine" strata in the San Norm area. In the north, there is a shear zone near the base of the feldspar-phyric dacite, and a fault scarp between rhyodacitic epiclastic rocks and pillowed basalt marks the southern extent of the Normandy Creek Shear Zone. Both structures strike 055° to 060° . Between these two shears, there are structures that trend 055° transecting the gabbroic unit at a shallow angle. The gold veins lie in these discordant shear zones.

CHAPTER 4

PETROGRAPHY AND CHEMICAL COMPOSITION OF GABBRO

Introduction

In order to recognize any effects of hydrothermal alteration within the mafic sills, it is essential to recognize the "unaltered" assemblages of each rock type. The unaltered samples were selected by hand specimen and thin section examination and finally by chemical analysis (Appendix 3). An unaltered sample is defined as a homogeneous rock without veins, epidote knots or other compositional heterogeneities and zero to trace amounts of calcite.

Results of the petrographic observations of each rock type in the gabbroic sills in the Rice Lake area are presented in the first part of this chapter and the chemical composition is presented in the latter part. In light of these observations, the interpretation of pseudomorphs, distribution of rock types and origin of the San Antonio Sill will be discussed.

4.1 Petrography

Mineral identification by petrographic techniques was supplemented by XRD, staining for carbonate species and microprobe analysis. The classification of chlorite species is after Hey (1954), (Figure 7).

Melagabbro ■ chlorite-1 □ chlorite-3
 Leucogabbro ▲ chlorite-2 △ chlorite-4

Figure 7: Classification of chlorite species in the gabbroic rocks, Rice Lake area, according to Hey (1954).

4.1.1 Least Altered Melagabbro

The melagabbro is characterized by the assemblage actinolite (55%), chlorite (15%), albite (15%), epidote (5%), hornblende (tr.) and 5-10% total, titanite, ilmenite, hematite, magnetite, calcite and chalcopryrite. This assemblage is typical of mafic rocks metamorphosed in the greenschist facies (Turner, 1981) and is, therefore, considered to be 'unaltered' relative to rocks within the sill that have been affected by hydrothermal alteration.

There are three types of amphibole present based on textural grounds for actinolite; 1) large single actinolite crystals (Plate 4a), 2) randomly oriented actinolite needles (Plate 4b), and 3) hornblende (Plate 4c). These amphiboles are all calcic (Appendix 2, Table 6), but further subdivision of the species after Leake (1978) requires the determination of ferrous and ferric iron. Due to the textural features of the amphiboles a single crystal cannot be removed for wet chemical analyses, without contamination by other minerals.

Large actinolite crystals form an average of 15% of the melagabbro (Plate 4a). They are large (2 mm average diameter with a maximum diameter of 4 mm) prismatic, crystals. The actinolite is poikiloblastic, with inclusions of pycnochlorite, (Appendix 2, Table 7), relict plagioclase, titanite and tremolite needles. Actinolite has been altered to pycnochlorite, brown in plane polarized light, and traces of epidote and calcite. The pycnochlorite

Plate 4: Petrographic characteristics of the unaltered melagabbro in the layered San Antonio Sill.

- A: Poikiloblastic actinolite (2 mm in diameter) with inclusions of pycnochlorite (chl_1), ilmenite, and randomly oriented tremolite needles. The cleavage planes are also pycnochlorite. Randomly oriented actinolite in upper corners. Transmitted light, crossed polars. (Sample 85-429) Scale bar is 0.5 mm.
- B: Randomly oriented actinolite needles after pyroxene. Transmitted, plane -polarized light. (Sample 85-429) Scale bar is 0.5 mm.
- C: Corona development showing disequilibrium textures. Orange-brown hornblende (hb) with a discontinuous (0.01 mm) rim of green hornblende surrounded by tremolite (tr). Transmitted, plane-polarized light. (Sample 85-428) Scale bar is 0.5 mm.
- D: Actinolite grain, pseudomorphous after clinopyroxene exhibits preservation of primary twinning defined by pycnochlorite (chl_1) twin plane with oblique extinction. Transmitted light, crossed polars. (Sample 85-437) Scale bar is 0.5 mm.
- E: Chlorite patches (chl-p), contain randomly oriented fractures outlined by titanite. They are pseudomorphous after olivine or orthopyroxene and occur in the melagabbro only. Transmitted, plane-polarized light. (Sample 85-429) Scale bar is 0.5 mm.
- F: Anhedral chlorite patches (chl-p) with titanite-rich randomly oriented fractures. Transmitted, plane-polarized light. (Sample 85-429) Scale bar is 0.5 mm.
- G: Hemo-ilmenite with a hematite (hmmt) inclusion-rich core surrounded by ilmenite (il) and replaced by titanite (ti). Reflected, plane-polarized light. (Sample 85-425) Scale bar is 0.2 mm.

occurs in blades parallel to the cleavage planes within the actinolite. No relict pyroxene has been observed, although oblique extinction of actinolite twin planes is common (Plate 4d). These large crystals are probably pseudomorphs after pyroxene and give the melagabbro a characteristic texture easily recognized in outcrop.

Colourless to pale green, randomly oriented needles of actinolite are pseudomorphous after prismatic (0.5 to 2.0 mm diameter) igneous pyroxenes (Plate 4b). These pseudomorphs constitute as much as 50% of the melagabbroic rocks, 40% on average. Actinolite is partially or totally altered to randomly oriented pycnochlorite. These tremolite-pycnochlorite patches are enclosed by single crystals of actinolite. Relict grain boundaries are only locally preserved because of the penetrative foliation and lineation present in all rocks.

The modal abundance of hornblende in the melagabbro varies from trace to 15% (<5% average). Unaltered hornblende crystals have rectangular to hexagonal outlines and are as long as 1.1 mm. Corona development is common in the hornblende; orange-brown hornblende has a discontinuous (0.01 mm) rim of green hornblende, which in turn is surrounded by tremolite or an actinolitic hornblende and trace amounts of quartz (Plate 4c), (Table 6, Appendix 2). The hornblende is commonly twinned, with a fine (0.1 mm) twin plane in the middle of the grain that is preferentially altered to pycnochlorite.

The chlorite is referred to as "chl₁" and is typical of chlorite in the unaltered melagabbro. This magnesium-rich chlorite is pseudomorphous after a mafic mineral and also replaces actinolite along cleavage planes. Modal estimates vary from 15-50%.

Rhombic to anhedral isotropic chloritic patches (5-10%), occur between the large actinolite porphyroblasts and albite laths. They contain titanite-rich inclusion trains, outlining randomly oriented fractures (Plate 4e,f). The composition of this chlorite plots near the pycnochlorite-ripidolite boundary (Figure 7). Chlorite in these patches contains less Si and slightly more Fe than chlorite in the patches enclosed by actinolite grains but is still classified as chl₁.

The plagioclase has a narrow composition range of An_{0.7-1.1} (Appendix 2, Table 8). Stubby laths vary in length (0.4 mm to 11 mm), with the crystals forming a bimodal size population in the upper portion of the melagabbro, averaging 0.2 mm and 11 mm, respectively. The modal estimate for albite is 15-20%. Combined albite and periclase twins have discontinuous twin planes. Carlsbad twinning is also present. Albite occurs within single crystal actinolite poikiloblasts. The original plagioclase was metamorphosed to a mixture of epidote (70-90%), with traces of chlorite and quartz, and (10-30%) albite. The grain boundaries between albite grains are obliterated by the saussuritization.

Epidote (Appendix 2, Table 9) is present in modal

amounts varying from 5-15% and occurs as fine granules with the calcic amphiboles and as relatively coarse (0.1 mm) grains within the quartz-plagioclase polycrystalline aggregates. Epidote also occurs with albite, as a metamorphic product of calcic plagioclase and is less iron-rich than the coarse epidote (Appendix 2, Table 9). Some patches of coarse epidote have cores of chalcopyrite. Polycrystalline quartz occurs in trace amounts and may form a groundmass with fine plagioclase and chlorite.

The oxide mineral content in the melagabbro is relatively constant between 5 and 7 %, and consists of ilmenite, hematite and magnetite. Titanite occurs in trace amounts.

Ilmenite grains commonly contain up to 20% hematite as fine inclusions in the core (Plate 4g). According to Buddington and Lindsley (1963) this is classified as hemo-ilmenite. The concentration of the hematite inclusions in weakly altered grains is greatest in the core and diminishes towards the edges of the grain. The ilmenite grains are partially to totally replaced by titanite and range in size from <0.1-0.4 mm, averaging <0.1 mm (Plate 4g). The grain boundary between titanite and ilmenite is irregular and jagged. In some grains, hematite is disseminated in both the titanite rims and relict ilmenite.

Titanite formed perpendicular to hemo-ilmenite walls, in a radial pattern around the ilmenite-hematite core or totally replaced the ilmenite as a fine granular mass. Trace

amounts of magnetite have exsolution lamellae of hematite, with ilmenite along fracture planes (Plate 4g).

Chalcopyrite occurs in trace amounts as disseminated anhedral blebs up to 0.35 mm (average <0.1 mm), usually within epidote. The largest (0.35 mm) observed grain, has overgrown a boxlike structure of ilmenite.

4.1.2 Least Altered Leucogabbro

The petrographic characteristics of the "unaltered" leucogabbro are described as a) leucogabbro b) granophryic leucogabbro and c) internal leucogabbro sills and pods.

4.1.2 a Leucogabbro

Leucogabbro consists of plagioclase (albite) (15-50%), chlorite and/or actinolite (25%), a fine polycrystalline mesostasis of quartz, chlorite and epidote, (25%), quartz (10-20%), and ilmenomagnetite and titanite (10-15%).

Plagioclase (An_{1.8-6.6}) occurs as laths 0.5-1.2 mm in length; grain boundaries are generally sharp, and contacts with quartz are serrated (Plate 5a). Fine granular epidote occupies as much as 80 % of the albite grains. Albite twin planes contain chlorite. The epidote is less iron-rich in the plagioclase compared to coarse epidote associated with chlorite (Appendix 2, Table 9). Within a thin section albite may occur as 1) small 0.1 mm laths and equant grains, and 2) large 1 mm long laths. Albite grains are randomly

Plate 5: Petrographic characteristics of the unaltered leucogabbro in the layered San Antonio Sill

Scale bar is 0.5 mm

- A: Strongly saussuritized plagioclase (pl), laths consist of albite, epidote and minor chlorite (green) with triangular interstices dominantly of quartz (gtz). Transmitted, plane-polarized light. (Sample 86-69)
- B: Actinolite porphyroblast with well developed twinning and oblique extinction. The actinolite has inclusions of ripidolite (chl₂), albite laths are strongly saussuritized and the quartz is polycrystalline. Transmitted light, crossed polars. (Sample 86-69)
- C: Pseudomorphs of mafic minerals consist of quartz, chlorite and minor hematite. The mafic pseudomorphs have a similar size and shape as actinolite. Transmitted, plane-polarized light. (Sample 86-62)
- D: Second type of mafic pseudomorph consisting of coarse epidote, chlorite and minor quartz. Transmitted, plane-polarized light. Sample (86-62)
- E: Quartz in this granophyric leucogabbro occurs as monocrystalline to polycrystalline grains (white) and as an inclusion-filled, fine mosaic (arrow). Transmitted, plane-polarized light. (Sample 85-149)
- F: Granophyric intergrowths of quartz and albite adjacent to euhedral saussuritized plagioclase laths. Ilmenomagnetite (upper left) with titanite filled exsolution lamellae. Transmitted light, crossed polars. (Sample 86-149)
- G: Complex twin patterns in inclusion-free albite rims epidote-rich albite laths within internal leucogabbroic sills, possibly representing post cumulus growth. Transmitted light, crossed polars. (Sample 85-426)
- H: Actinolite interstitial to albite laths with well developed twinning and oblique extinction angles, probably representing primary clinopyroxene. Transmitted light, crossed polars. (Sample 85-418)

oriented, and poikilitically enclosed by ilmenomagnetite grains and actinolite single crystals.

Actinolite is present as individual large crystals (<4 mm), some with twinning parallel to the long axis with an oblique extinction ($5-10^\circ$), similar to those in the melagabbro. The actinolite encloses strongly epidotized plagioclase laths. It is partially altered along cleavage planes to a purplish-brown chlorite (Plate 5b). The growth boundaries of chlorite are very sharp against plagioclase. This chlorite (chl_2) differs from that in the melagabbro (chl_1) in its higher Fe/(Fe+Mg) (ripidolite-pychnochlorite, Figure 7). Fine-grained epidote occurs disseminated within the chloritic alteration in actinolite.

Two assemblages with the same shape, size and textural relationships as the single grains of actinolite were observed:

- 1) fine polycrystalline quartz and randomly oriented chlorite (chl_2), $\pm$ calcite and hematite (Plate 5c)
- 2) quartz, chlorite (chl_2), coarse epidote, $\pm$ calcite (Plate 5d).

Anhedral quartz grains constitute 10-15% of the leucogabbro. Large (0.5 mm average, maximum 1.4 mm) subrounded quartz occurs as monocrystalline, granoblastic-polygonal and polycrystalline grains with a moderate undulose extinction and more rarely a straight extinction.

Magnetite grains average 2 mm (maximum of 2.4 mm), with exsolution lamellae altered to titanite. Oxidation of

magnetite to hematite occurs along narrow portions between exsolution lamellae and at intersection points of lamellae. Hematite is concentrated along crystallographic planes. The modal content of magnetite, hematite and/or titanite varies between 10 and 15%.

4.1.2.b Granophyric Leucogabbro

Large (2 mm) laths of randomly oriented albite constitute 40% of the rock. The laths are usually in mutual contact producing triangular interstices. Fine granular epidote occupies 30-90% of the plagioclase grains. Local preferential saussuritization of twin planes and cores suggests that the original igneous anorthite-rich plagioclase probably had a calcium-rich core and a calcic-poor rim, indicative of normal zoning. Albite contacts are sharp with all minerals except quartz, where complex intergrowths of albite and quartz occur.

Quartz occurs in four main forms interstitial to plagioclase laths:

- 1) as monocrystalline to polycrystalline subrounded grains (0.4 mm average diameter)
- 2) as a fine mosaic (Plate 5e)
- 3) as a myrmekitic intergrowth with albite (Plate 5f).
- 4) as fine granular polycrystalline grains associated with chlorite.

Myrmekitic and mosaic quartz and albite form between subrounded quartz grains and plagioclase laths. Three to

four grains typically form subrounded quartz aggregates, with straight, curved and embayed grain boundaries. Granoblastic-polygonal textures also occur. Fractures in quartz are filled with chlorite and epidote. The quartz mosaic has abundant inclusions.

Aggregates of quartz, chlorite and trace amounts of epidote are pseudomorphs (1.2 and 0.8 mm) after, rhombic crystals. They have sharp outlines with the plagioclase laths. These mafic pseudomorphs, which constitute 30-40% of the rock have the same characteristics as those in the leucogabbro without granophytic intergrowths. The oxide minerals in the granophytic leucogabbro are similar to those in the leucogabbro.

4.1.2.c Internal Leucogabbro Sills and Pods

These sills are composed principally of albite (30-45%), with subordinate actinolite, chlorite, hornblende, epidote, quartz and magnetite. Modal estimates vary within individual sills. Albite crystals are variable in size and shape from subequant (0.2-0.4 mm) twinned grains to laths with aspect ratios of 1:5. Albite crystals have epidote-rich cores with 5-10% epidote randomly oriented throughout and an outer rim of plagioclase that is inclusion-free with complex twinning patterns and mottled textures (Plate 5g). This may reflect adcumulus growth.

Rhombic grains of actinolite (Appendix 2, Table 6) occur between albite laths and vary from 0.1 to 0.7 mm in

diameter. They have Carlsbad twinning with oblique (8°) to parallel extinction angles and make up 10-35% of the rock (Plate 5h). Complex twin planes are rare. Fracturing occurs along cleavage planes perpendicular to the twin planes and relict 90° cleavages were observed, possibly indicating pseudomorphs after pyroxene.

Green hornblende, identified as actinolitic hornblende (<5%) surrounds actinolite grains with cores of chlorite and quartz. Hornblende also occurs at the edge of actinolite grains and as individual grains surrounded by a purple pleochroic chlorite. This chlorite occurs as an alteration product along cleavage planes within single actinolite crystals or totally replaces actinolite grains as a felted mass within distinct relict grain boundaries making up 10-30% of the sill.

Relict ilmenomagnetite grains, up to 3 mm in diameter contain exsolution lamellae of ilmenite which have been totally altered to titanite. Ilmenomagnetite is partially altered to hematite. Titanite also rims small (0.2 mm), hemo-ilmenite grains situated adjacent to the ilmenomagnetite crystals. The large grains of ilmenomagnetite enclose small twinned plagioclase laths and hornblende, overgrow actinolite, and have chlorite along exsolution planes. They grow over the large plagioclase laths and are locally interstitial.

The only sulphide mineral observed is chalcopyrite, which forms fine-grained blebs associated with epidote in

the plagioclase.

4.1.3 Gabbro

In the central part of the San Antonio sill, the transition zone from melagabbro to leucogabbro is gabbroic in composition, as observed along transect III (Figure 6, 87-535). In transect III, the gabbro has a subophitic texture and contains dominantly amphibole and plagioclase. Actinolite (2 mm maximum diameter, average 1 mm) occurs as rhombs. Twinning in the calcic amphiboles has parallel extinction. The modal estimate is 15-20%. Actinolite is variably altered to a brown chlorite. There is a trace of green hornblende, pleochroic from light green to dark green, which occurs as blades within the core of actinolite grains and forms as rims around chlorite-rich patches. The gabbro contains smaller actinolite crystals than the melagabbro and has no randomly oriented fibrous calcic amphiboles.

Plagioclase occurs as short stubby laths, strongly altered to epidote. Plagioclase ~~encloses~~ and is enclosed within actinolite. The modal estimate of plagioclase is 60%; 90% of the grains contain fine granular epidote. Sharp grain boundaries are difficult to determine due to saussuritization. Epidote also occurs as coarse euhedral grains (0.2 mm) associated with chlorite and quartz. The coarse epidote grains make up 10% of the rock.

Quartz is fine, polycrystalline, with <1 mm grains occurring with chlorite in the altered actinolite. The modal

estimate is <3%. Titanite forms anhedral masses with a modal estimate of 5-10%. The grain size is variable with a maximum of 1.2 mm. Titanite contains inclusions of actinolite and chlorite. Traces of fine opaque minerals occur associated with coarse epidote-rich areas.

4.1.4 Chilled Margin

The fine-grained chilled margin of the central sill is sheared and carbonate-rich immediately adjacent to the contact with the volcanoclastic rocks. More than 50 cm away the effects of alteration are less pronounced. Within the strongly sheared margin, the sill consists of chlorite, plagioclase, quartz, epidote, calcite, rutile and leucoxene. In the less deformed and altered chilled margin further away from the contact, the mineral assemblage consists of actinolite, chlorite, plagioclase, quartz, epidote and titanite.

Actinolite occurs as 0.4 mm grains with intersertal plagioclase laths. The modal estimate of actinolite is 15%. Actinolite has been altered to a brown chlorite. Chlorite is also disseminated within the groundmass and constitutes 25% of the gabbro away from the immediate contact. In the sheared rocks adjacent to the volcanoclastic rocks, there is no actinolite and chlorite is purple to light brown. In these rocks, chlorite constitutes 35-45%; it is aligned, forming the foliation planes.

Plagioclase forms porphyroclasts in a fine matrix of polycrystalline quartz and chlorite. Modal estimates of

plagioclase vary from 10-30% (average 20%). Plagioclase is strongly saussuritized with fine granular epidote over 80-90% of the laths away from the immediate contact with the volcanoclastic unit. Calcite has replaced the epidote in the laths, adjacent to the contact and is finely disseminated within the plagioclase.

In the less deformed gabbro, quartz forms anhedral grains, 0.3 mm in diameter; the modal estimate is <3 %. Quartz modal estimates, including polycrystalline grains in the altered marginal rocks, average 25%. A trace of coarse 0.2 mm epidote is present.

Calcite partially, and locally totally, has replaced actinolite and forms elongate grains parallel to the foliation. Calcite also has nucleated on epidote and titanite. The average modal estimate of calcite in the chilled zone is ~15%.

Primary oxides have been totally replaced by titanite, and, in the rocks with more carbonate, they are composed of rutile and leucoxene. Titanite forms pseudomorphs after skeletal oxides; in the sheared samples, the calcium-, titanium-bearing silicates are dismembered and aligned parallel to the foliation. In the less deformed sample, the titanite is 0.3 mm and modal estimates are approximately 5%.

4.1.5 Northern Gabbro

The northern intrusion is entirely gabbroic, with a subophitic texture and no hydrothermal alteration. The mineral assemblage is actinolite, chlorite, plagioclase,

epidote, quartz, titanite and a trace of calcite.

Actinolite forms single crystals (0.35 mm average diameter and a maximum of 1 mm). They are variably altered to purplish-brown (birefringence) chlorite. Modal estimates vary from 15 to 40% with an average of 20%.

Plagioclase occurs as short (0.5 mm average diameter, 30-40% modal estimate) stubby laths and equidimensional grains and is uniformly metamorphosed to epidote and chlorite. Recrystallization of the plagioclase during metamorphism has obliterated primary grain boundaries. Epidote and chlorite makes up 95% of the grains. The metamorphic products form equigranular-holocrystalline plagioclase-quartz, chlorite and fine granular epidote.

Coarse epidote (0.15 mm, 10-20% modal estimate) forms the rim around chlorite patches (1 mm in diameter). Epidote grains have grown perpendicularly to the outer "relict grain" boundaries. These patches are anhedral and rhombic, randomly distributed and may contain quartz. A fine 0.01 mm rim of quartz may surround these patches. Traces of calcite have partially replaced epidote. The modal estimates of anhedral monocrystalline grains of quartz range from 5-10%.

Titanite forms randomly distributed anhedral (0.1 mm) grains with modal estimates averaging 5-10%.

4.2 GEOCHEMISTRY

Thirty-one samples from the central sill, and five samples of the northern gabbro were analyzed to determine

the chemical characteristics of the unaltered gabbros. In addition, three samples of the southern gabbro are included in this discussion to depict the sills, although the carbonate mineral content is higher. Table 18 lists the computed average chemical composition of the three sills and the subdivisions within the sills. Individual analysis are listed in Appendix 3.

Chemical Variation

Analyses plotted on an AFM diagram (Irvine and Baragar, 1971) indicate the differentiated nature of the sill, with the melagabbro closest to the MgO apex and the leucogabbro at the opposite end of an iron enrichment curve (Figure 8a). The northern gabbro and a sample from the southern gabbro lie between these end members along the trend defined by the San Antonio Sill samples. Two samples from the upper portion of the southern gabbro are similar to the leucogabbro. On an AFM diagram, the Rice Lake gabbros form two distinct groupings with the chilled margin situated between in the tholeiite field (Irvine and Baragar, 1971). On a Jensen (1976) diagram (Al_2O_3 -FeO+Fe₂O₃+TiO₂-MgO), (Figure 8b), the fine grained chilled margin is situated in the iron-rich tholeiitic basalt field. There is no appreciable increase towards the F apex, unlike typical Fe-enrichment trends present in large differentiated iron-rich tholeiites (Skaergaard, Golden Mile Dolerite, Defiance Dolerite).

	San Mela- gabbro n=13	Antonio Leuco- gabbro n=14	Gabbro n=1	Sill Gabbro margin n=3	Northern gabbro n=5	Southern gabbro n=3
SiO ₂	43.94	51.44	50.5	46.90	47.54	46.43
TiO ₂	0.61	1.20	0.75	0.74	0.84	1.199
Al ₂ O ₃	12.32	16.41	14.1	13.47	14.34	13.47
Fe ₂ O ₃ t	16.54	12.86	13.4	13.83	15.10	14.90
Fe ₂ O ₃	3.64	6.08	3.00	2.83	4.00	3.37
FeO	11.62	6.10	9.3	9.90	9.98	10.37
MnO	0.24	0.18	0.2	0.19	0.22	0.19
MgO	13.07	3.66	7.98	7.22	7.74	5.56
CaO	7.06	8.27	7.62	7.24	9.03	7.48
Na ₂ O	1.58	2.62	2.5	1.93	2.02	1.89
K ₂ O	0.08	0.13	0.04	0.12	0.02	0.34
H ₂ Ot	5.40	3.29	4.00	5.17	3.94	4.43
CO ₂	0.08	0.37	0.05	3.53	0.54	5.63
P ₂ O ₅	0.06	0.12	0.1	0.08	0.09	0.09
S	0.0	0.01	0.00	0.01	0.00	0.03
Total	99.69	99.87	100.6	99.33	100.30	100.47
Ba	42	69	80	10	76	36
Be	0	1	0	0	0	1
Ni	363	38	160	143	160	70
Co	76	30	50	43	54	47
Cr	370	23	160	38	170	76
Zn	118	110	110	86	97	82
Cu	46	114	42	64	74	109
As	2	2	0	2	0	0
Br	1	0	0	0	0	0
Mo	2	1	0	3	0	2
Nb	2	2	0	4	0	4
Sr	205	368	245	252	282	85
La	6	12	12	6	81	2
V	165	246	180	223	236	287
Y	9	15	0	19	0	14
Yb	1	2	2	2	2	1
Zr	34	58	27	37	43	55

Table 18: Average composition of the Rice Lake gabbros

Figure 8: AFM (a) and Jensen cation plot (b) of unaltered gabbro in the Rice Lake area (Jensen, 1976).

Bivariate diagrams with MgO as the abscissa and Al_2O_3 , TiO_2 , SiO_2 , and $\text{FeO}^* = (\text{FeO} + 0.8998\text{Fe}_2\text{O}_3)$ as the ordinate (Figure 9) show that the members, melagabbro, leucogabbro and gabbro form clusters with a distinct gap between them. The lack of sample overlap along the abscissa indicates the MgO content may be used as an important discriminator in the unaltered rocks.

The melagabbro samples are characterized by MgO wt% content greater than 10% with a maximum of 18 wt. %. The SiO_2 , TiO_2 and Al_2O_3 contents are lower than those in the gabbro and leucogabbro analyses. The MgO content within the leucogabbro is restricted to values between 2 and ~5 wt. %. Variations in TiO_2 , Al_2O_3 and SiO_2 contents are larger than in the melagabbro or gabbro. Analyses of the northern sill, part of the southern sill and the gabbro analyses from the central sill lie between the leucogabbro and melagabbro with a MgO content between ~5 and 10 wt. %.

The abundance and the variation in Ni content is high within the melagabbro (260-500 ppm) and low in the leucogabbro (20-54 ppm) and the sulphur content of the melagabbro is low. Olivine is interpreted to have been a liquidus phase in the melagabbro, based on the Ni distributions. This, coupled with the change in the $\text{FeO}^*/(\text{FeO}^* + \text{MgO})$ ratio from 0.5 in the melagabbro to 0.7 in the leucogabbro, reflects a change in the composition of the ferromagnesian mineral(s) and/or a change in the ferromagnesian species.

Figure 9: Bivariate plots of the three sills in the Rice Lake area (volatile-free basis).

compositional similarities favour pseudomorphs after clinopyroxene. Modal amounts of actinolite single crystals (clinopyroxene) remain constant throughout the melagabbro and actinolite forms large poikiloblastic grains, making up 15%. Similar pseudomorphs are found in the Mt. Kilkenny tholeiitic sill where relict clinopyroxene has been documented (Williams and Hallberg, 1973). Mafic pseudomorph inclusions in large clinopyroxene may indicate postcumulate or intercumulus growth (Plate 4a). Fibrous actinolite is compositionally similar to the 'postcumulus' clinopyroxene pseudomorphs and occurs in euhedral pyroxene shapes. These pseudomorphs may be the replacement of finer cumulate clinopyroxene grains. The modal estimates of 'cumulus' clinopyroxene pseudomorphs within the melagabbro vary between 20 and 40%.

Isotropic chlorite patches occur in small amounts as pseudomorphs after pyroxene euhedra, with abundant oxide filled fractures. These may represent orthopyroxene or olivine. Some pynochlorite patches, poikilitic in clinopyroxene, have a low Al content and a high (0.51 wt%) Cr₂O₃ content relative to the others (Appendix 2, Table 7). Chloritization of olivine is also reported from the Mt. Kilkenny sill, a tholeiite metamorphosed to the greenschist facies (Williams and Hallberg, 1973). The modal estimate for all mafic minerals varies between 50 and 75%.

Plagioclase pseudomorphs make up 20-40% and oxide grains <10%. Plagioclase forms fine grains in the matrix,

Figure 10: Variation in rock composition across three sections of the San Antonio Sill (see Figure 2 for location of transects) (volatile-free basis).

Table 19: Computed bulk composition

Gabbro margin		Mine section	East shore	San Norm
Transect		I	II	III
SiO ₂	46.90	50.52	44.54	48.42
TiO ₂	0.74	1.06	0.65	0.95
Al ₂ O ₃	13.47	15.59	12.64	14.73
Fe ₂ O _{3t}	13.83	13.32	16.24	14.34
Fe ₂ O ₃	2.83	5.28	3.83	5.04
FeO	9.90	7.23	11.17	8.37
MnO	0.19	0.19	0.23	0.20
MgO	7.22	5.38	12.32	7.51
CaO	7.24	8.03	7.16	7.77
Na ₂ O	1.93	2.50	1.66	2.20
K ₂ O	0.12	0.11	0.08	0.11
H ₂ O _t	5.17	3.63	5.23	4.15
CO ₂	3.53	0.28	0.11	0.25
P ₂ O ₅	0.08	0.11	0.06	0.10
S	0.01	0.01	0.00	0.01
Total	99.33	99.99	99.70	99.82

composition from the San Antonio Sill at transect I was too felsic relative to the analyses of the chilled margin. At transect II, the sill is thinner and is composed dominantly of melagabbro showing little deformation; the calculated bulk composition is more mafic than the gabbroic margins. This may be due in part to the structural modification and differentiation processes. The sill is 42 m thick at transect II and 125 m thick at transect I. Deformation in the vicinity of the San Antonio Mine has altered the primary thickness of the sill (as shown on level 6); the melagabbro is thicker than the leucogabbro in the west and is vice versa in the central mine area. At transect III, intense deformation of the sill is not present and each member is homogeneous. This section is representative of the bulk composition of the sill.

4.3 Interpretation

The primary mineralogical variations causing the chemical variations are difficult to assess due to metamorphic recrystallization. No relict pyroxene has been observed to date, so inferences are made from pseudomorphs. Despite deformation and regional metamorphism, primary textures are moderately well preserved and reasonable compositional constraints are imposed by the metamorphic mineral assemblage.

In the melagabbro, oblique extinction of twin planes in actinolite, relict 90° cleavages, euhedral shapes and

compositional ~~schlierites~~ favour pseudomorphs after clinopyroxene. Modal amounts of actinolite single crystals (clinopyroxene) remain constant throughout the melagabbro and actinolite forms large poikiloblastic grains, making up 15%. Similar pseudomorphs are found in the Mt. Kilkenny tholeiitic sill where relict clinopyroxene has been documented (Williams and Hallberg, 1973). Mafic pseudomorph inclusions in large clinopyroxene may indicate postcumulate or intercumulus growth (Plate 4a). Fibrous actinolite is compositionally similar to the 'postcumulus' clinopyroxene pseudomorphs and occurs in euhedral pyroxene shapes. These pseudomorphs may be the replacement of finer cumulate clinopyroxene grains. The modal estimates of 'cumulus' clinopyroxene pseudomorphs within the melagabbro vary between 20 and 40%.

Isotropic chlorite patches occur in small amounts as pseudomorphs after pyroxene euhedra, with abundant oxide filled fractures. These may represent orthopyroxene or olivine. Some pycnochlorite patches, poikilitic in clinopyroxene, have a low Al content and a high (0.51 wt%) Cr₂O₃ content relative to the others (Appendix 2, Table 7). Chloritization of olivine is also reported from the Mt. Kilkenny sill, a tholeiite metamorphosed to the greenschist facies (Williams and Hallberg, 1973). The modal estimate for all mafic minerals varies between 50 and 75%.

Plagioclase pseudomorphs make up 20-40% and oxide grains <10%. Plagioclase forms fine grains in the matrix,

that may be intercumulus, and large laths (11 mm) near the top of the melagabbro. The large laths may represent trapped cumulus grains. Based on the interpretation of the pseudomorphs, the melagabbro may represent a clinopyroxene and plagioclase cumulate with minor orthopyroxene or olivine.

The leucogabbro consists predominantly of plagioclase laths without postcumulus growth, making up 60% of the rock on average. The mafic pseudomorphs are rarely single crystal actinolite but occur as Fe-chlorite (ripidolite), epidote and minor quartz. With the observed relict mineral outline and inferences from the composition of the minerals present (Ca-Fe->Mg-Al-Si), these pseudomorphs probably represent clinopyroxenes. The metamorphic products of clinopyroxene in the leucogabbro represent a more iron-rich mineral assemblage than those in the melagabbro.

Textural evidence of single crystal actinolite (clinopyroxene) enclosing laths of plagioclase implies an original intersertal texture; titanite also encloses plagioclase laths. This indicates that clinopyroxene and titanite crystallized late. Plagioclase and small actinolite-chlorite grains probably represent cumulate clinopyroxene and plagioclase that possibly crystallized simultaneously. Ilmenomagnetite makes up 15% of the leucogabbro. The fibrous actinolite and isotropic chlorite-titanite pseudomorph after pyroxene in the melagabbro are absent in the leucogabbro. It is inferred that the

leucogabbro represents a gabbro with cumulus plagioclase, clinopyroxene and intercumulus iron-oxides.

The chemical bimodality of the rock types (melagabbro and leucogabbro) in the San Antonio Sill may be explained by;

- 1) immiscibility
- 2) two different magmas
- 3) "in situ" differentiation

Observational criteria for immiscibility, stated by Bowen (1928), are two glasses of contrasting composition, the occurrence of identical crystals in both glasses and the coalescence of globules to form distinct layers. Philpotts (1978) emphasized the textural evidence for immiscibility in crystalline tholeiites and stated that immiscibility usually occurs when 20-50% of the liquid remains. The only possible evidence would be in the granophyric leucogabbro with the fine mosaic of quartz interstitial to plagioclase laths (Plate 5f), but mafic globules in the silica-rich portion have not been observed. It may be that the granophyre formed by immiscibility but not the melagabbro and leucogabbro.

If multiple intrusions or flows were proposed to explain the San Antonio Sill, the following points would have to be explained. The contact between the melagabbro and leucogabbro is visually gradational over 1 m but relatively sharp compositionally. Sharp contacts, country rock septa or repetition of units (gabbro) are not present, as would be expected for injection of separate magmas. If the initial magma still had been hot, there would not be a sharp contact

and some evidence of mixing should be observed at the contact. Also, the same source must have been tapped and a very rapid differentiation of the magma chamber must occur to produce the feldspar-rich leucogabbro. This hypothesis seems unlikely.

In situ differentiation by gravitational settling of ferromagnesian minerals and the flotation of plagioclase can explain many of the features of the San Antonio Sill. The rapid changes in chemical composition from the melagabbro to the leucogabbro may reflect the addition and removal of cumulate phases during differentiation. The melagabbro probably contained phases, inferred on the basis of textural criteria, which were not present in the leucogabbro. The pronounced chemical change from melagabbro to leucogabbro probably is the result of the disappearance of orthopyroxene or olivine grains, a decrease in clinopyroxene and the change in the composition of the clinopyroxene to a more iron-rich variety, deduced from the presence of epidote and ripidolite in the leucogabbro in contrast to Mg-rich pycnochlorite in melagabbro, at the lower contact of the leucogabbro. The San Antonio Sill probably has both phase and cryptic layering. The absence of well-developed rhythmic layering may indicate that convection was not strong in the magma chamber. The wispy melagabbro may reflect weak convection in the unsolidified magma.

The granophyric leucogabbro reflects the most differentiated portion of the sill and represents the late

stage liquids. The formation of the sill probably involved pyroxene settling from a magma compositionally similar to the chilled margins, leaving a plagioclase-rich residue. During the flotation of plagioclase, the remaining liquid would be forced down and the final differentiated liquid would collect immediately above the pyroxene-rich rocks. The occurrence of granophyric leucogabbro at the mine immediately above the melagabbro supports this concept.

The northern gabbro formed without any significant crystal-liquid separation after intrusion but the southern gabbro shows similarities to the San Antonio Sill, although data are limited.

4.3.1 Distribution of Rock Types

The distribution of the rock types may be explained by:

- 1) lateral flow of the less dense material (evolved liquids) laterally due to pressure from the overlying rocks or variations in the paleotopography or,

- 2) a host rock control due to assimilation of felsic xenoliths, which is similar to the Doré Lake complex (Allard and Gobeil, 1984).

The first hypothesis cannot be tested without reconstructing the paleotopography. Few xenoliths have been observed in any of the sills. In the San Antonio Sill on the east shore of Rice Lake west of Transect II, a dacitic xenolith with very sharp contacts was observed in the melagabbro and an angular xenolith, similar to the

leucogabbro, approximately 10 m south of the upper contact. Partial assimilation of these xenoliths is not evident. Significant widths of leucogabbro occurs where the sill is in contact with the andesite and but not the felsic volcaniclastics. At these localities xenoliths are not present in the sill.

The distribution may be dominantly due to variations in the paleotopography.

4.3.2 Origin of the San Antonio Mine Unit

Several hypotheses have been presented for the origin of the San Antonio Mine Unit. An intrusive diabase has been suggested by Stockwell (1938) and Poulsen et al., (1986). Stephenson (1972) called the unit a diabase sill. Whiting and Sinclair, (1986) favoured a sequence of Fe-rich tholeiitic flows and Theyer (1983) suggested a series of flows and tuffaceous rocks. It is concluded in this thesis that it is either a differentiated sill or may represent a single differentiated massive flow.

When discussing intrusive versus flow or tuffaceous rocks the following points must be taken into account:

The unit in question must be carefully mapped to determine the relationship of this unit with the volcanic rocks. If the unit is a series of flows or tuffaceous rocks, the unit must be parallel to bedding in the volcanic sequence. Although, Theyer (1983) favoured this theory, he showed the unit crosscutting stratigraphy. Drill hole data

from San Antonio Mines east of the mine in Rice Lake, reported on the map of Stockwell (1938), show the exposed gabbro on the east shore trending towards the projected mine workings. Little room is available to project the sill further south.

Rocks considered to be tuffaceous by Theyer (1983) contain 2 mm patches of granophryic intergrowths within the leucogabbro. The "pinhead" variety (carbonate mineral) of mafic flows, reported within the sill, corresponds to alteration within the melagabbro and leucogabbro.

The presence of granophryic intergrowths implies cotectic precipitation of quartz and plagioclase, compatible with an intrusive origin. Xenoliths near the hanging wall contact in the mafic body would provide good evidence. These have not been found to date. The hanging wall contact is marked by 50 cm of fine grained cherty felsic volcanoclastic rock, not present at the footwall contact or in the thick volcanoclastic pile away from the mafic body. With stratigraphic tops to the north, heat would rise and affect the stratigraphically higher rocks, possibly explaining this feature.

CHAPTER 5

ALTERATION OF THE GABBRO

5.1 Alteration Types

Two types of alteration occur in the mafic rocks in the Rice Lake area. These are epidotization and carbonatization. Field observations of epidotization will be documented. Field, petrographic and geochemical observations of carbonatization will be documented to establish the effects of the hydrothermal alteration on the mineral assemblages and chemical composition of the different host rocks and to establish the relative timing and spatial distribution of alteration.

5.1.1 Epidotization

Epidosite pods, oval and irregular in shape, ranging from 4 X 2 cm to 25 X 25 cm are randomly distributed throughout the entire sill. Epidosite pods form across the contact between leucogabbroic sills and dykes in the melagabbro and the melagabbro. These pods formed after consolidation of both the leucogabbro and melagabbro. Locally the epidote is fracture controlled, associated with quartz-epidote rich fractures. Brittle fractures in the epidosite pods are filled with quartz, chlorite and epidote and trend $310 - 335^{\circ}$. The epidosite pods developed prior to deformation and possibly during metamorphism. Similar epidosite pods occur in the cores of the pillowed basalts

and have been altered by carbonatization.

5.1.2 Carbonatization

The mafic rocks in the San Antonio Mine area have been carbonatized, that is, replaced by various amounts of carbonate minerals. The identification of carbonate minerals was facilitated by staining hand samples and thin sections with a solution of potassium ferricyanide and alizarin-S red to determine their textural and spatial relationships in the mafic rocks. The composition of the carbonates was verified by microprobe analyses (Appendix 2, Table 11).

Zones, up to 5 cm wide adjacent to veins are composed of carbonatized, bleached, beige-weathering, leucogabbro. In these zones, proximal to the veins, muscovite, paragonite and pyrite are present but in smaller amounts than the carbonate minerals. The term carbonatized was used since CO₂ is the dominant substance added to the rock (see 5.4.2). Carbonatization has been subdivided on the basis of mineral associations documented in the petrographic description (see sections 5.2.1, 5.3). The terms weak, moderate, strong and intense alteration are relative measures of carbonatization. In the leucogabbro they correspond to the assemblages calcite + chlorite, ankerite + paragonite, ankerite + muscovite + paragonite and ankerite + muscovite + albite respectively. In the melagabbro weak alteration is characterized by the assemblage calcite and chlorite and in the moderate and strongly altered melagabbro by ankerite and

chlorite. The spatial distribution and timing of these alteration zones are discussed in 5.3. Modal estimate data are documented in Appendix 1 and summarized in section 5.3.

5.2 Petrography of Carbonatized Gabbro

Individual minerals will be documented in the melagabbro, leucogabbro and granophyric leucogabbro, the gabbro and veins, in the San Antonio Sill and the Southern Sill, to describe textures, mineral associations and relative timing of the alteration.

5.2.1 Melagabbro

The base of the sill at the San Antonio Mine is variable in width from 7 m to 40 m and is dominantly carbonatized. East and west of the power line on the east shore, there are shear zones with carbonate haloes (Figure 2). The common mineral assemblage is chlorite₃ + quartz + plagioclase + epidote + calcite + titanite + magnetite + hematite + rutile + leucoxene + ankerite.

Pale green chlorite (chl₃) (birefringence colours), found in altered melagabbro and identified by electron microprobe analysis as pycnochlorite and pycnochlorite-ripidolite (Appendix 2, Figure 7), has a lower Fe/(Fe+Mg) value than the chlorite identified in the unaltered samples (chl₁). Felted masses of chlorite₃ (1.4 mm average diameter) replaced metamorphic actinolite and also form part of the groundmass. The altered rocks are variably deformed with

chlorite defining the penetrative fabric. The modal amount of chlorite decreases with increasing carbonate content (Figure 11).

Chlorite also forms randomly oriented euhedral plates intergrown with calcite and quartz. These minerals constitute patches (Plate 6a) similar in size (2mm) to the single actinolite grains. This site-specific association is a key textural observation in classifying the alteration.

Plagioclase is strongly altered to fine aggregates of albite (An 0.7) + clinozoisite + chlorite + quartz + calcite or ankerite forming pseudomorphs of the primary grains. Stubby laths average 0.2 mm and the maximum is 0.5 mm. Twinning is weak, obscured by the alteration. Ankerite partially to totally replaces plagioclase.

Fine epidote, originally formed as a metamorphic product during saussuritization of the feldspar, is commonly replaced by calcite. Epidote also occurs in the matrix as coarse (0.2 mm) isolated grains with chlorite, as islands within the calcite grains and in trace amounts with calcite and/or ankerite (Plate 6b). Relict epidote in the strongly altered melagabbro is surrounded by chlorite, leaving a relatively unaltered domain in thin section. Allanite, identified by electron microprobe analysis (Appendix 2, Table 8) occurs in trace amounts occupying a euhedral, strongly pleochroic brown mineral commonly as the core of epidote (85-1026).

Figure 11: Modal mineralogy with increasing alteration in the melagabbro (a) and leucogabbro (b). Solid lines represent the minerals stable in the phases of alteration.

Plate 6: Petrographic characteristics of altered melagabbro and leucogabbro in the layered San Antonio Sill.
Scale bar is 0.5 mm.

- A: Calcite, (red) chlorite (chl_3) and quartz patches in weakly altered melagabbro are of similar size (0.9 mm) and shape as actinolite porphyroblasts in the unaltered melagabbro. Magnetite (mt) and rutile (rt) are also representative of this early alteration stage. Transmitted, plane-polarized light, stained. (Sample 85-1060)
- B: In weakly altered melagabbro calcite (red) replaces and encloses epidote (ep). A typical assemblage is calcite- chl_3 (khaki green)-quartz-rutile-magnetite with trace amounts of epidote. Transmitted light, crossed polars, stained. (Sample 85-1020)
- C: In moderately altered melagabbro and leucogabbro ankerite (blue), replaces calcite (red). Ankerite contains relict calcite as inclusions and the ankerite-calcite grain boundary is scalloped. Relict magnetite is retained from the weakly altered stage. Transmitted, plane-polarized light, (Sample 84-100a)
- D: Subhedral secondary magnetite (mt) with a rim of hematite partially encloses relict primary oxide grain consisting of rutile and leucoxene. Secondary magnetite is stable in weakly altered leucogabbro. Reflected, plane-polarized light. (Sample 86-32)
- E: Inclusion-free hydrothermal albite at the contact of a vein and leucogabbro, representing the most intense alteration with ankerite, muscovite and quartz. Transmitted light, crossed polars. (Sample 86-41)
- F: Transition from weak to strong alteration in the leucogabbro. The assemblage calcite- chl_3 -quartz is replaced by ankerite-paragonite (pg) and muscovite (mu). The six minerals are present ankerite replaces calcite, paragonite replaces chl_3 and muscovite is an alteration product of albite. Transmitted, plane-polarized light, of stained section. (Sample 86-33)
- G: Intensely altered granophyric leucogabbro with the granophyric texture retained. Albite is partially altered to muscovite. Transmitted light, crossed polars. (Sample 86-003)
- H: Pyrite (py), overgrowth on relict ilmenomagnetite in a strongly altered leucogabbro adjacent to a stockwork type vein. Ilmenite exsolution lamellae are outlined by rutile. Reflected, plane-polarized light. (Sample 86-65)

2

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Metric

Quartz (<5%) occurs as anhedral, dominantly monocrystalline, primary grains with weak to strong undulose extinction. In the presence of rutile and calcite, fine polycrystalline quartz occurs in calcite-chlorite-quartz patches as quartz-chlorite ribbons and in anhedral chlorite patches. Triple junctions are common. This quartz is interpreted as an alteration mineral. Secondary quartz also occurs perpendicular to porphyroblast grain boundaries in pressure shadows. These quartz grains have irregular, indistinct grain boundaries. This secondary quartz makes up 25% on average, with a maximum of 30% of the altered melagabbro.

Rutile is ubiquitous in altered melagabbro, forming masses of fine euhedral crystals with leucoxene and chlorite as pseudomorphs of primary oxide grains. Rutile and titanite rarely occur in the same section. Rutile is enclosed in ankerite. The modal amount of titanite, or rutile, and leucoxene averages 7%.

In weak and moderately altered melagabbro, calcite occurs as coarse patches, randomly oriented in the matrix (0.5 mm in diameter, with a maximum of 2 mm). Within these calcite patches, recrystallized chlorite and quartz are present. Calcite grains are inclusion-poor. Twin lamellae are present and the carbonate is variably aligned parallel to the penetrative fabric indicating that calcite formed pre- or syn-deformation. Fracture fillings of calcite are also deformed.

Idioblastic (0.6 mm in diameter) ankerite encloses calcite, epidote, quartz-chlorite patches and magnetite-rutile-leucoxene intergrowths (Plate 6c). In samples devoid of calcite, inclusion-free ankerite is associated with the plates of chlorite and quartz in the calcite site. Ankerite also partially replaces plagioclase and is deformed by the penetrative fabric. Granular ankerite occurs as smaller grains in the groundmass. In the absence of calcite, ankerite nucleates on altered primary oxide grains, forming inclusion-rich grains.

Weakly altered melagabbro contains titanite as pseudomorphs of skeletal ilmenomagnetite grains. Titanite is overgrown by euhedral secondary magnetite (0.1 mm average), (Plate 6d). This magnetite has inclusions of epidote, quartz and titanite. Hematite occurs as rims around the secondary magnetite. Locally magnetite has sharp boundaries with hematite without evidence of a reaction rim. Hematite also occurs as ragged poikiloblastic grains in sample 86-072.

Magnetite and ankerite rarely occur within the same sample, except in the presence of calcite (Plate 6c). Magnetite was evidently unstable in strongly altered rocks. Magnetite-chlorite bands occur in foliated samples and the magnetite has asymmetric pressure shadows of quartz and chlorite.

Anhedra! chalcopryrite grains, averaging 0.05 mm, occur in the core of coarse epidote, as fracture fillings in magnetite, and disseminated in the matrix.

Summary of Alteration Mineral Assemblages in the Melagabbro

Alteration at the millimeter scale occurs in preferential mineral sites during weak and moderate alteration (Figure 11, Plate 6), producing a domain structure of alteration, which results in a patchy distribution.

In the weakly altered rocks, inclusion-free calcite, ripidolite and quartz patches occur as a replacement of metamorphic actinolite in the unaltered rocks. The chlorite species is an Fe-poor variety (chl_3). Epidote is commonly found as inclusions in calcite. Calcite also occurs as an alteration product spatially associated with secondary magnetite and rutile, that are alteration products of titanite and ilmenomagnetite.

In the more strongly altered melagabbro, ankerite occurs in the same sites occupied by calcite in the less altered rocks; this ankerite forms inclusion-free grains associated with chlorite and quartz. Inclusion-rich ankerite enclose rutile and leucoxene. Secondary magnetite is not stable at this more advanced stage of alteration. Secondary quartz is produced in the altered melagabbro spatially associated with the calcite+ripidolite+quartz patches and oxide alteration products. The modal amount of chalcopyrite remains constant in the altered and unaltered melagabbro.

5.2.2 Leucogabbro and Granophyric Leucogabbro

Carbonatized leucogabbro in the San Antonio Sill is located on surface at the mine site, west of the mine and is best studied underground in the San Antonio Mine (Figure 2).

Chlorite (20%) in the altered leucogabbro has steel blue, purplish blue or bright green birefringence colours and is identified by electron microprobe analysis as ripidolite, (chl_4) with higher $\text{Fe}/(\text{Fe}+\text{Mg})$ than in the unaltered leucogabbro (Appendix 2, Table 7). In undeformed altered rocks, ripidolite forms felted masses, as pseudomorphs after actinolite and is finely disseminated between the plagioclase laths. In deformed leucogabbro, the foliation is defined by the alignment of ripidolite. Coarse euhedral plates are associated with patches of calcite and quartz, similar to the textures present in the melagabbro (Plate 6a), and anhedral chlorite is associated with rutile.

Albite (An_4) occurs as euhedral to subhedral laths (maximum 1.25 mm) variably altered to clinozoisite, calcite and chlorite (weak alteration) or muscovite, paragonite and ankerite (strong alteration). Albite twinning is present. In strongly altered and deformed rocks, albite is difficult to determine and has been altered dominantly to white mica. Immediately adjacent to veins (< 2 cm), in the most intensely altered zones, there is inclusion-free albite, termed hydrothermal albite (Plate 6e). Hydrothermal albite is distinctly different from the muscovite-rich, altered metamorphic albite in that it is inclusion-free. Modal

estimates of albite vary from trace amounts to 60%, depending on the intensity of alteration.

White mica assemblages include paragonite and/or muscovite. Back-scattered electron photographs and electron microprobe analyses aided in determining the association of each mica and the relationship between the two micas (Appendix 2, Table 12). In sample 86-033, paragonite occurs as coarse blades replacing chlorite in calcite-chlorite-quartz patches that are rimmed with ankerite (Plate 6f). Muscovite forms as an alteration product of albite. In one paragonite grain, a fine layer of muscovite was observed on a photograph of a back scatter image. Muscovite formed after chlorite defines a foliation that crosscuts chlorite and ankerite, has sharp boundaries with ankerite and is partially enclosed in the ankerite. Ambiguous textural relationships between ankerite and muscovite suggest that they were coeval. White mica occurs as inclusions and fracture fillings in pyrite and in pressure shadows around pyrite.

Igneous quartz grains retain their anhedral shape during alteration where pervasive deformation is absent. With increasing deformation, the grain size of the quartz decreases (sample 86-048). In the strained areas, quartz has strong undulose extinction and serrated grain boundaries. Attenuated ribbons of polycrystalline quartz aggregates occur in intensely deformed rocks, and monocrystalline grains with granulated edges are formed in rocks ranging

from strongly deformed to undeformed. Fractures in the monocrystalline grains are filled with calcite and minor chlorite. Granophyric textures are retained in the undeformed altered rocks (Plate 6g).

Quartz forms as inclusion-free grains with a granoblastic texture in the groundmass and is associated with chlorite-calcite patches. The groundmass is dominantly quartz with variable amounts of epidote, chlorite and sericite. Quartz also formed in pressure shadows, perpendicular to the porphyroclasts, as elongate grains with poorly defined intergranular boundaries.

Modal estimates of epidote in the variably altered leucogabbro range from trace to 20%, depending on the intensity of alteration. Coarse (0.2 mm) epidote is enclosed within calcite and ankerite porphyroblasts, occurs as isolated grains in the matrix, or is totally replaced by ankerite. Traces of clinozoisite (optically determined) occur in weakly altered samples.

Titanite occurs in unaltered and weakly altered rocks, locally coexisting with rutile. Titanite mimics the exsolution lamellae of igneous ilmenomagnetite grains, and rutile, together with chlorite, forms the inter-lamellae material. In the absence of titanite, dusty leucoxene is present with rutile as a constant accessory in altered rocks of all intensities. In weakly altered rocks, rutile occurs with calcite and quartz, and in moderate to strongly altered samples with ankerite, forming a rutile-ankerite-quartz

assemblage. The maximum length of rutile is 0.05 mm.

Calcite encloses epidote, rutile, trace actinolite, chlorite and quartz forming large 2 mm anhedral grains. Ankerite rims calcite and, locally, totally replaces calcite (see documentation of white mica). Idioblastic ankerite rhombs (0.4 mm) in undeformed samples have inclusions of epidote, chlorite, quartz, rutile and plagioclase. Ankerite formed around relict oxide minerals and plagioclase laths. Fine-grained ankerite is pseudomorphic after coarse epidote. Adjacent to shear zones and in shear zones the ankerite forms ragged grains, porphyroclasts and elongate ribbons parallel to the shear fabric. The ankerite is granulated.

In weakly altered leucogabbro (sample 85-1113), primary ilmenomagnetite grains have been replaced by titanite and rutile in the exsolution lamellae sites leaving magnetite preserved. Secondary magnetite does not have relict exsolution lamellae like the primary magnetite and occurs as euhedral, generally monomineralic, rhombs that typically have incorporated rutile-leucoxene aggregates. This idiomorphic magnetite (0.2 mm) is poikiloblastic with epidote, quartz, chlorite, titanite, rutile and is locally enclosed by chalcoppyrite. Idiomorphic magnetite has overgrown the rutile-leucoxene aggregates and in sample 85-1742-12 occurs in the quartzose polycrystalline matrix. The maximum modal estimate is 10%. With a small amount of alteration, the titanite-bearing assemblages are converted to rutile-leucoxene and calcite. The ilmeno-magnetite in the

unaltered samples is metallic grey, whereas the rutile-leucoxene pseudomorphs are light brown. Due to the large grain size and greater modal amount of primary oxides in the leucogabbro, this change in assemblage is readily visible in hand specimen. Strongly altered rocks do not contain magnetite.

Trace amounts of hematite rim secondary magnetite grains and occur along fractures in the magnetite in the weakly altered leucogabbro. It also forms twinned, ragged plates (average 0.1 mm, maximum of 0.3 mm) in sample 86-030. These grains are spatially associated with the rutile-leucoxene aggregates. Hematite forms fan-like aggregates.

Pyrite occurs typically less than 25 cm from quartz veins. In the wallrock, the pyrite occurs as overgrowths on the rutile-leucoxene aggregates (Plate 6h), muscovite, ankerite and quartz. Idiomorphic grains of pyrite have a maximum diameter of 2 mm. White mica and quartz are found in pressure shadows and fracture fillings in pyrite. Some deformation postdates the growth of pyrite.

Chalcopyrite is very commonly associated with coarse epidote patches, occurring as fine (0.05 mm) inclusions in the epidote. Coarser anhedral grains (0.2 mm) rim ankerite and may occur between secondary magnetite and ankerite. Chalcopyrite is found as inclusions in secondary magnetite and as fracture fillings in pyrite. Chalcopyrite and lesser bornite and chalcocite occur in trace amounts.

Summary of Alteration in the Leucogabbro

The modal estimates for the carbonate minerals are higher in the most intensely altered melagabbro than in the altered leucogabbro (Figure 11). The association of inclusion-free calcite with coarse chlorite plates and quartz in 2 mm patches is similar to that in the melagabbro. The chlorite species changes to ripidolite-pseudothuringite (chl_4) in the altered leucogabbro from a ripidolite (chl_3) in the unaltered leucogabbro (Figure 7). This reveals an increase in $\text{Fe}/(\text{Fe}+\text{Mg})$ and a decrease in Si content with alteration in the leucogabbro. The variation between metamorphic and alteration chlorite species is much greater than that in the melagabbro. There is an increase in the modal amount of secondary quartz with increasing alteration similar to that in the melagabbro.

Metamorphic epidote is replaced by calcite and ankerite and, in strongly altered leucogabbro, coarse epidote occurs in trace amounts as relics in weakly altered domains at the millimeter scale. Secondary magnetite and minor hematite formed in the weakly altered leucogabbro in association with rutile, leucoxene and calcite but is not present in strongly altered leucogabbro. The strongly altered leucogabbro is characterized by ankerite, rutile and leucoxene.

In strongly altered leucogabbro, ankerite and paragonite and/or muscovite occur, in contrast to calcite and greater modal amounts of albite and chlorite in less altered leucogabbro. In the transition to strongly altered

rocks, ankerite rims calcite in the calcite (ankerite) + chl₄ (paragonite) + quartz patches (Figure 11). Paragonite partially replaced the coarse chl₄ (alteration chlorite) blades and muscovite partially replaced metamorphic albite. Muscovite defines a foliation that crosscuts chl₄ and ankerite and it also occurs as inclusions in ankerite. Ambiguous relationships between ankerite and muscovite suggest coeval formation.

In the strong alteration adjacent to veins, muscovite tends to dominate the mica population, together with hydrothermal albite. Pyrite formed late in the alteration sequence in the leucogabbroic wallrocks as it encloses ankerite and muscovite.

5.2.3 Gabbro

Altered gabbro occurs as the fine grained chilled margin of the sill and as the upper 15 m (minimum and 24 m maximum) of the sill on the 16 Level.

In the upper portion of the sill, the gabbro contains a purplish-blue birefringent chlorite, aligned along the foliation. Chlorite is abundant and is associated with quartz and opaque minerals. It occurs in patches with ankerite and as coarse plates with quartz. Individual plates are composed of chlorite and muscovite in the strongly altered rocks. The chlorite is partially replaced by muscovite. Modal amounts are estimated to be 15% on average.

In weakly altered samples, the plagioclase remains

relatively unaltered as part of the primary metamorphic assemblage. In strongly altered gabbro, plagioclase is altered with (10-80%) fine inclusions of muscovite. Poorly defined laths of albite are 1 mm long. Modal estimates vary from trace to 15%.

The groundmass consists of fine polycrystalline quartz, plagioclase and chlorite making up approximately 15% of the rock. Subrounded monocrystalline quartz grains average 0.2 mm and modal estimates vary from 5 to 15% with an average of <10%.

White micas have been identified as muscovite and paragonite by XRD and by probe investigation (Appendix 2, Table 12). Similar to the leucogabbro (sample 86-033), muscovite partially replaced albite. These micas occur within the plagioclase laths and as randomly oriented coarse blades within the groundmass. White mica also replaced chlorite and defines the foliation in strongly deformed, altered gabbro.

Calcite occurs in patches with chlorite plates and with quartz, and it surrounds epidote. In the strongly altered rocks, calcite and epidote are not present. Instead, ankerite occurs as inclusion-free rhombs associated with chlorite-quartz patches and as inclusion-filled rhombs with leucoxene and rutile. Inclusion-free ankerite also forms in the groundmass as fine grains (average 0.2 mm in diameter). The ankerite in the matrix may form as the replacement of coarse epidote grains.

In the weakly altered zones, titanite occurs with secondary magnetite and calcite. In strongly altered samples, the primary ilmenomagnetite grains have been altered to a mixture of rutile, leucoxene and ankerite, with minor quartz and chlorite. These aggregates are 0.5 mm in size, variably deformed and make up 10-15% of the gabbro.

Pyrite encloses chalcopyrite. Chalcopyrite also occurs as isolated anhedral blebs in the strongly altered rocks. Pyrite is fractured, inclusion-filled and is poikilitic with white mica, chlorite, ankerite and quartz. The development of pyrite clearly postdates that of muscovite and carbonate, as indicated by the abundant inclusions of these minerals in the sulphide. Pressure shadows of chlorite, white mica and quartz form on these grains adjacent to shear-type veins. The modal estimate of pyrite is 10%.

The mineral associations and timing are the same as those in the leucogabbro.

5.2.4 Southern Gabbro

The southern gabbro was observed from the 26 level in the mine and is compositionally similar to the leucogabbro and granophyric leucogabbro within the central sill. The samples are magnetic and contain 5-10% opaque minerals (thin section only) which form in patches with abundant quartz, lesser ankerite and chlorite. A trace of pyrite was observed in hand specimen.

The chlorite birefringence is purplish brown and steel

blue in the two samples studied. Euhedral plates of chlorite are again associated with calcite and quartz rich patches. Chlorite occurs as anhedral, randomly oriented grains in a groundmass also including quartz and minor epidote.

Plagioclase occurs as short stubby laths in the groundmass or enclosed in quartz, and it has trace amounts of sericite inclusions. In the granophyric portion, plagioclase exhibits an arcuate extinction (sample 85-1070). Locally, quartz is intergrown with the plagioclase forming a granophyric texture. Large (0.4 mm to 1.4 mm) anhedral monocrystalline quartz grains make up 10-20 % of the rock. Quartz has straight extinction and has been fractured.

Calcite and ankerite occur in both samples. Fine granoblastic calcite occurs in 2 mm patches with chlorite and quartz. Ankerite contains inclusions of calcite, forms discontinuous rims around calcite patches and is intimately associated with the relict titano-magnetite grains, where it fills the interstices between exsolution lamellae. Calcite, rutile and leucoxene are associated in patches. Ankerite partially surrounds the calcite in this association. Rutile + titanite are the principal phases in the titano-magnetite pseudomorph. Rutile mimics the exsolution lamellae relicts. The relict grains are 0.7 to 1 mm and make up 10-15% of the gabbro.

5.2.5 Wallrock and Vein Mineralogy

Gold mineralization at the San Antonio Mine is associated with two vein types; the shear- and stockwork-type veins. Two other vein sets; the "southeast dippers", temporally related to the shear-type veins and the '130-faults', temporally the latest vein set were not mined due to either inadequate mining widths or lack of gold. All four vein sets are spatially associated with bleached wallrocks, restricted to the zones immediately adjacent to the veins. Mineralogy of the shear- and stockwork- type veins and the 130-faults will be documented.

5.2.5 a Shear-type Veins

A major shear-type vein (the 16 vein), was studied on the 7th level at the 716 raise along two transects (Figure 12) and on the 6 and 16th levels. The 608 vein and stringers adjacent to each of these veins and those in the footwall to the 1351 vein were also studied. The economic gold-bearing veins are within leucogabbro.

Immediate contact of the veins

At the contact of the vein, the leucogabbro is intensely foliated, as defined by muscovite-rich bands with a trace of chlorite, porphyroclasts of ankerite + quartz + white mica and anatase-leucoxene + quartz, that form discontinuous ribbons. The average porphyroclast is 0.2 mm

Figure 12: Cross-section of a shear-type ("16-type") vein at two localities on the 7 level.

wide with an aspect ratio averaging 6:1. The wallrock immediately adjacent to the vein contains pyrite and tourmaline. Tourmaline is in a narrow band with white mica and has abundant fine grained oxide inclusions.

Breccia fragments

The wallrock fragments are undeformed and the quartz in the vein surrounding the fragments has straight extinction and irregular grain boundaries. In the altered leucogabbroic breccia fragments in the footwall section of the vein, calcite is replaced by ankerite. In the veins, calcite replaces ankerite and quartz (Plate 7a).

Pyrite occurs as idiomorphic grains (0.01 mm) enclosing rutile-leucoxene aggregates in the wallrock, as fine granular aggregates aligned in quartz + ankerite + white mica-rich bands, and as fine disseminations within ankerite grains. Ilmenite occurs as 0.2 mm anhedral grains with anatase replacing primary oxide grains in the intensely altered leucogabbroic wallrock inclusions.

Vein Mineralogy

There are three veins distinguished by their mineral assemblages and textural relationships. 1) The main shear-type vein assemblage consists of quartz, albite, ankerite, muscovite, tourmaline, pyrite, pyrrhotite, chalcopryrite, sphalerite, rutile and gold. 2) Chlorite-quartz veins are parallel to the contact of the gold-bearing veins and

Plate 7: Textural relationships among vein minerals.

Scale bar is 0.5 mm

- A: Late calcite (red) vein with partially consumed ankerite (blue) and quartz in main shear-type vein. Transmitted, plane-polarized light. (Sample 86-46)
- B: Fine granular pyrite (py) with inclusions of tourmaline (tm) at the contact between intensely altered leucogabbro and a late calcite quartz vein. Transmitted, plane-polarized light. (Sample 86-46)
- C: Fine granular pyrite seam with inclusions of chalcopyrite (cpy), pyrrhotite (po) and gold (Au). The pyrite seam occurs at the contact between the shear-type vein and leucogabbro. Reflected, plane-polarized light. (Sample 85-40b)
- D: Gold (Au) and chalcopyrite (cpy) also occur as fracture fillings in pyrite (py). Reflected, plane-polarized light. (Sample 86-47):
- E: Tourmaline (tm), occurs adjacent to the vein in the intensely altered leucogabbro intergrown with pyrite (py). In addition, the mineral assemblage consists of ankerite, muscovite, rutile, and quartz. Transmitted, plane-polarized light. (Sample 86-47)
- F: Lath-shaped hydrothermal rutile (rt), with twinning perpendicular to the long axis associated with pyrite (py) and chalcopyrite (cpy). Reflected light, crossed polars. (Sample 86-47)
- G: Ankerite (ank), albite (alb) and minor quartz (qtz) vein with chequer-structured twins (arrow). Transmitted, plane-polarized light. (Sample 86-12a)
- H: Late chlorite-quartz veins crosscut auriferous stockwork vein. Surface exposure on the northwest shore of Rice Lake. Yellow pencil is 17 cm long.

crosscut them. This second type of vein is clearly later. 3) Calcite veins crosscut the shear-type vein assemblage and replace quartz and ankerite.

In the 616 shear-type main vein, silicate and carbonate minerals are quartz, albite and ankerite which are crosscut by calcite, chlorite and quartz filled veins. Vein quartz (2 mm) is fractured with serrated edges. The fractures are filled with fine-grained ankerite. Ankerite forms large (1 mm) grains with radial extinction. Albite present in minor amounts in the vein occurs as 0.1 mm clear, distinctly twinned grains. In the vein, portion of the laminated wallrock and in veins adjacent to the hanging wall contact (Figure 13), albite is a major constituent with ankerite interstitial to large albite grains.

Fine, discontinuous granular pyrite forms anastomosing 0.2 mm wide bands, known in mine terminology as the 'lead-slips' (DeHuff Jr., 1940), that have been reported as gold-rich portions of the veins (Stockwell, 1938). These sulphide-rich veinlets are situated at the contact between the vein and the wallrock (Plate 7b), or within the vein adjacent to wallrock inclusions. Pyrite is the main sulphide with chalcopryrite, pyrrhotite, sphalerite and gold as inclusions. Chalcopryrite rims the pyrite, fills fractures and occurs as isolated anhedral. Pyrrhotite and sphalerite are not in mutual contact. Gold occurs in the pyrite as fine inclusions and also occurs along pyrite grain boundaries (Plate 7c,d). Gold is synchronous to post pyrite deposition.

Pyrite encloses the tourmaline (Plate 7e). Lath-shaped rutile (0.5 mm long) coexists with pyrite in the central portion of the 616 vein. Rutile laths have lamellar twinning parallel to the short axis of the grain (Plate 7f).

Adjacent to the shear-type veins are narrow (1 cm on average), fibrous, quartz-filled extensional veins, developed perpendicular to the shear vein, with associated visible alteration (~1 cm wide). They are composed dominantly of quartz with lesser ankerite and albite. Quartz forms perpendicular to the vein walls as 0.8 mm strongly undulose grains with sutured intergranular boundaries. Inclusion-free albite grains are distinctly twinned (Plate 7g). The diameter is variable and less than 0.2 mm. Ankerite encloses quartz and fills the interstices between quartz and albite grains. These veinlets are deformed with a strong penetrative fabric development and the quartz is polycrystalline with sutured intergranular boundaries.

Seams of white mica and chlorite crosscut the quartz-ankerite-albite veinlets. Chlorite, with steel-blue birefringence forms felted masses enclosing and partially replacing white mica. Chlorite also replaces ankerite and quartz in the vein. Calcite also encloses ankerite, quartz and white mica. The chlorite crosscuts the calcite and is enclosed in calcite. These two minerals may be contemporaneous, both the latest feature in the vein development.

5.2.5 b Stockwork veins

The mineral assemblage of the stockwork-type veins was determined by examining the 838 stockwork, a vein set in the 705 crosscut, and a breccia sample from the 97 stockwork on the 33rd level. The proportions of minerals in the veins are variable depending on the vein (Appendix 1). Albite with lesser quartz fills the interstices between the leucogabbro wallrock breccia fragments. Albite porphyroblasts form clear, well-twinning grains within the vein, distinct from the altered metamorphic albite in the wallrock, which is inclusion-rich with white mica. Albite also forms fan-like aggregates with a radial extinction.

Pyrite encloses rutile-leucoxene aggregates and incorporates muscovite, ankerite and quartz. These mm-sized idiomorphs also have cores of randomly oriented rutile needles and are intensely fractured. Anhedral chalcopryite occurs as inclusions in the pyrite and is in sharp contact with pyrite at the edge of the idiomorph.

Ladder veins at the 838 stockwork consist dominantly of quartz, with metasomatic albite at the contact with the wallrock. Ankerite fills interstices between the quartz grains in the vein. Pyrite is abundant in the wallrock up to approximately 10 cm from the contact.

Pyrite grains also cross the boundary between the breccia fragment and the vein material. Pyrite is poikilitic with metasomatic albite, quartz, muscovite and ankerite from the vein. Chlorite-calcite veins crosscut the gold-bearing

veins (Plate 7h).

5.2.5 c "130-faults"

'130'-type faults, with or without vein material, were observed on the 6, 7, and 8 levels. The vein on the 6th level was studied, as it has a distinctive 2 cm-wide bleached alteration zone adjacent to it (Plate 3). The foliation in the visibly altered wallrock is at a high angle to the strike of the vein. Within the 130-vein, there are chlorite-quartz veins subparallel to the contact. A fine (mm-scale) seam of ankerite is present adjacent to the leucogabbro and around angular stoped blocks of leucogabbro in the core of the vein. Ankerite bands occur at the contact with the bleached wallrock and at the contact of an internal 2 cm wide quartz vein.

The quartz vein has large monocrystalline quartz grains with strong undulose extinction and sutured intergranular contacts. Ankerite surrounds quartz that has irregular contacts. Sericite occurs as fracture fillings and defines shear planes. The fine (3 mm) ankerite seam encloses quartz- and sericite-bearing pods and occurs as a rim on quartz grains. Pyrite occurs along fractures in the ankerite band and chalcopryite rims the pyrite. Isolated grains of chalcopryite occur in fractures. Calcite occurs along the contact between the quartz vein and the ankerite-rich band and as fractures within both. Calcite is clearly later than the principal vein constituents.

Ankerite also forms asymmetric rims around stoped wallrock fragments in the vein. Pyrite grows over the ankerite rim, wallrock fragment and vein material and encloses sericite, leucoxene and anatase. The pyrite thus formed late in the history of the vein. Calcite occurs as fracture fillings within the ankerite and its relationship to pyrite is not known.

In the 702-crosscut, stringers in the 130-fault are composed of albite and ankerite in equal proportions, with lesser quartz and minor white mica, chlorite, rutile, calcite and pyrite. The albite-ankerite-quartz veins are crosscut by greenish-blue chlorite, white mica and rutile stringers. Chlorite overgrows the white mica in these seams. Calcite fills fractures within the ankerite and encloses ankerite and quartz. The relationship between the calcite and chlorite-rich stringers is unclear.

5.3 Summary of Alteration Assemblages and Timing

In the melagabbro 5 different mineral assemblages have been observed; 8 distinct mineral assemblages are present in the leucogabbro and 3 different mineral assemblages in the gabbro, based on data in Appendix 1 (Table 20).

The wallrock alteration can be subdivided into four categories in the leucogabbro (weak, moderate, strong and intense) based on recurring silicate and carbonate mineral associations and textures.

These are:

- (1) weak chlorite(4) + calcite + quartz

Table 20 : Metamorphic and Alteration Mineral Assemblage Data

$N_{(1)}$ = number of samples with assemblage (1)

Mineral abbreviations in appendix 1.

Capitals denote characteristic minerals

() denotes minerals replaced with relict trace amounts left.

Melagabbro

Metamorphic Assemblages

1. ${}^{+}_{-}\text{Hb} + \text{ACT} + \text{CHL}_1 + \text{ALB} + \text{EP} + \text{TNT} + \text{ILM} (\text{cc})$
 ${}^{+}_{-} \text{cpy, mt, hmnt}$
2. $({}^{+}_{-}\text{Hb}), (\text{act}) + \text{CHL}_1 + \text{ALB} + \text{ep} + \text{TNT} + \text{CC}$
 ${}^{+}_{-} \text{cpy, ilm, mt, hmnt}$

Alteration Assemblages

3. $\text{CHL}_2 + {}^{+}_{-}\text{alb} + {}^{+}_{-}\text{qtz} + \text{ep} + \text{RUT} + \text{CC}$
 ${}^{+}_{-} \text{cpy, mt, hmnt}$
4. $\text{chl}_2 + {}^{+}_{-}\text{alb} + {}^{+}_{-}\text{qtz} + (\text{ep}) + \text{rut} + \text{CC} + \text{ANK}$
5. $\text{chl}_2 + {}^{+}_{-}\text{alb} + {}^{+}_{-}\text{qtz} + \text{rut} + \text{ANK}$

$N_1=14, N_2=6, N_3=3, N_4=3, N_5=3.$

Samples utilized for mass balance calculations; assemblages, 1,2. average analyses Table 18 3. 85-1060 4. 84-100a 5. 85-1059

Leucogabbro

Metamorphic Assemblages

1. $\text{ACT} + \text{CHL}_3 + \text{ALB} + \text{QTZ} + \text{EP} + \text{TNT} + \text{ti-mt, cpy, mt, hmnt}$
 $\text{CHL}_3 + \text{ALB} + \text{QTZ} + \text{EP} + \text{TNT}$

Alteration Assemblages

2. $\text{CHL}_4 + \text{alb} + \text{qtz} + \text{ep} + \text{TNT} + \text{RUT} + \text{CC} + \text{mu}$
3. $\text{chl}_4 + \text{alb} + \text{qtz} + \text{ep} + \text{RUT} + \text{CC} + \text{mu}$
4. $\text{chl}_4 + \text{alb} + \text{qtz} + (\text{ep}) + \text{rut} + \text{cc} + \text{ANK}$
 ${}^{+}_{-} \text{PG, MU}$
5. $\text{chl}_4 + \text{alb} + \text{qtz} + \text{rut} + \text{ANK} + \text{PG}$
6. $\text{chl}_4 + (\text{alb}) + \text{qtz} + \text{rut} + \text{ANK} + \text{PG} + \text{MU}$
7. $\text{chl}_4 + (\text{alb}) + \text{qtz} + \text{rut} + \text{ANK} + \text{MU}$
8. $(\text{alb}) + \text{qtz} + \text{rut} + \text{ANK} + \text{MU}$

Table 20: (cont'd)

$N_1=1,3$ $N_2=2$, $N_3=12$, $N_4=8$, $N_5=4$, $N_6=11$, $N_7=5$, $N_8=1$.

Samples utilized for mass balance computations; assemblage
 1, . average of 86-062,063,069 2. 86-032 3. 85-148 4. 86-031
 5. 86-1742-10 6. 86-1742-7 7. 86-066

Gabbro

Metamorphic Assemblages

1) $hb + ACT + CHL + ALB + QTZ + EP + TNT$

Alteration Assemblages

2) $CHL + alb + qtz + (ep, all) + tnt + CC + mt$

3) $chl + alb + qtz + RUT + ANK$
 $+PG + MU + mt, cpy, py$

$N_1=1$ $N_2=1$ $N_3=3$

Samples utilized for mass balance calculations; 1. 87-535
 2. 85-1025 3. 86-070.

(2) moderate	ankerite + paragonite
(3) strong	ankerite + paragonite + muscovite
(4) intense	ankerite + muscovite.

In the melagabbro, weak alteration is characterized by the assemblage 1) chlorite (chl_3) + calcite + quartz. Moderate and strongly altered melagabbro are represented by the assemblage 2) ankerite + chlorite₃. Strongly altered melagabbro contains greater modal amounts of ankerite (average 30 %) compared to the moderately altered melagabbro (10-15 % ankerite).

With weak alteration in both rock types, calcite replaced actinolite. With progressive alteration titanite remained stable with calcite replacing epidote, but before the epidote was totally consumed, the titanite became unstable (Figure 11, pp 77). Calcite formed during the replacement of actinolite and epidote from the metamorphic assemblage and was then replaced by ankerite with increasing alteration. Ambiguous textural relationships between ankerite, muscovite and paragonite in the leucogabbro, suggest coeval formation. Pyrite formed after paragonite, muscovite and ankerite during strong and intense alteration, occurring as overgrowths around these minerals.

With weak alteration in both rock types, rutile, leucoxene and calcite replace titanite, and secondary magnetite ± hematite is present. During moderate alteration, rutile and leucoxene remain, ankerite appears and calcite and secondary magnetite ± hematite disappear. Rutile and

Each inferred reaction represents an alteration isograd. The nomenclature used is based on the more intensely altered side, determined by the mineralogical evolution changing the original (metamorphic) assemblage. Alteration isograds were mapped on seven levels in the San Antonio Mine, deduced by petrographic and XRD documentation of mineral species and textural relationships in the rocks close to the isograds (Figures 13-15). The occurrences of reactant and product mineral assemblages were mapped and both the reactant and product assemblages were located,

Figure 13: Spatial Distribution of isograd (1) chlorite and calcite, upper levels of the San Antonio Mine.

Figure 14a: Spatial distribution of isograd (2) rutilite and calcite, upper levels of the San Antonio Mine.

Figure 14b: Spatial distribution of isograd (2) rutile and calcite, lower levels of the San Antonio Mine.

Figure 15a: Spatial distribution of isograd (3): paragonite and ankerite and (4) muscovite and ankerite, upper levels of the San Antonio Mine.

Figure 15b: Spatial distribution of isograd (3) paragonite and ankerite and (4) muscovite and ankerite, lower levels of the San Antonio Mine.

defining a point on the alteration "isograd". The number of observed assemblages are summarized in Table 21.

Table 21. Number of specimens with reactant, product and isograd surface assemblages.

Isograd	Melagabbro	Leucogabbro
1.	14 vs. 9 (7 all)	4 vs. 43
2.	20 vs. 9	4 vs. 41 (2 all)
3.	none	18 vs. 21 (8 all)
4.	none	14 vs. 21 (8 all)

5.4.1 Isograd (1): Chlorite and Calcite

The chlorite- calcite- quartz- bearing specimens are uniformly dark green in contrast to the unaltered melagabbro that contains minor epidotized (pale green) plagioclase amongst dark actinolite porphyroblasts. In the leucogabbro, the pistachio green of the abundant epidotized plagioclase laths, in contrast to the darker actinolite and chlorite, is clearly visible compared to the lighter chlorite + calcite alteration assemblage. The metamorphic actinolite + epidote assemblage was found in the eastern extremities of the mine workings on the upper levels (Figure 13). On the lower levels in the mine, all samples collected were altered. The chlorite and calcite isograd represents the lower limit of the alteration zone

most distal from any gold-bearing structure. In the mine chlorite and calcite dominate, but on the surface the

gabbros contain actinolite and epidote east of the mine site.

5.4.2 Isograd (2): Rutile and Calcite

Titanite-bearing assemblages versus rutile and quartz are easily discerned in hand specimen due to the light brown leucoxene associated with rutile. Titanite is present with chlorite + calcite + quartz as close as 2 m from the major shear-type vein on the 6 level (Figure 14 a,b). The proximity of this isograd to the structures is dependent on the spacing of the fractures. Rutile is present with a carbonate (calcite or ankerite) in the altered samples giving a crude outline to the alteration halo, but it is closer to the auriferous structures than the chlorite and calcite isograd (Figure 11).

5.4.3 Isograd (3): Paragonite and Ankerite

The alteration assemblage paragonite and ankerite is recognized only by utilizing XRD and/or microprobe analyses to identify paragonite. Ankerite weathers rusty brown and is easily distinguished in surface mapping, while carbonate stain is useful for distinguishing ankerite in drill core or underground. This alteration isograd is situated between 1.6 and 0.60 m from the veins, which is closer than isograd (2), (Figure 15 a,b).

5.4.4 Isograd (4): Muscovite and Ankerite

The samples containing isograd (4) assemblages may be determined by similar methods as isograd (3). In intensely altered leucogabbro, the muscovite replaces chlorite and as a result is lighter in colour. This assemblage is found within 0.5 m of both the shear and stockwork zones (Figure 15 a,b). Stopped leucogabbroic fragments within the vein contain this strong alteration assemblage.

The assemblage ankerite and white mica (muscovite and/or paragonite) defines the envelope of intense alteration around the structures. Metasomatic albite occurs at the interface between the vein and wallrock and is distinguishable at the millimeter scale.

5.5 Geochemistry of Alteration

One approach used to examine the chemical aspects of alteration is to first determine the mass gain and loss of components during metasomatism and then relate the oxide gains and losses of whole rocks to mineralogy. The purpose of using mass balance calculations to establish metasomatic processes is to define the intensive chemical parameters that produced the different alteration assemblages (Table 20) in the San Antonio Sill.

The principles of mass balance were established by Akella (1966) and Gresens (1967) and these were incorporated into a program, SOMA (Appleyard and deBeer, 1983), to calculate the mass exchange of chemical components in

hydrothermally-altered rocks relative to an unaltered parent rock. This program was utilized for mass balance computations. Use of raw chemical data from altered rock to establish the addition or loss of components does not account for mass and volume changes. To avoid any erroneous results due to the differentiation process, the criteria used in the selection of unaltered samples for comparison with the altered samples are; 1) that the comparison pairs be from the same approximate position in the sill relative to the top.; 2) samples are from the same unit within the sill (ie. leucogabbro, melagabbro and gabbro); 3) sheared samples were rejected to avoid retrograde alteration and structurally induced volume changes.

The majority of samples are relatively homogeneous and pseudomorphic textures are recognizable. The preservation of primary textures has been interpreted as evidence of constant volume metasomatism (Gresens, 1967; Clark, 1987), although Taylor (1965) found that a significant volume was occupied by grain boundaries with the fine-grained pseudomorphic replacement of primary minerals. In this study, each unaltered "parent" sample represents an average of several samples, where available, to decrease the effects of compositional inhomogeneity.

All leucogabbro samples used in the mass balance computation were selected from half to one quarter the distance from the top of the sill in the mine workings. All melagabbro samples within the mine area have been altered.

An average of the unaltered melagabbro samples from the east shore (Table 18) was used and is assumed to be a valid precursor since the variability within the melagabbro is small (see Figure 10). The least altered gabbro was selected from Transect III (Figure 2), and compared to the altered gabbro from the upper 15 m of the sill in the mine.

5.5.1 Mass Balance

Inspection of the weight ratios of altered rocks to parent rocks resulted in the selection of two least mobile elements or inert components for the mafic rocks in the San Antonio Mine area: Al_2O_3 and TiO_2 . The average volume factor for these elements was determined for each sample pair; it ranged from 0.934 to 1.15, generally showing an overall volume increase of 10 to 15%. This result is similar to that found by Clark (1987) but in contrast, Kerrich (1986) and Kashida and Kerrich (1987) found volume factors less than one in the outer alteration zones and volume factors greater than one adjacent to auriferous veins. Kerrich interpreted these observations as hydrothermal leaching in the outer zone and hydrothermal deposition adjacent to the auriferous veins.

The oxide percentage gains and losses are illustrated for each rock type and alteration assemblage from Table 20 (Figure 16) and listed in Table 22 (Appendix 4). Low values of the mole fraction of a component (X_n), can represent a large proportion of an oxide which has a low absolute

Figure 16: Mass gains and losses of carbonatized melagabbro, leucogabbro, and gabbro, San Antonio Sill.

abundance e.g. P_2O_5 . In the absence of large gains of a component, these oxides present in trace amounts are very sensitive to primary igneous variations and to analytical error. The changes of P_2O_5 are not included in Figure 16.

Titanium, assumed immobile, shows an overall increase up to 20%. This is due to primary variations in the parent samples within each rock type, illustrated on the bivariate plot of TiO_2 vs. MgO (wt. %) (Figure 9), and to the low abundances in the parent rocks. Additions or losses up to 20% are considered within the range of geological variability and those higher are significant.

Obvious features are the gains in CO_2 , K, S and the inverse relationship between ferrous and ferric iron. The progressive changes indicated by mass balance are a systematic increase in carbon dioxide and ferrous iron and a progressive decrease in ferric iron. These chemical changes are reflected in the oxide and sulphide mineral assemblages from hematite-magnetite in the alteration zones away from the veins to magnetite and, closest to the veins to pyrite. Epidote is destroyed at early stages in the carbonatization process, also evidence for the reduction of Fe^{3+} .

In the melagabbro, hornblende, actinolite and epidote are replaced by carbonates and chlorite. More CO_2 has been fixed in this rock type than in either the leucogabbro or gabbro. The increase in Na^+ is minor in the melagabbro and mimics the pattern of Al; this is probably related to a primary variation in the feldspar content. The mineralogical

and geochemical data for the altered melagabbro suggest an absence of major introduction of K.

In the leucogabbro, silica shows a negligible variation and is relatively immobile, indicating that the increase in modal amounts of quartz in the altered samples is a consequence of the recrystallization of silicates involving the release of silica to form quartz. This would indicate that the quartz in the veins is not a result of lateral secretion, as suggested by Stephenson (1972) for the San Antonio Mine, and that silicification is not a form of alteration in the sill, as suggested by Bragg (1943).

The alkali elements show variable patterns in the leucogabbro. Calcium has minor gains and losses, which are considered insignificant. Sodium shows a variable overall increase. In assemblage (4) (moderate alteration), the sample contains 15% paragonite and yet no apparent increase in Na. This suggests that sufficient sodium was present in the rocks in the form of metamorphic albite to supply the cation required to form paragonite. Gains of Na^+ are irregular with minor gains in weak and moderate altered leucogabbro (assemblages (2) and (4)). The restriction of albite-rich wallrocks to vein margins indicates that Na^+ from the hydrothermal fluid does not migrate far from the fluid channelway. This millimetre-scale alteration was not analyzed geochemically and is not represented in the mass balance.

A large increase in potassium between moderate and

strong alteration (assemblages (6) and (7)) is reflected by the presence of muscovite. The large gains of potassium in weak to moderate alteration (assemblages (2) - (6)) are due to a low mole fraction of this element in the least altered rock. A larger gain exists between assemblages (6) and (7), which indicates a chemical front. The chemical front of potassium is restricted to less than one m from the gold-bearing structure.

In the most intensely altered rocks, mass transfer affects the chemical composition of the rock, masking the natural variations in the parent rock. At lower intensities of alteration, exchange reactions, incongruent dissolution and the precipitation of new minerals can explain the change in weight proportion of elements. The close relationship between the gains and losses and the changes in mineral assemblages allow ionic exchange reactions to be considered. Carbon dioxide, potassium and sulphur addition to the leucogabbro are the major mechanisms of metasomatism.

5.6 Summary of Alteration of the Gabbro

The description of mineral associations, composition and chronological relationships among alteration minerals relative to the metamorphic minerals allows the definition of various stages of alteration in each rock type. Three vein-types in the San Antonio Mine were examined to determine the vein assemblages, textural and chronologic relationships. The hydrothermal alteration adjacent to the

different vein-types is similar. Changes in the hydrothermal alteration assemblages were treated as isograds, which were deduced from chronologic and textural relationships in the silicate and carbonate minerals. This enabled the distribution of alteration zones to be mapped in a systematic manner. Mass balance calculations demonstrate that large quantities of CO_2 were added to the melagabbro. There also is a change in the oxidation state of iron. The leucogabbro and gabbro, host to the gold-bearing veins had large mass additions of CO_2 , K_2O and S accompanied by a systematic increase in FeO and decrease in Fe_2O_3 , which is reflected in the mineralogical changes. Modal estimates of quartz increase in alteration but mass balance indicates no gain or loss of SiO_2 . A comparison of a paragonite-bearing sample and unaltered leucogabbro demonstrates that a gain in sodium is not required to form paragonite from the parent metamorphosed leucogabbro.

CHAPTER 6

DISCUSSION

6.1 Effect of Bulk Rock Composition on Alteration Assemblages

The shear zones crosscut the entire sill with differing characteristics of associated hydrothermal alteration depending on the host rock composition. Greenwood (1975) has shown that the mineral assemblages are capable of buffering the composition of the fluid phase.

The pre-alteration metamorphic mineral assemblage is similar in both the melagabbro and leucogabbro, with only slight variations in the mineral compositions, but large differences of modal contents. The unaltered melagabbro has higher $Fe_{tot} + Mg$ (Table 18) than the leucogabbro; this is reflected in increased modal amounts of actinolite and chlorite. In the leucogabbro, the iron and magnesium are bound in chlorite, epidote and ilmenomagnetite. The higher modal amount of carbonate minerals precipitated in the melagabbro (Figure 11) is related to the availability of calcium, magnesium and iron in the host rock (Whitehead et al., 1981; Phillips and Brown, 1987).

Mass balance calculations indicate that with constant amounts of Al_2O_3 and TiO_2 , and a negligible volume change, large quantities of CO_2 were added to the leucogabbro and melagabbro. In addition, K_2O and S showed large mass gains adjacent to the gold-bearing structures.

Four alteration isograds, chlorite - calcite (1), rutile - calcite (2), paragonite - ankerite (3) and ankerite - muscovite (4)) are present in the leucogabbro. Moderate alteration in the melagabbro corresponds to the alteration assemblage ankerite and chlorite, (no paragonite) and isograds (1) and (2) representing weak alteration, are similar to those in the leucogabbro. The assemblage ankerite and muscovite (4) does not occur in the melagabbro.

The chlorite - calcite (1) association is well documented (Billings and White, 1950; Harte and Graham, 1975; Smith and Kesler, 1985; Clark, 1986, 1987; and, Kishida and Kerrich, 1987), and Clark (1986, 1987) dealt with it as an alteration isograd in addition to rutile - calcite (2). The assemblages are characteristic of either hydrothermal alteration or metamorphism of a metabasite involving a CO_2 -rich fluid phase with low levels of XCO_2 . Billings and White (1950) described four assemblages in metabasites from the Woodsville Quadrangle, Vermont and New Hampshire that all contain albite and quartz:

- a) actinolite + epidote + chlorite (low XCO_2)
- b) actinolite + epidote + chlorite + calcite
- c) chlorite + calcite
- d) chlorite + ankerite (high XCO_2).

An additional assemblage (ankerite + epidote + quartz) was suggested by Harte and Graham (1975), but is not present in the Rice Lake area.

The melagabbro, in the San Antonio Mine displays the

sequence of alteration described by Billings and White (1950) with assemblage a the regional metamorphic assemblage. Calcite is produced from a fluid with low XCO_2 and ankerite at higher levels of XCO_2 . This sequence also occurs in the leucogabbro, reflecting an increase in the mole fraction of carbon dioxide approaching the auriferous veins. The addition of K_2O and S is observed only close to the veins where the alteration assemblages (3) and (4) are present.

The composition of carbonate species is not related to primary compositional variations in the gabbro, since the ankerite in the melagabbro, in the leucogabbro and in veins is similar, as is the calcite in the melagabbro and leucogabbro (Table 11, Appendix 2). The composition of metamorphic chlorite species was dependent on the primary igneous rock composition in the San Antonio Sill (Figure 7). The metamorphic chlorite (chl_1) in the melagabbro is lower in $\text{Fe}/(\text{Fe}+\text{Mg})$ (0.4) than the metamorphic chlorite (chl_2) in the leucogabbro (0.49). The bulk ratio of $\text{FeO}^*/(\text{FeO}^*+\text{MgO})$ in the melagabbro (0.48) is also lower than that in the leucogabbro (0.7). The composition of the chlorite species therefore partially reflects the difference in the bulk composition. The leucogabbro contains higher modal amounts of other iron-rich minerals (ilmenomagnetite and epidote) than the melagabbro. The melagabbro contains higher modal amounts of actinolite than the leucogabbro but, compared to epidote and ilmenomagnetite it is a relatively iron-poor

mineral. Actinolite in the melagabbro has lower $\text{Fe}/(\text{Fe}+\text{Mg})$ than the calcic amphiboles in the leucogabbro. The chlorite $\text{Fe}/(\text{Fe}+\text{Mg})$ ratio is close to that of the melagabbro (0.4 chl_1 and 0.48 bulk rock) but the leucogabbro ratios show a larger difference (0.49 chl_2 and 0.70).

The alteration chlorite (chl_3) produced with weak alteration (calcite - chl_3 - secondary magnetite) in the melagabbro has lower $\text{Fe}/(\text{Fe}+\text{Mg})$ than the metamorphic chlorite (chl_1), but the opposite relationship is present in the leucogabbro. There is an increase in $\text{Fe}/(\text{Fe}+\text{Mg})$ from the metamorphic chl_2 , (pynochlorite-ripidolite) to the alteration chl_4 , (ripidolite-pseudothuringite) with the production of calcite and an additional increase with ankerite. This reflects the availability of iron in the metamorphic minerals (epidote, ilmenomagnetite, actinolite) to form the alteration minerals chl_4 , secondary magnetite and later ankerite in the leucogabbro and the relative lack of those minerals in the melagabbro. In contrast, in the Bourbeau Sill, Chibougamau (Dube et al., 1987) and in the Golden Mile Dolerite (Phillips and Brown, 1987, Neall and Phillips, 1987) found the iron content of the chlorites to increase away from the gold-bearing structures. In the leucogabbro of the San Antonio Sill, relict epidote can remain in the strongly altered rocks. Epidote was destroyed by interaction with the hydrothermal fluid before dissolution of the chlorite.

Ankerite + paragonite + muscovite formed simultaneously

in different sites. Paragonite replaced coarse chlorite plates in calcite (ankerite), chlorite (4), quartz patches. The change from calcite to ankerite reflects an increase in XCO_2 . The rare occurrence of paragonite and ankerite without muscovite indicates that paragonite was formed slightly earlier. Muscovite replaced albite initially due to a massive addition of potassium from the hydrothermal fluid. The stability of the potassium-bearing alteration assemblage in the leucogabbro is related to the availability of aluminum. Kishida and Kerrich (1987) utilize "saturation indices" to map the intensity of alteration in that the molar ratios $(3\text{K} + \text{Na})/\text{Al}$, $3\text{K}/\text{Al}$ and Na/Al reflect the alteration minerals muscovite and albite, muscovite and albite, respectively. Textural evidence in the San Antonio Sill leucogabbro suggests that muscovite formed at the expense of albite more readily than chlorite.

The paragonite - ankerite alteration isograd (3), has not been documented elsewhere as a common gold-related alteration assemblage. This is perhaps due to the difficulty in identifying paragonite. Paragonite has been reported in trace amounts at the Hollinger and O'Brien Mines (Wood et al., 1986 and Krupka et al., 1977) and the Golden Mile Dolerite (Phillips and Brown, 1987) but, has not been utilized to define alteration zones. In the Golden Mile Dolerite, paragonite is present in the "carbonate zone", the bleached alteration prior to the pyrite zone. In the San Antonio Mine, paragonite is found in similarly altered rocks

but is also present with pyrite, which is the key indicator of gold. The presence of substantial quantities (10-15%) of paragonite in the alteration zones at the San Antonio Mine enables an additional step to be taken towards understanding the formation of the alteration zones, the effects of the hydrothermal fluid on the wallrock and the gold-mineralizing event.

Mass balance calculations indicate an decrease in ferric iron and a increase in ferrous iron related to the increased intensity of alteration towards the gold-bearing veins. This is represented by the mineral transformations from ilmenomagnetite to secondary magnetite, hematite, leucoxene and rutile (plus calcite), to leucoxene and rutile (plus ankerite) and finally pyrite adjacent to the veins. The progression from oxidizing to reducing conditions is explained by Dube et al.(1987) as the function of H_2O dissociation in the presence of iron-bearing minerals (after Eugster and Skippen, 1967), producing a reducing fluid and the introduction of sulphur as H_2S . It can be represented by the reactions:

ilmenomagnetite + hydrogen = ferrous iron + rutile
(leucoxene)

ilmenomagnetite pyrite + rutile (leucoxene)

Sulphide- and potassium-bearing phases in the leucogabbro were stabilized immediately adjacent to the gold-bearing veins and shear zones. Potassium from the fluid reacted with the metamorphic albite to form muscovite, and released sodium to form paragonite, muscovite also formed by the breakdown of chlorite and paragonite. Sulphur in the fluid phase reacted with iron-bearing phases (ilmeno-magnetite and chl₄) to form pyrite.

6.2 Alteration Paragenesis

Alteration reactions have been deduced, corresponding to petrographic features and the intensive chemical parameters determined by mass balance. These reactions represent the observed discontinuities between compatible mineral assemblages that define a repeatable sequence of isograds enveloping the auriferous structures. For such a treatment, it is necessary to regard each alteration zone as a frozen state.

6.2.1 Constraints Placed on Physical Conditions

Indirect methods must be used to estimate suitable P and T conditions. Calcite is clearly replaced by ankerite in the gabbro, which inhibits the use of the calcite-dolomite geothermometer. Suitable minerals are not present for geobarometry in the San Antonio gold deposit. Stephenson

(1972) assumed that the gold was formed between 250 and 400°C at a depth of 8 to 20 km, at pressures between 2 and 5 kb. He utilized the upper limits of low-grade regional metamorphism and the observation that vertical zoning of the sulphides has not been recognized for a depth of 5000 ft; therefore, the deposit must have formed at a considerable depth where the geothermal gradient is minimal. He assumed that plutonic activity had ceased and a normal geothermal gradient of 25-35°C/km had been attained.

Recent fluid inclusion studies of quartz in gold veins in Archean gold deposits indicate a remarkable similarity in fluid composition and temperature estimates, enabling a temperature range to be assumed. The fluids have low salinity (1-6 wt. % NaCl equivalent and typically <2 wt % NaCl equivalent), contain up to 25 mole % CO₂ with an average of 15 mole %, with the majority of homogenization temperatures between 250 and 350°C (Ho et al., 1987). Trapping pressures lie between 1-2.5 kb on average. A temperature range of 350 ± 100°C and a pressure of 2 kb were assumed and the effects of changing pressure on the stability of assemblages from 1-3 kb were noted (6.2.2).

6.2.2 Model Path of Alteration

Mineral-fluid reactions account for the zonation of alteration minerals at the San Antonio Mine. T-XCO₂ diagrams have been used to illustrate the effects of increasing CO₂ on a metamorphic mineral assemblage and to help place

constraints on the fluid properties (Clark, 1987; Kishida and Kerrich, 1987). On this temperature-composition diagram the only components in the rocks that are changing are H_2O and CO_2 ; the multicomponent metasomatic processes involving potassium and sulphur such as those present at the San Antonio sill are not portrayed. This type of diagram deals with the solid phases in the rock and portrays part of the observed alteration path at the San Antonio Mine (Figure 17). The model alteration path in the leucogabbro corresponds to the area below $440^\circ C$ at 2 kb, restricted by the stability of clinozoisite + tremolite + rutile. Calcite is formed during weak alteration and, with progressive carbonatization, ankerite (dolomite) replaces calcite. During isothermal, isobaric CO_2 metasomatism of carbonate-free leucogabbro at the San Antonio Mine, calcite forms at lower values of XCO_2 in the fluid than dolomite (Figure 17).

During strong alteration, the univariant reaction:

is portrayed, but with intense alteration the model predicts an epidote (cz)-forming stage in rocks lacking albite:

In nature this has not been reported, although Harte and Graham (1974) suggested that in the Na-free system Al_2O_3 -CaO-(Mg,Fe)O a restricted XCO_2 space for epidote and dolomite exists.

Figure 17: Temperature-composition diagram for the Sap Antonio Sill, leucogabbro at 2 kb, in the model system CaO-Na₂O-MgO-TiO₂-Al₂O₃-SiO₂-CO₂-H₂O. Bold numbers represent isograds 1, 2 and 3. Binary CO₂ - H₂O solution on the X axis. Mineral abbreviations are listed in Appendix 1. Calculated using GEO-CALC (Berman et al., 1987).

Variation of the pressure from 1-3 kb shifts the invariant points up and to the left, with a proportionate change of 20°C per kb. The topology remains consistent with the mineralogical changes documented approaching the veins.

The following assumptions and simplifications were used to construct T-XCO₂ and aCO₂ vs. aK⁺/H⁺ diagrams (Figures 17 and 18).

1. The mineral compositions were averaged. Chlorite₃ and epidote compositions were taken from the unaltered leucogabbro. (Table 23).

2. Activities (Table 24) were calculated assuming ideal activity models listed in Appendix 5.

3. $P(\text{total}) = P(\text{H}_2\text{O}) + P(\text{CO}_2)$

4. All rocks contain quartz.

Mass balance studies clearly indicate that carbon dioxide, potassium and sulphur have been added to the gabbros at the San Antonio Mine. The mineral assemblages in the model system Ca-Mg-Na-Al-Ti-Si-C-O-H do not allow for balancing of the reactions involving the mobile components potassium and sulphur. An activity diagram for mineral assemblages at the San Antonio Mine (Figure 18) illustrates the effect of two volumetrically important mobile components in the model system K-Ca-Mg-Na-Al-Ti-Si-C-O-H.

On an aCO₂ vs. aK⁺/H⁺ diagram (Figure 18), the reaction:

Figure 18: Activity diagram for the San Antonio Sill leucogabbro at 2 kb and 350°C, in the model system $K^+-H^+-CaO-Na_2O-MgO-TiO_2-Al_2O_3-SiO_2-CO_2-H_2O$. The arrow marks the model alteration path. Calculated using computer program PTA (Brown et al., unpublished).

Table 23: Average Mineral Formulae From Microprobe Analyses

Actinolite-act Chloritechl₁ chl₂ chl₃ chl₄ Epidote-ep Calcite-cc Ankerite-ank Muscovite-mu Paragonite-pg

Average of analyses

act Table 6; 12-13
 chl1 Table 7; 1-8
 chl2 ; 9-12
 chl3 ; 13-15
 chl4 ; 16-22

ep Table 9; 10,11
 cc Table 11; 1-6, 10-13
 ank 11; 4-9
 mu Table 12; 6-8
 pg 12; 1-5,11

Table 24: Activities used in temperature-composition and activity diagrams.
(assuming ideal mixing, calculations in Appendix 5)

Leucogabbro	Component
chl ₄ = 0.004	clinochlore
act = 0.04	tremolite
ep = 0.66	clinozoisite
cc = 0.96	calcite
ank = 0.43	dolomite
mu = 0.80 [X _{ms} = 0.84]	muscovite
pg = 0.84 [X _{pg} = 0.92]	paragonite
alb = 0.96	albite

[] taken from solvus (Chatterjee and Flux, 1986)

has a restricted stability and increasing a_{K^+} causes the reaction to be metastable. Dolomite and epidote are stable only at low values of a_{K^+}/H^+ and high X_{CO_2} and in the absence of albite.

Petrographic evidence supporting a progressive carbonatization model includes the distribution and timing of calcite and ankerite. Mass balance and compositional constraints dictated by mineral compositions on the alteration assemblage enables the identification of components added to the system, thus defining the intensive chemical parameters that may be used to explain the variations in alteration mineral assemblages. There are no constraints placed on the maximum X_{CO_2} in this system by the mineral compositions and textural observations alone.

Sulphur has a pronounced influence on the iron-bearing minerals in the system. Since the Mg-end members were utilized to illustrate some of the effects of the hydrothermal fluid on the gabbros, the addition of $f(S_2)$ on a third axis would not apply to this system, since magnesium sulphides do not exist.

Gold is intimately associated with pyrite in the alteration assemblage albite-muscovite-paragonite and albite-muscovite. In the ideal system $K_2O-Na_2O-Al_2O_3-SiO_2-H_2O-HCl$ at $300^\circ C$ and 1 kb this equilibrium assemblage defines a triple point reflecting an approximate log ratio of K^+/Na^+ of $3/4$ for the fluid (Rose and Burt, 1979). Strong and intensely altered assemblages are restricted to the bold

line (Figure 19). The triple point corresponds to the reaction:

paragonite + K^+/H^+ + quartz = albite + muscovite + H_2O (Figure 18). This defines a restricted space in this system for gold precipitation.

The mineral assemblages for the shear-, stockwork- and late 130- type veins and the wallrock alteration adjacent to these veins are similar. The source fluid composition probably remained relatively constant over the time required to form the vein sets in the San Antonio Mine, although locally the composition of the fluid evolved through interaction with the leucogabbroic wallrock producing unique, systematic mineralogical zoning adjacent to the fluid channels.

The model alteration path above can be used to formulate exploration strategies and better define potential areas of mineralization.

6.2.3 Timing of the Calcite-chlorite Veins and its Implication to Gold Deposition

In the Norseman-Wiluna belt, Western Australia, Clark (1987) described a regional carbonatization event that was overprinted by gold-related carbonatization. At the San Antonio Mine, there are texturally two ankerites that replace inclusion-free calcite or oxide pseudomorphs. There is no evidence for an earlier carbonatization event in the San Antonio Sill. In the Norseman Wiluna belt, there are

Figure 19: Activity diagram $\log a_{\text{Na}^+/\text{K}^+}$ vs. $\log a_{\text{K}^+/\text{H}^+}$ showing the restricted fluid path in intensely altered leucogabbro. System $\text{K}_2\text{O}-\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}-\text{HCl}$ at 300°C and 1 kb (Rose and Burt, 1979).

discrete zones of intense deformation that are the loci for fluids; the surrounding rocks are relatively strain-free (Clark, 1987). In the Rice Lake area, the strain is partitioned over a large area in the form of penetrative fabrics and lineations; this causes a weak diffuse alteration pattern in the region (abundant calcite in the surrounding volcanoclastic rocks). The fluid flow is not focussed.

Calcite forms in two distinct generations at the San Antonio Mine: 1) in the wallrocks, and 2) in the veins. In weakly altered rocks, calcite forms during the replacement of actinolite and epidote from the metamorphic assemblage. This calcite is then replaced by ankerite with increasing alteration, as the effect of increasing XCO_2 at a constant temperature (Figure 18).

A second generation of calcite formed later than the main mineralizing process and clearly overprinted the vein minerals. This calcite may have been precipitated

- 1) a completely different fluid
- 2) the same fluid with an increase in temperature
- 3) the same fluid that had been modified by a physical process, possibly boiling.

There is no evidence that the rocks have been affected by a higher temperature fluid. The chlorite and quartz veins may be related to the same fluid. Textural evidence alone cannot determine whether the fluid was the same for the deposition of the sulphide-gold bearing veins and the later

calcite veinlets. One way of determining this, is by fluid inclusion studies. Rare gold-rich zones associated with calcite have been documented at the San Antonio Mine (Bragg, 1943). This relationship, although minor in exploration terms, may reflect local remobilization of gold by later fluids.

Seward (1988) noted that simple cooling or initial boiling does not cause gold deposition, but boiling causes gold deposition after major changes in reduced sulphur activity, oxidation potential (hydrogen loss) and pH (CO_2 loss) which are reflected in the wallrock assemblages.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

Pervasive alteration and associated gold mineralization defining the San Antonio deposit are localized within a synvolcanic, gabbroic sill which intruded the subaerial volcanic sequence of the Archean Rice Lake Group. This rock sequence was subsequently deformed and metamorphosed to greenschist grade.

The San Antonio Sill, host to the San Antonio Mine, is a layered mafic intrusion consisting of melagabbro at the base, locally granophyric leucogabbro at the top, and gabbroic chilled margins. The starting composition of the magma was that of an Fe-rich tholeiite. The melagabbro is ubiquitous but variable in width along the strike length of the sill, with local internal sill-like leucogabbro bodies. The leucogabbro is discontinuous and more abundant in the western and eastern ends.

The melagabbro contained clinopyroxene, (represented by obliquely twinned actinolite with relict 90° cleavages and euhedral shapes), olivine and possibly orthopyroxene, (pseudomorphically replaced by chlorite with randomly oriented titanite filled fractures) and minor plagioclase. The leucogabbro was dominantly plagioclase, clinopyroxene, quartz and ilmenomagnetite.

Deformation of the San Antonio Sill associated with

reverse faulting resulted in the formation of shear and stockwork zones within the intrusion. Spatially associated with the structures in the melagabbro, these are zones of weak to moderate carbonate alteration which overprint the metamorphic assemblage, while zones of more intense alteration and associated gold mineralization are restricted to localities where the structures cross the leucogabbro and minor gabbro.

f Mapping of the alteration has demonstrated a zonation of alteration mineral assemblages with proximity to the shear, stockwork and 130-veins and a difference in alteration mineralogy between the melagabbro and leucogabbro. In the leucogabbro with increasing alteration these are: 1) chlorite - calcite, 2) rutile - calcite, 3) paragonite - ankerite and 4) muscovite - ankerite. In the melagabbro, (1) and (2) are the same as in the leucogabbro, chlorite and ankerite is present instead of assemblage (3) and (4) does not exist. The pre-alteration chlorite species is dependant on the original parent composition but the alteration chlorite compositions are dependent on a combination of XCO_2 and bulk $Fe/(Fe+Mg)$. Paragonite and muscovite occur only in the leucogabbro due to the availability of aluminum. Carbonate and plagioclase species are independent of the wallrock composition.

Gold is intimately associated with pyrite in the leucogabbroic wallrocks and veins. Pyrite nucleated on the relict ilmenomagnetite grains that are present in greater

abundance and larger size in the leucogabbro than the melagabbro. The oxide content of the wallrock has a direct control on precipitating pyrite and associated gold.

The shear-type veins consist dominantly of quartz, albite, ankerite and muscovite with minor pyrite; pyrrhotite, chalcopyrite, sphalerite, rutile and gold. Near the contact, the vein is pyrite-rich and contains tourmaline and hydrothermal albite. Stockwork-type and 130-veins contain abundant albite, quartz and albite with lesser muscovite, pyrite, chalcopyrite. The stockwork-type veins are a major producer of gold.

There is a two-stage calcite precipitating process. In the wallrocks, ankerite replaces calcite in the vicinity of the vein. In a late-stage vein system, calcite replaces the ankerite in the mineralized veins. The late calcite overprints the gold-related alteration and the main mineralization.

Mass balance calculations demonstrate the chemical changes produced by the metasomatic processes and reflected in the mineralogy. Major gains in carbon dioxide, potassium and sulphur are accompanied by minor gains in ferrous iron combined with losses in ferric iron. SiO_2 , Al_2O_3 , TiO_2 , MnO , MgO and CaO remain immobile and there is a minor volume change. The presence of tourmaline and albite at the vein margins suggests localized boron and sodium addition to the wallrocks.

7.2 Conclusions

1. The San Antonio Sill formed from pyroxene settling from a magma compositionally similar to the chilled margins, forming the melagabbro base and leaving a plagioclase-rich residue represented by the leucogabbro. The final differentiated liquid is represented by the granophyric leucogabbro.
2. Carbonatization and associated gold deposition occurred later than greenschist metamorphism.
3. Systematic variation of mineral associations with distance from the veins indicate lateral variation of the fluid composition due to the progressive interaction with the wallrocks. The composition of the fluid in the channelways remained constant over the time span required to form the shear- and stockwork-type veins and the "130"-veins.
4. Mapping of alteration isograds based on four reactions involving CO_2 , H_2O and/or K^+/H^+ indicate that the intensity of alteration increases towards the gold-bearing structures which acted as fluid conduits. CO_2 and K metasomatism is more widespread than the addition of sulphur, boron or sodium; the latter three are reflected in pyrite, tourmaline and albite at the vein contact. Pyrite contains inclusions of muscovite and ankerite and is intimately associated in time and space with gold deposition; therefore, gold mineralization occurred late in the alteration event. The

magnitude of the alteration halo is dependent on the fracture density. Precipitation and character of hydrothermal alteration minerals is dependent on the host rock composition. Fluid-rock interaction changes the local chemical composition of the fluid phase to conditions suitable for gold deposition. In the San Antonio Sill, the composition of the leucogabbro is favourable for gold deposition.

5. The importance of paragonite in gold-related alteration has been largely unrecognized to date. Mass balance calculations indicate that the formation of paragonite was due to CO_2 metasomatism and did not require an addition of sodium. The isograd paragonite - ankerite is an essential step towards achieving equilibrium between the gold-bearing fluid phase and the wallrock.

6. A temperature-composition diagram in the model system Ca-Na-Al-Ti-Si-O-C-H. demonstrates that during isothermal, isobaric metasomatism, calcite formed at a lower mole fraction of CO_2 than ankerite. The maximum temperature of metasomatism is constrained by the mineral assemblages at 440°C . Utilizing the important chemical parameters K^+ and CO_2 , the path of alteration was modelled corresponding to textural and timing observations. During isothermal-isobaric CO_2 and K^+ metasomatism, the model alteration path represents the trend to attaining complete stability between the wallrock and a hydrothermal fluid. The alteration assemblage paragonite, muscovite and albite associated with

gold deposition provides a constraint, at that point, of the
log Na/K ratio of approximately, $3/4$.

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APPENDIX 1: MINERAL ASSEMBLAGE DATA

Mineral Abbreviations

hb = hornblende	cc = calcite
act = actinolite	ank = ankerite
act-s=single crystals	act-f= fibrous
chlorite	chl-p= chl/oxide patches
chl ₁ = unaltered melagabbro	pg = paragonite
chl ₂ = " " leucogabbro	mu = muscovite
chl ₃ = altered melagabbro	mt = magnetite
chl ₄ = altered leucogabbro	hmmt = hematite
alb = albite	cpy = chalcopyrite
qtz = quartz	py = pyrite
ep = epidote	op = opaque
all = allanite	po = pyrrhotite
tnt = titanite	sph = sphalerite
ilm-mt = ilmenomagnetite	bo = bornite
rut, rt= rutile	ch = chalcocite
leux = leucoxene	Au = gold
dol = dolomite	cz = clinozoisite
tr = tremolite	

* denotes granophyric intergrowths

tr = trace amounts

t = total (mica-pg and mu), (rut and leux)

ep () = metamorphic minerals dominantly epidote comprise -% of grain

~ = approximately

Table 2: Melagabbro mineral assemblages

Table 3: Leucogabbro mineral assemblages

Table 4: Gabbro mineral assemblages

Table 5: Vein mineral assemblages

Table 2: Melasabbro mineral assemblages

	East	shore	transect II						
	85-433	85-432	85-431	85-430	85-429	85-428	85-427	85-425	85-419
hb	.5	tr	tr		tr	15	tr	tr	tr
act-s	15	15	15	15	10-15	15		10	20-25T
act-f	25	20-25	25	30	35	40	50	25	
chl-p	10	10-15	10	15	5-10				
chl,	5	<5	10		5	15-20	20	30	15
alb	30	40	15	20	20				
matrix	5		8	15	30	10	15	20	5-10
ep	(50)	(60)	(90),tr	(75)	(75)	10-15	7	5-10	<5
tnt	5	7	tr	5	tr	<5	3	2-3	10
ilm	tr	tr	5	3	5	tr	2	2-3	
cpy					tr	tr	tr		tr
mt		tr			tr				
hgmt			tr		tr	tr	tr	tr	
cc									
op									5-10

	Windsock Island		Normandy		Creek Transect III		San Norm Area
	87-298b	87-270	87-278		87-537	87-536	
hb		10					
act-s	30	20	20		10-15		
act-f	10-15	40	30		25	40	
chl-p		5-10	5-10				
chl,	10-15	5	20		20	25-30	
alb	35		10-15				
matrix		15			30		
ep	(25),5				(15)	15-20	
ti	5	tr	tr		10-15	10	
ilm							
cpy							
mt			tr				
hgmt							
cc	5		tr				
op			5-10				tr

Table 2: (cont'd)

	San Antonio Mine altered melagabbro										
	85- 1108	85- 1025	85- 1020	86- 072	85- 1019	85- 1060	84- 100a	85- 1023	84- 099	85- 1059	85- 1026
act	-	-	tr								
chl ₂	40	15	30	40	40	35-40	25	50	40	15	25
alb	<5	10-15		<5			15				20
qtz					5		5		5		<5
matrix	25	25-30	30	20	20	25	20	20	25	45	15
ep	3-10	tr	5-7	10	<5	5	5-10		tr		tr
all		tr									
tnt	5	5	5-7								
rut				7	5	5	7	5-10	10	10T	10T
leux					5				10		
ilm	2-3										
mt	tr		10	10							
hmt	tr			5							
cc	10	20	10-15	15	20	20-25	10	5	5		
ank							10	15	15	30	30
mu											
cpy			tr		tr						
py											
op		15-mt				5-10 mt	8 mt				

Windsor Normandy
Island

Creek Area

altered melagabbro
(unaltered)

	85- 1109	85- 437	87- 273	87- 274	87- 281	87- 277
hb		tr				
act		30	10	tr		
chl ₂	20-25	15	55	50		40
alb		20				
qtz	5					tr
matrix	20-25		20		20	
ep	tr	15				
all						
tnt		5	tr	5		10-15
rut	5T					
mt			tr		10	
hmt						
cc			10	10-15	15	20
ank	15					
op						5-mt

Table 3: Leucogabbro mineral assemblages

San Antonio Mine Area unaltered leucogabbro							
	86-069	*86-062	*86-063	*85-149	86-030	86-032	85-d-022
hb							
act	20	5	-	-	-	-	-
chl ₂	25	15	15	15	20	20	15
alb	30	40	35	30	25-30	15	50
qtz	10-15	10-15	15	15-20	20	20	15
matrix		15	15				
ep	(80),10	(80),5	(30-90),10		(25),15	(70),15	30
all		tr	-				10
tnt	10-15	tr	10	7rut	7rut	7rut	10 rut
ti-mt		10-15		ilm			
cpy		tr					
mt		5	15			8	
hmt					10	tr	
cc				<5	5	tr	5

Internal Sills Transect III
unaltered leucogabbro

	85-426	85-418	87-532	87-533	87-534
hb		tr <5	-	-	tr
act	10	35	-	-	10
chl ₂	20	10	80	15-20	15
alb	40	30	35-40	50-60	50
qtz			15-20	15	10-15
matrix	10	10-15			
ep	5	10	(<20),5	15	(80),15
all					
tnt		tr	15	15	15
ti-mt	15				
cpy					
mt					
hmt					
cc			tr	tr	
op					tr py?

altered leucogabbro
San Antonio Mine Area

	86- 34	86- 35	86- *004	86- *005	86- *006	85- 1112	85- 1113	85- 1111	85- d20	85- 400	85- 148
act											
ail	20	20	15-20	15	10-15	25	15	20	25	15-20	15
alb	30	25	40	25	25-30	25	25	10	20	20	25
qtz	10	15	20	20	15	15	15-20	10	5-10	15-20	10-15
matrix						5	10-15	20	10		*15
ep	10	15	10-15	25	10	15	10	-	15-20	15	10
all											
tnt				15		tr	7				
rut		tr 3			5	10	7	3		tr 3	7
ieux	15		10-15		10			7	10	5	
mt	<5	5			5		tr	<5	tr	5	
hmt											
cc	15	10	10	<5	10	5	10	10-15	15	5-10	10
ank						tr					
pg					tr						
mu					5		tr	15	5-10		
tr											
cpy											
py								3			
op								2			

[illegible]

Table 3: (cont'd)

altered leucogabbro San Antonio Mine											
	86- 018	86- 020	86- 022	86- 023	86- 024	85- 011	85- 018	84- 100b	84- 101	84- 102	84- 105
act											
chl	15	tr	tr	10	10	tr	15	10	15	15-20	15-20
alb	10	10	10	10	15	10-15	10	15	30	10	10-15
qtz	5	10	15	15	15	15-20	5-10	5-10	5-10	10-15	15
matrix	15	15	10	15	10		10-15				15
ep							5-10				
all											
tnt											
rut	3	tr	3	tr	tr	5	<5	<5	<5	tr	<5
leux	7	10-15	7	10-15	10	10	5	5	5	5-10	5
mt				tr	2-3		5				
mmt				tr	tr						
cc	tr						5				
ank	30	25-30	30	25	25	35	20	25	20	30	20-25
pg	15t	25t	10	20t	15	5	10	15	15	25	7
mu			15			10	5	15			7
cpy				tr							
py		5-10			<5						
op											

altered leucogabbro San Antonio Mine 85-1742-											
	4	6	7	8	9	10	11	12	13	15	16
act											
chl	15	15-20	10-15	15-20	15	10	15-20	tr-5	5	20	25
alb	20	30	15	10	30	15	40	tr	15-20	15	15
qtz	15	10	10	10	10	10-15	10	10-15	10-15	15-20	15
matrix	5-10	15	20	25		15	15	5-10	15		15
ep											
all											
tnt											
rut	10t	<5	10-15	<5	10	<5	<5		<5	<5	<5
leux		5		5	5	5	5			5	5
mt	tr			tr	tr	tr	tr	tr			
mmt											
cc											
ank	20-25	10-15	20-25	20	30	25	20	30	25	25	20
pg	10	10-15	15	10	5	20	>5	25	20	10	5
mu			tr				<5			10	3
cpy					tr	tr		tr			
py						<5					
op	tr	<5		5			5		<5	<5	tr

Table 3: (cont'd)

altered leucogabbro San Antonio Mine										
	85- d-007	85- d-008	85- d-010	85- 1110	86- 66	86- 28	86- 29	86- 36	86- 44	86- 48
act										
chl	10	25	15-20	15	10	25	15	25	20	
alb	30	5	5	15	25	30	30	10-15	10-15	tr
qtz	10-15	10	10	20	*10-15	5	10-15	15	15	15
matrix	15	20	15					20-25		
ep						5-10	<5			
all										
tnt										
rut	tr	tr	tr	10	10	<5	<5	<5	5	<5
leux		10-10	10			5	5	5	10	5
mt										
hmmt										
c.					tr 15	5				
ank	15-20	25	20	20	25	5	10	15	35	10
pg		10	15	20						
mu			10		15-20	5-10	15		15	60
cpy		tr		tr			tr		tr	
py				tr		tr				tr
op	tr		tr		15					

altered leucogabbro

San Antonio Mine

	85- 1027	84- 103	85- 1061	85- 019
act				
chl	25	15	25	15
alb	25	30	20	20
qtz	15	5-10	10	5
matrix	5-10	10-15		10
ep	10			15
all				
tnt				
rut	5	<5	<5	tr
leux	10	5	8	8-10
mt				
hmmt				
cc	tr			10-15
ank	15	20	25	5
pg				
mu	15	10-15	10	10
cpy				
py		<5	tr	
op	tr	adj qv		

Table 4: Gabbro mineral assemblages

San Antonio Sill-Gabbro

	unaltered		altered				Chilled margin		
	Transect III		San Antonio Mine East			shore	Transect II		
	87- 535	87- 531	85- 1025	86- 070	84- 105	84- 106	lower 85- 434	upper 85- 424	upper 85- 417
hb	tr	-							
act	15-20	-							15
chl	5-10	15	15	15-20	15-20	20	35	45	25
alb	60	30	10-15		10-15		5-10	30	20
qtz	tr	10-15			15	5-10			3
matrix		20	25-30	10-15	15	25	30		10
ep	(90),5		tr						5
all			tr						
tnt	10	15	5						10
ti-mt									
rut=leux				10	10	5-10	10	10-15	
cc		20	20				20	10-15	10
ank				35	20-25	25			
pg				9	15	20			
mu				7	10	tr			
mt				5					
hmmt									
cpy				tr					
py				10					
op			15-mt						

Table 4: (cont'd)

	Northern Gabbro				Southern Gabbro	
	unaltered Transect III				San Antonio Mine	
	87- 543	87- 541	87- 288	87- 540	85- 1070	85- 1069
lib					-	-
act	30-40	15-20	15	20	-	-
chl	20	20-25	10-15	5-10	20	15
alb	30-40	40	-	30-40	15	25
qtz		5-10		5	10-15	20
matrix			30		20-25	15
ep	(10), 10	(95), 10-15		25-30	30	tr
all				5	-	-
tnt	5-10	5	15		-	-
ti-mt					-	-
rut-leux					10-15	10-15
cc					tr 5-10	5
ank					5	15
pg						
mu						
mt					tr	
hmt						
cpy						
py					tr	
op					5-10, mt	5-10

Table 5: Vein mineral assemblages

Capital letters = >10%, lower case = 1-10% trace =
tr <1%

1. Shear-type veins

86-12a: 608 shear-type vein QTZ, ANK, ALB > sericite
sericite crosscuts the vein
ank- partially replaced qtz and
fills fractures in qtz

85-17: 608 shear, stringer QTZ, ANK, alb

86-37: 716 vein, vein breccia QTZ, ANK, ALB, tr cc
wallrock fragments undeformed

86-41: 716 vein ALB >> ANK > QTZ

86-42: 716 vein ANK, QTZ, mu, tr alb

86-43a: 716 vein QTZ, ANK, ALB, tr py, mu

86-040b: 716 vein pyrite seam PY, tm, po, cpy, sph, Au

86-44: 716 vein pyrite seam, PY, TM, SERICITE, cpy tr po
vein, QTZ, ANK, ALB, tr cc

86-47: 716 vein pyrite seam PY, tm, tr cpy, po

86-48: 716 veinlet, ANK >> QTZ > MU tr alb

2. Stockwork-type veins

86-52: 7 level, ANK, QTZ, tr cc

85-78a: stringer ALB, ANK, rut, py, tr cc

86-68a: ladder vein QTZ, ANK tr alb, py in wallrock

86-65: ladder vein, polished section PY, cpy

86-64a: ladder vein, ANK, ALB, QTZ, py, tr cpy

3. 130-faults

86-53a: 6 level ANK >> ALB > QTZ > sericite > chl > cc
> tr rut

alb-, ank-, qtz-rich vein crosscut by greenish
-blue chlorite and sericite
chlorite partially replaced sericite
cc cuts ank, fills fractures in ank

Table 5: (cont'd)

86-53b: 6 level ANK = ALB > QTZ > CC > sericite > chl
 tr py
 inclusions of sericite and ank in py
 contact with wallrock - hydrothermal albite
 cc partially replaced qtz and ank

85-d-011: 6 level

a) wallrock | ankerite band at contact | quartz vein

ank band: ANK, qtz, tr mu, chl, cc, py cpy
 ank partially replaced qtz
 cc, qtz, ser, chl fracture fillings

qtz vein: QTZ, ank, mu

b) late "vein parallel" vein

QTZ, ank, mu tr cc

APPENDIX 2: MINERAL CHEMISTRY

Table 6: Amphibole analyses

Table 7: Chlorite analyses

Table 8: Plagioclase analyses

Table 9: Epidote and allanite analyses

Table 10: Titanite analyses

Table 11: Carbonate analyses

Table 12: Mica analyses

Table 13: Identification of oxide and sulphide minerals

Microprobe analyses of amphibole, chlorite, epidote and mica totals corrected for oxygen equivalent of fluorine and chlorine.

Table 6: Amphibole Analyses

	1	2	3	4	5	6	7	8	9	10
Na ₂ O	3.23	0.59	0.14	1.75	1.83	3.08	0.18	1.97	1.87	0.43
MgO	15.82	10.06	17.97	12.75	14.4	15.33	17.08	14.48	14.82	16.14
Al ₂ O ₃	8.22	0.64	2.18	6.73	7.65	8.19	0.82	6.59	5.35	5
SiO ₂	45.19	53.31	54.27	48.84	48.94	44.98	55.6	49.55	51.01	49.11
K ₂ O	0.72	0.03	0.01	0.05	0.07	0.76	0.02	0.05	0.09	0.07
CaO	11.46	11.59	11.97	11.51	11.31	11.24	12.87	10.54	10.9	10.96
TiO ₂	2.91	0.06	0.05	0.6	0.16	3.29	0	0.34	0.25	0.19
Cr ₂ O ₃	0.09	0	0	0.4	0.02	0.12	0.06	0.06	0	0.03
MnO	0.1	0.39	0.19	0.3	0.13	0.18	0.22	0.41	0.34	0.28
FeO	10.94	22.98	11.67	15.21	13.83	11.43	11.8	14.04	14.54	14.15
F	1.46	0.11	0	0	0.12	1.15	0.08	0	0	0
Cl	0.17	0.04	0	0.15	0.18	0.16	0	0.21	0.002	0.01
(Total)	100.31	99.78	98.44	98.32	98.62	99.9	98.73	98.22	99.34	96.37
O=F	0.61	0.05	0	0	0.05	0.48	0.03	0	0	0
O=Cl	0.04	0.01	0	0.03	0.04	0.04	0	0.05	0	0
TOTAL	99.66	99.77	98.44	98.29	98.53	99.38	98.7	98.17	99.34	96.37

FORMULA	BASIS 23			OXYGEN						
Na	0.911	0.169	0.038	0.497	0.514	0.873	0.048	0.555	0.521	0.123
Mg	3.431	2.219	3.8	2.783	3.109	3.336	3.608	3.137	3.177	3.554
Al	1.41	0.112	0.365	1.162	1.307	1.408	0.137	1.129	0.907	0.87
Si	6.58	7.89	7.698	7.154	7.092	6.564	7.884	7.203	7.336	7.254
K	0.133	0.005	0.002	0.008	0.012	0.141	0.003	0.01	0.016	0.014
Ca	1.787	1.837	1.82	1.805	1.756	1.757	1.956	1.642	1.679	1.734
Ti	0.318	0.006	0.005	0.07	0.017	0.361	0.001	0.037	0.027	0.021
Cr	0.01	0	0.001	0.046	0.002	0.013	0.006	0.007	0	0.003
Mn	0.013	0.048	0.022	0.037	0.016	0.022	0.026	0.05	0.041	0.034
Fe	1.33	2.845	1.384	1.863	1.675	1.395	1.399	1.707	1.748	1.748
F	0.673	0.053	0	0	0.054	0.532	0.034	0	0	0
Cl	0.042	0.009	0	0.038	0.045	0.038	0.001	0.051	0.045	0.003
100Mg	72	43	73	59	65	70	72	64	64	67
/Mg+Fe+Mn										

- 1 85-428 Brown hornblende, pargasite
2. Green actinolite
3. Clear, actinolite-tremolite
4. Brown hornblende, hastingsite (4 and 5 same grain)
5. Fibrous amphibole, hastingsite
- 6-8, Corona
6. Brown hornblende in core, pargasite
7. Deep blue-green actinolite rimming 6, pargasite
8. Clear amphibole surrounding 6 and 7, actinolitic hornblende
9. 85-427 Fibrous, actinolitic hornblende
10. Porphyroblast, actinolitic hornblende, hastingsite

Table 6: (cont'd)

	11	12	13
Na ₂ O	1.62	1.46	1.73
MgO	13.77	10.45	11.09
Al ₂ O ₃	6.08	4.05	2.11
SiO ₂	49.99	48.92	51.97
K ₂ O	0.08	0.52	0.18
CaO	11.8	10.86	8.75
TiO ₂	0.65	0.84	0.29
Cr ₂ O ₃	0.08	0.02	0
MnO	0.32	0.39	0.95
FeO	14.51	20.4	21.81
F	0.04	0.01	0
Cl	0.14	0.31	0.2
(Total)	99.07	98.23	99.07
O=F	0.02	0	0
O=Cl	0.03	0.07	0.04
TOTAL	99.02	98.16	99.03

FORMULA	BASIS	23	OXYGEN
Na	0.453	0.427	0.499
Mg	2.97	2.347	2.454
Al	1.04	0.719	0.369
Si	7.232	7.371	7.72
K	0.014	0.1	0.034
Ca	1.828	1.753	1.392
Ti	0.071	0.096	0.033
Cr	0.009	0.002	0
Mn	0.039	0.049	0.12
Fe	1.756	2.571	2.709
F	0.017	0.004	0
Cl	0.035	0.079	0.049
100Mg /Mg+Fe+Mn	62	47	47

Melagabbro

11. 85-427 Brown hornblende, hastingsite

Internal leucoqabbro sill

12. 85-426 Actinolitic hornblende, hastingsite

13. Actinolite

Table 7: Chlorite Analyses

	1	2	3	4	5	6	7	8	9	10
Na ₂ O	0.05	0	0	0	0.09	0	0	0.02	0.05	1.34
MgO	18.15	18.5	19.5	19.53	19.51	17.21	17.24	17.6	15.96	14.8
Al ₂ O ₃	18.55	18.81	17.71	18.01	17.73	18.98	18.57	18.8	19.92	19.81
SiO ₂	26.2	27.27	27.7	27.39	27.58	26.47	26.82	26.57	25.45	27.92
K ₂ O	0.01	0	0.02	0.02	0.05	0.02	0.02	0	0	0
CaO	0.06	0.05	0.04	0.07	0.05	0.07	0.01	0.05	0.08	0.03
TiO ₂	0.06	0	0.05	0.02	0.05	0.03	0.03	0.04	0.04	0
Cr ₂ O ₃	0.17	0.04	0.51	0.07	0.51	0.13	0.05	0.05	0.03	0
MnO	0.27	0.32	0.35	0.3	0.3	0.36	0.4	0.37	0.85	0.72
FeO	22.77	23.48	22.34	22.42	21.11	24.63	23.9	23.76	24.3	23.61
F	0.05	0	0.03	0.03	0	0	0.05	0	N/A	N/A
Cl	0.01	0.01	0.01	0.03	0.04	0.02	0.01	0.01	N/A	N/A
Total	86.35	88.48	88.27	87.92	87.03	87.93	87.09	87.33	86.68	88.23
O=F	0.02	0	0.01	0.01	0	0	0.02	0		
O=Cl	0	0	0	0.01	0.01	0	0	0		
TOTAL	86.33	88.48	88.26	87.90	87.02	87.93	87.07	87.33		

FORMULA

BASIS 28 OXYGEN

Na	0.0198	0	0	0.02	0.036	0.001	0	0.008	0.019	0.541
Mg	5.743	5.702	6.007	6.0376	6.061	5.386	5.424	5.533	5.079	4.59
Al	4.641	4.586	4.314	4.404	4.355	4.696	4.62	4.663	5.011	4.857
Si	5.559	5.64	5.724	5.682	5.747	5.56	5.663	5.591	5.432	5.807
K	0.002	0.001	0.005	0.004	0.014	0.006	0.006	0.002	0	0
Ca	0.014	0.0115	0.009	0.015	0.011	0.015	0.003	0.012	0.018	0.007
Ti	0.009	0	0.008	0.003	0.007	0.005	0.005	0.007	0.007	0
Cr	0.028	0.006	0.083	0.011	0.083	0.0222	0.007	0.009	0.006	0
Mn	0.049	0.0562	0.062	0.052	0.053	0.065	0.071	0.066	0.154	0.126
Fe	4.041	0.061	3.861	3.89	3.683	4.325	4.22	4.181	4.338	4.106
F	0.031	0	0.02	0.02	0	0	0.03	0	N/A	N/A
Cl	0.005	0.002	0.003	0.01	0.013	0.007	0.003	0.005	N/A	N/A

CHLORITE-1

1. 85-427, ripidolite-pycnochlorite from melagabbro, brown-khaki
2. , pycnochlorite from melagabbro brown-khaki
3. , pycnochlorite from melagabbro within single crystal actinolite
4. 85-428, pycnochlorite from melagabbro, patch within single crystal actinolite
5. , pycnochlorite from melagabbro, adjacent to fibrous actinolite
6. 85-432, ripidolite-pycnochlorite from melagabbro, brown chlorite adjacent to opaque
7. , pycnochlorite from melagabbro, chlorite patch with oxides along fractures
8. , ripidolite-pycnochlorite from melagabbro, chlorite patch with titanite-rich fractures

CHLORITE-2

9. 86-062, pycnochlorite from leucogabbro, purplish-brown
10. , ripidolite from leucogabbro, purplish-brown

Table 7: (cont'd)

	11	12	13	14	15	16	17	18	19
Na2O	0	0	0.05	0.03	0	0.01	0.07	0.02	0.01
MgO	14.98	15.03	19.95	21.98	20.82	10.49	9.12	15.03	10.66
Al2O3	18.23	18.07	18.67	17.93	19.53	20.51	22.54	19.03	21.93
SiO2	25.84	25.91	27.53	28.31	27.43	24.45	23.34	25.91	23.55
K2O	0.02	0	0	0.01	0	0	0.05	0.01	0.03
CaO	0.03	0.04	0.07	0.03	0.06	0.19	0.12	0.03	0.22
TiO2	0.04	0.04	0.02	0.04	0.05	0.09	0.05	0.03	0.08
Cr2O3	0	0.02	0.24	0.25	0.03	0.03	0.02	0.03	0.05
MnO	0.5	0.55	0.25	0.34	0.27	0.12	0.03	0.62	0.03
FeO	27.56	28.4	21.64	18.49	19.18	32.32	32.11	27.55	31.56
F	0.04	0.03	0.07	0.09	0	0.08	0.05	0.13	0.01
Cl	0.01	0.01	0.03	0.01	0.01	0.01	0.02	0	0.04
Total	87.24	88.08	88.51	87.5	87.38	88.3	87.52	88.39	88.41
OF	0.02	0.01	0.03	0.04	0	0.03	0.02	0.05	0
OC	0	0	0.01	0	0	0	0	0	0.02
TOTAL	87.22	88.07	88.47	87.46	87.38	87.27	87.50	88.34	88.39

FORMULA BASIS 28 OXYGEN

Na	0	0.001	0.019	0.011	0	0.005	0.028	0.007	0.005
Mg	4.816	4.807	6.098	6.682	6.349	3.412	2.991	4.769	3.454
Al	4.636	4.569	4.512	4.311	4.709	5.275	5.841	4.772	5.617
Si	5.573	5.559	5.646	5.776	5.612	5.337	5.133	5.514	5.119
K	0.005	0	0	0.003	0	0	0.013	0.003	0.008
Ca	0.006	0.008	0.015	0.007	0.012	0.044	0.028	0.008	0.051
Ti	0.007	0.006	0.003	0.005	0.007	0.0143	0.009	0.005	0.013
Cr	0	0.003	0.039	0.041	0.005	0.005	0.004	0.005	0.008
Mn	0.092	0.1	0.043	0.058	0.046	0.023	0.005	0.112	0.049
Fe	4.97	5.098	3.712	3.154	3.282	5.897	5.906	4.904	5.737
F	0.03	0.02	0.045	0.056	0	0.054	0.0347	0.085	0.01
Cl	0.003	0.003	0.011	0.002	0.005	0.004	0.008	0	0.014

CHLORITE-2

11. 85-426, ripidolite from leucogabbroic sill, purple
 12. " " "

CHLORITE-3

13. 85-1020, pycnochlorite from altered melagabbro, khaki
 14. 85-1025, pycnochlorite from altered melagabbro, khaki
 15. " , pycnochlorite from altered melagabbro, khaki

CHLORITE-4

16. 86-033, ripidolite from weakly altered leucogabbro, blue-grey
 17. " , ripidolite from weakly altered leucogabbro, blue-grey
 18. 85-149, ripidolite from weakly altered granophyric leucogabbro, purplish-brown
 19. 85-1111, ripidolite from altered leucogabbro, blue-grey

Table 7: (cont'd)

	20	21	22
Na ₂ O	0.09	0.03	0.05
MgO	0.69	6.8	7.02
Al ₂ O ₃	21.45	21.8	21.69
SiO ₂	22.83	22.15	22.57
K ₂ O	0.01	0.01	0
CaO	0.07	0.27	0.06
TiO ₂	0.05	0.04	0.09
Cr ₂ O ₃	0.06	0.02	0.02
MnO	0.07	0.03	0.07
FeO	36.83	37.16	36.51
F	0	0.02	0.01
Cl	0.04	0.02	0.02
Total	88.38	88.35	88.22
ΣF	0	0.01	0
ΣCl	0.01	0	0
TOTAL	88.37	88.34	88.22

FORMULA BASIS 28 OXYGEN

Na	0.041	0.014	0.02
Mg	2.295	2.779	2.346
Al	5.663	5.778	5.736
Si	5.113	4.982	5.063
K	0.004	0.004	0.001
a	0.016	0.064	0.015
Ti	0.009	0.007	0.015
Cr	0.011	0.004	0.003
Mn	0.013	0.006	0.014
Fe	6.9	6.99	6.851
F	0	0.015	0.088
Cl	0.015	0.007	0.006

CHLORITE-4 (cont'd)

20. 85-1742-6. pseudothuringite-ripidolite from leucogabbro, green chlorite in fracture, with muscovite and ankerite

21. , pseudothuringite-ripidolite from leucogabbro, green chlorite in matrix, near muscovite

22. , pseudothuringite-ripidolite from leucogabbro, blue-green.

Table 8: Plagioclase analyses

	1	2	3	4	5	6	7	8	9	10
SiO ₂	69.93	69.57	70.77	70.09	71.2	68.54	67.88	63.86	66.27	68.07
Al ₂ O ₃	20.66	20.39	20.82	20.47	20.68	20.7	21.28	20.34	21.1	20.22
Na ₂ O	11.95	12.2	11.86	12.08	10.77	11.62	11.54	11.15	11.1	11.82
CaO	0.19	0.25	0.16	0.14	0.2	0.78	0.79	1.39	1.43	0.39
K ₂ O	0.02	0.09	0.07	0.03	0.08	0.06	0.07	0.11	0.07	0.09
FeO	0.19	0.28	0.31	0.18	0.39	0.21	0.17	0.51	0.17	0.1
Total	102.94	102.78	103.99	102.99	103.32	101.91	101.73	97.36	100.14	100.69

FORMULA BASIS 32 OXYGENS

Si	11.88	11.87	11.9	11.91	12	11.79	11.7	11.58	11.63	11.84
Al	4.14	4.1	4.13	4.1	4.11	4.2	4.32	4.35	4.37	4.15
Total	16.02	15.97	16.02	16	16.11	15.99	16.03	15.93	16	15.99
Na	3.94	4.04	3.87	3.98	3.52	3.88	3.86	3.92	3.78	4
Ca	0.04	0.05	0.03	0.03	0.04	0.15	0.15	0.27	0.27	0.07
K	0	0.02	0.02	0.01	0.02	0.01	0.02	0.03	0.02	0.02
Total	3.98	4.1	3.91	4.01	3.57	4.03	4.02	4.21	4.06	4.09
Fe	0.03	0.04	0.04	0.03	0.05	0.03	0.03	0.08	0.03	0.02

WEIGHT % END MEMBERS

AB	101.16	103.21	100.37	102.21	91.18	98.33	97.68	94.31	93.94	100
AN	0.95	1.22	0.8	0.71	0.96	3.9	3.92	6.89	7.1	1.94
OR	0.11	0.52	0.44	0.16	0.47	0.32	0.43	0.64	0.4	0.53
	102.22	104.95	101.61	103.08	92.61	102.56	102.03	101.85	101.43	102.47

MOLECULAR % END MEMBERS

AB	99.02	98.44	98.85	99.2	98.54	96.11	95.97	93	93.01	97.72
AN	0.88	1.1	0.74	0.65	0.98	3.59	3.63	6.41	6.62	1.79
OR	0.1	0.46	0.41	0.15	0.48	0.3	0.4	0.59	0.37	0.49

Metamorphic albite

Melagabbro

1, 2. 85-432, unaltered

3. 85-1025, weakly altered

Leucogabbro

5-104, 85-062, unaltered

Table 8: (cont'd)

	11	12
SiO ₂	68.19	68.61
Al ₂ O ₃	20.7	20.15
Na ₂ O	12.2	12.31
CaO	0.27	0.17
K ₂ O	0.05	0.06
FeO	0.05	0.16
Total	100.96	101.46

FORMULA	BASIS	32	OXYGENS
Si	11.84	11.86	
Al	4.13	4.11	
Total	15.97	15.96	
Na	4.11	4.3	
Ca	0.05	0.03	
K	0.01	0.01	
Total	4.17	4.17	
Fe	0.01	0.02	

WEIGHT	%	END	MEMBERS
AB	103.24	104.2	
AN	1.33	0.83	
OR	0.27	0.38	
Total	104.84	105.41	

MOLECULAR	%	END	MEMBERS
AB	98.56	98.92	
AN	1.2	0.74	
OR	0.24	0.34	

Hydrothermal albite

11, 12. 84-104, 716 vein

Table 9: Epidote and Allanite Analyses

	1	2	3	4	Epidote		7	8	9	10
					5	6				
Na2O	0.01	0.1	0	1.38	0.52	0.01	0	0.14	0	0.05
MgO	0.02	0	0.05	0.02	1.24	0.04	0.02	0	0	0.06
Al2O3	23.01	21.71	22.97	21.46	23.34	22.19	21.99	21.85	22.06	21.49
SiO2	38.19	38.15	38.13	41.42	38.82	37.87	37.95	38.13	39.19	38.86
K2O	0.01	0.03	0	0.02	0.09	0	0.02	0.07	0.02	0.08
CaO	23.68	23.14	23.88	20.8	21.34	23.68	23.93	23.46	23.7	23.6
TiO2	0.08	0.01	0.04	0.02	0.08	0.1	0.1	0.07	0.02	0.04
Cr2O3	0.04	0.02	0.12	0.02	0	0.09	0.06	0.25	0.17	0.11
MnO	0.07	0.11	0.09	0.13	0.2	0.14	0.09	0.16	0	0.15
FeO	11.74	13.45	11.94	11.69	11.51	13.41	13.25	13.19	13.26	13.87
F	0.14	0	0	0.07	0.08	0	0.07	N/A	N/A	N/A
Cl	0.00	0	0.01	0	0.04	0	0.01	N/A	N/A	N/A
Total	96.99	96.71	97.23	97.32	97.24	97.53	97.49	97.32	98.42	98.31
O=F	0.06	0	0	0.03	0.03	0	0.03			
O=Cl	0	0	0	0.01	0	0				
TOTAL	96.93	96.71	97.23	97.29	97.2	97.53	97.46			
FORMULA	BASIS 25	OXYGEN								
Na	0.004	0.031	0	0.432	0.163	0.003	0	0.044	0	0.017
Mg	0.005	0	0.011	0.005	0.299	0.01	0.005	0	0	0.014
Al	4.445	4.237	4.429	4.139	4.463	4.301	4.266	4.242	4.218	4.136
Si	6.26	6.318	6.239	6.685	6.3	6.228	6.249	6.281	6.358	6.345
K	0.21	0.006	0	0.004	0.018	0	0.005	0.014	0.005	0.016
Ca	4.159	4.105	4.187	3.596	3.71	4.173	4.222	4.14	4.119	4.129
Ti	0.01	0.001	0.005	0.002	0.009	0.013	0.012	0.008	0.003	0.005
Cr	0.005	0.003	0.015	0.002	0	0.012	0.008	0.033	0.021	0.014
Mn	0.01	0.015	0.013	0.018	0.027	0.019	0.013	0.023	0	0.021
Fe	1.61	1.863	1.634	1.578	1.563	1.845	1.824	1.817	1.798	1.894
F	0.071	0	0	0.0345	0.04	0	0.036	N/A	N/A	N/A
Cl	0.00	0.001	0.004	0	0.011	0.08	0.003	N/A	N/A	N/A

1. 85-427, Epidote in melagabbro
2. , Granular epidote in melagabbro
3. 85-428, Coarse epidote in melagabbro, chalcopyrite core
4. , Granular epidote in melagabbro
5. 85-432, Granular epidote associated with plagioclase in melagabbro
6. 85-1020, Coarse epidote in altered melagabbro
7. , Coarse epidote with cluster of oxide in altered melagabbro
8. , Epidote
9. , Epidote
10. 86-062, Epidote in leucogabbro

3

MicroD

Table 9: (cont'd)

	Epidote							Allanite			
	10	11	12	13	14	15	16		1	2	3
Na2O	0.05	0.28	0.01	0.03	0.02	0.03	0	SiO2	30.22	30.47	30.34
MgO	0.06	0.03	0.06	0.03	0.01	0.02	0.03	TiO2	1.27	1.03	1.61
Al2O3	21.49	20.91	21.59	26.02	21.74	20.78	21.82	ThO2	0.02	0	0.01
SiO2	38.86	36.68	37.92	38.75	38.09	38.05	39.7	Al2O3	12.78	13.46	12.59
K2O	0.08	0.03	0	0.01	0.03	0.01	0.02	Y2O3	1.01	0.9	0.46
CaO	23.6	22.22	24.19	24.88	23.43	23.79	23.4	Ce2O3	12.47	12.61	12.23
TiO2	0.04	0	0.07	0.07	0.09	0.18	0.06	La2O3	6.05	5.81	6.09
Cr2O3	0.11	0	0.04	0	0.03	0.02	0.07	FeO	16.34	15.53	16.2
MnO	0.15	0.1	0.07	1.03	0.4	0.1	0.21	MnO	0.03	0.09	0.02
FeO	13.87	12.77	12.47	7.4	13.6	14.1	11.99	MgO	0.75	0.84	0.74
F	N/A	N/A	0.11	0.13	0.06	0	0.19	CaO	10.59	10.66	10.91
Cl	N/A	N/A	0	0	0.01	0	0				
Total	98.31	93.02	96.51	97.43	97.51	97.06	97.49		91.51	91.41	91.18
O=F			0.05	0.05	0.03	0	0.08				
O=Cl			0	0	0	0	0				
TOTAL			96.46	97.38	97.48	97.06	97.41				
FORMULA BASIS	25	OXYGEN									
Na	0.017	0.092	0.002	0.01	0.008	0.009	0	Si	6.188	6.199	6.211
Mg	0.014	0.007	0.014	0.007	0.001	0.004	0.007	Ti	0.195	0.158	0.247
Al	4.136	4.243	4.224	4.894	4.224	4.068	4.189	Th	0.001	0	0
Si	6.345	6.314	6.29	6.186	6.28	6.318	6.467	Al	3.084	3.228	3.036
K	0.016	0.005	0	0.001	0.005	0.001	0.003	Y	0.11	0.097	0.05
Ca	4.129	4.099	4.302	4.255	4.138	4.232	4.083	Ce	0.935	0.939	0.917
Ti	0.005	0	0.008	0.009	0.011	0.022	0.007	La	0.457	0.436	0.46
Cr	0.014	0	0.005	0	0.004	0.003	0.009	Fe	2.798	2.643	2.772
Mn	0.021	0.015	0.009	0.014	0.056	0.014	0.029	Mn	0.005	0.016	0.003
Fe	1.894	1.839	1.73	0.988	1.874	1.959	1.633	Mg	0.228	0.256	0.224
F	N/A	N/A	0.057	0.067	0.031	0.02	0.097	Ca	2.323	2.322	2.392
Cl	N/A	N/A	0	0	0.002	0	0				

Table 10: Titanite analyses

	1	2	3	4	5
Na ₂ O	0	0	0.19	0	0.03
MgO	0	0	0.65	1.1	0
Al ₂ O ₃	0.48	1.1	1.69	1.98	1.02
SiO ₂	31.07	29.86	30.56	30.34	28.99
K ₂ O	0.04	0.04	0.09	0	0.04
CaO	28.96	28.1	27.15	26.59	27.35
TiO ₂	40.31	37.61	36.6	35.51	35.36
Cr ₂ O ₃	0.13	0.6	0.48	0.92	1.98
MnO	0	0.1	0	0.07	0.16
FeO	1	1.93	2.02	3.43	6.51
TOTAL	101.99	99.34	99.43	99.94	101.44

FORMULA BASIS 20 OXYGEN

Na	0	0	0.049	0	0.008
Mg	0	0	0.129	0.217	0
Al	0.073	0.172	0.262	0.307	0.16
Si	3.992	3.961	4.028	3.993	3.859
K	0.006	0.007	0.016	0	0.007
Ca	3.986	3.994	3.825	3.756	3.901
Ti	3.895	3.752	3.629	3.52	3.54
Cr	0.014	0.063	0.05	0.096	0.208
Mn	0	0.011	0	0.008	0.018
Fe	0.108	0.214	0.222	0.379	0.725

1, 85-1020, weakly altered melagabbro

2, 3: 85-432, unaltered melagabbro

4, 5. 85-428, unaltered melagabbro

Table 11: Carbonate Analyses

	1	2	3	4	5	6	7	8	9	10
MgO	0	0.44	0.13	0.03	0.67	0	8.55	7.79	8.25	0
CaO	53.5	51.54	53.27	53.44	48.92	52.54	28.65	28.13	28.52	52.73
MnO	0.89	1.01	0.71	0.54	0.6	0.44	1.05	0.48	0.61	0.65
FeO	0.69	0.96	0.72	1.44	3.57	1.54	17.98	20.24	20.02	1.28
Total	55.08	53.95	54.83	55.45	53.76	54.52	56.23	56.64	57.4	54.66

FORMULA BASIS 1 OXYGEN

Mg	0	0.01	0	0	0.02	0	0.22	0.19	0.21	0
Ca	0.98	0.96	0.98	0.97	0.92	0.97	0.52	0.51	0.51	0.97
Mn	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
Fe	0.01	0.01	0.01	0.02	0.05	0.02	0.25	0.29	0.28	0.02
Total	1	1	1	1	1	1	1	1	1	1

WEIGHT % END MEMBERS

MgCO ₃	0	0.89	0.25	0.08	1.44	0	17.91	16.34	17.29	0
CaCO ₃	95.46	92.01	95.07	95.36	87.31	93.74	51.13	50.21	50.87	94.1
MnCO ₃	1.46	1.65	1.12	0.9	0.98	0.67	1.7	0.79	1.04	1.11
FeCO ₃	1.13	1.55	1.13	2.27	5.82	2.46	28.97	32.59	32.23	2.02
	98.05	96.1	97.56	98.61	95.54	96.87	99.72	99.93	101.43	97.23

MOLECULAR % END MEMBERS

MgCO ₃	0	1.1	0.3	0.1	1.8	0	21.5	19.7	20.5	0
CaCO ₃	97.7	96	97.7	97.1	92.01	97.2	51.7	51	50.8	97.2
MnCO ₃	1.3	1.5	1	0.8	0.9	0.6	1.5	0.7	0.9	1
FeCO ₃	1	1.4	1	2	5.29	2.2	25.6	28.6	27.8	1.8

Melagabbro

- 1, 2. 85-1025, calcite adjacent to chlorite
3. , calcite adjacent to rutile

Leucogabbro

- 4-6. 86-033, calcite, inclusion-free
7-9. , ankerite
10. 85-1111, coarse calcite

Table 11: (cont'd)

	11	12	13	14	15	16	17
MgO	0	0	0	8.18	9.37	9.24	8.37
CaO	52.4	52.36	52.65	27.99	28.9	29.84	31.04
MnO	0.65	0.41	0.63	0.56	0.33	0.44	0.37
FeO	1.16	1.16	1.17	20.59	19.84	19.3	19.3
Total	54.21	53.93	54.45	57.32	58.44	58.82	59.08

FORMULA BASIS 1 OXYGEN

Mg	0	0	0	0.2	0.22	0.22	0.2
Ca	0.97	0.98	0.97	0.5	0.5	0.51	0.53
Mn	0.01	0	0.01	0.01	0.01	0.01	0.01
Fe	0.02	0.02	0.02	0.29	0.27	0.26	0.26
Total	1	1	1	1	1	1	1

WEIGHT % END MEMBERS

MgCO ₃	0	0	0	17.14	19.61	19.31	17.54
CaCO ₃	93.57	93.43	93.97	49.96	51.59	53.3	55.42
MnCO ₃	1.1	0.66	1	0.92	0.59	0.71	0.59
FeCO ₃	1.89	1.80	1.9	33.25	31.94	31.09	31.18
Total	96.56	95.97	96.86	101.27	103.73	104.41	104.74

MOLECULAR % END MEMBERS

MgCO ₃	0	0	0	20.38	22.6	22.1	20.08
CaCO ₃	97.3	97.7	97.4	50.05	50.1	51.4	53.45
MnCO ₃	1	0.6	0.9	0.8	0.5	0.6	0.5
FeCO ₃	1.7	1.7	1.7	28.77	26.8	25.9	25.97

Leucogabbro

11. 85-1111, inclusion-free calcite
 12. , inclusion-rich calcite
 13. , inclusion-free calcite

716 vein

- 14-15. 84-104, ankerite
 16. , ankerite with inclusions
 17. , ankerite

Table 12: Mica Analyses

	1	2	3	4	5	6	7	8	9	10 ³	11
Na2O	6.89	6.57	7.05*	6.79	6.72	1.66	0.72	0.9	3.71	2.88	6.89
MgO	0.2	0.04	0.03	0.02	0.05	0.4	1.17	0.34	0.14	0.6	0.03
Al2O3	37.64	38.16	38.31	38.81	38.67	33.56	31.84	34.11	36.35	34.79	38.45
SiO2	49.29	47.53	47.44	47.79	48.31	47.89	48.96	46.96	47.55	48.58	48.73
K2O	1.4	1.6	1.05	0.79	0.96	8.98	9.88	9.63	5.57	6.53	1.16
CaO	0.34	0.26	0.32	0.36	0.24	0.03	0	0	0.06	0.03	0.03
TiO2	0.08	0.06	0.04	0.01	0.07	0.16	0.14	0.26	0.11	0.04	0.02
Cr2O3	0.89	0	0.02	0	0.01	0	0.04	0	0.03	0.03	0
MnO	0.02	0	0.06	0.02	0	0	0.05	0.01	0	0	0.03
FeO	0.8	1.11	0.935	0.83	0.01	2.22	2.72	3.26	1.96	2.11	0.8
F	0.08	0.24	0	0	0.03	0.08	0.15	0.12	0	0.42	0.28
Cl	0.01	0.01	0.02	0.02	0.02	0.02	0	0.02	0	0	0.02
Total	97.64	95.58	95.28	95.14	95.85	94.98	95.66	95.59	95.45	96.01	96.44
O=F	0.03	0.1	0	0	0.1	0.03	0.06	0.05	0	0.18	0.12
O=Cl	0	0	0	0	0	0	0	0	0	0	0
TOTAL	97.61	95.48	95.28	95.14	95.84	94.95	95.60	95.54	95.45	95.83	96.32

FORMULA BASIS 22 OXYGEN

Na	1.678	1.635	1.753	1.685	1.654	0.428	0.185	0.231	0.937	0.73	1.692
Mg	0.038	0.008	0.005	0.004	0.009	0.079	0.232	0.067	0.027	0.116	0.005
Al	5.569	5.777	5.8	5.809	5.789	5.269	4.987	5.364	5.59	5.356	5.741
Si	6.189	6.106	6.09	6.117	6.136	6.379	6.508	6.267	6.205	6.347	6.174
K	0.224	0.261	0.172	0.129	0.155	1.525	1.674	1.639	0.926	1.089	0.187
Ca	0.046	0.036	0.044	0.049	0.033	0.005	0	0	0.008	0.005	0.004
Ti	0.008	0.006	0.004	0.001	0.006	0.016	0.014	0.026	0.011	0.004	0.002
Cr	0.089	0	0.002	0	0.001	0	0.004	0	0.003	0.003	0
Mn	0.002	0	0.006	0.002	0	0	0.006	0.001	0	0	0.003
Fe	0.083	0.119	0.1	0.089	0.084	0.247	0.302	0.364	0.213	0.23	0.085
F	0.03	0.097	0	0	0.011	0.033	0.062	0.049	0	0.175	0.114
Cl	0.003	0.003	0.004	0.004	0.003	0.003	0.001	0.004	0	0	0.003

Leucogabbro

1-5. 86-033, coarse paragonite

6. , muscovite

7-8. 85-1111, muscovite

9. 85-1742-6, altered muscovite-paragonite

10. , muscovite

11. , paragonite

Table 13: Identification of Oxide and Sulphide Minerals

1. 86-pea-040b 16-type vein (716), fine granular pyrite seam

in pyrite, brown, anisotropic: Fe, S pyrrhotite
 yellow : CuFeS chalcopyrite
 grey : Zn(Fe)S sphalerite
 bright yellow : Au, (trace Ag) electrum

2. 86-047 16-type vein (716)

in pyrite, yellow : CuFeS chalcopyrite
 brown, anisotropic: FeS pyrrhotite

3. 86-027 weakly altered leucogabbro

cluster of pink and blue, pink: CuFeS bornite
 blue: CuS probably chalcocite.

grey: Fe, Ti Ti-magnetite
 lamellae: Ti, Fe ilmenite
 rutile, possibly titanite

4. 86-046 16-type vein, (716)

brown translucent: Ti rutile
 : pyrite

From G.S.C. Mineralogy Laboratory Report, Files M87-199, M88-38
 identified by G. LeCheminant, Geological Survey of Canada.

APPENDIX 3: WHOLE ROCK AND TRACE ELEMENT COMPOSITIONS

Table 14: Whole rock and trace element compositions of the San Antonio Sill

Table 15: Whole rock and trace element compositions of the Northern and Southern Gabbros.

Major and trace elements were analyzed by ICP except for 1) As, Nb, Rb, Sr, Y, Zr were determined by XRF (EDS) and 2) H₂O, CO₂, S, FeO were determined by chemical methods. The estimates of error are:

C.R.= concentration range, D.L.= detection limit

	Absolute		Relative		
SiO ₂	± 0.4%	+	2%		
TiO ₂	± 0.02	+	"		
Al ₂ O ₃	± 0.2	+	"		
Fe ₂ O ₃ t	± 0.1	+	"		
Fe ₂ O ₃	calculated Fe ₂ O ₃ =Fe ₂ O ₃ t(ICP) -			1.11134*FeO	(volumetric)
FeO	± 0.2	+	5%		
MnO	± 0.01	+	2%		
MgO	± 0.1	+	"		
CaO	± 0.1	+	"		
Na ₂ O	± 0.1	+	"		
K ₂ O	± 0.1	+	"		
H ₂ Ot	± 0.1	+	5%		
CO ₂	± 0.1	+	3%		
P ₂ O ₅	± 0.02	+	1%		
S	± 0.04	+	5%		
				C.R. (ppm)	D.L. (ppm)
Ba	± 20 ppm	+	5%		
Be	± 0.5 ppm	+	5%		
Ni	± 10 ppm	+	"		
Co	± 5 ppm	+	"		
Cr	± 10 ppm	+	"		
Zn	± 5 ppm	+	"		
Cu	± 10 ppm	+	"		
As	± 30 ppm	+	10	0-7000	30
Nb	± 10 ppm	+	"	0-400	10
Rb	± 10 ppm	+	"	0-2200	10
Sr	± 10 ppm	+	"	0-2300	10
La	± 10 ppm	+	5		
V	± 5 ppm	+	"		
Y	± 5 ppm	+	"	0-750	10
Yb	± 0.5 ppm	+	"		
Zr	± 10 ppm	+	10	0-1400	10

Table 14: Whole rock and trace element compositions of the San Antonio Sill.

	<u>Unaltered melagabbro</u>								
	85- 428	87- 270	85- 427	87- 536	85- 429	85- 425	85- 430	85- 432	85- 431
SiO ₂	41.30	43.60	42.80	44.60	44.10	43.80	44.10	44	44.5
TiO ₂	0.5	0.48	0.5	0.77	0.56	0.66	0.52	0.55	0.49
Al ₂ O ₃	10.40	11.20	11.30	11.30	11.90	11.80	12.60	13.40	13
Fe ₂ O ₃ t	17	17.40	16.20	17.30	16.5	16	15.70	16.20	15.5
Fe ₂ O ₃	3.40	3.00	3.60	3.20	3.20	3.20	2.70	3.80	3.30
FeO	12.20	13.00	11.30	12.70	12	11.5	11.70	11.20	11
MnO	0.23	0.27	0.22	0.28	0.26	0.23	0.22	0.23	0.22
MgO	16.60	15.61	14.80	13.95	13.80	13.20	12.5	12.20	12.10
CaO	7.07	6.20	7.38	6.97	7.44	6.37	6.63	7.55	7.02
Na ₂ O	0.72	1.20	1.36	1.10	1.41	1.92	1.80	1.90	2
K ₂ O	0.05	0.04	0.05	0.42	0.05	0.04	0.06	0.07	0.05
H ₂ O _t	6	5.80	5.5	5.10	5.5	5.80	5.60	5.60	5.30
CO ₂	0.10	0.10	0	0.10	0	0	0.10	0.10	0.10
P ₂ O ₅	0.04	0.00	0.05	0.06	0.06	0.06	0.06	0.08	0.05
S	0.00	0.00	0.01	0	0	0	0.02	0	0
Total	98.61	100.50	98.97	100.55	100.27	98.58	98.61	100.68	99.13
Ba	10	40	10	129	10	10	60	0	60
Be	0.30	0.20	0.30	0.40	0.40	0.40	0.30	0.40	0.30
Ni	490	500	420	390	410	390	340	310	320
Co	87	93	79	81	80	74	73	72	73
Cr	470	430	400	330	420	400	370	380	350
Zn	100	150	110	130	130	130	100	97	110
Cu	70	28	69	93	73	31	58	14	17
As	3		0		0	12	0	0	3
Mo	4		4		3	3	0	2	3
Nb	4	0	4	0	2	3	3	2	6
Rb	0	0	0	0	0	0	0	0	0
Sr	73	61	150	105	170	130	200	260	280
La	4	5	4	8	7	4	3	7	6
V	130	140	130	190	150	160	150	160	150
Y	9	0	7	0	14	9	14	15	12
Yb	0.60	0.60	0.70	1.30	1.20	1	1.10	1.5	1.10
Zr	23	30	23	64	30	29	32	28	26
Density		3.01						3	

Table 14: (cont'd)

	<u>unaltered melagabbro</u>			
	85- 433	85- 419	87- 537	87- 298b
SiO ₂	44.10	41.40	46.30	46.60
TiO ₂	0.62	0.77	0.80	0.67
Al ₂ O ₃	13.5	13.10	13	13.60
Fe ₂ O ₃ t	16.60	19.60	16	15
Fe ₂ O ₃	3.40	6.90	3.60	4
FeO	11.90	11.40	11.20	9.90
MnO	0.24	0.26	0.23	0.21
MgO	12.10	11.60	10.74	10.65
CaO	7.59	6.29	7.84	7.44
Na ₂ O	1.66	1.21	1.70	2.5
K ₂ O	0.08	0.11	0	0.03
H ₂ O _t	5.40	5.5	4.70	4.40
CO ₂	0.10	0.10	0.20	0.10
P ₂ O ₅	0.09	0.09	0.08	0.06
S	0	0.01	0	0
Total	100.78	98.74	100.39	100.16

Ba	60	30	76	51
Be	0.40	0.40	0.40	0.30
Ni	320	290	260	280
Co	73	72	66	71
Cr	400	360	270	230
Zn	120	160	96	100
Cu	12	24	73	35
As	10	1	0	0
Mo	3	4	0	0
Nb	4	4	0	0
Rb	0	0	0	0
Sr	250	260	302	422
La	7	7	11	9
V	180	220	210	170
Y	15	21	0	0
Yb	1.40	2.20	1.80	1.20
Zr	29	44	30	37

Table 14: (cont'd)

unaltered leucogabbro

	87- 547	86- 069	87- 255	87- 534	87- 254	87- 532	87- 546	852- 022	87- 538	86- 062	86- 030
SiO ₂	50.80	49.20	51.20	48.5	51.30	51.80	51.90	51.60	53.20	52.20	51.10
TiO ₂	1.09	0.95	1.11	1.06	1.22	1.34	1.22	1.17	1.45	1.35	1.20
Al ₂ O ₃	16.40	17.90	16.20	18.20	16.20	15.20	15.90	17.80	14	15.70	16.90
Fe ₂ O _{3t}	12.90	11.10	12.40	12.40	13.20	13.60	13.30	13	15	13.30	13
Fe ₂ O _{3s}	5.70	4	4.80	5.20	5.10	4.70	5.80	6.80	8.20	7.90	6.10
FeO	6.5	6.40	6.80	6.5	7.30	8	6.70	5.60	6.10	4.90	6.20
MnO	0.17	0.16	0.17	0.17	0.19	0.20	0.18	0.16	0.23	0.16	0.16
MgO	5.16	4.32	4.25	4.15	4.01	3.99	3.85	3.76	3.56	3.07	3.01
CaO	7.96	10.80	8.82	9.81	8.91	7.76	7.70	7.28	5.80	7.70	8.47
Na ₂ O	1.80	2.55	2.40	3	1.90	2.5	2.60	2.96	3.40	2.79	2.20
K ₂ O	0.49	0.16	0	0.11	0.03	0.06	0.17	0.01	0.45	0.07	0
H ₂ O _t	3.70	3	3.60	3.30	3.80	3.70	3.5	3.40	3.60	2.90	3
CO ₂	0.20	0	0.80	0.10	0.20	1	0.40	0.40	0.20	0.10	0.90
P ₂ O ₅	0.09	0.16	0.09	0.10	0.11	0.10	0.11	0.14	0.15	0.14	0.11
S	0	0	0	0.02	0.01	0	0	0	0.01	0	0
Total	100.06	99.60	100.24	100.22	100.28	100.35	100.03	101.08	100.35	98.98	99.35
Ba		130	73	175	91	86	61	20	92	70	40
Be		0.5	0.5	0.60	0.60	0.70	0.60	0.60	0.60	0.70	0.60
Ni	69	54	54	54	47	31	41	35	29	23	30.1
Co	37	28	35	33	36	31	33	28	35	26	26
Cr	50	54	33	56	29	5	20	19	9	9	11
Zn	92	71	93	87	110	100	100	93	150	92	180
Cu	38	11	120	190	130	130	120	180	190	19	160
As		10						12		1	0
Mo		2						2		0	2
Nb	0	3	0	0	0	0	0	4	0	2	5
Rb	0	0	0	0	0	0	0	0	0	0	0
Sr	434	320	343	358	381	407	377	390	267	340	400
La	11	7	13	14	14	13	13	9	18	12	11
V	260	240	260	230	270	280	280	250	240	230	260
Y	0	20	0	0	0	0	4	22	14	28	27
Yb	2	1.5	2	2.20	2.30	2.30	2.40	2	3.20	2.40	2.20
Zr	47	41	40	45	50	52	56	61	66	66	67
Density		3.03						2.96		2.97	

Table 14: (cont'd)

unaltered leucogabbro

	86- 032	86- 063	85- 149
SiO ₂	51.5	52.40	53.40
TiO ₂	1.24	1.23	1.16
Al ₂ O ₃	17.5	15.90	16
Fe ₂ O ₃ t	12.40	12.5	11.90
Fe ₂ O ₃	6.5	7.30	7
FeO	5.30	4.70	4.40
MnO	0.18	0.16	0.17
MgO	2.92	2.64	2.53
CaO	9.70	7.77	7.34
Na ₂ O	1.98	3.01	3.64
K ₂ O	0.03	0.04	0.18
H ₂ Ot	3.10	2.5	2.90
CO ₂	0.60	0.10	0.20
P ₂ O ₅	0.13	0.15	0.13
S	0.03	0.04	0
Total	100.71	97.94	99.05
Ba	40	20	70
Be	0.60	0.70	0.70
Ni	24	20	23
Co	25	24	24
Cr	8	9	12
Zn	100	120	150
Cu	77	150	86
As	0	4	5
Nb	2	4	4
Rb	0	0	0
Sr	380	330	420
La	11	14	14
V	240	210	200
Y	29	32	31
Yb	2.40	2.90	3.10
Zr	66	75	83
Density	3.03	2.97	2.95

Table 14: (cont'd)

	<u>carbonatized melagabbro</u>										
<u>unaltered gabbro</u>	87- 535	87- 278	87- 281	87- 274	87- 277	87- 273	87- 1108	85- 437	85- 1020	85- 1060	85- 1019
SiO2	50.50	43.20	39.00	44.00	42.50	44.30	43.30	45.70	45.50	41.50	40.50
TiO2	0.75	0.55	0.62	0.58	0.72	0.74	0.69	0.55	0.83	0.68	0.78
Al2O3	14.10	10.40	12.50	11.80	11.80	12.20	13.40	13.60	12.60	11.00	13.20
Fe2O3t	13.40	18.20	21.60	16.40	16.40	18.00	16.80	13.50	13.50	16.00	15.40
Fe2O3	3.00	4.50	6.60	4.20	2.70	6.10	6.10	3.50	3.60	5.10	2.10
FeO	9.30	12.40	13.50	11.00	12.30	10.70	9.60	9.00	8.90	9.80	12.00
MnO	0.20	0.28	0.21	0.23	0.20	0.23	0.18	0.19	0.16	0.21	0.19
MgO	7.98	15.99	14.13	13.80	12.46	11.80	11.00	10.70	9.04	11.90	10.50
CaO	7.62	5.37	2.65	4.54	5.92	4.14	4.84	7.06	7.47	7.41	7.54
Na2O	2.50	0.10	0.10	0.00	0.00	0.90	1.59	2.95	1.51	0.19	0.75
K2O	0.04	0.18	0.24	0.23	0.00	0.42	0.11	0.07	0.06	0.09	0.07
H2O _t	4.00	6.70	7.20	7.20	6.80	6.40	6.30	4.30	5.10	6.10	6.50
CO2	0.50	1.10	3.80	3.00	4.60	2.60	3.00	1.20	4.70	5.90	5.60
P2O5	1.00	0.02	0.05	0.05	0.05	0.06	0.07	0.07	0.09	0.06	0.06
S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.04
Total	101.49	100.79	100.60	100.63	100.05	100.59	100.18	98.89	99.56	99.99	99.85
Ba	80	84	68	65	50	99	10	70	0	470	0
Be	0.40	0.30	0.30	0.30	0.30	0.40	0.40	0.30	0.40	0.40	0.40
Ni	160	450	500	410	350	300	290	260	220	370	180
Co	50	100	37	87	78	78	67	59	52	70	55
Cr	160	420	270	390	270	370	350	280	230	370	240
Zn	110	190	100	120	99	140	86	100	81	100	200
Cu	42	220	12	70	97	34	90	25	54	87	31
As							1	0	6	0	7
Nb	0	0	0	0	0	0	5	3	4	2	4
Rb	0	0	0	0	0	0	0	0	0	0	0
Sr	245	33	28	115	160	70	200	340	250	400	130
La	12	5	9	7	10	9	5	3	7	5	7
V	180	150	230	150	170	200	190	140	160	160	200
Y	0	0	0	0	0	0	16	11	17	10	17
Yb	1.60	0.60	0.90	0.90	1.20	1.5	1.40	0.70	1.5	0.70	1.70
Zr	37	30	38	33	44	71	34	28	49	31	38
Density	3.11	2.98			2.85					2.83	

Table 14: (cont'd)

	carbonatized melagabbro					carbonatized leucogabbro				
	95- 1023	84- 100a	86- 072	85- 1109	84- 99	85- 1059	85- 400	85- 1027	87- 533	85- d020
SiO ₂	43.80	42.80	43.70	39.70	42.30	41.50	49.90	49.70	53	47.80
TiO ₂	0.78	0.76	0.71	0.63	0.70	0.68	0.99	0.90	1.38	1.12
Al ₂ O ₃	12.50	12.70	13.20	10.00	10.70	11.90	16.10	17.60	14.40	15.70
Fe ₂ O ₃ t	15.20		14.70	13.60		13.80	11.90	10.20	13.60	11.20
Fe ₂ O ₃	2.10	6.40	5.40	1.40	1.60	1.70	5.20	1.80	4.70	2.5
FeO	11.80	8.30	8.40	11.00	11.40	10.90	6	7.60	8	7.30
MnO	0.19	0.22	0.18	0.21	0.23	0.20	0.18	0.12	0.18	0.16
MgO	10.40	9.59	8.94	10.80	10.60	8.95	4.19	3.72	3.44	3.31
CaO	5.90	7.09	6.64	8.78	7.50	7.50	8.75	5.95	8.54	7.81
Na ₂ O	0.79	1.10	2.47	0.81	0.00	2.21	2.47	4.26	2.20	3.77
K ₂ O	0.16	0.00	0.01	0.14	0.00	0.08	0.24	0.80	0.14	0.23
H ₂ O _t	5.30	4.40	4.90	4.00	4.60	3.80	4	3.60	3.30	3.5
CO ₂	7.40	6.80	5.00	12.20	9.80	10.80	2.80	4.30	1.5	4.70
P ₂ O ₅	0.11	0.10	0.07	0.07	0.08	0.09	0.12	0.09	0.11	0.13
S	0.00	0.00	0.00	0.03	0.02	0.00	0.01	0.02	0.01	
Total	101.23	100.26	99.62	99.77	99.53	100.31	100.95	100.46	100.90	98.53
Ba	0	0	0	0	0.30	0	40	130	120	100
Be	0.40		0.30	0.5		0.40	0.60	0.60	0.70	0.70
Ni	220		210	300		210	45	42	32	31
Co	57		52	60		50	32	24	32	24
Cr	250		250	300		220	43	38	12	15
Zn	110		92	90		85	84	73	120	69
Cu	69		46	66		60	22	49	140	40
As	8	0	8	2	6	0	1	1		1
Nb	4	0	4	3	0	4	3	4	0	3
Rb	0	0	0	0	0	0	0	9	0	2
Sr	110	260	290	280	200	150	420	290	411	270
La	8		5	6		7	8	6	18	9
V	170		180	150		170	230	210	270	240
Y	18	17	15	13	17	17	21	18	8	27
Yb	1.5		1.40	1		1.20	2	1.30	2.90	1.70
Zr	43	37	38	40	38	44	53	49	69	62
Density		2.84				2.84				

Table 14: (cont'd)

	<u>carbonatized leucogabbro</u>								
	86- 006	85- 1112	87- 501	85- 1113	86- 036	86- 035	86- 034	85- 148	85- d004
SiO ₂	49.30	50.90	50.30	51.70	52.5	55.30	52.60	52.40	56
TiO ₂	1.02	1.16	1.17	1.37	1.30	1.30	1.14	1.27	1.31
Al ₂ O ₃	15.80	16.5	15.5	14.5	13.70	13.70	15.10	13.5	13.90
Fe ₂ O ₃ t	11.5	12.30	12	13.40	13	12.90	11.5	12.60	12.30
Fe ₂ O ₃	2.40	5.20	2.5	5	2	3.30	2.80	4.90	2
FeO	8.20	6.40	8.60	7.60	9.90	8.60	7.80	6.90	9.30
MnO	0.17	0.17	0.14	0.17	0.19	0.19	0.15	0.17	0.13
MgO	3.23	3.01	2.77	2.65	2.62	2.59	2.51	2.37	2.33
CaO	7.11	8.55	6.61	5.37	5.93	5.86	7.15	5.71	3.32
Na ₂ O	5.10	2.72	3.5	4.60	3.26	3.33	3.58	4	4.15
K ₂ O	0.10	0.04	1.01	0.30	0.32	0.01	0.07	0.47	0.27
H ₂ O _t	3.10	2.80	3.30	2.70	3.5	2.80	3.10	3.40	2.60
CO ₂	4.70	1.40	4.80	4.10	4.60	2.90	3.80	4.10	4.10
P ₂ O ₅	0.11	0.11	0.11	0.15	0.20	0.18	0.15	0.18	0.27
S	0.0	0	0	0.05	0	0.03	0.01	0	
Total	100.34	98.96	100.31	100.21	100.07	100.06	99.98	99.38	99.68
Ba	70	0	185	80	480	20	30	130	100
Be	0.40	0.60	0.60	0.60	0.80	0.60	0.5	0.70	0.5
Ni	38	23	24	18	25	14	17	19	14
Co	30		25	29	22	22	22	23	20 22
Cr	22	23	9	9	9	8	8	10	10
Zn	91	88	75	90	110	120	100	110	150
Cu	120	120	29	150	120	160	95	150	140
As	2	0	4	0	1	8	0		
Nb	0	2	0	5	6	4	5	2	6
Rb	0	0	0	3	0	0	0	0	
Sr	204	490	234	260	150	190	310	310	170
La	14		10	12	16	17	13	16	21
V	220	240	210	170	130	140	170	140	80
Y	0	26	3	31	29	35	28	34	51
Yb	2.30	2.10	2.5	2.30	3.30	3.5	2.60	1.60	4.20
Zr	47	68	58	79	96	93	79	87	130
Density					2.86	2.8		2.84	2.83

Table 14: (cont'd)

	<u>carbonatized leucogabbro</u>								
	87- 280	86- 029	85- d-019	85- 1110	85- 1742-15	85- 1111	85- d708-10	85- 1742-4	84- 101
SiO ₂	47.60	47.80	48.40	50.70	49.60	46.70	48.90	49.80	48.5
TiO ₂	1.33	0.87	1.11	1.29	1.27	1.06	1.12	1.31	1.32
Al ₂ O ₃	12.40	16.40	15.20	14.10	14.10	16.20	15.60	14.30	15.80
Fe ₂ O ₃ t	12.40	9.80	11.20	12.40	13.10	11.20	10.80	12.70	
Fe ₂ O ₃	12.40	0.70	2.30	1.60	1.70	2.5	2.90	2.30	1.40
FeO	8.20	8	9.70	10.3	7.80	7.10	9.40	10.5	
MnO	0.10	0.11	0.15	0.15	0.15	0.16	0.14	0.16	0.15
MgO	4.13	3.52	3.23	3.21	3	2.94	2.93	2.93	2.92
CaO	8.70	8.49	7.70	5.57	5.19	8.85	6.62	5.35	4.76
Na ₂ O	4.10	3.75	3.44	2.36	3.22	1.87	3.33	3.60	3.80
K ₂ O	0.26	0.48	0.45	0.94	0.38	1.85	1.25	0.26	0.47
H ₂ O _t	3	3.10	3.20	3	3.60	3.20	2.90	2.40	
Cu ₂	7.30	7.30	6.5	6.90	7.60	6.20	5.60	7.70	6.80
P ₂ O ₅	0.09	0.09	0.12	0.18	0.15	0.11	0.11	0.13	0.14
S	1.24	0	0.02	0	0.29	0.04	0.01	0.01	0.04
Total	99.65	100.71	99.72	99.90	99.95	99.88	98.81	100.15	99.00
Ba	88	140	190	170	150	650	210	90	0.01
Be	0.3	0.70	0.60	0.5	0.70	0.70	0.60	0.60	
Ni	55	30	33	27	28	39	47	22	
Co	49	26	24	26	31	22	21	24	
Cr	15	16	16	11	7	7	45	8	
Zn	59	80	77	100	170	99	56	95	
Cu	63	33	22	120	240	94	11	98	
As		3	14	0	0	14	0	0	12
Nb	0	4	5	5	3	4	4	5	0
Rb	0	25	7	11	6	33	5	1	11
Sr	324	270	220	220	210	160	430	230	280
La	9	10	9	7	9	8	6	10	
v	280	230	230	230	210	230	200	200	
Y	4	27	24	26	34	22	20	31	35
Yb	2.20	1.80	1.5	1.90	2.40	1.80	1.40	2.30	
Zr	44	67	62	6	81	53	54	76	79
Density				2.89				2.91	

Table 14: (cont'd)

carbonatized leucogabbro

	85- d-007	85- 1742-16	84- 102	96- 033	86- 031	85- d-002	85- d-008	86- 1061	86- 066	86- 003
SiO ₂	50.40	51.30	51.5	48.90	48.5	55.70	54.10	43.90	42.30	47.60
TiO ₂	1.36	1.24	1.36	1.25	1.07	1.23	1.27	0.85	1.16	1.05
Al ₂ O ₃	13.80	14.10	13.60	15.30	15	13.30	13.30	15.30	14.40	15
Fe ₂ O ₃ t	13.80	12.80		11.60	11	12.70	13.30	10.10	11.30	11.10
Fe ₂ O ₃	2.10	1.5	1.90	3	3.10	4.40	1.30	0.90	1.60	1.10
FeO	10.5	10.20	10.40	7.70	7.10	7.5	10.80	8.30	8.70	9
MnO	0.21	0.16	0.15	0.17	0.15	0.18	0.18	0.14	0.15	0.15
MgO	2.81	2.80	2.76	2.56	2.36	2.29	2.19	4.18	3.74	3.29
CaO	5.08	4.82	5.30	8	7.64	4.22	4.71	7.83	7.57	7.40
Na ₂ O	3.41	3.66	2.30	2.48	2.56	4.99	3.16	3.96	2.80	3.90
K ₂ O	0.56	0.23	0.38	0.84	0.39	0.14	0.27	1.03	1.85	0.53
H ₂ O _t	2.80	2.90	2.5	2.60	2.70	1.60	2.5	2.20	2.70	2.70
CO ₂	7.30	7	7.5	7.80	8.30	5	6.40	11	10.80	8.5
P ₂ O ₅	0.25	0.14	0.17	0.13	0.10	0.22	0.21	0.08	0.09	0.09
S	0.02	0.03	0.09	0	0.01	0	0.03	0.04	0.37	0.01
Total	100.60	100.08	99.91	100.73	98.98	100.77	100.42	99.71	98.23	100.32
Ba	250	90	0.01	290	190	70	60	170	180	140
Be	0.80	0.5		0.60	0.60	0.5	0.5	0.5	0.90	0.5
Ni	17	20		28	25	12	13	64	46	39
Co	24	24		23	22	19	21	29	25	30
Cr	8	8		9	9	6	6	75	29	24
Zn	160	180		100	110	130	130	76	75	85
Cu	93	110		160	130	39	180	110	58	84
As	15	0	10	0	0	2	1	0	18	
Nb	5	6	1	3	6	5	5	4	4	0
Rb	9	1	10	14	3	0	0	17	33	0
Sr	220	190	230	260	330	310	220	320	260	353
La	23	8		10	11	19	18	5	7	13
V	87	190		200	200	86	83	180	290	230
Y	43	28	47	25	24	43	46	17	21	0
Yb	3.90	2.20		1.70	2	3.40	3.5	1.10	1.5	2.20
Zr	130	75	89	67	69	120	110	48	47	56
Density					2.9	2.64	2.86		2.82	

Table 14: (cont'd)

	<u>carbonatized leucogabbro</u>									
	86- 024	86- 049	85- d018	84- 79	86- 022	85- 1742-10	85- 1742-7	84- 100b	84- 103	85- 1742-6
SiO ₂	46	47.70	46.80	47.70	45.20	48.70	49.20	46.80	43.70	50.40
TiO ₂	1.01	1.02	1.10	1.14	0.96	1.20	1.19	1.12	1.14	1.28
Al ₂ O ₃	14.80	15.20	15.30	14.5	14.90	13.60	14.10	15.5	14.30	14.30
Fe ₂ O ₃ t	11	10	11.60		10.20	11.60	11.80			11.70
Fe ₂ O ₃	1.30	0.90	3.30	1.70	1.40	1.5	1.90	1.1	1.40	2
FeO	8.70	8.20	7.5	8.60	7.90	9.10	8.90	8.40	8.90	8.70
MnO	0.15	0.17	0.16	0.19	0.16	0.17	0.17	0.15	0.16	0.16
MgO	3.28	3.28	3.14	3.01	2.96	2.84	2.81	2.80	2.77	2.74
CaO	7.36	6.74	7.90	8.90	8.41	6.48	6.20	7.23	7.12	5.72
Na ₂ O	3.70	3.30	3.11	2.5	2.5	2.89	3.63	2.20	4.80	3.34
K ₂ O	0.95	1.58	0.62	0.48	1.89	0.29	0.34	1.21	0.93	0.38
H ₂ Ot	2.30	2.5	2.40	2.40	2	2.70	2.5	1.80	1.80	2.70
CO ₂	10.80	9.70	9.80	8.20	12.40	9.5	8.90	10.20	11	8.30
P ₂ O ₅	0.07	0.08	0.09	0.12	0.09	0.14	0.12	0.14	0.10	0.12
S	0.03	0	0.02	0	0.01	0.21	0.06	0	0.96	0
Total	100.45	100.37	101.24	99.44	100.78	99.32	100.02	98.55	99.08	100.14
Ba	128	245	220	0.01	194	110	140	0.02	0.02	140
Be	0.80	0.60	0.60		0.70	0.70	0.60			0.70
Ni	40	38	48		35	22	26			24
Co	31	27	26		27	27	23			23
Cr	25	23	14		17	9	7			8
Zn	85	79	71		78	110	83			93
Cu	130	19	54		44	110	150			130
As			23	9		0	5	27	19	40
Nb	0	0	4	1	0	4	4	3	2	5
Rb	0	37	11	12	82	4	2	29	21	6
Sr	340	246	310	270	304	320	280	360	360	260
La	13	11	8		12	11	10			9
V	240	220	240		220	190	200			200
Y	0	0	22	29	0	30	30	27	28	29
Yb	2	2	1.40		1.90	2	2.10			2.10
Zr	47	41	53	66	41	74	72	64	68	73
Density			3.01			2.89	2.87			2.92

Table 14: (cont'd)

	carbonatized leucogabbro						chilled margin gabbro			
	1742-13	1742-8	1742-9	1742-11	1742-12	d010	d011	1025	434	417
SiO2	48.10	48.5	49.40	48	49.30	52.60	53.70	47.10	47.20	46.80
TiO2	1.18	1.17	1.28	1.27	1.19	1.22	1.25	0.89	0.75	0.71
Al2O3	12.80	13.60	14.10	14.5	13.40	12.60	13.30	13	14.20	12.5
Fe2O3t	11.70	11.90	12.10	12.30	11.80	12.10	6.60	14.5	13.20	13.80
Fe2O3	2.40	2.10	2.10	2.10	3.90	1.41	0.60	5.80	1.60	4.80
FeO	8.40	8.80	9	9.20	7.10	9.60	5.40	7.80	10.40	8.10
MnO	0.17	0.17	0.14	0.17	0.17	0.22	0.22	0.19	0.16	0.20
MgO	2.73	2.73	2.68	2.54	2.46	2.31	1.62	8.15	7.36	7.29
CaO	7.12	6.31	5.67	6.30	6.78	6.49	7.32	6.34	5.36	10.70
Na2O	2.26	3.57	4.17	3.99	2.76	3.19	4.60	2.35	3.04	0.32
K2O	0.26	0.24	0.22	0.31	0.27	0.31	0.81	0.18	0.10	0.08
H2Ot	2.30	2.30	2.40	2.40	2.10	2.10	1	4.5	5.5	4.30
CO2	10.60	8.90	8	9	9.90	9.30	10.20	3.80	3.80	2.90
P2O5	0.12	0.13	0.14	0.14	0.14	0.23	0.20	0.14	0.10	0.05
S	0.04	0.08	0.14	0.22	0.01	0.04	0.04	0.03	0.01	0
Total	98.48	98.60	99.44	100.14	99.48	101.62	100.26	100.27	99.58	98.75
Ba	140	110	100	130	120	100	328	0	0	10
Be	0.60	0.60	0.5	0.60	0.70	0.5	0.70	0.40	0.40	0.5
Ni	23	27	21	22	22	17	12	170	150	140
Co	24	21	24	24	22	18	10	47	43	44
Cr	10	8	8	8	8	7	13	210	180	150
Zn	120	85	95	140	130	110	33	96	63	76
Cu	130	130	130	150	140	240	280	110	19	160
As	17	11	2	15	0	13		0	4	1
Nb	5	5	6	4	2	4	0	4	4	3
Rb	3	4	2	4	2	4	0	0	0	0
Sr	320	260	220	260	340	260	351	330	56	620
La	11	11	10	11	12	18	22	9	9	5
V	200	190	200	210	200	85	96	170	200	260
Y	27	30	31	30	33	41	51	23	22	12
Yb	2.30	2.10	2.20	2.30	2.20	3	3.90	2.20	2.40	1.5
Zr	73	73	78	78	78	110	102	50	46	24
Density	2.92		2.91				2.96	2.91		

Table 14: (cont'd)

	<u>chilled</u>	<u>carbonatized</u>	<u>gabbro</u>			
	<u>margin</u>					
	85- 424	86- 044	84- 76	86- 070	85- 105	85- 106
SiO ₂	46.70	44.70	43.40	40.30	39.40	44.70
TiO ₂	0.75	0.92	0.75	0.80	0.93	0.98
Al ₂ O ₃	13.70	13.40	12.60	13	13.80	13.5
Fe ₂ O ₃ t	14.5	14.20		13.30		
Fe ₂ O ₃	2.10	0.90	2	1.40	1.40	1.80
FeO	11.20	11.90	10.40	10.70	10.5	10
MnO	0.22	0.16	0.21	0.18	0.17	0.17
MgO	7.01	7.26	6.35	6.10	5.77	5.42
CaO	5.67	5.77	10.40	8.28	9.38	7.77
Na ₂ O	2.44	1.5	1.30	1.89	2.5	0.90
K ₂ O	0.18	0.66	0	0.43	0.59	0.58
H ₂ O _t	5.70	4.5	4.5	3.30	2	2.70
CO ₂	3.90	8.90	8.10	13	13.90	10.30
P ₂ O ₅	0.09	0.07	0.09	0.08	0.07	0.13
S	0.01	0.01	0	0.09	0.01	0
Total	99.67	100.65	100.10	99.55	100.42	98.95
Ba	20	87	0.00	80	0.01	0.01
Be	0.30	0.40		0.5		
Ni	140	190		99		
Co	41	57		37		
Cr	170	190		120		
Zn	120	130		79		
Cu	13	100		55		
As	0		0	9	16	12
Nb	5	0	0	4	0	0
Rb	0	0	0	3	12	13
Sr	79	120	170	300	350	300
La	5	11		5		
V	210	210		220		
Y	23	0	23	20	14	28
Yb	2.10	1.5		0.80		
Zr	41	31	40	38	29	59
Density				2.99		2.97

Table 15: Whole rock and trace element compositions
of the Northern and Southern Gabbros

	Southern Gabbro			Northern Gabbro				
	87- 509	86- 1070	86- 1069	87- 289	87- 543	87- 541	87- 288	87- 540
SiO ₂	45.20	47.30	46.80	46.60	47.90	46.60	48.70	47.90
TiO ₂	0.91	1.25	1.41	0.78	0.80	0.87	0.87	0.90
Al ₂ O ₃	15.80	12.40	12.20	13	13	16.30	14.70	14.70
Fe ₂ O ₃ t	14	15.70	15	15.70	14.60	15.30	14.60	15.30
Fe ₂ O ₃	2.80	4.10	3.20	3.80	2.5	4.20	5.5	4
FeO	10.10	10.40	10.60	10.70	10.90	10	8.20	10.10
MnO	0.18	0.19	0.21	0.24	0.23	0.21	0.20	0.22
MgO	8.05	4.68	3.94	9.17	9.63	7.19	6.46	6.26
CaO	6.28	7.82	8.35	9.26	7.63	8.75	9.94	9.56
Na ₂ O	1.20	2.08	2.38	1.5	2.80	2.10	1.5	2.20
K ₂ O	0.78	0.13	0.11	0.04	0	0	0.04	0
H ₂ O _t	5.60	4	3.70	4.20	4	4	3.70	3.80
CO ₂	3.60	5.60	7.70	1.20	0.40	0.10	0.30	0.70
P ₂ O ₅	0.05	0.10	0.12	0.09	0.07	0.10	0.10	0.09
S	0.02	0.03	0.03	0	0	0	0	0
Total	100.57	100.08	100.75	100.58	99.86	100.42	100.21	100.43

Ba	68	20	20	86	76	66	77	75
Be	0.40	0.70	0.60	0.40	0.40	0.5	0.5	0.5
Ni	130	51	30	230	200	100	130	140
Co	55	46	39	63	59	48	47	51
Cr	170	45	12	220	210	100	150	170
Zn	85	62	100	100	98	92	86	110
Cu	41	230	57	84	55	91	68	76
As		0	1	0	0	0	0	0
Nb	0	6	7	0	0	0	0	0
Rb	0	0	0	0	0	0	0	0
Sr	80	96	80	341	202		496	371
La	3	3	1	12	10	355	15	13
V	250	320	290	220	210	250	250	250
Y	0	20	23	0	0	0	0	1
Yb	1.10	1.70	1.60	1.90	1.90	2.70	2.40	2.40
Zr	30	67	68	36	69	38	39	34

Appendix 4: Mass balance data

Table 22: Mass gains and losses (%) between altered and unaltered San Antonio Sill

(-) denotes a loss

() denotes a gain

998- unaltered melagabbro; average from Table 18

999- unaltered leucogabbro; average of samples 86-62,63,69

leucogabbro sulphur; assuming a net parent concentration of $S = 0.05$

Table 22: Mass gains and losses (%) between altered and unaltered
San Antonio Sill

Assemblage	Melagabbro				Leucogabbro		
	3	4	5	2	3	4	5
	998	998	998	999	999	999	999
Altered	85-1060	84-100a	85-1059	86-32	85-148	86-031	1742-10
Unaltered							
SiO ₂	2.6	5.9	-2.5	-5	9.7	3.6	4.6
TiO ₂	20.9	20.3	15	-0.6	15.6	-0.6	12.1
Al ₂ O ₃	-3	0.3	-0.2	0.5	-12.1	-0.4	-9.2
Fe ₂ O ₃	53.6	71.43	-51.2	-3.9	-17.8	-46.9	-74.1
FeO	-8.4	-110.7	0	-5.3	39.8	46.8	89.1
MnO	-5.1	11.5	-14	6.5	13.7	2.4	17.1
MgO	-1.5	-29.4	-29.5	-16.9	-23.9	-22.6	-6.3
CaO	13.8	-3	9.6	4.8	-30	-4.4	-0.1
Na ₂ O	-86.6	33.5	42.4	-32.6	54.4	1	14.6
K ₂ O	22.1	100.6	3.2	-71.4	491.4	400	272.9
P ₂ O ₅	8.5	61.5	55	1250	2000	1100	1575
CO ₂	6370	6518	11148	36	2829	5951	6878
O	12.8	3.96	13.9	-3.4	10.3	15.7	16.82
S	-	0	0	56	122	122	420
FV	1.15	1.02	1.09	0.93	1.13	1.13	1.14

Assemblage	Gabbro		Assemblage	Leucogabbro	
	2	3		6	7
	999	999		999	999
Altered	85-1025	86-70	Altered	1742-7	86-66
Unaltered			Unaltered		
SiO ₂	-10.1	-19.5	SiO ₂	4	-10.5
TiO ₂	14.3	7.7	TiO ₂	9.9	3.3
Al ₂ O ₃	-11.1	-6.9	Al ₂ O ₃	7.3	-5.3
Fe ₂ O ₃	86.2	-52.9a	Fe ₂ O ₃	-67.9	72.8
FeO	19.2	16.2	FeO	82	78.2
MnO	-8.5	-9.2	MnO	16	1.7
MgO	-1.6	-2.3	MgO	-8.8	21.5
CaO	-19.8	9.7	CaO	23	-6.3
Na ₂ O	-9.4	-23.7	Na ₂ O	41.7	9.3
K ₂ O	370	1090	K ₂ O	330	2271
P ₂ O ₅	86.7	-92	P ₂ O ₅	1250	995
CO ₂	635	2529	CO ₂	6317	7463
O	4	5	O	15.8	11.6
S	0	1	S	130.2	802
FV	1.03	1.05	FV	1.13	1.15

APPENDIX 5
ACTIVITY MODELS AND CALCULATIONS

Chlorite

No mixing in the tetrahedral site.

Activity of clinocllore in chl₃

$$= \frac{(\text{Mg}^{2+}/(5))^5}{5/6} \frac{(\text{Al}/(5))}{1/6}$$

$$= (3.19/5)^5 (1.1)$$

$$= 0.12$$

Activity of clinocllore in chl₄

$$= (1.58/5)^5 (1.36)$$

$$= .004$$

Activity of tremolite in actinolite
(after Skippen and Carmichael (1977))

$$= (3-\text{Ca}-\text{Na}-\text{K})(\text{Ca}/2)^2 (\text{Mg}/5)^5 (\text{OH}/2)^2$$

$$= (3-1.56-0.07-0.08)(1.56/2)^2 (2.38/5)^5$$

$$= 0.02$$

Activity of clinozoisite in epidote

$$(\text{Al}/3)^3$$

$$= (2.02)^3$$

$$(3)$$

$$= 0.29$$

Activity of calcite

(after Skippen and Carmichael (1977))

$$= (\text{Ca})$$

$$= 0.96$$

Activity of dolomite in ankerite

$$= (\text{Mg})$$

$$= 0.43$$

Activity of muscovite

$a_{\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2}$
= (K)
= 0.80

Activity of paragonite

$a_{\text{NaAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2}$
= (Na)
= 0.84

Activity of albite

$a_{\text{NaAlSi}_3\text{O}_8}$
= (Na)
= 0.96

95°41'42"

51°01'47"

R I

0 100 200 300 metres

0 100 200 300 metres

95°36'36"

51°01'47"

LIMIT

R

I

OF

ank
py

ank
py
Au

ank

64

45

5c

5c

5c

5c

LIMIT

ank py

TAILINGS POND

OF

Hydro

Windsock Island

L A K E

SYMBOLS

	Geological boundary (defined, approximate)
	Bedding (tops known, unknown, dip inclined, vertical, unknown)
	Flow contact (tops unknown)
	Primary foliation with lineation, secondary foliation
	Shear foliation with lineation
	Shear zone
	Quartz vein
	Trench
	Shaft
	Outcrop
	Road
	drillhole
	cc calcite
	ank ankerite
	py pyrite
	Au gold

RICE LAKE GROUP DYKES

- 7** Feldspar porph
6 Diabase

GABBROIC SILLS

- 5** a) Gabbro
b) Melagabbro
c) Leucogabbro

VOLCANIC ROCKS

- 4** Dacite: plagioc
3 Basalt: a) pilló
b) pilló
c) mass

LEGEND

GROUP

spar porphyry

ase

S

abbro

elagabbro

eucogabbro

CKS

te: plagioclase-phyric tuff, breccia

lt: a) pillowed

b) pillow breccia

c) massive

Figure 2a: Geology of the San Antonio Mine a

51°00'35"

95°41'42"

Windsock Isla

CC.
x 5a

MAPPING

5c

5c

L

A

K

area, Rice Lake

Windsock Island

5b

48

5b

L

A

K

E

5c

5c

Primary foliation with lineation, secondary foliation

Shear foliation with lineation

Shear zone

Quartz vein

drillhole

Trench

cc

calcite

Shaft

ank

ankerite

Outcrop

py

pyrite

Road

Au

gold

Swamp

Primary foliation with lineation, secondary foliation

Shear foliation with lineation

Shear zone

Quartz vein

Trench

Shaft

Outcrop

Road

Swamp

drillhole

cc

calcite

ank

ankerite

py

pyrite

Au

gold

[5]

a) Ga

b) Me

c) Le

VOLCANIC RO

[4]

Dacit

[3]

Basa

[2]

Andes

[1]

Rhyoda

bbro

lagabbro

ucogabbro

KS

e: plagioclase-phyric tuff, breccia

t: a) pillowed

b) pillow breccia

c) massive

ite: tuff, lapilli tuff

icite: tuff, breccia

51°00'35"

95°36'36"

51 01'47"

85 41'42"

87-265

87-267

87-268

87-269

85-102

87-263

87-264

85-406

85-148, 149

87-501, 502

RICE

87-509

87-265

HIGHWAY

304

SAN ANTONIO
MINE

LIMIT

87-507,508

87-503 - 505

87-506

87-291 - 293

87-294 to 299 c

85-437

87-500

87-262

87-290

AND

OF

MAPPING

87-426

87-547

87-546

87-528(North)

to

87-537(South)

87-542

87-543

87-541

87-540

87-253

87-254

87-255

87-288

87-287

87-286

87-289

87-272

87-273

to

87-278

OF

87-279 280

MAPPING

87-426

87-547

87-546

87-528(North)

to

87-537(South)

87-542

87-543

87-541

87-253

87-540

87-254

87-255

87-273

to

87-278

MAPPING

OF

95 36'36"

51 01'47"

87-267

87-268

87-269

85-102

85-406

85-148,149

87-501,5

RICE

87-509

5° 00' 35"

95° 41' 42"

SAN ANTONIO
MINE

LIMIT

502

87-507,508

87-503 - 505

87-506

87-291 - 293

HARES

ISLAND

87-294 to 299c

85-437

87 500

85-418

85-419

LAKE

87 2

87 2

ANTONIO
MINE

LIMIT

87-507,508

87-503 - 505

87-506

87-291 - 293

87-294 to 299 c

85-437

87-500

87-290

87-286

87-262

87-283,284

85-418

85-419

87-270

87-271

85-424(north)

to

85-434(South)

LAKE

MAPPING

OF

87-426

87-547

87-546

87-528(North)

to

87-537(South)

87-542

87-543

87-541

87-253

87-540

87-254

87-255

87-288

87-287

87-289

7-272

87-273

to

87-278

87-279,280

37-285

87-281

POWER

LINE

LIMIT

OF

Figure 2b: San

all san

Sample Location Map-surface

sample numbers contain pea

51 00'35"

95 36'36"

4 of/de 4

Microl

85-1027

85-1025

86-1023

A'

85d-010
85d-011

85d-007'
85d-008

86-010-015

86-003
86-004
86-005
86-006

86-008
86-007

86-019
86-020
86-022
86-023
86-024

LEVEL 6

85-001

85-1020

85-1019

A

85-1027

85-1025

86-1023

A'

86-036

86-035

86-034

86-033

86-032

86-031

86-030

86-029

86-028

86-44-49

50-052

86-053

86-062

86-063

LEVEL 6

001

85-1020

85-1019

A

LEVEL 7

6-050-052

86-053

-070

53

LEVEL 7

86-066

36-069

LEVEL 8

FIGURE 2c

: Sample location map: San Antonio Mine (Upper

all sample numbers contain pea

ple location map: San Antonio Mine (Upper Levels)

numbers contain pea

LEVEL 8

FIGURE 2d: Sample location map: San A

all sample numbers contain pea

Stockwork-type vein

Shear-type vein

SE dippers

130-vein

Antonio Mine: (Lower Levels)

LEVEL 13

85-1742-004 to 016

A hand-drawn map on a piece of paper. The map shows a terrain with several contour lines. A path or road is drawn across the middle of the map, with several points marked along it. The points are labeled with numbers: 85-1742-004 to 016, 85-1110, 85-1109, and 85-1108. The path is drawn with a series of connected line segments, some of which are shaded with diagonal lines. There are also several small, dark, rectangular shapes scattered along the path, possibly representing buildings or other structures. The map is drawn on a piece of paper with a vertical line on the left side and a horizontal line at the bottom.

85-1110

85-1109

85-1108

LEVEL 17

LEVEL 17

85-1113

85-1112

85-1111

LEVEL 26

END

1 1 | 0 7 | 8 9

FIN