THE UNIVERSITY OF CALGARY

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ORIGIN OF COLUMNAR JOINTING IN RECENT BASALTIC FLOWS, GARIBALDI AREA, SOUTHWEST BRITISH COLUMBIA

· · by

LINDA J. LEE

A THESIS

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DEPARTMENT OF GEOLOGY AND GEOPHYSICS

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FACULTY OF GRADUATE STUDIES.

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Origin of Columnar Jointing in Recent Basaltic Flows, Garibaldi Area, Southwest British Columbia" submitted by Linda Jean Lee in partial fulfillment of the requirements for the degree of Master of Science.

Supervisor, Dr. J.W. Nicholls Department of Geology and Geophysics

. C. Wholland

N.C. Wardlaw Department of Geology and Geophysics

Simony_

Department of Geology and Geophysics

Kerr Ken

K.A. Kerr Department of Chemistry

J.K. Russell University of British Columbia

March 10, 1988

ABSTRACT

Columnar joints are structures which occur most frequently in basic lava flows and shallow intrusions. A number of different hypotheses have been proposed to explain the origin of columnar joints. The most widely accepted theory suggests that the columns form by contraction during cooling. It has also been proposed that thermal convection currents are in motion as the magma cools and that the columns are images of these convection cells. Recent studies on double-diffusive convection have resulted in the development of a third hypothesis for the origin of columnar joints. According to the third theory, the combined effect of temperature gradients and chemical gradients acting of melt density result in long, fingerlike convection cells which define the boundaries of the columnar joints. Later in the cooling process, contraction causes the joints to form along these boundaries.

Recent alkali olivine basalt flows in the Garibaldi Area of British Columbia exhibit abundant columnar jointing. Flows showing typical twoand three-tiered arrangements of joints can also be seen. Basaltic flows range in thickness from approximately 1 to 10 metres and occurrences of columnar jointing in the region are varied. Shapes and sizes of columns and the degree to which they are developed change markedly among flows. The presence and spacing of chisel structures is also variable.

The electron microprobe was used in conjunction with standard thin section examination and wet chemical techniques to provide detailed

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physical, petrographic, mineralogical and chemical studies of samples from a number of different jointed flows. The data caused the theory of simple convection to be rejected and found very little evidence to support a double-diffusive origin to the columns. A purely contractive origin for the joints is favored by the data.

Mathematical modelling of the cooling of a typical flow allowed calculations of the Rayleigh number for a range of flow thicknesses. Theoretically, if a critical value of the Rayleigh number is exceeded, double-diffusive convection is possible, provided that this value is exceeded for sufficient time to establish the convective currents. Calculations showed that such a process could, in theory, occur in flows whose thickness was greater than 2 metres.

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I - INTRODUCTION

Columnar joints are structures whose origin is most often attributed to contraction during the cooling of the rock mass. Prismatic columns are defined by the joints. These columns are generally much longer than they are wide and show a continuous range of sizes, as well as a range in the number of sides of the column. Most commonly the columns have five or six sides.

Columnar joints occur most frequently in basic lava flows and shallow intrusions. Some intermediate and acidic flows have this kind of jointing, however, as do certain sedimentary units which are adjacent to igneous intrusions.

The fractures which define the polygonal outline of the column are dominant. The column may display secondary cross-fractures which lie in a plane approximately normal to the long axis of the column. These fractures generally do not pass from one column to another, although in a few cases they have been reported to do so (Spry, 1962). The crossjoints may be planar joints, perpendicular or oblique to the axis of the prism, or they may be curved joints. In the later case they are refered to as ball and socket joints and may be either concave upwards or downwards (James, 1920; Spry, 1962). The cross-joints are irregularly spaced and are not always visible, being much less prominent than the column itself. In places where the cross-joints are close together and have been affected by weathering, the result is a "Dutch cheese" structure, illustrated by James (1920).

The sides of the columns are often marked by chisel structures (Figure 1). These structures consist of a basal line, perpendicular to the length of the column, which circumscribes the column. The basal lines are often found along the entire length of the column. Irregular curved lines which resemble the markings left by a chisel may be seen between these horizontal lines (James, 1920; Spry, 1962).

Tomkeieff (1940) observed that columnar jointing in the Giant's Causeway in Ireland could be divided into three distinct zones. The lower zone consisted of regular, straight, vertical columns, which he termed the colonnade. This zone was overlain by a haphazard arrangement of thinner columns, which was called the entablature. The upper zone was crudely columnar and hence was termed pseudocolumnar. Spry (1962) modified the terminology to lower colonnade, entablature, and upper colonnade (Figure 2).

There have been a large number of studies done on columnar jointing, and a number of different hypotheses have been proposed to explain the origin of these features. The earliest record of such a study is that by Watt (1804). Watt proposed a crystallization (or concretion) hypothesis for the origin of the columns. Such a hypothesis was based on his observations that a large mass of basalt which had been melted down in a furnace crystallized radially from a series of isolated, evenly spaced centers and a hexagonal network was formed by the intersection of these bundles.

Work in the late 1800's and early 1900's (Delesse, 1858; Thomson, 1863, 1887; Mallet, 1875; Jellet, 1879; O'Reilly, 1879; Iddings, 1886; James, 1920) resulted in a contraction hypothesis to explain the origin



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Figure 1. Schematic view of a column showing chisel structures. Chisel structures consist of regularly spaced horizontal striations on the column face (basal lines) and irregular curved lines between the basal lines which resemble the markings left by a chisel.



Figure 2. The typical zonation typically seen in jointed flows is seen in this section through a flow. The lower colonnade consists of regular, straight, vertical columns. Overlying this is a haphazard arrangement of thinner columns, the entablature. The upper colonnade is crudely columnar to well developed.

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of columnar jointing. The contraction hypothesis proposed that the major controlling factor in the formation of the columns was the thermal stresses which resulted from contraction during cooling. The attitude, size, shape and regularity of the columns depend on such factors as the viscosity, temperature and homogeneity of the lava, and the rate and regularity of cooling. James (1920) gives a summary of work on columnar jointing to this point.

A comprehensive study of columnar jointing was done by Tomkeieff (1940). Tomkeieff's paper reviews the history of investigation of the subject as well as discussing a number of field observations of the joints of the Giant's Causeway in northern Ireland. The paper also discusses the petrography and chemistry of these lavas and attempts to relate them to the jointing and its origin. Tomkeieff (1940) proposes a detailed, but non-mathematical contraction hypothesis for the origin of the joints.

Spry (1962) provided another study on the origin of columnar jointing. He also proposed a contraction origin for the joints. His hypothesis is somewhat more advanced and mathematical than that of Tomkeieff (1940).

Early observations of convection phenomena were described by Weber (1855) and Thomson (1882). Thorough investigation of convection by Benard (1901) and Dauzere (1907, 1908) showed that a polygonal pattern can be set up in a thin layer of liquid, large in its lateral extent, when the liquid is losing heat from its upper surface. The similarity between the cells produced in these studies and columnar joints in igneous rocks was deemed significant. As a result, a convection

hypothesis for the origin of the joints was proposed (Benard, 1901; Dauzere, 1907, 1908; and Sosman, 1916). Sosman (1916) proposed that if convection cells could be set up in a cooling body of magma, and if these cells left a permanent record in the solid rock, that subsequent contraction of the rock could cause cracking along the boundaries of the cells. Evidence of these convection currents may be preserved as variations within the columns, such as in the distribution of phenocrysts.

At most, only some columnar joints can be attributed to a convective origin. In dikes, for instance, joints are oriented perpendicular to the walls of the dike and result from thermal stresses. Columnar jointing can also be produced in sandstone units adjacent to intrusive contacts, again resulting from the thermal stress. Sosman (1916) agreed that certain columns could definitely be attributed to a contraction origin.

Several authors (eg. Peterlongo, 1951; Lafeber, 1956) have reported chemical, physical or petrographic variations within individual columns. The specific observations made by these authors will be discussed in detail in a later section. Such variations tend to support the idea that convection occurred in the cooling lava. Thermal convection cells, however, typically have widths much greater than heights while basalt columns are generally very long and narrow (Sosman, 1916). This has been the primary reason for the rejection of the thermal convection theory by later workers (eg. Spry, 1962; Kantha, 1981).

More recently there has been renewed interest on the subject of columnar jointing. The generally accepted contraction hypothesis has

been replaced by a hypothesis involving double-diffusive convection (Kantha, 1981; Hsui, 1982). Double diffusion can occur if two or more components in a liquid possess different diffusivities and if these components have opposing effects on the vertical density gradient. It has been shown that long narrow convection cells can be set up in liquids as a result of the different rates of chemical and thermal diffusion. It is proposed that this process is responsible for the development of columnar joints. Such a hypothesis is consistent with the evidence for convection mentioned earlier and can also account for the tiered structure commonly seen in jointed flows.

Long and Wood (1986) reject the double-diffusive theory, however, on the basis of their studies of Columbia River basalts. Textural evidence in the flows led Long and Wood (1986) to propose that influx of water was responsible for the tiered structure of the flows.

Although considerable work has been conducted on columnar jointing and the origin of such joints there remain many unanswered questions. The purpose of this study is to describe the external and internal nature of columnar jointing in basaltic flows from the Garibaldi area of southwest British Columbia and to use this evidence to constrain and test theories as to the origin of the columns. The accepted theories should explain:

- why columnar joints may be well developed in some areas but not in others.
- the variations in size and shape of columns which occur. Variations both within individual flows and between flows should be explained.
- 3) the nature of the basal line surface and why chisel structures may

be absent in certain areas. Variations in the spacing of basal lines should also be explained.

- any changes in the mineralogy, mode or texture which are found to occur in the flows or in individual columns.
- 5) the vertical zonation of columnar jointing which occurs in the flows.

Studies with the electron microprobe and optical microscope provide data to answer these questions. Accurate mineral analyses and modal determinations can be obtained using this equipment. These properties of the rock are important characteristics which can be used to compare different samples. The whole rock chemistry will reveal any bulk chemical variations in the flows. A large number of samples obtained from areas of different jointing styles will reveal any relationship between the different jointing styles and the properties of the rock (such as mineralogy, mode and texture). Such a relationship will constrain interpretations as to the jointing process.

II - FIELD WORK AND ANALYTICAL METHODS

Field Work

The Garibaldi area is located in southwestern British Columbia, in the southern part of the Coast Mountains (Figure 3). Access to the area is by Highway 99 from Vancouver, a distance of approximately 100 kilometres. Highway and railway cuts as well as numerous gravel roads and trails provide access to the rocks of interest.

At least thirty different volcanic centers exist in the vicinity of Mount Garibaldi (about 100 square kilometre area) (Mathews, 1957). The area was recently mapped in detail by Green (1977).

The lava flows studied are members of the Garibaldi Group. This group consists of basalts through dacites belonging to the calc-alkaline suite (Mathews, 1958). The Pleistocene to Recent lavas which occupy the Cheakamus River and Callaghan Creek valleys in the study area have been termed the Cheakamus Valley Basalts. Four episodes of volcanism are recognized in these lavas (Green, 1977). Well developed columnar jointing is displayed in the Recent lavas and many varied occurrences of columnar jointing are present. Locations of the flows studied are shown in Figure 3.

The first flow studied, called here Flow 1, is a complete cross-section of a flow exposed along the railway, near the Stanley Lake turnoff (Figure 3). The flow has a width of 12.4 m and an average height of about 2 m. The bottom of the flow is very well defined as the underlying rocks are darker in colour and more pumiceous; a carbonaceous



Figure 3. Sample location map of the Garibaldi Area of British Columbia. Approximate locations of the flows studied are shown.

layer also separates this flow from the underlying flow. The top of the flow corresponds to the ground surface. Columnar joints are poorly developed with an average width of approximately 1 m. Chisel structures are moderately well developed throughout the flow with a spacing of 6 -10 cm between basal lines. A map was made of the exposed surface, showing jointing and sample locations. This section is shown in Figure 4. Plate 1-a also shows this flow. A comparison of the photograph to the map may be helpful to the reader. Samples later chosen for detailed studies are shown on the plates. Examination of these figures shows that the width of the joints seems to increase at the edges of the flow.

Flow 2 is located in a quarry area on the eastern side of the highway, just past the Callaghan Creek/Northair Mines turnoff (Figure 3). The flow is at least 100 m wide by 8 m high in the exposed section and exhibits well developed columnar jointing. Columns average about 50 cm across. The columns are broken by a set of regularly spaced cross-fractures, producing the ball and socket joints which Thomson (1887) and many others have described (Plate 1-b). The distance between these cross-fractures is approximately 15 cm. The cross-fracturing of the columns made it relatively easy to obtain samples from different areas of individual columns. Samples were taken from different 'discs' within individual columns (here a disc refers to the volumne of rock between two cross-fractures, and hence between two basal lines) and at various places in the discs in order to detect any changes from column to column, or within individual columns.

Figures 5 and 6 are exploded sketches of two columns from which a total of eleven samples were obtained. The relative positions of the



Figure 4. A cross-section of Flow 1 showing columnar jointing and sample locations. The outer edges of columns are shown with a solid line, while inner edges correspond to dashed lines. A comparison with Plate 1-a may be helpful.

- PLATE 1-a: Cross-section of Flow 1 showing sample locations. The scale in the photograph is 2 m in height.
- PLATE 1-b: Well developed columnar jointing and chisel structures in Flow 2. Note the prominent cross-fracturing along basal lines. See hammer for scale.
- PLATE 1-c: Unusual jointing style in Flow 3. Note the lack of columnar jointing with prominent basal lines. The scale in the photograph is 2 m in height. Sample locations are illustrated on the photograph.
- PLATE 1-d: Sample locations in Flow 4. The width of the photograph is about 16 metres.









Not to scale

Figure 5. An exploded sketch of Column 1, from Flow 2. The upper disc, from which samples 02-01, 02-02, and 02-03 were taken averages 12 cm in thickness, while the lower disc is 15 cm thick.



Not to scale

Figure 6. An exploded sketch of Column 2, from Flow 2. The upper disc is 12 cm in thickness while the lower one is 15 cm thick.

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samples are illustrated in these figures. Note that the number of sides of the columns, the length of the sides and the interior angles of the column all may vary significantly along the length of the column (Figures 5 and 6).

An example of near nonexistent columnar joints is shown in Flow 3. A complete cross-section of the flow is exposed along the railway, about 400 m south of Flow 1 (Figure 3). The flow is approximately 125 m in width and varies in thickness from about 1.5 m at the north end, to approximately 6 m at the south. Throughout the flow, columnar joints are poorly developed, and at the north end they are practically nonexistent. The chisel structures, however, are very prominent at the north end of the flow, with an average spacing of about 16 cm between basal lines. The top of the flow corresponds to the ground surface, while a carbonaceous layer separates Flow 3 from the darker, more pumiceous underlying flow. Plate 1-c illustrates the unusual jointing displayed in the area. Three samples were taken from the northern end of Flow 3, as shown in Plate 1-c.

A gravel logging road leaves the highway just north of the Callaghan Creek bridge, heading in a south-easterly direction. Flow 4 is located 2.5 kilometres along this road, on the western side (Figure 3). The flow is approximately 20 m wide and up to 8 m thick and is exposed by the road along its length for several hundred metres. The section mapped is at the southernmost point exposed. The top of the flow corresponds to the ground surface, however the base of the flow is not visible due to the broken nature of the rock. In the section sampled, the columns are very well developed, averaging about 60 cm across. Basal lines are prominent with an average spacing of about 2 cm; some cracking has occurred along these lines. The narrow spacing of the chisel structures displayed at this location is quite unusual. An average spacing of basal joints from other flows in the area is approximately 12 cm. A total of nine samples were taken along the length of the flow. A map was made of the exposed surface to show the development of jointing and the sample locations (Figure 7). Plate 1-d also shows the sample locations for this flow.

Near the southern end of Daisy Lake one can get a very good plan view of columnar jointing by walking the B.C. Hydro right of way (Plate 2-a). Flow 5 is located at the turnoff to Pinecrest Estates, while Flow 6 is located several kilometres south of this, near the Daisy Lake Dam (Figure 3). Flows 5 and 6 were chosen in order to make measurements of the size and shape, in plan view, of the columns. It is difficult to estimate the thickness of the flow at the northern location, as it is not cut by the road. To the south, however, the flow is exposed by the highway and ranges up to 6 m in thickness. The exposed section also shows fairly well developed columnar joints. Chisel structures are not ubiquitous, but where present the basal lines have an average spacing of about 15 cm. Between the two locations, two hundred columns were measured. The number of sides and the maximum dimension of the columns was recorded. This information is tabulated in a following section. Samples were also taken from columns with different sizes and shapes; four samples were taken from each location. The number of sides and the maximum dimension of the columns sampled are shown, along with the sample numbers in Table 1.



- outer edge of column

--- Inner edge of column

... rubbly section - unmapped



Figure 7. A section along the length of Flow 4 showing columnar jointing and sample locations. Outer edges of columns are shown by solid lines and dashed lines represent inner edges. Sections of the flow which were composed of broken, talus-like material are shown by a stippled pattern.

- PLATE 2-a: Plan view of basaltic columns. The average width of the columns is about 400 cm.
- PLATE 2-b: Highway exposure of a flow showing the three zones of columnar jointing described by Tomkeieff (1940).

A = upper colonnade

- B = entablature
- C = lower colonnade

The width of the photograph is about 50 m.

PLATE 2-c: Zonation of columnar jointing in Flow 7.

- A = entablature
- B = lower colonnade

The scale in the photograph is 2 m in height.

PLATE 2-d: Well developed columns and chisel structures in Flow 8. The basal lines are spaced about 6 cm apart.



TABLE 1

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SAMPLES FROM FLOWS 5 AND 6

Sample	Number of sides	Maximum size
	of column	of column (cm)
05-01	5	400
05-02	6	300
05-03	5	260
05-04	4	460
06-01	6	260
06-02	5	300
06-03	5	360
06-04	,5	380

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The zonation of jointing which Tomkeieff (1940) proposed, and which was described previously, can be seen at various locations in the Garibaldi area. One of the most impressive examples is a highway exposure, located about 500 m north of the Black Tusk Village entrance. The flow is large, approximately 70 m wide by 10 m high, and shows the three characteristic zones of jointing (Plate 2-b). The location and large size of the flow makes it very difficult to sample. A smaller flow, Flow 7, was therefore chosen in order to obtain samples from the different zones seen. Flow 7 is exposed along the railway, directly opposite the Callaghan Creek/Northair Mines turnoff (Figure 3). The flow is 3 to 3.5 m in height and can be followed for approximately 50 m along the railway. Two zones, the lower colonnade and the entablature. are visible (Plate 2-c). The exposed thickness of the lower colonnade is approximately 2 m. This zone consists of well developed regular columns averaging 70 cm across. Chisel structures are absent. There is an abrupt transition to the overlying entablature, a zone of very poor jointing. The upper boundary of the entablature corresponds to the ground surface. A total of seven different samples were taken from various places in the two zones (Figure 8).

Flow 8 is a large flow, located in the same rock quarry area as Flow 2 (Figure 3). At this particular location the columns are well developed with prominent basal lines (Plate 2-d). Two different samples were taken from the same column which measured approximately 50 cm across. The samples obtained each contained more than one basal line. These lines have an average spacing of approximately 5.5 cm. From such samples a series of thin sections and microprobe mounts were cut with


Figure 8. Section through Flow 7 showing the zonation of jointing and locations of samples. Outer edges of columns are shown in solid and inner edges in dashed lines.

different spatial relationships to the basal line in order to determine the nature of this surface. Specific locations of such sections will be described in Chapter IV. It should be noted that the basal lines are very prominent on the exposed surfaces of the columns and often appear to be raised up in relief. On freshly broken surfaces, however, the lines cannot be seen.

A total of fifty-three samples of representative, unaltered lava were collected. Forty of these samples were later selected for more detailed analysis.

Sample Preparation and Analytical Methods

Mineral analyses were obtained using an ARL SEMQ electron microprobe, operated with an accelerating voltage of 15 kilovolts and a beam current of 300 microamps. Twenty second counting times were used. A list of the electron microprobe standards used for the analyses is contained in Appendix 1.

Cores and rims of minerals were analyzed separately, if size permitted. From each phenocryst eight spot analyses (four from rims, four from cores) were taken. Two spot analyses were taken from groundmass phases, if possible. Plagioclase was the only groundmass phase which allowed separate analyses from cores and rims. A minimum of twenty spot analyses were obtained from each phase in every sample analyzed. In cases where cores and rims were analyzed separately, at least twenty analyses of each were obtained. Difficulty was encountered

in obtaining good analyses for Fe-Ti oxide phases due to the small size of these grains. This is especially true of the rhombohedral phase because of the needle-like occurrence of these grains. In such cases, twenty good mineral analyses may not have been achieved.

Mineral analyses collected with the electron microprobe were corrected using the methods of Bence and Albee (1968) and Albee and Ray (1970). Total iron detected by the microprobe is quoted as FeO. In the analyses of Fe-Ti oxide phases percent of FeO and Fe₂O₃ have been recalculated from the amount of total iron.

Values for the detection limit and precision of the elements analyzed for are listed in Appendix 3 (with the mineral analyses).

Modal analyses for the rocks studied were obtained using an automated set-up with the electron microprobe. With such a technique, minerals are identified by comparing the rankings of x-ray intensities from the spot analyses to rankings of a set of standards. The porosity of the sample can also be determined with this set-up. If the total number of counts obtained for each spot is less than a minimum value then the spot is classified as a hole. A detailed description of this procedure is given by Nicholls and Stout (1986).

A number of factors influence the accuracy with which minerals can be identified. These include the choice of elements, the background values for the x-ray lines of these elements, and the relative sizes of the electron beam and the mineral grain.

In this study a one second counting time was used with an increment step of 200 microns. The smallest possible beam size was used since the grain size in the groundmass of the samples is very small. The number of spots counted on each sample was variable as a result of varying sample sizes, among other things. The actual number of spots counted ranged from 4600 to 7400; an average number of counts of approximately 5500 was achieved.

The eight elements which were selected for the collection of x-rays were Si, Al, Fe, Mg, Ca, Ti, Na, and Mn. In retrospect, a better choice of elements would have been one which included Cr in place of Mn. This would have enabled the Cr-rich spinel to be distinguished from the magnetite-ulvospinel phase.

Six different mineral phases, plagioclase, olivine, augite, apatite and two Fe-Ti oxide phases, a magnetite-ulvospinel phase and a hematite-ilmenite phase were identified. Modes for these six minerals were determined using the electron microscope. Using the automated point counting technique it is not possible to distinguish between groundmass crystals and phenocrysts. In the samples studied, two phenocryst phases were present, plagioclase and olivine. Standard point counting with an optical microscope was used in order to determine the percentages of phenocrysts versus groundmass for these two minerals. For every sample, 3000 points were counted.

The precision of the mode was estimated by running triple runs on the same sample with the electron microprobe. This method was also used to estimate the precision of the standard point counting method used in determining the percentages of phenocrysts. The reproducibility in determining the percentages of phenocrysts is poor, due to the large size of the phenocrysts and the glomeroporphyritic nature of the samples. This large error must be incorporated into that quoted for the

groundmass. It should be noted, however, that the error in the total percentage of minerals which occur both as phenocrysts and in the groundmass is much less that that quoted for either phenocryst or groundmass phases individually.

When the minerals have a very small grain size and when the phases are present only in small amounts, as is the case with the Fe-Ti oxide phases and with apatite, the precision becomes very poor. This sharp decrease in the precision results from the decreased probability that the electron beam will sit essentially on the grain and hence give a good analysis.

Approximate relative errors (volume percent) were found to be as follows: total plagioclase = 3.3%; total olivine = 3.3%; plagioclase phenocrysts = 8.6%; olivine phenocrysts = 8.2%; augite = 7.5%; magnetite-ulvospinel = 30%; hematite-ilmenite = 70%; apatite = 200%. Since these are relative errors the error in the mode is a function of the amount of the phase present. These relative errors have been translated into absolute errors. The maximum absolute error for each phase is quoted for the eight different flows studied in the listing of the sample modes.

Whole rock analyses for six samples were measured using the standard wet chemical techniques described in Carmichael <u>et al.</u> (1968). Two standard deviation analytical uncertainties (absolute weight percent) for the different elements using these wet chemical techniques are as follows: $SiO_2 = 0.02$; $Al_2O_3 = 0.02$; $TiO_2 = 0.02$; $Fe_2O_3 = 0.04$; FeO = 0.04; MnO = 0.002; $P_2O_5 = 0.006$; CaO = 0.06; MgO = 0.06; Na₂O = 0.02-0.04; K₂O = 0.02; H₂O⁺ = 0.02; H₂O⁻ = 0.02.

III - CHEMISTRY

Whole rock chemical analyses representing two of the flows studied were determined by wet chemical methods. These analyses are listed in Appendix 2.

Average chemical analyses were used to compute CIPW norms. The rocks are hypersthene normative with varying amounts of normative olivine.

Total alkalies of the samples analyzed have been plotted against silica in Figure 9. The field boundaries between the tholeiite, high-alumina basalt and alkali basalt suites determined by Kuno (1968) are shown on the diagram. The samples analyzed fall near the boundary of the alkali basalt and high-alumina basalt suites.



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Figure 9. $(Na_20 + K_20)$ versus SiO₂. The field boundaries between tholeite, high-alumina basalt and alkali basalt suites determined by Kuno (1968) are shown. Values determined by wet chemistry are plotted and fall near the boundary of the alkali basalt and high-alumina basalt suites.

IV - PETROGRAPHY AND MINERALOGY OF THE LAVAS

Petrography

The samples show typical basaltic textures with phenocrysts of plagioclase and olivine in a groundmass of plagioclase, olivine, augite, Fe-Ti oxides (both spinel and rhombohedral series are present), and apatite. Small amounts of glass are also present in the groundmass of the samples. A minor amount of a Cr-rich spinel phase was detected in the groundmass in some cases. Plagioclase is the dominant phenocryst phase in all the flows studied. Detailed textural descriptions of individual flows are included in Appendix 4. Variations within individual flows are discussed later in this chapter.

Only a single pyroxene (augite) was detected in the groundmass of the samples studied. This is consistent with the findings of Green (1977). J. K. Russell (pers. comm.), however, identified a calcium-poor clinopyroxene (pigeonite) as a result of electron microprobe analyses of samples of the Cheakamus Valley basalt. The samples in which pigeonite was detected were obtained nearby samples analyzed in this study in which only a single clinopyroxene was found. Fiesinger (1975) did not detect this second pyroxene in his study of the Cheakamus Valley basalts, however reanalysis of his rocks by Nicholls <u>et al.</u> (1982) revealed minor pigeonite in the groundmass. It is suspected that the presence of the calcium-poor pyroxene is a very localized phenomena resulting from varied cooling conditions.

Modal analyses for the samples studied are given in Table 2. Values

TABLE 2 MODAL ANALYSES (VOLUME %)

SAMPLE	PHENOCRY	<u>'STS</u>	GROUNDMA						
Flow 1	Plag (.6)	<u> 0liv (.6)</u>	Plag (2.4)	Augite (1.7)	<u>Oliv (.9)</u>	Mag (.5)	Ilm (1.3)	Apat (1.2)	Porosity
01-02	7.2	6.5	52.5	21.8	8.6	1.5	1.5	0.3	22.75
01-04	6.6	7.1	55.4	19.1	8.6	1.0	1.8	0.4	15.44
01-05	6.5	6.6	53.7	22.1	8.3	1.7	1.0	0.1	32.55
01-06	7.1	7.5	54.4	20.1	7.2	1.3	1.9	0.6	23.48
Flow 2	Plag (.9)	0liv (.6)	Plag (2.8)	Augite (1.5)	0liv (.8)	Mag (.7)	Ilm (1.0)	Apat (1.8)	
02-01	8.4	5.6	55.4	20.3	7.3	1.7	1.2	0.2	22.77
02-02	9.0	5.7	56.0	19.4	6.9	1.8	1.1	0.1	17.40
02-03	8.1	5.7	58.2	20.1	7.4	0.4	0.0	0.1	19.20
02-04	9.7	6.8	55.4	18.8	6.7	1.1	1.4	0.1	20.41
02-05	9.9	5.8	57.0	18.0	6.6	1.4	1.3	0.1	19.50
02-06	9.7	7.0	56.2	17.6	6.7	2.0	0.9	0.0	17.76
02-07	8.6	6.0	56.3	19.4	7.0	2.0	0.9	0.0	17.82
02-08	7.0	6.1	56.8	19.6	7.1	2.2	0.8	0.0	16.84
02-09	9.8	6.5	54.2	19.9	6.9	1.4	1.3	0.1	18.16
02-10	7.4	7.6	58.3	17.7	6.8	1.2	1.0	0.9	16.40
02-11	7.8	6.3	56.6	19.5	6.5	1.9	1.4	0.0	15.57
-1 -7	-1		-1 -0						
FLOW 3	Plag (./)	<u>(.5)</u>	Plag (2.5)	Augite (1.7)		<u>Mag (.4)</u>	<u>Ilm (1.4)</u>	Apat (1.4)	Porosity
03-01	7.8	6.2	53.2	22.2	7.4	1.3	1.3	0.6	19.98
03-02	7.1	6.5	54.7	19.8	8.4	0.9	2.0	0.7	23.94
05-05	7.0	6.6	53.7	19.8	10.0	1.4	1.5	0.2	23.22
Flow 4	Plag (1.2)	Oliv (.7)	Plag (2.9)	Augite (1.4)	Oliv (.8)	Mag (.5)	Ilm (.9)	Apat (.8)	Porosity
04-01	13.9	8.7	52.0	18.6	4.1	1.7	0.9	0.1	17.54
04-05	13.2	7.5	52.8	19.1	4.6	1.4	1.1	0.4	18.69
04-08	12.2	6.6	54.4	19.0	4.8	1.3	1.3	0.4	18.66

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TABLE 2, cont...

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SAMPLE	PHENOC	RYSTS		GROUNDMASS					
Flow 5	Plag (.9)	<u> Oliv (.6)</u>	Plag (2.7)	Augite (1.4)	Oliv (.9)	Mag (.5)	Ilm (1.0)	Apat (.2)	Porosity
05-01	10.2	6.6	55.2	16.7	9.1	1.1	0.9	0.1	16.45
05-02	10.2	6.2	53.4	19.2	8.4	1.5	1.0	0.0	16.28
05-03	8.8	6.1	55.3	17.7	9.2	1.4	1.4	0.0	16.41
05-04	9.4	7.0	54.4	18.7	8.1	1.1	1.2	0.0	17.11
Flow 6	<u> Plag (.8)</u>	<u>Oliv (.6)</u>	Plag (2.6)	Augite (1.3)	Oliv (.9)	Mag (.4)	Ilm (1.3)	Apat (.2)	Porosity
06-01	7.1	6.6	56.0	17.5	10.5	0.9	1.6	0.0	15.72
06-02	8.7	7.4	56.1	17.5	7.6	1.2	1.6	0.1	15.65
06-03	9.0	7.0	54.7	16.6	9.8	1.1	1.8	0.0	15.06
Flow 7	Plag (.9)	0liv (.6)	<u> Plag (2.7)</u>	Augite (1.5)	0līv (.8)	Mag (.8)	Ilm (1.0)	Apat (.8)	Porosity
07-01	10.0	6.6	54.8	17.9	7.7	1.8	0.9	0.4	18.68
07-02	8.8	6.1	53.1	20.4	8.6	2.0	1.0	0.0	22.97
07-03	10.1	6.5	55.2	17.9	7.3	2.2	0.8	0.1	16.74
07-04	9.9	6.5	53.6	20.1	5.6	2.8	1.0	0.0	24.62
07-05	9.5	6.5	54.3	20.2	6.0	1.9	1.4	0.3	21.68
07-06	10.1	7.4	53.9	20.2	5.5	1.6	1.1	0.2	17.87
Flow 8	Plag (.9)	Oliv (.6)	Plag (2.7)	Augite (1.5)	0liv (.8)	Mag (.7)	Ilm (.8)	Apat (1.0)	Porosity
08-01-1	9.9	6.6	55.2	18.4	6.8	1.7	0.8	0.5	19.05
08-01-2	9.1	7.3	53.9	20.2	5.8	2.2	1.2	0.3	16.48
08-01-3	9.1	7.4	55.6	19.4	5.4	1.8	1.0	0.2	19.24
08-01-4	10.6	6.4	52.2	19.7	7.5	1.8	1.2	0.5	20.96
08-01-5	5.0	5.7	64.0	17.3	5.4	1.8	0.7	0.2	16.83
08-01-6	11.0	7.1	52.5	19.8	6.7	1.6	1.1	0.3	16.31

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listed in parentheses next to the name of the phase are the approximate errors in the volume percent of that phase.

The abundant olivine present in the groundmass of the lavas suggests that the flows belong to the alkali olivine basalt suite. This classification is substantiated by Figure 9, a plot of total alkalies versus silica, in which the samples analyzed fall within the field boundary for alkali olivine basalts defined by Kuno (1968). Chemical analyses indicate hypersthene in the norm. This and the reported presence of pigeonite in the groundmass suggests that the rocks may belong to the tholeiite suite. The evidence to support the alkali olivine basalt classification seems to outweigh that contradicting it, however, so this nomenclature has been chosen.

Mineral Chemistry

Mineral analyses for the samples studied were obtained using an electron microprobe. Six mineral phases were analyzed. These phases were plagioclase, olivine, augite, a magnetite-ulvospinel phase, a hematite-ilmenite phase, and a Cr-rich spinel. Apatite and volcanic glass were not analyzed. Complete analyses for the phases studied are contained in Appendix 3. Variations within and between flows studied are summarized below. Complete mineralogical descriptions for each flow are included in Appendix 4.

All flows contained both a rhombohedral (hematite - ilmenite series) and spinel phase (magnetite - ulvospinel series) Fe-Ti oxide. A Cr-rich

spinel was also found. In many cases, the rhombohedral phase, which generally occurred as small needle-like crystals, was too small for accurate microprobe analyses. Where possible the analyses of coexisting phases were used to determine the temperature and oxygen fugacity of equilibrium of the two phases, using the curves derived experimentally by Buddington and Lindsley (1964). Bad ilmenite analyses, indicated by high Si content, tend to give a temperature which is too high using this method. It is therefore important to ensure that analyses used for this purpose are good.

FLOW 1 : Four samples from Flow 1, a small flow with only moderately well developed columnar jointing, were studied in detail, 01-02, 01-04, 01-05, and 01-06. These samples were obtained from different positions, both laterally and vertically, in the flow, and from various sizes of columns (see Figure 4, Plate 1-a).

> No obvious variations in mineralogy or texture were detected in Flow 1. Subtle variations which were noticed are, first, that olivine in sample 01-06 was richer in iron than that in other samples from the flow (Fo₅₄ versus Fo₅₉ for groundmass olivine and Fo₇₂ versus Fo₇₇ for cores of phenocrysts). Secondly, the pyroxene in sample 01-05 was less titaniferous that that in other samples (1.1% TiO₂ compared to 1.8% TiO₂ in other samples).

FLOW 2 : Flow 2 is a very large flow with extremely well developed columnar jointing (Plate 1-b). Eleven samples were taken from individual columns in the lower portion of the flow (Figures 5 and 6) and detailed analyses of all eleven samples were made.

> Several important variations were noted in the samples studied. Samples 02-01 and 02-06 (from the edges of columns) gave groundmass olivine compositions which were considerably more forsteritic than the average composition determined (Fo₇₂ versus Fo₆₇). The percentages of Fe-Ti oxides detected in sample 02-03 was much less than that in other samples. Microscopic examination reveals that the opaque phases in sample 02-03 also seem to be slightly smaller than in other samples.

<u>FLOW 3</u> : Flow 3 is a moderate sized flow with extremely well developed chisel structures but practically nonexistent columnar jointing. Three samples were obtained from the flow and all were studied in detail (Plate 1-c).

> Several textural and mineralogical variations were noted between the samples. Although the trachytic texture is never extremely well developed, an increase in the alignment of the plagioclase laths is seen. Sample 03-01 shows the poorest alignment of plagioclase laths while the texture is considerably better developed in sample 03-03.

Another textural variation which was noted is the occurrence of pyroxene as large optically continuous masses

enclosing other minerals in the groundmass. This effect was much more pronounced in sample 03-01 than in the other samples. Sample 03-01 also contains more augite than the other samples (22% compared to 20%). Analysis of the pyroxene in sample 03-03 showed it to be somewhat more titaniferous than that in samples 03-01 and 03-02.

The amount of glass present in the goundmass of the samples is also variable; sample 03-03 contains considerably less glass than the other samples. Sample 03-03 also has a higher temperature for the coexistence of magnetite and ilmenite than the other samples (1044°C versus 954°C).

FLOW 4 : Flow 4 was a moderate sized flow with well developed jointing and narrowly spaced (about 2 cm) chisel structures. Nine samples were taken from a section along the length of the flow (Figure 7, Plate 1-d). Three of these samples, 04-01, 04-05 and 04-08 were studied in detail.

> Minor variations were noted between the samples studied. The amount of glass present in the groundmass of 04-05 was less than that in the other samples. In addition, sample 04-05 contained plagioclase phenocrysts which were slightly more anorthite rich than those in other samples. The groundmass plagioclase was, however, slightly more albitic. Olivine phenocrysts in sample 04-01 were less forsteritic than those in other samples, while the groundmass olivine showed the opposite effect.

<u>FLOW 5</u> : Four samples were collected from the upper surface of Flow 5. The samples were taken from individual columns of different shapes and sizes, as listed in Table 1. All of these samples were studied in detail.

> Samples 05-02 and 05-04 are very similar in mineralogy and texture, however these samples show several distinctions from samples 05-01 and 05-03. Samples 05-02 and 05-04 contain a greater amount of augite and lesser groundmass olivine than do samples 05-01 and 05-03. In addition, samples 05-02 and 05-04 exhibit plagioclase phenocrysts with rims which are slightly more anorthite rich than those in other samples. Samples 05-02 and 05-04 also contain augite with less TiO_2 than that in samples 05-01 and 05-03 (1.6% versus 2.2%).

FLOW 6 : Four samples were obtained from this flow which showed well developed columnar joints. The samples were obtained from the upper surface of the flow, from individual columns of different shapes and sizes (Table 1). Three of these samples, 06-01, 06-02, and 06-03 were studied in detail.

> Sample 06-01 contains a smaller percentage of plagioclase phenocrysts than do the other samples. The plagioclase phenocrysts in sample 06-01 have more anorthite-rich rims while groundmass plagioclase laths have rims depleted in anorthite compared to those in other samples.

Other variations noted are the lesser amount of groundmass olivine in sample 06-02 (7.6% versus 10.2%) and the decreased

 TiO_2 content of the pyroxene in sample 06-03 (1.2% TiO_2 compared to an average of 1.9% for the other samples).

FLOW 7 : Flow 7 was a relatively small flow which displayed distinct entablature and lower colonnade zones (Plate 2-c). Seven different samples were taken from the two different zones. Six of these samples, 07-01 to 07-06, were studied in detail (Figure 8, Plate 2-c).

The amount of glass present was quite variable. Samples 07-01, 07-05 and 07-06 contained considerably more glass than did samples 07-02, 07-03 and 07-04. Other variations noted were the enrichment of groundmass olivine in sample 07-02 and the considerable variation in the composition of the groundmass olivine. Extreme compositions were shown by sample 07-05, in which olivine was analysed to be Fo_{55} , and sample 07-04, which contained groundmass olivine whose composition was Fo_{67} . In sample 07-05 plagioclase phenocrysts had rims of An_{64} while an average rim compositions for plagioclase phenocrysts in other samples was about An_{60} . Rims of groundmass plagioclase in sample 07-05 were slightly less anorthitic than those in other samples, however. A final variation which was noted was the small amount of pyroxene detected in samples 07-01 and 07-03 compared to other samples from the flow.

FLOW 8 : Six samples were studied from a single column averaging 50 cm across. Both columnar joints and chisel structures are well

developed in this large flow (Plate 2-d); the average spacing of the basal lines was about 5.5 cm.

Samples 08-01-1 and 08-01-2 were taken from a horizontal plane which contained the basal line. 08-01-1 was obtained at the column edge, where the line was visible. 08-01-2 was taken from the same plane, but from the interior of the column. Samples 08-01-3 and 08-01-4 were also taken in order to study the nature of the basal line. This time, however the samples were cut from a vertical plane, so as to span the basal line. Sample 08-01-3 was taken at the column edge while 08-01-4 is from the interior of the column. Finally, two samples, 08-01-5 and 08-01-6 were taken from a horizontal plane (parallel to the plane containing samples 08-01-1 and 08-01-2). In this case, however, the plane did not correspond to one containing a basal line, but rather to one half way between two adjacent lines. Again, sample 08-01-5 is obtained from the edge of the column, while 08-01-6 is from the interior. Figure 10 illustrates these sample locations.

Sample 08-01-5 displayed many features not apparent in the other sample. The most obvious of these were the markedly lower percentage of phenocrysts present. Sample 08-01-5 contained 5% plagioclase phenocrysts, compared to an average value of 10%, and 5.7% olivine phenocrysts, compared to about 7% in other samples. In addition, the olivine phenocrysts had distinctly more forsterite-rich rims in sample 08-01-5, though this effect was also noted in 08-01-1.





Figure 10. An exploded sketch of a columns from Flow 8 showing sample locations. Samples 08-01-1 and 08-01-2 were taken from the column edge and interior, respectively, in a horizontal plane containing a basal line. Samples 08-01-3 and 08-01-4 were taken a vertical plane spanning a basal line, from the columns edge and interior, respectively. Samples 08-01-5 and 08-01-6 were taken from a horizontal plane halfway between adjacent basal lines, from the column edges and interior, respectively.

The percentage of groundmass plagioclase in 08-01-5 is much greater than in the other samples from the column, while augite in the groundmass is depleted. A weak alignment of the plagioclase laths is shown in samples 08-01-3, 08-01-4, and 08-01-5. The occurrence of augite as large masses poikilitically enclosing other groundmass phases, is however, much more prominent in sample 08-01-5 than in other samples. In addition, the TiO₂ content of the pyroxene is considerably greater (2.4% compared to 1.1%). Finally, 08-01-5 contains less glass than do the other samples studied.

The composition of the groundmass olivine was found to vary significantly between samples (Fo₅₅ to Fo₆₅). Samples 08-01-1 and 08-01-4 had groundmass olivine with a composition of Fo₅₅ while olivine in the groundmass of 08-01-5 was Fo₆₅. Other samples had olivine compositions intermediate to these.

Minor variations were also noted in the compositions of groundmass plagioclase. Rims of plagioclase laths in 08-01-4 were depleted in anorthite, while cores of groundmass plaioclase in 08-01-1 showed similar effects.

The mineralogical and petrographic properties of the eight different flows studied are summarized in Table 3. The average composition and volume percent of each phase have been tabulated. Compositional ranges listed in the table are the average range of zoning for the flow. The temperature and oxygen fugacity for the coexistence of the spinel phase and the rhombohedral phase determined using the method of Buddington and Lindsley (1964) are also included in Table 3.

	FLOW 1		FLOW 2		FLOW 3		FLOW 4	
	<u>%</u>	Comp	%	Сотр	%	Comp	%	Comp
Phenocrysts								
Plag	7	An63-61	9	An63-61	7	An63-59	13	An61-57
Olivine	7	F076-69	6	Fo78-75	6	Fo71-66	8	F067-64
Groundmass								
Plag	54	An54-50	56	An53-49	54	An54-50	53	An53-48
Augite	21		19		21		19	
Olivine	8	Fo58	7	F067	9	Fo49	5	Fo57
Magnetite	1.5		1.6		1.2		1.5	
Ilmenite	1.5		1.0		1.6		· 1.1	
Apatite	•		-		-		-	
Cr-spinel	-		-		-		-	
Glass	•		-		-		-	
Temp (^O C)	935	5	ſ	1041		954	99	0
Ox. fugacity	12.	.0	-1	10.1		-11.9	-1	1.0

TABLE 3 SUMMARY OF MINERALOGY AND PETROLOGY

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- : present in minor amounts

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TABLE 3, cont...

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	FLOW 1		FLO	FLOW 2		FLOW 3		FLOW 4	
	%	Comp	%	Comp	%	Comp	%	Comp	
<u>Phenocrysts</u>									
Plag	10	An63-61	8	An64-61	10	An63-61	10	An63-61	
Olivine	6	Fo77-72	7	Fo74-70	7	Fo73-69	7	Fo77-70	
<u>Groundmass</u>									
Plag	55	An53-52	56	An54-51	54	An54-50	54	An53-52	
Augite	18		17		19		20		
Olivine	9	F065	9	F064	7	Fo61	6	Fo58	
Magnetite	1.3		1.0		2.0		1.8		
Ilmenite	1.1		1.7		1.0		1.0		
Apatite	-		-		-		-		
Cr-spinel	-		-		-		-		
Glass	-		-		-		-		
Temp (^O C)		1015	99	8	10	19	98	9	
Ox. fugacity	-	10.6	-10	.7	-	10.7	-11	.2	

- : present in minor amounts

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To facilitate comparison of the flows, average compositions for the major phases in the rocks have been plotted on a series of compositional diagrams (Figures 11 to 14). Variations within individual flows and columns will be discussed in more detail in Chapter V. FIGURE 11: Electron microprobe analyses of feldspar phenocrysts plotted in terms of mole percent An-Ab-Or. Average compositions for each flow are indicated by small black squares.

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A : analyses from rims of phenocrysts

B : analyses from cores of phenocrysts



FIGURE 12: Electron microprobe analyses of groundmass feldspar plotted in terms of mole percent An-Ab-Or. Average compositions for each flow are indicated by small black squares.

A : analyses from rims of groundmass lathsB : analyses from cores of groundmass laths



FIGURE 13: Electron microprobe analyses of olivine plotted in terms of mole percent Fo-Fa.

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Fo _}		60	40	20	Fa
FLOW 1	}				
FLOW 2					
FLOW 3	<u>}</u>	F	-		
FLOW 4	H				ж. Алагана Алагана
FLOW 5	<u>}</u> 1 1	⊢ i			
FLOW 6		} 4			
FLOW 7	}	+			
FLOW 8	· j	·			,



FIGURE 14: Electron microprobe analyses of pyroxene plotted in terms of atom percent Ca-Mg-Fe. Average compositions for each flow are indicated by small black squares.

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V - CHARACTERISTICS OF COLUMNAR JOINTS

AND JOINTED FLOWS

Size and Shape of Columns

An understanding of the distribution of sizes and shapes of columnar joints may be important in determining the origin of such joints. There are numerous records in the literature of measurements of the number of sides of basalt columns and of the angles between sides of the columns from a variety of different localities (eg. Spry, 1962; Beard, 1959; James, 1920; Jellett, 1879; O'Reilly, 1879). Little attention has, however, been placed on the variation in size of the columns.

In order to obtain information as to the typical size and shape of the columns in the Garibaldi area, two hundred columns were counted, in plan view. The maximum dimension was recorded, as well as the number of sides of the column. In choosing columns to be counted, some care had to be taken because rounding of the columns between faces made a unique interpretation of the number of sides difficult. Tables 4 and 5 summarize these results.

The number of sides of the columns show a normal distribution with a mean value of about 4.8 (Figure 15). The distribution in size, or maximum dimension of the columns sampled has also been illustrated graphically (Figure 16). This distribution seems to be slightly skewed to the right and has a mean value of about 28 cm. The mode is also in the 25 - 29 cm range. The size of columns can vary considerably both within and between flows. This size is not, therefore, an average for

TABLE 4

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DISTRIBUTION OF NUMBER OF SIDES OF COLUMNS

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Number of sides	Number of columns	Average size (cm)
3	3	19
4	53	26
5	· 113	30
6	29	31
7	0	-
8	1	43
Total	200	-

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TABLE 5

DISTRIBUTION OF SIZES OF COLUMNS

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Size range (cm)	Number of columns
10 - 14	2
15 - 19	. 22
20 - 24	43
25 - 29	51
30 - 34	40
35 - 39	. 23
40 - 44	12
45 - 49	5
50 - 54	1
55 - 59	1
Total	200

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Figure 15. Histogram showing the distribution of the number of sides of basalt columns from the Garibaldi Area of British Columbia.



Figure 16. Histogram showing the distribution of sizes of basalt columns from the Garibaldi Area of British Columbia.

the Garibaldi area, but rather represents the average size of columns in the upper portion of the flow studied. Figure 17 illustrates the change in size of the columns with the number of sides. A progressive increase in size with an increase in the number of sides of the column can be seen.

It is interesting to compare the results from the Garibaldi area with results obtained by James (1920) from basalt columns in the Sydenham area of Australia (Figure 18). James' data is strongly normally distributed with a mean value of 6.2. Data from the Garibaldi area shows quite a different mean value, 4.8, with a standard deviation of about 0.71. The mean value from the Syndenham area falls 2 standard deviations above the mean value from Garibaldi. Assuming a Gaussian distribution a mean value of 6.2 is significantly different (at the 95% confidence level) from a mean value of 4.8. A possible explanation is that the distribution of the number of sides of columns does vary significantly between different areas. Alternately, results obtained by different samplers may show inconsistencies due to judgement differences.

The Giant's Causeway basalt in Ireland is probably the best studied area of columnar jointing. Beard (1959) and O'Reilly (1879) both give the distribution of the number of sides of the columns from this area. These results are displayed in Figures 19 and 20. The similarity of the results obtained at this locality by Beard (1959) and O'Reilly (1879) suggests that the varying values noted earlier may not be a result of judgement differences, but caused by real variations in the distribution of the number of sides of columns between localities.


Figure 17. The average size of basalt columns from the Garibaldi Area of British Columbia is plotted against the number of sides of the columns. A progressive increase in size occurs with increased number of sides of the columns.



Figure 18. Histogram showing the distribution of the number of sides of basalt columns from the Syndenham Area of Australia (from James, 1920).

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Figure 19. Histogram showing the distribution of the number of sides of basalt columns from the Giant's Causeway, Ireland (from Beard, 1959).

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Figure 20. Histogram showing the distribution of the number of sides of basalt columns from the Giant's Causeway, Ireland (from O'Reilly, 1879).

Jellet (1879) made a number of measurements of angles of basalt columns in the Giant's Causeway. A total of 142 measurements were made from 4,5,6,7, and 8 sided columns and the measurements recorded in terms of the number of sides of the columns. Percent frequency is plotted against the angle between the sides for each of the types of polygon (Figures 21 to 25). The interior angle expected from a perfectly regular column is shown on the figures for each different polygon. While the distributions are generally not normal or symmetric, probably a result of the small sample sizes, it is interesting to note that in each case the mean value calculated from the data is in very close agreement with the expected angle.

All available data concerning variation in the interior angles and number of sides of basalt columns has been combined to determine an overall average shape of the columns. Data from James (1920) is omitted in the construction of these diagrams since the exact number of columns sampled is unknown. Results from Beard (1959) and O'Reilly (1879) were used in conjunction with those collected from the Garibaldi area to construct the distribution of the number of sides of basalt columns (Figure 26). Angular measurements collected by Spry (1962), Jellett (1879) and O'Reilly (1879) were combined in order to show the average distribution for the interior angles of basalt columns. This distribution is shown in Figure 27. The combined data show that both the number of sides of columns and the interior angles show normal distributions. A mean value of the number of sides of the column of 5.5 with an average interior angle in the range 115° - 125° is calculated. There is limited data concerning sizes of columns, and since the size is



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Figure 21. Histogram showing the distribution of the interior angles of tetragonal columns from the Giant's Causeway, Ireland (from Jellett, 1879). The mean value is 90° which corresponds exactly with the expected value for a tetragonal column.



Figure 22. Histogram showing the distribution of the interior angles of pentagonal columns from the Giant's Causeway, Ireland (from Jellett, 1879). The mean value is 107° which agrees closely with the expected angle of 104° for pentagonal columns.



Figure 23. Histogram showing the distribution of the interior angles of hexagonal columns from the Giant's Causeway, Ireland (from Jellett, 1879). The mean value is 123° which agrees closely with the expected angle of 120° for hexagonal columns.



Figure 24. Histogram showing the distribution of the interior angles of heptagonal columns from the Giant's Causeway, Ireland (from Jellett, 1879). The mean value is 128° which agrees closely with the expected angle of 128.5° for heptagonal columns.



Figure 25. Histogram showing the distribution of the interior angles of octagonal columns from the Giant's Causeway, Ireland (from Jellett, 1879). The mean value is 135° which corresponds exactly with the expected angle for a octagonal column.



Figure 26. Histogram showing the overall distribution of the number of sides of basalt columns. Data from this study is combined with data from Beard (1959) and O'Reilly (1879) to give a mean value of 5.5 with approximately equal numbers of 5 and 6 sided columns.

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probably widely variable between localities, no indication of the average size of basalt column is made.

Finally, the distribution of the number of sides of columns obtained by Beard (1959) on the phonolite columns from the Devil's Tower, Wyoming, has been plotted (Figure 28). Comparison of this figure with Figure 26 (the overall distribution of number of sides of basalt columns) show the two plots to be very similar. Any differences which exist may be a result of the smaller sample size for the phonolite. Thus, it can be seen that the composition of the rock, at least in the compositional range from basalt to phonolite, probably has no effect on the shape of the columns developed.

Variations Within Jointed Flows

A thorough understanding of the cooling history of flows which display columnar jointing is essential in order to determine the origin of such joints. Any variations in chemistry, petrography or mineralogy found to occur within or between these jointed flows will aid in the understanding of the cooling process.

Detailed mineralogical studies have detected only minor variations in the composition of mineral phases between the different flows studied and point counting techniques have shown that the percentages of these phases are essentially constant between flows. This suggests that only minor chemical variations exist between the flows and that these changes can not explain the varied jointing styles.



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Figure 28. Histogram showing the distribution of the number of sides of phonolite columns from the Devil's Tower, Wyoming (from Beard, 1959).

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Flow 3 displays a drastically different style of jointing from that seen in any of the other flows studied (Plate 1-c). As stated above, all flows contain the same phenocryst and groundmass assemblages; only subtle differences in mineralogy or petrography occur between different flows. The composition of the phenocrysts in all the flows is very similar (Figures 11 and 13). Flow 3 does contain fewer phenocrysts than any of the other flows, however. All the groundmass phases, with the exeption of olivine, show only minor variation in composition or abundance between the flows. The composition of groundmass olivine, however, varies somewhat (Figure 13). Flow 3 contains olivine in the groundmass which is more abundant and much less forsteritic than that in other flows. These variations do not seem to account for the dramatically different jointing style seen in this flow.

Samples obtained from the same flows were also compared in order to detect variations within individual flows. A number of samples were taken from across the width of a relatively small flow, Flow 1, showing only moderately well developed columnar joints (Figure 4, Plate 1-a). No notable variations in mineralogy or petrography existed across the flow.

Several samples were taken along the length of Flow 4, a larger flow with well developed joints (Figure 7 and Plate 1-d). Again, no variation in mineralogy or petrography was found.

Another flow was sampled, this time a moderate sized flow with practically nonexistent columnar joints, but prominent basal lines. Sample locations from Flow 3 are shown in Plate 1-c. Whole rock chemical analyses were obtained for two of the samples from Flow 3. Only very minor differences in whole rock chemistry exist between the samples. These variations are felt to be simply a result of the sample powder split. Several important petrographic variations exist within the flow. First, an increase in the alignment of plagioclase laths is seen, with sample 03-01 showing the poorest alignment and sample 03-03 the best. In addition, sample 03-03, obtained near the base of the flow, contained substantially less glass than the other samples. A downwards increase in the percentage of groundmass olivine is also seen in the flow. These observations suggest that the flow was in motion during much of the crystallization process and that the base of the flow cooled more slowly than the rest of the flow. The increase in alignment of the plagioclase laths to the base of the flow may be a result of the higher temperatures here, making the flow less viscous and hence the alignment of crystals easier.

A number of samples were taken from individual columns of different shapes and sizes, from the upper surface of two different flows (see Table 1). Although minor differences in the mineralogy and textures of the samples were noted, none of these differences are consistent with a particular size or shape of column. It is believed that any differences noted are simply a result of inhomogeneities in the magma and that these inhomogeneities do not in any way affect the jointing style.

Certain jointed flows show a distinct two or three tiered structure (Figure 2). Such a structure can be explained by several different hypotheses. Variations in chemistry, petrography, and mineralogy between the different zones in jointed flows may provide evidence to support or contradict these hypotheses.

If the tiered structure formed according to the double-diffusive hypothesis proposed by Kantha (1980, 1981), chemical variations should exist between the different zones. Kantha (1981) did not conduct any studies to see whether such variations did in fact exist. Other studies have found that generally there is no change in composition or degree of crystallinity between the colonnade and entablature (Spry, 1962; Macdonald, 1968).

Only one case of chemical variation between the different zones in jointed flows is documented in the literature (Tomkeieff, 1940). In the Giant's Causeway, the upper portion of flows were generally slightly richer in alkalies and poorer in MgO and CaO than were the lower portions of the flows. In addition, the amount of water present in the upper zones was much greater than that present in the lower zones.

Petrographic variations were also noted in flows from the Giant's Causeway (Tomkeieff, 1940). The percentage of groundmass varied considerably between the different zones in the flows. The variation was not, however, consistent. In one flow studied the entablature contained almost twice as much groundmass as the colonnade (29.8% versus 15.8%), while in a different flow the opposite effect was seen (13.3% groundmass in the entablature and 21.4% groundmass in the colonnade).

Only one other study which examined the different zones of jointed flows was documented in the literature. Long and Wood (1986) did a petrographic study of fifteen different flows of the Columbia River Basalts. The flows were classified as one of three types, depending on the development of columnar jointing. The first type of flow was generally thin (10 to 30 m) and consisted entirely of an irregular

colonnade; no entablature was seen. These flows showed intersertal to intergranular textures with no textural variations across their thickness. Some flows showed glassy tops. Type II flows were characterized by repeated colonnade and entablature zones and possibly an upper colonnade. In these flows the entablature contained substantially more groundmass than did the colonnade (35-65% versus 15-25%). Other distinguishing features between the colonnade and the entablature were first, that the groundmass in the entablature was glassy and rich in inclusions, and secondly, that the opaque minerals tended to show a dendritic morphology in the entablature. The third type of flow had a single entablature and lower colonnade and possibly an upper colonnade. In Type III flows the entablature also contained more groundmass than the colonnade. The groundmass in the entablature was also richer in glass and inclusions than that of the colonnade.

The textural evidence from this study indicates that the entablature cooled more quickly than the colonnade. Water influx along existing fractures has been proposed to explain the observed zonation (Long and Wood, 1986).

Six samples were obtained from a flow in the Garibaldi area (Flow 7) which showed a distinct entablature and lower colonnade (Figure 8, Plate 2-c). The samples were studied in order to determine if any chemical, mineralogical or petrographic differences existed between the two zones of the jointed flow.

Wet chemical analyses showed only minor chemical differences between the samples studied. These differences are not consistent with a particular zone in the flow and are believed to be simply a result of

sampling splits. No chemical variation was discovered between the lower colonnade and entablature. Samples from the entablature may contain marginally fewer phenocrysts than do those from the lower colonnade (15.6% versus 16.7%). Such a difference is within the error of counting, however, because of the large size and glomeroporphyritic nature of the phenocrysts. Additionally, samples from the entablature contained less glass than did samples in the colonnade. A smaller amount of glass in the entablature suggests slower cooling of this region, contradicting evidence provided by Long and Wood (1986).

It thus appears that the zonation in flows may develop in more than one manner. The entablature is the last portion of the flow to crystallize but will develop whether cooled at a faster of slower rate than the upper and lower colonnades. There is little evidence in the literature to support the theory that the zones originate as a result of a chemical gradient, as suggested by Kantha (1980, 1981). No further evidence arises from studies of tiered flows in the Garibaldi region.

Intracolumnar Variations

Physical, chemical or petrological variations found to occur in basalt columns might support a convective origin to these columns. Several references to such variations are found in the literature.

Although Sosman (1916) himself did not detect any intracolumnar variations when studying basalts from several different localities, he makes reference to several others who have reported such variations.

Poulett Scrope (1872) studied volcanoes of Central France and observed columns characterized by compact, black basalt cores with the remainder of the column lighter in colour and less dense. Sosman (1916) also refers to Delesse (1858) who found that the cores of the columns usually had a slightly higher density than the surrounding rock.

Peterlongo (1951) studied the orientation of microlites in columns from Saint-Flour, France. On horizontal faces the microlites were oriented in a radial direction, while on lateral faces they were vertical suggesting that convection currents may have occurred. Other authors (eg. Long and Wood, 1986) have found no such alignment of minerals and therefore believe that flow parallel to columnar joints does not occur.

Spontaneously cracking basalts from the Upper Tumut area in Australia were studied by Lafeber (1956). Columnar jointing was well developed in these basalts and samples were taken from different positions within individual columns. Petrological and petrochemical studies revealed a characteristic zonation of nepheline, analcime, and various types of plagioclase within the basalt columns. Lafeber (1956) suggested that the observed zonation in minerals across the basalt columns must be explained by fractional crystallization. Early crystallized plagioclase did not react with the remaining melt, indicating that the Na-rich melt must have migrated elsewhere. The zonation is visible in early formed Ca-rich plagioclase, so the intracolumnar differentiation must have started very early in the crystallization process. From the normative mineralogy, Lafeber (1956)

of the melt had not yet solidified. Since the differentiation is controlled by the structure of the columns, he felt that the columnar structure must be evident in the magma prior to solidification and that convection currents were responsible for the observed zonation.

Symons (1967) studied the magnetic and petrologic properties of a basalt column from the Giant's Causeway. Fifty-six samples were taken from a systematic grid across a transverse surface of the basalt column. A very detailed study was carried out in which density, thin section petrology, electron microprobe analysis, x-ray analysis, natural remanent magnetism, as well as a number of other properties were studied. Systematic variations across the basalt column were discovered, however these variations were not apparent in density, grain size, mineral abundance or chemical composition. This indicates that the magma was uniform, both chemically and physically, initially and until the column had been formed. Variations in the magnetic properties which did occur were explained by a continuous contraction hypothesis in which there is a gradient in the oxygen and titanium content of titanomagnetite on cooling. Symons (1967) felt that no evidence to support a convective origin of the columns was seen.

In his paper which proposes a double-diffusive mechanism to explain columnar jointing, Kantha (1980, 1981) states that in most cases the composition is uniform across individual columns. He does quote several exceptions, however. One such exception is columns from Steens Mountains, Oregon, where centers of columns are lighter in colour and contain zeolites and altered olivine. The opposite effect has also been recorded for these columns. Kantha (1981) explains this apparently

contradictory evidence with a double-diffusive mechanism (finger regime) the details of which will be explained in the following chapter. Kantha (1981) uses the analogy of salt fingers, where cool, fresh water is going up one finger and hot salty water going down in adjacent fingers to explain this compositional difference. He suggests that alternating compositional differences may exist between columns.

Samples taken from different positions within individual columns were obtained from jointed flows in the Garibaldi area. These samples were analyzed to determine whether or not any intracolumnar variations could be detected.

Eleven samples from two different columns in Flow 2 were taken to test whether or not the interior of the columns was mineralogically or petrographically distinct from the exterior. In mineralogical studies it was noted that two of the samples from the column exterior showed groundmass olivine compositions which were considerably more forsteritic than the average composition from the other samples (Fo_{72} versus Fo_{67}). A total of eleven samples were taken from the columns, however, and eight were from column exteriors (see Figures 5 and 6). Since the effect was only seen in two samples it is suspected that such a variation is simply due to inhomogeneities in the magma and not a result of differentiation during cooling. No other variations in petrography or mineralogy were noted in the columns.

In summary, certain intracolumnar variations which are consistent with a convection hypothesis have been recorded in the literature. The evidence is far from complete, however, and by no means conclusive. No evidence to support such a hypothesis resulted from studies of basalts

from the Garibaldi region.

Chisel Structures

Several hypotheses exist to explain the presence of chisel structures, or basal lines, in jointed flows. The convection hypothesis proposes that they represent the boundaries of convection cells in the magma, while in the contraction hypothesis the lines are said to mark hiatuses in the propogation of the cracks which outine the columns. The observed characteristics of these chisel structures may help to determine their origin.

Chisel structures are present in most flows in the Garibaldi area. The most notable feature of the basal lines studied is the fact that, while the lines are very prominent on the exposed surface of the columns and often appear to be raised up in relief, on freshly broken surfaces they cannot be seen. The spacing of these chisel structures varies between flows, from 2 to 16 cm, with an average of about 12 cm. Within individual flows, basal lines have approximately equal spacing. Several samples were obtained from an individual column from Flow 8, in which the basal lines were well developed with spacings of about 5.5 cm. The samples were taken from different positions relative to the basal lines in order to determine whether or not the basal line was characterized by any mineralogical or petrographic features (see Figure 10 for sample locations). It was not possible to chemically analyze the samples from Flow 8. The sample sites were very specific and hence the large volume of material required for such analyses could not be collected. A number

of variations in mineralogy and petrography were, however, noted in the samples. A weak trachytic textrure was seen in both samples cut vertically from the column (08-01-3 and 08-01-4), suggesting that flow parallel to column edges did occur, as one would expect if convection were taking place. One other sample, 08-01-5, also showed this alignment of plagioclase laths, this time indicating flow perpendicular to columns edges, again consistent with the convection cell hypothesis.

Benard (1901) showed that suspended substances of various densities will distribute themselves in an established pattern in convection cells (Figure 29). Variations in mineralogy which support such a distribution might suggest that convection cells did exist in the cooling magma. Sample 08-01-5 (see Figure 10) contained a much lower percentage of phenocrysts than the other samples (10.7% versus 16.9%). The percentage of augite in the groundmass of this sample was also depleted, while plagioclase in the groundmass was enriched. Both these observations suggest that sample 08-01-5 is enriched in lighter components and depleted in heavy components. This corresponds to what one would expect from a sample located near the edge of the column and from the upper portion of a convection cell. If this is in fact the case, sample 08-01-6 should also show a depletion in heavy components and sample 08-01-4 should be enriched in heavy components. Neither of these is true, however.

Data concerning chisel structures is scarce. While studies of these features in rocks from the Garibaldi area have provided some evidence to support a convection type hypothesis, the results are far from conclusive.



Figure 29. Side and plan views of a typical convection cell showing the distribution of solid particles of different densities within the cell. Heavy particles are concentrated in the bottom centre portion of the cell while light particles occupy the top, outer region of the cell.

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VI - THE ORIGIN OF COLUMNAR JOINTS

Three main hypotheses have been proposed in the literature to explain the origin of columnar jointing (Spry, 1962; Sosman, 1916; Kantha, 1981). These hypotheses will be discussed in chronological order. Evidence from the literature and from this study will then be used to substantiate or contradict the different theories.

Contraction Hypothesis

In the late 1800's and early 1900's a number of different authors (eg. Mallet, 1875; Iddings, 1886; James, 1920) proposed that columns in igneous rocks result from contraction during cooling. More recently several different papers expanding these ideas have arisen (Tomkeieff, 1940; Jaeger, 1961; Spry, 1962; Long and Wood, 1986).

Cooling of the flow causes contraction to occur. The amount of contraction depends in part on the coefficient of thermal expansion of the magma and on the decrease in temperature. A typical value for the coefficient of thermal expansion for a basalt magma is in the order of $2.5 \times 10^{-5} \, {}^{\circ}C^{-1}$ (Suppe, 1985). At high temperatures contraction will be taken up by movement in the vertical sense, since viscosity is low and contraction occurs by fluid flow. This has the effect of decreasing the thickness of the flow. As the lava starts to solidify, the viscosity increases greatly and the rate of contraction begins to exceed the rate

of relief by flow. As a result, thermal stresses are built up. The rock stretches plastically, and rupturing occurs when the tensile strength of the rock has been exceeded (Spry, 1962).

The complexity of the problem makes it difficult to express the built up thermal stresses mathematically. Stresses are generated in one of several ways. First, thermal stresses develop because of constraint, but the effect is very complicated, for several reasons. Fractures will develop in one part of the cooling body while other portions of the body are not yet solid and hence unable to transmit constraining forces. In addition, external constraints must be considered. These external constraints vary with position, however, so that at each point in the body the effect is different. If the problem is simplified by assuming that no external constraints exist, one can express the stresses due to constraint by:

$$S = E\alpha \quad \frac{(T_o - T_1)}{1 - u}$$

where: S = stress (MPa), E = Young's Modulus (MPa) $\alpha = coefficient of thermal expansion (°C⁻¹)$ $T_0 - T_1 = temperature difference (°C)$ u = Poisson's ratio, (Spry, 1962).

Tpical values for these physical properties for basaltic magmas are given by Suppe (1985) as:

S = -10 MPa $E = 4 \times 10^4 MPa$ $\alpha = 3 \times 10^{-5} \circ C^{-1}$ u = 0.2

Fracturing is thus predicted for a change in temperature of about 70°C.

Thermal stresses also develop because of unequal temperature distribution. Contraction occurs as a result of cooling; because contraction cannot occur freely in a large body, thermal stresses result. Again it is very difficult to express such stresses mathematically because of factors such as the rate of cooling and the shape of the body.

The factors upon which thermal stresses at any point in a cooling body depend are given by Spry (1962) as:

- Physical properties of the rock such as the conductivity, the coefficient of expansion, Young's modulus and Poisson's ratio.
- 2) Constraints
- 3) Rate of cooling
- 4) Shape of the cooling body
- 5) Symmetry of cooling
- 6) The influence of previously existing fractures.

While we know that these factors play an important role in the development of thermal stresses, it is often difficult to evaluate their effect. The development of columns in the cooling body is more easily understood if the problem is simplified by assuming that the magma was originally homogeneous and that it cooled by uniform, but not identical heat loss from the upper and lower surfaces. Since the upper surface will usually cool more quickly that the lower surface, the temperature at which fracturing takes place will occur on the upper surface before it is reached on the lower surface. The tension on the upper surface will be equal in all directions, according to the above assumptions. Since it requires energy to produce fractures, the system of fractures which develops will be the one which requires the least amount of energy. Mallet (1875) showed that such a system would be one of equidimensional hexagons.

The hexagonal pattern is not produced by the instantaneous development of a number of interlocking hexagons but rather by the continuous propagation of fractures (Spry, 1962; Peck and Minakami, 1968). The tensile strength will be exceeded in one place, causing a straight fracture to form and relieving the stress perpendicular to the fracture. Stress builds up parallel to the existing fracture and cannot be relieved except by fracturing in a new direction. Tension still exists in a direction perpendicular to the existing fracture, beyond the ends of the fracture, so the overall stress is best relieved by a new fracture at 60°. Spry (1962) discusses this process in detail. The hexagonal pattern is produced by continued propagation in such a manner. A system of polygons, rather than a perfect hexagonal pattern is expected, since there is only a small difference between the energy required to break a rock into pentagons or septagons, rather than

hexagons.

Such a method of fracture propagation is thus capable of explaining the polygonal shape of the columns. It also allows the size of the columns to be related to the physical properties of the rock, since the size of the columns depends on how far the intitial fracture propagates before it bifurcates. This distance will depend on the thermal stresses. The larger the stresses are, the more quickly bifurcation will take place and the smaller the columns will be. Thermal stresses depend primarily on the rate of cooling and the physical properties of the rock, such as the coefficient of expansion, therefore, these govern the size of the columns. A slow rate of cooling and small coefficient of expansion give rise to small thermal stresses and, hence, large columns. The variation in sizes of columns between different flows can thus be explained. Varied rates of cooling within individual flows could also explain the variation in sizes of columns within these flows.

Fractures are initiated on both the upper and lower surface in this manner. These fractures penetrate inwards, until they reach zones where the accumulated stress is not great enough to cause fracturing to occur. As cooling progresses, stresses are concentrated at the ends of the fractures. The result is that the fractures continue to propagate inwards, causing columns to form. In some flows, the fractures grow inwards at a very steady rate. In other cases, propagation occurs in steps and the columns are marked by a series of chisel structures. This process has been observed in the Kilauea Iki lava lake by Peck and Minakimi (1968). Fractures were observed to form at about 900°C. These fractures propagated inwards to regions where the magma was about

1000°C. The fractures remained stationary until sufficient cooling occurred to initiate their propagation.

The basal lines thus mark the stationary period in the penetration of the joint, when stresses are accumulating. The spacing of these lines is related to the rate of cooling. Presumably, in a slowly cooled body the chisel structures will have wider spacings.

Columns do not necessarily form perpendicular to isotherms, as often stated, but rather, form perpendicular to surfaces on which the tensile stress is equal in all directions. In simple situations, such surfaces are parallel to isotherms (Jaeger, 1961).

The three tiered structure commonly seen in jointed flows is believed to form in the following manner. Joints begin to form on both the upper and lower surfaces and penetrate inwards towards the interior of the flow. Since the central region is still liquid and is unable to transmit stresses, the two sets of joints form independently into regular, well developed columns. When the entire flow becomes solid, however, a complex stress distribution results in the center. A zone of randomly oriented, poorly developed columns thus develops (Jaeger, 1961; Spry, 1962). Late stage influx of water along existing joints may also contribute to the development of the entablature, since the increased rate of cooling would prohibit well developed columns from forming (Long and Wood, 1986). The rate and symmetry of cooling and the geometry of the flows will all effect the development of such a zonation.

Certain columns are undoubtably a result of contraction during cooling. Columns developed in sandstones adjacent to igneous intrusions, for example, must be attributed to such a formation. In

addition, columns such as those developed in dikes or sills, which are obviously oriented perpendicular to surfaces of equal stress, also result from contraction on cooling.

Convection Hypothesis

Detailed studies of convection phenomena were first conducted around the turn of the century by Benard (1901) and Dauzere (1907, 1908). A polygonal pattern is generally produced in a thin layer of liquid, large in its lateral extent, which is losing heat from the upper surface. Convection currents develop as the dense, colder liquid on top settles, and the warmer bottom layer rises. If steady state flow results, the current patterns consist of parallel rising and descending columns. Minimum friction occurs when the currents divide the liquid into hexagonal cells (Sosman, 1916). The convection hypothesis proposes that convection cells are set up in the cooling magma and they leave a permanent record in the solid rock. Subsequent contraction of the rock causes cracking along the boundaries of these convection cells.

In an ideal situation, columns formed in such a manner should have perfect hexagonal cross sections. If conditions are not constant and a steady state of flow is not established, then deviations from this perfect pattern occur, explaining the variation in shapes of columns seen.

The dimensions of convection cells, and hence the columnar joints, depend on the thickness of the flow, the temperature difference between the top and bottom surfaces, and on the temperature and viscosity of the liquid (Sosman, 1916). The actual effect which each of these factors has is not discussed, however.

It has been suggested that the basal lines commonly seen, mark the boundaries between convection cells (Longchambon, 1912), however not all supporters of the convection hypothesis believe this (Sosman, 1916).

No attempt is made to explain the development of the tiered structure often seen in jointed flows.

The authors of the convection hypothesis do not propose that all columns form in such a manner. Sosman (1916) points out that columns formed as a result of convection should be vertical. Obviously, not all columns are oriented in this manner. In addition, Sosman (1916) states that convection columns should be much wider than they are high and that one should see evidence of the convection currents preserved in the columns as intracolumnar variations.

There are obvious flaws and omissions in the convection hypothesis. Most columns do not have the characteristices which convection type columns should possess. Such a hypothesis would thus be capable of explaining only a very few of the columns seen.

Double-Diffusive Convection Hypothesis

Recently studies concerning double-diffusive convection (eg. Turner, 1973, 1974, 1978; Chen and Turner, 1980; Huppert and Sparks, 1984) have led to the development of a third hypothesis for the development of columnar joints (Kantha, 1980, 1981).

Double-diffusive convection develops when a system contains two or more components that have different molecular diffusivities and opposing effects on the vertical density gradient (Huppert and Sparks, 1984). Instabilities can develop even when the net density decreases upwards. In geological problems the two properties of concern are heat, with a diffusivity in the order of 10^{-3} cm² s⁻¹, and composition. Reasonable diffusivities for chemical components in silicate melts are in the order of 10^{-6} to 10^{-10} cm² s⁻¹ (Huppert and Sparks, 1984). For simplicity a system with heat and only a single chemical phase will be discussed. In such a system four different situations are possible. In the first case, illustrated in Figure 30-a, the concentration of the heavy chemical component increases downwards while the temperature increases upwards in the body of interest. Both these have a stable configuration so that the system is absolutely stable and no convection is possible. In the second situation, both the heat and the chemical component have unstable effects on the density and simple convection is possible. The compositional effect simply adds to the thermal effect. Figure 30-b illustrates this case. A third possibility, illustrated in Figure 30-c is the diffusive regime. The heavy chemical component increases downwards as does the temperature. The system is stable with respect to composition, but unstable with respect to temperature and the conditions for double-diffusive convection are thus met. It has been shown experimentally that under such conditions a series of horizontal layers, each with a specific temperature and composition will develop (eg. Turner, 1974; Huppert and Sparks, 1984). Finally, a system in which the





Figure 30. Possible temperature and chemical composition profiles in a fluid layer. Detailed descriptions of each of the four cases are given in the text.

temperature distribution is stable and the distribution of the chemical component is unstable can occur (Figure 30-d). Again the conditions required for double-diffusive convection are met by such a system. This situation is called the finger regime, since experiments have shown that long, thin, fingerlike convection cells result. Hsui (1982) states that at the base of a flow the temperature gradient is stable. The compositional gradient will be unstable, due to crystal fractionation and the conditions for the finger regime will be met. Kantha (1980, 1981) and Hsui (1982) propose that basalt columns are images of these finger-like convection cells. Once the cells are established, contraction causes fracturing along cell boundaries. As in the pure contraction hypothesis, basal lines mark periods of fracture propogation.

The three tiered structure commonly seen in jointed flows can be produced in double-diffusive experiments. The entablature crystallizes at a later time than the upper and lower colonnades. Kantha (1981) proposes that a chaotic structure in the entablature indicates that the zone formed relatively early in the crystallization history when convection was still strong and the compositional differences were large. A more ordered entablature would indicate solidification later in the crystallization history. According to this theory, then, chemical analyses of the differences which caused the convection process to occur. These differences should be more apparent in flows with chaotic entablatures, since fluxes were still quite large when the zone formed.
Mathematical Modelling of a Cooling Flow

In theory, double diffusive convection is possible in a single layer . of fluid if the following conditions are met (Huppert and Sparks, 1984). First, the ratio of the compositional molecular diffusivity (k_s) to the thermal molecular diffusivity (k_t) must be much less than one. That is:

1)
$$k_s/k_t << 1$$

Since k_s is in the order of $10^{-6} - 10^{-10}$ cm² s⁻¹ and k_t is approximately 10^{-3} cm² s⁻¹ (Huppert and Sparks, 1984), this condition is satisfied. Secondly, the Prandtl number, which is the ratio of kinematic viscosity (ν) to thermal diffusivity (k_t), must be significantly greater than one.

2)
$$\Pr = \nu/k_{+} >> 1$$

The kinematic viscosity is variable, depending on temperature, between about 2.5 and 3.5 stokes in the range of temperatures of interest, so this condition is also met. Finally, the difference in the thermal Rayleigh number and the compositional Rayleigh number must exceed some critical value. This critical value is given by Huppert and Sparks (1984) as 1000. The condition can be written as:

3)
$$\operatorname{Ra}_{t} - \operatorname{Ra}_{s} = \operatorname{gd}^{3} (\alpha \, \Delta T - \beta \, \Delta S) > 10^{3}$$

$$\frac{\nu \, k_{t}}{\nu \, k_{t}}$$

where: g = gravitational constant (cms⁻²)

 α = coefficient of thermal expansion (°C⁻¹)

 β = coefficient of expansion due to compositional change (moles⁻¹)

- $\Delta S =$ compositional change (moles)
- ν = kinematic viscosity (stokes)
- $k_t =$ thermal diffusivity (cm²s⁻¹)

Values of d and ΔT will be explained in the following discussion.

Consider the cross section of a cooling flow, some time after emplacement, such as the one shown in Figure 31. When the flow has undergone a certain amount of crystallization the suspended crystals will interfere with the convection currents, so that convection will no longer be possible. It is uncertain what percent crystallinity this would correspond to, but it seems that 50% crystals in a melt would certainly be sufficient to cause this interference. Fifty percent crystallinity would be achieved at a temperature of 1115°C. Convection is not possible in any regions of the flow where the temperature is low enough that this much crystallization has occurred, as illustrated in Figure 31. ΔT (°C) is the difference between the maximum temperature and the temperature at which the critical value of crystallization occurs, labelled T_x in the diagram. d (cm) is the distance between the points at which these temperatures occur.

If it can be shown that the critical Rayleigh number is exceeded in the flows studied, then theoretically double-diffusive convection is possible. Since no compositional variations were detected, values of β and ΔS were impossible to determine. The compositional Rayleigh number can, however, be set to zero, and this problem avoided. If: $Ra_t > 10^3$ then, since $Ra_s > 0$, $Ra_t - Ra_s > 10^3$ and the third condition will be satisfied. The expression which needs to be solved is, therefore:



Figure 31. Schematic representation of a cooling flow slowing a possible temperature distribution. T_x is the critical temperature beyond which convection cannot occur due to interference resulting from crystallization. d is the distance between the points in the flow which correspond to the maximum and critical temperatures.

$$\frac{g d^3 \alpha \Delta T}{\frac{\nu k_t}{\nu k_t}} > 10^3$$

It is necessary to know the crystallization history of the flow in order to calculate ΔT and d. J.K. Russell has developed a computer program to calculate equilibrium assemblages as a function of temperature, pressure and bulk composition allowing one to model the fractional and equilibrium crystallization paths. Early crystallization histories of mafic to intermediate flows have been successfully modelled using this program (Russell and Nicholls, 1985). The equilibrium state of the magma is calculated by simultaneously solving equations for the bulk magma composition, mass balance equations for the equilibrium assemblages and equations describing thermodynamic equilibrium between the solid and melt phases.

This program was used to infer the eruption temperature and to determine the temperatures corresponding to various percent crystallinity for a magma of equivalent composition. An eruption temperature of 1155°C. was determined. Temperatures at which 30, 40, and 50 percent crystallinity occurred are shown in Table 6. The coefficient of expansion, thermal diffusivity and kinematic viscosity can all be computed if the chemical composition and temperature of the flow are known. These calculations were done using a computer program written by J. Nicholls and using a representative set of analyses. Constant values of α , K_t and ν were assumed for each critical value of crystallinity. A temperature halfway between the eruption temperature and the critical temperature was used to estimate these unknowns. Values

TABLE 6

Coefficients for Rayleigh number calculations

Critical % crystallinity:	30	40	50
Temperature (°C)	1150	1135	1115
$\alpha \ge 10^5 (°C^{-1})$	7.70	7.71	7.71
$k_t \ge 10^3 (cm^2 s^{-1})$	2.85	2.80	2.74
ν (stokes)	2.85	3.08	3.39
ΔT (°C)	5	20	40

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used in Rayleigh number calculations are listed in Table 6.

Various thicknesses of flows were now considered and the cooling profiles for these flows determined. A computer program written by J.K. Russell was used to calculate these temperature profiles for various times since eruption. The program models the cooling of a layer of fluid of some initial temperature by solving a basic heat conduction equation. Internal heat loss is by conduction alone, while heat is lost by free convection at the upper surface. The upper and lower surfaces of the fluid layer are held at constant temperatures throughout the cooling history. For this problem an initial temperature of the country rock was chosen to be 20°C. Both the upper and lower surfaces were maintained at 20°C throughout the cooling history.

Jaeger (1961) gives the exact solution for the temperature distribution of an extrusive sheet of initially uniform magma with temperature T_0 , where the country rock is initially at 0°C and the upper surface is maintained at 0°C throughout the cooling history. This is a similar problem to that solved in this study. Figure 32 compares the calculated cooling profile for a 5 m thick flow with the exact solution for such a flow given by Jaeger (1961). T/T_0 is plotted against depth to yield a series of curves with constant values of τ , where:

$$r = \frac{k_t t}{\frac{d^2}{d^2}}$$

Since we are only concerned with the validity of the model at high temperatures and relatively short times, only three curves of the exact solution are shown, $\tau = 0.01$, 0.02 and 0.03. Calculated points Figure 32 - The calculated cooling profile for a 5 m thick flow is compared with the exact solution from Jaeger (1961) on a plot of T/T_0 against depth in metres. The exact solution determined by Jaeger is shown in dashed lines. Numbers on the curves correspond to values of τ , where:

$$r = k_t t$$
$$-\frac{1}{d^2}$$

Calculated points are shown with the following symbols:

• , $\tau = 0.01$ • , $\tau = 0.02$ • , $\tau = 0.03$



corresponding to each of these curves are shown. A constant value of the thermal diffusivity of $2.8 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1}$ was used to determine for the calculated temperature profile. The agreement of the calculated and exact solutions is excellent in the upper portion of the flow. In the lower portion the agreement is not as good, because in calculations the lower surface was held at a constant value. The closeness of the model to the exact solution is, however, good enough to use the modelled temperature profiles to calculate Rayleigh numbers.

The Rayleigh number can now be computed at various times since eruption for flows of different thicknesses and assuming a range of critical values for the percent crystallinity. Calculations using the temperature at which 50% crystallinity was achieved, as well as temperatures for 30 and 40% crystallinity were conducted.

The time since eruption is plotted against the Rayleigh number for flows 1, 2, 5, and 10 metres thick. These results are shown in Figures 33, 34, 35, and 36 respectively. Curves for 30, 40 and 50% crystallinity as the boundary of convection (labelled as T_{30} , T_{40} , and T_{50}) are shown for each different thickness of flow. The time necessary to reach the critical Rayleigh number for the different flows is tabluated in Table 7.

A certain amount of time is required to establish the finger-like convection cells in a fluid layer. The actual amount of time necessary for such a pattern to develop in a lava flow is unknown, however. Examination of Figure 33 shows that for a 1 metre thick flow, convection is only possible for a maximum of about three hours. Intuitively, this does not seem to be enough time to establish the system of convection



Figure. 33. Time since emplacement of the flow is plotted against the Rayleigh number for a 1 metre thick flow. Assuming a critical value of 50% crystallinity (see text), the critical Rayleigh number is exceeded for about 3 hours.



Figure. 34. Time since emplacement of the flow is plotted against the Rayleigh number for a 2 metre thick flow. Assuming a critical value of 50% crystallinity (see text), the critical Rayleigh number is exceeded for about 2 hours.



Figure. 35. Time since emplacement of the flow is plotted against the Rayleigh number for a 5 metre thick flow. Assuming a critical value of 50% crystallinity (see text), the critical Rayleigh number is exceeded for about 17 days.

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Figure. 36. Time since emplacement of the flow is plotted against the Rayleigh number for a 10 metre thick flow. Assuming a critical value of 50% crystallinity (see text), the critical Rayleigh number is exceeded for about 80 days.

TABLE 7

Time (since emplacement of flow) to reach critical Rayleigh number

	TIME (HRS)	TIME (DAYS)
1 METRE FLOW		
T ₃₀	0.5	0.02
T ₄₀	1.0	0.04
^T 50	3.1	0.13
2 METRE FLOW		
T ₃₀	6.7	0.28
T ₄₀	30.5	1.27
т ₅₀	47.6	1.98
5 METRE FLOW		
^T 30	190.5	7.94
T ₄₀	335.8	13.99
T ₅₀	446.4	18.60
10 METRE FLOW	•	
т ₃₀	1017.4	42.39
T ₄₀	1549.2	64.55
T ₅₀	1948.4	81.18

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cells. For a 2 metre thick flow, convection would be possible for the first two days of the cooling history (see Figure 34). Two days is beginning to sound like enough time for the finger-like convection cells to develop. For a 10 metre thick flow, about eighty days elapses before the critical Rayleigh number is reached. This certainly seems like sufficient time for the convection cells to develop.

Theoretically, then, thermally induced convection currents are possible, at least in flows thicker than about 2 metres.

Column Formation in the Flows Studied

Column geometry in the region and a lack of evidence of convection are sufficient to reject a simple convection origin to the joints. Although mathematical calculations showed that double-diffusive convection was theoretically possible in flows thicker than about 2 metres, no chemical, physical or petrographic evidence of double-diffusive convection was found. No change in jointing style between flows thicker than 2 metres and those thinner than 2 metres is seen. Additionally, no chemical or petrographic changes which can be attributed to different methods of joint formation are observed. It is therefore believed that all the columns in the area formed by the same method. All evidence suggests a purely contractive origin to the columnar joints in the Garibaldi area.

Since the physical properties of the different flows are essentially constant, the thermal stresses developed during cooling are primarily a function of the rate of cooling. A slow rate of cooling will produce large columns, while a faster rate of cooling will generate smaller columns. The spacing of basal lines is also a function of the cooling rate. Closely spaced basal lines imply rapid cooling while slower cooling causes basal lines to be more widely spaced. The cooling histories of the different flows studied can thus be deduced from the nature of the jointing. Chemically, mineralogically and petrographically, the flows studied are very similar. Only very minor variations in these properties between flows exist which can be attributed to the varied rates of cooling.

Cracking has been observed in the Kilauea Iki lava lake by Peck and Minakimi (1968). Fractures were observed to form at about 900°C. These fractures propagated inwards to regions where the magma was about 1000°C. Since cracking occurs late in the cooling history and flow of the magma has ceased by this time, it appears that flow of the magma does not affect the jointing process.

The first flow studied, Flow 1, is a relatively small flow with poorly developed columnar joints measuring about 1 m across. Basal lines have spacings of 6 to 10 cm. Both the large size of the columns and the reasonably widely spaced chisel structures suggest a slow rate of cooling. Since the flow is quite thin, a slow rate of cooling would not be expected. Such a cooling rate could develop if the underlying flow were not completely cooled when emplacement occurred. The poorly developed columns may be a result of irregular cooling.

Flow 2 is a very large flow. Columnar joints average 50 cm across and are well developed. Basal lines are spaced about 15 cm apart. The small columns indicate a rapid cooling rate. This is confirmed by the dendritic morphology of the opaque minerals. Spacing of basal lines suggest only a moderate cooling rate, however.

Basal lines are prominent and widely spaced in Flow 3, a small flow with virtually nonexistent columns. The basal lines are widely spaced with about 16 cm between lines. This suggests a very slow rate of cooling. Flows 1 and 3 are located very close together and it is not unreasonable to assume that Flow 3 could also have been emplaced onto a flow which was not entirely cooled, resulting in such a rate of cooling. The absence of columnar jointing is difficult to explain, however.

Flow 4 is a moderate sized flow with well developed columns, about 60 cm across, and very narrowly spaced basal lines, about 2 cm apart. Both these features suggest a very rapid cooling rate. This is confirmed by the presence of glass in the groundmass.

Flows 5 and 6 are moderate sized flows with good column development. Column sizes were measured from the top surface of the flows. Here, columns averaged about 30 cm across, consistent with the very rapid cooling we would expect in this region. Basal line spacings were measured to be about 15 cm at a lower point in the flow. Columns were also larger here, implying that the lower portions of the flows cooled more slowly than the upper surface, as expected.

A distinct entablature and lower colonnade was exhibited by Flow 7. Well developed columns averaging about 70 cm across were seen in the colonnade of the moderate sized flow. No chisel structures were seen, indicating that fracture propagation was steady, perhaps a result of rapid cooling. A higher percentage of glass in the colonnade suggested that cooling of this region was more rapid that that of the entablature, contradicting observations of Long and Wood (1986). Since the flow is not covered by a more recent flow, the only plausible explanation which could result in such a cooling profile seems to be that the lava flowed overtop an ice sheet. Melting of the ice sheet resulted in rapid cooling of the lower portion of the flow. The slower rate of cooling and the complex stress distribution in the upper portion could have prevented ordered columns from forming.

The last flow studied, Flow 8, was a large flow with well defined columns averaging 50 cm across. Chisel structures were closely spaced, about 5.5 cm between basal lines. Both these observations suggest rapid cooling of the flow.

Chemical, mineralogical and petrographic studies do not support either the simple convection or double-diffusive convection hypotheses for the development of columnar joints. While these studies do not provide conclusive proof of column formation by contraction, they do not contradict such a hypothesis. No evidence exists to explain the origin of columnar jointing in the Garibaldi area by any hypothesis other than a purely contractive one. The development of columnar jointing in all the flows studied can be adequately explained by such a hypothesis.

VII - SUMMARY

Three theories have been proposed to explain the origin of columnar joints. The first hypothesis suggests that the columns form by contraction during cooling of the magma. Simple convection has also been proposed to explain the joints. Finally, some people believe that double-diffusive convection may be responsible for the column formation.

Recent alkali olivine basalt flows from the Garibaldi area of southwest British Columbia were studied. The chemistry, mineralogy, and petrography of these flows was examined with the primary objective of determining the origin of the columnar jointing in the unit.

Whole rock chemical analyses did not reveal any variations in chemistry which influence the jointing styles. In addition, no variations in chemistry between the entablature and lower colonnade were detected, contrary to what is expected if the zones form as a result of double-diffusive convection. Mineralogically and petrographically the flows are very similar. No evidence to support a convection hypothesis was seen. Chemical, mineralogical and petrographic evidence all suggest a contractive origin to the joints.

Mathematical modelling of the cooling of a typical flow allowed calculations of the Rayleigh number for different thicknesses of the flow. These calculations showed that in theory, double-diffusive convection is possible in flows whose thickness is greater than about 2 metres. However, no change in jointing style is seen in flows less than 2 metres versus flows greater than 2 metres in thickness, so it is

believed that all joints form by the same mechanism and that this mechanism is one of contraction during cooling. The joint development in all the flows studied can be adequately explained by such a hypothesis.

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STANDARDS USED IN ELECTRON MICROPROBE ANALYSES

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	Olivine	Augite	Plag	Ilmenite	Mag	Cr-Spinel
Si	Sus. Oliv. EPS 45	Pyx-1 EPS 91	An50 glass EPS 58	Ferrosal. EPS 27	Ferrosal. EPS 27	Ferrosal. EPS 27
Al	Diopside EPS 186	Diopside EPS 186	An50 glass EPS 58	Spinel EPS 20	Spinel EPS 20	Spinel EPS 20
Fe	Sus. Oliv. EPS 45	Ferrosal. EPS 27	Alm. 4 EPS 239	Il/Hem EPS 115	Hem. EPS 51	Hem. EPS 51
Mg	Ev. Oliv. EPS 1	Ev. Enst. EPS 2	Pyx-1 EPS 91	Spinel EPS 20	Spinel EPS 20	Spinel EPS 20
Ca	Pyx-1 EPS 91	Pyx-1 EPS 91	An50 glass EPS 58	Ferrosal. EPS 27	Ferrosal. EPS 27	Ferrosal. EPS 27
Ti	TiO2 EPS 79	TiO2 EPS 79	• •	TiO2 EPS 79	Il/Hem EPS 115	Il/Hem EPS 115
к			Or-1 EPS 90			
Na	Diopside EPS 186	Diopside EPS 186	Albīte EPS 113	Albite EPS 113	Albite EPS 113	Albite EPS 113
Mn	Rhodonite EPS 84	Rhodonite EPS 84				
Ba			Hyalophane EPS 83			
Cr				Cr2O3 EPS 18	Cr203 EPS 18	Cr203 EPS 18

EPS: electron probe standard, Department of Geology and Geophysics, University of Calgary.

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APPENDIX 2

WET CHEMICAL ANALYSES (wt %)

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	<u>03-01</u>	<u>03-02</u>	<u>07-02</u>	<u>07-03</u>	<u>07-04</u>	<u>07-06</u>	<u>Analytical</u>
							Uncertainty
	1						
sio2	49.75	49.99	49.89	51.00	50.05	50.35	0.02
TiO2	1.46	1.50	1.47	1.50	1.45	1.48	0.02
Al203	15.62	15.65	15.66	15.63	15.46	15.55	0.02
Fe203	0.55	0.73	0.99	1.86	1.14	1.42	0.04
FeO	9.68	9.94	9.60	8.81	9.27	9.24	0.04
MnO	0.15	0.19	0.16	0.18	0.16	-	0.002
MgO	7.84	7.35	7.39	6.85	7.41	7.09	0.06
Ca0	8.66	8.94	8.84	8.99	8.80	8.39	0.06
Na2O	3.50	3.47	3.38	3.50	3.39	3.53	0.02-0.04
к20	0.49	0.50	0.47	0.51	0.48	0.52	0.02
P205	0.22	0.24	0.22	0.23	0.22	0.23	0.006
H20+	0.28	0.29	0.49	0.33	0.44	0.57	0.02
H20-	0.37	0.38	0.19	0.18	0.19	0.15	0.02

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Total 99.65 100.28 99.82 100.55 99.49 99.54

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= not analyzed

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APPENDIX 3

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- a) ANALYTICAL PRECISION AND DETECTION LIMITS FOR THE ELECTRON MICROPROBE
- b) ELECTRON MICROPROBE ANALYSES OF MINERAL PHASES

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	Detection Limit (wt. %)	Precision (wt. %)
PLAGIOCLASE		
Si02	0.050	0.471
Al203	0.044	0.425
FeO	0.038	0.039
MgO	0.028	0.016
CaO	0.013	0.084
Na2O	0.021	0.071
K20	0.012	0.011
OLIVINE		
si02	0.047	0.312
TiO2	0.022	0.010
Al203	0.041	0.020
FeO	0.042	0.194
MnO	0.068	0.041
MgO	0.027	0.224
CaO	0.014	0.010
PYROXENE		
SiO2	0.044	0.351
TiO2	0,022	0.016
Al203	0.040	0.077
FeO	0.041	0.115
MnO	0.064	0.036
MgO	0.028	0.116
CaO	0.013	0.058
Na2O	0.021	0.015
Fe-Ti OXIDES		
si02	0.045	0.037
TiO2	0.025	0.075
Cr203	0.082	0.029
Al203	0.036	0.057
FeO	0.045	0.297
MgO	0.025	0.022
CaO	0.015	0.008

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FLOW 1 - PLAGIOCLASE ANALYSES

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	01-02			01-04			01-05				01-06					
	RP	СР	RG	CG	RP	CP	RG	CG	RP	СР	RG	CG	RP	CP	RG	CG
SiO2	52.32	52.16	55.08	54.25	52.69	52.35	54.84	54.36	53.46	52.45	55.80	54.79	52.91	52.34	55.51	54.51
Al203	29.06	29.36	27.06	27.83	28.92	29.34	27.65	27.88	28.68	29.41	27.06	27.70	29.06	29.39	26.94	27.74
FeO	0.61	0.53	0.83	0.79	0.68	0.59	0.92	0.87	0.72	0.54	0.89	0.87	0.66	0.54	0.90	0.95
MgO	0.18	0.13	0.09	0.11	0.12	0.14	0.09	0.10	0.12	0.15	0.09	0.10	0.11	0.14	0.06	0.16
Ca0	12.91	13.15	10.53	11.36	12.59	12.99	10.92	11.31	12.24	13.02	10.28	10.99	12.55	12.99	10.04	10.96
Na2O	4.22	4.06	5.51	5.09	4.38	4.18	5.30	5.08	4.59	4.15	5.65	5.22	4.35	4.18	5.72	5.21
K20	0.11	0.09	0.24	0.19	0.14	0.09	0.24	0.22	0.15	0.09	0.26	0.20	0.14	0.10	0.31	0.24
Total	99.41	99.48	99.34	99.62	99.51	99.68	99.96	99.82	99.96	99.81	100.03	99.87	99.78	99.68	99.48	99.77

WEIGHT PERCENT END MEMBERS

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An	64.04	65.23	52.24	56.35	62.46	64.44	51.00	56.11	60.72	64.59	51.00	54.52	62.26	64.44	49.81	54.37
Ab	35.71	34.35	46.62	43.07	37,06	35.37	47.81	42.98	38.84	35.12	47.81	44.17	36.81	35.37	48.40	44.08
Or	0.65	0.53	1.42	1.12	0.83	0.53	1.54	1.30	0.89	0.53	1.54	1.18	0.83	0.59	1.83	1.42

MOLE PERCENT END MEMBERS

An	62,43	63.82	50.66	54.62	60.87	62.87	52.51	54.47	59.06	63.09	49.39	53.16	60.96	62.83	48.36	53.01
Ab	36.93	35.66	47.97	44.29	38.32	36.61	46.12	44.27	40.08	36.39	49.12	45.69	38.23	36.59	49.86	45.60
Or	0.63	0.52	1.37	1.09	0.63	0.52	1.37	1.26	0.86	0.52	1.49	1.15	0.81	0.58	1.78	1.38

- RP = rim of phenocryst
 CP = core of phenocryst
 RG = rim of groundmass plagioclase
- CG = core of groundmass plagioclase

note : all iron as FeO

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FLOW 1 - OLIVINE ANALYSES

	01-02		01-04			01-05			01-06			
	RP	CP	GM	RP	CP	GM	RP	СР	GM	RP	CP	GM
SiO2	37.89	38.49	36.15	38.17	38.76	36.26	37.23	38.86	36.42	37.30	38.21	35.62
TiO2	-	-	0.05	-	-	0.05	-	-	0.06	0.04	-	0.05
Al203	-	-	0.05	-	-	0.04	-	-	0.05	0.06	-	0.07
Fe0	25.41	21.28	35.20	24.05	20.04	33.30	28.92	19.96	33.47	28.73	24.10	38.13
MnO	0.33	0.27	0.48	0.31	0.25	0.44	0.38	0.26	0.45	0.39	0.32	0.52
MgO	36.25	39.71	28.08	37.44	40.82	29.72	33.47	40.95	29.65	33.43	37.47	25.72
CaO	0.26	0.21	0.30	0.25	0.22	0.25	0.26	0.21	0.30	0.31	0.24	0.26
Total	100.14	99.96	100.31	100.22	100.09	100.06	100.26	100.24	100.40	100.26	100.34	100.37

WEIGHT PERCENT END MEMBERS

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Fo	63.26	69.30	49.01	65.34	71.24	51.87	58.41	71.47	51.75	58.34	65.39	44.89
Fa	36.04	30.18	49.92	34.11	28.42	47.23	41.01	28.31	47.47	40.74	34.18	54.08
La	0.40	0.32	0.46	0.38	0.34	0.38	0.40	0.32	0.46	0.48	0.37	0.40
Тр	0.47	0.38	0.68	0.44	0.36	0.63	0.54	0.37	0.64	0.56	0.46	0.74

MOLE PERCENT END MEMBERS

Fo	71.24	76.43	58.11	73.00	77.95	60.86	66.81	78.08	60.63	66.87	72.98	54.04
Fa	28.02	22.98	40.87	26.31	21.47	38.26	32.39	21.35	38.40	32.24	26.33	44.95
La	0.37	0.29	0.45	0.35	0.30	0.37	0.37	0.29	0.44	0.45	0.34	0.39
Тр	0.37	0.30	0.56	0.34	0.27	0.51	0.43	0.28	0.52	0.44	0.35	0.62

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RP = rim of phenocryst CP = core of phenocryst GM = groundmass olivine

note : all iron as Fe0
- = below detection limit

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	01-02	01-04	01-05	01-06
Si02	49.71	49.33	51.35	49.89
TiO2	1.78	1.95	1.08	1.73
Al203	3.00	2.92	2.14	2.91
FeO	11.73	12.26	11.10	11.53
MnO	0.23	0.24	0.25	0.23
MgO	13.62	13.65	15.61	14.20
Ca0	19.04	18.90	18.25	18.79
Na2O	0.47	0.45	0.38	0.42
Total	99.58	99.70	100.16	99.70

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NUMBER OF IONS ON BASIS OF 12 POSITIVE CHARGES

Si	1.881	1.870	1.916	1.882
Al iv	0.119	0.130	0.084	0.118
Ti	0.051	0.056	0.030	0.049
AL	0.015	0.001	0.010	0.011
Fe2	0.371	0.389	0.346	0.364
Mn	0.007	0.008	0.008	0.007
Mg	0.768	0.771	0.868	0.798
Ca	0.772	0.768	0.730	0.759
Na	0.034	0.033	0.027	0.031
Total	2.018	2.026	2.019	2.019

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note : all iron as FeO

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FLOW 1 - Fe-Ti OXIDE ANALYSES

Magnetite-Ulvospinel Series

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	01-02	01-04	01-05	01-06	
5102	0.08	_	0.07	-	
Ti02	10.82	16 50	23 21	22 70	
AI 203	0.90	0 69 0	0.08	0.75	
FeO	46 00	/3 53	40.50	40.07	
Fe203	28 /8	45.55	47.07	49.03	
MaO	1 28	1 /7	1 70	4.41	
ngo CaO	0.08	0.11	0.1/	1.05	
Total	0.00	0.11	0.14	0.09	
Totat	77.54	90.04	90.00	90.01	
	Maximum Mole Percent End Members				
Magnetite	40.85	51.17	63.55	61.55	
Ulvospinel	56.41	46.06	32.36	34.36	
<u>Hematite-I</u>	lmenite Ser	ies			
	01-02	01-04	01-05	01-06	
Si02	0.36	0.45	0.34	-	
TiO2	49.48	46.88	49.39	50.50	
AL203	0.13	0.14	0.12	0.07	
FeO	41.42	37.93	40.47	40.81	
Fe203	5.23	11.30	6.44	5.56	
MgO	1.90	2.51	2.18	2.47	
CaO	0.09	0.23	0.36	0.17	
Total	98.61	99.44	99.30	99.58	
Max % Hem.	6.07	11.95	7.09	5.37	
<u>Chrome-ric</u> ł	<u>ı spinel</u>		,		
	01-02	01-04	01-05	01-06	
SiO2	-	-		-	
TiO2	-	13.97	-	18.72	
Cr203	-	8.02	-	5.51	
Al203	-	2.30	-	0.77	
Fe0	-	41.05	-	45.69	
Fe203	-	31.45	-	26.56	
MgO	-	2.00	-	1.69	
CaO	-	0.05	-	0.08	
Total	-	98.84		99.02	

note : - below detection limit

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FLOW 2 - PLAGIOCLASE ANALYSES

		0	2-01			Ő	2-02			02	2-03			02	2-04	
	RP	СР	RG	CG	RP	СР	RG	CG	RP	CP	RG	CG	RP	CP	RG	CG
sio2	52.85	52.71	56.06	55.01	53.12	52.61	56.95	55.34	52.91	52.56	56.62	54.95	53.37	52.30	56.48	54.98
Al203	29.12	29.34	26.83	27.43	28.80	29.37	26.42	27.42	29.17	29.51	26.43	27.08	28.62	29.41	26.23	27.27
Fe0	0.65	0.58	1.04	0.95	0.68	0.57	0.95	0.94	0.72	0.57	0.96	1.14	0.66	0.55	0.94	0.95
MgO	0.14	0.15	0.13	0.14	0.13	0.14	0.09	0.14	0.14	0.15	0.10	0.31	0.14	0.15	0.09	0.12
CaO	12.97	13.05	10.10	10.99	12.37	12.87	9.41	10.70	12.68	13.03	9.52	10.95	12.20	12.96	9.44	10.67
Na2O	4.19	4.15	5.66	5.25	4.39	4.11	6.06	5.34	4.28	4.10	5.98	5.17	4.46	4.04	6.06	5.40
K20	0.11	0,09	0.25	0.19	0.15	0.12	0.33	0.24	0.14	0.09	0.34	0.20	0.16	0.11	0.33	0.24
Total	100.03	100.07	100.07	99.96	99.64	99.79	100.21	100.12	100.04	100.01	99.95	99.80	99.61	99.52	99.57	99.63

WEIGHT PERCENT END MEMBERS

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 An
 64.34
 64.74
 50.10
 54.52
 61.37
 63.85
 46.68
 53.08
 62.90
 64.29
 47.23
 54.32
 60.52
 64.64
 47.23
 52.93

 Ab
 35.45
 35.12
 47.89
 44.42
 37.15
 34.78
 51.28
 45.18
 36.22
 34.18
 50.60
 43.75
 37.74
 34.69
 51.28
 45.69

 Or
 0.65
 0.53
 1.48
 1.12
 0.89
 0.71
 1.95
 1.42
 0.83
 0.65
 2.01
 1.18
 0.95
 0.53
 1.95
 1.42

MOLE PERCENT END MEMBERS

An 62.71 63.14 48.93 53.05 60.36 62.93 45.31 51.82 61.58 63.39 45.89 53.30 59.62 63.52 45.39 51.48 Ab 36.66 36.34 49.62 45.86 39.44 35.83 52.72 47.14 38.77 36.37 52.80 46.80 37.61 36.09 52.16 45.54 Or 0.63 0.52 1.44 0.81 0.52 1.95 1.16 0.93 0.64 1.89 1.38 1.09 0.87 0.70 1.89 1.38

> RP = rim of phenocryst CP = core of phenocryst RG = rim of groundmass plagioclase

CG = core of groundmass plagioclase

note : all iron as FeO

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FLOW 2 - PLAGIOCLASE ANALYSES, CONT.

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		0	2-05			02	-06			02	2-07			0	2-08	
	RP	CP	RG	CG	RP	CP	RG	CG	RP	CP	RG	CG	RP	CP	RG	CG
Si02	52.91	52.28	55.53	55.66	52.99	52.57	55.03	54.60	52.99	52.62	55.94	55.06	53.09	52.63	55.93	55.04
Al203	29.24	29.72	27.28	27.14	28.53	28.97	26.88	27.46	28.94	29.12	26.55	27.15	28.86	29.29	27.04	27.66
Fe0	0.64	0.54	0.98	1.12	0.68	0.58	0.96	0.91	0.64	0.56	0.96	0.97	0.67	0.55	0.87	0.88
MgO	0.14	0.14	0.13	0.15	0.15	0.15	0.16	0.14	0.14	0.15	0.12	0.15	0.15	0.15	0.12	0.15
Ca0	12.50	12.99	10.33	10.35	12.57	12.99	10.76	11.21	12.75	12.97	10.23	10.89	12.56	13.02	10.41	11.25
Na2O	4.41	4.14	5.60	5.51	4.35	4.11	5.37	5.15	4.25	4.14	5.65	5.29	4.35	4.10	5.58	5.09
K20	0.12	0.09	0.24	0.27	0.12	0.09	0.21	0.18	0.12	0.09	0.24	0.20	0.12	0.09	0.24	0.18
Total	99.96	99.90	100.09	100.20	99.39	99.46	99.37	99.65	99.83	99.65	99.69	99.71	99.80	99.83	100.19	100.25

WEIGHT PERCENT END MEMBERS

 An
 62.01
 64.44
 51.25
 51.34
 62.36
 64.44
 53.38
 55.61
 63.25
 64.34
 50.75
 54.02
 62.31
 64.59
 51.64
 55.81

 Ab
 37.32
 35.03
 47.38
 46.62
 36.81
 34.78
 45.44
 43.58
 35.96
 35.03
 47.81
 44.76
 36.81
 34.69
 47.22
 43.07

 Or
 0.71
 0.53
 1.42
 1.60
 0.71
 0.53
 1.42
 1.18
 0.71
 0.53
 1.42
 1.06

MOLE PERCENT END MEMBERS

An 60.61 63.09 49.78 50.14 61.06 63.26 51.91 54.04 61.94 63.06 49.32 52.61 61.05 63.37 50.06 54.41 38.70 36.39 48.84 48.30 Ab 38.24 36.22 46.88 44.93 37.36 36.42 49.30 46.24 38.26 36.11 48.56 44.55 0.52 1.38 Or 0.69 1.56 0.69 0.52 1.21 1.03 0.69 0.52 1.38 1.15 0.69 0.52 1.37 1.04

> RP = rim of phenocryst CP = core of phenocryst RG = rim of groundmass phase CG = core of groundmass phase

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note : all iron as FeO

FLOW 2 - PLAGIOCLASE ANALYSES, CONT.

		02	2-09			02	2-10			02	- 11	
	RP	CP	RG	CG	RP	CP	RG	CG	RP	CP	RG	CG
si02	53.30	52.60	55.74	54.88	53.43	52.95	55.46	55.01	53.62	52.83	55.49	55.26
Al203	29.02	29.43	27.48	27.74	29.40	29.97	28.15	28.10	28.48	29.16	27.10	27.22
Fe0	0.69	0.58	0.94	0.98	0.68	0.57	0.91	0.99	0.69	0.55	0.96	0.97
MgO	0.14	0.15	0.13	0.16	0.15	0.15	0.14	0.15	0.15	0.15	0.13	0.17
CaO	12.48	12.86	10.66	11.15	12.53	12.94	10.90	11.13	12.27	12.94	10.55	10.93
Na2O	4.44	4.14	5.45	5.15	4.36	4.13	5.26	5.12	4.49	4.09	5.42	5.20
к20	0.13	0.10	0.22	0.19	0.12	0.09	0.19	0.20	0.13	0.10	0.22	0.19
Total	100.20	99.96	100.62	100.25	100.67	100.80	101.01	100.70	99.83	99.82	99.87	99.94

WEIGHT PERCENT END MEMBERS

An	61.91	64.29	52.88	55.31	62.16	64.19	54.07	55.21	60.87	64.19	52.34	54.22
Ab	37.57	35.03	46.12	43.58	36.89	34.95	44.51	43.32	37.99	34.61	45.86	44.00
Or	0.77	0.59	1.30	1.12	0.71	0.53	1.12	1.18	0.77	0.59	1.30	1.12

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MOLE PERCENT END MEMBERS

An	60.38	63.00	51.29	53.88	60.94	63.06	52.80	53.94	59.71	63.24	51.16	53.15
Ab	38.87	36.42	47.45	45.03	38.37	36.42	46.11	44.90	39.54	36.17	47.57	45.75
Or	0.75	0.58	1.26	1.09	0.69	0.52	1.10	1.15	0.75	0.58	1.27	1.10

RP = rim of phenocryst
CP = core of phenocryst
RG = rim of groundmass plagioclase

CG = core of groundmass plagioclase

note : all iron as FeO

FLOW 2 - OLIVINE ANALYSES

		02-01			02-02	2		02-03	;		02-04	÷
	RP	CP	GM	RP	CP	GM	RP	CP	GM	RP	CP	GM
sio2	38.02	38.01	37.65	38.17	38.48	37.04	38.31	38.95	37.31	38.23	38.79	37.17
TiO2	-	-	0.03	-	-	0.04	-	-	0.03	-	-	0.04
Al203	-	-	-	-	-	0.06	0.06	0.04	0.04	-	-	-
FeO ·	21.95	20.96	24.92	22.83	20.09	28.46	22.54	20.15	28.64	22.91	20.30	29.18
MnO	0.30	0.29	0.35	0.31	0.26	0.40	0.32	0.27	0.41	0.32	0.27	0.42
MgO	39.71	40.48	37.22	38.83	41.26	34.01	39.15	41.14	33.94	38.79	41.03	33.41
CaO	0.23	0.23	0.27	0.24	0.21	0.32	0.26	0.23	0.30	0.24	0.21	0.30
Total	100.21	99.97	100.44	100.38	100.30	100.33	100.64	100.78	100.67	100.49	100.60	100.52

WEIGHT PERCENT END MEMBERS

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Fo	69.30	70.65	64.96	67.77	72.01	59.35	68.32	71.80	59.23	67.70	71.61	58.31
Fa	31.13	29.73	35.34	32.38	28.49	40.36	31.97	28.58	40.62	32.49	28.79	41.38
La	0.35	0.35	0.41	0.37	0.32	0.49	0.40	0.35	0.46	0.37	0.32	0.46
Тр	0.43	0.41	0.50	0.44	0.37	0.57	0.46	0.38	0.58	0.46	0.38	0.60

MOLE PERCENT END MEMBERS

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Fo	75.84	77.00	72.14	74.69	78.10	67.43	75.05	77.97	67.26	74.60	77.82	66.51
Fa	23.52	22.37	27.10	24.64	21.34	31.66	24.24	21.43	31.85	24.72	21.60	32.59
La	0.32	0.31	0.38	0.33	0.29	0.46	0.36	0.31	0.43	0.33	0.29	0.43
Тр	0.33	0.31	0.39	0.34	0.28	0.45	0.35	0.29	0.46	0.35	0.29	0.48

RP = rim of phenocryst CP = core of phenocryst GM = groundmass olivine

note : all iron as FeO - = below detection limit

FLOW 2 - OLIVINE ANALYSES, CONT.

		02-05	;		02-06			02-07			02-08	
	RP	CP	GM	RP	CP	GM	RP	CP	GM	RP	СР	GM
Si02	38.06	38.72	37.52	37.57	38.20	37.16	38.36	38.56	36.71	38.17	38.98	36.98
TiO2	-	-	0.03	-	-	0.03	-	-	0.06	0.03	-	0.05
Al203	0.04	-	0.04	-	0.04	0.04	-	-	0.05	0.04	0.04	0.05
FeO	23.07	19.93	27.57	22.93	20.43	25.19	20.22	18.65	29.40	22.45	18.05	28.59
MnO	0.31	0.27	0.40	0.32	0.27	0.36	0.26	0.24	0.40	0.30	0.23	0.39
MgO	38.69	41.20	34.78	38.50	40.60	36.63	40.70	41.93	32.73	38.60	42.25	33.44
CaO	0.24	0.21	0.30	0.25	0.23	0.29	0.22	0.21	0.36	0.26	0.21	0.31
Total	100.41	100.33	100.64	99.57	99.77	99.70	99.76	99.59	99.71	99.85	99.76	99.81

WEIGHT PERCENT END MEMBERS

Fo	67.52	71.90	60.70	67.19	70.86	63.93	71.03	73.18	57.12	67.36	73.73	58.36
Fa	32.72	28.26	39.10	32.52	28.97	35.72	28.68	26.45	41.70	31.84	25.60	40.55
La	0.37	0.32	0.46	0.38	0.35	0.45	0.34	0.32	0.55	0.40	0.32	0.48
Тр	0.44	0.38	0.57	0.46	0.38	0.51	0.37	0.34	0.57	0.43	0.33	0.56

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MOLE PERCENT END MEMBERS

Fo	74.43	78.20	68.61	74.43	77.51	71.58	77.74	79.59	65.84	74.87	80.23	66.98
Fa	24.90	21.22	30.52	24.87	21.88	27.62	21.67	19.86	33.18	24.43	19.23	32.13
La	0.33	0.29	0.43	0.35	0.32	0.41	0.30	0.29	0.52	0.36	0.29	0.45
Тр	0.34	0.29	0.45	0.35	0.29	0.40	0.28	0.26	0.46	0.33	0.25	0.44

RP = rim of phenocryst
CP = core of phenocryst
GM = groundmass olivine

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note : all iron as FeO - = below detection limit FLOW 2 - OLIVINE ANALYSES, CONT.

		02-09)		02-10			02-11	
	RP	CP	GM	RP	CP	GM	RP	CP	GM
Si02	38.25	39.00	36.27	38.32	38.70	36.60	38.50	38.69	36.97
Ti02	-	-	0.08	-	-	0.05	-	-	0.06
Al203	-	0.04	0.11	0.04	-	0.04	0.04	0.04	-
Fe0	22.28	19.20	33.44	21.53	19.32	29.40	22.34	20.68	31.60
MnO	0.29	0.25	0.48	0.31	0.26	0.40	0.29	0.27	0.44
MgO	38.94	41.74	29.37	39.60	41.52	32.81	39.27	40.70	31.32
Ca0	0.24	0.21	0.37	0.23	0.22	0.34	0.25	0.22	0.36
Total	100.00	100.44	100.12	100.03	100.02	99.64	100.69	100.60	100.75

WEIGHT PERCENT END MEMBERS

Fo	67.96	72.84	51.26	69.11	72.46	57.26	68.53	71.03	54.66
Fa	31.60	27.23	47.42	30.53	27.40	41.70	31.68	29.33	44.82
La	0.37	0.32	0.57	0.35	0.34	0.52	0.38	0.34	0.55
Тр	0.41	0.36	0.68	0.44	0.37	0.57	0.41	0.38	0.63

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MOLE PERCENT END MEMBERS

Fo	75.21	79.04	60.34	76.12	78.84	65.91	75.30	77.35	63.20
Fa	24.14	20.40	38.55	23.22	20.58	33.14	24.04	22.05	35.78
La	0.33	0.29	0.55	0.32	0.30	0.49	0.34	0.30	0.52
Тр	0.32	0.27	0.56	0.34	0.28	0.46	0.32	0.29	0.50

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RP = rim of phenocryst CP = core of phenocryst GM = groundmass olivine

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note : all iron as FeO - = below detection limit

FLOW 2 - PYROXENE ANALYSES

	02-01	02-02	02-03	02-04	02-05	02-06	02-07	02-08	02-09	02-10	02-11
SiO2	51.49	51.29	51.63	51.71	51.10	50.62	50.16	50.72	50.48	50.68	50.30
TiO2	1.17	1.32	1.02	1.10	1.17	1.07	1.34	1.09	1.18	1.27	1.55
Al203	2.29	2.93	2.32	2.39	2.49	2.31	2.42	2.31	2.43	2.13	2.51
Fe0	11.76	12.30	11.60	11.24	12.57	10.26	11.70	11.15	11.22	12.35	12.38
MnO	0.29	0.28	0.25	0.26	0.29	0.23	0.26	0.25	0.24	0.29	0.27
MgO	15.39	13.93	15.77	15.48	15.33	15.64	15.00	15.77	15.60	15.16	14.39
CaO	17.93	17.64	17.79	17.82	16.92	18.87	18.24	17.90	18.00	17.48	18.43
Na2O	0.39	0.61	0.40	0.39	0.44	0.36	0.39	0.36	0.39	0.34	0.41
Total	100.71	100.30	100.78	100.39	100.31	99.36	99.51	99.55	99.54	99.70	100.24

NUMBER OF IONS ON BASIS OF 12 POSITIVE CHARGES

Si	1.914	1.917	1.915	1.922	1.910	1.903	1.894	1.905	1.899	1.909	1.892
Al iv	0.086	0.083	0.085	0.078	0.090	0.097	0.106	0.095	0.101	0.091	0.108
Ti	0.033	0.037	0.028	0.031	0.033	0.030	0.038	0.031	0.033	0.036	0.044
Al	0.015	0.046	0.016	0.026	0.020	0.006	0.002	0.007	0.006	0.004	0.003
Fe2	0.366	0.384	0.360	0.349	0.393	0.323	0.369	0.350	0.353	0.389	0.389
Mn	0.009	0.009	0.008	0.008	0.009	0.007	0.008	0.008	0.008	0.009	0.009
Mg	0.853	0.776	0.872	0.857	0.854	0.876	0.844	0.883	0.875	0.851	0.807
Ca	0.714	0.706	0.707	0.709	0.678	0.760	0.738	0.720	0.725	0.706	0.743
Na	0.028	0.044	0.029	0.028	0.032	0.026	0.029	0.026	0.028	0.025	0.030
Total	2.018	2.002	2.020	2.008	2.019	2.028	2.028	2.025	2.028	2.020	2.025

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note : all iron as FeO

FLOW 2 - Fe-Ti OXIDE ANALYSES

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Magnetite-Ulvospinel Series

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	02-01	02-02	02-03	02-04	02-05	02-06
Si02	0.34	0.19	0.16	0.13	0.35	0.88
TiO2	20.83	20.60	20.42	21.43	20.37	21.50
Al203	1.34	1.07	0.93	1.10	1.03	1.11
Fe0	48.61	47.97	47.81	48.31	48.10	49.47
Fe203	25.80	27.17	27.77	25.54	27.02	22.35
Mg0	1.10	1.33	1.27	1.45	1.14	0.99
Ca0	0.20	0.11	0.14	0.17	0.17	0.29
Total	98.22	98.44	98.50	98.18	98.18	96.59

Maximum Mole Percent End Members

Magnetite	36.63	38.53	39.41	36.25	38.45	32.20
Hemetite	60.92	58.58	57.85	60.51	59.06	65.46

Hematite-Ilmenite Series

	02-01	02-02	02-03	02-04	02-05	02-06
SiO2	1.89	-	1.36	-	2.66	-
TiO2	45.74	-	45.93	-	45.18	-
Al203	0.35	-	0.27	-	0.39	-
Fe0	41.36	-	40.72	-	41.30	-
Fe203	7.15	-	8.49	-	7.03	-
MgO	0.88	-	0.92	-	1.14	-
CaO	0.36	-	0.44	-	0.37	-
Total	97.73		98.13		98.07	-
Max % Hem.	12.21	-	12.00	-	14.01	-
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Chrome-rich spinel

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	02-01	02-02	02-03	02-04	02-05	02-06
Si02	-	_	-	_	_	-
TiO2	-	-	-	-	-	-
Al203	-	-	-	-	-	-
Cr203	-	-	-	•	-	-
Fe0	-	-	-	-	-	-
Fe203	-	-	-	-	-	-
MgO		-	-	-	-	-
CaO	-	-	-	-	-	-
Total	-	-	-	-	-	-

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FLOW 2 - Fe-Ti OXIDE ANALYSES, CONT.

Magnetite-Ulvospinel Series

	02-07	02-08	02-09	02-10	02-11
SiO2	0.58	0.42	0.60	0.41	0.64
TiO2	20.40	19.98	19.98	20.59	20.12
Al203	1.28	0.93	1.50	1.11	1.35
Fe0	48.24	47.64	47.89	47.91	48.09
Fe203	25.10	27.18	26.49	25.48	26.56
MgO	0.98	1.08	· 1.21	1.22	1.26
Ca0	0.22	0.20	0.23	0.13	0.22
Total	96.80	97.43	97.90	96.85	98.24
		Maximum M	lole Percent	End Members	
Magnetite	36.15	39.01	37.65	36.68	37.63
Ulvospinel	61.62	58.63	59.67	60.57	59.59
<u>Hematite-Iln</u>	menite Serio	es			
	02-07	02-08	02-09	02-10	02-11
SiO2	-	1.06	1.01	0.64	1.36
TiO2	-	46.48	46.21	46.06	47.01
Al203	-	0.25	0.23	0.22	0.31
Fe0	-	41.26	40.31	40.30	41.59
Fe203	-	7.51	8.50	9.25	6.77
Mg0	-	0.68	1.05	0.89	1.11
CaO	-	0.46	0.45	0.23	0.26
Total	-	97.70	97.76	97.59	98.41

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Chrome-rich spinel

Max % Hem.

	02-07	02-08	02-09	02-10	02-11
SiO2	-	-	-	-	0.12
TiO2	-	-	-	-	13.15
Cr203	-	-	-	-	16.97
Al203	-	-	-	-	3.21
Fe0	-	-	-	-	40.74
Fe203	-	-	-	-	22.25
MgO	-	-	-	-	1.90
Ca0	-	-	-	-	0.08
Total	-	-	-	-	98.42

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10.93

FLOW 3 - PLAGIOCLASE ANALYSES

	03-01					03-02				03-03			
	RP	CP	RG	CG	RP	CP	RG	CG	RP	ĊP	RG	CG	
Si02	52.93	52.53	55.76	54.63	53.03	52.31	54.73	53.98	53.37	52.33	55.81	54.15	
Al203	28.70	29.23	26.89	27.80	28.85	29.30	27.36	28.00	28.58	29.38	26.81	27.90	
FeO	0.71	0.59	0.86	0.86	0.69	0.56	0.93	0.91	0.68	0.54	0.88	0.78	
MgO	0.09	0.13	0.06	0.07	0.10	0.14	0.07	0.07	0.11	0.14	0.10	0.10	
Ca0	12.24	12.82	10.13	11.02	12.27	13.13	11.05	11.44	12.08	12.99	10.34	11.32	
Na2O	4.48	4.24	5.75	5.22	4.42	4.09	5.22	4.98	4.64	4.14	5.61	5.05	
К20	0.16	0.12	0.29	0.23	0.16	0.10	0.24	0.22	0.16	0.09	0.29	0.21	
Total	99.31	99.66	99.74	99.83	99.52	99.63	99.60	99.60	99.62	99.61	99.84	99.51	

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WEIGHT PERCENT END MEMBERS

An	60.72	63.60	50.25	54.67	60.87	65.14	54.82	56.75	59.93	64.44	51.29	56.16
Ab	37.91	35.88	48.65	44.17	37.40	34.61	44.17	42.14	39.26	35.03	47.47	42.73
0r	0.95	0.71	1.71	1.36	0.95	0.59	1.42	1.30	0.95	0.53	1.71	1.24

MOLE PERCENT END MEMBERS

An	59.60	62.13	48.51	53.13	59.97	63.58	53.17	55.23	58.45	63.09	49.62	54.66
Ab	39.47	37.18	49.83	45.55	39.10	35.84	45.45	43.51	40.63	36.39	48.72	44.13
Or	0.93	0.69	1.65	1.32	0.93	0.58	1.37	1.26	0.92	0.52	1.66	1.21

RP = rim of phenocryst CP = core of phenocryst RG = rim of groundmass CG = core of groundmass

note : all iron as FeO

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FLOW 3 - OLIVINE ANALYSES

		03-01			03-02				03-03			
	RP	CP	GM	RP	CP	GM	RP	CP	GM			
SiO2	37.19	37.88	35.34	37.23	37.75	34.97	38.17	38.71	35.24			
TiO2	-	-	0.06	-	-	0.06	-	-	0.09			
Al203	0.04	0.04	0.07	0.06	-	-	0.09	0.04	0.10			
Fe0	30.23	25.92	40.37	29.27	25.67	41.96	24.07	20.81	39.90			
Mn0	0.43	0.36	0.62	0.41	0.34	0.64	0.30	0.27	0.59			
MgO	32.35	36.05	23.58	33.08	36.25	22.44	37.51	40.36	24.10			
CaO	0.26	0.24	0.28	0.26	0.23	0.27	0.26	0.22	0.26			
Total	100.50	100.49	100.32	100.31	100.24	100.34	100.40	100.41	100.28			

WEIGHT PERCENT END MEMBERS

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Fo	56.46	62.91	41.15	57.73	63.26	39.16	65.46	70.44	42.06
Fa	42.87	36.76	57.25	41.51	36.41	59.51	34.14	29.51	56.59
La	0.40	0.37	0.43	0.40	0.35	0.41	0.40	0.34	0.40
Тр	0.61	0.51	0.88	0.58	0.48	0.91	0.43	0.38	0.84

MOLE PERCENT END MEMBERS

Fo	65.03	70.73	50.40	66.26	71.06	48.22	73.02	77.10	51.27
Fa	34.10	28.53	48.42	32.90	28.23	50.59	26.29	22.30	47.62
La	0.38	0.34	0.43	0.37	0.32	0.42	0.36	0.30	0.40
Тр	0.49	0.40	0.75	0.47	0.38	0.78	0.33	0.29	0.71

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RP = rim of phenocryst CP = core of phenocryst GM = groundmass olivine

note : all iron as Fe0
- = below detection limit

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FLOW 3 - PYROXENE ANALYSES

	03-01	03-02	03-03
Si02	51.16	50.71	49.70
TiO2	1.32	1.42	1.90
Al203	2.46	2.55	3.14
Fe0	10.89	11.38	12.08
Mn0	0.27	0.26	0.25
MgO	14.75	14.54	13.37
CaO	18.83	18.56	19.33
Na2O	0.39	0.40	0.53
Total	100.07	99.82	100.30

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NUMBER OF IONS OF BASIS OF 12 POSITIVE CHARGES

Si	1.912	1.905	1.872
Al iv	0.088	0.095	0.128
Ti	0.037	0.040	0.054
Al	0.021	0.018	0.012
Fe2	0.340	0.357	0.381
Mn	0.009	0.008	0.008
Mg	0.822	0.814	0.751
Ca	0.754	0.747	0.780
Na	0.028	0.029	0.039
Total	2.011	2.013	2.025

note : all iron as FeO

FLOW 3 - Fe-Ti OXIDE ANALYSES

Magnetite-Ulvospinel Series

	03-01	03-02	03-03
SiO2	0.17	0.15	0.13
TiO2	23.42	21.23	19.20
Al203	0.95	0.86	0.70
FeO	49.10	47.51	46.08
Fe203	22.46	26.57	29.86
MgO	2.27	1.97	1.14
CaO	0.12	0.06	0.09
Total	98.49	98.35	97.20

Maximum Mole Percent End Members

Magnetite	31.54	37.56	42.85
Ulvospinel	63.25	58.15	54.13

Hematite-Ilmenite Series

	03-01	03-02	03-03
si02	0.17	0.06	0.16
TiO2	49.79	50.27	45.96
Al203	0.08	0.07	0.18
FeO	39.11	39.82	36.74
Fe203	7.00	6.51	14.03
MgO	3.01	2.99	2.61
CaO	0.39	0.10	0.10
Total	99.55	99.82	99.78
		•	
Max % Hem.	7.08	6.32	13.82

Chrome-rich spinel

	03-01	03-02	03-03
sio2	-	-	0.70
TiO2	•	-	23.99
Cr203	-	-	4.80
Al203	-	•	1.38
Fe0	-	-	49.74
Fe203	-	-	13.55
MgO	-	-	2.42
CaO	-	-	0.08
Total	-	-	96.66

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FLOW 4 - PLAGIOCLASE ANALYSES

		04	-01			04-05				04-08			
	RP	СР	RG	CG	RP	CP	RG	CG	RP	СР	RG	CG	
SiO2	53.97	52.97	55.80	54.91	53.56	52.70	56.84	55.07	53.76	52.68	54.95	53.97	
Al203	27.87	28.60	26.57	27.27	28.58	29.12	26.30	27.35	28.25	29.15	27.33	28.07	
FeO	0.81	0.64	0.90	0.92	0.73	0.59	0.86	0.89	0.78	0.60	0.95	0.88	
MgO	0.10	0.11	0.08	0.09	0.09	0.12	0.06	0.07	0.09	0.09	0.07	0.07	
Ca0	11.83	12.66	10.07	10.93	12.13	12.76	9.53	10.78	11.66	12.49	10.60	11.34	
Na2O	4.86	4.39	5.83	5.38	4.70	4.33	6.17	5.45	4.91	4.44	5.46	5.06	
K20	0.16	0.13	0.25	0.20	0.16	0.12	0.32	0.24	0.19	0.14	0.25	0.22	
Total	99.60	99.50	99.50	99.70	99.95	99.74	100.08	99.85	99.64	99.59	99.61	99.61	

WEIGHT PERCENT END MEMBERS

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An	58.69	62.80	47.28	54.22	60.17	63.30	47.28	53.48	57.84	61.96	52.58	56.26
Ab	41.12	37.15	52.21	45.52	39.77	36.64	52.21	46.12	41.55	37.57	46.20	42.82
Or	0.95	0.77	1.89	1.18	0.95	0.71	1.89	1.42	1.12	0.83	1.48	1.30

MOLE PERCENT END MEMBERS

An	56.83	60.99	45.22	52.29	58.25	61.53	45.22	51.51	56.13	60.36	51.01	54.63
Ab	42.25	38.27	52.98	46.57	40.84	37.78	52.98	47.13	42.78	38.83	47.55	44.11
Or	0.92	0.75	1.81	1.14	0.91	0.69	1.81	1.37	1.09	0.81	1.43	1.26

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RP = rim of phenocryst CP = core of phenocryst RG = rim of groundmass plagioclase

CG = core of groundmass plagioclase

note : all iron as FeO

FLOW 4 - OLIVINE ANALYSES

		04-01			04-05		04-08				
	RP	CP	GM	RP	CP	GM	RP	СР	GM		
si02	36.56	36.87	35.45	36.78	37.42	35.59	36.72	37.06	35.46		
TiO2	-	-	0.09	-	-	0.05	-	-	0.05		
Al203	-	-	0.06	-	-	-	-	-	-		
FeO	32.02	30.42	35.44	31.00	27.40	36.12	29.89	27.49	36.40		
MnO	0.44	0.42	0.50	0.43	0.38	0.51	0.42	0.37	0.52		
MgO	30.88	32.20	28.13	31.91	34.84	27.31	32.40	34.37	26.89		
CaO	0.26	0.27	0.28	0.24	0.24	0.29	0.24	0.24	0.26		
Total	100.16	100.18	99.95	100.36	100.28	99.87	99.67	99.53	99.58		

WEIGHT PERCENT END MEMBERS

Fo	53.89	56.20	49.09	55.69	60.80	47.66	56.54	59.98	46.93
Fa	45.41	43.14	50.26	43.96	38.86	51.23	42.39	38.99	51.62
La	0.40	0.41	0.43	0.37	0.37	0.45	0.37	0.37	0.40
Тр	0.63	0.60	0.71	0.61	0.54	0.73	0.60	0.53	0.74

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MOLE PERCENT END MEMBERS

Fo	62.66	64.79	58.00	64.18	68.85	56.81	65.35	68.50	56.26
Fa	36.45	34.34	41.00	34.98	30.38	42.16	33.82	30.74	42.73
La	0.38	0.39	0.41	0.35	0.34	0.43	0.35	0.34	0.39
Тр	0.51	0.48	0.59	0.49	0.43	0.60	0.48	0.42	0.62

RP = rim of phenocryst CP = core of phenocryst GM = groundmass olivine .

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note : all iron as Fe0
- = below detection limit

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FLOW 4 - PYROXENE ANALYSES

	04-01	04-05	04-08
SiO2	50.90	51.53	51.29
TiO2	1.07	0.99	0.99
Al203	1.97	1.97	2.09
Fe0	10.72	10.07	10.03
MnO	0.24	0.22	0.23
MgO	15.66	15.93	15.92
CaO	18.46	18.84	18.98
Na2O	0.38	0.36	0.37
Total	99.40	99.91	99.90

NUMBER OF IONS ON BASIS OF 12 POSITIVE CHARGES

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Si	1.914	1.921	1.914
Al iv	0.086	0.079	0.086
τi	0 070	0.028	0.038
11	0.030	0.028	0.028
AL	0.001	0.008	0.006
Fe2	0.337	0.314	0.313
Mn	0.008	0.007	0.007
Mg	0.878	0.885	0.886
Ca	0.744	0.753	0.759
Na	0.028	0.026	0.027
Total	2.026	2.021	2.026

note : all iron as FeO

Magnetite-Ulvospinel Series

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	04-01	04-05	04-08
SiO2	0.09	0.10	0.09
TiO2	21.99	21.35	21.53
A1203	1.64	1.49	1.26
Fe0	47.94	47.11	47.11
Fe203	25.03	26.75	25.87
MgO	2.32	2.54	2.39
CaO	0.08	0.07	0.07
Total	99.09	99.41	98.32
		Maximum Mole Percent	End Members
Magnetite	34.87	37.15	36.38
Ulvospinel	59.96	57.34	47.11
<u>Hematite-Ilme</u>	nite Series		
	04-01	04-05	04-08
si02	0.09	0.07	-
Ti02	47.34	48.58	48.18
Al203	0.13	0.16	0.10
FeO	38.92	38.65	38.32
Fe203	10.09	9.41	8.90
MgO	1.99	2.79	2.74
CaO	0.16	0.11	0.12
Total	98.72	99.77	98.36
Max % Hem.	10.01	9.21	8.66
<u>Chrome-rich</u> s	pinel		
	04-01	04-05	04-08
si02	-		-
Ti02	-	-	-
Cr203	-	-	-
Al203	-	•	-
FeO	-	-	-
Fe203	-	-	-
MgO	-	-	-
Ca0	-	-	-
Total	-	-	-

note : - below detection limit

FLOW 5 - PLAGIOCLASE ANALYSES

	05-01					05-02				05-03				05-04			
	RP	CP	RG	CG	RP	CP	RG	CG	RP	CP	RG	CG	RP	CP	RG	CG	
SiO2	53.26	52.65	55.18	54.60	53.10	52.50	55.33	55.19	53.45	52. 54	55.07	55.01	52.94	52.59	54.66	54.55	
Al203	28.29	28.95	27.11	27.27	28.72	29.17	26.95	27.12	28.91	29.62	26.97	27.15	29.05	29.40	27.64	27.74	
Fe0	0.67	0.60	0.92	0.89	0.66	0.56	0.92	0.95	0.71	0.57	1.18	0.96	0.66	0.55	0.89	0.83	
MgO	0.15	0.15	0.14	0.18	0.14	0.15	0.14	0.17	0.16	0.15	0.15	0.17	0.14	0.15	0.15	0.15	
Ca0	12.38	12.94	10.82	11.12	12.70	13.07	10.72	11.05	12.35	13.04	10.75	10.95	12,63	12.95	11.09	11.18	
Na2O	4.49	4.12	5.35	5.16	4.32	4.10	5.43	5.20	4.53	4.12	5.28	5.30	4.35	4.16	5.22	5.17	
к20	0.14	0.11	0.20	0.18	0.12	0.10	0.21	0.19	0.13	0.10	0.24	0.19	0.12	0.11	0.19	0.18	
Total	99.38	99.52	99.72	99.40	99.76	99.65	99.70	99.87	100.24	100.14	99.64	99.73	99.89	99.91	99.84	99.80	

WEIGHT PERCENT END MEMBERS

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An	61.41	64.19	53.68	55.16	63.00	64.84	53.18	54.82	61.27	64.69	53.33	54.32	62.65	64.24	55.02	55.46
Ab	37.99	34.86	45.27	43.66	36.55	34.69	45.95	44.00	38.33	34.86	44.68	44.85	36.81	35.20	44.17	43.75
Or	0.83	0.65	1.18	1.06	0.71	0.59	1.24	1.12	0.77	0.59	1.42	1.12	0.71	0.65	1.12	1.06

MOLE PERCENT END MEMBERS

An	59.89	63.04	52.17	53.79	61.47	63.42	51.55	53.42	59.65	63.26	52.21	52.73	61.18	62.84	53.41	53.88
Ab	39.31	36.32	46.68	45.17	37.84	36.00	47.25	45.49	39.60	36.17	46.40	46.18	38.13	36.53	45.50	45.09
Or	0.81	0.64	1.15	1.04	0.69	0.58	1.20	1.09	0.75	0.58	1.39	1.09	0.69	0.64	1.09	1.03

RP = rim of phenocryst CP = core of phenocryst RG = rim of groundmass plagioclase CG = core of groundmass plagioclase

note : all iron as FeO

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FLOW 5 : OLIVINE ANALYSES

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	05-01		05-02				05-03	5	05-04			
	RP	CP	GM									
Si02	38.31	39.02	36.65	37.78	38.49	36.99	37.93	38.53	36.88	38.12	38.61	37.36
Ti02	-	-	0.05	0.03	-	0.04	-	-	0.05	-	-	0.05
Al203	-	0.04	0.07	-	-	-	-	-	-	-	0.04	-
Fe0	23.32	19.10	30.53	26.08	22.19	30.80	25.31	21.92	31.27	24.53	21.71	27.98
Mn0	0.32	0.24	0.45	0.36	0.30	0.43	0.37	0.30	0.46	0.34	0.31	0.39
MgO	38.19	41.72	32.07	35.83	39.08	31.83	36.72	39.65	31.50	37.28	39.59	34.05
Ca0	0.27	0.19	0.37	0.31	0.23	0.34	0.31	0.23	0.38	0.31	0.24	0.34
Total	100.41	100.31	100.19	100.39	100.29	100.43	100.64	100.63	100.54	100.58	100.50	100.17

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WEIGHT PERCENT END MEMBERS

Fo	66.65	72.81	55.97	62.53	68.20	55.55	64.08	69.20	54.97	65.06	69.09	59.42
Fa	33.07	27.09	43.30	36.99	31.47	43.68	35.89	31.09	44.35	34.79	30.79	39.68
La	0.41	0.29	0.57	0.48	0.35	0.52	0.48	0.35	0.58	0.48	0.37	0.52
Тр	0.46	0.34	0.64	0.51	0.43	0.61	0.53	0.43	0.65	0.48	0.44	0.56

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MOLE PERCENT END MEMBERS

Fo	73.94	79.15	64.50	70.41	75.35	64.17	71.50	75.83	63.53	72.45	75.96	67.81
Fa	25.33	20.33	34.45	28.75	24.00	34.84	27.65	23.52	35.39	26.75	23.37	31.26
La	0.38	0.26	0.53	0.44	0.32	0.49	0.43	0.32	0.55	0.43	0.33	0.49
Тр	0.35	0.26	0.51	0.40	0.33	0.49	0.41	0.33	0.53	0.38	0.34	0.44

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RP = rim of phenocryst CP = core of phenocryst GM = groundmass olivine

note : all iron as FeO - = below detection limit

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FLOW 5 - PYROXENE ANALYSES

	05-01	05-02	05-03	05-04
si02	48.89	50.01	48.59	49.70
TiO2	2.14	1.56	2.37	1.70
AL203	3.15	2.86	3.13	2.97
FeO	12.99	11.54	13.48	11.69
MnO	0.28	0.25	0.27	0.24
MgO	12.80	14.56	12.38	14.16
CaO	18.81	18.53	19.14	18.89
Na2O	0.47	0.39	0.49	0.41
Total	99.53	99.70	99.85	99.76

NUMBER OF IONS OF BASIS OF 12 POSITIVE CHARGES

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Si	1.864	1.885	1.854	1.876
Al iv	0.136	0.115	0.146	0.124
τī	0.061	0.044	0 068	0.0/9
	0.001	0.044	0.000	0.040
AL	0.000	0.012	0.000	0.008
Fe2	0.414	0.364	0.430	0.369
Mn	0.009	0.008	0.009	0.008
Mg	0.727	0.818	0.704	0.797
Ca	0.768	0.748	0.783	0.764
Na	0.035	0.028	0.036	0.030
Total	2.020	2.022	2.030	2.024

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note : all iron as FeO

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FLOW 5 - Fe-Ti OXIDE ANALYSES

Magnetite-Ulvospinel Series

	05-01	05-02	05-03	05-04
sio2	0.52	0.42	0.31	0.74
TiO2	20.44	21.48	18.77	20.33
Al203	1.33	1.24	1.56	1.30
Fe0	48.28	48.83	46.17	48.39
Fe203	25.89	23.69	28.91	25.73
MgO	1.21	1.18	1.30	1.29
CaO	0.12	0.18	0.09	0.11
Total	97.79	97.02	97.11	97.89

Maximum Mole Percent End Members

Magnetite	36.88	34.00	41.49	36.57
Ulvospinel	60.42	63.28	55.72	60.55

Hematite-Ilmenite Series

	05-01	05-02	05-03	05-04
\$i02	1.59	-	1.23	0.40
TiO2	46.61	-	45.75	46.93
Al203	0.36	-	0.26	0.12
Fe0	42.02	-	41.17	41.31
Fe203	7.76	-	9.52	8.91
MgO	0.72	-	0.54	0.59
CaO	0.40	-	0.37	0.25
Total	99.46	-	98.84	98.51
Max % Hem.	11.87	-	12.61	9.77

Chrome-rich spinel

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	05-01	05-02	05-03	05-04
si02		0.37	0.64	0.16
TiO2	-	16.46	15.25	18.03
Cr203	-	10.72	9.00	8.96
Al203	-	3.16	1.93	2.04
Fe0	-	42.81	43.65	45.80
Fe203		22.01	26.61	22.08
MgO	-	2.59	1.54	1.46
CaO	-	0.20	0.12	0.01
Total	-	98.32	98.74	98.54

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FLOW 6 - PLAGIOCLASE ANALYSES

		06	-01			06	-02			06-03			
	RP	CP	RG	CG	RP	CP	RG	CG	RP	CP	RG	CG	
SiO2	52.46	52.56	55.90	54.62	53.29	52.36	55.24	54.68	53.17	52.12	55.12	54.54	
Al203	29.04	29.15	26.71	27.53	28.48	29.31	27.28	27.57	28.73	29.63	27.20	27.64	
Fe0	0.61	0.53	0.93	0.82	0.70	0.54	0.85	0.79	0.66	0.54	0.96	0.90	
MgO	0.13	0.15	0,13	0.14	0.14	0.13	0.13	0.15	0.14	0.14	0.16	0.14	
CaO	12.95	13.11	10.36	11_41	12.38	13.21	10.85	11.25	12.50	13.31	10.84	11.34	
Na2O	4.15	4.04	5.63	5.07	4.52	4.03	5.42	5.18	4.47	3.99	5.40	5.13	
к20	0.11	0.10	0.24	0.17	0.14	0.10	0.22	0.18	0.14	0.10	0.22	0.19	
Total	99.45	99.64	99.90	99.76	99.65	99.68	99.99	99.80	99.81	99.83	99.90	99.88	

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WEIGHT PERCENT END MEMBERS

An	64.24	65.04	51.39	56.60	61.41	65.53	53.82	55.81	62.01	66.03	53.78	56.26
Ab	35.12	34.18	47.64	42.90	38.25	34.10	45.86	43.83	37.82	33.76	45.69	43.41
Or	0.65	0.59	1.42	1.00	0.83	0.59	1.30	1.06	0.83	0.59	1.30	1.12

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MOLE PERCENT END MEMBERS

An	62.89	63.83	49.73	54.89	59.73	64.06	51.86	53.99	60.22	64.46	51.93	54.39
Ab	36.47	35.59	48.90	44.14	39.46	35.36	46.88	44.98	38.97	34.97	46.81	44.53
Or	0.64	0.58	1.37	0.97	0.80	0.58	1.25	1.03	0.80	0.58	1.25	1.08

- RP = rim of phenocryst CP = core of phenocryst
- RG = rim of groundmass plagioclase
- CG = core of groundmass plagioclase

note : all iron as FeO

FLOW 6 - OLIVINE ANALYSES

		06-01			06-02	2		06-03		
	RP	CP	GM	RP	CP	GM	RP	CP	GM	
SiO2	37.51	38.10	36.22	37.54	38.12	36.48	37.47	38.06	36.90	
TiO2	0.03	-	0.06	0.03	-	0.05	-	•	0.05	
Al203	0.05	0.04	0.08	0.05	0.04	-	-	-	-	
FeO	26.30	23.56	32.22	26.04	23.54	31.10	26.09	23.91	29.85	
MnO	0.36	0.32	0.42	0.37	0.31	0.43	0.35	0.31	0.41	
MgO	35.72	38.14	30.76	35.38	38.15	31.64	35.95	37.79	32.42	
CaO	0.32	0.24	0.38	0.32	0.25	0.37	0.32	0.25	0.37	
Total	100.29	100.40	100.14	99.73	100.41	100.07	100.18	100.32	100.00	

WEIGHT PERCENT END MEMBERS

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Fo		62.34	66.56	53.68	61.75	66.58	55.22	62.74	65.95	56.58
Fa		37.30	33.41	45.69	36.93	33.38	44.11	37.00	33.91	42.33
La		0.49	0.37	0.58	0.49	0.38	0.57	0.49	0.38	0.57
Тр	-	0.51	0.46	0.60	0.53	0.44	0.61	0.50	0.44	0.58

MOLE PERCENT END MEMBERS

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Fo	70.16	73.75	62.33	70.16	73.77	63.79	70.47	73.29	65.27
Fa	28.98	25.56	36.63	28.97	25.54	35.18	28.69	26.02	33.72
La	0.45	0.33	0.55	0.46	0.35	0.54	0.45	0.35	0.54
Тр	0.40	0.35	0.48	0.42	0.34	0.49	0.39	0.34	0.47

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RP = rim of phenocryst
CP = core of phenocryst
GM = groundmass olivine

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note : all iron as FeO - = below detection limit

FLOW 6 - PYROXENE ANALYSES

	06-01	06-02	06-03
\$i02	49.86	49.31	51.36
TiO2	1.84	2.16	1.15
Al203	3.19	3.46	2.71
Fe0	11.48	12.18	9.40
MnO	0.23	0.23	0.20
MgO	14.20	13.45	15.55
CaO	18.94	19.05	19.50
Na2O	0.43	0.45	0.36
Total	100.17	100.29	100.23

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* NUMBER OF IONS OF BASIS OF 12 POSITIVE CHARGES

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Si	1.872	1.858	1.906
Al iv	0.128	0.142	0.094
Ti	0.052	0.061	0.032
Al	0.013	0.011	0.024
Fe2	0.360	0.384	0.292
Mn	0.007	0.007	0.006
Mg	0.795	0.755	0.860
Са	0.762	0.769	0.775
Na	0.031	0.033	0.026
Total	2.020	2.020	2.015

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note : all iron as FeO

FLOW 6 - Fe-Ti OXIDE ANALYSES

Magnetite-Ulvospinel Series

	06-01	06-02	06-03
Si02	0.23	0.20	0.13
TiO2	20.00	19.67	17.92
Al203	1.45	1.11	1.40
FeO	47.15	47.17	46.07
Fe203	27.63	28.56	31.89
MgO	1.48	1.19	0.81
CaO	0.14	0.15	0.28
Total	98.08	98.05	98.50
	Maximum	Mole Percent End	Members

Magnetite	39.20	40.72	45.40
Ulvospinel	57.58	56.73	52.94

<u>Hemetite-Ilmenite Series</u>

	06-01	06-02	06-03
Si02	1.72	• 0.51	0.37
TiO2	44.39	46.91	45.33
Al203	0.33	0.16	0.12
Fe0	41.04	41.34	40.04
Fe203	10.35	8.77	11.82
MgO	0.36	0.63	0.48
CaO	0.23	0.26	0.24
Total	98.42	98.58	98.40
Max % Hem.	14.82	9.97	12.54

Chrome-rich spinel

	06-01	06-02	06-03
Si02	-	0.06	-
TiO2	-	17.19	-
Cr203	•	6.03	-
Al203	•	1.59	-
FeO	-	44.54	-
Fe203	-	26.75	-
MgO	-	1.31	-
CaO	•	0.15	-
Total	-	97.62	-

FLOW 7 - PLAGIOCLASE ANALYSES

	07-01				07-02					07-03				07-04			
	RP	CP	RG	CG	RP	CP	RG	CG	RP	СР	RG	CG	RP	CP	RG	CG	
Si02	53.22	52.30	55.19	54.39	53.73	53.08	56.09	55.03	53.68	52.77	55.47	54.93	53.17	52.93	55.60	55.14	
Al203	28.65	29.42	27.22	27.77	28.50	29.06	26.59	27.24	28.41	29.16	26.89	27.39	28.83	29.20	27.27	27.66	
Fe0	0.72	0.55	0.85	0.82	0.72	0.56	0.90	0.92	0.71	0.62	0.91	0.86	0.67	0.56	1.02	0.86	
MgO	0.12	0.14	0.09	0.11	0.12	0.14	0.10	0.14	0.12	0.16	0.11	0.13	0.13	0.14	0.13	. 0.12	
Ca0	12.32	13.03	10.64	11.31	12.35	13.10	10.41	11.33	12.35	13.23	10.72	11.22	12.63	13.07	10.77	11.32	
Na2O	4.61	4.18	5.55	5.17	4.53	4.09	5.66	5.17	4.65	4.15	5.43	5.17	4.39	4.11	5.46	5.16	
К20	0.15	0.10	0.24	0.19	0.14	0.10	0.24	0.19	0.15	0.10	0.20	0.18	0.10	0.09	0.21	0.18	
Total	99.79	99.72	99.78	99.76	100.09	100.13	99.99	100.02	100.07	100.19	99.73	99.88	99.92	100.10	100.46	100.44	

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WEIGHT PERCENT END MEMBERS

An	61.12	64.64	52.78	56.11	61.27	64.99	51.64	56.21	61.27	65.63	53.18	55.66	62.65	64.84	53.43	56.16
Ab	39.01	35.37	46.96	43.75	38.33	34.61	47.89	43.75	39.35	35.12	45.95	43.75	37.15	34.78	46.20	43.66
Or	0.89	0.59	1.42	1.12	0.83	0.59	1.42	1.12	0.89	0.59	1.18	1.06	0.59	0.53	1.24	1.06

MOLE PERCENT END MEMBERS

An	59.11	62.91	50.74	54.14	59.62	63.53	49.72	54.18	58.97	63.43	51.58	53.97	61.03	63.40	51.53	54.24
Ab	40.03	36.52	47.90	44.78	39.57	35.89	48.92	44.74	40.18	36.00	47.28	45.00	38.39	36.08	47.27	44.74
Or	0.86	0.57	1.36	1.08	0.80	0.58	1.36	1.08	0.85	0.57	1.15	1.03	0.58	0.52	1.20	1.03

RP = rim of phenocryst

CP = core of phenocryst

RG = rim of groundmass plagioclase

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CG = core of groundmass plagioclase

note : all iron as FeO

FLOW 7 - PLAGIOCLASE ANALYSES, CONT.

		07-0	05		07-06
	RP	CP	RG	CG	RP CP RG CG
SiO2	52.28	52.53	56.07	54.78	52.85 52.70 55.66 54.91
Al203	29.32	29.29	26.72	27.55	29.09 29.42 27.01 27.20
FeO	0.62	0.55	0.91	0.90	0.62 0.53 0.88 1.00
MgO	0.12	0.14	0.10	0.12	0.13 0.15 0.11 0.33
CaO	13.07	13.11	10.12	11.18	12.78 13.01 10.40 11.18
Na2O	4.08	4.08	5.76	5.15	4.31 4.18 5.65 5.21
K20	0.11	0.09	0.26	0.19	0.12 0.09 0.24 0.20
Total	99.60	99.79	99.94	99.87	99.90 100.08 99.95 100.03

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WEIGHT PERCENT END MEMBERS

An	64.84	65.04	50.20	55.46	63.40	64.54	51.59	55.46	
Ab	34.52	34.52	48.74	43.58	36.47	35.37	47.81	44.08	
Or	0.65	0.53	1.54	1.12	0.71	0.53	1.42	1.18	

MOLE PERCENT END MEMBERS

An	63.50	63.64	48.53	53.94	61.67	62.91	49.74	53.63
Ab	35.87	35.84	49.99	44.97	37.64	36.58	48.90	45.23
Or	0.64	0.52	1.48	1.09	0.69	0.52	1.37	1.14

RP = rim of phenocryst

CP = core of phenocryst

RG = rim of groundmass plagioclase

CG = core of groundmass plagioclase

note : all iron as FeO

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FLOW 7 - OLIVINE ANALYSES

	07-01				07-02			07-03			07-04			
	RP	CP	GM	RP	CP	GM	RP	CP	GM	RP	CP	GM		
sio2	37.34	38.00	35.66	37.16	37.82	36.39	37.01	37.65	36.21	37.56	38.21	37.35		
Ti02	-	-	0.06	-	-	0.05	0.03	-	0.05	0.03	-	0.04		
Al203	-	-	-	-	-	-	-	-	-	0.04	0.04	0.04		
Fe0	27.64	23.83	34.75	27.65	24.23	31.68	29.19	25.48	32.77	26.45	23,51	28.08		
MnO	0.38	0.32	0.50	0.39	0.33	0.44	0.42	0.34	0.46	0.36	0.30	0,38		
MgO	34.38	37.61	28.32	34.58	37.48	31.13	33.01	36.17	30.00	35.36	37.83	33.93		
Ca0	0.29	0.24	0.33	0.29	0.24	0.34	0.31	0.26	0.35	0.31	0.23	0.35		
Total	100.03	100.00	99.62	100.07	100.10	100.03	99.97	99.90	99.84	100.11	100.12	100.17		

WEIGHT PERCENT END MEMBERS

Fo	60.00	65.64	49.42	60.35	65.41	54.33	57.61	63.12	52.36	61.71	66.02	59.21
Fa	39.20	33.80	49.28	39.21	34.36	44.93	41.40	36.14	46.47	37.51	33.34	39.82
La	0.45	0.37	0.51	0.45	0.37	0.52	0.48	0.40	0.54	0.48	0.35	0.54
Тр	0.54	0.46	0.71	0.56	0.47	0.63	0.60	0.48	0.65	0.51	0.43	0.54

MOLE PERCENT END MEMBERS

Fo	68.33	73.26	58.59	68.44	72.87	63,02	66.22	71.14	61.35	69.84	73.66	67.65
Fa	30.82	26.05	40.33	30.71	26.43	35.98	32.85	28.12	37.60	29.31	25.68	31.41
La	0.41	0.34	0.49	0.41	0.34	0.49	0.45	0.37	0.51	0.44	0.32	0.50
Тр	0.43	0.35	0.59	0.44	0.36	0.51	0.48	0,38	0.53	0.40	0.33	0.43

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RP = rim of phenocryst CP = core of phenocryst GM = groundmass olivine

note : all iron as Fe0
 - = below detection limit

FLOW 7 - OLIVINE ANALYSES, CONT.

		07-05			07-06				
	RP	CP	GM	RP	CP	GM			
SiO2	37.10	37.78	35.42	37.68	38.15	36.61			
TiO2	-	-	0.05	-	-	0.04			
Al203	-	-	0.10	-	-	0.04			
Fe0	26.88	23.40	36.95	26.08	22.84	31.75			
MnO	0.36	0.28	0.52	0.34	0.28	0.43			
MgO	35.52	38.39	26.46	36.04	38.84	30.90			
Ca0	0.27	0.23	0.35	0.27	0.23	0.32			
Total	100.13	100.08	99.85	100.41	100.34	100.09			

WEIGHT PERCENT END MEMBERS

Fo	61.99	67.00	46.18	62.90	67.78	53.93
Fa	38.12	33.19	52.40	36.99	32.39	45.03
La	0.41	0.35	0.54	0.41	0.35	0.49
Тр	0.51	0.40	0.74	0.48	0.40	0.61

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MOLE PERCENT END MEMBERS

Fo	69.65	74.05	55.43	70.58	74.72	62.82
Fa	29.57	25.32	43.43	28.66	24.65	36.22
La	0.38	0.32	0.53	0.38	0.32	0.47
Тр	0.40	0.31	0.62	0.38	0.31	0.50

RP = rim of phenocryst CP = core of phenocryst GM = groundmass olivine

note : all iron as FeO

- = below detection limit

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	07-01	07-02	07-03	07-04	07-05	07-06
si02	51.30	51.30	51.04	51.66	50.64	50.84
Ti02	1.04	1.13	1.09	0.99	1.22	1.18
Al203	2.04	2.22	1.81	2.17	2.33	2.39
Fe0	10.60	10.79	10.23	9.78	10.65	10.69
MnO	0.24	0.23	0.22	0.21	0.22	0.23
MgO	15.46	15.25	15.39	15.65	15.24	15.28
CaO	18.72	18.91	19.22	18.95	19.07	18.77
Na2O	.0.37	0.41	0.40	0.36	0.40	0.41
Total	99.77	100.24	99.40	99.77	99.77	99.79
		NUMBEI	R OF IONS OF BA	SIS OF 12 POS	ITIVE CHARGES	
Si	1.920	1.914	1.919	1.925	1.901	1.905
Al iv	0.080	0.086	0.081	0.075	0.099	0.095
Ti	0.029	0.032	0.031	0.028	0.034	0.033
AL	0.010	0.011	0.000	0.021	0.004	0.011

0.322

0.007

0.862

0.774

0.029

2.025

0.305

0.007

0.869

0.757

0.026

2.013

0.334

0.007

0.853

0.767

0.029

2.028

Fe2

Mn

Mg

Ca

Na

Total

0.332

0.008

0.863

0.751

0.027

2.020

0.337

0.007

0.848

0.756

0.030

2.021

note : all iron as FeO

0.335

0.007

0.854

0.754

0.030

FLOW 7 - Fe-Ti OXIDE ANALYSES

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Magnetite-Ulvospinel Series

	07-01	07-02	07-03	07-04	07-05	07-06
\$i02	0.16	0.10	0.13	0.36	0.12	0.12
TiO2	22.47	21.86	22.02	21.74	21.82	22.73
Al203	1.06	1.67	1.69	1.16	1.19	1.14
FeO	49.31	48.87	48.82	49.53	48.34	49.77
Fe203	23.98	24.85	24.53	23.90	25.23	23.65
MgO	1.62	1.63	1.79	0.98	1.79	1.53
CaO	0.10	0.11	0.10	0.20	0.15	0.09
Total	98.70	99.09	99.08	97.87	98.64	99.03
		Maximum Mol	e Percent E	nd Members		
Magnetite	33.79	34.80	34.29	34.08	35.52	33.23
Ulvospinel	62.55	61.54	61.68	63.67	60.48	63.31
<u>Hematite-Ilmeni</u>	<u>te Series</u>					
	07-01	07-02	07-03	07-04	07-05	07-06

SiO2	0.23	0.28	0.07	-	0.20	-
TiO2	48.20	47.54	47.04	-	48.32	-
Al203	0.10	0.22	0.14	-	0.13	-
Fe0	40.51	40.48	40.04	-	40.34	-
Fe203	7.62	8.88	6.24	-	7.69	-
MgO	1.60	1.29	1.20	-	1.77	-
Ca0	0.20	0.24	0.16	-	0.15	-
Total	98.46	98.93	94.89	-	98.60	-
Max % Hem.	8.01	9.50	6.60	-	8.02	-

Chrome-rich spinel

	07-01	07-02	07-03	07-04	07-05	07-06
\$i02			-	-	-	
TiO2	-	-	•	-	-	-
Cr203		-	-	-	-	-
Al203	-	-	-	-	-	-
Fe0	-	-	-	-	-	-
Fe203	-	-	-	-	-	-
MgO	-	-	•	-	-	-
CaO	-	-	-	-	-	-
Total	-	-	-	-	-	-

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FLOW 8 - PLAGIOCLASE ANALYSES

	08-01-1			08-01-2				08-01-3				08-01-4				
	RP	CP	RG	CG	RP	CP	RG	CG	RP	СР	RG	CG	RP	CP	RG	CG
SiO2	53.38	52.43	55.10	55.58	52.99	52.65	54.95	54.99	53.17	52.73	55.02	54.84	52.85	52.33	55.75	55.02
Al203	28.86	29.55	27.52	27.09	29.45	29.55	27.88	27.85	29.01	29.31	27.77	27.53	29.27	29.59	27.37	27.63
Fe0	0.71	0.58	0.97	0.91	0.63	0.55	0.90	0.90	0.68	0.58	0.97	0.96	0.62	0.54	0.90	0.93
MgO	0.12	0.14	0.09	0.10	0.13	0.15	0.10	0.10	0.13	0.15	0.09	0.11	0.12	0.15	0.09	0.10
Ca0	12.20	13.10	10.64	10.33	13.08	13.39	11.46	11.42	12.81	13.27	11.25	11.19	12.92	13.28	10.43	10.90
Na2O	4.60	4.11	5.40	5.58	4.27	4.11	5.20	5.22	4.43	4.20	5.30	5.30	4.29	4.09	5.63	5.36
к20	0.14	0.09	0.24	0.26	0.11	0.09	0.20	0.20	0.13	0.10	0.22	0.21	0.12	0.09	0.25	0.23
Total	100.01	100.00	99.96	99.85	100.66	100.49	100.69	100.68	100.36	100.34	100.62	100.14	100.19	100.07	100.42	100.17

WEIGHT PERCENT END MEMBERS

An	60.52	64.99	52.78	51.25	64.89	66.43	56.85	56.65	63.55	65.83	55.81	55.51	64.09	65.88	51.74	54.07
Ab	38.92	34.78	45.69	47.22	36.13	34.78	44.00	44.17	37.48	35.54	44.85	44.85	36.30	34.61	47.64	45.35
Or	0.83	0.53	1.42	1.54	0.65	0.53	1.18	1.18	0.77	0.59	1.30	1.24	0.71	0.53	1.48	1.36

MOLE PERCENT END MEMBERS

An	58.96	63.45	51.41	49.81	62.47	63.96	54.29	54.11	61.05	63.22	53.31	53.21	62.04	63.88	49.87	52.22
Ab	40.23	36.03	47.21	48.69	36.90	35.53	44.58	44.76	38.21	36.21	45.45	45.60	37.28	35.60	48.71	46.47
Or	0.81	0.52	1.38	1.49	0.63	0.51	1.13	1.13	0.74	0.57	1.24	1.19	0.69	0.52	1.42	1.31

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RP = rim of phenocryst
CP = core of phenocryst
RG = rim of groundmass plagioclase

CG = core of groundmass plagioclase

note : all iron as FeO

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FLOW 8 - PLAGIOCLASE ANALYSES, CONT.

		08-0	01-5		08-01-6					
	RP	CP	RG	CG	RP	CP	RG	CG		
SiO2	52.98	52.39	54.80	53.74	53.09	52.53	55.15	54.84		
Al203	28.68	29.26	27.20	27.60	28.56	29.03	27.05	27.23		
Fe0	0.63	0.57	0.88	0.81	0.67	0.58	0.96	0.94		
MgO	0.15	0.15	0.13	0.14	0.14	0.15	0.11	0.11		
CaO	12.67	13.21	10.86	11.40	12.33	12.91	10.66	10.91		
Na2O	4.48	4.21	5.51	5.10	4.48	4.18	5.44	5.33		
K20	0.12	0.09	0.22	0.18	0.13	0.10	0.22	0.21		
Total	99.71	99.88	99.60	98.97	99.40	99.48	99.59	99.57		

WEIGHT PERCENT END MEMBERS

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An	62.85	65.53	53.87	56.55	61.17	64.04	52.88	54.12
Ab	37.91	35.62	46.62	43.15	37.91	35.37	46.03	45.10
Or	0.71	0.53	1.30	1.06	0.77	0.59	1.30	1.24

MOLE PERCENT END MEMBERS

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An	60.56	63.10	51.49	54.69	59.88	62.69	51.33	52.44
Ab	38.75	36.39	47.27	44.28	39.37	36.73	47.41	46.36
Or	0.68	0.51	1.24	1.03	0.75	0.58	1.26	1.20

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RP = rim of phenocryst
CP = core of phenocryst
RG = rim of groundmass plagioclase
CG = core of groundmass plagioclase

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note : all iron as FeO

FLOW 8 - OLIVINE ANALYSES

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	08-01-1				08-01-2		08-01-3			
	RP	CP	GM	RP	CP	GM	RP	CP	GM	
si02	38.12	39.11	35.73	37.47	38.43	36.19	37.44	38.55	36.32	
TiO2	-	-	0.08	-	-	0.04	-	-	0.03	
Al203	0.06	0.04	0.04	-	0.04	0.05	-	-	0.04	
Fe0	24.27	19.31	37.32	27.08	22.21	34.03	26.93	20.48	32.61	
Mn0	0.32	0.23	0.54	0.36	0.29	0.49	0.37	0.35	0.44	
MgO	37.53	41.74	26.56	34.97	38.98	28.85	35.47	40.85	30.60	
CaO	0.23	0.21	0.31	0.26	0.22	0.30	0.24	0.21	0.31	
Total	100.53	100.64	100.58	100.14	100.17	99.95	100.45	100.34	100.35	

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WEIGHT PERCENT END MEMBERS

Fo	65.60	72.84	46.35	61.03	68.03	50.35	61.90	71.29	53.40
Fa	34.42	27.39	52.93	38.40	31.50	48.26	38.12	29.04	46.25
La	0.35	0.32	0.48	0.40	0.34	0.46	0.37	0.32	0.48
Тр	0.46	0.33	0.77	0.51	0.41	0.70	0.53	0.36	0.63

MOLE PERCENT END MEMBERS

Fo	72.88	78.97	55.30	69.17	75.30	59.56	69.60	77.61	61.98
Fa	26,44	20.50	43.60	30.05	24.07	39.42	29.65	21.83	37.06
La	0.32	0.29	0.46	0.37	0.31	0.45	0.34	0.29	0.45
Тр	0.35	0.25	0.64	0.40	0.32	0.57	0.41	0.27	0.51

RP = rim of phenocryst
CP = core of phenocryst

GM = groundmass olivine

note : all iron as Fe0
- = below detection limit

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FLOW 8 - OLIVINE ANALYSES, CONT.

	08-01-4				08-01-5		08-01-6			
	RP	CP	GM	RP	СР	GM	RP	CP	GM	
SiO2	37.41	38.69	35.72	38.13	38.86	36.93	37.32	38.51	35.92	
TiO2	-	-	0.06	0.04	-	0.05	-	-	0.05	
Al203	-	-	-	0.12	0.04	0.08	-	0.04	0.05	
Fe0	26.52	20.38	37.34	24.85	20.27	30.13	27.67	20.47	35.04	
Mn0	0.36	0.26	0.52	0.34	0.26	0.40	0.38	0.25	0.48	
MgO	34.95	40.16	25.75	36.88	40.96	32.39	34.66	40.65	28.31	
Ca0	0.25	0.22	0.31	0.31	0.23	0.35	0.25	0.22	0.32	
Total	99.49	99.71	99.70	100.67	100.62	100.33	100.28	100.14	100.17	

WEIGHT PERCENT END MEMBERS

Fo	60.99	70.09	44.94	64.36	71.48	56.53	60.49	70.94	49.41
Fa	37.61	28.90	52.96	35.24	28.75	42.73	39.24	29.03	49.69
La	0.38	0.34	0.48	0.48	0.35	0.54	0.38	0.34	0.49
Тр	0.51	0.37	0.74	0.48	0.37	0.57	0.54	0.36	0.68

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MOLE PERCENT END MEMBERS

Fo	69.60	77.38	54.53	71.98	77.80	65.07	68.52	77.52	58.40
Fa	29.63	22.03	44.37	27.21	21.60	33.96	30.69	21.90	40.56
La	0.36	0.30	0.47	0.43	0.31	0.51	0.36	0.30	0.47
ĩр	0.41	0.28	0.63	0.38	0.28	0.46	0.43	0.27	0.56

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RP = rim of phenocryst
CP = core of phenocryst

GM = groundmass olivine

note : all iron as FeO

- = below detection limit

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FLOW 8 - PYROXENE ANALYSES

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	08-01 - 1	08-01 - 2	08-01-3	08-01-4	08-01-5	08-01-6
\$i02	51.26	51.34	51.33	51.12	48.71	51.43
TiO2	1.09	1.06	1.15	1.06	2.40	1.04
Al203	2.07	1.95	1.99	1.98	3.53	2.08
Fe0	11.20	11.23	11.32	11.12	12.58	10.22
MnO	0.27	0.25	0.24	0.26	0.22	0.23
MgO	15.29	15.54	15.38	15.59	12.57	15.74
CaO	18.08	18.25	18.40	18.09	19.22	18.84
Na2O	0.37	0.36	0.38	0.36	0.54	0.36
Total	99.63	99.98	100.19	99.58	99.77	99.94

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NUMBER OF IONS ON BASIS OF 12 POSITIVE CHARGES

Si	1.923	1.921	1.918	1.919	1.852	1.919
Al iv	0.077	0.079	0.082	0.081	0.148	0.081
Tī	0.031	0.030	0.032	0.030	0.069	0.029
AL	0.015	0.007	0.005	0.007	0.010	0.010
Fe2	0.351	0.351	0.354	0.349	0.400	0.319
Mn	0.009	0.008	0.008	0.008	0.007	0.007
Mg	0.855	0.866	0.857	0.872	0.712	0.875
Ca	0.727	0.731	0.737	0.728	0.783	0.753
Na	0.027	0.026	0.028	0.026	0.040	0.026
Total	2.015	2.019	2.021	2.020	2.021	2.019

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note : all iron as FeO

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FLOW 8 - Fe-Ti OXIDE ANALYSES

Magnetite-Ulvospinel Series

	08-01-1	08-01-2	08-01-3	08-01-4	08-01-5	08-01-6
si02	0.16	0.13	0.12	0.09	0.07	0.07
TiO2	22.45	22.95	22.94	22.42	20.97	23.41
Al203	1.11	0.91	· 1.03	0.90	0.64	0.78
FeO	48.90	49.70	49.34	49.19	48.13	50.51
Fe203	24.39	23.37	23.74	23.79	26.81	22.77
MgO	1.92	1.62	1.96	1.45	1.17	1.37
CaO	0.15	0.12	0.09	0.08	0.14	0.09
Total	99.08	98.80	99.22	97.92	97.93	99.00
		Maximum Mc	le Percent	End Members	5	
Magnetite	34.14	32.91	33.19	33.86	38.35	32.09
Ilmenite	61.55	63.40	62.39	62.84	59.09	64.78
<u>Hematite-Ilme</u>	<u>nite Series</u>					
	08-01-1	08-01-2	08-01-3	08-01-4	08-01-5	08-01-6
Si02	0.39	0.42	0.22	-	0.44	0.09
TiO2	47.72	49.34	49.28	49.09	48.00	49.55
Al203	0.21	0.13	0.10	0.08	0.18	0.07
FeO	39.26	41.19	40.47	40.71	39.68	41.29
Fe203	9.75	5.63	6.76	7.33	8.33	6.46
MgO	2.10	1.88	2.10	1.87	2.11	1.72
CaO	0.20	0.26	0.28	0.10	0.19	0.24
Total	99.63	98.85	99.21	99.10	98.93	99.42
Max % Hem.	10.21	6.58	7.08	7.11	9.25	6.43
<u>Chrome-rich s</u>	pinel					
	08-01-1	08-01-2	08-01-3	08-01-4	08-01-5	08-01-6
SiO2	-	-	-	-	0.26	-
TiO2	-	•	-	-	15.33	-
Cr203	-	-	-	-	4.69	-
Al203	-	-	-	-	1.18	-
FeO	-	-	-	-	43.84	-
Fe203	-	-	-	-	33.03	-
MgO	-	-	-	-	1.16	-
CaO	-	•	-	-	0.15	-
Total	-	-	-	-	99.64	-

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note : - below detection limit

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APPENDIX 4

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PETROGRAPHIC AND MINERALOGICAL DESCRIPTIONS OF FLOWS

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The flow is glomeroporphyritic and slightly vesicular. Phenocrysts of plagioclase and olivine are present in approximately equal amounts (7%). There is a complete gradation in phenocryst size from groundmass upwards. Euhedral phenocrysts of plagioclase reach a maximum length of 2.5 mm. These larger phenocrysts may show resorption or embayment effects. The average length of plagioclase phenocrysts is approximately 0.3 mm. Phenocrysts are weakly zoned from about An_{63} in cores to An_{61} at rims.

Olivine phencrysts, which typically contain euhedral inclusions of opaque phases, are also zoned, with cores of about Fo_{76} and rims Fo_{69} . The average size of these phenocrysts is 0.4 mm, although grains may reach a maximum size of about 1.8 mm. Cores of larger phenocrysts may be partly replaced by groundmass phases.

Plagioclase is the predominant groundmass constituent, comprising 54% of the rock. These lath shaped crystals have an average length of about 0.1 mm and show a weak trachytic texture. They are also zoned, with cores of An_{54} and rims of An_{50} .

Pale brown, anhedral, titaniferous augite in the groundmass makes up 21% of the lava. Mineral analyses reveal that the pyroxene contains approximately 1.8% TiO₂. Typically the augite occurs as small grains averaging about 0.07 mm across; it may occur as large optically continuous masses which poikilitically enclose groundmass plagioclase and olivine.

Olivine is also present in the groundmass, with a composition of approximately Fo₅₈. The small anhedral grains which average 0.05 mm in diameter comprise make up 8% of the rock.

The groundmass contains euhedral grains of a magnetite-ulvospinel phase and a hematite-ilmenite phase. Magnetite_{solid} solution occurs as cubic crystals averaging 0.08 mm across while needle-like ilmenite_{solid} solution grains have lengths up to 0.1 mm. The two phases occur in near equal amounts, about 1.5%. An approximate temperature of 935°C. and oxygen fugacity of -12.0 were determined from the analyses of the two phases using the methods of Buddington and Linsley (1964).

Minor apatite and Cr-rich spinel were found in the groundmass. Traces of reddish brown glass are also seen in the groundmass of some of the samples.

The flow is glomeroporphyritic with tabular euhedral plagioclase phenocrysts averaging 0.8 mm in length. Rarely phenocrysts reach a maximum length of 3.0 mm. The plagioclase phenocrysts, which comprise 9% of the lava, often show partially resorbed cores. This feature is especially apparent in the larger crystals. Phenocrysts show slight normal zonation with cores of An_{63} and rims An_{61} .

Olivine phenocrysts are also present and account for 6% of the rock. Anhedral and averaging 0.2 mm across, the phenocrysts commonly contain euhedral opaque inclusions. Phenocrysts up to 1.2 mm in size are found in the samples. Minor embayment effects can be seen. Slight zoning is also noted in olivine phenocrysts whose cores average Fo₇₈ while rims are about Fo₇₅.

The groundmass is composed primarily of euhedral plagioclase laths with no apparent alignment. The plagioclase laths make up 56% of the lava and average 0.15 mm in length. Compositions of these laths are somewhat variable between samples. They are however, normally zoned from approximately An_{53} in cores to An_{49} at rims.

Pale green brown titaniferous augite is present in the groundmass, comprising 19% of the rock. The titanium content of the pyroxene is about 1.2%. Anhedral pyroxene grains average about 0.05 mm across.

Small (0.05 mm) anhedral grains of olivine are also present in the groundmass. The composition of the groundmass olivine, which makes up about 7% of the lava, is somewhat variable between samples. The average composition of the olivine is about Fo_{67} .

Euhedral magnetite_{solid} solution grains averaging about 0.05 mm across comprise 1.6% of the lava. Needle-like ilmenite_{solid} solution grains (about 0.1 mm in length) are slightly less abundant, making up 1% of the rock. Opaques may also show dendritic morphology. An average temperature of 1041°C and an oxygen fugacity of -10.1 are calculated from the coexistence of magnetite_{solid} solution and ilmenite_{solid} solution in the samples.

The groundmass contains minor apatite and Cr-rich spinel. A brown glass is also present in very small amounts in the groundmass.

Phenocrysts of plagioclase (7%) and olivine (6%) are found in this glomeroporphyritic flow. Plagioclase phenocrysts are normally zoned from An_{63-59} . The average size of the euhedral phenocrysts is 0.5 mm with a complete gradation in size to about 4 mm. These rare large phenocrysts show substantial resorption.

Olivine phenocrysts are somewhat smaller with an average size of 0.4 mm and reaching a maximum size of about 0.9 mm. They are anhedral and often contain inclusions of Fe-Ti oxide phases. The compositions of the olivine phenocrysts is about Fo₇₁ in cores and Fo₆₆ at rims.

Euhedral plagioclase laths in the groundmass (0.15 mm in length) make up about 54% of the lava. The laths are normally zoned from An_{54-50} and show weak trachytic texture.

Pale brown titanium rich augite occurs in the groundmass, making up approximately 21% of the rock. The augite occurs as small anhedral grains (about 0.05 mm across) and as larger optically continuous masses which poikilitically enclose groundmass plagioclase and olivine. Although somewhat variable between samples, the TiO₂ content of the augite is about 1.5%.

Anhedral olivine grains in the groundmass average about 0.05 mm across and comprise 9% of the lava. The groundmass olivine has a composition of about Fo_{49} .

Magnetite_{solid} solution and ilmenite_{solid} solution are present in the groundmass in small amounts (1.2% and 1.6% respectively). Both phases occur as subhedral disseminated grains averaging 0.08 mm across. To a lesser extent the oxides occur as anhedral masses filling intersticies in the groundmass. The compositions of the two phases provided a temperature of 954°C and an oxygen fugacity of -11.9.

Minor amounts of apatite and Cr-spinel were also detected in the goundmass of the samples. A brown glass occurs in the groundmass as well, in small, but variable, amounts. The glass contains tiny acicular crystallites.

The flow is glomeroporphyritic and slightly vesicular. Plagioclase phenocrysts are the dominant phenocryst phase comprising about 13% of the lava. There is a complete range in size of these euhedral phenocrysts, with an average length of approximately 0.7 mm. Rare phenocrysts reach sizes of 4.0 mm, often showing evidence of resorption. Plagioclase phenocrysts are slightly normally zoned from An_{61-57} .

About 8% of the rock is composed of anhedral olivine phenocrysts. Typically these phenocrysts are about 0.5 mm in size, although a maximum size of 2.3 mm may be reached. The compostion of the phenocrysts is about Fo₆₇₋₆₄ with the more forsteritic regions located in cores of phenocrysts. Euhedral Fe-Ti oxide inclusions are often found in the phenocrysts of olivine.

Randomly oriented lath shaped plagioclase crystals are the major groundmass constituent. Approximately 53% of the lava is made up of these crystals, whose average length is about 0.15 mm. The composition of the groundmass plagioclase is about An_{53} in cores and An_{48} at rims.

Small (0.05 - 0.1 mm) anhedral grains of very pale green augite are present in the groundmass. The augite contains about 1% TiO_2 and makes up 19% of the lava.

Olivine (about 5%) occurs in the groundmass as small anhedral grains. These grains have similar sizes to the groundmass pyroxene and in thin section the two phases look very similar. Olivine compositions were found to be about Fo₅₇.

Coexisting magnetite_{solid} solution (1.5%) and ilmenite_{solid} solution (1.1%) grains are found in the groundmass of the flow. Magnetite_{solid} solution grains are subhedral and range in size up to approximately 0.15 mm, with an average size of 0.05 mm. Elongate ilmenite_{solid} solution grains reach lengths of about 0.2 mm. The temperature and oxygen fugacity of equilibrium for the two phases were determined to be 990°C and -11.0.

A small amount of reddish brown glass containing acicular crystallites is found in the groundmass. Minor apatite and Cr-rich spinel are also present. Flow 5 is glomeroporphyritic with plagioclase phenocrysts as the primary phenocryst phase. These phenocrysts are tabular and euhedral and average 0.8 mm in length. They comprise about 10% of the lava and have a complete range in sizes, with larger crystals reaching lengths of about 4 mm. Significant resorption effects are displayed in the cores of these larger phenocrysts. Plagioclase phenocrysts show very minor normal zoning with a range of compositions from An_{63} to An_{61} .

Phenocrysts of olivine (about 6%) are also present. These subhedral phenocrysts average about 0.5 mm in size, although crystals up to 1.5 mm are seen. Commonly, the olivine phenocrysts contain euhedral inclusions of Fe-Ti oxides. Olivine phenocrysts are also zoned, with core compostions of Fo₇₇ and rims of approximately Fo₇₂.

The groundmass is composed primarily of randomly oriented lath shaped plagioclase. The plagioclase crystals average 0.15 mm in length and comprise 55% of the lava. Cores of plagioclase laths have compositions of An_{53} while rims are only slightly less anorthite rich at An_{52} .

About 18% of the rock is composed of pale brown titaniferous augite. The augite occurs in the groundmass as small anhedral grains (0.05 mm) and as larger optically continuous masses which poikilitically enclose groundmass plagioclase. The titanium content of the pyroxene is somewhat variable, 1.6% to 2.2%.

The groundmass also contains anhedral grains of olivine, approximately 0.05 mm in size. The olivine has a composition of Fo_{65} and makes up 9% of the lava.

Magnetite_{solid} solution and ilmenite_{solid} solution are also present in the groundmass, 1.3% and 1.1% respectively. Magnetite_{solid} solution occurs as small subhedral crystal approximately 0.1 mm across, while needle-like ilmenite_{solid} solution crystals reach lengths of about 0.1 mm. The small size of the ilmenite_{solid} solution in the rock make it very difficult to accurately calculate a temperature and oxygen fugacity using the methods of Buddington and Lindsley (1964). Analyses from one of the samples are thought to be sufficiently accurate and a temperature of 1015°C and oxygen fugacity of -10.6 was calculated.

Minor apatite, Cr-spinel and reddish brown glass also occur in the groundmass.

Flow 6 shows glomeroporphyritic textures with euhedral plagioclase phenocrysts making up about 8% of the rock. Minor normal zoning, An₆₄₋₆₁, is observed in these phenocrysts, whose average length is 0.6 mm. Rare larger phenocrysts, up to 4.5 mm in size, show strong resorption effects.

Anhedral olivine phenocryts are also present (7%), averaging 0.4 mm in size. These phenocrysts reach sizes of about 1.2 mm and often contain euhedral opaque inclusions. Cores of phenocrysts have compositions of Fo74 while rims are Fo70.

Randomly oriented lath shaped plagioclase in the groundmass comprises 56% of the rock. The plagioclase laths are normally zoned, An₅₄₋₅₁ and average 0.1 mm in length.

Pale brown titaniferous augite in the groundmass makes up 17% of the lava. The augite occurs as small anhedral grains (0.04 mm across) and as larger optically continuous masses poikilitically enclosing groundmass plagioclase, and less frequently, olivine. The TiO₂ content of the pyroxene is variable, but high, averaging 1.8%.

Small anhedral grains of olivine in the groundmass are also present (9%). The grains average 0.05 mm across and have compositions of Fo₆₄.

Magnetite_{solid} solution (1%) occurs in the groundmass as small subhedral grains averaging approximately 0.02 mm in size. Ilmenite_{solid} solution needles are also present (1.7%); these needles may be slightly longer than magnetite_{solid} solution crystals. A temperature of 998°C and an oxygen fugacity of -10.7 are calculated for the coexisting Fe-Ti oxide phases.

Minor amounts of apatite, Cr-spinel and reddish brown glass are also present in the groundmass.

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The glomeroporphyritic flow contains euhedral plagioclase phenocrysts which average about 0.4 mm in length and make up about 10% of the rock. They may reach sizes of 4 mm, with the larger phenocrysts showing zones of resorption. Minor normal zoning, An₆₃₋₆₁ is present in the plagioclase phenocrysts.

Anhedral olivine phenocrysts are also present (7%). The olivine phenocrysts range in size up to 1 mm, averaging 0.3 mm in size. Euhedral inclusions of Fe-Ti oxides are often present in the zoned phenocrysts. Cores of the phenocrysts have compositions of Fo₇₃, while rims are Fo₆₉.

Plagioclase in the groundmass makes up 54% of the lava. The euhedral laths average 0.15 mm in length and show weak alignment in certain samples. Plagioclase laths are normally zoned with compositions of An₅₄₋₅₀.

Pale green titaniferous augite is present in the groundmass (19%). The pyroxene has a titanium content of about 1.1% and occurs predominantly as small (0.05 mm across) anhedral grains.

Small anhedral grains of olivine also occur in the groundmass. These grains have similar sizes to pyroxene grains and comprise 7% of the lava. There is a considerable variation in the composition of the groundmass olivine, from Fo₅₅ to Fo₆₇, however the average composition is approximately Fo₆₁.

Euhedral magnetite_{solid} solution (2%) and ilmenite_{solid} solution (1%) are also found in the groundmass. Magnetite_{solid} solution crystals average 0.05 mm across while needle-like ilmenite_{solid} solution crystals reach lengths of 0.1 mm. A temperature of 990°C and oxygen fugacity of -11.2 were determined for the flow.

Minor apatite, Cr-spinel and reddish brown glass were also found in the groundmass. The volcanic glass contains acicular crystallites.

Flow 8 is glomeroporphyritic. Plagioclase is the dominant phenocryst phase, present in somewhat variable amounts, but averaging approximately 10%. Phenocrysts of plagioclase are euhedral and average 0.5 mm in length. There is a complete range in the sizes of phenocrysts, however. Larger plagioclase phenocrysts reach sizes of 3 mm, often displaying effects of resorption in cores. Cores of phenocrysts have compositions of An_{63} while rims are An_{61} .

Anhedral to subhedral phenocrysts of olivine are also present (7%). The olivine phenocrysts reach maximum diameters of about 2 mm, with an average size of 0.3 mm. Occassional larger phenocrysts are perfectly euhedral. Often the olivine phenocrysts contain euhedral inclusions of Fe-Ti oxide phases. Olivine phenocrysts are zoned from Fo77 to Fo70 with the forsterite rich regions located in cores.

The majority of the groundmass is comprised of euhedral laths of plagioclase (54% of the lava). The laths average 0.15 mm in length and are weakly aligned in several of the samples studied. The groundmass plagioclase is very weakly zoned with cores of An_{53} and rims An_{52} .

Pale greenish brown augite in the groundmass comprises about 20% of the lava. The augite occurs as small (0.05 mm) anhedral grains and as larger optically continuous masses poikilitically enclosing groundmass plagioclase, Fe-Ti oxides and rarely olivine.

Groundmass olivine accounts for a further 6% of the rock. The olivine averages Fo₅₈ in composition, occurring as anhedral grains, approximately 0.05 mm across.

Magnetite solid solution and ilmenite solid solution are both present in the groundmass in amounts of 1.8% and 1.1%, respectively. Euhedral magnetite solid solution crystals occur in sizes up to 0.1 mm across, while ilmenite solid solution crystals are elongate and up to 0.1 mm in length. The temperature and oxygen fugacity determined for the coexistence of the two phases were found to be 989°C and -11.2 respectively.

A minor amount of reddish brown glass, which contained acicular crystallites was observed in the groundmass. Traces of apatite and Cr-spinel were also present.