POTASSIUM-ARGON AGE DETERMINATIONS ON BIOTITES AND AMPHIBOLES, BETHLEHEM COPPER PROPERTY, B. C.

by

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B.A.Sc. University of British Columbia, 1962

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in the Department

of

GEOPHYSICS

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

June, 1965

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ABSTRACT

Potassium-argon apparent ages obtained on biotite and amphibole from various phases of the Guichon Creek batholith present on the Bethlehem Copper property are reported and their geological significances are discussed in this thesis. Although the individual phases were found to be essentially indistinguishable in terms of their potassium-argon apparent ages, the results obtained indicated with considerable certainty that these phases were emplaced during an interval not greater than 10 m.y. centered around 200 m.y. ago and that no major metamorphic event has occurred in this area since this time. It is also believed that this average apparent age of 200 m.y. may represent a better approximation to the maximum age of the Triassic-Jurassic boundary than that previously reported in the literature.

The potassium and argon analytical techniques employed are described briefly, and the analytical precision and accuracy obtained are discussed. Descriptions of the samples collected and samples analyzed are given as an appendix.

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ACKNOWLEDGEMENTS

Many persons have contributed to the completion of this thesis. The author is especially indebted to Dr. G.P. Erickson, of the Department of Geophysics, who supervised the research, and whose guidance and enthusiasm have contributed immeasurably to this study. The author is also grateful to Dr. W.H. White, of the Department of Mining and Geological Engineering, and Mr. J.E. Harakal, research assistant, Department of Geophysics, for their assistance and many helpful suggestions. Particular thanks are due Mr. K.E. Northcote, graduate student in the Department of Geology, who generously donated several samples for the present research and contributed to many aspects of this study. The facilities of both the Department of Geology and the Department of Mining and Metallurgy are gratefully acknowledged. Appreciation is also extended to the officials of the Bethlehem Copper Corporation Ltd., for their permission to use samples collected from their property. Thanks are due to Miss S. Newman who typed the final draft of this thesis. This work was supported mainly by grants from the National Research Council and also from Canadian Exploration, Limited.

INTRODUCTION

The potassium-argon results given in this thesis are among the first obtained in the potassium-argon laboratory at the University of British Columbia. This laboratory was set up in order to further investigate the geological history of British Columbia as well as the theoretical aspects of the potassium-argon techniques. Construction of the laboratory began in early 1963 under the supervision of Drs. G.P. Erickson and W.H. White. Dr. Erickson was responsible for the design and application of the analytical equipment in the laboratory. The writer joined the laboratory in September 1963 and assisted with the assemblage, development, and testing of the equipment. Full details regarding the design and construction of the apparatus will be given elsewhere and will not be described here. The application of these facilities to the problem of dating minerals low in potassium is one of the purposes of the present study.

Most of the useful potassium-argon age determinations have, until recently, been obtained on micas. With the available potassium-argon techniques, however, it is possible to determine the ages of minerals in which potassium occurs as a minor element. This ability has made it possible to apply potassium-argon age determination techniques to a much wider range of geological problems. It is now possible to date acid, intermediate, and even basic igneous rocks using potassium-argon methods on micas

and amphiboles, and, to a limited extent, on feldspars, pyroxenes, and other minerals (Hart, 1960; 1961; Aldrich et al, 1960; Erickson and Kulp, 1961). Potassium-argon apparent ages have also been obtained from whole rock samples.

Laboratory diffusion studies of the retentivity of argon by various minerals and the investigations of apparent mineral ages across contact metamorphic zones have shown that some minerals low in potassium, such as pyroxenes and amphiboles, are often more resistant to argon loss than micas (Aldrich et al, 1960; Hart, 1960; 1961). Damon and Kulp (1958), however, had previously suggested that amphiboles might contain excess radiogenic argon that had been occluded by the mineral at the time of its formation. This hypothesis has been considered by Hart (1960; 1961), who compared the apparent ages of associated biotite, hornblende, actinolite, feldspar, and zircon using K-Ar, Sr-Rb, and U-Th techniques and found no evidence of excess argon in amphiboles. Studies made by Evernden and Richards (1962) essentially confirmed Hart's conclusions. All evidence to date, therefore, indicate that reliable potassium-argon ages may be obtained on amphiboles.

The different behaviour of biotite and amphibole under thermal influences may be used to evaluate the relative merits of the apparent ages obtained from these minerals when they coexist. Greater confidence may be attached to concordant apparent ages obtained on coexisting biotite and amphibole than to an apparent age obtained on either of these minerals alone. When the biotite apparent age is less than the hornblende

apparent age, and this is believed to be due to reheating, the latter age would be closer to, although not necessarily equal to, the true age.

In order to further investigate the value of potassium-argon age determinations on minerals other than micas, it was decided that a study should be made on amphiboles and micas from a geologically complex area where sufficient geological information was available. The Bethlehem Copper property in the Highland Valley area of south-central British Columbia met these requirements and was selected for the study. This property has been mapped in considerable detail (White et al, 1957; Carr, 1959; 1960) and contains a number of the intrusive phases which comprise the Guichon Creek batholith. The purpose of this thesis is to discuss the geological significance of the potassium-argon age results obtained by the writer on biotite and amphibole present in these phases with the aim of resolving the geological history of the batholith more definitely than may be done by potassium-argon age determinations on biotite alone. A description of the potassium and argon analytical techniques employed is also presented.

Chapter I of this thesis reviews briefly the general geology of the Bethlehem Copper property. Chapter II describes the criteria used in selecting the samples and the procedures used in selecting mineral concentrates suitable for analysis. Chapter III gives a review of the potassium and argon analytical

techniques used and discusses the precision and accuracy of the potassium and argon results. Analytical results and calculated ages for the various samples studied are given in Chapter IV and are discussed in Chapter V. Petrographic descriptions of the samples collected for this study are given as an appendix.

CHAPTER I

GENERAL GEOLOGY OF THE BETHLEHEM COPPER PROPERTY

1.0 Introduction

The Bethlehem Copper property in the Highland Valley area of south-central British Columbia is located approximately 30 miles southeast of the town of Ashcroft. (See Figure 1.1.) The regional geology of the Highland Valley area has been mapped on a scale of 4 miles to the inch and described in two Memoirs of the Geological Survey of Canada, one by Cockfield (1948), and the other by Duffell and McTaggart (1952). The geology and mineral deposits of the Highland Valley were described by White, Thompson, and McTaggart (1957), and a paper discussing the porphyries, breccias, and copper mineralization in Highland Valley was published by Carr (1960). A doctorate dissertation on the geology and biotite K-Ar ages of the various phases of the Guichon Creek batholith, which underlies the Highland Valley, is currently being prepared at the University of British Columbia by K.E. Northcote. Much of the geological material used in this present study has been obtained from the works of these authors and from unpublished reports by company geologists.

1.1 Guichon Creek Batholith

The intrusive rocks underlying the Highland Valley are part of the Guichon Creek batholith, a northerly trending mass

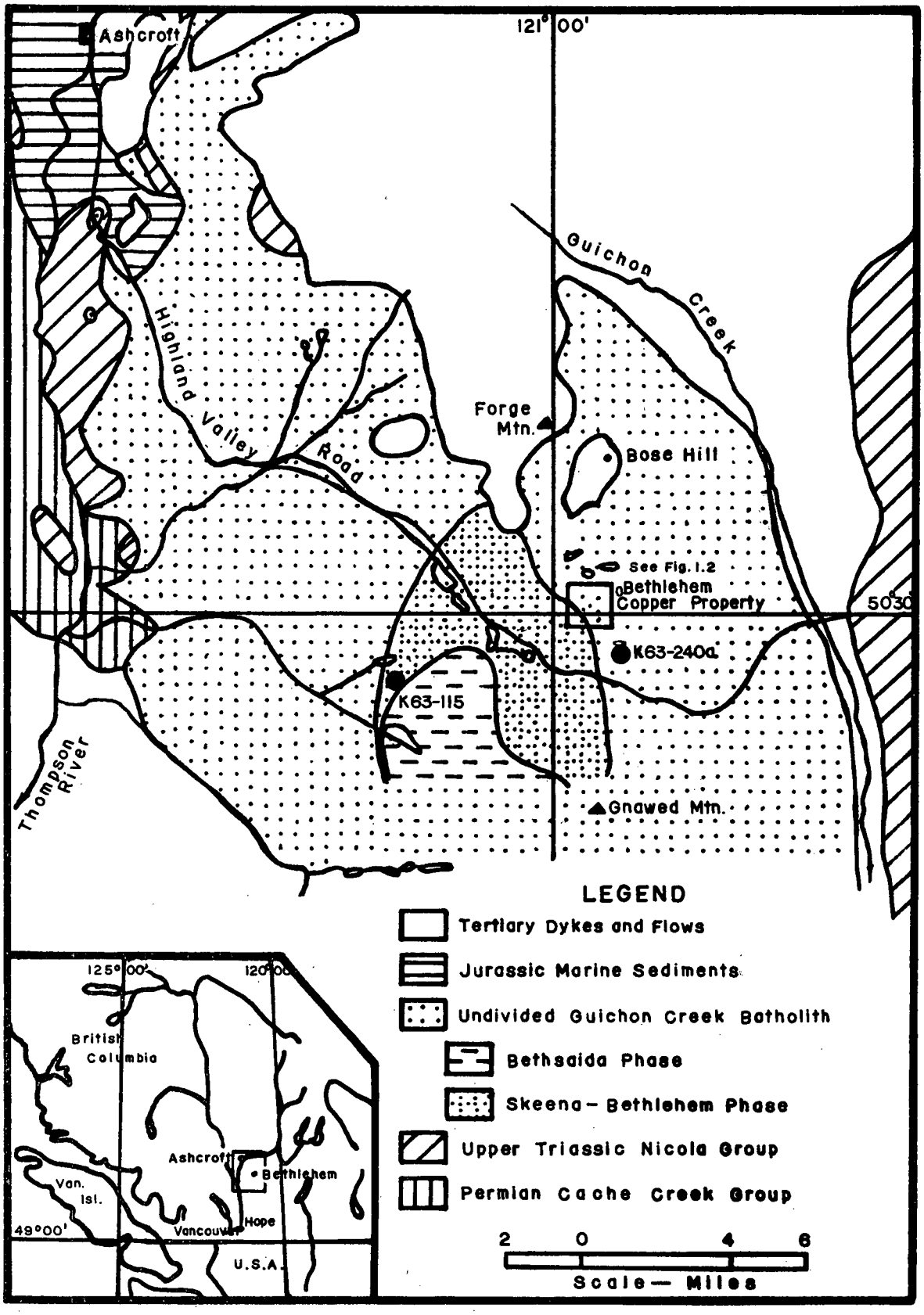

Fig. 1.1: Northern Portion of the Guichon Creek Batholith. (After Cockfield, 1948; Duffell and McTaggart, 1952; Northcote, personal communication.)

some 40 miles long and 16 miles wide. Rock types comprising the Guichon Creek batholith are described in the early literature simply as quartz diorite, and granodiorite with local gabbroic phases (Cockfield, 1948). It is now evident that the batholith is a complex body consisting of a number of individual phases ranging from granitic to gabbroic in composition that may be distinguished petrographically and separated in the field on the basis of textural, mineralogical, and structural relationships (White et al, 1957; Northcote, personal communication).

The emplacement age of the batholith is known within close limits because of its contact relationships with other rocks. It intrudes Upper Triassic volcanic rocks of the Nicola group and locally is unconformably overlain by Middle and Upper Jurassic fossiliferous marine sediments of the Ashcroft Jurassic group (Duffell and McTaggart, 1952).

Several K-Ar age determinations have been made on specimens from the Guichon Creek batholith by the Geological Survey of Canada (Leech et al, 1963; Wanless et al, 1965). The apparent biotite K-Ar ages that they reported range from 224 to 265 m.y. An average K-Ar apparent age of 181 m.y., based on the results obtained on three samples of biotite from the Guichon Creek batholith, was reported by Folinsbee et al (1960). This date was used as a control point by Kulp (1961) to establish the base of the Jurassic on his geological timescale.

1.2 Phase Relations on the Bethlehem Copper Property

On the Bethlehem Copper property, the dominant country rock, generally referred to as Guichon quartz diorite, is intruded by an irregular salient composed of granite (Bethlehem granite), a younger quartz diorite (Bethlehem quartz diorite), and several varieties of porphyry. Porphyry dykes also occur outside of the salient. The porphyry intrusions on the Bethlehem Copper property are of particular interest since it is believed that they are responsible for the explosion breccia zones which are favourable hosts for copper mineralization (White et al, 1957; Carr, 1960; Coveney, 1962). The distribution of rock phases described is shown in Figure 1.2. Figure 1.2 is a generalized geological map of the Bethlehem Copper property which was traced, with some modification, from a preliminary geological map prepared by Carr (1959).

1.2.1 Guichon Quartz Diorite

The Guichon quartz diorite is the oldest igneous phase present on the Bethlehem property (White et al, 1957; Carr, 1959). It is a massive, coarse-textured, mesocratic rock composed of biotite, hornblende, grey plagioclase, quartz, and pink feldspar and is characterized by evenly distributed mafic minerals, poikilitic biotite, and interstitial quartz exhibiting a wedge-shaped habit.

1.2.2 Bethlehem Granite

There is some disagreement regarding the relative age of

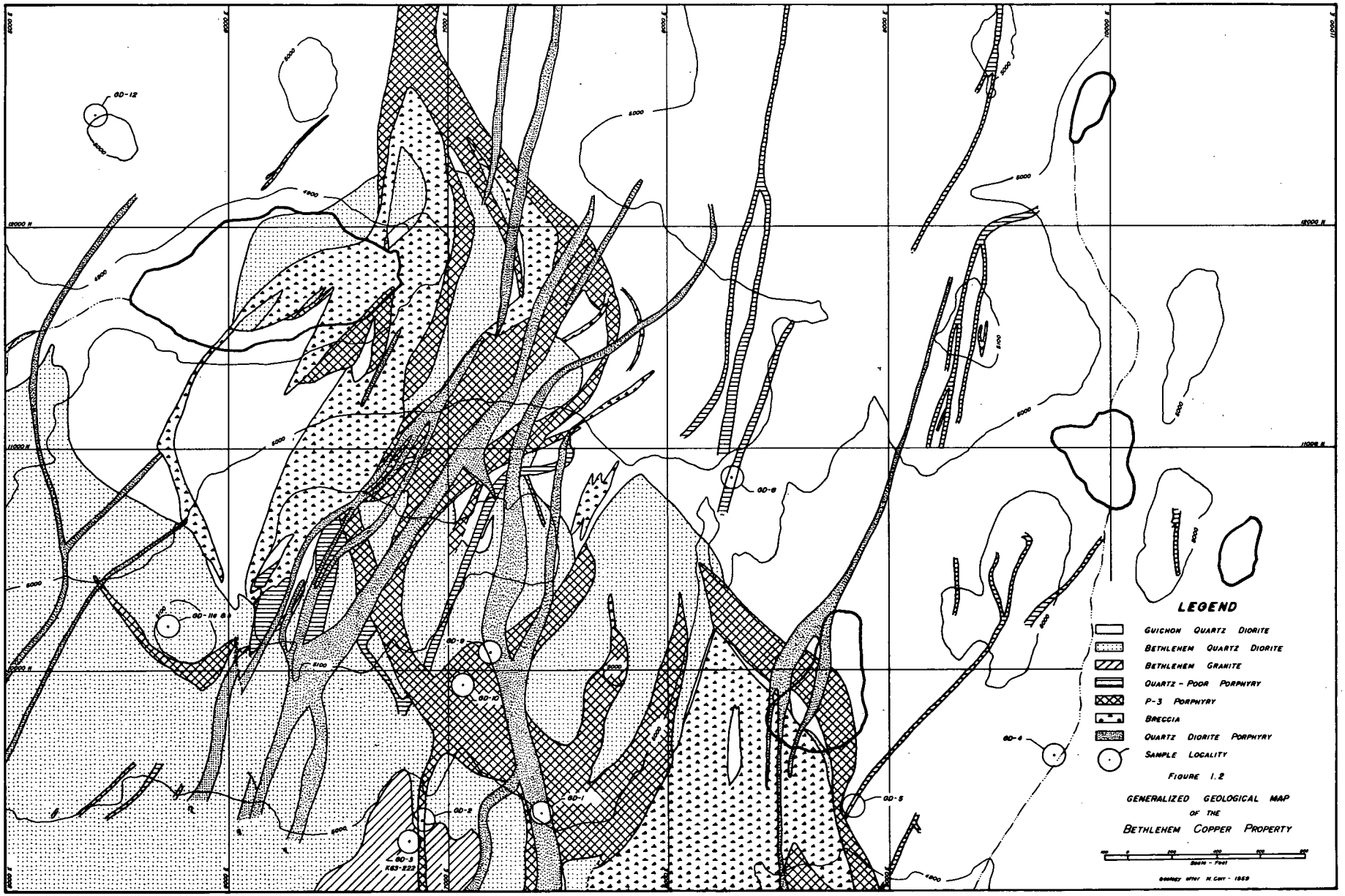

Figure 1.2

GENERALIZED GEOLOGICAL MAP OF THE BETHLEHEM COPPER PROPERTY

Geology after M. Carr - 1969

the Bethlehem granite. White et al (1957) consider the Bethlehem granite to be younger than the Guichon quartz diorite but older than the Bethlehem quartz diorite. Carr (1959), however, believes that the Bethlehem granite is "probably gradational to Bethlehem quartz diorite but also segregational and locally intrusive into latter rock." The Bethlehem granite is a fine- to medium-grained, reddish rock composed of pinkish-red orthoclase, quartz, white plagioclase, and minor biotite. With increasing plagioclase, the rock grades into a quartz monzonite.

1.2.3 Bethlehem Quartz Diorite

Carr (1960) and Northcote (personal communication) believe that the Bethlehem quartz diorite may be part of a larger body of quartz diorite, referred to by Northcote as the Skeena-Bethlehem phase, which crops out on the south side of the Highland Valley. (See Figure 1.1.) On the basis of structural relationships, White et al (1957) and Carr (1959; 1960) have concluded that the Skeena-Bethlehem phase is younger than the Guichon quartz diorite and older than the porphyry dykes which intrude the Bethlehem quartz diorite on the Bethlehem Copper property. The Bethlehem quartz diorite is a light grey, granitic to porphyritic rock composed of hornblende, biotite, quartz, plagioclase, and potassium feldspar. The porphyritic varieties are characterized by large, well-shaped, poikilitic hornblende phenocrysts. The granitic varieties are distinguished from Guichon quartz diorite by their lower mafic content and uneven distribution of mafic minerals.

1.2.4 Porphyry Intrusions

The various porphyry intrusions on the Bethlehem Copper property are part of a much larger porphyry dyke swarm that embraces all the principle copper deposits of Highland Valley (Carr, 1960). Although the porphyry intrusions are of different ages, they are all younger than the Bethlehem quartz diorite. White et al (1957) recognized two types of porphyry on the Bethlehem Copper property. The first type, referred to as a dacite porphyry, consists of phenocrysts of plagioclase, poikilitic hornblende, and quartz set in an abundant fine-grained, often greenish matrix. The other, referred to as a quartz diorite porphyry is similar in composition but differs in that it contains phenocrysts of considerably larger size which make up more than 80 per cent of the rock. Other characteristic features of this latter rock are well developed, rounded quartz phenocrysts and the replacement of hornblende by radial aggregates of epidote.

Carr (1959) has subdivided the dacite porphyry into two main categories based on the presence or absence of quartz phenocrysts. Those with few or no quartz phenocrysts are called the quartz-poor porphyry, which may be further subdivided into the P-1 and P-2 porphyries on the basis of textural differences, while those with abundant kidney or round shaped quartz phenocrysts are called either the P-3 porphyry or aplitic quartz porphyry. Aplitic quartz porphyry is a phaneritic variety of the P-3 porphyry and is easily confused with porphyritic Bethlehem quartz diorite.

A porphyritic dyke-like body, referred to as the Spud Lake porphyry, crops out a short distance east of the Bethlehem salient. White et al (1957) suggest that the Spud Lake porphyry is an offshoot of the Bethsaida granodiorite, the main body of which intrudes the Skeena-Bethlehem phase on the south side of Highland Valley. The Bethsaida granodiorite is a coarse-grained rock composed of euhedral books of biotite, sub-rounded quartz grains, grey plagioclase, and rare hornblende. The Spud Lake porphyry differs somewhat from the main Bethsaida body in that it contains large, well altered, phenocrysts of hornblende as well as phenocrysts of the other constituents set in a somewhat aphanitic groundmass.

1.2.5 Breccia

Breccia bodies on the Bethlehem Copper property form inclined tabular bodies closely associated with the porphyry intrusions (Carr, 1960). The breccia is a dense rock without voids. It contains a varied assemblage of rock-fragments representing the following types: Guichon quartz diorite, Bethlehem quartz diorite, P-1 porphyry, P-2 porphyry, and fine-grained or aphanitic varieties of the P-3 porphyry and, therefore, must be younger than all of these (Carr, 1959; 1960). To date, no fragments of the quartz diorite porphyry have been recognized in the breccia indicating that this porphyry is probably post-breccia in age. The matrix of the breccia contains broken grains of feldspar and quartz, and small rock fragments. This cataclastic matrix is partly replaced by new minerals including

biotite and tourmaline as the result of recrystallization and accompanying metasomatism (White et al, 1957). Carr (1959) suggests that brecciation took place immediately following the partial chilling of the P-3 porphyry as the result of the explosive release of volatiles contained in the porphyry. White et al (1957) suggest that the origin of the breccia involves explosion in the lower part of a volcanic structure as the result of the volatile pressure in a cupola exceeding the confining pressure.

1.3 Rock Alteration on the Bethlehem Copper Property

Alteration is widespread on the Bethlehem Copper property. White et al (1957) suggest that there are two types of alteration that are probably related in time and origin. The first, not obviously related to mineralization, produced widespread but weak propylitic alteration and is probably deuteric in nature. The second, related to mineralization, produced locally intense alteration effects including tourmalization, silicification, chloritization, feldspathization, and development of biotite, calcite, and clay minerals.

CHAPTER II

SAMPLE COLLECTION AND PREPARATION

2.0 Sample Collection

The degree of alteration in the vicinity of the Bethlehem Copper property made it exceedingly difficult to obtain specimens suitable for this study. An effort, however, was made to collect samples representative of each phase present on the property which showed the least evidence of alteration and surface weathering.

Two, 60 pound samples of each phase were collected from outcrops at different sites on the property. These sites were chosen on the basis of contact relationships, alteration, and accessibility. The locations of the samples collected by the writer and those collected by K.E. Northcote are shown on Figures 1.1 and 1.2.

The samples selected for actual K-Ar analysis were chosen on the basis of thinsection studies of specimens typical of each collected sample. Several of the samples collected were found to contain no useable hornblende or biotite and, therefore, could not be used in this study. Descriptions of samples collected and samples analyzed are given as an appendix.

2.1 Mineral Separations

After the removal of all weathered surfaces, an amount of

each sample necessary to give approximately 50 grams of pure biotite or amphibole concentrate was crushed to pea size using, in turn, a jaw crusher, a gyratory crusher, and a cone crusher. The samples were then passed through a disc grinder and sieved into four size fractions ranging from -28 to +100 mesh. Each size fraction was washed in water and dried by heating to less than 100°C to facilitate mineral separation.

Rough biotite and amphibole concentrates were obtained by the following means. Each washed size fraction of a sample, if it contained both biotite and amphibole, was first passed through an electrostatic separator (Dings Magnetic Separator Co., model 2LAB) set up to concentrate biotite. The electrostatic reject was then passed through a Frantz isodynamic magnetic separator, set up in the vertical position, to remove amphibole and other remaining mafic minerals.

The biotite concentrate, approximately 90 percent pure, from the electrostatic separator, was further purified by means of the heavy liquids tetrabromoethane and diiodomethane. Strongly magnetic grains were removed from the concentrate with a hand magnet. The purified biotite concentrate was washed several times in acetone to remove the heavy liquids before analysis. Impurities in the biotite concentrates were generally less than 2 per cent by volume. The size fraction most commonly employed in the biotite K-Ar analysis was -48 to +100 mesh.

Amphibole was separated from the rough mafic concentrate by means of heavy liquids, the inclined isodynamic magnetic separator, further crushing and screening, and a charged plastic sheet. The final amphibole concentrates were generally better than 95 per cent pure. The common impurity was epidote which proved to be very difficult to separate from amphibole due to its similar physical properties. The presence of a small amount of epidote in the amphibole concentrates, however, was shown not to affect the analyses. The amphibole concentrates contained both hornblende and actinolite as it was not practical to make a clean separation of these two minerals when they occurred together. The amphibole concentrates were washed several times in acetone before analysis. The size fraction most commonly employed in the amphibole K-Ar analysis was -80 to +100 mesh.

CHAPTER III

ANALYTICAL TECHNIQUES

3.0 Introduction

Potassium-argon dating of minerals requires both high precision and absolute accuracy for the potassium and argon determinations. Pinson (1961) has aptly pointed out that it is generally possible to analyze for argon, which occurs in trace amounts in a mineral sample, to a much greater accuracy and with more confidence than it is possible to analyze for one of its major constituents, potassium.

The aim of this portion of the present writer's research programme was to develop a suitable procedure, with the equipment available in this laboratory, for determining the potassium and argon contents of amphibole with sufficient accuracy that the results may be used in potassium-argon age investigations.

All potassium-argon apparent mineral ages in this study were obtained by determining the radiogenic argon content of a mineral by isotope dilution techniques using a gas source, statically operated mass-spectrometer and its potassium content by flame photometric techniques. The techniques used will be considered in turn.

3.1 Potassium Analysis

3.1.1 Equipment

The potassium content of the amphibole and biotite concentrates were determined on a Baird Atomic, model KY-1, clinical flame photometer using propane as fuel and lithium as an internal standard. Results were recorded on a two second response, 10 millivolt, zero center Weston recorder connected in series with the photometer meter. The installation of high quality pressure regulating valves in the air and fuel lines, along with the installation of an external voltage regulator on the photometer supply line, effectively reduced instrument instabilities. Except for the above modifications, the instrument was set up and operated according to the manufacturer's instructions.

3.1.2 Contamination

Special care was taken to insure against contamination of sample and standard solutions. All glassware used was washed in hot HNO_3, rinsed in pure water, and siliclad at frequent intervals. Sample digestions were made in teflon dishes which were soaked in hot HNO_3 between useage. The water used for rinsing glassware and for diluting standard and mineral solutions was first distilled and then purified in an ion exchange column. Both sample and standard solutions were stored in tightly stoppered polyethylene bottles. The analytical results of total procedure blanks indicated that the level of potassium contamination was negligible for the analyses of this work.

3.1.3 Chemical Procedures

(a) Preparation and Analysis of Biotite Solutions

Biotite solutions were prepared and analyzed by the following procedures. Samples of between 0.5 and 1.0 gram were decomposed at a temperature generally less than 200°C in a total of 3 ml. concentrated H_2SO_4, 35 ml. 49% HF, and 2 ml. concentrated HNO_3 and finally held in solution in approximately 3 ml. of concentrated H_2SO_4. The residual solutions were brought up to exactly 1000 ml. with pure water and 100 ml. stock solution containing 2000 ppm lithium and 5000 ppm sodium prepared from reagent grade LiCl and Na_2SO_4. The potassium contents of the biotite sample solutions were determined by comparing the unknown solutions with standard solutions containing 200 ppm lithium, 500 ppm sodium, and an appropriate amount of potassium. These standard solutions were prepared by dissolving weighed quantities of desiccated, reagent grade K_2SO_4 in pure water and 100 ml. of the same lithium and sodium stock solution used to prepare the biotite sample solutions and diluting with pure water to a final volume of 1000 ml.

(b) Preparation and Analysis of Amphibole Solutions

Amphibole solutions were prepared by decomposing 1.5 to 2.5 gram samples in the same reagents used for preparing the biotite solutions although in some cases perchloric acid was used instead of nitric acid. The decomposed samples were diluted to 250 ml. with pure water and 25 ml. of the same lithium and sodium stock solution used for the biotite solutions. The

amphibole solutions were compared with standards that contained the same quantity of sulphuric acid as the solutions themselves for the reasons explained in the next section. These standards were about 0.4N H_2SO_4 and contained 200 ppm lithium, 500 ppm sodium, and an appropriate amount of potassium.

3.1.4 Investigation of Interference Effects

Mineral samples used in potassium-argon age determinations contain some or all of the following cations as major constituents: Si, Al, Fe, Ca, Mg, Na, and K. During sulphuric and hydrofluoric acid digestion of a sample, Si is volatilized as fluoride, and the remaining elements are left as sulphates in a residual sulphuric acid solution. Numerous references, (eg. Burriel-Marti and Ramírez-Munoz, 1957; Dean, 1960; Abbey and Maxwell, 1960; Cooper, 1963) many of them contradictory, may be found concerning the interference effects in flame photometry caused by variations in acidity or mutual repression or enhancement between cations and anions. While some ignore these effects and analyze the sample solutions directly against pure alkali standards, others attempt to overcome them by using correction curves, by buffering with the troublesome ions, or by the removal of all or some of the interfering ions. Since it was evident that some of these effects may relate to the flame characteristics and the optical resolution of the particular flame photometer use, it was considered desirable to evaluate them independently for the instrument used in this work.

Experiments were, therefore, carried out to determine the effects of the various cations (Al, Fe, Ca, and Mg) present in the sample solutions and the effect of the sulphuric acid which was introduced during the digestion procedure. The cation interference may be of greater significance for amphibole potassium analyses than for mica since the cation/potassium ratio of amphibole is considerably larger than that of mica. The possible effect of sodium was eliminated by buffering both standard and sample solutions with an overwhelming quantity of that ion.

The problem of determining the mutual interference between one element and another is difficult because the apparent potassium content of a solution may be depressed by one element and enhanced by another. The procedure used in this study involved the analysis of different aliquots of an amphibole solution diluted to different volumes with a standard of known potassium content. The effect of this procedure is to reduce the cation/potassium ratio so that if interference is taking place it should be evident in the results. The results obtained indicated that the interference effects due to the presence of other cations in the amphibole solutions were negligible.

The only significant interference effect was found to be due to sulphuric acid. It was observed that the apparent amount of potassium in solution was non-linearly related to the concentration of sulphuric acid. An attempt to obtain correction curves proved unsuccessful since it was impossible to obtain consistent results due to the variability of the interference effects with

certain non-reproducible instrument adjustments. The observations were consistent with the interpretation that the sulphuric acid was somehow reducing the lithium emmission and, therefore, affecting the apparent potassium concentration since this is always measured relative to that of the lithium internal standard. A modified form of the buffer technique was, therefore, utilized and was found to yield satisfactory results. This involved the addition of the same amount of sulphuric acid to the standard solution as was present in the unknown sample solutions. These acidic standards were only used for amphibole analysis because tests had shown that the interference effect of sulphuric acid in the less acidic biotite solutions was negligible.

The potassium content of epidote was investigated because it was a common contaminant of the amphibole concentrates. Analysis of an epidote solution, treated in a manner similar to the procedure used in the amphibole analyses, indicated that the epidote contained less than 0.03% potassium. Since most of the amphibole concentrates contained less than 5 per cent epidote, the contribution of potassium from this source could be neglected.

3.1.5 Precision and Accuracy

The results of the potassium analyses are given in Chapter IV. Twelve replicate results obtained on separately weighed portions of the interlaboratory biotite standard, GE 2060, indicate a precision of 1 per cent for the biotite flame photometer potassium analyses. The accuracy of the mica potassium

analysis is also believed to be approximately 1 per cent since the results obtained at this laboratory on GE 2060 and the U.S.G.S. muscovite standard, P-207, agree within 1 per cent with those quoted by other laboratories. (See Table 4.2.) The results of triplicate amphibole potassium analyses indicate a precision of approximately 1 per cent. No interlaboratory standard was available with which to determine the accuracy of the amphibole analysis, however, it is believed, on the basis of the results of several experiments with standard solutions and a careful accounting of interference and contamination effects, that the absolute error of the amphibole potassium analysis is less than 2 per cent.

3.2 Argon Analysis

3.2.1 Introduction

The argon content of the amphibole and biotite concentrates were determined on an analytical system designed by Dr. G.P. Erickson. (See Figure 3.1.) Full details of the system and analytical procedures used will be given elsewhere and, therefore, will not be described in detail here. Basically, the method of isotope dilution was used employing a known quantity of Ar^{38} as tracer or spike and correction for atmospheric argon contamination based on the Ar^{36} concentration in the gas sample.

3.2.2 Fusion

The sample to be analyzed, approximately 0.7 to 1.0 gram

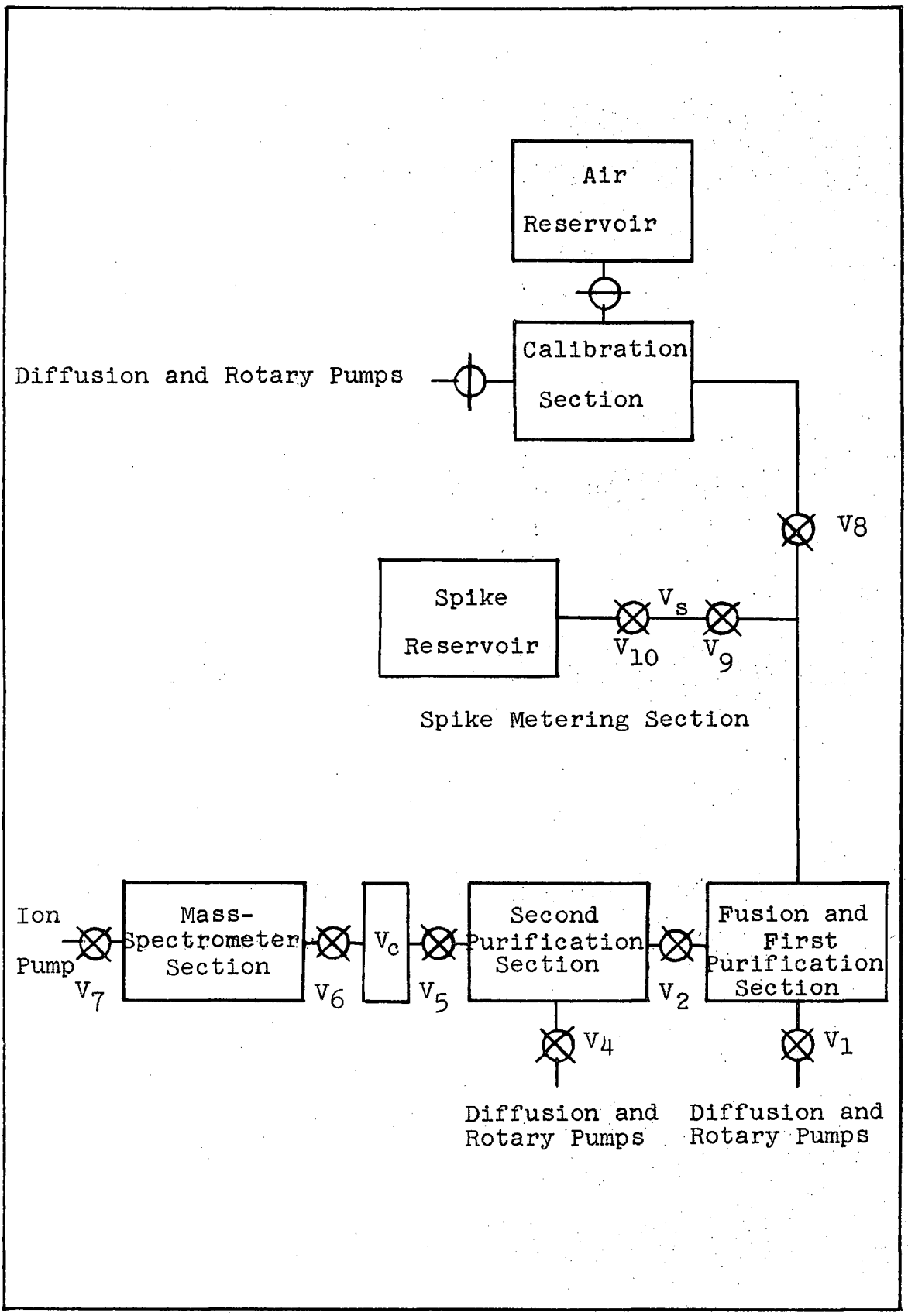

Figure 3.1: Block Diagram of the Argon Analytical System.

biotite and 9 to 11 grams amphibole was placed in an alundum enclosed molybdenum crucible and mounted on a molybdenum wire stand in a water-jacketed pyrex fusion jar. This fusion jar was connected to the argon line by means of a copper-gasketed flange coupling. A leak test of the argon line was carried out before each analysis by opening each section in turn to the mass-spectrometer and observing the build-up of the mass-40 and mass-28 signals. It was found that the fusion section and sample normally did not require outgassing, by baking, if pumped on for periods in excess of 12 hours.

The molybdenum crucible was heated to the fusion temperature of the sample by means of a 6 KW, radio frequency generator and induction coil which was constructed to fit around the fusion jar. The temperature of the sample was gradually raised so as to prevent decrepitation of the sample. When the temperature of the sample reached approximately 1000°C, the Ar^{38} spike was metered into the fusion section by means of the metal valves V_9 and V_{10}. A final temperature of about 1500°C, maintained for at least 10 minutes, was found to be sufficient to completely fuse the sample and release all the argon. The pressure of the fusion section was monitored by means of a pirani gauge and was controlled by either varying the temperature of a hot titanium metal sponge in the fusion section or placing liquid nitrogen on a charcoal trap. A cold finger trap was kept at the temperature of dry ice throughout the fusion in order to remove H_2O.

3.2.3 Purification

The released gases, still isolated in the fusion section of the system, were purified by allowing them to react with the hot titanium sponge as it cooled to room temperature from 700°C. Argon and most other remaining gases were then adsorbed in a charcoal trap kept at the temperature of liquid nitrogen. Once equilibrium had been reached, the metal valve, V_1, connecting the fusion section to the pumps was opened and the remaining gas, chiefly hydrogen, was pumped out. This valve was then closed and the gas was transferred through the connecting metal valve, V_2, to the second purification section by adsorbing it on another charcoal trap. Further cleanup of the gas could be achieved in this portion of the system by allowing the gas to react with a second titanium sponge which could be isolated by a metal valve. When necessary, any number of purification cycles could be carried out by simply alternating the gas back and forth between these purification sections. Between each cycle, the titanium sponge would, of course, be outgassed by heating to a temperature greater than 950°C. The gas released during the fusion of amphibole samples generally required at least 2 such steps before it was suitable for isotopic analysis while the gas released during the fusion of biotite samples normally only required 1 cleanup. After the final reaction on the titanium sponge, the gas was always adsorbed on charcoal at liquid nitrogen temperature and any remaining gas pumped away.

3.2.4 Measurement of Isotopic Ratios

After purification, sufficient gas was allowed to pass through the leak valve, V_6, into the mass-spectrometer section of the system to give conveniently measurable isotopic signals, the mass-40 signal being generally between 5 and 10 volts. The isotopic composition of the gas was measured statically (V_6 and V_7 closed) using a 180° deflection, 2 inch radius, mass-spectrometer (Associated Electrical Industries, type MS10) and a vibrating reed electrometer amplifier (Applied Physics, model 31) using a 10^{11} ohm input resistor. Results were displayed on a 1/4 second response, 10 millivolt full scale, potentiometer-type recorder, having an eleven inch wide strip chart (Brown Instrument Division, Minneapolis-Honeywell Regulator Co.).

The average of 10 scans for both the 40/36 and 40/38 ratios was taken to represent the argon isotopic ratios since the standard deviation of the average was always less than 1/4 per cent. The 40/36 ratio was used to determine the correction to apply to the 40/38 ratio due to the presence of atmospheric argon in the gas sample. Systematic changes in observed ratios during analyses were negligibly small so that it was not necessary to extrapolate the ratios to the time of admission to the mass-spectrometer. For each analysis, a check was made to determine the fraction of the total quantity of gas actually admitted to the mass-spectrometer so that fractionation effects at the leak valve could be evaluated. The small volume, V_c, which is approximately 10 per cent of the volume of the second purification system, was used

for this purpose. The measured 40/36 and 40/38 ratios were corrected for fractionation at the valve and discrimination in the mass-spectrometer before being used in the age calculations.

3.2.5 Precision and Accuracy

The results of the argon analyses are given in Chapter IV. The results of quadruplicate argon analyses of standard GE 2060 indicate a precision of approximately 1 per cent for the argon analyses. Absolute methods, involving accurately measured quantities of atmospheric argon, were used to calibrate the argon-38 spikes with which the argon concentrations of the various samples were determined. However, analyses of standards based upon such calibrations were found to be systematically low, by a few per cent, from those reported by other laboratories. (See Table 4.2) For this reason, the argon analyses performed in this laboratory are considered to be accurate to within approximately 3 per cent for those analyses having less than 50 per cent atmospheric argon contamination. For those analyses having more than 50 per cent atmospheric argon contamination, the formula given by Lipson (1958) is used to determine the error in the argon-40 radiogenic concentration.

CHAPTER IV

RESULTS

The analytical data determined during the course of this study on specimens from the Bethlehem Copper property are presented in Table 4.1. Sample numbers correspond to those given in Figures 1.1 and 1.2. Table 4.2 compares the results obtained on the interlaboratory biotite standards, GE 2060 and B-3203, and muscovite standard, P-207, with those obtained elsewhere. Table 4.3 compares the potassium-argon apparent ages of the various phases of the Guichon Creek batholith with their relative ages deduced on the basis of structural evidence.

The flame photometric potassium analyses were carried out at least in duplicate for each sample. The average potassium content was calculated for each sample and was used in the apparent age calculations. The potassium values used in the biotite and amphibole apparent age calculations are believed to be accurate within 1 and 2 per cent, respectively and have a precision of approximately 1 per cent as discussed in section 3.1.5.

Normally, only a single argon analysis was made on each sample. The argon values used in the apparent age calculations are believed to be accurate within a few percent and have a precision of approximately 1 per cent as discussed in section 3.2.5.

TABLE 4.1

K-Ar Analytical Results
Bethlehem Copper Property

$\lambda_\epsilon = 0.58 \times 10^{-10} yr^{-1}$; $\lambda_\beta = 4.72 \times 10^{-10} yr^{-1}$; $K^{40}/K = 0.01181\%$

Sample Number Rock Name	Mineral	Potassium %	$\frac{Ar^{40*}}{\text{Total } Ar^{40}}$	Ar^{40*} (in 10^{-5} cc STP/g)	$\frac{Ar^{40*}}{K^{40}}$	Apparent Age (my), Estimated Analytical Error
GD-2 P-3	Amphibole	0.1406 0.1386 0.1402 Av.0.140	0.24 0.39	0.09845 0.09879	0.01041 0.01044	170±12 171±10
GD-4 Guichon Quartz Diorite	Amphibole	0.1708 0.1684 0.1691 Av.0.169	0.60	0.1474	0.01285	208±8
GD-5 Quartz-poor Porphyry	Biotite	5.586 5.529 Av.5.56	0.50	4.717	0.01253	203±8
GD-10 P-3	Amphibole	0.2899 0.2941 Av.0.292	0.53	0.2432	0.01230	199±8
GD-11a Bethlehem Quartz Diorite?	Amphibole	0.1617 0.1614 Av.0.162	0.44	0.1305	0.01193	194±10

TABLE 4.1 (Cont.)

Sample Number Rock Name	Mineral	Potassium	$\frac{Ar^{40*}}{\text{Total } Ar^{40}}$	Ar^{40*} (in 10^{-5} cc STP/g)	$\frac{Ar^{40*}}{K^{40}}$	Apparent Age (my), Estimated Analytical Error
GD-12 Guichon Quartz Diorite	Biotite	5.544 5.577 Av.5.56	0.83	4.663	0.01239	201±8
	Hornblende	0.4204 0.4282 Av.0.424	0.60	0.3629	0.01264	205±8
K63-115 Skeena-Bethlehem	Biotite**	5.98 5.84 5.91 5.87 Av.5.90	0.90	4.307	0.01196	195±8
	Hornblende	0.3805 0.3936 Av.0.387	0.39	0.3121	0.01192	194±10
K63-222 Bethlehem Granite	Biotite	7.154 7.175 Av.7.16	0.87	5.903	0.01218	198±8
K63-240 Breccia	Biotite***	5.60 5.61 5.59 5.61 Av.5.60	0.84	4.643	0.01225	199±8

* Radiogenic
** Concentrate prepared and analyzed by K.E. Northcote
*** Concentrate prepared and analyzed by Dr. W.H. White
'Amphibole' indicates those samples containing both actinolite and hornblende

TABLE 4.2

Interlaboratory Results

Standard Number Mineral	Laboratory Analyst	Potassium %	$\frac{Ar^{40*}}{Total\ Ar^{40}}$	Ar^{40*} (in 10-5 cc STP/g)
GE 2060 Biotite	Columbia	6.92 I	0.97	5.579
	Erickson, G.P.	6.91 I	0.90	5.628
	McDowell, F.	6.89 P		
	Yale	6.81 P		
	Armstrong, D.	6.82 P		
	U.B.C.			
	Northcote, K.E.	6.85±.06	0.95	5.484
	Harakal, J.E.	P**	0.63	5.438
	Dirom, G.E.		0.83	5.423
			0.48	5.394
P-207 Muscovite	Summary of Results (Lanphere and Dalrymple, 1965)	8.58±.12		2.840±.063
	U.B.C.	8.65	0.77	2.742
	Northcote, K.E.	8.63	0.90	2.666
	Dirom, G.E.	8.56	0.66	2.722
	Harakal, J.E.	8.59		
B-3203 Biotite	Summary of Results (Hurley et al, 1962)			38.77±.14
	U.B.C.			
	Harakal, J.E.		0.72	38.37

P Flame photometric analyses
I Isotope dilution analyses
* Radiogenic
** Average and standard deviation of 12 potassium analyses

TABLE 4.3

Relative Ages of the Various Phases
on the
Bethlehem Copper Property

Phase Name	Sample Number	Relative Age on Structural Evidence	Mineral	K-Ar App Age (my)
Guichon Quartz Diorite	GD-4	1	Amphibole	208
	GD-12		Hornblende	205
	GD-12		Biotite	201
Skeena-Bethlehem Quartz Diorite	GD-11a	2 or 3	Amphibole	194
	K63-115		Hornblende	194
	K63-115		Biotite**	195
Bethlehem Granite	K63-222	2 or 3	Biotite	198
Quartz-poor Porphyry	GD-5	4	Biotite	203
P-3 Porphyry	GD-2	5	Amphibole	170
	GD-10		Amphibole	199
Breccia	K63-240	6	Biotite***	199
Quartz Diorite Porphyry	ND	7	ND	
Spud Lake Porphyry	ND	Post Skeena-Bethlehem	ND	

** Concentrate prepared and analyzed by K.E. Northcote
***Concentrate prepared and analyzed by Dr. W.H. White

'Amphibole' indicated those samples containing both actinolite and hornblende

The apparent age of each sample analyzed was calculated on the basis of the data presented in Table 4.1. The calculated apparent age also shows the estimated error limits. These limits, ranging from 4 to 6 per cent of the associated apparent age, were estimated both on the basis of the results obtained on the interlaboratory standards and a mathematical evaluation, similar to that outlined by Wanless et al (1965), of the individual sources of error. The apparent ages of those samples having less than 50 per cent atmospheric argon contamination, however, are believed to be internally accurate to within 2 per cent. This relative accuracy may be used to determine whether there are any real age differences between the various intrusive phases studied.

CHAPTER V

DISCUSSION

The biotite and amphibole potassium-argon apparent ages obtained during the course of this study on the various phases of the Guichon Creek batholith present on the Bethlehem Copper property are of value as clues to the geological history of this batholith and to the age of the Triassic-Jurassic boundary. Although the individual phases are essentially indistinguishable by means of their potassium-argon apparent ages (see Figure 4.3), the results obtained indicate with considerable certainty that these phases were emplaced during an interval of not more than 10 m.y. centered around 200 m.y. ago.

The stratigraphic age of the Guichon Creek batholith is considered to be known within close limits since it is believed to intrude early Upper Triassic volcanic rocks of the Nicola group and to be unconformably overlain by fossiliferous early Middle Jurassic marine sediments (Duffell and McTaggart, 1952). The unconformity between the Guichon Creek batholith and the Middle Jurassic marine sediments favours placing the emplacement age of the batholith near the top of the Triassic. The age of this batholith may, therefore, indicate the age of the Triassic-Jurassic boundary. The average of all the potassium-argon apparent ages obtained in this study on both biotite and amphibole except GD-2 is 200 m.y. with a standard deviation of the mean of

less than 2 per cent. This average apparent age of 200 m.y. is, therefore, believed to represent a better approximation to the maximum age of the Triassic-Jurassic boundary than the 181 m.y. age suggested by Folinsbee et al (1960), which was based on the potassium-argon results obtained on biotite from samples collected elsewhere in this batholith.

Leech et al (1963) and Wanless et al (1965) of the Geological Survey of Canada, reported biotite potassium-argon apparent ages ranging from 224 m.y. to 265 m.y. on rocks representing various phases of the Guichon Creek batholith including Guichon quartz diorite, Bethlehem quartz diorite, and Bethsaida granodiorite. These Middle Permian results have led Wanless et al (1965) to suggest that the Nicola group strata are in fault contact with, or rest unconformably on the Guichon Creek batholith, or that the contact rocks are not part of the Nicola group but are older.

The results obtained in the present study are incompatible with those reported by Leech et al (1963) and Wanless et al (1965) unless all the samples used in this study suffered metamorphism approximately 200 m.y. ago. This hypothesis seems improbable for several reasons. First, the concordant apparent ages obtained on the coexisting hornblende and biotite in samples K63-115 and GD-12 indicate that no major metamorphic event has occured since the initial crystallization of these rocks unless both the biotite and hornblende 'clocks' in these samples were completely reset as the result of such metamorphism. Second,

these two samples were collected six miles apart geographically indicating that, if the 'clocks' in these samples were completely reset, the metamorphic event required would probably have been sufficiently widespread to have affected the batholith as a whole. Third, no petrographic evidence was found in the thinsections studied to indicate the occurrence of a metamorphic event sufficiently intense to completely reset the amphibole 'clocks'. Fourth, the essentially identical apparent ages obtained on two different samples of the Guichon quartz diorite, GD-4 and GD-12, which show different degrees of alteration of hornblende to actinolite, indicate that this alteration was deuteric in nature, that is, it took place during the final stages of the crystallization process rather than as the result of a later metamorphic event. And finally, if, as generally accepted, the Guichon Creek batholith intrudes early Upper Triassic Nicola rocks, the date of the Middle-Upper Triassic boundary suggested by Kulp (1961) to be 200±10 m.y. can be used to place a rough upper limit on the age of this batholith. Kulp (1961) based this date on the biotite potassium-argon apparent age of 195±5 m.y. obtained by Erickson and Kulp (1961) on the Palisade Diabase of the Newark series which is believed to be Upper Triassic.

The concordant biotite and amphibole apparent ages obtained in this study also serve to indicate that these amphiboles do not contain appreciable excess radiogenic argon. This is essentially in agreement with the conclusion, suggested by Aldrich et al (1960) and Hart (1960; 1961), that amphiboles do

not normally contain excess radiogenic argon as had earlier been considered possible by Damon and Kulp (1958).

The one possibly anomalous apparent age obtained, that on GD-2, is difficult to resolve in light of the other results obtained during this study. The analytical data was independently checked and are considered reliable and accurate within the limits assigned. Structurally, this sample should be older than the breccia and younger than the quartz-poor porphyry. The obtained apparent age of 170 m.y. is, therefore, approximately 30 m.y. younger than one would expect on structural evidence alone. It is possible that this sample is not representative of the P-3 porphyry but rather a later phase, although there is no present petrographic evidence to support this suggestion. Sample GD-2 does contain a greater percentage of actinolite than any other sample analyzed, however, the results obtained by Hart (1961) on actinolite indicate that this mineral should retain argon equally as well as hornblende. The apparent ages obtained in this present study on two different samples of the Guichon quartz diorite, GD-4 and GD-12, which show different degrees of alteration of hornblende to actinolite, also confirm that actinolite retains argon well.

Another possibility is that sample GD-2 was affected by dislocation or, less likely, contact or regional metamorphism. This possibility seems improbable since it is unlikely that sample K63-222, a biotite, collected within 200 feet of GD-2 would then still give an apparent age in good agreement with its

structural position. Aldrich et al (1960) have considered the variation of potassium-argon apparent ages of minerals as a function of distance from an intrusive contact. They found that, while hornblende retained essentially all its argon within 100 feet of such a contact, biotite lost essentially all its argon within 300 feet of the contact and as much as 50 per cent of its argon within 5000 feet. Such values would be expected to be strongly dependent on the size of the heat source, the depth of burial, and other factors. However, they do serve to indicate the improbability that biotite will retain argon within a few hundred feet of amphibole which has apparently lost 15 per cent of its radiogenic argon unless the thermal event was of a very local nature.

CONCLUSIONS

It is evident from the amphibole and biotite apparent ages obtained during the course of this study, that the various phases of the Guichon Creek batholith present on the Bethlehem Copper property were emplaced during a probably short interval, not longer than 10 m.y., centered around 200 m.y. ago and that no major metamorphic event has taken place in this area since this date. It is also evident, that one cannot differentiate between the various phases of the Guichon Creek batholith on the basis of their potassium-argon apparent ages since the variations in the apparent ages obtained were within the analytical limits of uncertainty of the technique used. The one amphibole apparent age which is significantly younger than the others obtained in this work may indicate an event in the formation of this batholith which followed the major intrusive event by approximately 30 m.y.

The average apparent age of 200 m.y. obtained on both biotite and amphibole from the various phases of the Guichon Creek batholith present on the Bethlehem Copper property may represent a better approximation to the maximum age of the Triassic-Jurassic boundary than that previously reported in the literature, however, this conclusion should be confirmed by further study of the stratigraphic age of this batholith and by further isotopic studies, preferably using methods other than potassium-argon.

The results obtained on the two samples containing coexisting

amphibole and biotite indicate that amphiboles give potassium-argon ages of quality at least comparable to those on biotite and that these samples do not contain significant excess radiogenic argon. The one perhaps anomalous amphibole result obtained, although of unambiguous interpretation, does not detract from the overall value of potassium-argon dating of amphiboles or from the value of the other amphibole apparent ages obtained.

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APPENDIX

DESCRIPTIONS AND LOCALITIES OF SAMPLES COLLECTED

GD-1 Quartz Diorite Porphyry Mine Coordinates: 9350N-7430E

This sample, collected from the center portion of a 200' wide dyke where it intrudes P-3 porphyry, is an altered, leucocratic quartz diorite porphyry composed of coarse, euhedral phenocrysts of altered hornblende up to 1 cm. in length and grey-white plagioclase, with glassy eyes of quartz set in an aphanitic, grey-green, chloritic groundmass. Aggregates of epidote appear to replace both hornblende and plagioclase. Phenocrysts comprise approximately 60% of the rock by volume.

In thin-section, this sample is seen to be made up largely of strongly saussuritized andesine phenocrysts set in a very fine-grained, allotriomorphic-granular matrix composed of plagioclase, quartz, and orthoclase. Quartz phenocrysts occur as large clear eyes which are sometimes larger than the plagioclase grains. Hornblende phenocrysts have been almost completely altered to actinolite, chlorite, or epidote and, for this reason, were not analyzed. Accessory minerals include apatite, sphene, and magnetite. The estimated mode is 70% plagioclase, 20% quartz, 4% altered hornblende, 2% orthoclase, 4% magnetite and other accessory minerals.

GD-2 P-3 Porphyry Mine Coordinates: 9310N - 6880E

This sample, collected from the center portion of a 30' wide dyke where it intrudes Bethlehem quartz diorite, is a leucocratic quartz diorite porphyry composed of large, well-formed but altered phenocrysts of hornblende up to 1 cm. in length, subhedral phenocrysts of fleshy-white plagioclase, and subrounded to kidney-shaped phenocrysts of quartz set in a light coloured groundmass which is resolvable under the handlens.

In thin-section, this sample is seen to be made up largely of zoned, mildly saussuritized, subhedral andesine phenocrysts set in a medium-grained groundmass, composed of quartz, plagioclase, and orthoclase, that shows a crude graphic texture. Quartz phenocrysts are rounded or kidney-shaped and are partially embayed by the matrix. Hornblende occurs as large, poikilitic phenocrysts that have been partially altered to epidote, chlorite, and pale green actinolite. Accessory minerals include apatite, sphene, and magnetite. The estimated mode is 65% plagioclase, 25% quartz, 5% altered hornblende, 3% orthoclase, and 2% magnetite and other accessory minerals.

Approximately 40 grams of -48 to +100 mesh amphibole concentrate was obtained from this sample. A grain

count indicated the following composition: 10% dark, green-black hornblende, 85% light, olive-green actinolite, and 5% impurities. Epidote was the chief impurity although some chlorite, apatite, and sphene was noted.

GD-3
K63-222 Bethlehem Granite Mine Coordinates: 9220N - 6820E

Both samples collected from same outcrop. This reddish brown, medium- to fine-grained, granitic rock consists of pinkish-red orthoclase, quartz, white plagioclase, and a small amount of dark biotite which occurs as flakes generally less than 2 mm. in diameter.

In thin-section, this granitic rock is found to be made up of perthitic orthoclase (50%), quartz(30%), oligoclase plagioclase (15%), and biotite (3%), with accessory apatite, magnetite, sphene, and zircon (2%). The subhedral flakes of biotite exhibit a wavey extinction and are very slightly chloritized. The perthitic orthoclase and oligoclase show slight sericitic and argillic alteration.

Approximately 40 grams of -48 to +100 mesh biotite concentrate was obtained from sample K63-222. A grain count indicated the following composition: 99% reddish-brown biotite and 1% impurities. The impurities include apatite, sphene, magnetite, and minor feldspar and quartz. The biotite grains are very slightly chloritic.

GD-4 Guichon Quartz Diorite Mine Coordinates: 9600N - 9750E

This sample, collected approximately 600' south of the Snowstorm adit, is a medium- to coarse-grained, mesocratic, moderately altered quartz diorite composed of feldspar, quartz, altered biotite, and altered laths of hornblende generally less than 5 mm. in length. The mafic minerals are distributed uniformly throughout the rock.

In thin-section, this hypidiomorphic-granular rock is seen to be made up of saussuritized andesine plagioclase (58%), altered, slightly perthitic, interstitial orthoclase (10%), interstitial, quartz (15%), and altered hornblende and biotite (15%), with accessory apatite, sphene, zircon, and magnetite (2%). Biotite has been almost completely altered to chlorite while hornblende has been largely altered to epidote and light green actinolite.

Approximately 40 grams of -48 to +100 mesh amphibole concentrate was obtained from this sample. A grain count indicated the following composition: 34% dark green-black hornblende, 64% olive-green actinolite, and 2% impurities. Epidote was the chief impurity noted.

GD-5 Quartz-poor Porphyry Mine Coordinates: 9380N - 8840E

This grey, porphyritic rock, collected from the center of a 20' wide dyke where it intrudes Guichon quartz diorite, contains phenocrysts of biotite, hornblende, and plagioclase set in a light coloured, aphanitic groundmass. A few small phenocrysts of quartz are also visible suggesting that this specimen may be equivalent to the P-1 porphyry as described by Carr (1959). Phenocrysts comprise approximately 40% of the rock by volume.

In thin-section, this rock is seen to be made up largely of weakly saussuritized phenocrysts of zoned, subhedral andesine plagioclase set in a fine-grained groundmass, composed of plagioclase, quartz, and orthoclase, that exhibits a crude graphic texture. Small rounded phenocrysts of quartz and partially chloritized, subhedral to euhedral flakes of biotite ranging up to 4 mm. in diameter are also distributed throughout the section. One large, poikilitic phenocryst of actinolite-hornblende was recognized in the section. The accessory minerals include apatite, magnetite, and sphene. The estimated mode of this section is 68% andesine plagioclase, 25% quartz, 3% orthoclase, 2% biotite, and 2% magnetite and other accessory minerals.

Approximately 40 grams of -35 to +100 mesh biotite concentrate was obtained from this sample. A grain count indicated the following composition: 98% slightly chloritized biotite, and 2% impurities. Impurities include hornblende, quartz, apatite, and feldspar.

GD-6 Quartz-poor Porphyry Mine Coordinates: 10860N-8300E

This grey-green, porphyritic rock, collected from the center of a 50' wide dyke where it intrudes Guichon quartz diorite, consists of small, altered phenocrysts of white feldspar and dark hornblende set in a totally aphanitic groundmass. Phenocrysts comprise approximately 40% of the rock by volume. This specimen is possibly equivalent to the P-2 porphyry described by Carr (1959).

In thin-section, this rock is seen to be largely made up of strongly saussuritized phenocrysts of zoned andesine plagioclase set in a fine-grained intergrowth of quartz and feldspar. Rare, rounded phenocrysts of quartz and small, altered laths of hornblende occur distributed throughout the section. Alteration minerals present include sericite, albite, calcite, actinolite, epidote, and possibly kaolinite. Accessory minerals include apatite, sphene, and magnetite. The mode of this rock is similar to that

given for GD-5 with the exception that hornblende occurs in place of biotite. This sample does not contain sufficient unaltered hornblende for K-Ar analysis.

GD-7 Bethlehem Quartz Diorite Mine Coordinates: 7800N - 9790E

This sample, collected from a trench in the White zone area, is a leucocratic, medium-grained, granitic rock composed of feldspar, quartz, and altered hornblende and biotite. Hornblende occurs as large poikilitic grains which have been almost completely altered to chlorite and actinolite.

In thin-section, this hypidiomorphic-granular rock is seen to be made up of slightly zoned, moderately saussuritized, andesine plagioclase (69%), interstitial quartz (15%), interstitial orthoclase (10%), and altered hornblende and biotite (5%), with accessory magnetite, apatite, and sphene (1%). Chlorite occurs as pseudomorphs after biotite, and less commonly, hornblende. Most of the hornblende has been replaced by actinolite and epidote. This sample does not contain sufficient unaltered biotite or hornblende for K-Ar analysis.

GD-8 K63-240a Spud Lake Porphyry Mine Coordinates: 6200N - 11450E

This medium-grey, porphyritic rock contains large euhedral to subhedral phenocrysts of fleshy-white plagioclase, subrounded eyes of quartz, and scattered phenocrysts of altered biotite and hornblende set in a dense, muddy brown, aphanitic groundmass. Phenocrysts comprise 50% of the rock by volume.

In thin-section, this rock is seen to be composed of a few large clear eyes of unaltered quartz, completely chloritized phenocrysts of biotite and hornblende, and relic crystals of saussuritized plagioclase set in a moderately altered groundmass composed of quartz and feldspar. Accessory minerals include apatite, sphene, and magnetite. These samples were not analyzed because they do not contain sufficient unaltered biotite or hornblende.

GD-9 Quartz Diorite Porphyry Mine Coordinates: 10110N - 7200E

This mesocratic, porphyritic rock contains euhedral to subhedral, fleshy-white phenocrysts of plagioclase, subrounded eyes of quartz, and altered phenocrysts of hornblende set in a scant matrix. Radial aggregates of epidote appear to have replaced original hornblende. Phenocrysts comprise approximately 80% of the rock by volume.

In thin-section, this rock is seen to be made up of strongly saussuritized, subhedral phenocrysts of plagioclase, clear rounded grains of quartz, and altered phenocrysts of hornblende set in a scant matrix composed of quartz and feldspar. Alteration minerals include sericite, albite, epidote, calcite, chlorite, and possibly kaolinite. Accessory minerals include apatite, sphene, and magnetite. The mode of this rock is similar to that given for GD-1. This sample does not contain sufficient unaltered hornblende for K-Ar analysis.

GD-10 P-3 Porphyry Mine Coordinates: 9920N - 7070E

Petrographically, this sample is the same as GD-2 with the exception that it contains a trace amount of biotite, along with the hornblende, quartz, and feldspar, set in a slightly coarser matrix. Both samples appear to have undergone the same degree of alteration.

Approximately 30 grams of -80 to +140 mesh amphibole concentrate was obtained from this sample. A grain count indicated the following composition: 65% actinolitized hornblende, 5% biotite, and 30% epidote.

GD-11a Porphyritic Bethlehem Quartz Diorite? Mine Coordinates: 10180N - 5730E

This sample was collected within 10' of GD-11b in an

area mapped by Carr (1959) as Bethlehem quartz diorite. GD-11b was classified as Bethlehem quartz diorite since it is similar to GD-7 but GD-11a differs from these samples in that it has a porphyritic rather than a granitic texture. No contact, however, was evident between GD-11a and GD-11b. GD-11a is a leucocratic, porphyritic rock composed of euhedral, milky-white phenocrysts of plagioclase, anhedral phenocrysts of quartz, and well-formed but slightly altered phenocrysts of hornblende set in an aphanitic, light green groundmass. Phenocrysts comprise approximately 35% of the rock by volume.

In thin-section, this rock is seen to be made up of scattered phenocrysts of moderately saussuritized andesine plagioclase (25%), quartz (4%), and altered hornblende (6%) set in a very fine-grained groundmass (65%) composed of quartz and feldspar. The hornblende phenocrysts, generally less than 5 mm. in length, have been largely altered to actinolite, chlorite, and epidote. Accessory minerals include apatite and magnetite.

Approximately 40 grams of -48 to +100 mesh amphibole concentrate was obtained from this sample. A grain count indicated the following composition: 21% dark green-black hornblende, 75% actinolite, and 4% impurities. Epidote was the chief impurity noted.

GD-11b Bethlehem Quartz Diorite Mine Coordinates: 10190N - 5730E

This sample is essentially the same as GD-7 with the exception that it is finer grained and darker in colour. This sample, however, does not contain sufficient unaltered hornblende or biotite for K-Ar analysis.

GD-12 Guichon Quartz Diorite Mine Coordinates: 12510N - 5400E

This sample is a typical example of the Guichon quartz diorite. It is a medium-grained, mesocratic, granitic rock composed of poikilitic hornblende and biotite, pink orthoclase, quartz, and white plagioclase. Biotite and hornblende crystals, generally less than 5 mm. in length, occur in equal amounts and are evenly distributed throughout the rock.

In thin-section, this rock is seen to be made up of slightly saussuritized andesine plagioclase (58%), slightly perthitic orthoclase (15%), interstitial quartz (10%), green poikilitic hornblende (10%), and slightly chloritized biotite (5%), with accessory magnetite, sphene, zircon, and apatite (2%). Some augite was noted in the hornblende grains suggesting that some of the hornblende formed at the expense of the pyroxene.

Approximately 100 grams of -65 to +100 mesh biotite concentrate was obtained from this sample. A grain count indicated the following composition: 98% biotite and 2% impurities. The impurities include hornblende, apatite, and minor amounts of quartz and feldspar.

Approximately 50 grams of -35 to +65 mesh hornblende concentrate was obtained from this sample. A grain count indicated the following composition: 98% dark green-black hornblende and 2% impurities. The impurities included actinolite, epidote, and less than 1.2% biotite.

K63-115 Skeena-Bethlehem Quartz Diorite Lat. 50°29'20"N, Long. 121°06'30"W

This sample, collected by K.E. Northcote, is considered to be equivalent to the Bethlehem quartz diorite. It is a medium grained, leucocratic to mesocratic, granitic rock composed of white plagioclase, clear interstitial grains of quartz, pinkish coloured orthoclase, poikilitic hornblende laths ranging up to 5 mm. in length, and hexagonal plates of biotite which seldom exceed 2 mm. in diameter. The mafic minerals are evenly distributed throughout the rock.

In thin-section, this hypidiomorphic-granular rock is seen to be made up of zoned, weakly altered andesine plagioclase (61%), slightly perthitic orthoclase (15%),

interstitial quartz (15%), poikilitic hornblende containing cores of augite (4%), and biotite (3%), with accessory apatite, magnetite, sphene, and zircon (2%).

Approximately 10 grams of -35 to +100 mesh biotite concentrate was obtained by K.E. Northcote from this sample. The estimated composition of the concentrate is as follows: 95% black, mottled by golden brown biotite and 5% impurities. Impurities mainly hornblende but some actinolite, epidote, feldspar, and quartz noted. The biotite appeared to be from 10 to 15% chloritized.

Approximately 30 grams of -48 to +100 mesh hornblende concentrate was obtained from this sample. A grain count indicated the following composition: 98% partially actinolitized hornblende and 2% impurities. Impurities include quartz, sphene, apatite, epidote, and less than 0.3% biotite.

K63-222 See GD-3

K63-240a See GD-8

K63-240 Breccia Mine Coordinates: 8850N - 8050E

Collected by K.E. Northcote and analyzed by Dr. W.H. White. The biotite concentrate separated from this sample is reported by White (personal commumication)

to contain a mixture of primary and secondary biotite. The apparent age obtained on this mixture, however, should represent the formation age of the breccia since it is probable that the primary biotite in this sample lost its original radiogenic argon at the same time the secondary biotite formed as the result of hydrothermal processes taking place during brecciation. See also description of breccia in text.