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The Takiyuak Metavolcanic Belt:

Geology, Geochemistry, and Mineralization.

by

James W. Gill BSc., MSc.

A thesis submitted to the Faculty of Graduate Studies in
partial fulfilment of the requirements for the degree of
Doctor of Philosophy.

Carleton University

Ottawa, Ontario

December, 1976

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ABSTRACT

The Takiyuak Metavolcanic Belt is an Archean volcano-plutonic belt in the Slave Structural Province of the Canadian Shield, Northwest Territories. Calc-alkaline volcanic rocks make up 60% of the area, range in composition from basalt to rhyolite, and include pillow lavas, tuffs, tuff breccias, felsic flows, and agglomerates. The area has been isoclinally folded into a northeasterly plunging syncline, and regional metamorphic grade is lower greenschist. Post deformational granitic and dioritic intrusions make up 40% of the area. This metavolcanic belt is believed to represent an Archean orogenic tectonic environment, possibly of the island-arc type.

Massive volcanogenic sulphide mineralization within this belt is coeval with and may be cogenetic with volcanism. Textural features, mineralogical zoning, and chemical data, suggest that the sulphides precipitated from a hot saline brine which mixed with seawater.

Mineralization within the Takiyuak Metavolcanic Belt is time-stratigraphically controlled and is spatially related to a center of felsic volcanism. Alteration, related to mineralization, is characterized by sodium depletion, and magnesium and potassium enrichment. Chemical equilibria indicate that this alteration is in part related to volcanic rock-seawater chemical interaction. The time-stratigraphic horizon related to mineralization is believed to reflect a pause in volcanic activity and a time of chemical reequilibration between volcanic rocks and seawater.

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1. INTRODUCTION

INTRODUCTION

General Statement

This thesis presents the results of a detailed study of the Takiyuak Metavolcanic Belt, Northwest Territories. This volcanic belt had not been previously recognized and represents a new volcanic belt in the Slave Structural Province of Canada. Stratigraphy, structure, petrology, chemistry, sulphide deposits and associated alteration, and the origin of both the volcanic rocks and the sulphide accumulations are considered in this study.

The presentation of the results is as a series of three separate and complete papers prepared for publication. Paper 1 considers the regional geology and chemistry of the Takiyuak Metavolcanic Belt. Paper 2 studies the correlation of alteration and mineralization in these volcanic rocks. Paper 3 considers the Takiyuak #10 sulphide deposit in detail and develops a genetic hypothesis for its origin. This method of presentation was chosen to facilitate reading of, and to emphasize, individual aspects of the study. Additional data and comments are appended following the main body of the thesis.

Location and Accessibility

The Takiyuak Metavolcanic Belt extends northeasterly from the southern tip of Takiyuak Lake, Northwest Territories (Figs. 1, 2). The center of the map area is approximately 410 km north of Yellowknife, N.W.T. and is readily accessible by float equipped aircraft from Yellowknife or Fort Smith. The area has numerous lakes and either canoe or helicopter support are required for geological mapping.

Figure 1. Location map, Takiyuak Metavolcanic Belt, Northwest Territories. (after McGlynn and Henderson, 1970)

Figure 2. Location of map area near Takiyuak Lake, N.W.T..

Elevation averages 1500 feet and relief is up to 500 feet. The western edge of the map area closely approximates the boundary between the Slave and Bear structural Provinces.

Previous Work

The area was mapped at 1" = 8 miles (Map 18-1960) by the Geological Survey of Canada in 1960 and was considered to consist of granite and metasediments. Laplante and Money (1972) recognized the volcanic nature of the rocks and prepared a reconnaissance geological map at 1" = 1 mile. The present study began in 1975 and geological mapping was done with the assistance of I. Hutcheon and J.N. Obregon.

Methods of Study

Field methods

This study was based on 6 months of field work in the summers of 1975 and 1976. Mapping at 1" = 1/4 mile was done with the use of air photographs as a base map. Detailed areas were mapped at 1" = 200, 100, and 50 feet with the use of a chained grid for control.

Laboratory methods

Whole rock chemical analyses of selected rock samples were used to classify the volcanic rocks and to compare the chemistry of the altered rocks related to mineralization and the regional volcanic rocks. The chemical analyses were done at the Science Laboratories

University of Durham, under the direction of Dr. J.G. Holland. Thin sections and polished sections were studied by standard petrographic methods. X-ray diffraction was done to confirm the presence or absence of alteration minerals observed in thin section. Electron Microprobe analyses of sulphides and chlorites were done as part of the study of the origin of the sulphide deposit and its related alteration. Diamond drill core logging allowed construction of a three dimensional model for the Takiyuak #10 sulphide deposit and a study of the stratigraphic relationship of the sulphides to the host volcanic rocks to be carried out.

II. PAPER 1

The Takiyuak Metavolcanic Belt: Regional Geology and Chemistry

James W. Gill

Abstract

The Takiyuak Metavolcanic Belt extends north-northeasterly from the southern end of Takiyuak Lake, N.W.T.. Two cycles of volcanism, with little time break between them, can be recognized. Volcanic rocks range from mafic to felsic in composition and include pillow lavas, tuffs, tuff breccias, pyroclastic tuff breccias, felsic flows, and agglomerates. The area has been isoclinally folded into a syncline which plunges steeply to the northeast. Second phase folding is about north-south axes. Post-deformational granitic and dioritic intrusions make up 40% of the area. Chemically the volcanic rocks include basalt, andesite, dacite and rhyolite of the calc-alkaline suite. The regional metamorphic grade is lower greenschist. Alteration related to mineralization is characterized by sodium depletion and magnesium and potassium enrichment.

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This study is part of a PhD thesis financially supported by Texasgulf Inc.. The author was supported in part by a Carleton Fellowship in 1975 and by N.R.C. Research Grant A7874 to Dr. D.H. Watkinson in 1975 and 1976. Field mapping was done with the assistance of I. Hutcheon and H.J. Obregon. I thank Ian Hutcheon, from whose work the easternmost portion of the map has been adapted. Geologic discussion with J.B. Heslop, P.L. Money, D. H. Watkinson, D.F. Sangster, and J.M. Franklin is gratefully acknowledged.

Introduction

The Takiyuak Metavolcanic Belt (Figs. 1,2), recently recognized by Texasgulf Inc. (Laplane and Money, 1972), is currently being explored for massive volcanogenic sulphide deposits. Regional geological mapping of this belt has outlined its stratigraphy and regime. Whole rock chemical analyses have characterized the volcanic suite. The close relationship between massive volcanogenic sulphide deposits and volcanism of the calc-alkaline suite indicates the economic importance of description and classification of the volcanic rock suite under study. Volcanic rocks in this belt have been metamorphosed to the lower greenschist facies and the prefix 'meta' will be omitted in this paper.

Lithologic Units

Volcanic and intrusive rocks respectively make up 60% and 40% of the area (Fig. 3). Volcanic units are composed of mafic to intermediate flows, tuffs, and agglomerates, as well as felsic flows, tuffs, and pyroclastic rocks. Intrusive rocks are mainly granite and diorite, with rare ultramafic and gabbroic intrusions. The volcanic pile is made up of approximately 25% felsic and 75% mafic-intermediate material. Field nomenclature refers to all greenstones as andesites; subsequent chemical data have differentiated the greenstones into andesites and basalts and these are discussed in the section dealing with whole rock chemistry.

Figure 1. Location map, Takiyuak Metavolcanic Belt, Northwest Territories. (after McGlynn and Henderson, 1970)

Figure 2. Location of map area near Takiyuak Lake, N.W.T..

Volcanic Rocks

Felsic volcanic rocks

Felsic volcanic rocks consist of porphyritic rhyolite, cherty rhyolite, and felsic tuff (Fig. 3).

Porphyritic rhyolite is characterized by an abundance of quartz phenocrysts, weak to moderate foliation, weak to strong sericitization, and pale green-yellow colour. The quartz "eyes" range from 1.6 mm to 3.2 mm in diameter and are milky white or dark (smoky) in colour. The dark phenocrysts seldom exceed 1.6 mm in diameter. Separation of individual units can be made on the basis of the colour of the phenocrysts. The matrix is the same regardless of the type of phenocryst and consists of fine grained quartz, plagioclase, sericite, and in places chlorite. Where the foliation is moderate the rock is a sericite schist.

Cherty rhyolite is characterized by its aphanitic texture, extreme hardness, brittleness, buff colour, and flow banding. The hardness of the rhyolite precludes the development of a prominent foliation and deformation is reflected in the sheared nature of these rocks. Alteration, where visible, is restricted to fractures in the unit and consists of minor sericite and chlorite. Distinction between individual flows was made only when a texturally different unit separates the flows.

Felsic tuff is characterized by its pale grey-green colour, well-bedded nature, presence of small fragments (30 mm), lateral consistency in thickness, bedding thickness (5 mm to 40 mm), and by its lateral extent. These rocks are a minor

component of the volcanic pile. Occasionally interbedded carbonate is also found within this unit.

Mafic volcanic rocks

Mafic volcanic rocks in the map area are made up of massive andesite, pillowed andesite, mafic tuff, amygdaloidal andesite, pyroclastic tuff breccia, and pyroclastic breccia.

Massive andesite is characterized by its medium to dark green colour, abundance of chlorite, smooth weathered surface, and low to moderate carbonate content. Andesite flows are very fine-grained and frequently contain plagioclase phenocrysts up to 6.4 mm long. Orientation of the phenocrysts ranges from random to parallel to the foliation. The andesite is metamorphosed to chlorite schist; epidote is found in fractures. Lack of bedding, restricted lateral extent, and lack of fragments, distinguish these flows from mafic tuffs. Massive andesites may be subdivided into carbonate-rich and carbonate-poor varieties. Carbonate-rich flows are distinguished by their greater hardness, abundance of carbonate, brown weathered surface, and blocky weathering.

Amygdaloidal andesite is characterized by large quartz amygdules from 1.6 mm to 6.4 mm in diameter, dark green colour, mottled weathered surface, and abundance of chlorite. Amygdules compose 2% to 40% of the rock volume. Sulphides often occupy the cores of the amygdules. Chlorite, the major alteration mineral of this unit, forms distinct and abundant clots as well as concentrations around the edge of the amygdules.

The restriction of this unit to two occurrences very close to Cu/Zn mineralization is notable.

Pillow andesite is characterized by pillows (with chilled and altered margins and vesicular outer rims) as well as pillow breccias. The majority of the mafic volcanic flows appear to be pillow lavas but heavy lichen cover made identification very difficult. Stratigraphic tops were rarely determined using pillow lavas because deformation made top determination ambiguous.

Mafic tuff is characterized by its bedded nature, lateral consistency, lateral extent, dark green colour, banding from 2 mm to 2 cm thick, occasional fragments, and softness. The presence of minor intercalated carbonate is also characteristic. Mafic tuffs usually contain up to 15% felsic bands which serve to distinguish them from mafic flows. Adjacent to large intrusions the tuffs have been transformed into well-banded amphibolites.

Pyroclastic tuff breccia

Pyroclastic tuff breccia is characterized by approximately 50% tuffaceous fragments in a matrix which ranges from felsic to mafic in composition. The tuffaceous fragments range from 2 cm to 7 cm in length and have an average length/width ratio of 5/1. This unit directly overlies felsic volcanic rocks and can be traced for 7 km along strike southward from the northwestern portion of the map area. The unit thins from 0.25 km in the north to 50 m at the southern end and the

matrix changes from mafic to felsic in this direction.

Locally quartz fragments up to 15 cm in diameter are observed although they seldom exceed 4 cm. In some respects the fragments resemble quartz cobbles. However, their absence within 30% of this unit, the lack of representative fragments of all underlying rock units, the stratigraphic position of this unit within the volcanic pile, the felsic matrix material, and the complete absence of a source rock, preclude the possibility that this unit is a conglomerate resulting from erosion of the preexisting stratigraphy. The presence of pyroclastic material in this unit, the close spatial relationship to felsic volcanics (believed to be related to central volcanic activity), and the thinning of the unit away from the area containing the quartz fragments, suggest that they are volcanic in origin and probably related to the explosive event which generated this pyroclastic tuff breccia. The quartz fragments may be recrystallized chert fragments or broken quartz aggregations related to the felsic volcanism.

Mafic pyroclastic breccia

Mafic pyroclastic breccia is characterized by abundant, highly contorted mafic fragments in an extensively chloritized matrix. Fragments range from 2.5 cm to 15.3 cm in their longest dimension and were apparently in a plastic state when incorporated into the matrix. In some cases chilled margins can be observed on the outer edges of the fragments with no corresponding chilled or alteration halo in the matrix.

Agglomerates

Agglomerate is characterized by angular to subround fragments in a highly chloritized matrix, and by a very restricted areal extent. The fragments were apparently solidified prior to incorporation into the matrix and are believed to represent preexisting flow material broken up on eruption. The agglomerates appear to be located proximal to volcanic centers.

Felsic agglomerate consists of felsic fragments in a mafic matrix. The fragments range from 5 cm to 15 cm in their longest dimension and are of mixed lithologies (porphyritic and cherty rhyolite).

Mafic agglomerate has mafic fragments of mixed lithologies in an even more mafic matrix.

Intrusive Rocks

Granitic intrusions occupy approximately 20% of the map area (Fig. 3). Large granitic bodies are characterized by their pink colour, coarse grain size, and quartz phenocrysts. Quartz phenocrysts occur as "eyes" up to 3.2 mm in diameter with alkali feldspar, and minor chlorite, biotite, and fluorite. The granites are mainly massive but are foliated along the contact with the volcanic rocks. The contact is characterized by a zone, approximately 37 m in width, with abundant volcanic inclusions. In several places along the contact the granite is an augen gneiss. Granitic dykes cutting the volcanic rocks deform the pervasive foliation and are believed to be related to the main intrusions.

Dioritic intrusions make up approximately 20% of the map area (Fig. 3) and are characterized by their coarse grain size, smooth grey weathered surface, and lack of foliation. They contain plagioclase, hornblende, and minor quartz. Within 37-55 m of the contact, diorite contains both granitic and volcanic inclusions. In a few places this unit is granodioritic.

Post deformational ultramafic rocks have light brown to rusty brown weathering, dark green color, fine-grain size, and serpentine veinlets. They clearly cut the volcanic rocks, are unfoliated, and essentially parallel the border of a large dioritic intrusion. No ultramafic flow textures have been observed.

Gabbroic intrusions are volumetrically insignificant in the map area. They are coarse-grained, massive, and composed of altered plagioclase and pyroxene.

Diabase dykes crosscut the map area and range in thickness from 30 cm to in excess of 37 m. They range from very fine-grained to coarse-grained as a function of their thickness. Fine-grained diabase is dark green and composed essentially of plagioclase and pyroxene, and coarse-grained diabase is medium to dark green and mineralogically the same. Magnetite is present in some cases. Large Proterozoic (McGlynn and Henderson, 1970) diabase sills cap large thrust sheets which mark the boundary of the Bear and Slave Provinces.

Several mafic dykes up to 9 m wide are characterized by a dark green groundmass and plagioclase phenocrysts up to 2.5 cm in length. Orientation of the phenocrysts is random and the porphyries clearly cut the volcanic and intrusive rocks.

Structural Geology

The Takiyuak Metavolcanic Belt in the map area has undergone at least two phases of deformation. Lithology and a penetrative foliation (S_1) outline a major fold axis striking northeasterly to the north of Shetland Lake. Minor structures and drill core lithologic correlations indicate that the hinge line of this first phase fold (F_1) strikes northeasterly and plunges approximately 70° to the northeast. The axial plane of F_1 folds dips to the east at approximately 80° . Pillow lavas on the south limb of the fold indicate that the stratigraphic top is to the north; fragment size gradation and minor graded bedding in the tuffs on the north limb indicate that the stratigraphic top is to the south and confirm its synclinal nature.

A second phase of deformation (F_2) is defined by minor folds, crenulation lineations (L_2), and foliation (S_2). The second phase foliation is very weakly developed and was not observed in most areas. Minor folds and crenulations indicate that F_2 was about north-south axes. The trend and plunge of the hinge line is approximately south-southeast and 70° to the south-southeast. Second phase folds clearly deform lithology (S_0) and first phase foliation (S_1) but lithologic units have not been transposed. First phase folding was isoclinal. No evidence was found for a third phase of deformation.

Faulting in the map area is extensive but the horizontal component of displacement is less than 0.53 km. Major faults strike approximately east-west and are clearly visible on air photographs of the area. Displacement is always north side

eastward relative to the south side. A second set of faults strike approximately north-south. No displacement was apparent and the horizontal component of displacement was probably small.

The volcanic rocks were deformed prior to the intrusion of granite and diorite as suggested by the intrusive nature of the volcanic-intrusive contacts, the unfoliated nature of the granite and diorite intrusions, and by the clear deformation of first phase foliation (S_1) by the granitic dykes which are related to the main granite intrusion. The granite and diorite intrusions are either very late deformational or post deformational. Foliation in the granite at the contact with the volcanic rocks is believed to have formed as a result of the intruding process itself. The diorite intrusion is definitely post granite because inclusions of mafic volcanics plus granite occur in the contact zones. No granite-diorite contact was observed. Archean diabase dykes, striking roughly north-south and east-west, cut all rock types in the area. Faulting in the area is post diabase dyke intrusion and clearly displaces the dykes. Porphyry dykes closely related genetically to the diabase dykes are the same age as the diabase. Westerly dipping low angle thrust sheets, composed largely of thick diabase sills, cap late Archean sediments of the Epworth Group and mark the boundary between the Bear and Slave Structural Provinces.

Metamorphism

Regional metamorphism

Volcanic rocks of the Takiyuak Metavolcanic Belt have been regionally metamorphosed to the greenschist facies. Mafic volcanic rocks are characterized by their medium to dark green colour, presence of abundant chlorite, presence of epidote mainly in fractures, and by occasional muscovite. Where foliation is strong the mafic volcanics are chlorite schists. Felsic volcanic rocks are characterized by the presence of minor to abundant sericite. Occasional chlorite is observed in the felsic rocks. Where the foliation is strong or where shearing is evident the felsic rocks are sericite schists. The assemblage quartz-chlorite-epidote-albite-muscovite identifies the regional metamorphic grade as lower greenschist facies. Ultramafic rocks are totally altered to serpentine-talc-oxides.

Contact metamorphism

Mafic tuffs along the eastern shore of Takiyuak Lake have been contact metamorphosed by the large granite intrusion. These rocks are amphibolites and are characterized by the assemblage garnet-hornblende-muscovite-cummingtonite-biotite.

Volcanic Regime

Field relationships in the Takiyuak Metavolcanic Belt outline a central area of felsic volcanism and a surrounding area of mafic flows and mafic to felsic tuffs.

The lowermost volcanic units are extensive mafic flows and tuffs. These mafic volcanics extend for a minimum of 48 km of strike length. Abundance of pillow lavas verify the subaqueous nature of the volcanism. The tuffs are well bedded, laterally homogeneous, and lack pumice or any other fragments. These features, together with intercalated carbonate seams, suggest that the tuffs were transported and deposited subaqueously.

The central area is characterized by rhyolitic flows, felsic and mafic agglomerates, and a few mafic flows. Individual flows are contorted and seldom exceed 0.91 km in lateral extent. Agglomerates are very limited in dimensions and are believed to be proximal to eruptive centers. The felsic/mafic rock ratio of 10/1, the restricted extent of the individual flows, and the clear evidence of explosive volcanism, indicate that this area was one of central volcanic activity.

Along strike with the inferred felsic center are pyroclastic tuff breccias, intermediate and felsic tuffs. The explosive activity, which generated the tuff breccias, and the felsic composition of some of the tuffaceous material suggest a close genetic relationship to the felsic center.

Stratigraphically above the felsic accumulation are laterally extensive mafic flows and tuffs, very similar to those below the felsic rocks. Abundant pillow lavas indicate subaqueous volcanism.

The Takiyuak volcanic pile seems to have evolved by first, fissure type volcanism generating laterally extensive,

subaqueous, mafic flows and tuffs; second, a change in volcanic style to central volcanic activity with proximal felsic flows, explosively generated agglomerates and pyroclastic tuff breccias, and distal felsic and intermediate tuffs; third, the end of central volcanic activity and resumption of fissure-type volcanism.

The volcanic rocks indicate two cycles of volcanism with little or no time break between them. Cycle one includes the succession from mafic flows and tuffs through felsic flows and tuffs. Cycle two, directly overlying cycle one, has only mafic flows and tuffs preserved; the large diorite intrusion

in the northeastern portion of the map area has eliminated all evidence of a felsic member to cycle two if there ever was one.

The total volcanic succession is a minimum of 5 km thick as measured on the south limb of the syncline. Large granite and diorite intrusions which truncate the volcanic pile make this a minimum stratigraphic thickness.

Chemical Classification of Takiyuak Volcanic Rocks

Chemical classification of these volcanic rocks, after Irvine and Baragar (1971), has been done using whole rock analyses. Modal analysis is not feasible due to the fine-grained nature of the volcanic rocks and the obliteration of primary mineralogy by regional metamorphism. Regional metamorphism is lower greenschist facies, as evidenced by the assemblage albite-muscovite-epidote-chlorite-sericite-quartz and a total absence of biotite. Data in Table 1 are not adjusted for alteration.

Table 1. Average whole rock chemical analyses, Takiyuk volcanic rocks.

	1	2	3	4	5	6	7	8	9	10	11	12	13*	14*	15
SiO ₂	75.44	76.31	76.80	72.66	74.3	57.75	47.66	53.37	54.7	50.12	44.30	48.9	47.65	40.00	77.08
Al ₂ O ₃	12.58	11.95	12.58	14.20	12.9	14.27	14.93	15.98	15.0	13.99	10.93	14.5	14.63	1.93	12.55
Fe ₂ O ₃	0.37	0.68	0.51	0.60	0.74	2.10	2.92	2.46	2.00	2.87	2.90	2.14	9.19	10.74	0.27
FeO	1.18	2.04	1.31	1.86	2.22	6.30	9.54	8.19	7.64	8.69	10.26	9.03	3.58	3.72	0.73
P ₂ O ₅	1.88	2.93	1.65	3.63	0.95	5.53	11.31	10.31	4.50	7.37	8.24	6.27	7.35	40.08	0.11
CaO	0.92	0.16	0.49	0.07	1.48	3.31	4.65	0.73	6.39	6.22	9.30	8.74	10.22	0.60	0.14
MgO	4.38	0.15	4.00	0.63	2.47	3.81	1.11	1.24	2.79	2.64	0.83	2.51	2.36	0.00	4.67
K ₂ O	1.63	3.16	1.55	3.43	2.10	0.42	1.55	1.36	0.55	0.90	0.63	0.45	0.60	0.08	4.18
TiO ₂	0.15	0.20	0.13	0.27	0.26	1.08	1.05	1.08	0.99	1.12	0.81	1.06	0.79	0.17	0.06
P ₂ O ₆	0.03	0.04	0.02	0.04	0.07	0.29	0.20	0.26	0.12	0.24	0.20	0.07	0.10	0.66	0.00
MnO	0.02	0.03	0.02	0.03	0.10	0.15	0.13	0.10	0.28	0.16	0.22	0.21	0.16	0.16	0.01
S	0.07	0.05	0.05	0.05		0.18	0.26	0.16		0.21	0.48				
CO ₂	0.66	0.34	0.51	0.40	0.86	1.62	0.53	0.47	1.93	2.26	5.10	1.93	0.31	0.32	0.00
H ₂ O	0.75	1.97	0.69	2.37	1.17	3.33	4.30	4.53	2.92	3.09	5.09	3.34	2.15	10.30	0.20

100.01	100.06	100.24	100.11	99.52	100.14	100.14	100.14	100.24	99.81	99.88	100.29	99.73	99.09	108.16	100.00
N	8	7	6	4	85	2	2	9	119	7	1	162	2	1	1

- 1 cherty rhyolite, Takiyuk volcanics
2 cherty rhyolite, Takiyuk volcanics, altered due to mineralization
3 porphyritic rhyolite, Takiyuk volcanics
4 porphyritic rhyolite, Takiyuk volcanics, altered due to mineralization
5 rhyolite, Goodwin (1968), Superior Province volcanics
6 massive andesite, Takiyuk volcanics
7 massive andesite, Takiyuk volcanics, altered due to mineralization
8 argillaceous andesite, Takiyuk volcanics, altered due to mineralization
9 andesite, Goodwin (1968), Superior Province volcanics
10 basalt, Takiyuk volcanics
11 basalt, Takiyuk volcanics, altered due to mineralization
12 basalt, Goodwin (1968), Superior Province volcanics
13 mafic gneiss, Takiyuk volcanics
14 argillaceous ultramafic, Takiyuk intrusion
15 granite, Takiyuk intrusion
* analyses by Bondar-Clegg Co. Ltd.

Alkaline-subalkaline classification

Subdivision of volcanic rocks as alkaline or subalkaline has been done by means of alkalies-silica plots (MacDonald, 1968; Irvine and Baragar, 1971) and with normative olivine-nepheline-quartz plots (Poldervaart, 1964; Irvine and Baragar, 1971). Both methods of classification (Figs. 4,5) indicate that the Takiyuak volcanic rocks are subalkaline. Alkali enrichment with silica enrichment is clearly evident (Fig. 4) and comparison of these volcanic rocks with those from Yellowknife, Coppermine, and Noranda (Fig. 5) indicate a general agreement but with a larger scatter and more analyses approaching the olivine-quartz join. This scatter is interpreted to be the result of alteration.

Volcanic rock series

Classification of Takiyuak volcanic rocks into a chemical rock series was done using the AFM diagram (Irvine and Baragar, 1971) and diagrams using FeO , MgO , and SiO_2 after Miyashiro (1974). The Takiyuak volcanic rocks exhibit a calc-alkaline trend with basaltic rocks compositionally on the tholeiitic side of Kuno's (1953) dividing line (Fig. 6). Goodwin's (1968) data (Fig. 6) for the average Superior Province rock indicate a similar calc-alkaline trend. Plots of SiO_2 versus FeO^*/MgO (Fig. 7) and FeO^*/MgO versus FeO^* (Fig. 8) verify the calc-alkaline nature of the volcanic suite but also indicate a tholeiitic mafic component. Calc-alkaline suites characteristically exhibit a tholeiitic mafic component and true (as defined

Figure 4. Alkali-Silica diagram indicating the subalkaline nature of Takiyuak volcanic rocks. (after Irvine and Baragar, 1971).

Figure 5. $01'-Ne'-Q'$ projection showing the subalkaline nature of Takiyuak volcanic rocks.

Figure 6. FMA diagram outlining the calc-alkaline nature of Takiyuak volcanic rocks.

Figure 7. Changes in SiO_2 content with increasing FeO^*/MgO ratio in Takiyuak volcanic rocks. Cal-alkaline - tholeiitic dividing line after Miyashiro (1974).

Figure 8. Changes in FeO^* content with increasing FeO^*/MgO ratio in Takiyuak volcanic rocks. Calc-alkaline - tholeiitic dividing line after Miyashiro (1974).

by Kuno, 1953) calc-alkaline intermediate through felsic components. This is shown by Goodwin (1968) (Fig. 6) for Superior Province volcanic rocks, by Irvine and Baragar (1971) (Fig. 9) for the Cascades and Mount Hood volcanics, and by Spitz and Darling (1975) (Fig. 9) for the Val D'Or area volcanic rocks. The author believes that the calc-alkaline suite should include basalt-andesite-dacite-rhyolite characterized by an essentially constant Fe/Mg ratio and increasing alkali content from mafic through felsic components. Kuno's (1953) dividing line (Fig. 6) would then not divide differentiation trends of tholeiitic and calc-alkaline affinities and the basaltic rocks of such areas as the Cascades, Mount Hood, Val D'Or, and Yellowknife would belong to the calc-alkaline differentiation trend.

Classification of rock types

Chemical classification of rock types can be made using normative parameters such as colour index, plagioclase composition, and the nature of the feldspars.

A normative plot of plagioclase composition versus colour index for many rock analyses (Irvine and Baragar, 1971) has allowed proposed dividing lines for distinguishing rock types to be constructed. Figure 10 indicates that the Takiyuak rocks include the suite basalt-andesite-dacite-rhyolite. The effect of alteration on colour index and especially plagioclase composition requires that care be taken to consider unaltered rocks. Figure 10 indicates the trend of variation for the

Figure 9. FMA diagrams showing calc-alkaline trends for Val d'Or area volcanics (Spitz and Darling, 1975), and the Cascades, Mount Hood, Aleutians, and the Parícutin region (Irvine and Baragar, 1971).

Figure 10. Plot of normative color index versus normative plagioclase composition for Takiyuak volcanic rocks. The suite basalt-andesite-dacite-rhyolite is represented.

unaltered rocks as determined from comparative whole rock chemistry of Goodwin (1968) (Table 1), and by petrographic study.

Unaltered rocks are those which exhibit good primary volcanic textures in thin section, lack of secondary introduction of carbonate and/or silica, chemical compositions consistent with the data for the Superior Province volcanic rocks (Goodwin, 1968), and chemical consistency with volcanic rocks clearly distal to mineralization. The andesites have been altered by the removal of calcium and subsequent decrease in anorthite content of the plagioclase.

The nature of the feldspars (Fig. 11) indicates that the rocks are mainly sodic rhyolite, K-poor to "average" andesites, and K-rich basalts. Alteration again must be carefully considered. The unaltered rocks outline the true nature of the volcanic rocks, a small cluster of analyses which plot near the orthoclase apex represent the highly altered rhyolites stratigraphically forming the footwall rocks to a small massive volcanogenic sulphide accumulation in the area and reflect intense sodium depletion and potassium enrichment. Similarly a cluster of points in the potassic rhyolite field represent highly altered amygdaloidal andesite in the mineralized zone.

A method for recognizing the felsic or mafic nature of highly altered volcanic rocks is needed, especially in areas of alteration resultant on mineralization. Titanium is an element which is relatively immobile (Hawkes and Webb, 1962) and may be useful for this purpose (Sakrison, pers. comm.). A plot of TiO_2 versus Zr (Fig. 12) for the Takiyuak volcanic rocks indicates a distinct gap between mafic and felsic components. The felsic

Figure 11. An - Ab' - Or projection of Takiyuak volcanic rocks after Irvine and Baragar (1971). Alteration associated with mineralization results in numerous samples within the potassic rhyolite field.

Figure 12. TiO_2 versus Zr plot for Takiyuak volcanic rocks. Regardless of alteration a clear separation between felsic and mafic rocks is apparent.

rocks have TiO_2 content always less than 0.4 wt% whereas the mafic rocks always exceed 0.8 wt%. This appears to be the case despite the effects of alteration observed in the variation diagrams previously discussed. It is suggested that the use of TiO_2 as a discriminator of the nature of the volcanic rock type be used in the case of highly altered rocks.

The variation diagrams (Figs. 4,5,7,8,12) indicate a distinct bimodal nature to the Takiyuak volcanic rocks. This bimodal nature, unlike the Dalv Gap which includes the basalt-rhyolite association of non-orogenic activity (Martin and Piwinski, 1972), excludes only dacitic lava compositions from the calc-alkaline basalt-andesite-dacite-rhyolite suite. Many calc-alkaline volcanic piles with associated sulphide accumulations contain abundant dacitic material as the felsic end member of the suite (Spitz and Darling, 1975; Horikoshi and Sato, 1970). It is believed that the break between rhyolite and andesite reflects the change in style of volcanism from fissure-type regional mafic and intermediate lava generation to local central volcanic activity generating felsic domes and pyroclastic accumulations. If a true bimodal rock association existed then subsequent alteration might generate a spread of chemical compositions which would overlap into the dacitic compositional field.

Summary and Conclusions

The Takiyuak Metavolcanic Belt is characterized by subalkaline volcanic rocks of the calc-alkaline suite. Volcanic flows, tuffs,

breccias, and agglomerates outline two cycles of volcanism with no apparent time break between them. Chemically the rocks are basalt, andesite, dacite, and rhyolite. Structurally the area has undergone two phases of deformation; the major structure is a syncline which plunges steeply to the northeast. Regional metamorphic grade is the lower greenschist facies. Local alteration associated with mineralization is characterized by sodium and calcium depletion and magnesium and potassium enrichment. The low mobility of titanium in the geochemical cycle makes it a useful discriminator in the separation of altered and fresh mafic-intermediate to felsic volcanic rocks.

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III. PAPER 2

Correlation of Mineralization and Alteration in Takiyuak
Volcanic Rocks

James W. Gill

Abstract

Geology, geophysics, and geochemistry indicate that a time-stratigraphic control on mineralization in Takiyuak volcanic rocks exists. Whole rock chemical data show that alteration along this time-stratigraphic horizon is characterized by sodium depletion, and magnesium and potassium enrichment. This alteration is independent of rock type. Chlorites within the alteration zone are more magnesium-rich than regional chlorites. Chemical equilibria involving some of the primary minerals of calc-alkaline volcanic rocks indicate that this alteration can be explained, in part, by volcanic rock-seawater chemical interaction. The time-stratigraphic horizon related to mineralization is believed to reflect a pause in volcanic activity and a time of chemical reequilibration between volcanic rocks, at the rock-water interface, and seawater.

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Correlation of Mineralization and Alteration in Takiyuak Volcanic Rocks

Introduction

The discovery of massive volcanogenic sulphide accumulations in the Takiyuak Metavolcanic Belt by Texasgulf Inc. (Heslop, 1973) has led to the search for new sulphide deposits in the area. Chemical alteration patterns in volcanic rocks can be useful in delineating potentially favourable horizons for exploration (Sangster, 1972; Franklin, 1975). This study outlines the parameters which can be used to outline the favourable horizon(s) in the Takiyuak Metavolcanic Belt using whole rock chemistry, and considers possible causes of the alteration patterns.

Regional geology of the Takiyuak Lake area

The Takiyuak Metavolcanic Belt extends north-northeasterly from the southern end of Takiyuak Lake, Northwest Territories (Figs. 1,2). Details of the region are described by Gill (1976a). This Archean greenstone belt consists of approximately 60% volcanic rocks and 40% late granite and diorite intrusions. Mafic and intermediate flows and tuffs are the major volcanic component with felsic rocks composing roughly 25% of the volcanic pile. The succession is a minimum of 5km thick and has been folded into a northeasterly plunging, easterly dipping syncline. Chemistry of these volcanic rocks indicates that they are

Figure 1. Location map, Takiyuak Metavolcanic Belt, Northwest Territories. (after McGlynn and Henderson, 1970)

Figure 2. Location of map area near Takiyuak Lake, N.W.T.

calc-alkaline and consist of basalt, andesite, dacite and rhyolite (Gill, 1976a). All volcanic rocks in this area have been regionally metamorphosed to the lower greenschist facies and are believed to be correlative with the Yellowknife Supergroup.

Deformation and syntectonic granitic intrusion of Yellowknife Supergroup rocks took place during the Kenoran Orogeny (McGlynn and Henderson, 1970; Stockwell et al, 1970).

Geology of the western half of the Takiyuak Metavolcanic Belt

The western portion of the Takiyuak Metavolcanic Belt

(Fig. 3) is characterized by a large accumulation of felsic volcanic rocks. In the southern portion of this area the felsic/mafic + intermediate rock ratio of 10/1, abundance of contorted, laterally restricted rhyolite flows, and the presence of small, well defined agglomerate accumulations, indicate that it is one of central volcanic activity (Gill, 1976a).

Detailed geological mapping (1"=50, 100, 200 feet) by Gill in 1975 and 1976 allowed subdivision of the volcanic rocks based on field criteria. Rhyolite was subdivided into cherty rhyolite characterized by aphanitic texture, extreme hardness, brittleness, buff colour, and lack of apparent alteration; and porphyritic rhyolite, characterized by an abundance of quartz phenocrysts, weak to moderate sericitization, weak to strong foliation, and pale yellow-green colour. Andesite was subdivided into massive andesite, characterized by medium to dark green colour, softness, abundance of chlorite, minor epidote and muscovite, smooth

weathered surface, and weak to moderate carbonate content; and amygdaloidal andesite, characterized by large quartz amygdules, dark green colour, mottled weathered surface, and abundance of chlorite. Basaltic rocks were not distinguished from andesites in the field.. Felsic agglomerates, characterized by felsic, angular to subangular fragments up to 8" in diameter, in a mafic chloritized matrix, are believed to occur at sites of possible volcanic vents. The mixed lithologies of the fragments and their very restricted areal extent support this concept. Field nomenclature was never inconsistent with the chemical classification in differentiating the felsic volcanics from the mafic-intermediate volcanic rocks.

The area has undergone at least two phases of deformation (Gill, 1976a). First phase folds (F_1) are isoclinal. The hinge lines trend northeasterly and plunge approximately 70° to the northeast. The axial planes of F_1 dip steeply to the east. Lithology and a pervasive foliation reflect the first phase of folding. A weak second phase of folding about north-south axes was recognized only in a few places by crenulations, minor folds, and second phase foliations. First phase foliation has been clearly deformed by second phase folding.

Geological mapping has defined a series of gossans, gossans with significant accumulation of sulphides, and ground geophysical anomalies. Based on lithology and structure these features are interpreted to outline a time-stratigraphic horizon (Fig. 3a). Geophysical anomalies (Fig. 3a) include at least two of horizontal loop electromagnetic, magnetometer, VLF, and

radem surveys.

In the immediate area of the #10 mineralized zone, the mineralized horizon is marked by a highly amygdaloidal andesite which has up to 40% amygdules in a heavily chloritized matrix. The amygdules are quartz and feldspar filled, with minor amounts of sulphide in their cores. This unit extends westward and dies out at a large, felsic agglomerate 3,500 feet west of the #10 zone. Gossan #461 lies on a mafic-felsic contact at this stratigraphic level. Gossan #462 lies within felsic volcanic rocks, as expressed on surface, but diamond drilling indicates that the major mineralization actually lies at a mafic-felsic contact just below the surface. The mineralized horizon, along the north limb of the syncline is characterized by several geophysical anomalies and gossan zones. Gossan #463, near the northern limit of the mineralized horizon, is a zone of abundant pyrite and pyrrhotite.

Major element chemistry of Takiyuak volcanic rocks

Because of the coincidence between geophysical anomalies and visible evidence of mineralization (gossans) along an assumed time-stratigraphic horizon, a chemical study of the alteration associated with this horizon was carried out. In part the limits of the mineralized horizon are defined by the chemical data.

The chemical classification of Takiyuak volcanic rocks has been discussed by Gill (1976a). Whole rock chemical analyses of rocks located within the mineralized horizon (Fig. 3a) and

Table 1. Average chemical composition of Taktiyuk volcanic rocks and standard deviations of the means.

Oxide	1	2	3	4	5	6	7	8	9	10	11							
SiO ₂	75.4	2.4	76.3	6.4	76.6	0.7	72.7	3.8	74.3	57.8	1.7	52.3	4.0	54.7	50.1	3.9	44.3	48.9
Al ₂ O ₃	12.6	1.2	12.0	3.1	12.6	0.3	14.2	2.3	12.9	14.3	1.0	15.8	2.0	15.0	14.0	1.0	10.9	14.5
Fe ₂ O ₃	0.37	0.28	0.68	0.25	0.51	0.24	0.60	0.22	0.74	2.10	0.05	2.54	0.41	2.00	2.87	0.70	2.90	2.14
FeO	1.18	0.77	2.04	0.72	1.31	0.64	1.86	0.57	2.22	6.30	0.22	8.44	1.47	7.64	8.69	2.10	10.26	9.03
MgO	1.88	0.88	2.93	0.95	1.65	0.74	3.63	2.01	0.85	5.53	0.81	10.49	2.26	4.50	7.37	1.86	8.24	6.27
CaO	0.92	0.66	0.16	1.46	0.49	0.39	0.07	0.02	1.48	3.31	3.37	1.44	2.49	6.39	6.22	1.29	9.30	8.74
Mn ₂ O	4.38	1.21	0.15	0.22	4.00	0.82	0.63	0.53	2.87	3.81	0.08	1.22	2.12	2.79	2.64	0.64	0.83	2.51
K ₂ O	1.63	0.97	3.16	0.94	1.55	0.91	3.43	0.72	2.10	0.42	0.21	1.39	0.85	0.55	0.90	0.50	0.63	0.45
TiO ₂	0.15	0.04	0.20	0.09	0.13	0.01	0.27	0.10	0.26	1.08	0.33	1.07	0.09	0.99	1.12	0.40	0.81	1.06
P ₂ O ₅	0.03	0.01	0.04	0.03	0.02	0.01	0.04	0.01	0.07	0.29	0.12	0.25	0.09	0.12	0.24	0.04	0.20	0.07
MnO	0.02	0.01	0.03	0.03	0.02	0.01	0.03	0.01	0.01	0.15	0.10	0.11	0.05	0.28	0.16	0.03	0.22	0.21
S	0.07	0.05	0.05	0.04	0.05	0.04	0.05	0.05		0.18	0.09	0.18	0.11		0.21	0.21	0.48	
CO ₂	0.65	0.80	0.34	0.32	0.51	0.38	0.40	0.51	0.86	1.62	1.67	0.48	0.60	1.93	2.26	2.77	6.10	1.93
H ₂ O	0.75	0.61	1.97	0.64	0.69	0.69	2.37	0.44	1.17	3.33	0.94	4.49	1.00	2.92	3.09	1.03	5.09	3.34
	100.01	100.06	100.24	100.11	99.52	100.14	100.20	99.81	99.88	100.29	99.13							
	8	7	6	4	85	2	11	119	7	1	162							

1. cherty rhyolite, Taktiyuk volcanics

2. cherty rhyolite, Taktiyuk volcanics, altered due to mineralization

3. porphyritic rhyolite, Taktiyuk volcanics

4. porphyritic rhyolite, Taktiyuk volcanics, altered due to mineralization

5. rhyolite, Goodwin (1968), Superior Province volcanics

6. andesite, Taktiyuk volcanics

7. andesite, Taktiyuk volcanics, altered due to mineralization

8. andesite, Goodwin (1968), Superior Province volcanics

9. basalt, Taktiyuk volcanics

10. basalt, Taktiyuk volcanics, altered due to mineralization

11. basalt, Goodwin (1968), Superior Province volcanics

from units stratigraphically above and below this horizon have been used to outline a zone of alteration believed to be related to mineralization. Detailed sample locations and analytical data, listed in Gill (1976), are mainly from the area between mineralized zones #10 and #462. Table 1 lists these chemical data as well as Goodwin's (1968) data for Superior Province volcanic rocks for comparison.

Classification of a rock as altered or unaltered was necessary for this study. This required that mineral assemblages resulting from regional metamorphism be recognized as such and excluded from the criteria used to classify a rock as altered. Unaltered rocks were those which exhibited good primary volcanic textures in thin section, lack of clearly secondary introduction of carbonate and/or silica, and chemical consistency with the rocks clearly distal to the mineralization. In addition the unaltered rocks showed chemical consistency with volcanic rocks of the Superior Province (Goodwin, 1968).

Takiyuak basaltic rocks are chemically very similar to Superior Province basalts but are slightly lower in CaO . Alteration of the andesites within the mineralized horizon is accompanied by a marked depletion in Na_2O , and Al_2O_3 and by enrichment in CaO , CO_2 , and H_2O .

Andesites are enriched in Na_2O and MgO but depleted in CaO by comparison with Superior Province andesites (Goodwin, 1968). Alteration of the andesites within the mineralized horizon indicates a marked enrichment in MgO , K_2O , and FeO , with a depletion of Na_2O . Data suggest a depletion in CO_2

but CO_2 data are highly variable as noted by the high standard deviation for the unaltered rocks. There is no unaltered equivalent of the amygdaloidal andesite. Relative to the unaltered massive andesites and to Goodwin's (1968) average andesite, the amygdaloidal andesite is enriched in MgO and K_2O , and depleted in Na_2O and CaO . CO_2 and H_2O parallel the behaviour for the massive andesite.

Porphyritic rhyolite, by comparison with Superior Province rhyolite, is lower in CaO and higher in Na_2O . Alteration of rhyolite resulted in K_2O and MgO enrichment, with marked depletion in Na_2O and CaO .

Cherty rhyolite is higher in MgO and Na_2O than Superior Province rhyolites but slightly lower in CaO and K_2O . Alteration of these rhyolites results in a marked Na_2O depletion, a depletion in CaO , and enrichment in K_2O and MgO . Chemical alteration was highly variable for SiO_2 and Al_2O_3 . This rhyolite is in direct contact with the #10 sulphide deposit and altered samples were mainly from this zone. Highly variable SiO_2 (73.3-89.2 wt%) and Al_2O_3 (5.84-14.27 wt%) contents caused relative adjustments in other elements. These rocks are definitely very highly altered and average values which fall within the range of values for the unaltered equivalents are a function of the variability of this alteration.

Takliyak volcanic rocks are slightly lower in CaO and higher in Na_2O and MgO than the average Superior Province volcanic rocks of Goodwin (1968). The restricted number of analyses may account for a portion of this difference; however,

the consistency of the difference from mafic through felsic rocks suggests that they are fundamental chemical differences.

The three elements whose behaviour is most clearly indicative of alteration are K, Mg, and Na (Fig. 4). The marked depletion in Na_2O , for all rock types, is consistent with the findings of Franklin (1975) for the Mattabi deposit, Gjelsvik (1968) for the Skorovass deposit in Norway, Nilsson (1968) for the Boliden deposit in Sweden, and is believed to be a key chemical indicator of potential sulphide accumulation in Takiyuak volcanic rocks. Increasing MgO has been considered a prospecting tool in massive volcanogenic sulphide exploration for many years (Sangster, 1972). Clear MgO enrichment, observed in data from the time-stratigraphic mineralized horizon for Takiyuak volcanic rocks, supports this concept. The magnesium enrichment is clearly evident in the andesitic and rhyolitic rocks, being expressed mineralogically as chlorite clots in the amygdaloidal andesite and as chlorite in fractures in the rhyolites. K_2O enrichment in the andesites and rhyolites also appears to be a good indicator of alteration in these units but basalts show no real change within the confidence limits of the analyses. More analyses are required to establish the behaviour of potassium on alteration of basalts. In summary, then, chemical parameters indicative of alteration resultant on mineralization are: Na_2O depletion; MgO and K_2O enrichment. Ideally, consistency in chemical behaviour for all rock types will provide the most useful means by which key alteration effects can be recognized and used in exploration. This study indicates that

Figure 4. Effects of alteration related to mineralization on the MgO , Na_2O , and K_2O content of Takiyuak volcanic rocks. MgO , Na_2O , K_2O contents in wt%, solid symbols=unaltered rocks, open symbols=altered rocks.

the behaviour of Na_2O , MgO , and K_2O on alteration is independent of rock type and therefore these parameters are excellent exploration tools in Takiyuak volcanic rocks.

Alteration patterns in Takiyuak volcanic rocks indicate that a horizon coincident with sulphide mineralization is chemically anomalous by comparison with rocks stratigraphically above and below it, or distal to the volcanic center. The geological extension of this mineralized horizon on the north limb of the syncline has not been systematically sampled; however, a sample of rhyolite at gossan #463 shows the characteristic Na_2O depletion and MgO and K_2O enrichment. This suggests that the chemical effects of alteration related to the mineralization probably extend all along the mineralized horizon.

Chloritic alteration

Chlorite is ubiquitous in the Takiyuak Metavolcanic Belt. Regionally it occurs as fine-grained matrix to phenocrysts in mafic volcanic rocks, with minor opaques, and outlining the pervasive foliation. In the immediate area of the #10 sulphide deposit chlorite appears as a fine-grained mat of dark green to black material and as chlorite clots up to 2 cm in diameter. Electron microprobe analyses of chlorites believed to be the result of regional metamorphism and those believed to be related to the mineralizing event were done in order to compare their compositions.

Tables 2, 3 indicate that there is a distinct chemical

Table 2. Average chemical data for chlorites from the Taklyuak Metavolcanic Belt.

Standard deviations in brackets.

Sample Number	FeO	MgO	Al ₂ O ₃	SiO ₂	N
GR-17	31.89 (0.23)	12.41 (0.38)	18.04 (0.30)	25.78 (0.32)	4
GR-44	25.37 (0.31)	16.08 (0.06)	20.16 (0.04)	25.50 (0.11)	3
X554	21.44 (0.13)	19.18 (0.07)	20.44 (0.02)	25.75 (0.25)	4
G-10-12	19.51 (0.64)	20.71 (0.50)	17.07 (0.93)	27.56 (1.99)	4
H-10-2#1	23.38 (0.30)	18.17 (0.25)	18.41 (0.35)	26.53 (0.43)	4
H-10-5#15	22.92 (0.28)	17.44 (0.39)	17.75 (0.25)	28.62 (0.23)	3

Table 3. Chemical composition of regional and alteration chlorites and the variation in their Fe and Mg contents.

Sample Number	Formula	Fe/Mg	Fe/Fe+Mg
Regional			
GR-17	$(\text{Mg, Fe, Al})_{12.071}(\text{Al, Si})_8\text{O}_{20}(\text{OH})_2$	1.442	0.591
GR-44	$(\text{Mg, Fe, Al})_{12.058}(\text{Al, Si})_8\text{O}_{20}(\text{OH})_2$	0.885	0.470
Alteration			
X554	$(\text{Mg, Fe, Al})_{12.110}(\text{Al, Si})_8\text{O}_{20}(\text{OH})_2$	0.627	0.385
G-10-12	$(\text{Mg, Fe, Al})_{12.058}(\text{Al, Si})_8\text{O}_{20}(\text{OH})_2$	0.599	0.346
H-10-2#1	$(\text{Mg, Fe, Al})_{12.084}(\text{Al, Si})_8\text{O}_{20}(\text{OH})_2$	0.722	0.419
H-10-5#15	$(\text{Mg, Fe, Al})_{11.818}(\text{Al, Si})_8\text{O}_{20}(\text{OH})_2$	0.737	0.424

difference between the two chlorite types. Regional chlorite is more iron-rich than the chlorite related to mineralization. Regional chlorite composition is quite variable as would be expected for rocks from different areas within a volcanic belt and whose bulk chemistry would likely be different. Chlorites related to mineralization are more magnesium-rich and variation in composition is most likely due to readjustment on regional metamorphism. Their low Fe/Mg ratio is consistent with the distinct magnesium enrichment of the altered rocks as outlined by whole rock chemistry.

Chemical controls on alteration

To study the hypothesis that part of the alteration associated with mineralization in the Takiyuak volcanic pile is related to rock-seawater interaction, some chemical equilibria involving primary minerals of volcanic rocks have been studied. Those minerals with the elements Na, K, and Mg were considered of prime importance since these parameters were clearly indicative of alteration as indicated by whole rock chemical data.

To study the equilibrium for a given reaction and to derive the equilibrium constant, for a given temperature, at a constant pressure of one atmosphere, values for the standard enthalpy and entropy of the reaction must be calculated according to

$$1. \quad \log K(T) = - \frac{[\Delta H_{ip}^0(T) - \Delta H_{ir}^0(T)] + T[\Delta S_{ip}^0(T) - \Delta S_{ir}^0(T)]}{2.303RT}$$

2.303RT

where ΔH_i^0 and S^0 are the standard enthalpy of formation and the standard third law entropy of a given species at temperature T , and p and r refer to the products and reactants respectively.

Calculation of ΔH^0 and S^0 values for given species at elevated temperatures was done using average heat capacity data and heat capacity power function coefficients from Helgeson (1969). Calculations using average heat capacity data employed equations 2 and 3, those using power function coefficients used equations 4 and 5, where C_p^0 is the standard heat capacity, a'' , b'' , c'' are the power function coefficients, and the relationship between heat capacity and both enthalpy and entropy is given by equations 6 and 7. Combining the data

$$2 \quad \Delta H_i^0(T) = \Delta H_{fi}^0(T_r) + C_{pi}^0 \int_{T_r}^T (T - T_r)$$

$$3 \quad S_i^0(T) = S_i^0(T_r) + C_{pi}^0 \int_{T_r}^T \ln[T/T_r]$$

$$4 \quad \Delta H_i^0(T) = \Delta H_{fi}^0(T_r) + a''(T - T_r) + b''/2(T^2 - T_r^2) - c''(1/T - 1/T_r)$$

$$5 \quad S_i^0(T) = S_i^0(T_r) + a'' \ln[T/T_r] + b''(T - T_r) - c''/2(1/T^2 - 1/T_r^2)$$

$$6 \quad \Delta H_i^0(T) = \Delta H_{fi}^0(T_r) + \int_{T_r}^T C_{pi}^0(T) dT$$

$$7 \quad S_i^0(T) = S_i^0(T_r) + \int_{T_r}^T C_{pi}^0(T) d \ln T$$

using equation 1 allows the equilibrium constants for a given reaction at elevated temperatures to be calculated.

Equilibrium constants for the reactions studied (Table 4) are listed in Table 5. The reactions studied consider equilibria

Table 4. Chemical equilibria, involving some primary minerals of calc-alkaline volcanic rocks, considered in studying the effects of chemical interaction between fresh volcanic rocks and seawater.

Reaction

Table 5. Equilibrium constants and ion activity ratios for chemical equilibria in Table 4 from 25°C to 300°C.

Log K. (T°C)							a_X^a/a_H^b				Reaction				
25	60	100	150	200	250	300	a_X^a/a_H^b	25	60	100	150	200	250	300	
48.53	44.05	39.91	35.92	33.09	30.17	28.64	a_{Na}^1/a_H^1	8.09	7.34	6.65	5.98	5.52	5.03	4.77	1.
16.22	14.56	12.97	11.43	10.31	9.38	8.37	a_{Na}^1/a_H^1	8.11	7.28	6.49	5.72	5.16	4.69	4.19	2.
16.76	13.85	11.17	8.19	5.99	3.62	1.18	a_{Na}^1/a_H^1	8.38	6.93	5.59	4.10	3.00	1.81	0.59	3.
10.85	10.16	9.54	8.90	8.50	8.13	7.88	a_K^1/a_H^1	5.43	5.08	4.77	4.45	4.25	4.17	3.94	4.
11.22	10.17	9.13	7.96	7.04	6.20	5.13	a_K^1/a_H^1	5.61	5.09	4.57	3.98	3.52	3.10	2.57	5.
15.29	12.87	10.74	8.05	6.08	4.05	1.47	a_K^1/a_H^1	7.65	6.44	5.37	4.03	3.04	2.03	0.74	6.
30.77	29.19	27.53	26.02	24.99	24.17	23.64	a_K^1/a_H^1	5.13	4.87	4.59	4.34	4.17	4.03	3.94	7.
17.92	15.65	13.60	11.60	10.10	8.89	8.07	a_{Mg}^1/a_H^2	17.92	15.65	13.60	11.60	10.10	8.89	8.07	8.
14.93	11.39	7.86	4.01	1.01	-1.77	-4.99	a_{Mg}^1/a_H^2	14.93	11.39	7.86	4.01	1.01	-1.77	-4.99	9.
69.54	60.67	52.90	45.54	40.36	36.29	34.17	a_{Mg}^1/a_H^2	13.91	12.13	10.58	9.11	8.07	7.26	6.83	10.
164.43	330.90	274.93	236.47	210.00	190.40	183.18	a_{Mg}^1/a_H^2	10.72	9.73	8.09	6.96	6.18	5.60	5.39	11.

involving primary minerals with Na, K, and Mg as major constituents and are presented in Figures 5, 6, 7. Kajiwara (1973) has calculated chemical equilibria involving these phases and produced similar equilibrium curves.

Plagioclase is the only primary sodium bearing mineral found in most calc-alkaline volcanic rocks. Volcanic glass is probably the host to the remaining sodium. Hydrolysis reactions involving albite result in the breakdown of albite and in the formation of sodium montmorillonite and/or kaolinite, both reactions liberating sodium ions. Equilibria for reactions 1 to 3 (Table 4) are presented in Figure 5, along with the value for present day seawater (Kajiwara, 1973). They indicate that, for chemical conditions similar to those of present day seawater, kaolinite is a stable mineral and both albite and sodium montmorillonite are unstable. If fresh volcanic rocks interacted chemically with seawater, sodium bearing minerals would break down with the release of sodium to the seawater.

Microcline is the primary potassic mineral of the calc-alkaline suite of volcanic rocks, with biotite as a minor mineral. Hydrolysis reactions involving microcline could result in the breakdown of microcline to K-mica or potassium montmorillonite (reactions 4 and 7, Table 4), and hydrolysis of these minerals could generate kaolinite (reactions 5 and 6, Table 4). However, with respect to present day seawater (Kajiwara, 1973) these equilibria indicate (Fig. 6) that microcline is stable with respect to K-mica or potassium montmorillonite. In addition both K-mica and potassium montmorillonite are stable with

Figure 5. Equilibrium curves for reactions 1-3 Table 4. $\bigcirc$ = present day seawater (Kajiwara, 1973). $a_{\text{H}_2\text{O}} = 1$.

Figure 6. Equilibrium curves for reactions 4-7 Table 4. $\bigcirc$ = present day seawater (Kajiwara, 1973). $a_{H_2O} = 1$.

respect to kaolinite. This indicates that for the chemical conditions of present day seawater, reactions resulting in the release of potassium to seawater would not take place. Enrichment of the volcanic rock in potassium could take place according to the exchange reaction

Albite is unstable in present day seawater and muscovite is stable, therefore the interaction of a fresh volcanic rock with seawater will result in the enrichment of the rock in potassium and its depletion in sodium.

The primary magnesium bearing minerals of calc-alkaline volcanic rocks are pyroxene, amphibole, biotite, and minor olivine. Figure 7 shows equilibria for reactions 8 to 11 (Table 4) involving some magnesium bearing minerals. These equilibria indicate that hydrolysis reactions liberating magnesium will not take place at the concentration levels of magnesium in present day seawater. Experimental studies (Hajash, 1975) of basalt - seawater interaction have shown that chemical interaction between tholeiitic glass of basaltic composition and natural seawater at 200 and 300°C, results in more than 98% of the magnesium in the seawater being removed and concentrated in a Mg-rich smectite clay. This suggests that for present day concentrations of magnesium in seawater, the extraction of magnesium from seawater and its enrichment in the volcanic rock is probable. Magnesium enrichment, within the alteration zone outlined in the Takiyuak Meta-volcanic Belt, is expressed by chlorite compositions which are more magnesium-rich than regional metamorphic chlorites (Table 3).

Figure 7. Equilibrium curves for reactions 8-11 Table 4. $\bigcirc$ = present day seawater (Kajiwara, 1973). $a_{H_2O} = 1$.

Reactions such as the breakdown of biotite to form chlorite

resulting in a higher Mg/Fe ratio in the product chlorite, are the likely cause of this magnesium enrichment.

These simple chemical equilibria indicate that chemical interaction between fresh volcanic rocks and seawater may generate alteration patterns similar to those observed in Takiyuk volcanic rocks. Sodium depletion, and magnesium and potassium enrichment can be explained by the effects of seawater on fresh volcanic rocks-provided reaction kinetics allow the reactions to take place as indicated. The main criteria for development of such alteration patterns is a time interval during which volcanic rocks may interact chemically with seawater. Such a time factor is most likely to be favourable at the end of a volcanic cycle where a hiatus in volcanic activity has been shown to have taken place. It is suggested that alteration patterns observed in volcanic rocks associated with massive volcanogenic sulphide deposits are in part the result of seawater-volcanic rock equilibration and indicate a pause in volcanic activity. Local intense alteration observed in crosscutting pipes beneath many massive volcanogenic sulphide deposits is interpreted as the product of continued chemical interaction between recycled seawater and volcanic rocks surrounding a vent through which the solutions pass.

Summary and conclusions

Whole rock chemical data from Takiyuak volcanic rocks indicate that alteration along the time-stratigraphic horizon related to mineralization is characterized by sodium depletion, and magnesium and potassium enrichment, an alteration which is independent of rock type. Chemical equilibria involving some of the primary minerals of calc-alkaline volcanic rocks indicate that this alteration can, in part, be explained by volcanic rock-seawater chemical interaction. It is believed that the time-stratigraphic horizon related to mineralization reflects a pause in volcanic activity and a time of chemical equilibration between the volcanic rocks at the rock-water interface and seawater. This time break in volcanic activity can be recognized using whole rock chemical analyses and is a useful tool in the search for massive volcanogenic sulphide deposits.

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IV. PAPER 3

The Takiyuak #10 Sulphide Deposit: Geology and Genesis

James W. Gill

Abstract

Takiyuak #10 is a Precambrian volcanogenic sulphide deposit made up of four mineralogically zoned sulphide lenses separated by volcanic rocks. The concordance of the lenses with host rock stratigraphy, the increasing Zn/Cu ratio (within and between lenses) toward the stratigraphic top, and the close spatial relationship to the host volcanic rocks, all indicate that the sulphides are coeval with the enclosing volcanic rocks. Chemical data suggest that the sulphides precipitated from a hot saline brine which mixed with seawater. Textural evidence indicates that post depositional recrystallization, remobilization, and deformation have taken place.

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The Takiyuak #10 Sulphide Deposit

Introduction

Massive copper-zinc sulphide deposits are the most economically important type of sulphide deposit in the Archean of the Canadian Shield. Genetic hypotheses for these deposits have swung, in recent years, from hydrothermal replacement to the current syngenetic, volcanogenic theory (Sangster, 1972; Gilmour, 1965). Petrologic evidence (Franklin et al, 1975), textural features of the ores (Walker et al, 1975), and the stratabound nature of the deposits (Sangster, 1972), provide compelling evidence to support the exhalative sedimentary origin for these deposits.

The #10 massive sulphide deposit, spatially associated with felsic volcanic rocks, was discovered in 1973 by Texasgulf Inc. through a program of geological and geochemical prospecting followed by careful geological mapping. The deposit is located approximately 4.8 km due east of the southern end of Takiyuak Lake, 408 km north of Yellowknife, Northwest Territories (Figs. 1,2). Data to date indicate a tonnage of 500,000 tons grading 5% copper, 3.5% zinc, and 1 oz/ton silver (Texasgulf, 1976).

Figure 1. Location map, Takiyuak Metavolcanic Belt, Northwest Territories. (after McGlynn and Henderson, 1970)

Figure 2. Location of map area near Takiyuak Lake, N.W.T..

Regional Geology

The Takiyuak Metavolcanic Belt, an Archean greenstone belt within the Slave Structural Province, extends north-northeasterly from the southern end of Takiyuak Lake, Northwest Territories (Fig. 3). Volcanic rocks make up approximately 60% of the area and late granite and diorite intrusions make up the remaining 40%. Felsic volcanic rocks compose 25% of the volcanic pile with mafic and intermediate flows and tuffs as the major volcanic component. The succession is a minimum of 5 km thick and has been folded into a northeasterly plunging, easterly dipping syncline (Gill, 1976a). Regional metamorphism of all the volcanic rocks in this belt is lower greenschist facies.

Local Geology

Geological mapping in the area of the #10 sulphide deposit (Fig. 4) by Heslop (1974) and Gill (1975, 1976) has outlined a major felsic center with subordinate mafic volcanic flows and several agglomerates. Felsic flows are porphyritic rhyolite, characterized by an abundance of quartz phenocrysts "eyes", in a matrix of siliceous material, sericite, and minor chlorite; and cherty rhyolite characterized by its cherty texture, extreme hardness, and minor chlorite in fractures. Basaltic flows lie stratigraphically below and above the main felsic buildup and are of minor importance in this area. An amygdaloidal andesite flow is characterized by an abundance of quartz and feldspar

amygdules in a highly chloritized matrix. Sulphides often occupy the cores of the amygdules and the main gossan zones lie within this unit which can be traced from a possible volcanic vent (Fig. 4). Zinc-copper mineralization is restricted to the cherty rhyolite, the amygdaloidal andesite, or to the contact zone of these two units. Structural data indicate that the rocks strike to the southeast in the immediate area of the #10 deposit. The volcanic rocks dip subvertically to the east and minor folds indicate that the strata plunge to the north-northeast at approximately 75° . The #10 area represents a minor fold of the regional syncline and has been slightly modified by the second phase of regional folding (Gill, 1976a).

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Sulphide Mineralization

The #10 sulphide deposit is made up of pyrrhotite, chalcopyrite, pyrite, sphalerite, galena, and marcasite in order of decreasing abundance. Magnetite is the only metal oxide observed. Arsenides, sulphosalts, and native metals, commonly found in massive volcanogenic sulphide deposits, have not been observed in this deposit. Within the sulphide-rich zones the gangue material is approximately 90% dark green to black chlorite; the remaining 10% is slightly chloritized rhyolite.

Types of Sulphide Concentration

Massive volcanogenic sulphide deposits typically display two distinct ore types; massive ore, consisting of mainly pyrite, sphalerite, galena, chalcopyrite, and pyrrhotite, and stringer ore, consisting of mainly chalcopyrite, pyrrhotite, pyrite, and sphalerite (Sangster, 1972).

On the basis of diamond drill core data (Gill, 1976; Appendix H) three sulphide types have been recognized in this deposit. Massive sulphides are characterized by; a total sulphide content in excess of 50% of the rock volume, mineralogical banding of sphalerite and pyrrhotite which is conformable with the host volcanic rocks, the mineral assemblage sphalerite, pyrrhotite, pyrite, chalcopyrite, galena, and sometimes magnetite, sphalerite in much greater abundance than chalcopyrite, and a Zn/Cu ratio much greater than unity. These massive sulphides seldom contain less than 75% total sulphides and are generally

truly massive sulphides. Stringer sulphides in the Takiyuak #10 deposit are characterized by a total sulphide content of between 10 and 50% of the rock by volume, the mineral assemblage chalcopyrite, pyrrhotite, sphalerite, and pyrite in order of decreasing abundance, a chalcopyrite content much greater than sphalerite, a Cu/Zn ratio much greater than unity, a silicate component of almost all chlorite intergrown with the sulphides, evidence of replacement of the host volcanic rocks, no recognizable banding, and evidence of sulphide remobilization. In addition stringer sulphides never contain galena or magnetite. Disseminated sulphides were defined as those sulphides which were characterized by the minerals pyrite, pyrrhotite, sphalerite, and chalcopyrite with chalcopyrite and sphalerite together equalling less than 1% of the total sulphide content, and a sulphide content of from 0 to 10% of the rock volume. Disseminated sulphides are recognized only as distinct from barren host rocks and are not discussed further in this paper. A summary of the criteria used in defining the sulphide types is given in Table 1.

Sulphide Bodies.

A three dimensional model of the Takiyuak #10 sulphide deposit was constructed using diamond drill core data which allowed correlation of lithologies and sulphide types to be made between drill holes. Geological cross sections through the sulphide deposit are listed in Gill (1976, Appendix H). Figures 5 and 6 are two typical geologic cross-sections

Figure 5. Geologic cross-section through sulphide lenses 1 and 2,
 Takiyuak #10 deposit.

Figure 6. Geologic cross-section through sulphide lenses 1,3,and 4,
Takiyuak #10 deposit.

Table 1. Criteria for the classification of sulphide types in the Takiyuak #10 deposit

Sulphide Type	Rock Volume (%)	Mineralogy	Megascopic Structures and Textures	Metal Ratio
massive	50	sp=po>py=cp> gr=mt	massive, mineralogically banded, gangue inclusions	$Cu/Zn \ll 1$
stringer	10-50	cp=po>sp=py	stringer sulphides, heavy chlorite, remobilization*	$Cu/Zn \gg 1$
disseminated	0-10	py=po>cp=sp	disseminated	$Cu/Zn \approx 1$

* where remobilization is evident the rock volume of sulphide may exceed 50%.

and can be located on Figure 4 where each drill hole is located.

The Takiyuak #10 sulphide deposit is made up of four main sulphide lenses. Each sulphide lens is characterized by the presence of massive and stringer sulphide types, by concordance with stratigraphy, and by compositional zoning from copper-rich in the stringer sulphide type to zinc-rich in the massive type mineralization. It has been shown by Sangster (1972) that volcanogenic sulphide deposits exhibit stringer ore stratigraphically beneath massive ore. Each sulphide lens in this deposit has stringer type sulphides changing to massive type from west to east stratigraphically and on this basis the lenses indicate that the stratigraphic top is to the east. Stringer mineralization underlies and is essentially concordant with the massive sulphides in the #10 deposit and each lens plunges to the north-northeast at approximately 60° as a pencil shaped body.

Examination of base metal contents of the four lenses has been done with the use of Cu/Zn ratios and Cu-Pb-Zn atomic percent calculations. Data (weighted averages of assay values for all the mineralized sections for each lens) are shown in Figure 7 and listed in Gill (1976; Appendix D). Assay data for sections through the four sulphide lenses indicate that there is an increasing Zn/Cu ratio from stratigraphic footwall to hanging wall for each lens (Table 2). Figure 7 shows that the four lenses can be separated into two distinct populations with respect to Cu/Zn ratios; lenses 1 and 4 have average Cu/Zn ratios of 1.07 and 1.44 respectively whereas lenses 2 and 3

Figure 7. Cu-Pb-Zn atomic percent diagram showing the variation in base metal assay values for the four sulphide lenses. Numbers refer to the lens number.

Lens #		Cu/Zn
(footage)	Hanging Wall	Foot Wall
1 (237-277)	0.02 0.01 0.30 0.06 0.04 0.03 0.11 0.17	
2 (209-253)	0.02 0.02 0.01 0.03 0.97 2.55 12.17 2.63 2.71	
3 (443-483)	0.06 0.05 0.21 0.13 0.05 0.25 0.36 0.25	
4 (296-304.3)	4.79	19:04

have ratios of 0.28 and 0.23 respectively. These ratios are based on total assays for each lens and do not differentiate between massive and stringer mineralization. The lenses ascend stratigraphically in the order 4, 1, 2, 3 and also show an increase in atomic percent Zn in this order. This indicates that there is not only a within lens increase in Zn/Cu ratio with increasing stratigraphic height, but also a distinct between lens increase. The separation of each lens from the other by volcanic rocks, and the increase in Zn/Cu ratio with increasing stratigraphic height, suggests that they may have resulted from different mineralizing events with fundamental differences in contained copper and zinc. This is particularly evident for the groupings lenses 1+4 and 2+3 where a large increase in the Zn/Cu ratio is evident in the stratigraphically younger lenses 2 and 3. In terms of the chemical evolution of the sulphide lenses it appears that the mineralization took place in four separate events. Each individual event was characterized by a relative increase of available zinc with time, and the overall mineralization process was also characterized by a relative increase in available zinc with time.

Silver assays of mineralized sections in the Takiyuak #10 sulphide deposit indicate that the deposit contains an average of 1 oz/ton of silver. The absence of sulphosalts, native silver, and silver sulphides, indicates that silver is in solid solution in another sulphide mineral. Mineralized sections with silver assays greater than 0.5 oz/ton were used in an attempt to locate the silver-bearing minerals. Electron microprobe analyses of

Figure 8. Plot of copper versus silver content of mineralized sections from various diamond drill holes, Takiyuak #10 deposit.

Table 3. Linear regression analysis for Cu-Ag-Pb assay data.

Hole Number	Linear Equation	Correlation Coefficient
H-10-2	$Ag = 0.13 + 0.088 Cu$	+0.93
H-10-4	$Ag = 1.20 + 0.345 Cu$	+0.86
H-10-5	$Ag = 1.26 + 0.184 Cu$	+0.70
H-10-6	$Ag = -0.81 + 0.512 Cu$	+0.99
H-10-8	$Ag = 1.14 + 0.005 Cu$	+0.30
H-10-16	$Ag = 0.07 + 0.450 Cu$	+0.93
H-10-17	$Ag = 0.89 + 0.297 Cu$	+0.94
H-10-2	$Ag = 0.98 + 0.250 Pb$	+0.05
H-10-4	$Ag = 2.72 - 0.440 Pb$	-0.33
H-10-5	$Ag = 1.66 + 0.066 Pb$	+0.10
H-10-6	$Ag = -1.00 + 13.30 Pb$	+0.15
H-10-8	$Ag = 0.73 + 33.00 Pb$	+0.64
H-10-16	$Ag = 1.30 - 2.810 Pb$	-0.05
H-10-17	$Ag = 1.87 + 1.100 Pb$	+0.42

Figure 9. Plot of lead versus silver content of mineralized sections from various diamond drill holes, Takiyuak #10 deposit.

chalcopyrite and pyrite showed no detectable silver as would be expected for such low concentrations. Sulphosalts containing silver are usually found as exsolved minerals in galena and/or chalcopyrite in massive volcanogenic sulphide deposits, and so plots of silver concentrations versus copper and versus lead assay values were constructed to test possible explanations. Assay data are listed in Gill (1976; Appendix D), and do not distinguish the individual sulphide lenses.

Figure 8 and Table 3 indicate that a strong positive correlation exists between the silver and copper content of the mineralized intersections for six of the seven holes plotted, whereas Figure 9 and Table 3 indicate that there is no strong correlation between silver and lead. Therefore, it is believed that the silver in the mineralization is held in crystalline solution in chalcopyrite. Examination of geological cross sections through the sulphide lenses indicates that with the exception of drill holes H-10-2 and H-10-8 all assay values for silver were for massive sulphides. The lower silver assays for the stringer sulphides, despite their higher copper content, suggests that silver was retained in the metal bearing solution until the deposition of the massive type mineralization.

Sulphide Textures and Paragenesis

Studies of polished sections were carried out in order to outline the depositional, structural, and metamorphic history of the deposit and to recognize primary depositional features of the sulphides. Data are listed in Gill (1976; Appendix C).

Pyrite occurs, in both massive and stringer type mineralization, as subhedral to euhedral megacrysts. These megacrysts are bimodally distributed; those whose dimensions range from 1.5 mm to 2.5 cm make up less than 10% of the population, the remaining 90% have dimensions from 0.1 to 1.0 mm.

Most large pyrite megacrysts have been fractured (Plate Ia) to an extent ranging from minor to complete disruption into smaller grains. These fractures appear as a network of mutually perpendicular cracks, apparently crystallographically controlled, filled with chalcopyrite and minor pyrrhotite. Typically pyrite has inclusions of galena, sphalerite, and pyrrhotite randomly distributed throughout the grains. Euhedral to subhedral magnetite grains are included within some of the megacrysts (Plate Ib). A few large megacrysts are characterized by a subrounded outline and concentric, chalcopyrite filled fractures (Plate Ic). The cores of these pyrite grains often have small inclusions of gangue; the outer part of the grain is always inclusion free.

Small pyrite megacrysts are characterized by well developed cubes and pyritohedra, small inclusions of galena, gangue, and pyrrhotite, and by the general absence of fracturing. Pyrite is also observed as fracture fillings and rims around pyrrhotite (Plate Id). This pyrite is unfractured, and occurs in veinlike bodies from 0.06 to 0.12 mm in thickness.

The often perfect euhedral habit of the pyrite megacrysts and the presence of randomly distributed anhedral inclusions of gangue and sulphides indicate that these megacrysts are formed

Plate I

- a. Large pyrite porphyroblast in a matrix of chalcopyrite and gangue (dark grey). Chalcopyrite has been remobilized into crystallographically controlled fractures in pyrite.
- b. Subhedral magnetite as inclusions in a highly fractured pyrite porphyroblast.
- c. Subround pyrite porphyroblast with concentric fractures. Inclusions in the core are chalcopyrite and gangue. Matrix of chalcopyrite and gangue.
- d. Pyrite veinlets interstitial to pyrrhotite grains.
- e. Mosaic of pyrrhotite grains with 120° triple junctions.
- f. Chalcopyrite exsolved from sphalerite as linear trails and outlining grain boundaries.
- g. Euhedral pyrite porphyroblasts with inclusions of galena, chalcopyrite, and gangue in a matrix of galena.

Plate I

by recrystallization processes and are pyrite porphyroblasts. The round concentrically fractured pyrite with inclusion rich cores may be relict pyrite framboids, and if so may indicate that the precipitation of some of the pyrite was biologically controlled. The fracturing of the porphyroblasts is post or late recrystallization. Pyrite in veinlets and as rims around pyrrhotite is considered to be post recrystallization, post deformational because fracturing and recrystallization are not observed.

Sphalerite is a major mineral in massive type mineralization and a minor mineral in the stringer sulphides. It occurs most commonly as anhedral matrix material to pyrrhotite and pyrite, and to a lesser extent as inclusions in pyrite and small blebs in chalcopyrite.

Pyrrhotite, the most abundant sulphide in this deposit, characteristically occurs as a mosaic of 0.04 to 0.30 mm grains with excellent 120° triple junctions (Plate 1e), indicating that textural equilibrium was attained on metamorphism (Stanton, 1964). The abundance of pyrrhotite, its occurrence as inclusions within pyrite porphyroblasts and the absence of pyrite inclusions within the pyrrhotite, are interpreted as evidence that the majority of the pyrrhotite was primary and is not the result of secondary replacement of pyrite by pyrrhotite. Pyrrhotite is also observed as small (0.01-0.04 mm) random blebs within sphalerite grains, probably the result of exsolution. Incomplete rims of pyrrhotite on some pyrite porphyroblasts are believed to be the result of replacement of pyrite by pyrrhotite.

after the formation of the porphyroblasts.

Chalcopyrite occurs as anhedral matrix material to pyrite, pyrrhotite, and magnetite, in fractures in pyrite porphyroblasts, as small blebs between pyrrhotite grains; forming linear trails within sphalerite, and as rings of discontinuous blebs showing sphalerite to be a mosaic of 0.12 to 0.20 mm grains (Plate If). The small (0.01-0.04 mm) blebs in sphalerite are crystallographically and/or grain boundary controlled and are interpreted to be the result of exsolution. Chalcopyrite filling fractures in pyrite is interpreted to be the result of remobilization coincident with or after deformation. In some stringer type mineralization chalcopyrite has been mobilized to give very high grade copper sections.

Galena, found only in massive type mineralization, occurs interstitially to pyrite, pyrrhotite, chalcopyrite, and sphalerite, and as inclusions in pyrite porphyroblasts. Pyrite porphyroblasts are frequently perfect euhedra when in galena-rich areas (Plate Ig). Galena has apparently behaved plastically on deformation and recrystallization and has accommodated itself interstitially to those minerals which possess stronger powers of recrystallization.

Marcasite, a very minor mineral in this deposit, appears as mottled patches replacing pyrite (Plate IIa) and as fingers with dark outer rims replacing pyrrhotite (Plate IIb).

Magnetite occurs as massive, thick (up to 15 cm) bands at the stratigraphic top of sulphide lenses 2 and 3. This massive magnetite is composed of aggregates of small, subhedral magnetite grains with minor interstitial pyrrhotite (Plate IIc) and is

Plate II

- a. Marcasite replacing pyrite as mottled patches.
- b. Marcasite replacing pyrrhotite as dark edged fingers.
- c. Contact between massive magnetite and pyrrhotite. Pyrrhotite has been altered to marcasite in places.
- d. Magnetite replacing a euhedral pyrite porphyroblast.
- e. Magnetite replacing pyrite along the outer margins of the porphyroblasts.

Plate II

found directly overlying massive type sulphides. Within the massive type sulphides magnetite occurs as subrounded inclusions in pyrite porphyroblasts (Plate Ib), as euhedral to subhedral grains in chalcopyrite, and as euhedral aggregates with gangue and pyrite. The presence of magnetite as massive bands at the stratigraphic top of two sulphide lenses and as inclusions in porphyroblasts, the absence of relict pyrite or pyrrhotite cores in magnetite grains, and the absence of evidence for reaction between magnetite and pyrite or pyrrhotite, all support a primary origin for the magnetite. In addition the presence of secondary magnetite replacing and pseudomorphing pyrite porphyroblasts (Plate II d,e) in the host amygdaloidal andesite, suggests that if the massive magnetite or the magnetite within the massive sulphide type mineralization were secondary, some remnants of the original material or pseudomorphs of original pyrite should have been preserved.

In order to derive a paragenetic sequence for the precipitation of the sulphides and oxides which make up this deposit, the post depositional history of the deposit must be unravelled. Textural studies of these ores indicate that recrystallization, deformation, and remobilization took place after deposition. The presence of pyrite porphyroblasts with inclusions of gangue, sulphides and magnetite, indicate that recrystallization took place. Fracturing of the porphyroblasts indicates that post recrystallization deformation took place, while the presence of sulphides filling the fractures indicates that remobilization

was post fracturing. Evidence for the attainment of textural equilibrium during metamorphism is observed in the development of good 120° interfacial angles between pyrrhotite grains. The presence of undeformed, unrecrystallized pyrite veinlets and pyrrhotite rims on pyrite porphyroblasts, and marcasite replacing both pyrite and pyrrhotite indicate that post deformational chemical reequilibration took place. Textural evidence shows that marcasite and some pyrite and pyrrhotite are not primary minerals in this deposit.

Textural evidence previously discussed, indicates that the primary minerals which make up the sulphide lenses are pyrrhotite, chalcopryite, sphalerite, galena, pyrite, and magnetite. Mineralogical zoning from chalcopryite-rich to sphalerite-rich from footwall to hanging wall within the sulphide lenses suggests that most chalcopryite and some pyrrhotite precipitated before sphalerite. Pyrrhotite, the most abundant sulphide in the deposit, is found in constant relative proportions in all sulphide types and probably was continuously precipitating. The restriction of galena to the massive type sulphides suggests that it was one of the later sulphides to precipitate, whereas pyrite, found as porphyroblasts in both massive and stringer sulphides is difficult to restrict paragenetically due to its recrystallized nature. Magnetite, was probably the latest mineral to form as evidenced by its location at the stratigraphic top of two of the sulphide lenses. Paragenetically, textural evidence and mineralogical zoning suggest that chalcopryite began precipitating prior to sphalerite and galena, pyrrhotite was continuously precipitating; magnetite

was the last mineral to appear; and pyrite could have precipitated at any time during the deposition of the sulphides.

Sphalerite Geobarometry

The composition of sphalerite in the assemblage sphalerite-pyrite-pyrrhotite (hex.) has been shown to be a potentially useful geobarometric tool (Scott and Barnes, 1971; Scott, 1973). Boorman (1967), Boorman et al (1971), and Scott and Barnes (1971) have shown that the pyrite-hexagonal pyrrhotite-sphalerite solvus is vertical from 550°C to 350°C at a sphalerite composition of 20.7 ± 0.6 mole % FeS. Scott (1973) has shown, both experimentally and by thermodynamic calculation, that the composition of sphalerite on the pyrite-hexagonal pyrrhotite solvus becomes less FeS rich with increasing pressure (Fig. 10). Figure 10 also shows that the geobarometer is independent of temperature between 350°C and 600°C at pressures in excess of 3kb. Phase relations in the Zn-Fe-S system below 300°C (Scott and Kissin, 1973) indicate that below 250°C at a pressure of 1 bar, the stable assemblage is pyrite-monoclinic pyrrhotite-sphalerite, and that a large shift in sphalerite composition from 20.7 mole % FeS to less than 14 mole % FeS takes place at equilibrium between 265°C and 200°C (Fig. 11).

The composition of sphalerites, in contact with pyrite and monoclinic pyrrhotite, for the #10 sulphide deposit (Table 4) are plotted on a modified form of Scott's (1973) sphalerite-pyrite-hexagonal pyrrhotite solvus geobarometer (Fig. 10).

Figure.10. T-X projection of the sphalerite + pyrite + hexagonal pyrrhotite solvus isobars (after Scott, 1973). Solid circles are sphalerite compositions for the Takiyuak #10 deposit plotted at the upper temperature limit of the lower green-schist facies of metamorphism.

Figure 11. T-X projection of part of the Zn-Fe-S system below 400°C (after Scott and Kissin, 1973).

Table 4. The composition of sphalerites from the #10 sulphide deposit.

Sample Number	Assemblage	Mole % FeS in Sphalerite (σ)	N
H-10-17 #5	py-po-sp	11.99 (0.36)	12
H-10-5 #7	py-po-sp	11.88 (0.50)	6

correct low pressure composition. The fact that many massive volcanogenic sulphide deposits are of much higher metamorphic grade and exhibit similar sphalerite compositions (Table 5) indicates that this explanation will not solve the pressure discrepancies for all such deposits.

Figure 12 shows sphalerite compositions for several massive volcanogenic sulphide deposits ranging in metamorphic grade from lower greenschist facies to upper amphibolite facies. It is of interest to note that the composition of sphalerite from Stall Lake, Anderson Lake, Takiyuak #10, Quemont, Geco, and Flin Flon, fall within the range 11.3 to 12.5 mole% FeS despite their wide range in metamorphic grade (Table 5). The restricted sphalerite compositions and broad metamorphic conditions are not compatible with the sphalerite geobarometer which indicates that for the pressure range from 2.5 to 7.5 kb the composition of sphalerite should range from 18 to less than 12 mole% FeS (Fig. 10). It is significant however that the sphalerite compositions approximate that composition predicted from the work of Scott and Kissin (1973) for the Zn-Fe-S system below 300°C (Fig. 11). It is believed that, for the currently available data, low temperature reequilibration of sphalerite best explains the large discrepancies which result on application of the sphalerite geobarometer to massive volcanogenic sulphide deposits. This suggests that the sphalerite geobarometer is not a useful tool in deriving either primary or metamorphic conditions for this type of sulphide deposit.

Figure 12. Sphalerite compositions for various Canadian massive volcanogenic sulphide deposits. Data are listed in Table 5.

Table 5. The composition of sphalerites from various sulphide deposits. Temperatures from Scott (1976) and from Gill (this study).

Deposit	Assemblage	Mole % FeS	Metamorphic Temperature	Reference
Quemont	py-po-sp	11.9	300°C	Lusk, 1975
Takiyuak #10	py-po-sp	11.9	325°C	this study
Geco	py-po-sp	12.19	600°C	Scott, 1976
Stall Lake	py-po-sp	12.5	640°C	Bristol, 1974
Anderson Lake	py-po-sp	12.5	640°C	Sangameshwar, 1972
Fish Flon	py-po-sp	11.3	300-430°C	Koo and Mossman, 1975

Genesis of the Takiyuak #10 Sulphide Deposit

Detailed geological mapping and drill core logging indicate that the #10 sulphide deposit is made up of four sulphide lenses each of which is at or very close to the contact between mafic and felsic volcanic rocks. The sulphide lenses are concordant with stratigraphy and no crosscutting alteration pipe with stringer mineralization exists. Each lens is zoned from copper rich at the base to zinc-rich at the top, as expressed by concordant Cu-rich stringer type sulphides occurring beneath Zn-rich massive banded-type sulphides in each lens. Sulphides intergrown with the host amygdaloidal andesite indicates that some replacement of the host volcanic rocks has taken place whereas the concordant banding of the massive sulphides indicates that a sedimentary origin for part of the mineralization is probable. The presence of volcanic rocks stratigraphically above and beneath the sulphide lenses, the concordance of the sulphide lenses with the volcanic rocks, and the concordant banding in the massive type sulphides indicate that the Takiyuak #10 sulphide deposit is coeval, and may or may not be cogenetic with the host volcanic rocks.

The role of metal bearing hydrothermal solutions in the formation of massive sulphide deposits has survived the transition from epigenetic to syngenetic theories for the origin of these deposits. Fluid inclusion studies on Kuroko type ore

deposits indicate that the ore solutions have a concentration of from 0.5 to 3 molal NaCl (Tokunaga and Honura, 1974). Temperatures of the solutions have been estimated at between 80°C and 250°C for Kuroko (massive type) ore (Kajiwara, 1970), and up to 300°C for the original ore solution. The ore bearing solutions were therefore most likely hot saline brines. Based on solubility data for minerals in the Fe-S-O system and on the boundary conditions of a temperature of 250°C and a salinity of 1 molar NaCl, Large (in press) has shown that in order for the solution to transport from 5 to 50 ppm iron the pH must be less than 5, f_{O_2} less than 10^{-36} , and S less than $10^{-2}M$ (Fig. 13). Precipitation of pyrite, pyrrhotite, or magnetite will result if any of these parameters increase. The major chemical effects which result when an ore bearing fluid mixes with the seawater will be: increase in pH, decrease in salinity, and a rise in f_{O_2} .

The Takiyuak #10 sulphide deposit is characterized by abundant pyrrhotite, minor pyrite, and massive magnetite as the last mineral to precipitate. Chalcopyrite apparently preceded sphalerite in precipitating. Stability fields for minerals in the Fe-S-O system and regions of base metal precipitation for solutions with pH = 5, $S = 10^{-3}M$, and salinity = 1M NaCl, have been calculated by Large (in press) from thermochemical data in Helgeson (1969). Figure 14 shows these stability fields and regions of base metal precipitation. Assuming an initial temperature of 300°C for the rising hydrothermal solution, and changes in pH, T, f_{O_2} , and salinity as described above, path AB (Fig. 14) is the path most likely taken by solutions which gave rise to

Figure 13. Effects of f_{O_2} , pH, and ΣS on the solubility of magnetite, pyrite, and hematite in a 1M NaCl solution at 250°C (from Large, in press).

Figure 14. Mixing path AB representing the sequential deposition and zonation of the #10 sulphide deposit. Deposition is from a 1M NaCl solution at $\text{pH}=5$, $\Sigma\text{S}=10^{-3}$ M. Chalcopyrite and sphalerite fields represent the areas of deposition between the 6ppm and 1ppm contours of soluble copper and zinc (adapted from Large, in press).

the #10 sulphide deposit. This mixing path indicates that precipitation of chalcopyrite and pyrrhotite would be early, followed by sphalerite and pyrrhotite, then sphalerite and pyrite. The continued precipitation of chalcopyrite during sphalerite precipitation would be determined by the amount of copper left in the solution. If the solution were depleted in copper and also because the solubility of copper is increasing in this direction, no chalcopyrite will precipitate. Finally, the stability field of magnetite is reached and the remaining iron available for precipitation deposits as magnetite. Neither chalcopyrite nor sphalerite will precipitate in this region and pure magnetite is deposited.

The mineralogical zonation in the Takiyuak #10 sulphide deposit can be explained by the response of a hot saline brine to changes in chemical conditions on contact with seawater. The presence of several sulphide lenses which exhibit the same mineralogical zoning (magnetite not always present) indicates that metal zoning did not result from successive fluids rich in either copper or zinc, but rather from several generations of fluids with similar initial bulk compositions which responded chemically to mixing with seawater. The #10 deposit, composed of a series of lenses, was formed by precipitation of sulphides and oxides from hydrothermal solutions during intermittent volcanism.

Summary and Conclusions

The Takiyuak #10 sulphide deposit is an Archean massive volcanogenic sulphide deposit composed of four lenses. Mineralogical zoning and sulphide type zoning, within each lens and also between lenses, is consistent with the typical increase in Zn/Cu ratio of massive volcanogenic sulphide deposits toward the stratigraphic top of the deposits. Metamorphic pressure as estimated from silicate mineral assemblages is inconsistent with that determined by the sphalerite geobarometer and suggests that the latter is not a valid tool in pressure determinations for these deposits. Chemical data indicate that the deposition of metals was most likely due to changes on f_{O_2} , pH, T, S, and salinity, resulting when a metal bearing brine mixed with seawater. The metal zoning within each lens can be explained by increasing f_{O_2} and decreasing temperature during the metal precipitation process. The presence of individual lenses, each with an increasing Zn/Cu ratio toward the top, and separated by volcanic rocks, suggests that volcanism was intermittently active and that mineralization was the result of several periods of fluid influx.

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V. THE ORIGIN AND TECTONIC REGIME OF THE
TAKIYUAK METAVOLCANIC BELT

The Origin and Tectonic Regime of the Takiyuak Metavolcanic Belt

Volcanic rocks of the Takiyuak Metavolcanic Belt belong to the calc-alkaline suite and consist of basalt, andesite, dacite, and rhyolite (Paper 1). Together with their plutonic equivalents, gabbro, diorite, granodiorite, and granite, these rocks are the most abundant igneous rocks in orogenic belts, and are believed to be genetically related to basic mechanisms of orogenesis and continental evolution. Whether classical geosynclinal theory or the current plate tectonic model of global tectonics is invoked, the basic premise that the origin of calc-alkaline magmas is related to orogenesis remains valid and only the details of how the magma was generated remains uncertain.

Hypotheses for the origin of the calc-alkaline suite, presented over the last 45 years, include : by fractional crystallization of basaltic magma; by partial or complete melting of lower crustal material; by contamination of basaltic magma with sialic crust; and by partial melting of eclogite or basalt. Bowen (1928) and Osborn (1962) have suggested that the calc-alkaline suite is generated by fractional crystallization of a basaltic magma. The large volume of basalt required to produce the observed volumes of andesite, dacite, and rhyolite; the fact that tholeiitic andesite is the end product of fractional crystallization of tholeiitic basalt (Green and Ringwood, 1968); and the absence of the iron enrichment trends in calc-alkaline suites which characterize tholeiitic suites, all indicate that this process is unlikely as a mechanism for generation of the calc-alkaline suite. Osborn (1962) suggests that, if the

oxygen pressure is kept constant, fractional crystallization of a basaltic magma could generate the calc-alkaline suite since magnetite would crystallize early and remove iron from the melt. This mechanism is not likely, since there is a lack of evidence for early magnetite precipitation in these rocks; plagioclase, commonly observed as early phenocrysts, reduces the efficiency of the process (Green and Ringwood, 1968); and iron-titanium oxides in some acid alkaline rocks indicate that oxygen fugacity was not constant during fractionation (Carmichael, 1967). Mechanisms for generating magmas which will give rise to the calc-alkaline suite, such as melting of deep crustal material, mixing of mantle derived basic magma and crustal derived acid magma, or, by hybridization of acid magma by more basic igneous material, have been proposed by such workers as Holmes (1932), Turner and Verhoogen (1960), Wilkinson (1966), and MacDonald and Katsura (1965). McBirney and Weill (1966) have shown that, on the basis of chemical, strontium isotopic, and volumetric relationships, some Miocene rhyolite ignimbrites of Central America are the product of partial fusion of basement rock. These mechanisms, although possible, and in some cases documented, cannot be invoked in areas such as the Kuriles, Aleutians, Fiji, or the Marianas Islands, where no continental crust was available for mixing or melting. These areas have calc-alkaline suites abundantly represented and another process is required to generate these calc-alkaline magmas. O'Hara (1963) has shown that partial melting of eclogite can give rise to silica oversaturated magmas only if parent oversaturated quartz eclogites are in the mantle. Ringwood (1966) has shown that the

mantle has an undersaturated composition, termed pyrolite (3 parts peridotite to 1 part basalt) and so calc-alkaline magmas can not be generated by partial melting of the mantle. Green and Ringwood (1966) have presented a two stage process by which the calc-alkaline suite can be derived. The model involves the early generation of basalt by partial melting of mantle material. This magma fractionates and results in the generation of large volumes of quartz-normative basalt. Subsequent transformation of the basalt to eclogite causes it to sink into the mantle and then partially melt to yield andesitic and other liquids of the calc-alkaline suite. Their experimental data indicates that, for dry conditions, the composition of the melt generated by partial melting of a rock of basaltic composition at high pressures, will be andesitic. For wet conditions their data supports the generation of the calc-alkaline series by partial melting or fractional crystallization of basalt. Green and Ringwood's model explains the following feature observed in calc-alkaline rock suites: the low initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios; the presence of magmatic almandine rich garnet in some members of the series; resorbed quartz phenocrysts in dacites and rhyolites; the absence of iron enrichment fractionation trends due to the Fe-rich mafic residual phases; and the sequence and volume of the different rock types.

The author believes that the origin of the volcanic rocks of the Takiyuak Metavolcanic Belt is best explained by the model of Green and Ringwood (1966). This conclusion is based on the apparent absence of basement crustal material in the Belt, the absence of

iron enrichment trends in Takiyuak volcanic rocks, and by the presence of abundant resorbed quartz phenocrysts in the porphyritic acid lavas.

Takiyuak volcanic rocks, as members of the calc-alkaline suite, are probably genetically related to a mechanism of orogenesis. Currently, plate tectonic theory suggests that orogenic zones are characterized by destructive plate boundaries where oceanic lithosphere is subducted beneath plates capped by oceanic crust or continental crust. Island arcs, such as those in the western Pacific, are believed to be generated by volcano-plutonic orogenic magmatism related to the subduction of oceanic lithosphere beneath a plate of oceanic crust (Dickinson, 1970b). Accepting that plate tectonic theory is valid, and knowing that plate tectonic processes are active today, can this global tectonic theory be extrapolated to the Precambrian? Sawkins (1972) has summarized evidence supporting plate tectonics for the Precambrian. The evidence includes: the chemical similarity of Precambrian volcanic suites to those of modern island arcs and continental margin volcanic suites; the chemical similarity and close spatial relationship of the intrusives related to the volcanic rocks in both the Precambrian and the modern; and the areal equivalence of Precambrian age provinces and areas of Tertiary subduction related volcano-plutonic activity in the southwestern Pacific. Langford and Morin (1976) have drawn a comparison between crustal belts of the Superior Province of the Canadian Shield and the major crustal belts of the western Canadian Cordillera which are considered to have formed as a series of island arcs which have merged

to form crustal blocks (Monger et al., 1972). They suggest that in broad geological terms the geology and geometry of these belts are similar. Chemical studies in the Wabigoon Belt of the Superior Province (Goodwin, 1970) indicate that: the K_2O content increases from south to north; tholeiitic rock suites and calc-alkaline suites are present in the south, whereas only calc-alkaline suites are in the north; mafic volcanics are twice as abundant in the south as in the north; and Ba, Zr, and Sr contents increase from south to north. These features are consistent with those of modern island arcs and suggest that the forearc portion is to the south (Langford and Morin, 1976). Krogh and Davis (1971) have shown that greenstone belts of the Superior Province progressively decrease in age from north to south. This may be interpreted as evidence for the southward migration of subduction zones in this area. In summary it appears that evidence for plate tectonic processes being active in the Precambrian is accumulating and that interpretation of Archean geology in terms of plate tectonic theory is valid.

The Takiyuak Metavolcanic Belt is believed to represent an Archean island arc. The presence of volcanic rocks of the calc-alkaline suite support its orogenic tectonic regime. The apparent lack of basement crustal material and the absence of subareal volcanic rocks suggest that the orogenic setting was an island arc type as opposed to an Andean type. In addition the massive volcanogenic sulphide deposits within the Takiyuak Metavolcanic Belt (as discussed in Paper 3) are of the same family as the Kuroko deposits of Japan which occur in an island arc type environment.

VI. SUMMARY AND CONCLUSIONS

Summary and Conclusions

Field and laboratory work have outlined and characterized the Takiyuak Metavolcanic Belt. This, previously unknown, belt is a volcano-plutonic complex which extends northeasterly from the southern tip of Takiyuak Lake, N.W.T., and forms part of the Slave Structural Province of the Canadian Shield.

Volcanic rocks of the calc-alkaline suite make up 60% of the area and are believed to be correlative with the Yellowknife Supergroup. Two cycles of volcanism, with little time break between them, are recognized. The area is believed to have evolved by first, fissure-type volcanism (cycle 1) generating laterally extensive, subaqueous, mafic flows and tuffs; second, a change in volcanic style to central volcanic activity (cycle 2) with proximal felsic flows, explosively generated agglomerates and tuff breccias, and distal felsic and intermediate tuffs; third, the end of central volcanic activity and resumption of fissure-type mafic volcanism (cycle 3). The area has been isoclinally folded into a steeply, northeasterly plunging syncline. Regional metamorphic grade is lower greenschist. Post deformational granite and diorite intrusions make up 40% of the area, and no basement rocks to the volcanics have been observed in the area. The volcanic rocks of this belt are believed to have originated by partial melting of a rock of basaltic composition at high pressure, and the belt itself is believed to represent an Archean orogenic tectonic environment, possibly of the island-arc type.

Takiyuak #10 is a massive volcanogenic sulphide deposit within this volcanic belt, and is spatially related to felsic central volcanism. The concordance of the sulphide lenses with host rock stratigraphy, the increasing Zn/Cu ratio toward the stratigraphic top (both within and between lenses), and the presence of massive, banded, sphalerite-rich sulphides directly overlying stringer, chalcopyrite-rich sulphides, all indicate that this is a typical massive volcanogenic sulphide deposit. Textural evidence indicates that recrystallization, remobilization, and deformation of the sulphides has taken place. Chemical data suggest that the sulphides precipitated, in response to an increase in f_{O_2} and pH and a decrease in temperature, on mixing of a hot, saline, metal bearing brine with seawater.

Geology, geophysics, and geochemistry indicate that a time-stratigraphic control on mineralization in Takiyuak volcanic rocks existed. Whole rock chemical data show that alteration along this time-stratigraphic horizon is characterized by sodium depletion, and magnesium and potassium enrichment. This alteration is independent of rock type. Chemical equilibria involving some of the primary minerals of calc-alkaline volcanic rocks indicate that this alteration can be explained, in part, by volcanic rock-seawater chemical interaction. The time-stratigraphic horizon related to mineralization is believed to reflect a pause in volcanic activity and a time of chemical reequilibration between volcanic rocks, at the rock-water interface, and seawater.

VII. LIST OF REFERENCES*

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VIII. APPENDICES

Appendix A

Major element chemistry and normative mineralogy
of analysed samples from Takiyuak volcanic rocks.

Appendix A, Table 1: Sample numbers and corresponding rock types
for Table 2, Appendix A and Table 2, Appendix B.

Basalt	GR-7,17,81; G-10-58,69,72; X389
Andesite	G-10-32,65
Dacite	G-10-42
Porphyritic Rhyolite	GR-69; G-10-11,17,27; X387,394
Cherty Rhyolite	GR-6,47; G-10-21,23,57; X57,503, X540
Mafic Tuff	HR-7,8
Granite	GR-9
Ultramafic	HR-9
Mafic Dykes	G-10-6,15; X79
Altered Basalt*	G-10-28
Altered Andesite*	G-10-7; X81,390,398,513,521,533, 534,536,541,554
Altered Porphyritic Rhyolite*	GR-10; G-10-9,53,54
Altered Cherty Rhyolite*	GR-68; G-10-1,3,33; X391,520,524

* Altered indicates alteration related to mineralization

Appendix A, Table 2. Major element content of analysed rocks from the Taklyuak Metavolcanic

Belt, N.W.T.. Table 1, Appendix A lists the rock types and corresponding sample numbers. Results in weight percent. }

	GR-6	GR-7	GR-9	GR-10	GR-17	GR-47	GR-68	GR-69	GR-81	G-10-1
SiO ₂	78.96	46.59	77.08	78.26	45.55	70.88	74.78	76.28	54.55	79.81
Al ₂ O ₃	10.98	14.45	12.55	10.83	14.74	12.22	12.26	13.01	14.28	10.63
Fe ₂ O ₃	0.45	2.92	0.27	0.92	4.20	1.00	0.73	0.20	2.70	0.73
FeO	1.26	8.77	0.73	2.64	12.23	2.90	2.10	0.56	7.58	2.12
MgO	0.61	8.08	0.11	1.34	7.06	2.70	3.36	1.45	6.30	2.03
CaO	1.08	7.23	0.14	1.34	6.12	2.19	0.00	0.15	6.43	0.12
Na ₂ O	3.56	2.59	4.67	0.36	2.19	2.34	0.36	3.72	3.61	0.01
K ₂ O	2.70	0.66	4.18	2.41	0.53	1.87	2.91	2.21	0.54	2.55
TiO ₂	0.12	0.78	0.06	0.39	1.67	0.15	0.13	0.10	1.06	0.34
P ₂ O ₅	0.03	0.23	0.00	0.03	0.24	0.03	0.00	0.00	0.28	0.09
MnO	0.03	0.18	0.01	0.04	0.23	0.03	0.02	0.02	0.15	0.02
S	0.01	0.13	0.02	0.13	0.33	0.02	0.07	0.04	0.07	0.07
CO ₂	0.10	3.40	0.00	1.26	0.66	1.82	0.59	1.03	0.40	0.00
H ₂ O	0.20	4.00	0.20	1.46	4.00	1.85	2.72	1.26	2.10	1.52
	100.09	100.01	100.02	100.07	99.75	100.00	100.03	100.03	100.05	100.04

Table 2. continued

	G-10-3	G-10-6	G-10-7	G-10-9	G-10-11	G-10-15	G-10-17	G-10-21	G-10-23	G-10-27
SiO ₂	74.28	44.20	52.52	71.34	76.35	53.17	77.58	77.59	74.82	76.90
Al ₂ O ₃	13.52	13.62	18.04	15.44	12.28	14.62	12.18	11.72	14.92	12.51
Fe ₂ O ₃	0.67	2.67	2.98	0.45	0.15	3.00	0.67	0.18	0.10	0.72
FeO	2.02	9.03	9.53	1.48	0.62	9.00	2.10	0.68	0.49	0.56
MgO	3.63	8.12	6.80	3.81	3.10	5.56	1.67	3.35	1.28	1.10
CaO	0.04	5.64	0.32	0.15	0.44	4.02	0.00	0.73	0.45	1.12
Na ₂ O	0.04	1.13	0.73	0.94	4.68	3.92	4.90	4.73	6.62	4.22
K ₂ O	3.60	3.32	2.48	3.80	1.10	0.00	0.25	0.60	0.47	0.92
TiO ₂	0.15	1.05	0.94	0.21	0.13	1.77	0.10	0.13	0.10	0.17
P ₂ O ₅	0.03	0.18	0.24	0.03	0.04	0.37	0.02	0.03	0.03	0.03
MnO	0.02	0.24	0.08	0.02	0.01	0.13	0.02	0.01	0.01	0.02
S	0.00	0.33	0.42	0.01	0.00	0.50	0.10	0.16	0.02	0.00
CO ₂	0.00	6.65	0.01	0.15	0.58	1.38	0.03	0.00	0.19	0.15
H ₂ O	1.97	4.01	5.19	2.19	0.53	2.82	0.31	0.17	0.51	0.08
	99.98	100.19	100.28	100.02	100.01	100.26	100.04	100.08	100.01	100.01

Table 2. continued

	G-10-28	G-10-32	G-10-33	G-10-42	G-10-53	G-10-54	G-10-57	G-10-58	G-10-65
SiO ₂	44.30	58.93	70.67	76.43	69.81	71.24	75.02	47.38	56.56
Al ₂ O ₃	10.93	14.99	12.04	10.47	14.53	16.00	13.75	11.84	13.54
Fe ₂ O ₃	2.90	2.13	1.12	0.65	0.60	0.42	0.27	3.31	2.06
FeO	10.26	6.47	3.27	1.86	1.93	1.37	0.88	10.57	6.13
MgO	8.24	6.10	3.96	2.62	6.21	3.14	1.60	8.89	4.95
CaO	9.30	0.92	3.96	1.06	0.06	0.05	0.22	6.79	5.70
Na ₂ O	0.83	3.75	0.04	2.62	0.02	1.18	4.80	1.57	3.87
K ₂ O	0.63	0.27	4.07	2.20	3.42	4.07	3.28	0.73	0.57
TiO ₂	0.81	1.31	0.29	0.16	0.31	0.15	0.20	1.69	0.84
P ₂ O ₅	0.20	0.37	0.07	0.04	0.06	0.03	0.04	0.16	0.20
MnO	0.22	0.19	0.11	0.06	0.04	0.02	0.02	0.16	0.11
S	0.48	0.24	0.11	0.01	0.02	0.05	0.07	0.63	0.12
CO ₂	6.10	0.43	0.79	0.78	0.10	0.09	0.38	2.89	2.80
H ₂ O	5.09	4.00	2.80	1.05	2.92	2.92	0.11	3.00	2.66
	100.29	100.10	99.98	100.01	100.03	100.73	100.64	99.61	100.11

Table 2. continued

	G-10-69	G-10-72	X57	X79	X81	X387	X389	X390	X391	X394	X398	X503
SiO_2	50.69	55.96	75.12	60.98	59.20	76.92	50.10	49.90	73.30	75.55	49.93	74.58
Al_2O_3	14.71	15.55	12.20	15.13	15.84	12.74	12.35	17.71	14.27	12.75	16.13	13.20
Fe_2O_3	2.75	2.32	0.14	0.89	1.90	0.33	1.92	2.94	0.56	0.52	3.09	0.44
FeO	8.52	6.91	0.57	2.99	5.91	1.03	6.28	9.68	1.77	1.61	10.37	1.36
MgO	8.35	6.58	1.50	12.53	7.83	1.06	6.31	9.30	3.09	1.54	11.63	1.52
CaO	5.18	3.96	1.40	0.07	0.89	0.64	7.81	0.55	0.23	0.34	0.33	1.05
Na_2O	2.64	2.98	4.67	0.05	1.29	3.90	2.92	0.72	0.55	2.60	0.01	4.08
K_2O	0.60	1.42	1.23	2.30	2.72	2.32	1.80	1.90	3.76	2.50	1.20	1.51
TiO_2	1.09	0.79	0.14	0.71	1.07	0.14	0.77	1.08	0.18	0.13	1.15	0.22
P_2O_5	0.26	0.21	0.03	0.02	0.19	0.02	0.28	0.26	0.03	0.02	0.18	0.04
MnO	0.16	0.11	0.03	0.03	0.05	0.02	0.15	0.06	0.02	0.03	0.10	0.02
S	0.25	0.04	0.10	0.13	0.18	0.06	0.05	0.17	0.00	0.11	0.20	0.11
CO_2	0.47	0.16	1.99	0.00	0.42	0.42	7.83	0.35	0.57	0.84	0.00	0.76
H_2O	4.47	3.00	0.88	4.24	3.10	0.43	1.70	5.40	1.68	1.52	5.83	1.16
	100.14	99.99	100.00	100.07	100.09	100.03	100.27	100.02	100.01	100.06	100.15	100.05

Table 2. continued

	X513	X520	X521	X524	X533	X534	X536	X540	X541	X554	HR-7
SiO ₂	45.41	72.08	53.65	89.23	59.11	51.65	52.11	76.49	51.34	51.12	47.30
Al ₂ O ₃	12.14	15.07	17.35	5.84	12.78	17.40	16.27	12.28	14.49	15.91	14.00
Fe ₂ O ₃	2.90	0.72	2.30	0.25	1.99	2.44	2.17	0.40	2.70	2.57	8.97
FeO	9.40	2.20	7.42	0.81	6.03	8.07	7.26	1.26	8.72	8.41	5.73
MgO	13.31	3.18	9.85	1.26	8.06	11.05	12.09	2.46	13.25	12.26	8.00
CaO	8.75	0.08	0.58	0.02	0.32	0.40	0.47	0.24	1.11	0.68	9.69
Na ₂ O	1.50	0.06	0.63	0.00	3.04	1.89	2.00	4.20	0.20	1.35	2.07
K ₂ O	1.20	3.84	2.10	1.41	0.16	0.78	0.33	1.35	1.69	0.76	0.75
TiO ₂	1.01	0.21	1.14	0.08	0.97	0.97	1.04	0.13	1.19	1.21	0.90
P ₂ O ₅	0.13	0.03	0.31	0.03	0.40	0.31	0.24	0.02	0.31	0.28	0.10
MnO	0.19	0.02	0.05	0.01	0.20	0.12	0.10	0.02	0.13	0.10	0.18
S	0.34	0.05	0.13	0.03	0.03	0.10	0.10	0.05	0.10	0.17	nd
CO ₂	0.72	0.34	0.00	0.06	2.08	0.12	0.71	0.02	0.66	0.21	0.34
H ₂ O	3.19	2.10	4.57	0.99	2.93	4.82	5.15	1.11	4.20	5.00	3.10
	100.19	99.98	100.08	100.02	100.03	100.04	100.04	100.03	100.09	100.03	101.13

Table 2, continued

	HR-8	HR-9
SiO ₂	48.00	40.00
Al ₂ O ₃	15.25	1.93
Fe ₂ O ₃	9.41	10.74
FeO	1.42	3.72
MgO	6.70	40.08
CaO	10.75	0.60
Na ₂ O	2.54	0.00
K ₂ O	0.45	0.08
TiO ₂	0.68	0.17
P ₂ O ₅	0.10	0.06
MnO	0.14	0.16
S	nd	nd
CO ₂	0.27	0.32
H ₂ O	1.20	10.30
	<hr/> 97.01	<hr/> 108.16

Appendix A, Table 3: Normative mineralogy of analysed rocks from the Takiyuk Metavolcanic Belt, N.W.T. Table 1, Appendix A lists the rock types and corresponding sample numbers. Results in weight percent. Normative values are zero for Ks, Ns, Hm, Cr, Ru, Wo, Ln, Ne, Lc, Ac, Kp.

Mineral	GR-6	GR-7	GR-9	GR-10	GR-17	GR-47	GR-68	GR-69	GR-81	G-10-1
Quartz	44.07	0.00	33.07	65.44	0.00	41.06	57.15	44.45	6.51	66.84
Corundum	0.31	0.00	0.09	7.91	0.01	2.52	8.81	4.32	0.00	7.97
Orthoclase	16.01	4.22	24.77	14.65	3.31	11.48	17.80	13.38	3.28	15.32
Albite	30.19	23.69	39.59	3.13	19.54	20.55	3.15	32.21	31.33	0.09
Anorthite	5.17	27.96	0.70	0.20	30.37	11.08	0.00	0.76	21.71	0.01
Diopside	0.00	4.71	0.00	0.00	0.00	0.00	0.00	0.00	4.74	0.00
Hedenbergite	0.00	2.81	0.00	0.00	0.00	0.00	0.00	0.00	2.71	0.00
Enstatite	1.52	14.04	0.27	3.43	17.93	6.98	8.65	3.70	13.89	5.13
Ferrosillite	1.76	9.62	0.96	3.07	18.21	4.39	2.88	0.58	9.10	2.52
Forsterite	0.00	3.88	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00
Fayalite	0.00	2.93	0.00	0.00	0.48	0.00	0.00	0.00	0.00	0.00
Magnetite	0.65	3.57	0.39	1.37	4.85	1.51	1.10	0.30	3.81	1.08
Ilmenite	0.23	1.60	0.11	0.71	3.35	0.30	0.26	0.19	2.07	0.66
Apatite	0.07	0.58	0.00	0.07	0.59	0.72	0.00	0.00	0.67	0.21
Pyrrhotite	0.03	0.39	0.06	0.37	0.95	0.57	0.20	0.11	0.20	0.20

Appendix A, Table 3 (continued)

Mineral	G-10-3	G-10-6	G-10-7	G-10-9	G-10-11	G-10-15	G-10-17	G-10-21	G-10-23
Quartz	54.60	0.00	23.83	45.55	39.53	10.72	44.17	41.27	31.68
Corundum	9.75	0.00	14.92	9.80	2.72	1.83	3.46	2.04	2.80
Orthoclase	21.73	21.98	15.47	23.01	6.58	0.00	1.48	3.56	2.80
Albite	0.35	10.70	6.51	8.14	40.04	34.62	41.60	40.09	56.41
Anorthite	0.00	24.93	0.02	0.56	1.94	18.29	1.11	3.43	2.05
Diopside	0.00	2.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hedenbergite	0.00	1.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Enstatite	9.22	12.95	17.86	9.71	7.81	14.45	4.17	8.36	3.21
Ferrosillite	2.99	7.70	13.97	2.04	0.83	9.72	2.52	0.25	0.59
Forsterite	0.00	5.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fayalite	0.00	3.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Magnetite	0.99	4.14	3.73	0.67	0.22	4.54	0.98	0.26	0.15
Ilmenite	0.31	2.23	1.88	0.41	0.25	3.51	0.19	0.25	0.19
Apatite	0.07	0.47	0.59	0.07	0.09	0.90	0.05	0.07	0.07
Pyrrhotite	0.00	1.01	1.22	0.03	0.00	1.43	0.28	0.44	0.06

Appendix A, Table 3 (continued)

Mineral	G-10-27	G-10-28	G-10-32	G-10-33	G-10-42	G-10-53	G-10-54	G-10-57	G-10-58
Quartz	43.62	3.41	23.79	47.53	46.32	47.65	44.30	31.58	5.08
Corundum	2.61	0.00	8.10	6.82	1.98	11.16	9.86	1.40	0.00
Orthoclase	5.45	4.20	1.67	24.99	13.26	20.86	24.64	19.50	4.62
Albite	35.78	7.91	33.21	0.35	22.58	0.17	10.22	40.81	14.22
Anorthite	5.37	27.29	2.25	2.82	5.09	0.09	0.05	0.83	24.74
Diopside	0.00	11.60	0.00	0.00	0.00	0.00	0.00	0.00	5.64
Hedenbergite	0.00	7.39	0.00	0.00	0.00	0.00	0.00	0.00	2.64
Enstatite	2.75	17.33	15.90	10.24	6.65	15.94	8.00	4.00	21.09
Ferrosillite	2.97	12.96	7.67	4.52	2.74	2.61	1.79	0.82	11.32
Forsterite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fayalite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Magnetite	1.05	3.77	3.23	1.69	0.96	0.90	0.62	0.39	4.95
Ilmenite	0.32	1.73	2.60	0.57	0.31	0.61	0.29	0.38	3.44
Apatite	0.07	0.52	0.90	0.17	0.09	0.14	0.07	0.09	0.40
Pyrrhotite	0.00	1.48	0.69	0.31	0.03	0.06	0.14	0.12	1.85

Appendix A, Table 3 (continued)

Mineral	G-10-65	G-10-69	G-10-72	X57	X79	X81	X387	X389	X390
Quartz	11.85	5.37	11.49	39.08	33.10	27.13	42.28	1.72	18.92
Corundum	0.00	0.97	2.49	0.73	13.03	10.90	2.72	0.00	14.97
Orthoclase	3.56	3.73	8.68	7.49	14.21	16.68	13.84	11.74	11.94
Albite	34.12	23.50	26.04	40.70	0.44	11.31	33.28	27.23	6.47
Anorthite	18.92	25.25	18.88	6.95	0.22	0.72	3.07	16.84	1.09
Diopside	5.03	0.00	0.00	0.00	0.00	0.00	0.00	13.05	0.00
Hedenbergite	2.80	0.00	0.00	0.00	0.00	0.00	0.00	6.33	0.00
Enstatite	10.70	21.88	16.93	3.85	32.58	20.21	2.66	11.27	24.60
Ferrosillite	6.84	11.82	9.90	0.35	3.24	7.12	1.19	6.28	14.73
Forsterite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fayalite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Magnetite	3.16	3.95	3.43	0.21	1.35	2.86	0.48	3.07	3.97
Ilmenite	1.69	2.18	1.55	0.27	1.41	2.11	0.27	1.61	2.18
Apatite	0.49	0.63	0.50	0.07	0.05	0.46	0.05	0.72	0.64
Pyrrhotite	0.35	0.72	0.11	0.28	0.37	0.51	0.17	0.15	0.50

Appendix A, Table 3 (continued)

Mineral	X391	X394	X398	X503	X513	X520	X521	X524	X533	X534
Quartz	50.67	48.14	22.18	40.83	0.00	52.15	23.69	82.38	22.56	16.81
Corundum	9.15	5.32	15.55	3.10	0.00	11.01	14.38	4.39	4.71	13.96
Orthoclase	22.75	15.14	7.54	9.11	7.39	23.29	13.01	8.43	1.00	4.85
Albite	4.76	22.53	0.90	35.20	13.21	0.52	5.59	0.00	27.07	16.82
Anorthite	0.97	1.59	0.49	5.05	23.78	0.21	0.89	0.09	9.00	0.51
Diopside	0.00	0.00	0.00	0.00	12.28	0.00	0.00	0.00	0.00	0.00
Hedenbergite	0.00	0.00	0.00	0.00	4.24	0.00	0.00	0.00	0.00	0.00
Enstatite	7.87	3.93	30.75	3.86	7.83	8.12	25.70	3.17	21.13	28.95
Ferrosillite	2.59	1.96	15.97	1.38	3.40	3.00	9.85	1.06	8.50	11.59
Forsterite	0.00	0.00	0.00	0.00	14.71	0.00	0.00	0.00	0.00	0.00
Fayalite	0.00	0.00	0.00	0.00	6.41	0.00	0.00	0.00	0.00	0.00
Magnetite	0.83	0.77	4.08	0.65	3.79	1.07	3.49	0.37	3.04	3.72
Ilmenite	0.35	0.25	2.32	0.43	2.00	0.41	2.27	0.15	1.94	1.94
Apatite	0.07	0.05	0.44	0.09	0.31	0.07	0.75	0.07	0.98	0.56
Pyrrhotite	0.00	0.31	0.58	0.31	0.97	0.14	0.37	0.08	0.09	0.29

Appendix A, Table 3 (continued)

Mineral	X536	X540	X541	X554	HR-7	HR-8	HR-9
Quartz	17.52	42.52	18.00	17.41	0.00	0.00	0.00
Corundum	13.11	3.56	11.61	12.98	0.00	0.00	0.93
Orthoclase	2.07	8.08	10.50	4.75	4.57	2.81	0.49
Albite	17.98	35.94	1.78	12.06	18.05	23.56	0.00
Anorthite	0.81	1.07	3.66	1.63	27.51	30.99	2.68
Dioptase	0.00	0.00	0.00	0.00	9.80	12.91	0.00
Hedenbergite	0.00	0.00	0.00	0.00	7.82	8.02	0.00
Enstatite	31.99	6.20	34.67	32.23	8.17	7.05	12.13
Ferrosillite	10.19	1.62	12.26	11.41	7.48	5.02	2.49
Forsterite	0.00	0.00	0.00	0.00	5.48	3.20	63.89
Fayalite	0.00	0.00	0.00	0.00	5.53	2.51	14.43
Magnetite	3.34	0.59	4.10	3.93	3.59	3.33	2.51
Ilmenite	2.10	0.25	2.38	2.43	1.76	1.36	0.33
Apatite	0.59	0.05	0.76	0.69	0.24	0.24	0.14
Pyrrhotite	0.29	0.14	0.29	0.49	0.00	0.00	0.00

Appendix B

Trace element chemistry of analyzed samples from
Takiyuak volcanic rocks.

Appendix B, Discussion.

Trace element data for Takiyuak volcanic rocks are listed in Appendix B, Table 1. These data have been summarized in Table 2, Appendix B, and standard deviations of the means are also listed. Consideration of trace elements indicates that because of high standard deviations for the data no real chemical trends can be outlined. The data does suggest that Nb, Zr, Rb, and Y may have increased and Sr decreased in passing from basalt through rhyolite. Increasing Rb and decreasing Sr are expected if they follow Ca and K in a normal differentiation sequence. Comparison of fresh and altered trace element data indicates that there are no significant changes in any elements resulting from alteration related to mineralization. Mean values suggest that Sr decreases and Rb increases on alteration and is supported by a corresponding Ca depletion and K enrichment in the altered rocks. Trace element geochemistry has not been useful in outlining alteration patterns or in indicating differentiation trends in Takiyuak volcanic rocks.

Appendix B, Table 1: Trace element content of analysed rocks from the Takfayuak Metavolcanic

Belt, N.W.T.: Table 1, Appendix A lists rock types and corresponding sample numbers.

Results in ppm. Blanks indicate no data.

	GR-6	GR-7	GR-9	GR-10	GR-17	GR-44	GR-47	GR-54	GR-68	GR-69	GR-81	G-10-1	G-10-3
Ba	640	277	707	238	155	180	433	273	544	307	206	604	640
Nb	24	5	33	8	9	8	21	19	16	40	11	16	23
Zr	311	116	207	119	139	153	371	360	264	384	223	308	314
Sr	56	28	94	15	42	24	58	49	54	90	30	39	46
Rb	63	422	23	22	252	44	83	15	6	71	213	7	8
Zn	91	34	162	109	19	28	49	99	89	62	17	75	97
Cu	32	147	9	35	133	162	22	139	53	12	100	24	40
Co	1	35	3	4	82	3	2	12	1	1	51	36	32
Ni	2	72	2	9	52	51	3	42	2	2	61	5	4
Ag												0	0
Pb												7	0
Cr	26	232	25	105	160	71	25	56	25	26	126	3	3

Table 1. continued

	G-10-6	G-10-7	G-10-9	G-10-11	G-10-15	G-10-17	G-10-21	G-10-23	G-10-27	G-10-28
Ba	368	1763	612	171	144	150	39	114	299	109
Nb	9	12	14	12	17	47	17	17	37	10
Zr	150	221	219	200	319	328	301	231	396	162
Y	24	23	35	37	36	76	40	40	93	27
Sr	86	19	27	95	205	143	148	107	63	102
Rb	57	63	104	18	2	9	14	25	34	15
Zn	167	165	54	24	155	53	26	22	28	240
Cu	71	63	6	0	58	255	14	3	4	958
Co	9	3	33	46	17	89	65	64	24	25
Ni	91	53	6	5	32	2	11	2	2	74
Ag	2	2	0	0	1	0	1	0	0	2
Pb	109	5	5	0	35	35	1	7	1	34
Cr	184	54	5	4	24	6	6	4	3	61

Table 1. continued

	G-10-32	G-10-33	G-10-42	G-10-53	G-10-54	G-10-57	G-10-58	G-10-65	G-10-69	G-10-72
Ba	94	328	191	506	467	906	506	305	378	518
Nb	11	14	14	13	16	14	8	12	11	11
Zr	211	328	266	249	234	275	136	251	246	223
Y	26	37	28	31	34	38	31	33	31	28
Sr	53	8	36	7	26	97	114	157	208	276
Rb	9	89	40	100	113	35	14	17	11	22
Zn	1217	121	49	87	38	40	301	108	374	107
Cu	113	5	4	4	4	6	69	5	87	39
Co	29	16	41	15	15	41	22	23	54	41
Ni	4	3	3	3	1	2	199	36	64	73
Ag	1	1	0	1	0	0	2	0	2	1
Pb	38	14	0	0	0	13	6	3	11	1
Cr	11	5	5	50	2	2	360	23	47	69

Table 1. continued

	X57	X79	X81	X387	X389	X390	X391	X394	X398	X503	X513	X520	X521	X524	X533
Ba	164	358	775	598	260	324	562	376	322	252	194	750	315	376	87
Nb	19	18	13	47	12	13	24	41	10	22	8	23	15	9	19
Zr	236	296	261	312	204	252	342	302	205	332	71	335	271	180	383
Y	62	13	34	108	34	32	59	83	28	54	0	50	41	26	48
Sr	110	5	39	46	160	18	11	21	7	155	139	10	27	7	80
Rb	43	77	88	59	61	59	116	94	38	48	42	116	55	40	5
Zn	96	161	155	35	88	287	79	68	225	37	182	31	76	28	155
Cu	9	8	9	2	2	6	4	4	8	10	124	6	7	12	13
Co	57	18	10	61	4	10	25	97	14	44	43	43	8	123	24
Ni	9	4	12	4	87	88	3	4	13	4	412	3	67	1	20
Ag	0	0	1	1	1	2	2	1	1	0	2	1	2	1	1
Pb	42	8	5	0	59	19	0	12	43	4	99	0	0	1	27
Cr	19	6	19	2	68	86	5	1	21	6	605	2	90	3	10

Table 1. continued

	X534	X536	X540	X541	X554
Ba	253	74	156	659	107
Nb	13	15	27	153	11
Zr	221	270	282	260	219
Y	28	32	59	39	40
Sr	48	41	77	15	44
Rb	44	9	27	38	13
Zn	367	196	34	243	251
Cu	4	3	2	46	43
Co	7	0	31	17	19
Ni	75	80	4	124	30
Ag	0	0	0	1	1
Pb	1	2	2	20	45
Cr	61	79	3	155	39

Appendix B, Table 2: Average trace element contents and standard deviations for volcanic rock types from the Takiyuak Metavolcanic Belt. N refers to the number of analyses.

Element	1	2	3	4	5	6	7	8						
	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6	σ_7	σ_8						
Ba	338	301	579	123	316	163	456	158	196	443	492	329	163	109
Nb	20	4	18	6	37	13	13	3	12	0.7	13	3	10	10
Zr	292	47	318	27	320	70	205	59	231	28	239	74	152	162
Y	51	10	44	11	81	24	29	9	30	5	31	12	32	27
Sr	102	36	42	17	78	42	21	9	105	74	43	37	235	102
Rb	42	23	89	26	46	31	107	6	13	6	41	25	25	15
N	8	7	6	4	2	11	7	1						1

1. cherty rhyolite, Takiyuak volcanics.
2. cherty rhyolite, Takiyuak volcanics, altered due to mineralization.
3. porphyritic rhyolite, Takiyuak volcanics.
4. porphyritic rhyolite, Takiyuak volcanics, altered due to mineralization.
5. andesite, Takiyuak volcanics.
6. andesite, Takiyuak volcanics, altered due to mineralization.
7. basalt, Takiyuak volcanics.
8. basalt, Takiyuak volcanics, altered due to mineralization.

Appendix C

Sulphide type, assemblages, and textures of sulphides from
the Takiyuak #10 sulphide deposit.

Appendix C, Table 1: Key for polished section data listed in
Appendix C, Table 2

A. Sulphide Type

1. m - massive
2. s - stringer

B. Phases

1. py - pyrite
2. po - pyrrhotite
3. sp - sphalerite
4. cp - chalcopryrite
5. gn - galena
6. ms - marcasite
7. mt - magnetite
8. qan - gangue

C. Textures

1. B - banded
2. C - contorted
3. F_{py} - relict framboids, subscript refers to framboidal phase
4. DF_{py} - deformation fracturing, subscript refers to fractured phase
5. $E_{cp,(sp)}$ - exsolution, subscript refers to the phase exsolved, brackets refer to the host phase
6. $I_{py,(gn)}$ - inclusions, subscript refers to the phase with inclusions, brackets refer to the included phases
7. P_{py} - porphyroblast, subscript refers to the porphyroblastic phase
8. $R_{po,(py)}$ - replacement, subscript refers to the replacing phase, brackets refer to the phase replaced
9. RB_{cp} - remobilized, subscript refers to the remobilized phase
10. Rx - recrystallization
11. T_{po} - triple junction 120° interfacial angles, sub-

Appendix C Table 2: Microscopic data from polished sections of the #10 sulphide deposit. Key for this Table is in Appendix Table

Section Number	Sulphide Type	Assemblage (%s)	Textures
H-10-1 #9	s	po,py,cp,sp,ms, (70,15,10,5,<1)	P _{py} , E _{cp,(sp)} , I _{py,(sp,qn)} , R _{ms,(py)} , T _{po,RX}
H-10-1 #12	m	cp,po,sp,py (70,15,10,<5)	P _{py} , F _{py} , R _{po,(py)} , DF _{py} , RB _{cp} , E _{cp,(sp)} , RX, B
H-10-1 #13a	m	sp,py,po,cp,qn (40,30,15, 10,<5)	P _{py} , DF _{py} , RB _{cp,po} , R _{po,(py)} , E _{cp,po,(sp)} , I _{py,(po,qn,cp)} , RX, B
H-10-1 #13b	m	cp,py,po,sp,qn,mt (20,20,50,10, 1,<1)	P _{py} , DF _{py} , I _{py,(mt,sp)} , F _{py} , RB _{cp} , RX
H-10-1 #13c	m	cp,po,sp,py (70,27,3,<1)	P _{py} , E _{cp,(sp)} , T _{po} , I _{po,(sp)} , RB _{cp} , RX

Table 2 (continued)

Section Number	Sulphide Type	Assemblage (%s)	Textures
H-10-2 #15	m	cp,py,po,sp (75,10,10,5)	P _{py} , DF _{py} , RB _{cp} , E _{cp,(sp)} , T _{po} , RX
H-10-2 #18	s	sp,po,cp,py (90,6,3,<1)	P _{py} , DF _{py} , RB _{cp} , E _{sp,(po)} , RB _{cp} , RX
H-10-4 #8	m	py,po,sp,cp,qn (50,38,10, 2,<1)	P _{py} , I _{py,(cp,qn,sp,qn)} , T _{po} , E _{cp,(sp)} , DF _{py} , RB _{cp} , RX
H-10-4 #9	m	sp,py,qn,mt (55,40,5,<1)	P _{py} , I _{py,(qn,sp,qn)} , RX, E _{cp,(sp)} , B
H-10-4 #10	m	cp,po,sp,py (40,35,20,<5)	P _{py} , DF _{py} , T _{po} , RB _{cp} , RX, R _{po,(py)}
H-10-5 #7	m	ms,po,sp,cp,py,qn,mt (1,40,25,15,15,4,2)	P _{py} , I _{py,(qn,sp,po,cp)} , B, R _{po,(py)} , T _{po} , I _{mt,(po)} , RX, R _{ms,(po)} , E _{cp,(sp)}

Table 2 (continued)

Section Number	Sulphide Type	Assemblage	Textures
H-10-5 #8	m	po, cp, sp, py, gn (57, 30, 8, 3, 2)	P _{py} , DF _{py} , R _B cp, sp, gn, RX, T _{po} , E _{cp} , (sp)
H-10-5 #13	m	sp, po, cp, gn (50, 43, 5, 2)	T _{po} , RX, B, E _{cp} , (sp)
H-10-5 #14	m	py, sp, cp, gn, po (65, 20, 5, 5, <1)	P _{py} , I _{py} , (gn, gan), R _{po} , (py), E _{cp} , (sp), RX, B, C
H-10-16 #1	m	cp, sp, gn, py (70, 25, 5, <1)	P _{py} , I _{py} , (po, sp, gn), T _{po} , (mt), E _{po} , (sp), R _{ms} , (po), RX
H-10-16 #2	m	po, py, sp, cp, gn (54, 40, 5, 1, <1)	P _{py} , I _{py} , (cp, sp, po, gn, gan), T _{po} , DF _{py} , R _B po, cp, sp, RX, E _{po} , cp, (sp)
H-10-17 #1	s	py, po, cp, sp (50, 48, 1, <1)	P _{py} , I _{py} , (po, cp, gan), RX, R _{po} , (py)

Table 2 (continued)

Section Number	Sulphide Type	Assemblage	Textures
H-10-17 #2	m	po, sp, cp, gn	B, RX, T _{po} , E _{cp, po, (sp)}
H-10-17 #3	m	cp, po, py, sp, gn (30, 25, 20, 20, 5)	P _{py} , I _{py} , (cp, sp, po, gn), F _{py} , T _{po} , DF _{py} , RX, B, E _{cp, po, (sp)}
H-10-17 #5	m	cp, po, sp, py, gn (40, 37, 20, 3, <1)	P _{py} , I _{py} , (gn, sp, cp, gan), B, DF _{py} , RB _{cp, po} , R _{po, (py)} , T _{po} , E _{cp, (sp)} , RX
H-10-19 #1	s	po, py, sp, cp (70, 30, 1, <1)	P _{py} , I _{py} , (cp, po, gan), RX, T _{po}
H-10-21 #3	m	po, sp, cp, gn (60, 40, 1, <1)	P _{po} , T _{po} , E _{cp, po, (sp)} , B, RX

Appendix D

Cu,Pb,Ag,Zn, data used in the construction of Cu-Ag,Pb-Ag, variation diagrams, and Cu-Pb-Zn atomic percent diagram.

Appendix D, Table 1: Cu, Ag, Pb, contents of sulphide lenses for
diamond drill holes used in construction of Cu-Ag and
Pb-Ag diagrams.

Hole Number	Section Length (feet)	Ag (oz/ton)	Cu (%)	Pb (%)
H-10-2	4	0.62	3.20	tr
	5	0.98	14.60	0.01
	5	1.14	11.40	0.02
	5	0.98	9.90	0.34
	6.1	1.70	17.30	0.03
	2	0.04	0.34	0.01
	5	1.04	10.20	0.02
	3.8	0.57	4.80	0.03
	2.1	1.91	16.60	0.03
H-10-4	1.5	1.18	0.30	0.50
	4.2	1.22	0.26	1.14
	4.9	1.94	0.34	3.20
	1.3	4.46	6.28	0.04
	2.5	1.24	1.29	0.04
	2.3	4.58	10.70	0.04
	3.6	2.92	5.50	0.03
	3.1	2.04	4.10	0.03

Table 1 continued

H-10-5	5	1.46	0.57	1.80
	5	1.74	0.68	1.90
	5	1.42	0.69	0.57
	5.5	2.00	3.40	0.25
	5.8	0.70	1.30	tr
	3	1.80	1.60	1.40
	3.7	1.98	4.10	0.77
	5.9	2.12	4.00	0.53
	5	2.24	5.00	0.46
	5	1.70	3.60	0.50
H-10-6	4.5	5.18	11.70	0.46
	3.9	0.72	3.40	0.17
	1.6	1.20	3.50	0.13
H-10-8	5.3	1.12	13.60	0.02
	6.1	1.14	15.00	0.01
	4.3	0.98	23.60	0.01
	2.4	1.66	20.20	0.02
H-10-16	5	0.56	1.40	0.06
	4.4	0.60	1.50	0.24
	5.6	1.72	3.60	0.07
	5	0.60	1.00	0.25

Table 1. continued

H-10-17	5	1.68	2.10	0.42
	5	2.50	4.10	1.17
	4.3	2.82	6.40	0.58
	4.6	2.08	4.60	0.24
	4.1	1.38	3.00	0.29
	5	3.64	8.70	0.53
	5	3.18	8.40	0.62

Appendix D, Table 2: Base metal contents of sulphide lenses used
in construction of Cu-Pb-Zn atomic percent diagram.

Hole Number	Section Length (feet)	Cu	Pb	Zn	Sulphide Type
			(atomic %)		m=massive s=stringer
<u>Lens #1</u>					
H-10-8	37.9	98.60	0.10	1.20	s
H-10-6	48.8	50.76	3.63	45.62	m
H-10-21	36.4	15.82	2.19	82.00	m
H-10-15	7.3	1.59	13.02	85.40	m
H-10-15	35.9	7.24	3.34	89.42	s
H-10-16	24.6	36.52	2.87	60.61	m
H-10-19	30.0	12.67	0.64	86.69	m
H-10-19	13.7	77.78	5.56	16.66	s
H-10-17	110.0	46.77	4.80	48.43	m
H-10-1	26.5	72.08	2.30	25.62	mts
H-10-2	52.3	94.73	0.76	4.50	s
H-10-5	25.0	31.74	5.42	62.84	m
H-10-10	7.6	91.30	0.00	8.70	s
Whole lens	455.9	50.24	3.09	46.67	Cu/Zn = 1.07

Lens #2

H-10-17	12.4	52.17	2.17	45.65	s
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Table 2. continued

H-10-4	41.3	15.52	10.23	74.23	m
H-10-5	25.5	11.05	10.68	78.27	m
Whole lens	66.8	19.82	9.11	71.06	Cu/Zn = 1.28
<u>Lens #3</u>					
H-10-21	16.8	35.52	0.27	64.21	m
H-10-16	9.6	6.39	8.79	84.82	m
H-10-19	44.9	12.65	9.24	78.11	m
Whole lens	71.3	17.20	7.07	75.74	Cu/Zn = 0.23
<u>Lens #4</u>					
H-10-20	10.0	66.67	3.51	29.83	s
H-10-15	9.0	62.22	2.22	35.56	m
H-10-15	8.3	11.88	7.02	81.10	m
H-10-3	6.8	89.29	0.00	10.71	s
Whole lens	34.1	57.67	3.62	40.01	Cu/Zn = 1.44

Appendix E: Thermochemical data and equations used in the
calculation of mineral equilibria.

3 3

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NATIONAL BUREAU OF STANDARDS-1963-A

Appendix E, Table 1: List of symbols used in thermochemical calculations.

List of Symbols

a''	- heat capacity power function coefficient
b''	- heat capacity power function coefficient
c''	- heat capacity power function coefficient
$C_{pi}^{\circ} ^T_{Tr}$	- standard heat capacity of species i from temperature T_r to temperature T
ΔG_r°	- standard Gibbs free energy of reaction
ΔH_1°	- standard enthalpy of formation of species i at temperature T
ΔH_r°	- standard enthalpy of reaction
$\Sigma \Delta H_p^{\circ}$	- sum of standard enthalpy of formation of products
$\Sigma \Delta H_r^{\circ}$	- sum of standard enthalpy of formation of reactants
R	- gas constant, equal to $1.9872 \text{ cal mole}^{-1} \text{ deg}^{-1}$
S_1°	- standard third law entropy of species i at temperature T
ΔS_r°	- standard entropy of reaction
T	- temperature in degrees Kelvin
T_r	- reference temperature equals 298.15° Kelvin

Appendix E, Table 2: Equations used in calculation of thermochemical data (from Helgeson, 1969).

1. $\Delta G_r^{\circ}(T) = [\Sigma \Delta H_p^{\circ}(T) - \Sigma \Delta H_r^{\circ}(T)] - T [\Sigma S_p^{\circ}(T) - \Sigma S_r^{\circ}(T)]$
2. $\Delta H_f^{\circ}(T) = \Delta H_{f1}^{\circ}(T_r) + C_{p1}^{\circ} \int_{T_r}^T (T - T_r)$
3. $S_i^{\circ}(T) = S_i^{\circ}(T_r) + C_{pi}^{\circ} \int_{T_r}^T \ln T/T_r$
4. $\Delta H_{f1}^{\circ}(T) = \Delta H_{f1}^{\circ}(T_r) + a''(T - T_r) + b''/2 (T^2 - T_r^2) - c''(1/T - 1/T_r)$
5. $S_i^{\circ}(T) = S_i^{\circ}(T_r) + a'' \ln T/T_r + b''(T - T_r) - c''/2 (1/T^2 - 1/T_r^2)$
6. $\log K(T) = -\Delta G_r^{\circ} / 2.303 RT$

Appendix E. Table 3.
 Calculated values of ΔH_f° and S_f° for silicates and ions used in determination of $\log K$, ΔH_f° and S_f° for equilibria listed in
 Paper 2, Table 4. Values of a° , b° , c° , $C_p^\circ(T_r)$ and $S_f^\circ(T_r)$ are from Helgeson (1969).

Species	Equation (Appendix, Table)	Temperature ($^{\circ}\text{C}$)						
		25	60	100	150	200	250	300
$\text{H}_2\text{O}, 33^\circ\text{A}^\circ 2.33^\circ\text{S}^\circ 3.67^\circ 10^\circ (\text{OH})_2$	4	ΔH_f°	-1366840	-1364179	-1360936	-1356632	-1352032	-1347405
	5	S_f°	62.8	71.26	80.35	91.20	101.32	110.87
$\text{K}_2\text{O}, 33^\circ\text{A}^\circ 2.33^\circ\text{S}^\circ 3.67^\circ 10^\circ (\text{OH})_2$	4	ΔH_f°	-1368920	-1366245	-1362969	-1358634	-1354001	-1349340
	5	S_f°	63.4	71.92	81.02	92.01	102.22	111.7
$\text{PbO}, 167^\circ\text{A}^\circ 2.33^\circ\text{S}^\circ 3.67^\circ 10^\circ (\text{OH})_2$	4	ΔH_f°	-1364140	-1361521	-1358320	-1354080	-1349537	-1344970
	5	S_f°	61.2	69.52	78.48	89.17	99.18	108.48
$\text{Pb}_2\text{O}, 167^\circ\text{A}^\circ 2.33^\circ\text{S}^\circ 3.67^\circ 10^\circ (\text{OH})_2$	4	ΔH_f°	-2109840	-2106858	-2103212	-2098390	-2093224	-2088037
	5	S_f°	112	121.47	131.67	143.83	155.22	165.78
H^+	2	ΔH_f°	0	805	2325	4125	6125	8325
	3	S_f°	0	2.55	6.94	11.55	16.77	20.79
H_2O	2	ΔH_f°	-68315	-67685	-66965	-66065	-65165	-64265
	3	S_f°	16.71	18.71	20.74	23.01	25.03	26.83
K^+	2	ΔH_f°	-60040	-59095	-57415	-55665	-53215	-50815
	3	S_f°	24.5	27.50	32.34	36.75	42.52	47.54
Na^+	2	ΔH_f°	-57279	-56054	-54204	-52154	-49404	-46704
	3	S_f°	14.4	18.29	23.58	28.75	35.19	40.81
Pb^{4+}	2	ΔH_f°	-110410	-108625	-105385	-101785	-97285	-92635
	3	S_f°	-28.2	-22.54	-13.19	-4.05	6.45	16.20

Appendix F: Petrography of Takjyuak volcanic rocks.

Appendix F. Discussion.

Takiyuak volcanic rocks have been metamorphosed to the green-schist facies, and most primary mineralogy has been obliterated. The fine-grained nature of these rocks and the rarity of primary minerals precludes modal analysis and so textural, metamorphic, and late secondary features of these rocks were studied. Appendix F, Table 2 lists mineral assemblages for the thin sections studied.

Cherty rhyolites, in the Takiyuak Metavolcanic Belt, are characterized by abundant spherulites, phenocrysts of plagioclase and minor alkali feldspar, and abundant very fine-grained (0.04mm) matrix material. Mineralogically they are now composed of quartz, plagioclase, alkali feldspar, sericite, chlorite, saussurite, carbonate, zircon, and opaques. Spherulites are round, range in size from 0.02mm - 0.6cm in diameter, and consist of a radial intergrowth of quartz and feldspar. These spherulites are often nucleated on phenocrysts of quartz, plagioclase, and sometimes microcline, and make up from 2% to 20% of the rock volume. The matrix material in the cherty rhyolite is made up of approximately 40% small spherulites which can be recognized mainly on the basis of their characteristic sweeping cross extinction. Phenocrysts make up less than 15% of the cherty rhyolite. They are mainly saussuritized, carbonatized, and albitized plagioclase laths up to 0.12mm in length, subround quartz phenocrysts (5%) and a few microcline phenocrysts. The very fine-grained matrix material is composed of quartz, feldspar, sericite, chlorite, minor opaques, and zircon. Sericite is the most abundant

alteration mineral and occurs as mat like material defining the foliation. Chlorite, in minor amounts, occurs with opaques as an alteration product of ferromagnesian minerals. Where cherty rhyolite is closely associated with mineralization sericite and chlorite are abundant and can comprise up to 50% of the rock volume. Late fractures in these rocks are filled with vein quartz, minor carbonate, and occasional sulphides. Spherulitic rhyolites show no textural evidence which would suggest that they are tuffaceous. The abundance of spherulites indicates that these rocks were initially composed of minor phenocrysts in a glassy matrix and they are interpreted to represent volcanic flows. Their restriction to a small area about a felsic volcanic center and their very restricted lateral extent support their origin as flows.

Porphyritic rhyolites in this volcanic belt are composed of from 5-40% quartz and feldspar phenocrysts in a very fine-grained (0.02mm) matrix. Subround to euhedral quartz phenocrysts up to 2.4mm in diameter occupy from 5-25% of the rock volume. These phenocrysts often pseudomorph beta quartz, and are commonly embayed. Fracturing of the phenocrysts and extensive subgrain development are believed to be the result of deformation and the fact that quartz phenocrysts elongate parallel to the foliation now appear as aggregates of subgrain quartz supports this conclusion. Plagioclase phenocrysts from 0.04-2.1mm in length make up from 0-15% of the rock by volume. These phenocrysts are albitized, saussuritized, chloritized, and/or carbonatized, from a minor extent to completely, leaving only pseudomorphs of the original crystals. A few phenocrysts

are zoned and have saussuritized cores and albitic rims. Occasional zircon and quartz grains are poikilitically enclosed by plagioclase. The effects of deformation are seen in the parallel alignment of the phenocrysts with the foliation, and in a few cases, by fracturing. Alkali feldspar phenocrysts make up less than 1% of these rocks. The matrix of quartz, feldspar, and sericite, with minor chlorite, opaques, and zircon, makes up from 60-95% of the rock volume. Quartz and feldspar occur as a mosaic of very fine-grained material with mat sericite comprising up to 50% of the matrix. In the vicinity of sulphide mineralization sericite and chlorite are more abundant. The foliation in these rocks is outlined by the elongation of the quartz-feldspathic matrix and secondary, post deformational quartz and carbonate veinlets cut across the foliation. Thin section studies revealed no textural evidence that these rocks are tuffaceous. The absence of tuffaceous textures and the restricted areal extent of these rocks (as determined in the field) suggest that these rocks are felsic flows.

Mafic tuffs in the Takiyuak Metavolcanic Belt are characterized by well defined bedding, occasional fragments and excellent foliation. In thin section these tuffs are made up of quartz, feldspar, chlorite, muscovite, epidote, and carbonate. Banding ranges from 0.05mm to 1cm and is defined by quartz-feldspathic and chlorite-rich layers. Plagioclase phenocrysts, up to 0.1cm in length, have been saussuritized and carbonatized in the cores and in some cases only pseudomorphs of the original zoned phenocrysts remain. Chlorite and epidote are the only ferromagnesian minerals present and occasional pseudomorphs of pyroxene phenocrysts are observed. Quartz

occurs as a mosaic of fine-grained material elongate parallel to the foliation, and in some cases these quartz-rich layers are boudined. Angular fragments of the host material are sometimes observed in these tuffs and support the interpretation that they are tuffs. In a zone parallel to the contact of a granitic intrusion in the area these rocks have been contact metamorphosed to the amphibolite facies. These amphibolites are well banded and consist of quartz, muscovite, garnet, cummingtonite, hornblende, plagioclase and opaques. Garnet appears as large subhedral grains poikilolitically enclosing quartz, feldspar, and minor opaques. These porphyroblasts are undeformed and the fact that they are observed cutting across the foliation and that they lack helicitic textures indicates that amphibolitization is post deformational. In thin section these tuffs show little evidence of their original tuffaceous nature other than the well developed bedding and the presence of fragments of the same material as the host rock.

Basaltic flows in this volcanic belt are mainly pillow lavas and porphyritic lavas. These rocks are typical greenstones and are made up of quartz, chlorite, epidote, feldspar, carbonate, chlorophaeite, and saussurite. Phenocrysts in these lavas are mainly plagioclase laths up to 0.3cm in length. These phenocrysts are zoned and now range from heavily saussuritized in the cores to completely altered to albite, carbonate, and saussurite. Chlorophaeite, present in minor amounts, is observed pseudomorphing olivine phenocrysts in a few thin sections. The matrix material in these rocks is a fine-grained mixture of chlorite, quartz, opaques, and feldspar. No relict pyroxene or pseudomorphs of primary

pyroxene were observed in these rocks. Epidote and minor carbonate occupy fractures in these rocks. The presence of quench plagioclase could not be identified with certainty, but possible swallowtail plagioclase was observed in a few thin sections. Basaltic rocks in the Takiyuak Metavolcanic Belt are characterized, in thin section, by the absence of primary minerals, highly altered plagioclase phenocrysts, a few pseudomorphs of former olivine phenocrysts, and by a typical greenstone matrix of chlorite, epidote, quartz, and altered feldspar.

Amygdaloidal andesite occurs as one flow in the Takiyuak Metavolcanic Belt, and is characterized by up to 40% amygdules ranging from 0.1mm to 2cm in diameter. The amygdules are filled with between 90-95% quartz, the remainder being alkali feldspar, chlorite, sulphides, and carbonate. The cores of most amygdules are occupied by a mixture of pyrite, pyrrhotite, chalcopyrite, galena, and sphalerite. Narrow fractures filled with sulphides, quartz, and minor carbonate join the amygdules together and evidence the good permeability of the unit. Deformation of the amygdules is evidenced by their elongation down plunge, by fracturing, and by development of subgrain quartz around the outer 0.01mm of most amygdules and at the extremities of elongate amygdules. The matrix to the amygdules varies from a very fine-grained, homogeneous, well foliated material to a chaotic mixture of spherulitic material and fragments of the flow itself. The homogeneous matrix material is composed of quartz, feldspar, chlorite, opaques, and minor sericite, and in most places

is a chlorite schist. The chaotic matrix material is mineralogically the same but the presence of abundant angular fragments of the flow material and its location at the top of the unit suggest that it represents a flow top breccia. Amygdules are insignificant in sections with this brecciated material and this brecciated material is associated with gossan material observed in surface mapping. The amygdaloidal andesite is restricted to one flow which in part hosts the mineralization of the #10 sulphide deposit. The stratigraphic relationship between this unit and the sulphide deposit, the fact that this unit can be traced to a probable volcanic vent (see Paper 3), the good porosity and permeability of this unit, and the fact that sulphides of the same mineralogy as those in the #10 deposit are found in the cores of the amygdules and their joining fractures, all suggest that the hydrothermal fluids which transported the base metals emanated from a volcanic center and passed through this amygdaloidal unit prior to precipitating the bulk of the sulphides.

Large granitic intrusions in the Takiyuak Metavolcanic Belt are characterized by their pink color and hypidiomorphic texture. Mineralogically they consist of quartz, plagioclase, and alkali feldspar, with minor biotite, zircon, and opaques. These granites are subsolvus as indicated by the presence of separate plagioclase and perthite. Perthite is present as both patch and rod perthite; biotite, zircon, and opaques are interstitial to the quartz and feldspar. The granites are zoned as evidenced by a marked decrease

in plagioclase relative to alkali feldspar with increasing distance from the margin of the intrusion. Where the granite is in contact with or has inclusions of the mafic volcanics, hornblende and muscovite are sometimes present.

Ultramafic rocks in the area are altered olivine pyroxenites. Cumulus olivine has been totally altered to serpentine and talc. Intercumulus pyroxene has been altered to serpentine, talc and oxides.

Appendix F, Table 1: Abbreviations for minerals used in
Appendix F, Table 2

Quartz	qtz
Plagioclase	pl
Orthoclase	or
Biotite	bi
Muscovite	ms
Sericite	
Chlorite	cl
Calcite	cc
Saussurite	sc
Cummingtonite	cm
Hornblende	hb
Garnet	gn
Epidote	ep
Opques	op
Olivine	ol
Pyroxene	px
Serpentine	sp
Talc	tc
Zircon	zr

Appendix F, Table 2: Mineral assemblages for Takiyuak volcanic rocks as determined by thin section study

Section # qtz pl or bi cl gn hb ms cc ep zr op sc cm ol px sp tc

G-10-68	X	X		X			X
GR-69	X	X	X			X	X
G-10-74	X	X		X		X	X
G-10-54	X	X		X		X	X
G-10-71	X	X		X		X	X
H46-1	X	X				X	X
G-10-64	X	X	X	X		X	X
G-10-11	X	X		X		X	X
G-10-59	X	X		X		X	X
G-10-56	X	X		X		X	X
G-10-51	X	X		X		X	X
G-10-48	X	X		X			X
G-10-9	X	X		X		X	X
G-10-70	X	X		X		X	X
H-10-2#7	X	X		X		X	X
H-10-4#4	X	X				X	X
H-10-3#2	X	X	X			X	X
H-10-1#1	X	X	X	X		X	X
H-10-2#20	X	X		X		X	X
X524	X	X	X	X		X	X
X503	X	X	X	X		X	X
X57	X	X		X		X	X
X391	X	X		X		X	X
G-10-21	X	X		X		X	X
G-10-23	X	X		X		X	X
X540	X	X		X		X	X
G-10-57	X	X		X			X
G-10-35	X	X		X			X
G-10-25	X	X		X			X
G-10-1	X	X		X			X

Table 2 (continued)

Section #	qtz	pl	or	bi	cl	gn	hb	ms	cc	ep	zr	op	sc	cm	ol	px	sp	tc
H-10-B#3	x	x	x		x			x				x						
H-10-B#11	x	x	x		x				x			x						
H-10-41#2	x	x	x		x				x		x	x						
H-10-1#5	x	x						x	x		x	x						
H-10-2#9	x	x	x		x			x	x			x	x					
H-10-B#13	x	x	x		x						x	x						
GR-9	x	x	x	x														
G-10-5	x	x	x		x			x	x			x						
G-10-47	x	x	x		x			x				x						
G-10-36	x	x	x		x			x			x	x						
G-10-19	x	x	x		x			x			x	x						
G-10-37	x	x	x		x			x				x						
X387	x	x	x		x			x	x		x	x						
X394	x	x	x		x			x	x		x	x						
G-10-13	x	x			x				x			x	x					
H-10-B#5	x	x			x			x				x	x					
H-10-1#10	x		x		x			x	x			x	x					
H-10-1#11	x	x			x													
H-10-B#7	x		x		x				x			x						
H-10-B#6	x		x		x				x			x						
G-10-12	x	x	x		x							x	x					
G-10-7	x		x		x							x						
H-10-3#6	x		x		x				x			x						
H-10-4#13	x	x			x							x	x					
H-10-2#5	x	x			x				x			x	x					
H-10-5#9	x	x			x				x			x						
H-10-4#1	x	x	x		x			x	x			x	x					
H-10-5#6	x				x							x						
H-10-B#1	x	x			x			x				x	x					
H-10-3#12	x				x			x					x					
H-10-5#11	x	x			x			x				x	x					

Table 2 (continued)

Section #	qt	pl	or	bi	cl	gn	hb	ms	cc	ep	zr	op	sc	cm	ol	px	sp	tc
H-10-B#10	x	x			x			x	x			x						
H-10-3#11	x	x	x					x				x	x					
H-10-4#6	x	x			x		x		x			x	x					
H-10-1#3	x	x			x				x			x	x					
H-10-5#10	x	x			x							x						
H-10-2#23	x				x			x										
H-10-3#8	x							x				x						
H-10-2#10	x				x			x				x						
H-10-2#22	x	x			x			x				x	x					
H-10-B#12	x	x	x		x			x				x	x					
H-10-5#17	x	x			x				x			x	x					
H-10-5#2	x	x			x				x			x	x					
H-10-4#5	x	x			x				x			x	x					
H-10-3#7	x	x			x				x			x	x					
G-10-39	x	x	x		x				x			x	x					
H-10-4#7	x	x			x							x						
H-10-4#11	x				x							x						
H-10-2#4	x				x			x				x						
H-10-3#4	x	x			x				x			x	x					
H-10-2#6	x				x							x						
H-10-4#12	x	x			x							x						
H-10-2#11	x	x			x			x				x						
H-10-3#4	x				x			x			x							
H-10-3#10	x	x			x			x	x			x	x					
H-10-5#12	x				x							x						
H-10-5#18	x	x			x			x				x	x					
G-76-31	x				x	x	x		x			x				x		
G-76-32	x	x			x		x	x				x	x	x				
G-76-33	x	x					x	x	x	x		x	x					
G-76-5	x	x			x			x	x		x	x	x	x				

Table 2 (continued)

Section #	qtz	pl	or	bi	cl	gn	hb	ms	cc	ep	zr	op	sc	cm	ol	px	sp	tc
G-76-9	x	x	x	x			x			x								
G-76-20A	x	x		x				x				x	x					
G-76-20B	x	x					x		x			x	x					
G-76-16	x	x					x					x	x					
G-76-30	x	x	x					x					x					
G-76-4	x	x			x				x			x						
G-76-3	x	x						x				x						
G-76-23	x	x			x			x										
G-76-43	x	x					x					x	x	x				
G-76-43a												x			x	x	x	x
H-10-2#6	x	x			x			x	x			x	x					
H-10-3#13	x	x	x		x				x			x						
H-10-1#8	x				x				x			x						
H-10-3#1	x	x	x		x			x	x									
H-10-1#4	x	x	x					x	x			x						
H-10-2#21	x				x			x	x			x						
H-10-2#3	x	x			x			x	x			x						
H-10-2#8	x	x	x		x				x			x	x					
H-10-3#3	x	x	x					x	x			x	x					
G-10-13	x	x			x				x			x	x					
H-10-B#5	x	x			x			x				x	x					
H-10-1#10	x	x	x		x			x	x			x	x					
H-10-1#11	x	x			x							x	x					
H-10-B#7	x		x		x				x			x						
H-10-B#6	x	x	x		x				x			x						
G-10-12	x		x		x							x						
G-10-7	x		x		x							x						
H-10-3#6	x		x		x				x			x	x					

Appendix G: Sample locations for Takiyuak volcanic
rocks studied in this thesis. (in pocket)

Appendix H: Geologic cross-sections for the Takiyuak
#10 deposit.

APPENDIX I : List of symbols used in chemical
calculations.

Appendix 1, Table 1: List of symbols used in chemical calculations.

List of Symbols

a''	- heat capacity power function coefficient
b''	- heat capacity power function coefficient
c''	- heat capacity power function coefficient
$C_{pi}^o]^T_{Tr}$	- standard heat capacity of species i from temperature T_r to temperature T
ΔG_r^o	- standard Gibbs free energy of reaction
ΔH_i^o	- standard enthalpy of formation of species i at temperature T
ΔH_r^o	- standard enthalpy of reaction
$\Sigma \Delta H_p^o$	- sum of standard enthalpy of formation of products
$\Sigma \Delta H_r^o$	- sum of standard enthalpy of formation of reactants
R	- gas constant, equal to $1.9872 \text{ cal mole}^{-1} \text{ deg}^{-1}$
S_i^o	- standard third law entropy of species i at temperature T
ΔS_r^o	- standard entropy of reaction
T	- temperature in degrees Kelvin
T_r	- reference temperature equals 298.15° Kelvin
FMA	- iron- magnesium- alkalies
Ab'	- Albite + 5/3 Nepheline
Ne'	- Nepheline + 3/5 Albite
Ol'	- Olivine + 3/4 Orthopyroxene
Q'	- Quartz + 2/5 Albite + 1/4 Orthopyroxene
FeO*	- $\text{FeO} + 0.9 \text{ Fe}_2\text{O}_3$

Appendix G

LEGEND

- 10 mixed unit - acid volcanics, mafic volcanics, tuffs heavily contorted and intruded by granite
- 9 diabase dyke
- 8 granite - pink, quartz eye rich
- 7 calcareous mafic dykes
- 6 gossan zone
- 5 agglomerate:
 - 5a - felsic fragments in a mafic matrix
 - 5b - felsic fragments in a felsic matrix
 - 5c - tuff breccia, felsic fragments, mafic matrix
 - 5d - mafic fragments, mafic matrix
 - 5e - mafic and felsic fragments, dacite matrix
 - 5b₁ - felsic fragments in flow quartz eye rhyolite matrix
- 4 rhyolite:
 - 4a - quartz eye rhyolite, clear to milky quartz eyes, 1/16"-1/8"
 - 4b - quartz eye rhyolite, dark quartz eyes, 1/10" diameter
 - 4c - massive siliceous to cherty rhyolite
 - 4d - quartz eye rhyolite - border zone
 - 4b₁ - quartz eye rhyolite, dark quartz eyes, 1/10" diameter, flow banded, sericitized, could be felsic tuff
- 3 dacite
- 2 tuffs:
 - 2a - mafic tuffs, 2a₁ recrystallized
- 1 andesite:
 - 1a - massive, dark green
 - 1b - amygdaloidal
 - 1c - calcareous
 - 1d - pillowed

SYMBOLS

- outcrop
- suboutcrop
- stream
- cliff

Shetland

Lake

2d

land

cliff

geologic contact; defined, assumed

geologic rock sample

fault

foliation, vertical; inclined

bedding or fragment alignment, inclined
unknown

parasitic fold

parasitic fold

48W

16S

20S

24S

40W

36W

32W

Area 461

Area 46I

Grid 'C' West Extension

Texasgulf Inc.

GEOLOGY
 GRID 46 (WEST EXTENSION)
 461 & 463 AREAS

WORK BY	MAP NO.	DRAFT.	PROJ.	N.T.S.	DATE
J. Gill	75H-1a	J.K.	294	86-I-2	Nov. 1975

1131

Wick Lake

G-10-1

G-10-6

X524

G-10-2

2a

1b

4a

2a

G-10-3

1c

1b

G-10-4

X398

2a

1c

2a

G-10-5

2a

2a

1b

1b

Appendix G

LOCAL GEOLOGY *

[2d]

AL GEOLOGY #10 SULPHIDE DEPOSIT

3 of

-11

LEGEND

- Gossan
- Dykes
 - a carbonate rich
 - b mafic
- Agglomerate
 - a felsic
 - b mafic
- 2 Felsic volcanics
 - a cherty
 - b porphyritic
- Mafic volcanics
 - a massive
 - b amygdaloidal
 - c carbonate rich

DDH - diamond drill hole

● - sample location

● - gossan

--- - geological contact

○ - lake

G-10-5

2b

G-10-4

X398

G-10-3

1c

1b

2a

1c

2a

3a

X387

X390

2b

X394

SCALE

feet

100

30

meters

SCALE

feet

100

200

30

60

meters

6012

LEGEND

- 10

mixed unit - acid volcanics, mafic volcanics,
tuffs heavily contorted and
intruded by granite
- 9

diabase dyke
- 8

granite - pink, quartz eye-rich
- 7

calcareous mafic dykes

Edw

L a k e

Shetland
Lake

3 of 1

- 8 granite - pink, quartz eye rich
- 7 calcareous mafic dykes
- 6 gossan zone
- 5 agglomerate:
- 5a - felsic fragments in a mafic matrix
 - 5b - felsic fragments in a felsic matrix
 - 5c - tuff breccia, felsic fragments, mafic matrix
 - 5d - mafic fragments, mafic matrix
 - 5e - mafic and felsic fragments, dacite matrix
 - 5b₁ - felsic fragments in flow quartz eye rhyolite matrix
- 4 rhyolite:
- 4a - quartz eye rhyolite, clear to milky quartz eyes, 1/16"-1/8"
 - 4b - quartz eye rhyolite, dark quartz eyes, 1/10" diameter
 - 4c - massive siliceous to cherty rhyolite
 - 4d - quartz eye rhyolite - border zone
 - 4b₁ - quartz eye rhyolite, dark quartz eyes, 1/10" diameter, flow banded sericitized, could be felsic tuff
- 3 dacite
- 2 tuffs:
- 2a - mafic tuffs, 2a₁ recrystallized
- 1 andesite:
- 1a - massive, dark green
 - 1b - amygdaloidal
 - 1c - calcareous
 - 1d - pillowed

SYMBOLS

- outcrop
- suboutcrop
- stream
- cliff

Area 462

GR-47

2a

2a

2a

4b

DDH-18,19

cliff

geologic contact; defined, assumed

geologic rock sample

fault

foliation, vertical, inclined

bedding or fragment alignment, inclined,
unknown

parasitic fold

parasitic fold

Lk.

Lake

low-

100W -

90W

90W

70W-

60W-

Appendix G

60W-

48W

SCALE: 1"=200'

Texasgulf Inc.

GEOLOGY
 GRID 46 (WEST EXTENSION)
 462 AREA

WORK BY	MAP NO.	DRAFT	PROJ.	N.T.S.	DATE
Jim Gill	75 H-1	J. K.	294	86-I-2	Nov 1976

Appendix G

THE TAKIYUAK METAVOLCANIC BELT (Western half)

LEGEND

- 7 DIORITE
- 6 GRANITE
- 5 ULTRAMAFIC INTRUSION
- 4 AGGLOMERATES
- 3 FELSIC VOLCANICS
- 2 MAFIC TUFFS
- 1 MAFIC FLOWS

0 1/4 1/2 MILES
0 3.1 KM

- Lake
- Stream
- Geologic contact
- Syncline
- Fault

IX

TAKIYUAK LAKE

TAKIYUAK

TAKIYU

Fig 3 Paper 1

THE TAKIYUAK METAVOLCANIC BELT

LEGEND

● Mafic volcanics		Outcrop
a pillowed		
b amygdaloidal		Lake
c up to 50% granite dykes		
d up to 50% diorite		Stream
e carbonate rich		Geologic contact
2 Tuffs		
● mafic tuffs		Foliation
vertical, inclined
● intermediate tuffs		
● felsic tuffs		Bedding
vertical, inclined
d amphibolite		
● mafic pyroclastic breccia		Lineation
trend, plunge
● pyroclastic tuff breccia		Minor folds
plunge
3 Felsic Volcanics		
a cherty		
b quartz eye		
c up to 50% diabase		
● Agglomerate		Pillows, top direction
a felsic agglomerate		
b mafic agglomerate		
● Granite		Synclinal
● Diorite		Fault
● Ultramafic with up to 50% mafic volcanics		
● Gabbro		
● Diabase		
a Archean		
b Proterozoic		

2d

This is a detailed geological map of a coastal or island region. The map features numerous landmasses and islands, many of which are labeled with the number '6'. A prominent dashed line runs diagonally across the lower half of the map, possibly indicating a geological boundary or a specific contour. Various labels are scattered throughout the map, including 'le', 'lc', 'ld', '9a', 'la', 'lac', and '1a'. A scale bar is located in the upper right corner, and a north arrow is positioned in the lower right corner. The map is characterized by its high contrast and the presence of many small, irregular shapes representing land features.

TAKIYUAK LAKE

10

Fig 3 Papers 2 and 3

THE TAKIYUAK METAVOLCANIC BELT
(Western half)

LEGEND

- 7 DIORITE
- 6 GRANITE
- 5 ULTRAMAFIC INTRUSION
- 4 AGGLOMERATES
- 3 FELSIC VOLCANICS
- 2 MAFIC TUFFS
- 1 MAFIC FLOWS

0 1/4 1/2 MILES
0 3.1 KM

Lake

Stream

Geologic contact

Syncline

Fault

LAKE

YUAK

TAKIYUAK

3 of

Fig 3a Paper 2

2d

LEGEND

GRANITES

AGGLOMERATES

FELSIC VOLCANICS

MAFIC VOLCANICS

Fig 4 Paper 3

LOCAL GEOLOGY

AL GEOLOGY #10 SULPHIDE DEPOSIT

3 of 1

11

LEGEND

- Gossan
- Dykes
 - a carbonate rich
 - b mafic
- Agglomerate
 - a felsic
 - b mafic
- 2 Felsic volcanics
 - a cherty
 - b porphyritic
- 4 Mafic volcanics
 - a massive
 - b amygdaloidal
 - c carbonate rich
- DDH - diamond drill hole
- - sample location
- ... - gossan
- - geological contact
- - lake
- - #10 sulfide deposit

SCALE

feet

100

200

meters

0

30

60

TAK

END

07 11 77

FIN