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BRITISH COLUMBIA GEOSCIENCE RESEARCH GRANT APPLICATION

GENESIS OF THE WINDY CRAGGY DEPOSIT: A CONTRIBUTION TO THE UNDERSTANDING OF MASSIVE SULFIDE FORMATION IN VOLCANO-SEDIMENTARY ENVIRONMENTS

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RESEARCH PROPOSAL

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Introduction

This proposal requests $98790 over a period of three years for the purpose of conducting a detailed field and laboratory study of the Windy Craggy deposit, British Columbia. The laboratory work will be done at the Department of Geology, University of Toronto.

In the ancient geological record there is a group of massive sulfide deposits that has been termed "Besshi-type" for their resemblance to the Paleozoic massive sulfides at the Besshi mine on Shikoku Island, Japan (Fig. 1)(Imai, 1978; Kase, 1977; Kanehira and Tatsumi, 1970; Banno et al., 1970; Doi, 1962; Yamaoki, 1962; Kato, 1937). Characteristically, Besshi-type deposits consist of stratiform, blanket-like sheets of massive pyrrhotite or pyrite with variable amounts of chalcopyrite and sphalerite and minor galena. The ores are within clastic metasediments such as metagreywacke, quartzite, and metapelite, mostly of deep-water facies (Fig. 2). Felsic meta-igneous rocks are scarce to absent and mafic meta-igneous rocks generally are subordinate. The intensely metamorphosed and deformed Besshi deposit serves as the type-deposit and namesake for this important style of seafloor sulfide mineralization. Besshi-type deposits are also known in Hokkaido, Japan (Fig. 1)(Miyake and Takatori, in press; Takatori et al., 1987; Bamba and Motoyoshi, 1985; Mariko, 1984; Mariko et al., 1982; Suzuki and Kubota, 1980; Mariko and Iino, 1978a,b; Miyake, 1980, 1965; visited by the proponents), Scandinavia (Bugge, 1978, Nilsen, 1978, Rai, 1977, Rui and Bakke, 1975, Rui, 1973a,b; visited by Scott), Namibia (Klemd et al., 1987; Adamson and Teichmann, 1986; Killick, 1986, 1982; Scott, 1983; Goldberg, 1976; visited by Scott), and Windy Craggy, B.C., which is the subject of this study.

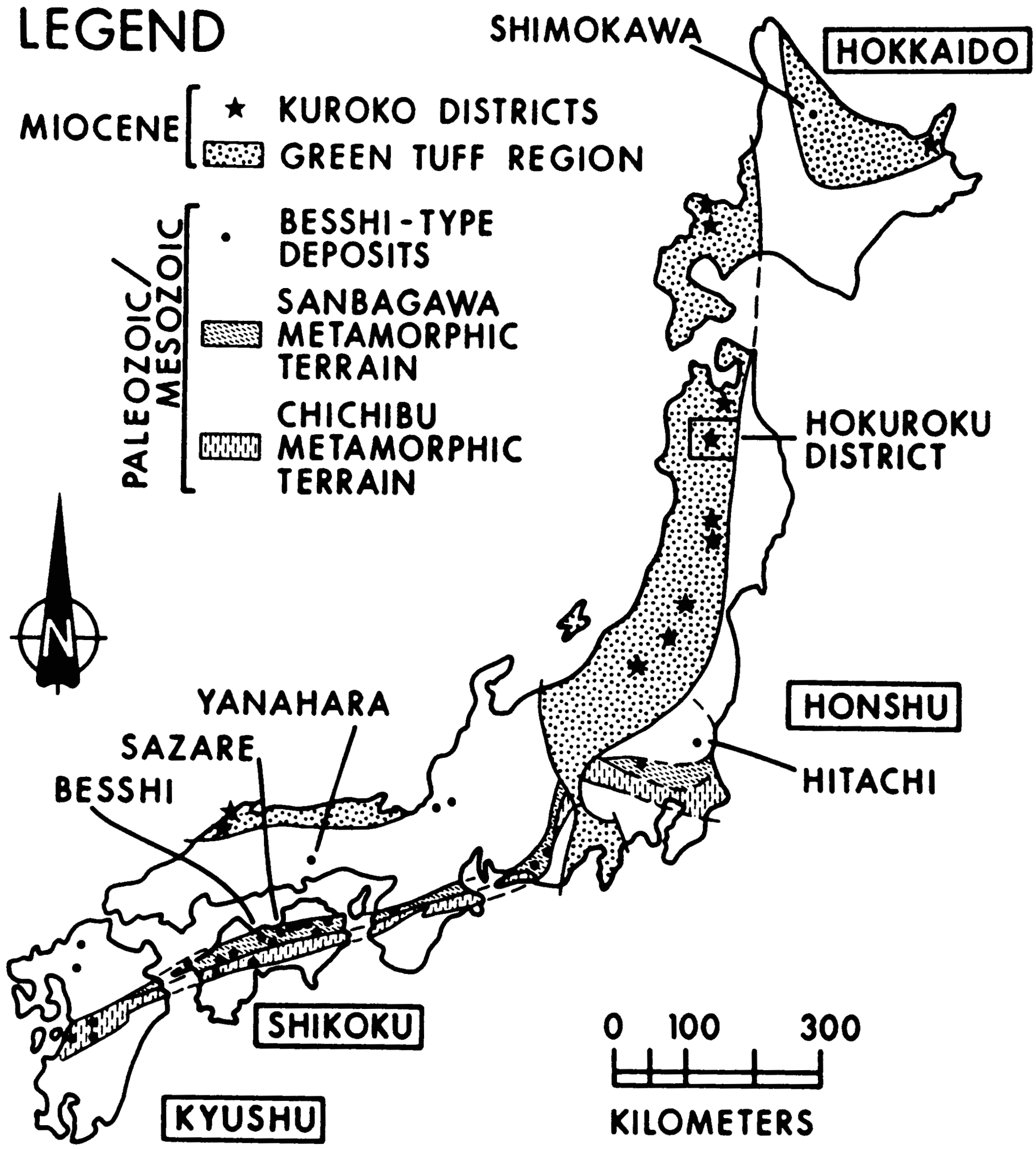

Figure 1. Location of Besshi-type deposits in Japan (from Scott, 1985).

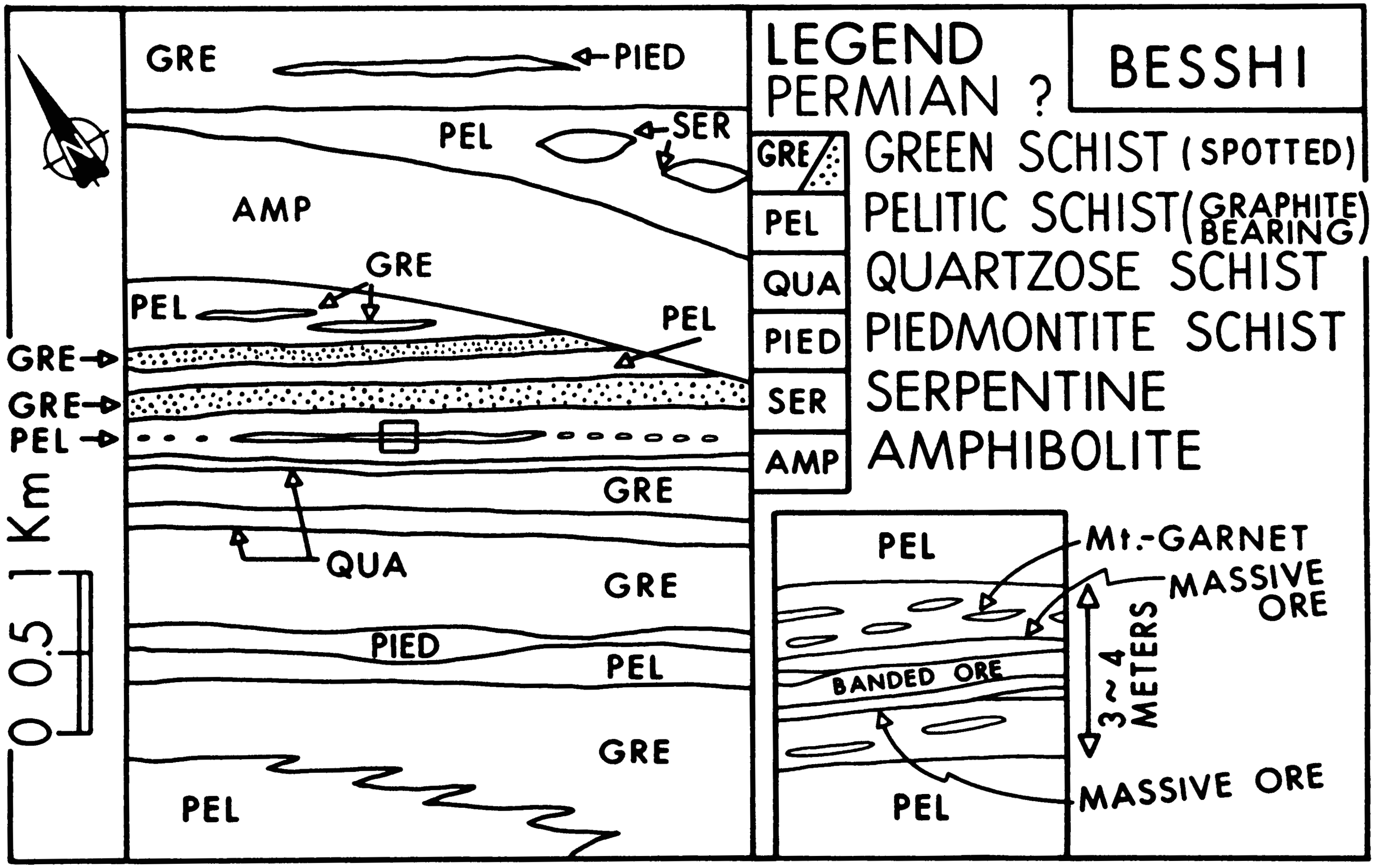

Figure 2. Schematic plan of the Besshi deposit, Japan (from Scott, 1985).

On the modern ocean floor massive sulfides have been found at sedimented rifts. These deposits are distinct from basalt-hosted massive sulfide deposits because of their intimate association with sediments and weaker association with volcanic rocks. They display many similarities in host rock composition, morphology, mineralogy and composition to ancient Besshi-type deposits. Four such sites are currently known: 1) Guaymas Basin, Gulf of California; 2) Middle Valley, Northern Juan de Fuca Ridge; 3) Escanaba Trough, Gorda Ridge); and 4) Red Sea. Direct access to actively forming sulfide deposits on the seafloor provides the unique opportunity to examine directly many features of the mineralizing process in a sedimented setting: tectonic and geologic setting, fluid chemistry, depositional mechanisms, and the physical and chemical conditions at the site of deposition.

Perhaps the most thoroughly studied of these deposits are those of Guaymas Basin (Koski et al., 1985; Lonsdale and Becker, 1985; Peter et al., 1986, Peter, 1986, Peter and Scott, in prep). The deposits consist of over 130 mineralized mounds along an 8 km long segment of a sedimented rift in the central Gulf of California. At least 500 m of pelagic and terrigenous sediment overlies the spreading center and is intruded by numerous igneous sills. There is evidence to suggest that some of the sulfides at Guaymas Basin may have formed primarily within sediments (epigenetically) rather than on top of them. This forces us to re-examine current models for formation of ancient massive sulfide deposits in volcano-sedimentary environments in light of this body of knowledge gained from modern deposits. Data taken largely from work on the Guaymas Basin deposits provide insight into the formation processes of similar modern deposits and provide a framework for testing applicability of these models to deposits in the ancient geological record. The study of ancient deposits complements research on modern seafloor mineralization. To date, it has not been possible to sample modern deposits in the third dimension. Therefore, in order to fully understand the ore-forming process, it is necessary to study a well-preserved, analogous ancient land-based deposit.

The Windy Craggy deposit (Fig. 3) is a particularly good example of an ancient Besshi-type deposit. It is underlain by mafic volcanic rocks, including pillow basalts near their contact with overlying graphitic shales and argillites which are intruded by igneous sills. The deposit bears many geological and geochemical similarities with Guaymas Basin. These similarities include: 1) the presence of igneous sills and/or dikes, 2) mineralogy (pyrrhotite/pyrite, chalcopyrite, sphalerite, galena, and carbonate are common to both deposits), and 3) mineral textures. However, there are some notable differences; among these are size and composition. The exposed portions of the Guaymas Basin deposits constitute some 500, 000 tonnes whereas Windy Craggy contains more than 350 million tonnes and may prove to be one of the largest massive sulfide deposits in the world. Windy Craggy contains up to 0.08% cobalt, and certain sections of the deposit are rich in gold. Guaymas Basin contains no significant cobalt or gold; however, only the surfaces of mounds have been sampled. The Windy Craggy deposit is extremely well-exposed, relatively unmetamorphosed and, on a small scale, primary textures and geologic relationships are pristine in many areas.

For the above-mentioned reasons, Windy Craggy serves as a far better example of a Besshi-type deposit than the classic Besshi mine itself. The Windy Craggy deposit has only recently begun to be explored and has not been the subject of any comprehensive geological study. Underground development and mining, which will continually provide new exposures, is expected to continue for the life of the study. Therefore, the Windy Craggy deposit is an ideal site to carry out a geological, mineralogical, and geochemical study for the purpose of better understanding the genesis of this type of deposit. Data obtained from this study will be compared with that already collected by the proponents from the Guaymas Basin deposits as an aid to interpreting the results obtained from Windy Craggy.

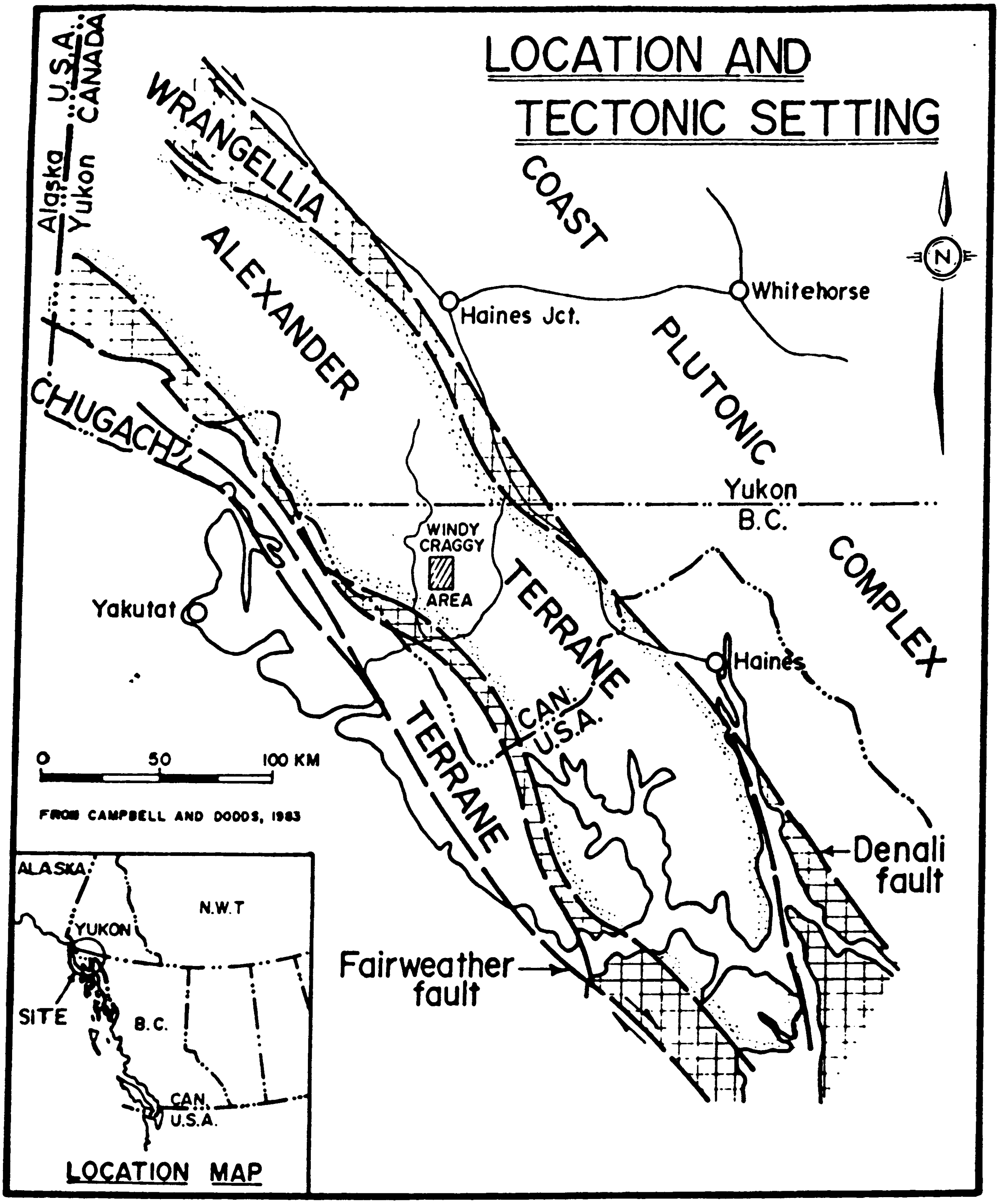

Figure 3. location and tectonic setting of the Windy Craggy deposit (from Gammon and Chandler, 1986).

Scientific Objectives

The salient objectives are defined below:

1) evaluate the role of sediments in the formation of massive sulfides in volcano-sedimentary environments. Work on modern sulfide deposits at sedimented rifts (primarily at Guaymas Basin) has shown that sediments may:

   a) provide a physical and/or chemical trap for ascending mineralizing fluids.

   b) influence the pH, fO_2, and chemistry of the circulating hydrothermal fluid.

   c) provide a source of metals, sulfur, and carbon.

   d) influence the hydrodynamic flow of mineralizing fluids (i.e., diffuse vs. focused flow).

   e) control the size of the deposits.

   In order to test the universality of these findings in the ancient geological record, it is necessary to document carefully the geological and geochemical characteristics of an ancient deposit deemed to be analogous to those of the modern seafloor (viz. Windy Craggy). Specifically, the following will be addressed:

   i) detailed descriptive and chemical mineralogy focusing on mineral textures. This will determine if mineral precipitation is causatively linked to the presence of sediments (i.e., epigenetic, replacement vs. syngenetic).

   ii) mineralogical and geochemical study of sedimentary host rocks. This will involve the examination of the relationship between sediment and massive sulfide bulk composition and evaluate the the existence and extent of hydrothermal alteration. The style of alteration will indicate if the sediments were a source of metals, sulfur and carbon. Its extent will determine if the sediments influenced the hydrodynamic flow of mineralizing fluids.

iii) Fluid inclusion microthermometry will provide information on the physical and chemical properties of the mineralizing fluid and may identify differing thermal regimes within the deposit.

iv) stable sulfur, carbon, oxygen, and hydrogen isotope geochemistry will determine if the sediments were a source of sulfur and carbon.

v) lead isotope geochemistry will determine if the sediments were a source of Pb.

2) determine the temporal importance of subvolcanic sills and dikes to the massive sulfide formation process. At Guaymas Basin, igneous sills appear to serve as a structural control and be a prerequisite for overlying sulfide mounds (Scott, 1985). At Windy Craggy, sills and dikes are also spatially related to mineralization. It is possible to test the hypothesis that sills/dikes predate mineralization at Windy Craggy using $^{40}Ar/^{39}Ar$ age dating. This method will be used to identify or refute a genetic link between the footwall rocks to sulfide mineralization and sill/dike intrusion.

3) determine what kind of control tectonic setting has, if any, on the deposits. This in turn may influence the composition of sediment associated with the deposit and, therefore, the chemical composition of the deposit. The Guaymas Basin deposits are forming in a rifted cratonic margin. Geology at Windy Craggy has many features that are similar to Guaymas Basin suggesting formation in a similar tectonic setting. The tectonic setting will be determined by igneous and sedimentary geochemistry, particularly REE patterns.

Study Area

The Windy-Craggy Cu-Co-Au-Zn deposit is situated at 59°44'N latitude and 137°44'W longitude in the extreme northwestern corner of British Columbia in the St. Elias Mountains (Fig. 3). The deposit is located within the Alexander Terrane, one of the allocthanous "suspect terranes" which are thought to have been accreted to the west coast of North America as a result of Pacific seafloor spreading during the Mesozoic (Coney et al., 1980; Van der Voo, 1980; Hillhouse, 1977). Recent regional geological mapping indicates this area is underlain by complexly deformed Paleozoic clastic and carbonate rocks of relatively low metamorphic grade (Fig. 4) (Campbell and Dodds, 1983). The Windy Craggy deposit is extremely large (>350 million tonnes) grading about 1.5% Cu, 0.08% (2 lb/tonne) Co, with a Au-rich zone grading up to 28.8 g/t over 6 m in one particular drillhole intersection. Indeed, this gold zone is providing the impetus for development of a 7000' exploration adit.

The deposit is located within a broad belt of volcanic and sedimentary rocks which has been informally named the Tats Complex (MacIntyre, 1984, 1983; Prince, 1983). These workers have defined five major subdivisions of the Tats Complex: Upper Tats Complex (mainly pillow basalt; Upper Triassic), Middle Tats Complex (mixed shales, argillites, pillowed and massive flows; Upper Triassic), Lower Tats Complex (intermediate to mafic flows, diorite sills; age unknown), Graphitic Shale Unit (calcareous graphitic shale, argillites, limestones; age unknown), Limestone Unit (grey platy limestone; Siluro-Devonian ?). Windy Craggy is hosted by the Middle Tats complex which has been regionally metamorphosed to lower greenschist facies. On a broad scale, the massive sulfides occur at or near the transition from volcanic to sedimentary rocks.

Gammon and Chandler (1986) interpret the deposit to be two distinct sulfide bodies, isoclinally folded, cross folded, faulted, and separated by a thick altered pillow volcanic unit (Fig. 5). An alternate explanation is the two sulfide bodies represent segments of the same unit. The footwall rocks immediately underlying both sulfide bodies are primarily chloritic pillowed basalts bearing disseminated and stringer sulfides. In a simplistic sense, pillow basalts are the stratigraphic footwall to the deposit. They are invariably altered and chloritized. These basalts also contain stockwork mineralization consisting of disseminations and veinlets of pyrite and silica

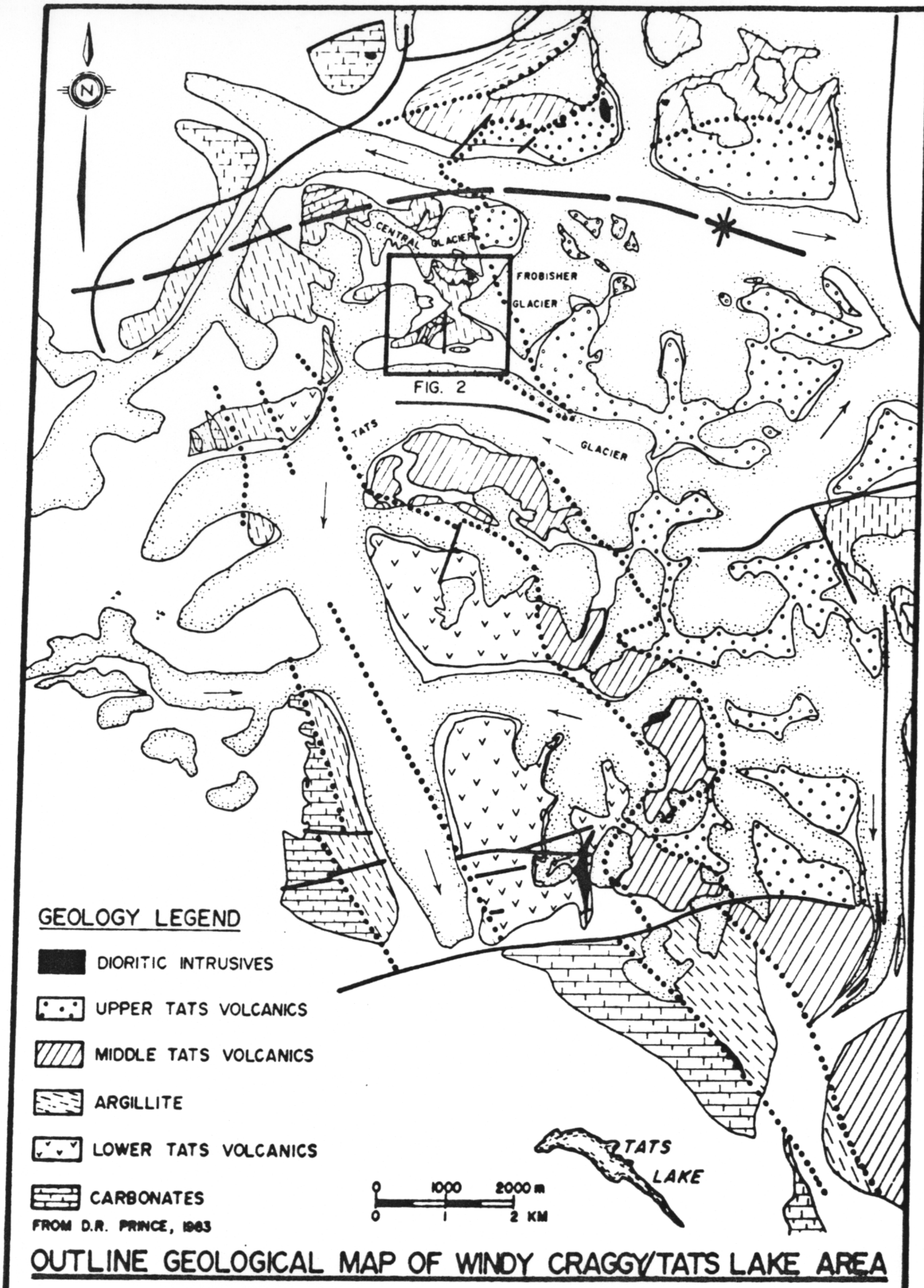

Figure 4. Geological map of the Windy Craggy area (from Gammon and Chandler, 1986).

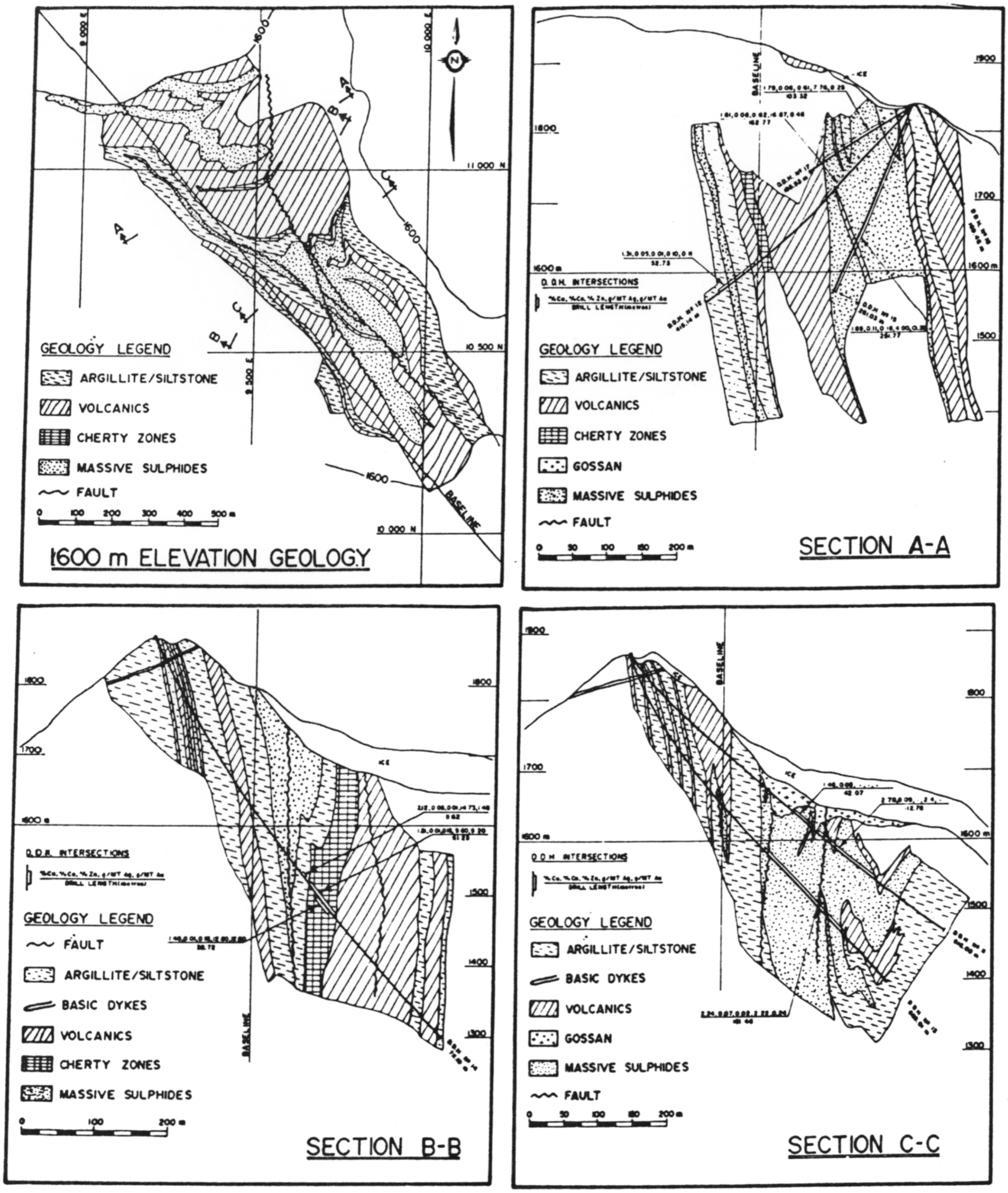

Figure 5. Geology of the Windy Craggy deposit (1600 m level) and cross sections based on surface mapping and drilling to 1983 (from Gammon and Chandler, 1986).

with lesser, rare chalcopyrite. Massive sulfides consist mainly of pyrrhotite, pyrite, and chalcopyrite with minor amounts of magnetite, chalcocite, marcasite, sphalerite, and trace amounts of galena, arsenopyrite, valleriite, cubanite, cobaltite, electrum, native silver, and native gold. The stratigraphic hangingwall to the sulfides is a thick sequence of dark grey, calcareous argillites and sills of dioritic appearance.

Permission to conduct a study of Windy Craggy as outlined herein has been granted by Geddes Resources Ltd. who are currently exploring and developing the deposit. J. Peter was employed by Geddes Resources Ltd. for a period of two months in 1987. A geological map of all four ridges and part of the North Face of Windy-Craggy peak was prepared at a scale of 1:2500. However, more surface mapping is needed in order to understand more precisely the relationship of sulfide mineralization to the transition from volcanic to sedimentary rocks. Extensive drill hole data and core samples will complement surface mapping and sampling. A total of 85 samples of all rock types and mineralization accessible from surface were collected this past field season. Further field work including surface and underground mapping and sampling of the deposit is planned for1988.

Research Methodology

Geologic and Tectonic Setting

The setting in which Besshi-type deposits were generated is uncertain (e.g., Sawkins, 1976) and could be interpreted to be an intracontinental rift, magmatic arc, outer arc trough or oceanic environment (Ishihara, 1978). They have most commonly been considered to have formed in subduction-related regimes, and to have some genetic relationship with island arcs. For example, Hutchinson (1980) considers Besshi-type deposits to have formed in a fore-arc trough or trench and Mitchell and Bell (1973) suggest they form coevally, but in a distal setting with respect to Kuroko-type deposits. Klau and Large (1980) also propose a genetic association between Kuroko and Besshi-type deposits and relate the two to different stages of arc development. Sawkins (1976) favors a tensional tectonic environment, and Scott (1983, 1985) and Fox (1984) consider Besshi-type deposits to have formed in a rifted cratonic margin such as the present-day Gulf of California. The recent discovery of deposits at Middle Valley on the Juan de Fuca Ridge and Escanaba Trough on the Gorda Ridge suggests that these deposits can form in a variety of tectonic settings.

It is herein hypothesized that the Windy Craggy deposit is hosted by Guaymas Basin-type ocean crust representative of the earliest episodes of basin development. This premise will be tested by geological field observations and igneous and sedimentary geochemistry. The abundance of igneous sills in the Windy-Craggy area suggests eruption of basalt was accompanied by shallow-level injection of basaltic magma into basinal sediments much like in the Guaymas Basin. Kelemen and Radford (1983) observed an "intraformational breccia" in argillite on the North Face of Windy Craggy with blocks of bedded siltstone to shale in massive black argillite, indicating deposition in a tectonically active basin.

Igneous Geochemistry

The chemistry of volcanic rocks hosting massive sulfide deposits may provide important clues to the paleotectonic environment in which the host volcanic rocks were erupted or intruded (e.g., Pearce and Gale, 1977) but recent studies from the modern seafloor raise some cautions (e.g. Binns and Whitford, 1987). Major element abundances, which discriminate magma types in recent volcanic rocks, are susceptible to modification during low-grade metamorphism and, in some instances, to contamination by pre-existing rocks formed in different tectonic settings. These are, therefore, of limited value in determining magmatic affinities. Immobile trace elements (Ti, Cr, Ni, Zr, Y, Nb, Co, Sc, U, Th, Ta, Hf, and rare earth elements (REEs)) are believed to be less sensitive to the alteration process (Floyd and Winchester, 1978; Winchester and Floyd, 1976; Garcia, 1978; Pearce, 1975; Pearce and Cann, 1973).

These elements show distinctive trends that, in most cases where contamination is not severe, allow ocean-floor basalts to be discriminated from most volcanic arc basalts.

Dolerites and basalts from the Guaymas Basin have mineralogies and major element chemistries typical of N-type MORB, but they are enriched in K, Rb, Ba, Sr, LREE, and Th relative to basalts from the mouth of the Gulf of California (Saunders et al., 1982a, 1982b). Some of this enrichment, particularly in Rb, K, and Ba is due to secondary processes, but the high Sr abundances are considered to be primary (Saunders, 1982a, 1982b; Saunders and Tarney, 1984). The authors suggest that these differences are due in part to variations in mantle source composition, with the mantle underlying the Basin containing a minor sub-continental (residual calc-alkaline) component. Guaymas Basin-type ocean crust representative of the earliest episodes of basin development may be present in the vicinity of Windy Craggy.

Previous petrographic examinations indicate that the igneous rocks of Windy Craggy are pervasively chloritized and also contain clay and carbonate alteration (MacIntyre, 1986; Baerg, 1984). A few samples of basalt from the Windy Craggy deposit and environs have been analyzed for major and trace elements by the B.C. Dept. of Energy, Mines, and Petroleum Resources (MacIntyre, 1986) and by Falconbridge Ltd. (Gregory, 1984). Basalts are characterized by relatively low TiO_2 and high Na_2O, K_2O, and P_2O_5 compositions relative to MORB; they are also enriched in large ion lithophile (LIL) elements. However, this alkali and LIL element enrichment may be due to spilitization. MacIntyre (1986) published two analyses of immobile and REEs for basalts from the Windy-Craggy area. The REE distributions show LREE enrichment which is characteristic of calc-alkaline and alkaline volcanic rocks (e.g., Jakes and White, 1972; Hanson, 1980). Based on field criteria and this chemical data, MacIntyre (1986) suggests that these calc-alkaline to alkaline volcanics are typical of island arcs or back arc basins developed in continental crust.

A systematic and thorough geochemical study of Windy Craggy igneous host rocks is necessary. Only a single sample of a sill which cross-cuts sediments was analyzed, and this was not from the Windy Craggy deposit. A major objective of our proposed study is to determine if the sills and basalts are genetically related and comagmatic; REE contents may correlate with major element chemistries. Recent work on volcanic rocks of the Western Woodlark Basin (Binns and Whitford, 1987) indicates that in tectonically complex regions, immobile trace element, REE, and strontium isotopic data must be considered together to unravel complex geochemical histories, and such a methodology may be required at Windy Craggy. Major element analyses will be performed by X-Ray Assay Labs (XRAL), and trace, and REE analyses will be performed at the University of Toronto using standard x-ray fluorescence (XRF) and instrumental neutron activation analysis (INAA) methods.

Sediment Mineralogy and Geochemistry

The geochemistry of sedimentary rocks reflects predominantly the nature and proportion of their detrital components and hence their provenance. The elements La, Ce, Nd, Y, Th, Zr, Hf, Nb, Ti, and Sc are most suited for determinations of provenance and tectonic setting because of their relatively low mobility during sedimentary processes and their low residence time in seawater (Holland, 1978). These elements are incorporated in clastic sediment during weathering and transportation and thus would reflect the signature of the parent material (McLennan et al., 1983).

There have been some recent successes in discriminating the tectonic setting of sedimentary rocks on the basis of trace element and REE characteristics (e.g., Bhatia and Crook, 1986; Bhatia, 1983; Bhatia and Taylor, 1981; Peterman et al., 1981). The latter authors have proposed a method of characterizing the tectonic setting of sedimentary basins based on the La, Th, U, Zr, Nb, Y, Sc, Co, and Ti content of greywacke from modern sedimentary basins in eastern Australia. They claim to be able to distinguish between four settings: oceanic island arc, continental island arc, active continental margin, and passive margin. Such analyses of sediments from Guaymas Basin recovered during a 1985 cruise will provide a test of the applicability of this method to sediments from a rifted continental margin and provide benchmark data for Windy Craggy.

Prior to geochemical analysis, all samples of sedimentary rocks will be examined by standard optical petrographic techniques to determine extent of alteration or metamorphism. All samples will be analyzed for whole-rock major elements and trace and REE elements in a similar manner as discussed for the igneous rocks. A foreseeable problem with this technique is that finer grained siltstones and mudstones may exhibit significant differences in geochemical characteristics compared with the associated greywackes because REEs partition strongly into high density accessory minerals and these may carry a major portion of the REEs.

Nature of the Mineralizing Fluid and Origin of its Components

Mineralogy and Mineral Chemistry

Reports on the mineralogy of drilled portions of the Windy Craggy deposit (e.g., Fox, 1986; Baerg, 1984; Buchan, 1984, 1983, 1981; Gasparrini, 1983; Mainwaring, 1983; Muir, 1980) are only of a descriptive nature. They do not address style of mineralization and mineral paragenesis or zonation on any scale which must be coupled with chemical mineralogy. A thorough mineralogical study will be conducted and will focus on interpretation of mineral textures with the aim of evaluating the influence of sediments on the style of mineralization. A sound mineralogical study is also a prerequisite for any isotope geochemistry. Mineralogy and mineral chemistry will be done by reflected and transmitted light microscopy, scanning electron microscopy (SEM) with EDA and electron microprobe analyses, all at the University of Toronto. Chemical mineralogy (particularly the Fe content of sphalerite in equilibrium with pyrite or pyrrhotite), in conjunction with fluid inclusion microthermometric studies will provide data on the sulfur and oxygen fugacity of the fluid (e.g., Bryndzia et al., 1983; Peter, 1986; Hannington, 1986, Hannington et al., 1986).

Fluid Inclusions

Fluid inclusion microthermometric studies of transparent gangue minerals associated with mineralization at Windy Craggy (e.g., carbonate and quartz, and possibly sphalerite) will be performed at the University of Toronto. The aims of this work are: 1) determine the temperature of the fluid from which the minerals precipitated, 2) determine if boiling or phase separation occurred at the site of mineral precipitation (boiling can be an important factor controlling the deposition of gold), 3) determine the relative proportions of major cations (e.g., Mg, Na, K, Ca, etc.) and 4) derive an apparent salinity of the fluid. Fluid inclusion studies, combined with mineral paragenetic studies, may reveal a thermal evolution of the fluids as was done so successfully , for example, for the Kuroko ores (Pisutha-Arnond and Ohmoto, 1983).

Fluid inclusion studies of Guaymas Basin mineralization (Peter and Scott, 1987; Peter, 1986) show that the fluids forming these deposits have a salinity close to but greater than seawater and a temperature range of 155° to 315°C. The distribution of fluid temperatures is skewed and is best explained in terms of the cooling of hot endmember hydrothermal fluid by mixing with cold ambient seawater. The high salinities can be explained by fluid boiling in the subsurface. Similar results are expected for Windy Craggy, and it is possible that evidence for fluid boiling may be found in the stockwork of the deposit.

Stable Isotopes

The combined use of stable sulfur, carbon, oxygen, and hydrogen isotopes with other isotopic systems (e.g., lead isotopes) provides increased constraints on mineral-forming processes. Samples from Windy Craggy will be sent out for analysis to either the Derry Laboratory, Ottawa or McMaster University.

Sulfur

Sulfur isotope analyses of sulfides and sulfates may help to constrain sources of sulfur at Windy Craggy. In addition, they will be used to determine if isotopic equilibrium between mineral phases has been achieved. If minerals are in isotopic equilibrium, geothermometric data can be derived from the analyses. Previous sulfur isotope analyses of hydrothermal vent precipitates from Guaymas Basin (Peter, 1986; Peter et al., 1986) indicate that sulfur was contributed from three sources: basaltic sulfide, reduced seawater sulfate, and bacteriogenic sulfide from the sediments. Additionally, an observed correlation between sulfur isotope values of sulfides and geographic sample location within the basin may be explained by the systematic variation of sediment thickness beneath the deposits. Such effects should also be looked for at Windy Craggy.

Carbon

Recent carbon isotope studies of calcite from Guaymas Basin (Peter, 1986) give values ranging from $\delta^{13}C = -9.6$ to -14 ‰ , which suggest CO_2 in the hydrothermal vent fluids was derived mainly by mixing equal amounts of carbon from two sources: oxidized organic matter and dissolved marine carbonate. Sediments may also be a major contributor of carbon to the mineralizing fluids at Windy Craggy. Carbon isotope analyses of Windy Craggy gangue minerals intimately associated with sulfides (e.g., calcite and graphite) will be performed in order to evaluate this hypothesis.

Oxygen and Hydrogen

O and H isotopes can be used as indicators of the origin and history of H_2O in hydrothermal fluids. These isotopes will be analysed for in gangue minerals intimately associated with sulfides at Windy Craggy (e.g., quartz, calcite, barite, and anhyrite for oxygen, and muscovite/sericite, chlorite for hydrogen). Temperatures of formation of these minerals will then be calculated utilizing fractionation factors. Isotopic ratios of waters in equilibrium with these minerals will complement fluid inclusion data.

Lead Isotopes

This study has two objectives: 1) assess the relative contribution of lead from volcanics, sediments, and seawater to mineralization at Windy Craggy; 2) characterize the Pb isotope signature of Windy Craggy sulfides and igneous and sedimentary host rocks and 3) add to the Pb-isotope database for this type of deposit. Characterization of the lead isotope character of Windy Craggy will serve for comparison with sulfide mineralization in the surrounding area. All chemical separations and analyses will be performed in the laboratory of R.M. Farquhar at the University of Toronto.

It is anticipated that the Windy Craggy sulfides will have a lead isotope signature intermediate between the igneous and sedimentary rocks hosting the deposit. There should be a significant variation in Pb isotope ratios of sulfides from different parts of the deposit. Sulfides associated with basalt are expected to plot close to the oceanic ridge tholeiite field and those within sediments should be more radiogenic and plot closer to the pelagic sediment field. It may be necessary to measure the U and Pb contents of the Windy Craggy host rocks which will enable a correction to be made for in-situ decay of U to Pb (R. Farquhar, pers. commun.).

Conditions and Mechanisms of Mineral Deposition

Geometry, Composition, and Texture of the Deposits

Determination of the geometry of the Windy Craggy deposit, its composition, zoning, and mineral textures, coupled with conceptual models of massive sulfide formation will be a useful indicator of the conditions and mechanisms of sulfide deposition. Mineralogical and compositional information from the Guaymas Basin deposits will provide a solid basis for comparison with Windy Craggy. The nature of large-scale sulfide zonation at Windy Craggy is particularly important as this cannot be evaluated at Guaymas Basin due to sampling limitations. Zoning will be evaluated through further field mapping and detailed examination of core drilled in 1987 and in previous years. A direct mineralogical comparison of the "Gold Zone" with other portions of the deposit will indicate if this important style of mineralization is genetically related to the other sulfides. This is of direct relevance to the formulation and/or refinement of an exploration philosophy for the Gold Zone and similar styles of mineralization in the vicinity of the deposit.

Relationship between igneous activity and mineralization

At Guaymas Basin, subsurface sills and dikes pre-date mineralization and serve as a structural control for mineralization (Scott, 1985). A fundamental question to be resolved at Windy Craggy is whether or not the igneous sills/dikes played a similar role in the mineralizing process. This will be answered by the use of $^{40}Ar/^{39}Ar$ age dating of 1) igneous rocks that are in the stratigraphic footwall and hangingwall to the deposit, 2) igneous sills and dikes spatially related to mineralization, and 3) hydrothermal sericite related to the intrusion of sills and dikes into the sediments. These analyses may be performed at the University of Toronto when this facility becomes automated in the near future. At present this facility is dedicated to development of analytical techniques and is not used for routine analyses.

Rocks in the stratigraphic hangingwall of the Windy Craggy deposit have been dated by the GSC (Orchard, 1986; MacIntyre, 1986) using conodont faunal assemblages collected from calcareous sediments in both drill core and surface samples of limy beds in basalt. Ages obtained are consistently Early Norian (245-240 Ma; Upper Triassic). Calcareous shale and argillite units of identical appearance have been intersected on both sides of the main stratiform sulfide zone suggesting that the mineralization may be coeval and Triassic in age. Therefore, isotopic age dating of hangingwall rocks will provide a good test of the dates derived from conodont assemblages. It is expected that the footwall and hangingwall rocks and sills/dikes will give closely similar ages. If so, they are comagmatic and this would indicate that sill and dike intrusion was an integral stage in the formation of the deposit.

The $^{40/39}Ar$ method, first described in detail by Merrihue and Turner (1966), is superior to the conventional K-Ar method of dating for several reasons: 1) argon may be lost by diffusion even at temperatures well below the melting point, and, therefore, K-Ar dates would represent time elapsed since cooling to temperatures at which diffusion loss of Ar is insignificant; 2) excess radiogenic ^{40}Ar may be present, and therefore, K-Ar ages will be too old; 3) K and Ar are determined in the same sample, and only isotope ratio measurements of Ar are required. Therefore, the problem of sample inhomogeneity and the need to measure absolute concentrations of K and Ar are eliminated. The incremental heating technique overcomes problems of Ar loss or excess Ar possibly induced by metamorphic events. Gas fractions released at higher temperatures have higher $^{40}Ar^*/^{39}Ar$ ratios because Ar is then removed from more retentive sites which lost smaller fractions of $^{40}Ar^*$ during metamorphism. Ultimately, the $^{40}Ar^*/^{39}Ar$ ratios may reach a plateau corresponding to a date that approaches (i.e., may be equal to, or slightly less than) the blocking temperature of the mineral. A foreseeable problem with the Windy Craggy samples may be that sill/dike samples may contain excess ^{40}Ar occluded during intrusion into the sediments. This would be evidenced by anomalously old dates for the low temperature fractions of step-heating and failure to establish reliable plateau ages at higher temperatures.

Sediment Geochemistry Evidence for Conditions and Mechanisms of Mineral Deposition

The study of the mineralogy and geochemistry of the sediments hosting the Windy Craggy deposit will allow for a comparison with the bulk chemical composition of the mineralization. It is expected that, as at Guaymas Basin and other modern seafloor sites, the composition of the sediments will reflect the composition of the mineralization. Much work has been done to distinguish pelagic sediments from metalliferous sediments in modern settings. This is facilitated by the recognition of a hydrothermal Fe and Mn component (e.g., Kalogeropoulos and Scott, 1983; Böstrom, 1973; Bonatti et al., 1972;

Böstrom and Peterson, 1969). Similar work may identify a hydrothermal component within unmineralized sediment hosting the Windy Craggy deposit. At Windy Craggy there appears to have been a period of quiescence following major sulfide formation. This hiatus is recognized by the presence of laminated detrital mudstones which are intercalated with ore or immediately overly the massive sulfides. On this basis, Kelemen and Radford (1983) suggested that at least some massive mineralization at Windy Craggy represents a chemical sediment. On the North Face, outcropping massive sulfide grades into mineralized and unmineralized calcareous argillite. Cherts, presumably chemically precipitated, together with carbonate facies "iron formation" are also associated with and in the vicinity of massive sulfides at Windy Craggy. The iron formation contains an assemblage of siderite, dolomite, calcite, and sulfides (thinly bedded pyrite and magnetite-bearing beds). Kalogeropoulos and Scott (1983, in press) and Troop and Scott (in prep.) have found such rocks to be good lithogeochemical tracers for massive sulfide deposits.

Alteration of Host Rocks

The main objective here is to recognize possible channelways and upflow zones for the mineralizing fluids in order to define the overall paleohydrothermal flow regime at Windy Craggy. This will prove useful in determining the stratigraphic top of the deposit and, coupled with models of massive sulfide formation, will provide an increased knowledge for the exploration for specific types of ore within the deposit (i.e., Cu-rich, Zn-rich, or Au-rich portions). Evaluation of hydrothermal alteration of igneous and sedimentary host rocks will involve the identification of the alteration mineral assemblages and changes in geochemical composition of the host rocks in order to document zones of diffuse fluid flow that may not be otherwise apparent. Microthermometric examination of fluid inclusions in veins cross-cutting host rocks will provide temperatures of the fluids responsible for hydrothermal alteration.

Alternatively, if no useable fluid inclusions are found, oxygen isotope geothermometry of hydrothermal minerals coexisting in equilibrium will be used.

Technical Resources Available

Within the Geology Department there is a modern analytical geochemical laboratory with atomic absorption and wet chemical facilities; ARL EMX and Etec Autoprobe electron microprobes and Siemens x-ray fluorescence spectrometer, all with automated data collection and output facilities; x-ray diffraction facility; a LINKAM TH600 programmable heating/freezing stage for microthermometric examination of fluid inclusions in minerals; an analytical scanning electron microscope equipped with both scattered electron detector and energy dispersive analysis system; and magnetic sector mass spectrometers for gas species and light stable isotope analysis. A new ultra-clean laboratory exists for the chemical preparation of samples for Nd/Sm and strontium isotopic analysis. The department has a Dual-Unix computer, and a micro computer laboratory with several MS-DOS and Apple Macintosh computers, dot matrix and laser printers, PDP special purpose computers, high speed printers, plotters, and Calcomp pen plotters. On-campus there is an IBM mainframe computer and a Cray supercomputer. The department has a fully equipped machine shop with two machinists, a thin and polished section laboratory with two technicians, a curator, a draughtsman and a photographer. A geological library (Coleman Library) is maintained in the department under the supervision of of a full-time librarian. In addition, we have access to an extensive map library which is housed on the first floor of the Robarts Library.

At the Royal Ontario Museum there is an automated DTA apparatus and a geochronology laboratory with a new fully-automated multiple collector mass spectrometer for U-Pb dating. In the Department of Physics there is a spectrometer for Pb isotope analyses (Prof. R.M. Farquhar) and a state-of-the-art $^{40}Ar/^{39}Ar$ dating laboratory (Prof. D. York). An ion probe, optimized for ultra-trace element analysis exists at ISOTRACE (Isotope and Rare Atom Counting Equipment) which is a Geology-Nuclear Physics collaboration. Elemental and isotopic micro-analyses in the sub ppb-range are performed on geological, archaeological, and metallurgical materials with this sophisticated equipment which includes a 3 million volt accelerator and several mass spectrometers. A SLOWPOKE nuclear reactor, under the control of the interdisciplinary SLOWPOKE Committee, is used extensively by members of the department in preparing samples for instrumental neutron activation analysis. Counting facilities are available in the geology department and in the SLOWPOKE building.

The department will move into the new $45,000,000 Earth Sciences Centre in December 1988.

Budget

A detailed budget is given in Table 1.

Reporting Format and Timetable

The project is expected to be completed within three years. Progress reports suitable for publication will be submitted and results will be presented at relevant meetings and conferences (e.g., GAC/MAC, GSA, Cordilleran Roundup). The completion of the project will coincide with the production of Jan Peter's Ph.D thesis which will serve as the final report. Ultimately, research results will be published in appropriate journals.

Socio-Economic Benefit to British Columbia and Industry

This study will provide insights into the genesis of the Windy Craggy deposit, a particularly economically attractive and potentially world-class massive sulfide ore body in a volcano-sedimentary setting. In particular, the study will identify geological and geochemical controls influencing massive sulfide and attendant gold deposition. Research focuses on: 1) examination of the many controls that sediment are thought to

Table 1. BUDGET DETAIL

	1988 (MAY-DEC) X	1989 (JAN-DEC)	1990 (JAN-DEC)
Personnel			
Research Trainee:			
Jan M. Peter (Ph.D.)-standard NSERC rate	8000	12000	12000
Field Assistant	3000	3000	3000
Travel			
field work travel	4000	4000	4000
travel to meeting to present results			
(e.g., Cordilleran Roundup)		1000	1000
accomodation at Windy Craggy	8820	8820	4400
(2 persons @ $63/day per person)			
Supplies and Materials			
field supplies	500	500	250
laboratory supplies (e.g. chemicals for			
lead isotope sample preparation)	500	500	300
shipment of samples (Whitehorse-Toronto)	300	250	200
Support Services			
duplicating	100	100	200
thin, polished, fluid inclusion sections	500	1000	1000
scanning electron microscope with EDA@$35/hr	600	400	400
electron microprobe@$35/hr.	1000	1000	500
whole rock analyses	750	1000	500
stable isotope analyses	1500	1000	1000
age dating analyses	1500	1000	
computer use	300	300	500
drafting services	100	300	1000
photography services	100	300	500
Total $	31570.00	36470.00	30750.00

(offer $20 000)

need Fieldwork report

time in Victoria before + after

+ (talk here in fall)

exert on the process of massive sulfide formation such as the size, geometry, grade, and composition of deposits; 2) determination of the importance of subvolcanic sills and dikes in the mineralizing process; 3) identification of the control that tectonic setting has, if any, on the formation of massive sulfide. The study will provide an improved understanding of the geology of a relatively sparsely mapped area of British Columbia and will therefore benefit both the Provincial Geological Survey Branch and the exploration community. Conclusions arising from this research will aid in the refinement of conceptual models of massive sulfide formation in volcano-sedimentary settings and the development of exploration strategies for similar deposits in the vicinity.

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