Structure and stratigraphy of the Marg volcanogenic massive sulphide deposit, north-central Yukon

Peter M. Holbek
Atna Resources Ltd.[1]

David A. Copeland
Ellesmere Minerals Ltd.[2]

Rob G. Wilson[3]
Atna Resources Ltd.

Holbek, P.M., Copeland, D.A. and Wilson, R.G., 2001. Structure and stratigraphy of the Marg volcanogenic massive sulphide deposit, north-central Yukon. *In:* Yukon Exploration and Geology 2000, D.S. Emond and L.H. Weston (eds.), Exploration and Geological Services Division, Indian and Northern Affairs Canada, p. 319-333.

ABSTRACT

The Marg (Cu-Zn-Pb-Au-Ag) volcanogenic massive sulphide deposit is hosted within metasedimentary and metavolcanic rocks of the Devonian–Mississippian Earn Group and Mississippian Keno Hill Quartzite. These rocks form part of the Selwyn Basin, an off-shelf sequence that developed at the continental margin prior to Cordilleran deformation and accretion.

Geological mapping and re-analysis of drill core was completed to re-assess the deposit and property-scale economic potential. The Marg deposit is deformed by at least three generations of structures that developed during Late Jurassic to Early Cretaceous time and are geometrically correlative with regional-scale structures such as the Robert Service Thrust and the Tombstone strain zone. The Marg deposit occurs within a southeasterly plunging, complex fold structure, a significant part of which has been removed by erosion. Discovery of additional stratigraphy comparable to the Marg sequence and new sulphide occurrences within the claims underscores both property and regional exploration potential. The presence of probable rift-related volcanism and mineralization within the Selwyn Basin, and the similarities of this mineralization to that within 'suspect' terranes, has implications for both regional tectonics and exploration.

RÉSUMÉ

Le gisement de sulfure massif volcanogénique (Cu-Zn-Pb-Au-Ag) de Marg est logé dans les roches métasédimentaires et métavolcaniques du Groupe d'Earn, d'âge Dévonien–Mississippien, et dans le Quartzite de Keno Hill, d'âge Mississippien. Ces roches font partie du Bassin de Selwyn, une séquence de talus qui s'est développée le long de la marge continentale avant le stade de déformation et d'accrétion de la Cordillère.

On a établi une carte géologique et analysé de nouveau les carottes de forage afin de réévaluer le potentiel économique du gisement et de l'ensemble de la propriété. Le gisement de Marg fut déformé par au moins trois générations de structures qui se sont succédées du Jurassique tardif au Crétacé précoce et sont en corrélation géométrique avec les structures régionales telles le Chevauchement de Robert Service, la zone déformée de Tombstone, et l'antiforme de Mayo. Le gisement de Marg repose dans une structure complexe de plis qui plongent vers le sud-est et dont une proportion importante a été effacée par l'érosion. La découverte d'autres unités stratigraphiques comparables à la séquence de Marg et de nouveaux indices de sulfures sur les claims révèle le potentiel d'exploration régionale. Les indices de volcanisme et de minéralisation dans le Bassin de Selwyn, qui sont probablement reliés à l'extension régionale, de même que les similitudes entre cette minéralisation et celle des terranes 'suspects', ont une influence à la fois sur la tectonique et l'exploration régionales.

[1]*Atna Resources Ltd., Suite 1550, 409 Granville Street, Vancouver, British Columbia, Canada V6C 1T2*

[2]*Ellesmere Minerals Ltd., Suite 220, 9797 45 Avenue, Edmonton, Alberta, Canada T6E 5V8. cpb1@canada.com*

[3]*rwilson@atna.com*

INTRODUCTION

The Marg volcanogenic massive sulphide deposit is hosted within a thick sequence of predominately metasedimentary rocks of the North American continental margin and, as such, represents an unusual setting for this deposit type. The deposit currently has a resource of 5.5 million tonnes grading 1.76% Cu, 4.5% Zn, 2.5% Pb, 86 g/t Ag and 0.9 g/t Au (Franzen, 1997). Recent geological work described herein suggests that the original deposit was substantially larger prior to erosion, demonstrating that the deposit type is an attractive exploration target. Exploration work during the 2000 field season consisted of geological mapping (1:5000 scale), geochemical sampling, prospecting, and re-logging drill core, plus geochemical analysis of previously drilled core. The purpose of this work was to better understand the geological setting, stratigraphy and structure of the deposit and its host rocks, as well as the geochemical changes associated with mineralization and alteration, in order to guide future exploration.

LOCATION AND ACCESS

The Marg claims are located in central Yukon on NTS map sheets 105M/15 & 16, 106D/1 & 2, centred at approximately 64°00' N and 134°30' W (Fig. 1). Access to the claim group is by helicopter from Mayo (located approximately 80 km to the southwest), or by small aircraft to a 380-m-long airstrip located near the Marg deposit area. The Marg property consists of 402 contiguous mineral claims covering approximately 8403 hectares. The property is owned by a joint venture between Atna Resources Ltd. ($66^2/_3$%) and Cameco Corporation ($33^1/_3$%).

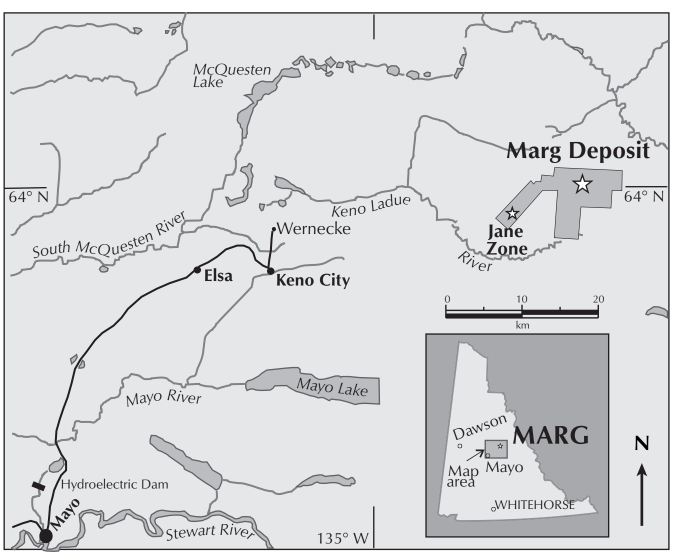


Figure 1. *Location map of the Marg property, north-central Yukon.*

Claims are situated within sub-alpine to alpine terrain within the Patterson Range with elevations varying from 600 to 1900 m. The majority of the claim block is covered with a thin veneer of talus or colluvium. Overall, outcrop exposure averages less than 10%, although some slopes within cirque headwalls approach 70% exposure.

EXPLORATION HISTORY

The Marg property has an extensive history with numerous owners and work programs attesting to both the difficulty of discovery, and the benefits of perseverance. Although there have been many owners, until the most recent program, all of the work carried out on the property, including its discovery, has been undertaken by Archer Cathro & Associates (1981) Ltd. and their predecessors.

The Marg area was first staked in 1965 by a joint venture between United Keno Hill Mines Ltd. and Canadian Superior Exploration Ltd. The joint venture program, following the release of the Geological Survey of Canada reconnaissance stream sediment survey results, entailed geochemistry and prospecting with the objective of finding Keno Hill-style silver veins. No significant silver mineralization was found and the claims were allowed to lapse. In 1982, the area was re-staked by the ZX joint venture between SMD Mining Company Ltd. (now Cameco), Chevron Minerals Ltd., and Enterprise Exploration Ltd. (an Australian exploration subsidiary of Rio Tinto). An exploration program included hand trenching in geochemically anomalous areas in search of sedimentary exahalative-style (SEDEX) lead-zinc mineralization. Enterprise abandoned their interest in the property and the project was optioned to All-North Resources Ltd. (All-North) who earned a 50% interest through a program that included geochemical and geophysical surveys (VLF and MaxMin EM, magnetometer, and IP) plus trenching. In 1987, NDU Resources Ltd. (NDU) purchased All-North's interest and Chevron converted its 25% working interest to a 5% net profits interest. This resulted in NDU controlling $66^2/_3$% of the joint venture and Cameco controlling $33^1/_3$% of the property.

The NDU/Cameco joint venture explored the property in two phases. NDU's portion of the second phase was financed through a short-lived option with Noranda Inc. and Brenda Mines Ltd. The 1988 work program included claim staking, geological, geochemical, and geophysical surveys (VLF and Pulse EM) plus 6038 m of diamond drilling in 33 holes, which defined extensive volcanogenic mineralization. Work also included construction of a 380-m-long airstrip, an airphoto survey, preliminary exploration of the Jane zone, and initiation of a baseline environmental program. In 1989, the NDU/Cameco joint venture continued to explore the property, and purchased Chevron's 5% net profits interest in proportion to existing ownership. Diamond drilling on the Marg zone consisted of 1819 m in five holes. Work on the Jane zone included grid geological, geochemical and geophysical (VLF-EM, Pulse EM and Magnetometer) surveys. Reconnaissance geochemical sampling was also completed over much of the property and further water samples were collected for environmental monitoring. Work continued in 1990, with an additional nine holes, totaling 4120 m, completed on the Marg zone. Hand (blast) trenching and sampling was carried out on the Jane zone. Baseline environmental monitoring surveys initiated in 1988 were continued and the resource estimate was updated.

The project was re-activated in 1996; work consisted of 8518 m of diamond drilling in 29 holes, and additional work was carried out on the Jane zone. Environmental monitoring water sample sites were re-established and sampled.

United Keno acquired NDU in 1997, thereby obtaining the majority interest in the Marg property. United Keno envisioned placing the property into production using the Keno mine site for processing the Marg ore. To this end, United Keno completed additional diamond drilling (7 holes for 2540 m) and nearly completed a winter road from the town of Keno to the property. In 1998, United Keno issued convertible debentures to Norvista Development Ltd. (Norvista) and withdrew cash through a promissory note using the Marg property as collateral. United Keno subsequently went into default on the promissory note. Norvista obtained a judgement against United Keno resulting in the court-ordered sale of United Keno's interest in the Marg claims. Atna Resources Ltd. (Atna) successfully bid on the property in late 1999. Atna and Cameco completed a novation agreement and formed a joint venture to further explore the property.

REGIONAL GEOLOGY

The Marg property lies south of a shelf/off-shelf regional boundary and within the Selwyn Basin, a predominantly off-shelf metasedimentary and metavolcanic sequence that forms part of the Foreland Belt of the northern Canadian Cordillera. Regional geology, as described by Green (1971, 1972) and Abbott (1990a,b), consists of three major tectonostratigraphic elements. These elements are, from north to south: Middle-Proterozoic shelf sequence carbonate rocks of the Wernecke Supergroup (that are unconformably overlain by Lower to Middle Paleozoic carbonate shelf sedimentary rocks); Neoproterozoic to Lower Cambrian off-shelf rocks of the Hyland Group; and Devonian to Mississippian rocks of the Earn Group and the Keno Hill Quartzite (Fig. 2). Deformation, metamorphism and imbrication of the varying stratigraphic units occurred during the Jurassic to Early Cretaceous (190 to 120 million years ago).

Three major fault structures control the geometry of the major stratigraphic units. The northern-most fault, the Dawson Thrust, separates off-shelf rocks of the Selwyn Basin (Keno Hill Quartzite, Earn Group, and Hyland Group) from shelf rocks of the Wernecke Supergroup. The central Tombstone Thrust (Fig. 2), imbricates rocks of the Keno Hill Quartzite and the Earn Group, host of the Marg deposit. The southern-most fault, the Robert Service Thrust, carries rocks of the Hyland Group onto Earn Group and Keno Hill Quartzite. The Wernecke Supergroup and other associated shelf rocks are not present in the vicinity of the Marg property and will not be discussed further.

All of the rock units have been deformed by at least two, and locally three, phases of deformation (Abbott, 1990a,b; Gordey, 1990; Turner and Abbott, 1990; Murphy, 1997). The structures are generally composed of varying degrees of ductile and brittle deformation, compatible with the lower- to middle-greenschist facies metamorphic grade of the region, and vary depending upon proximity to the thrust faults (Gordey, 1990). The first phase of deformation is characterized by north- to northeast-vergent, overturned, isoclinal folds whose axial surface parallels the south-dipping, regional-scale thrust faults (Turner and Abbott, 1990). These folds, and related thrust faults, define the major south-dipping aspect of the thrust panel, with the majority of fold axes and associated linear features plunging to the southeast. Refolding of first phase structures locally produces a penetrative rodding and mineral lineation plunging to the southeast

Figure 2. Regional geology of the Marg property, north-central Yukon (after Turner and Abbott, 1990).

(Abbott, 1990a) and a second axial planar cleavage (Gordey, 1990). A later phase of deformation consists of upright, open to tight, southwest-vergent folds. These third phase folds have axial planes with steep northeasterly dips and fold axes that plunge to the south-southeast.

The two (or more) early episodes of deformation are related to shortening, imbrication, and thickening caused by overthrusting of the off-shelf and shelf sequences during a Jurassic orogeny. Elongation lineations associated with, or developed in, earlier fold structures are compatible with northwesterly motion along the thrust faults (Abbott, 1990a; Gordey, 1990), however, the northeasterly vergence of folds may also indicate earlier, northeasterly directed motion. The later generation of deformation overprints earlier structures, and may be related to re-activation along older faults.

MARG PROPERTY GEOLOGY

INTRODUCTION

Work by the Yukon Territorial Government and Federal Government in recent years has provided a new geological framework for the Marg area. In order to place the property and deposit geology within this new framework, geological mapping at 1:5000 scale, detailed core logging and evaluation of previous work was undertaken. Previous workers classified and described stratigraphy using metamorphic mineral assemblages. Although the rocks are highly strained, the abundance of drill core permits the classification of rock units using both primary textures and composition, as indicated by metamorphic mineral assemblages. An attempt has been made to keep map unit notations consistent with existing maps.

STRATIGRAPHY

The Marg property is primarily underlain by a thrust panel between the Robert Service and Tombstone thrust faults (Abbott, 1990a,b). This thrust panel consists of four major stratigraphic/lithologic groups within the property map area (Fig. 3). A precise stratigraphic progression within this thrust panel is difficult to determine due to extensive folding and faulting. However, chronological data, discussed below, provides a reasonable context with which to order the various map units. These map units consist of the following: the Late Precambrian to Early Cambrian Hyland Group (PCh); probable Earn Group rocks, which includes a package of black shales and graphitic argillite (DMps); felsic fragmental metavolcanic rocks (DMv); a mixed metasedimentary, metavolcanic and carbonate package (DMvs); Mississippian Keno Hill Quartzite (Mq); and Triassic diorite to gabbro dykes and sills (Td).

HYLAND GROUP

Unit PCh

The oldest rocks within and surrounding the Marg property are believed to be Neoproterozoic to Lower Cambrian Hyland Group siliciclastic metasedimentary rocks (PCh on Figs. 2, 3). Rock types included in this unit regionally are quartz sandstone, quartzite, quartz-feldspar grit, buff-weathering grey phyllite, buff- to grey-weathering limestone, and silty to sandy limestone that locally grades to calcareous grit (Gordey, 1990). Within the Marg area, lithologies consist of dirty sandstones or greywackes, quartzo-felspathic grits, phyllite and minor carbonate and mafic volcanic rocks. The minor units, a thin, relatively pure marble (PCmb) and a thin sequence of mafic volcanic rocks (PCmv) have been broken out (Fig. 3) as these units are distinctive and may be useful as marker horizons.

The Hyland Group is the lowest mapped unit in the property area and is distinctive due to an abundance of blue, relatively coarse-grained, quartz grains. These rocks, situated just north of the Marg deposit (1.5 km), were initially mapped as Hyland Group by Abbott (1990a), but were later considered (Abbott, 1990b) to belong to a younger (Mississippian?) suite of volcanic and volcaniclastic metasedimentary rocks. Lithologies present on the Marg claims are typified by the presence of blue quartz grains, not observed in any of the overlying rocks, and closely match the description of the Hyland Group provided by Gordey (1990) for the map area immediately south of the Marg property. On the Marg property, the Hyland Group rocks are separated from the overlying Earn Group stratigraphy by a thrust fault, which, although not exposed, is inferred from a subtle upwards truncation of stratigraphy from east to west. Intrusive rocks are not observed crossing this contact. The lower contact of the Hyland Group is the Tombstone Thrust Fault (Abbott, 1990b). The upper thrust, which places younger on older rocks, may represent later movement on a synclinal infold of the Hyland Group within the Earn Group. Hyland Group rocks above the Robert Service Thrust Fault were not investigated.

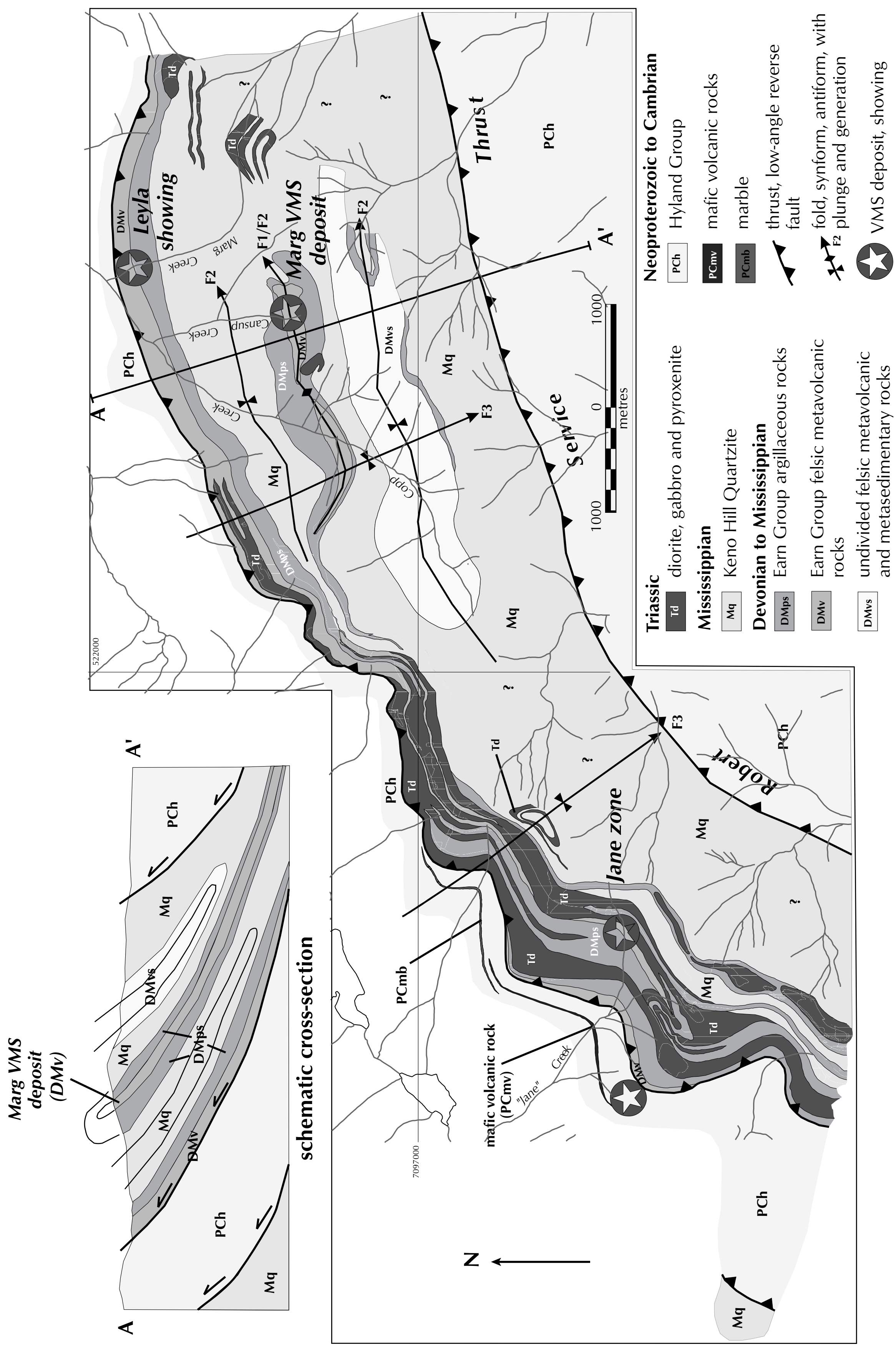


Figure 3. *Property-scale geology map of the Marg property.*

During mapping, the Hyland Group rocks were defined by an abundance of blue quartz grains, both within greywackes or grits and within quartz and sericite-rich phyllites that are thought to be distal or reworked tuffaceous rocks. Meta-tuffaceous rocks are fine-grained, strongly foliated, and lack primary macroscopic volcanic features, except rare, lapilli-sized, lithic fragments. They occur as 1- to 15-m-thick bands intercalated with argillaceous and siliceous (greywacke) metasedimentary rocks. The overall sequence of the Hyland Group is generally thick-bedded and may have a total thickness in excess of 1 km. Sulphide mineralization was recently discovered to be associated with altered meta-tuffaceous rocks of the Hyland Group, in the Jane zone vicinity. This mineralization is in close proximity to mafic volcaniclastic and mafic rocks (see below) but lacks the anomalous base and trace element chemistry associated with the mineralization in the Earn Group.

Unit PCmf

Mafic volcanic rocks were discovered in the western part of the property, enclosed within metasedimentary rocks of unit PCh. These mafic volcanic rocks occur as thin bands, from 1 to 10 m thick, along what is interpreted to be a single stratigraphic horizon. Mafic rocks are characterized by a fine-grained matrix of chlorite and amphibole. Volcanic textures include quartz and calcite amygdules, which may indicate basalt flows deposited in a sub-aerial to sub-aqueous environment. In one location, the rocks seemingly display pillow shapes with fine-grained chloritic rinds and siliceous knots within rind (pillow?) interstices. These basalts are the only mafic flow rocks discovered to date on the Marg property. Mafic, probably volcaniclastic rocks, are intimately associated with the interpreted flow rocks, forming thin (<10 m) but laterally continuous bands. Mafic volcaniclastic lithologies have a large biotite component that together with grey, fine-grained, feldspar and quartz bands, defines alternating millimetre-scale microlithons. Mafic clastic rocks can contain minor (up to 10%) blue quartz grains that are coarser-grained than the surrounding matrix. Mafic flow and volcaniclastic rocks have similar chemistry, which indicates that these rocks are alkali basalts with anomalous levels of barium (4000 ppm) and zirconium (300–500 ppm).

Unit PCmb

Weakly foliated, homogeneous marble, hosted within metasedimentary rocks of the Hyland Group, occurs as thin, 5- to 25-m-thick bands that are laterally continuous for distances of 1 km. The white to pale brown marble is a minor component of the overall stratigraphy, and suggests a brief period of deposition within a shelf sequence in a shallow marine environment.

EARN GROUP

Metasedimentary and metavolcanic rocks form three distinct sequences on the Marg property, one of which is a 300-m-thick, but folded, succession that surrounds and hosts the Marg deposit. These rocks are correlated with the Earn Group, although lack of clear diagnostic features such as fossils or the chert-pebble conglomerate unit (Abbott, 1990a) makes this correlation tentative. Zircons from quartz-phyric sericite schist (crystal tuff; Turner and Abbott, 1990a) have poor U-Pb systematics but yield a minimum age of 344 Ma (Mortensen, pers. comm., 2001). Zircons from other units within this sequence have similarly poor U-Pb systematics but yield dates ranging from 368 to 375 Ma indicating a probable early Late Devonian age (J.K. Mortensen, pers. comm., 2001).

The Earn Group rocks have been informally subdivided into three map units, which are structurally, and probably stratigraphically interlayered with the Keno Hill Quartzite. The units are described in structural sequence. The ‘upper’ package (DMvs) of metasedimentary rocks consists of graphitic, argillaceous material with abundant intercalations of fine-grained volcaniclastic rocks and, locally, thin carbonate lenses. The ‘middle’ unit (DMps) is composed of black argillaceous rocks (graphitic schist). The ‘lower’ unit (DMv) is a volcanic sequence composed of quartz- and feldspar-phyric tuffs and possible flows, fine-grained ash tuffs and related volcanic sedimentary rocks, and massive sulphide mineralization.

Unit DMvs

This unit occurs as a synclinal keel located approximately 1 km south of the Marg deposit and consists of intercalated argillaceous metasedimentary rocks with subordinate, thin, pale green, fine-grained tuffs and limestone lenses. Outcrop exposures consist of brown to dark grey phyllites, minor pale green phyllites and white to cream coloured limestone. The significant differences between this unit and the other units correlated with the Earn Group is the lower graphite and quartz contents of the sediments, fine grain-size of the tuffaceous rocks, and most importantly, the presence of limestone lenses. Contacts with Keno Hill Quartzite are only exposed in a few locations and are sheared in all but one, where the contact appears to be gradational.

Unit DMps

This unit is primarily composed of graphitic, argillaceous metasedimentary rocks with minor metatuffaceous rocks. The sedimentary rocks are characterized by a phyllitic metamorphic and structural character, with fine alternating quartz and graphitic microlithons. This unit is defined as being approximately 90% black shale or mudstone with only minor intervals of volcanic ash and no quartzite. Minor intercalations of quartzite invariably signal the start of the Keno Hill Quartzite unit. There is significant variation in the silica content of the black shales as indicated by the presence of up to 40% quartz 'sweats' within the argillite, notably, those proximal to mineralization. Graphitic argillites of the Earn Group indicate a deep-water, off-shelf depositional setting (Roots, 1997a).

Unit DMv

Felsic, metavolcanic rocks are the primary host to the Marg massive sulphide deposit. Lithologies range from lithic and crystal-lithic ash tuffs through rare lapilli tuffs to coarse-grained, quartz-feldspar crystal tuffs or flows. Typically, these lithologies are yellow green to medium dark green depending upon relative amounts of muscovite and chlorite. Lithic fragments, grain-size and even phenocrysts are difficult to discern in outcrop, except on weathered, lichen-free surfaces, but are readily visible in drill core. Volcanic lithologies are generally thin (<25 m) and commonly interbedded with minor argillaceous material. Contacts between volcaniclastic units are commonly gradational, whereas contacts between volcaniclastic and sedimentary lithologies can be either sharp or gradational.

Coarse-grained quartz porphyry occurs between massive sulphide layers, near the central part of the deposit, and both unit thickness and quartz (± feldspar) grain size diminish along strike in both directions, as well as down dip, suggesting a possible flow-dome complex or the centre of a pyroclastic flow channel.

Earn Group felsic metavolcanic rocks are thought to be mainly pyroclastic flows based on observed textures in drill core as well as their lateral extent (kilometres) relative to thickness, limited compositional variation, and lack of broken phenocrysts. These features suggest volcanic derivation from a regional felsic dome or intrusive complex (Roots, 1997a).

KENO HILL QUARTZITE

Unit Mq

The Keno Hill Quartzite (Green, 1971) consists of black to dark-grey weathering (but light grey on fracture surfaces), homogeneous, fine- to medium-grained, 'clean', quartz-rich (>90% quartz) rock, commonly containing 2- to 30-m-thick intercalations of graphitic argillite and rare interbeds of metatuffaceous rocks. The quartzite is anomalously thick and laterally extensive within the Marg area (Abbott, 1990a) commonly forming extensive lenses in excess of 100 m thick. The Keno Hill Quartzite is intruded by deformed, Triassic (?) meta-diorite to meta-pyroxenite sills and/or dykes. A Mississippian age of the Keno Hill Quartzite is indicated from fossil evidence at a number of localities in the Dawson area (Mortensen and Thompson, 1990; and Orchard, 1991).

Quartzite and intercalated argillite likely had sandstone and shale protoliths that were deposited in a near-shore environment. This is based on the occurrence of non-marine plant fossils and gastropods (Roots, 1997a; Tempelman-Kluit, 1970). Contacts between the quartzite and probable Earn Group rocks are commonly fractured due to the rheological differences, however, unfractured, both gradational and sharp contacts with argillite and tuffaceous rocks are observed within drill core, suggesting conformable relations with adjacent rocks on the Marg property.

INTRUSIVE ROCKS

Unit Td

Metasedimentary and metavolcanic rocks of the Keno Hill Quartzite and Earn Group in the Marg map area are intruded by deformed meta-diorite to meta-pyroxenite dykes and/or sills and undeformed Cretaceous (?) granite to granodiorite plutonic rocks (Abbott, 1990a). The Cretaceous intrusions have pervaded the stratigraphy within the Mt. Westman map area (106D/1) and Abbott (1990a) interprets this to indicate that much of the region may be underlain by Cretaceous granitic stocks.

The mafic intrusive rocks are part of a belt, which extends for at least 200 km to the northwest (Green, 1972; Abbott, 1990a). These rocks have an indicated Triassic age, based on a zircon and baddelyite U/Pb age of 232 ± 1.5-1.2 Ma, obtained on a sample from the

Tombstone Range, (Mortensen and Thompson, 1990) in the northwestern end of the belt. Within the Marg area, the mafic intrusive rocks are typified by medium-grained, equigranular, euhedral hornblende-plagioclase diorite to gabbro that locally contains porphyritic K-feldspar. In isolated locations, the gabbros have differentiated K-feldspar- to plagioclase-rich margins that may indicate tops. Larger bodies of these intrusive rocks have been observed to contain pyroxenite cores. Intrusive bodies vary in thickness between 10 and 150 m and have strike extents up to 3.5 km. Hornblende and pyroxene within these dykes or sills is frequently replaced or pseudomorphed by actinolite, chlorite or fuchsite.

Contacts of the intrusive rocks with surrounding older metasedimentary and metavolcanic rocks are typified by moderate to intense ferroan carbonate alteration and/or hornfelsed metasedimentary rocks. These contact zones are generally 5–15 m thick and commonly extend for considerable lengths along the intrusive body. The sills locally contain sheet-like xenoliths of foliated Earn Group argillite, Earn Group tuff or Keno Hill Quartzite (up to 10 m in length). Chilled margins within diorite are defined by a conspicuous reduction in grain size, although the margins and contact aureoles are less developed where intrusions are thin (10–20 m).

The medium-grained crystalline nature of the majority of the intrusive rocks suggests emplacement into the surrounding metasedimentary and metavolcanic rocks at depth, where residency times were long enough to accommodate significant crystallization.

There is the possibility of an older suite of mafic intrusions, which occur in the vicinity of the sulphide deposit. Thin, mafic intrusions proximal to the sulphide deposit display unusual textures, some that resemble peperites, possibly indicating intrusion into wet sediments. Termed 'greenstone' in drill logs, these units are commonly fine-grained, foliated and occur in various stages of iron-carbonate replacement, which varies from pale yellow to bright orange. The thicker units (>5 m) generally have green core zones with pervasive iron carbonate alteration along the margins. Iron carbonate alteration may also be replacing part of the host rocks adjacent to the intrusive contact, and may partly account for some of the unusual textures. As all of the intrusions were emplaced prior to deformation, it is not possible to distinguish syngenetic from epigenetic intrusions based on deformation state. Chemical analyses from the mafic intrusions are pending and may help determine if there is any difference between the mafic intrusive units.

STRUCTURAL GEOLOGY

Rocks within the Marg deposit area record a complex history of strain and deformation during the Jurassic to Cretaceous orogeny. Deformation has substantially modified the geometry of massive sulphide mineralization and its host rocks. Three distinct structural events are preserved and likely represent a continual deformation sequence that accommodated crustal shortening in both northwesterly and northeasterly directions. Structural data is presented in Fig. 4a, whereas actual structures are shown in Fig. 4b. A schematic illustration of structural features, fold geometries and the effect on mineralization is presented in Fig. 4c, which is similar to that presented by Gordey (1990) for the Tiny Island Lake map area.

Generation 1 structures

The earliest generation of deformation (D_1) observed within the area is marked by northeast-vergent, isoclinal folds (F_{1a}) that deform primary features. Fold closures were rarely observed, but where visible, plunge moderately (35° to 45°) to the southeast (100° to 130°). These folds contain axial surfaces that dip 35° to 45° to the south-southeast (120° to 160°), parallel to the regional south-southeast dip of bedrock within the region. In areas of higher strain, defined by intense foliation (S_1) that completely transposes all earlier features, phase 1 is represented by sheath folds (F_{1b}). Sheath folds are contained within the plane of maximum strain (S_1), exhibit parallel fold hinges with opposing asymmetry, plunge to the southeast, and are recognizable as minor folds in outcrop by characteristic elliptical features referred to as 'lipstick pattern' (Fig. 4b). Larger scale sheath folds are manifested as the double fold closures or elliptical outcrop patterns of unit DMv in the Marg deposit area (Fig. 3). The presence of sheath folds (F_{1b}) is supportive of a ductile shear zone style of deformation and may be related to northwest-vergent deformation (Murphy, 1997) associated with the Tombstone strain zone.

Generation 2 structures

The second generation of deformation (D_2) is characterized by tight to isoclinal asymmetric folds (F_2) that deform phase 1 isoclinal and sheath folds. Phase 2 folds are recognizable as map-scale structures (200–500 m) that fold contacts between the Earn Group, Keno Hill Quartzite and mafic intrusions. These fold structures verge to the northeast and have fold hinges that are coaxial with older F_1 folds. Foliation (S_2) related to this phase results in a crenulation cleavage and S_1/S_2 intersection lineation (L_2).

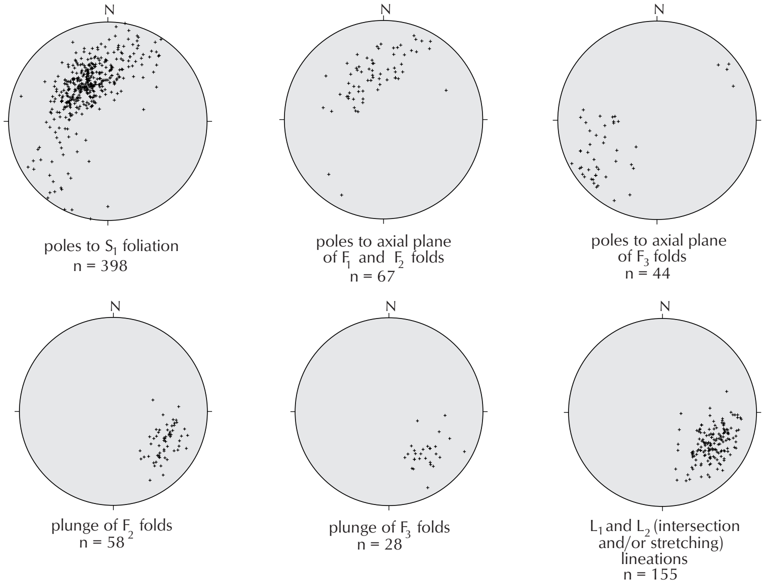
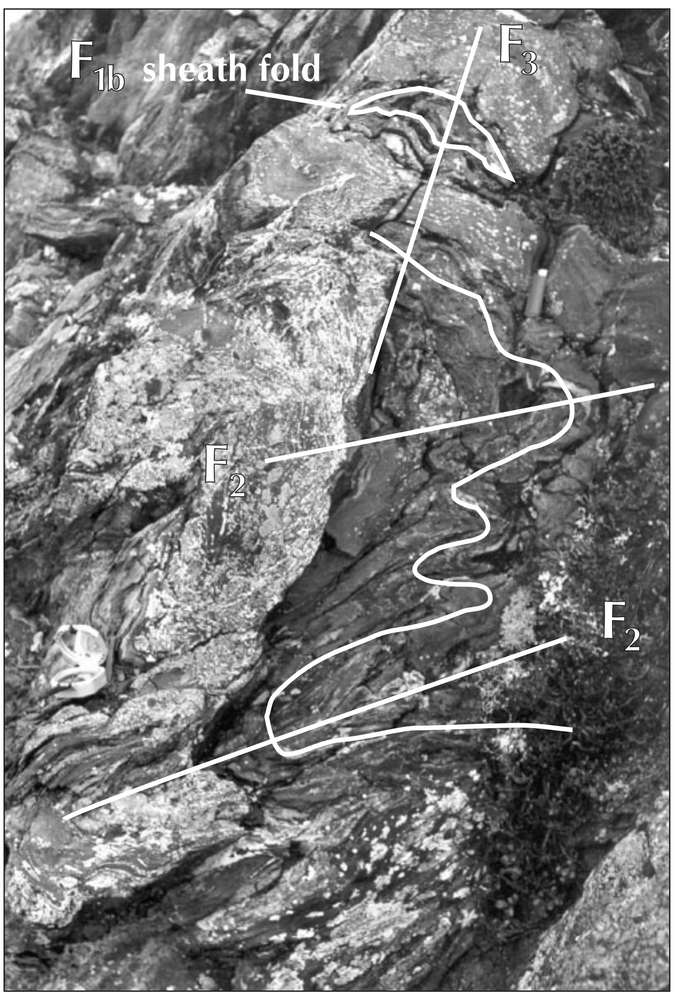


Figure 4a. *Stereographic presentation of structural data.*

Figure 4c. *Schematic illustration of fold styles on the Marg property. Folded bedding (S_0), or massive sulphide mineralization, may be attenuated along limbs. Penetrative cleavage (foliation, S_1) is folded by F_2 folds which are coaxial to F_1. Intersection of F_2 axial planar cleavage (S_2) with S_1 produces L_2 lineations. F_1 hinge lines may be irregular due to formation of sheath folds (F_{1b}, not shown). F_2 and F_1 axial traces plunge moderately to the southeast. F_3 folds are generally open with upright axial planes and gentle to moderate plunges to the southeast. Actual folds are tighter than shown.*



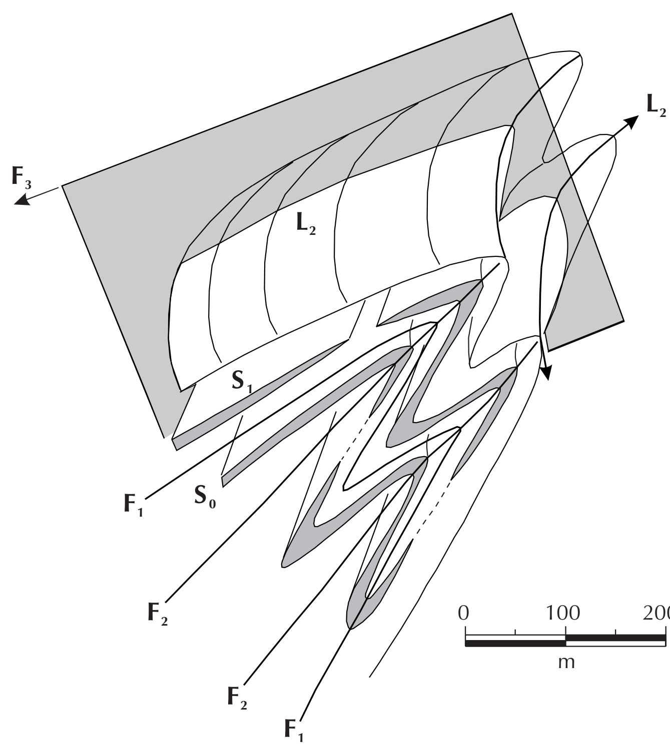


Figure 4b. *Photograph illustrating the relation between F_{1b} sheath fold (note opposing closure, identical plunge), F_2 northeast-vergent, isoclinal S-folds, and late open F_3 non-coaxial folds. Lithology is unit DMvs (metasedimentary rock). Note compass in lower left of photo for scale; compass needle is oriented north.*

Generation 3 structures

Phase 3 deformation (D_3) is non-coaxial with earlier folds, and is represented by open to tight folds (F_3) that deform map- and outcrop-scale D_1 and D_2 folds and foliations (Fig. 4b, c). F_3 folds verge to the southwest and have steep to upright (45° to 85°) axial surfaces that strike west-northwest (290° to 330°).

Significance to exploration

The Marg polymetallic massive sulphide deposit has been deformed by all three phases of deformation described above. The deposit is interpreted to be hosted within an early F_1 fold (or F_{1b} sheath fold) that has been subsequently deformed during coaxial D_2 deformation and non-coaxial D_3 deformation (Fig. 4c). In cross-section, the F_2 fold is an M-shaped fold, and the deposit shifts from being concentrated in the southern limb to the northern limb going from west to east.

Exploration drilling at the eastern end of the deposit (section 21+00 E, Fig. 5) intersected massive sulphide mineralization that terminates along strike to the east within isoclinal fold hinges. Mineralization plunges 45° to the southeast within coaxial F_1/F_2 fold closures. At the western end of the deposit, mineralization was observed to terminate along section 10+00 E, which could be due to the closure of stratigraphy within an isoclinal (sheath) fold hinge (mapped on surface). The termination of the stratigraphy on both ends of the deposit in folds that are geometrically correlative and have the same plunge and opposite sense of closure, supports the hypothesis that the Marg deposit is contained within the core of an F_{1b} sheath fold. Mineralization is known to continue down plunge along the eastern fold nose and is interpreted to continue at depth along the southeast plunge of the western closure. In a similar fashion, the Marg host stratigraphy is repeated west of the deposit area in another elliptical shaped sheath fold (Fig. 3); an area that hereto has received minimal exploration.

Non-coaxial F_3 folds deform the stratigraphy of the Marg sequence, but are not visible on the north-south drill sections as the fold axial trace strikes at a low angle (300°) to the north-south sections. F_3 folds are more obvious in longitudinal sections and plan, where they

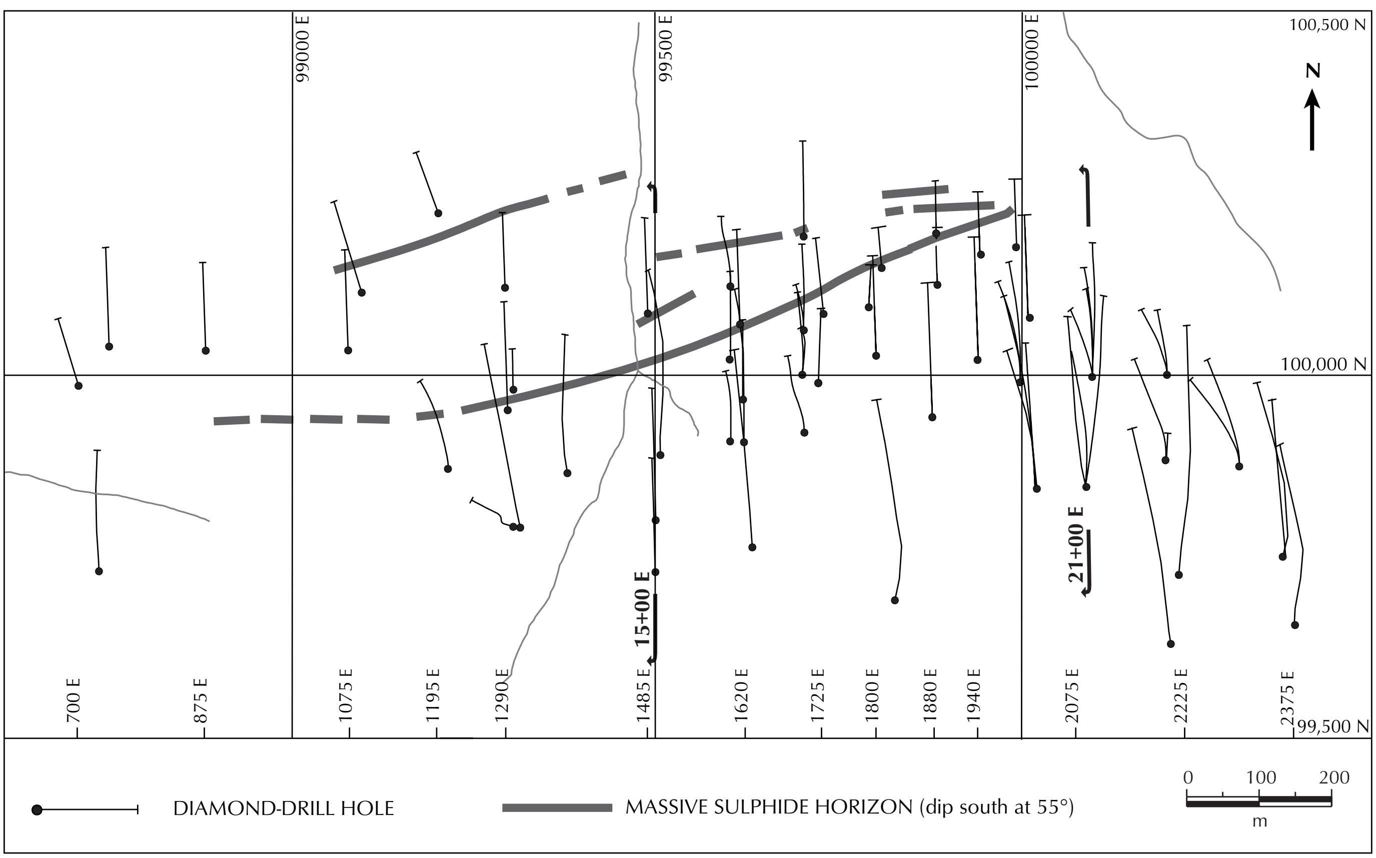


Figure 5. *Diamond-drill hole plan of the Marg property, displaying section locations.*

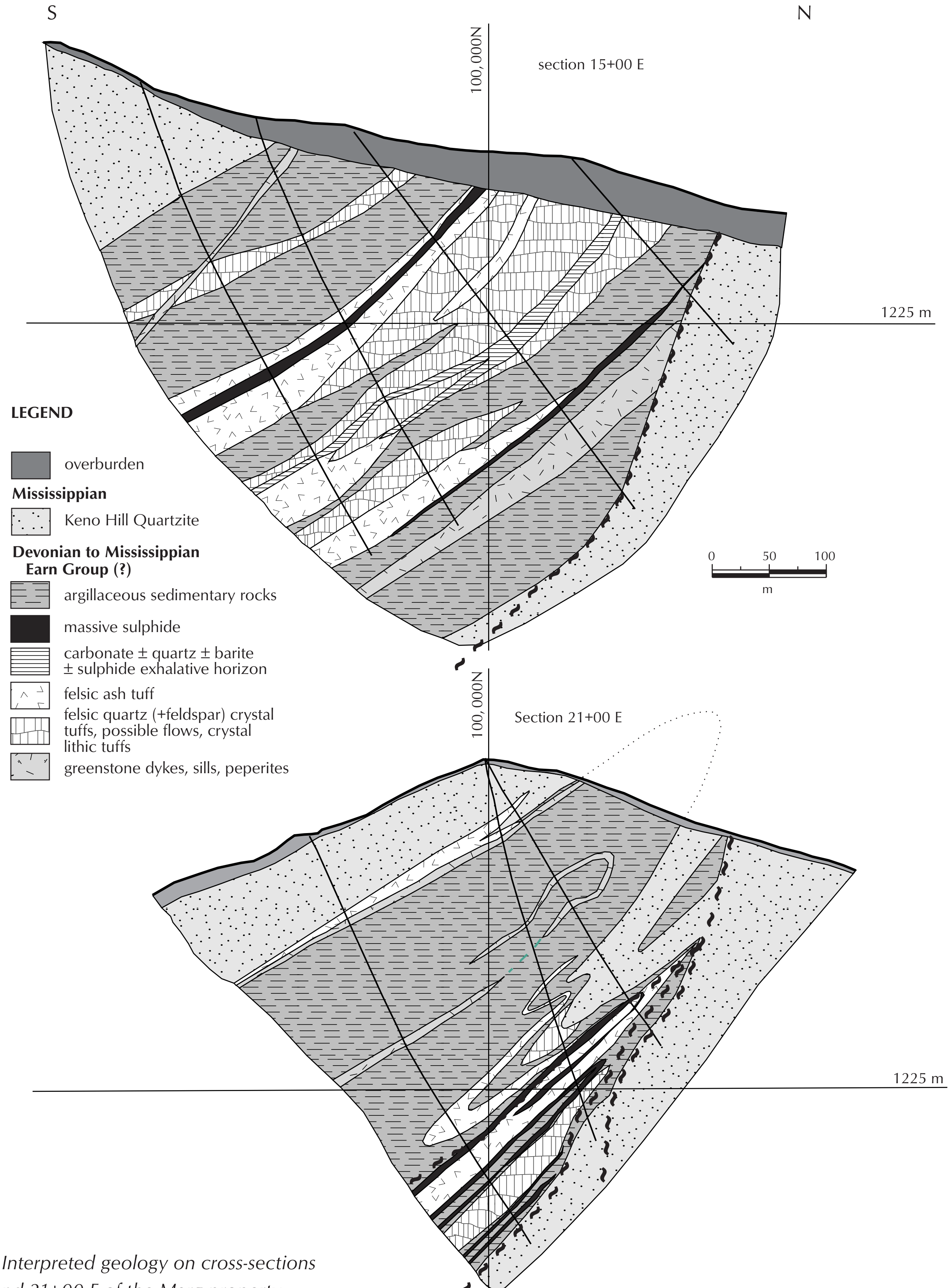


Figure 6. *Interpreted geology on cross-sections 15+00 E and 21+00 E of the Marg property.*

broadly fold the mineralized horizons. These folds will vary the drill depth to massive sulphide intersections along the length of the deposit.

Although not directly connected with Marg deposit host rocks, both the Jane zone and the newly discovered showing Leyla zone occur in structural continuations of the prospective DMv stratigraphy.

MINERALIZATION AND ALTERATION

The Marg deposit is made up of a series of continuous to discontinuous sheets of massive and semi-massive sulphide mineralization. Up to eight sulphide sheets can occur on a single section although most of the mineralization occurs within four sheets. A resource estimate was calculated by Franzen (1997), using the polygonal method and a minimum 3 m true thickness of 135 drill intercepts in 76 holes; this estimate is 5,527,000 tonnes grading 1.76% Cu, 2.46% Pb, 4.60% Zn, 62.7 g/t Ag and 0.98 g/t Au. The resource is contained in parallel sheets within an area 700 m along strike and 450 m down-dip. The average thickness of the >3 m intersections is 6.0 m (Fig. 6). The upper two sulphide horizons account for 82% of the resource.

Sulphide mineralization occurs at, or near, the contact between footwall volcaniclastic rocks and hanging wall argillaceous sediments. It is believed that the mineralized stratigraphy occurs within a refolded sheath fold that appears as an approximate 'M' shape in cross-section (Fig. 6). Minor folds, irregular stratigraphy, attenuation along isoclinal fold limbs, and foliation parallel faults with minor displacement, further complicate the geometry. It is probable that the main sulphide sheets represent a single refolded sulphide lens, an interpretation that is not particularly critical to exploration, but is supported by Turner and Abbott (1990), who documented the zonation of sulphide assemblage facies and metal ratios. Metal ratios, although variable within a single sheet, do not display any statistical differences between the various mineralized sheets, which might be expected if the sheets were separate stratiform deposits.

Mineralization is concentrated within the southern and central limbs of the 'M' fold in the western part of the deposit, but becomes progressively concentrated in the northern, or lower fold nose to the east (and down plunge), as illustrated in the two cross-sections of Figure 6. This transition from upper to lower fold limbs indicates that the original strike of the deposit was at a shallow angle to the F_2 fold structure. The cross-sections are not completely orthogonal to the strike direction and therefore dips appear to be shallower than they are in reality.

The lower contacts of the sulphide host rocks are locally truncated by the quartzite unit and the contacts are marked by fracturing or narrow intervals of gouge, which has been previously interpreted as a thrust fault. Kinematic indicators are lacking and sense of movement and actual displacement are not known, however, these faults are brittle fractures, which cut all deformation fabrics, including F_3 folds, and are therefore, unrelated to the regional thrust faulting (D_1/D_2).

Sulphide minerals consist of pyrite, sphalerite, chalcopyrite, galena, tetrahedrite and arsenopyrite in a gangue of quartz, ferroan carbonate, muscovite and rare barite. Magnetite is notably absent. It is probable that sulphide textures have been modified by strain but compositional layering on the millimetre to centimetre scale may be primary. Sulphide sheets are massive to semi-massive, with sharp, or less commonly, gradational, interlayered contacts. Alteration haloes of pervasive muscovite and carbonate are moderately developed and most conspicuous within the volcanic rocks. Black chlorite occurs locally, most notably near the up-dip footwall of the upper sheet. Because of the close proximity of the sulphide sheets, it is difficult to discern where the footwall alteration of one sheet ends relative to the hanging wall alteration of the adjacent sheet, or vice versa. Alteration is accompanied by enrichment in base metals as well as Hg, Mo, As, Ag, Ni, Ba and Mn. Lithogeochemical studies are ongoing and although zonation of 'indicator' elements does not appear to be as consistent and reliable as in some deposits, lithogeochemistry will still be useful to exploration, particularly within the argillaceous rocks where mineral alteration is not visually distinctive.

Sulphide mineralization is commonly overlain or underlain by silica, ferroan carbonate and more rarely, barite layers of possible exhalative (± replacement) origin. Exhalative horizons range from 3 to 300 cm thick and are most prominent in the central to eastern part of the deposit, commonly marking the structurally inferred location of the sulphide horizon where sulphide mineralization is minimal or absent. Interpreted exhalites are highly anomalous in base and precious metals as well as the indicator elements.

Lithogeochemical haloes (elements listed above) surrounding the massive sulphide horizons generally display both a decrease in thickness and intensity in the down-dip direction for all sulphide horizons, but most notably in the two upper (southernmost) horizons. This down-dip decrease is also more pronounced in an overall westerly direction. These trends in lithogeochemistry reflect the overall antiformal structure of the 'M' fold and the southeasterly plunge direction. A corresponding decrease in the thickness and grain size of the quartz-feldspar-phyric pyroclastic/flow rock and zonation of chloritic alteration suggests that the original, central core zone of the deposit was situated up-dip from surface and has been eroded. Thus, the original deposit may have been substantially larger prior to erosion.

DISCUSSION

Although deformation at the Marg property is probably too extreme to fully reconstruct the stratigraphy and setting of the Marg deposit, detailed studies of the lithologies, alteration, structure and lithogeochemistry are shedding light on the nature of the deposit and, more importantly, on the exploration potential of the property.

Exploration potential within the Marg property is high. Recognition of the structural style of the sheath folds allows the prediction of the location of prospective stratigraphy in the sub-surface. Mapping and prospecting have discovered structural repetitions of the volcanogenic massive sulphide (VMS) host stratigraphy that contain sulphide occurrences, such as the Leyla showing zone, which highlight the potential for discovery of new zones of massive sulphide mineralization. The previously discovered Jane zone is hosted by the strike extension of the Marg deposit host rocks, however, the thickness of the volcanic package and the intensity of alteration appears to be significantly greater than that present in the Marg area.

An 'undeformed' Marg deposit displays many features that are similar to the VMS deposits of Yukon-Tanana Terrane, namely the Kudz Ze Kayah (KZK) and Wolverine (Hunt, 1997; Tucker et al., 1997) deposits, and deposits of the Bonnifield district, Alaska. Marg metal ratios are most similar to KZK, whereas the alteration and setting (most notably, the tabular massive sulphide mineralization overlying a thin sequence of felsic crystal tuffs, flows and related volcaniclastic rocks within a thick package of sedimentary rocks) is more similar to the Wolverine deposit. Further studies will compare the chemistry of the volcanic rocks hosting the Marg deposit with those at Wolverine and elsewhere. Do the Marg volcanic rocks represent a slice of Yukon-Tanana-equivalent rocks imbricated into, and deformed along, the Tombstone strain zone? Stratigraphic evidence indicates probable conformity between the volcanic rocks and the Keno Hill Quartzite supporting VMS formation within the Selwyn Basin.

Geochemical, geological and structural data suggest that the central core zone of the deposit has been eroded, supporting speculation that the original deposit may have been two or three times larger than what is indicated by the estimated resource. The amount of volcanic rock, in relation to the massive sulphide mineralization, is relatively minimal, (a possible sub-volcanic intrusion, or reasonable facsimile, is inferred to have been present lower in the stratigraphy, prior to thrust faulting) making regional exploration based on mapping difficult. Given the overall size of the Selwyn Basin and the limited stratigraphic thickness of volcanic rocks required to host Marg-style VMS deposits, the potential for undiscovered VMS deposits is significant (Roots, 1997b).

Massive sulphide mineralization is spatially, and probably genetically, related to quartz-phyric volcanic rocks that likely originated within rift basins related to faults along the shelf edge of the continental miogeocline. The Keno Hill Quartzite, although the most resistant, and therefore, most prominent rock within the host stratigraphy, is likely not significant to mineralization. Anomalous thickness of the quartzite unit may, however, indicate the presence of a rift-related basin.

ACKNOWLEDGEMENTS

This paper is based on exploration carried out in the summer of 2000 but could not have been done without the extensive data collected and documented previously by Rob Carne and Frank Gish of Archer Cathro and Associates (1981) Ltd. Field mapping and structural analysis was carried out, mostly in inclement weather, by Dave Copeland with assistance from Nick Mitchell. Drill core logging was conducted by Leyla Weston and Peter Holbek. Prospecting and geochemical sampling was performed by Duncan MacRea. Camp management, computer systems control, drafting and geological supervision was performed by Rob Wilson. The paper benefited from review by Julie Hunt and discussions with

Don Murphy. Thanks are also due to Leyla Weston and Diane Emond for formatting, editing and guiding the manuscript through to publication.

Fieldwork on the Marg property would not have been carried out without the Yukon Mineral Exploration Tax Credit.

REFERENCES

Abbott, J.G., 1990a. Preliminary results of the stratigraphy and structure of the Mt. Westerman map area, central Yukon. *In:* Current Research, Part E, Geological Survey of Canada, Paper 90-1E, p. 15-22.

Abbott, J.G. 1990b. Geology of the Mt. Westman Map Area (106D/1), 1:50 000 scale. Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Open File 1990-1.

Franzen, J.P., 1997. Assessment of mineral reserves: Marg Zn-Cu-Pb-Au-Ag property. Unpublished company report of NDU Resources Ltd., 23 p.

Gordey, S.P., 1990. Geology and mineral potential, Tiny Island Lake map area, Yukon. *In:* Current Research, Part E, Geological Survey of Canada, Paper 90-1E, p. 23-29.

Green, L.H., 1971. Geology of Mayo Lake, Scougdale Creek and Mcquesten Lake map areas, Yukon Territory (105M15, 106D2, D3). Geological Survey of Canada Memoir 357.

Green, L.H., 1972. Geology of Nash Creek, Larsen Creek and Dawson map areas, Yukon Territory (105M15, 106D2, D3). Geological Survey of Canada Memoir 364.

Hunt, J.A., 1997. Massive sulphide deposits in the Yukon-Tanana and adjacent terranes. *In:* Yukon Exploration and Geology 1996, Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 35-35.

Mortensen, J.K. and Thompson, R.I., 1990. A U-Pb zircon-baddeleyite age for a differentiated mafic sill in the Ogilvie Mountains, west-central Yukon. *In:* Radiogenic Age and Isotopic Studies: Report 3, Geological Survey of Canada, Paper 89-2.

Murphy, D.C., 1997. Geology of the McQuesten River Region, northern McQuesten and Mayo map areas, Yukon Territory (115P/14,15,16; 105M/13, 14). Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada Bulletin 6, 122 p.

Orchard, M.J., 1991. Conodonts, time and terranes: an overview of the biostratigraphic record in the western Canadian Cordillera. *In:* Ordovician to Triassic Conodont Paleontology of the Canadian Cordillera, M.J. Orchard and A.D. McCracken (eds.), Geological Survey of Canada, Bulletin 412, p. 1-25.

Roots, C.F., 1997a. Geology of the Mayo Map Area, Yukon Territory (105M). Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Bulletin 7, 82 p.

Roots, C.F., 1997b. Upper Paleozoic strata with potential for massive sulphide mineralization, northwestern Lansing map area (105N), Yukon. *In:* Yukon Exploration and Geology 1996, Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 138-146.

Tempelman-Kluit, D.J., 1970. Stratigraphy and structure of the "Keno Hill Quartzite" in Tombstone River - upper Klondike River map-areas, Yukon Territory. Geological Survey of Canada, Bulletin 180, 102 p.

Tucker, T.L., Turner, A.J., Terry, D.A. and Bradshaw, G.D., 1997. Wolverine Massive Sulphide Project, Yukon. *In:* Yukon Exploration and Geology 1996, Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 53-55.

Turner, R.J.W. and Abbott, G., 1990. Regional setting, structure and zonation of the Marg volcanogenic massive sulphide deposit, Yukon. *In:* Current Research, Part E, Geological Survey of Canada, Paper 90-1E, p. 31-41.