Geology of the Wolverine polymetallic volcanic-hosted massive sulphide deposit, Finlayson Lake district, Yukon Territory, Canada[1]

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ABSTRACT

The Wolverine polymetallic volcanic-hosted massive sulphide deposit occurs in a highly deformed but coherent stratigraphic succession of early Mississippian to early Permian metavolcanic and metasedimentary rocks of the Yukon-Tanana Terrane. The deposit is part of the emerging Finlayson Lake volcanic-hosted massive sulphide district and contains a geological resource of 6,237,000 tonnes grading 12.66% zinc, 1.33% copper, 1.55% lead, 370.9 g/t silver and 1.76 g/t gold. Local stratigraphy consists of four major units including (from oldest to youngest): (1) quartz- and feldspar-phyric volcaniclastic, carbonaceous sedimentary and porphyritic intrusive rocks; (2) interbedded argillite, aphyric rhyolite and magnetite-carbonate-pyrite exhalite; (3) fragmental rhyolite; and (4) interbedded carbonaceous argillite, greywacke, basalt and rhyolite. The mineralization consists of pyrite and sphalerite, with lesser pyrrhotite, chalcopyrite, galena, tetrahedrite-tennantite and arsenopyrite. Mineralization occurs as massive stratiform, massive replacement and sulphide stringer veins. Sulphides are typically massive, fine-grained, layered and locally brecciated. Styles of hydrothermal alteration identified in the host rocks include proximal silicification and more distal chloritization, sericitization and, in places, carbonatization. Future research will be focussed on identifying the salient physico-chemical controls on the mineralization process and their implications for volcanic-hosted massive sulphide exploration in the district and elsewhere.

RÉSUMÉ

Le gisement de sulfure massif volcanogène polymétallique de Wolverine est logé dans une succession stratigraphique fortement déformée mais concordante, composée de roches méta-volcaniques et méta-sédimentaires du terrane de Yukon-Tanana, d'âge Mississippien précoce à Permien précoce. Ce gisement est situé dans le district minier émergent de Finlayson Lake; il contient une ressource géologique de 6 237 000 tonnes de minerai ayant une teneur de 12,66% de zinc, 1,33% de cuivre, 1,55% de plomb, 370,9 g/t d'argent et 1,76 g/t d'or. La stratigraphie locale comprend quatre unités majeures (en ordre d'âge décroissant) : (1) roches volcaniclastiques à porphyres de quartz et feldspaths, roches sédimentaires carbonées et intrusions porphyritiques; (2) interstratifications d'argilite, de rhyolite aphanitique et de roches exhalatives à magnétite, carbonate et pyrite; (3) rhyolite bréchique; et (4) interstratifications d'argilite carboné, de grauwacke, de basalte et de rhyolite. Le minerai se compose de pyrite et de sphalérite, et de quantités moindres de pyrrhotite, chalcopyrite, galène, tetrahédrite-tennantite, et arsénopyrite. La minéralisation est présente sous forme de veines massives stratiformes, de remplacements massifs, et de veinules de sulfures. Les sulfures sont généralement massifs, à grains fins, laminés et, localement, bréchiques. Les types d'altération hydrothermale reconnus dans les roches encaissantes comprennent une silicification proximale, une chloritisation et sericitisation plus distales, et une carbonatisation localisée. Les études à venir seront concentrées sur l'identification des principaux facteurs physico-chimiques contrôllant les processus de minéralisation et leurs influence sur l'exploration pour des sulfures massifs volcanogènes dans cette région et ailleurs.

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INTRODUCTION

The discovery of the Wolverine polymetallic volcanic-hosted massive sulphide (VHMS) deposit in 1995 was one of the most exciting events on the Canadian exploration scene in the mid-1990s. Its discovery, together with that of several other base metal deposits and mineral occurrences of potential economic significance (e.g., Fyre Lake, Ice, GP4F, Kudz Ze Kayah) heralded the emergence of the Finlayson Lake area in the Yukon as a potentially significant VHMS district. As of 1998, the Wolverine deposit contains a high-grade geological resource of 6,237,000 tonnes containing 12.66% zinc, 1.33% copper, 1.55% lead, 370.9 g/t silver and 1.76 g/t gold. Drilling in 2000 modestly expanded this geological resource and the deposit remains open at depth. Exploration efforts in and around the Wolverine deposit by joint-venture partners Expatriate Resources Limited (Expatriate) and Atna Resources Limited (Atna) continue, with the ultimate aim of expanding the existing resource and defining new areas of VHMS potential.

The discovery of significant VHMS mineralization in the Finlayson Lake district has provided the impetus to better understand the tectonic and geological history of the area. Regional geological mapping by the Yukon Geology Program was initiated in 1996 and results are summarized in Murphy and Timmerman (1997), Murphy (1998), and Murphy and Piercey (1999a,b,c). Tectonic and metallogenic studies conducted under the auspices of the Geological Survey of Canada's (GSC) National Mapping program (NATMAP) were initiated in 1999 (Thompson et al., 2000). More recently, another GSC project to study the characterization and genesis of VHMS deposits in the district was initiated. The present study forms part of this last project.

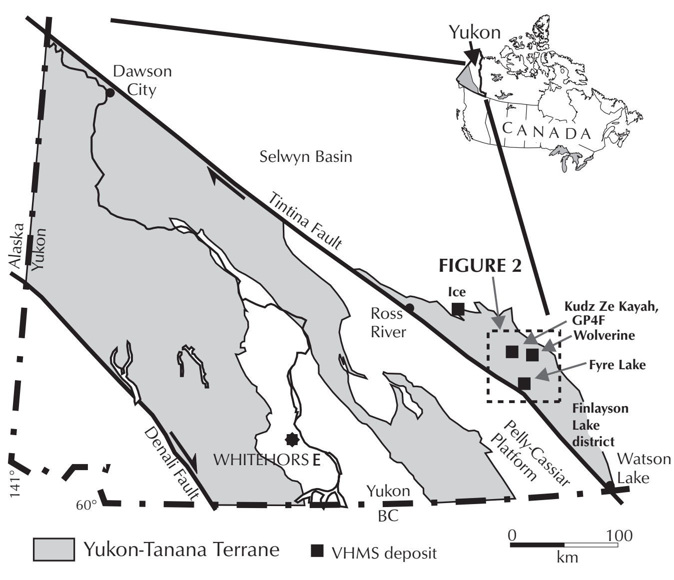

Figure 1. *Location map of the Yukon-Tanana Terrane (YTT), the Finlayson Lake district and the Wolverine deposit, plus other significant VHMS deposits in the Finlayson Lake district (from Piercey and Murphy, 2000). Location of Fig. 2 is also shown.*

In this contribution, we briefly review the exploration history of the Wolverine discovery, and update and expand upon the geological setting and field characteristics of the Wolverine VHMS deposit as outlined in Tucker, et al. (1997). In particular, we focus on the major host lithology, the types and styles of mineralization present, and the related hydrothermal alteration. Preliminary interpretations of the tectonic setting and mode of emplacement are presented.

EXPLORATION HISTORY

Due to its geographic isolation, the metallogenic potential of the area hosting the Wolverine deposit was virtually unknown until the 1970s and early 1980s, when exploration by the Finlayson Joint Venture exploration syndicate (a consortium managed by Archer, Cathro & Associates (1981) Limited) identified numerous, strong, multi-element, geochemical anomalies in soils over a gossanous area devoid of vegetation (termed the "Fetish showing"). Two small-diameter core holes were drilled in 1974 to test this geochemical anomaly, and both intersected low-grade copper- and zinc-sulphide mineralization up dip of the present Wolverine deposit. Despite this discovery of base metal mineralization, the claims were allowed to lapse.

Equity Engineering Limited (Equity) showed renewed interest in the area in 1993 after concluding that the region held promise for hosting VHMS-style mineralization based on favourable stratigraphy and the presence of surficial geochemical anomalies. On behalf of Atna, Equity staked claims over the deposit area and carried out a field exploration program, which consisted of geological mapping, prospecting, and rock/soil sampling. In 1995, Westmin Resources Limited (Westmin) optioned the property from Atna and undertook a vigorous exploration program designed to evaluate the mineral potential of favourable volcanic stratigraphy, which had a strike-length in excess of 10 km. Exploration activity consisted of detailed geological mapping and systematic grid-soil sampling. This fieldwork led to the identification of several additional multi-element geochemical anomalies. The strongest of these was in the area of the original Fetish showing, which was subsequently renamed the "Wolverine zone".

A diamond-drilling program by Westmin in August, 1995 intersected massive sulphide mineralization in the Wolverine zone in the first hole. The first follow-up drill hole, completed in early September of 1995, intersected 8.4 m of massive sulphide mineralization grading 7.63 g/t gold, 1358.3 g/t silver, 0.56% copper, 3.45% lead and 14.22% zinc. The discovery merited extensive drilling in the fall of 1995, and in the following summers of 1996 and 1997. After the 1997 program, 71 drill holes had intersected the mineralization and Westmin calculated a resource of 6,237,000 tonnes grading 12.66% zinc, 1.33% copper, 1.55% lead, 370.9 g/t silver and 1.76 g/t gold (Tucker et al., 1997). The deposit was defined over a strike length of approximately 750 m and remained open down dip to the northeast where it crossed onto the WOL claims owned by Cominco Limited (Cominco).

In 1996, Westmin carried out metallurgical testing on the Wolverine sulphide mineralization. Results in late 1997 confirmed the presence of unusually high levels of selenium (average of 1035 ppm Se, Expatriate Resources, 2000, unpublished data), a deleterious contaminant, which could significantly impact the saleability of the mineral concentrates. Further investigations of the problem, however, were terminated by the takeover of Westmin by Boliden Limited (Boliden) in early 1998. Following the takeover, Expatriate concluded a letter of agreement to purchase Boliden's interests in the Wolverine Project and by June 1999, a new Wolverine Joint Venture (Expatriate and Atna) announced that it was beginning an evaluation of alternative metallurgical methods for processing the sulphides.

In March 2000, Expatriate reached an agreement with Cominco to purchase Cominco's Finlayson Lake assets including the WOL claims immediately adjoining the Wolverine deposit. Metallurgical studies demonstrated that blending the ore from the Wolverine deposit with that from the newly acquired Kudz Ze Kayah deposit would dilute the selenium content to an acceptable level. Drilling programs by Expatriate in July, August, and October, 2000 expanded the existing resource and further defined the known mineralization on the Wolverine property.

REGIONAL GEOLOGY

The Yukon-Tanana Terrane (YTT) is an extensive, elongate, autochthonous terrane, which underlies much of the Yukon and Alaska and is one of the innermost terranes of the Canadian Cordillera (Fig. 1). The YTT is bounded to the northeast by rocks of the North American continental margin and to the southwest by rocks of Stikinia and Slide Mountain terranes. This complex, heterogeneous terrane of pericratonic origin is interpreted to be a Late Devonian to Early Jurassic composite arc sequence underlain by pre-Devonian sedimentary rocks of continental affinity (Mortensen, 1992). The rocks that host the Wolverine deposit are bounded to the northeast by the Finlayson Lake fault zone and to the southwest by the Tintina Fault, along which approximately 450 km of dextral offset (e.g., Mortensen, 1992) has separated this zone from the main portion of the YTT (Fig. 1).

The following summary of the regional geological setting of the Wolverine deposit comes mainly from the work of Murphy (1998), and Murphy and Piercey (1999a,b). Murphy (1998) placed the Fyre Lake, Kudz Ze Kayah and Wolverine VHMS deposits in a highly deformed but coherent stratigraphic succession of early Mississippian to early Permian metamorphosed plutonic, volcanic, and sedimentary rocks (Fig. 2). An angular unconformity separates a lower sequence of polydeformed felsic and mafic metavolcanic rocks, carbonaceous metaclastic rocks, marble and granitic orthogneiss (termed the "Grass Lakes succession") from a younger sequence consisting primarily of carbonaceous metaclastic rocks and quartz- and feldspar-phyric felsic metavolcanic rocks (termed the "Wolverine succession"; Fig. 3). It is the lower sequence that hosts the Kudz Ze Kayah, Fyre Lake and GP4F deposits. A possible second unconformity separates the Wolverine succession from the overlying Campbell Range succession, the latter of which is composed primarily of massive meta-basalt (Fig. 3).

In the immediate vicinity of the Wolverine deposit, three units are mapped (note that although all rocks are metamorphosed, the prefix "meta" is omitted from all rock names for purposes of simplicity). These units are (from oldest to youngest): Unit 5 – a sequence of carbonaceous phyllite, sandstone, conglomerate, muscovite-quartz phyllite, and quartz- and feldspar-phyric porphyry; Unit 6 – interbedded carbonaceous phyllite and siliceous rock; and Unit 7 – carbonaceous phyllite, greywacke, pale green argillite, gritty sandstone, chert and diamictite. The Wolverine deposit lies at the contact

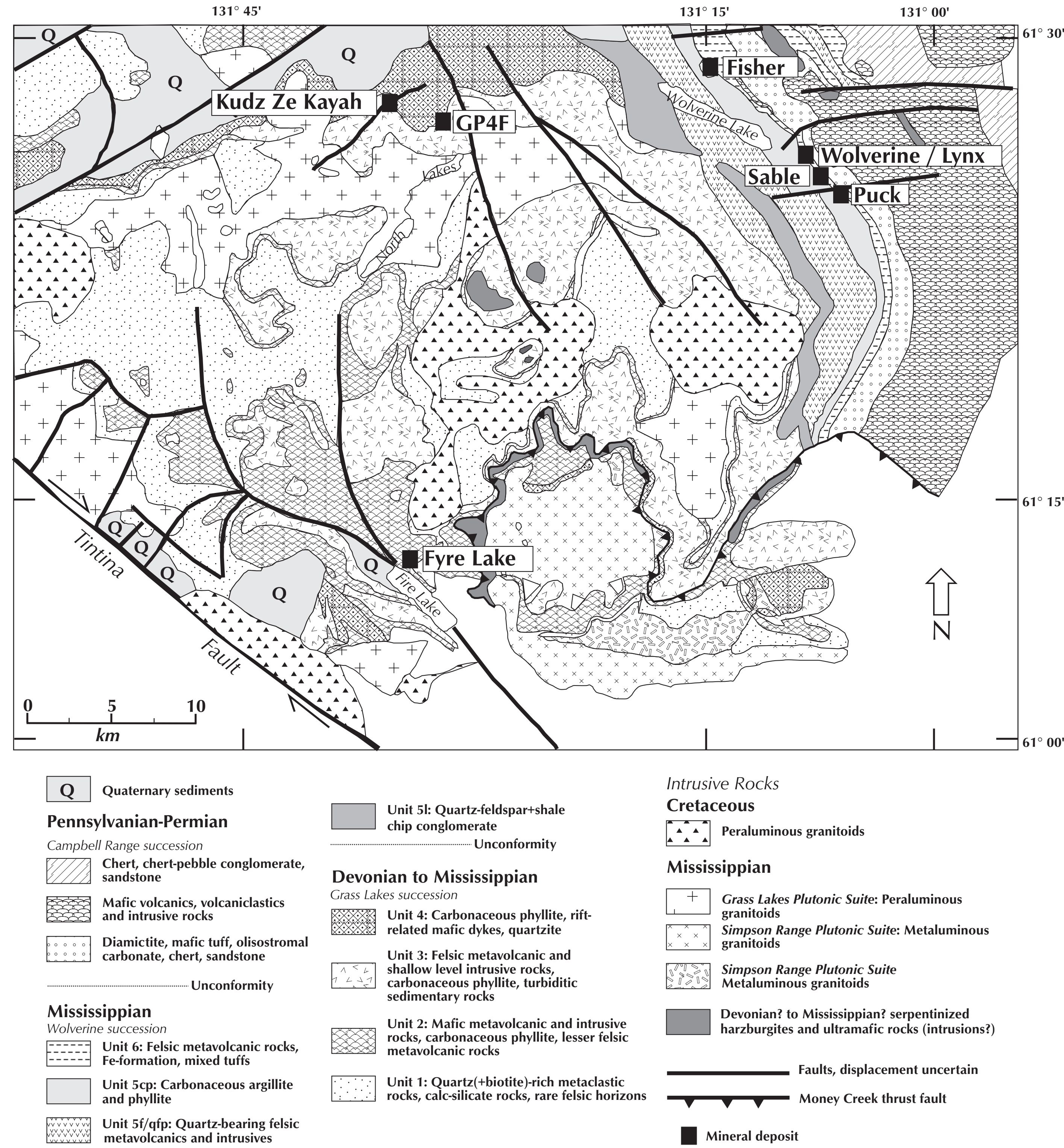

Figure 2. *Geological map of the Finlayson Lake region modified from Murphy (1998) and Piercey (1999c) with locations of different zones of the Wolverine VHMS deposit and other VHMS deposits of the Finlayson Lake district.*

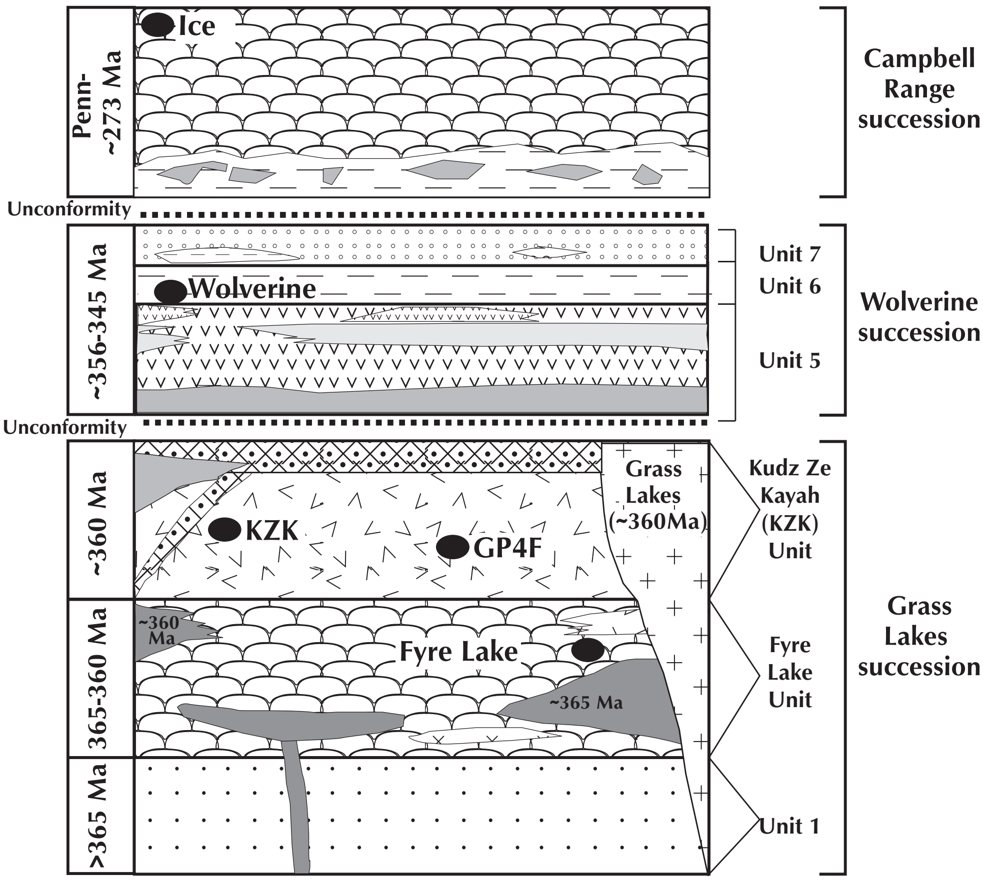

Figure 3. *Regional stratigraphic column of the host rocks to the VHMS deposits in the Finlayson Lake district (modified after Murphy and Timmerman, 1997; Murphy, 1998; Murphy and Piercey, 1999a,b,c; Piercey and Murphy, 2000).*

between Units 5 and 6 (Fig. 3). The deposit stratigraphy, which is described in the subsequent section, includes the uppermost part of Unit 5, Unit 6, and the lowermost part of Unit 7.

DEPOSIT GEOLOGY

The stratigraphic sequence hosting the deposit will be hereafter referred to as the “Wolverine stratigraphy.” The Wolverine stratigraphy is defined in this paper as those rocks 400 m above and 70 m below the massive sulphide mineralization for which there are sufficient data from drill core to establish confidently a coherent stratigraphy that is consistent throughout the entire area of the deposit. The lithologies forming the immediate host-rocks to the deposit are further subdivided below. The surface geology of the Wolverine deposit area is illustrated in Figure 4.

METAMORPHISM AND STRUCTURE

Rocks in the vicinity of the Wolverine deposit have been metamorphosed to middle- or upper-greenschist grade based on a defining metamorphic mineral assemblage of chlorite, actinolite, albite, titanite, carbonate and, in places, biotite. A single major deformational event has obliterated most primary volcanic and sedimentary features in the rocks. This deformational event is recorded as a prominent S_1 foliation, which trends northwest and dips gently to the northeast. This fabric is a curviplanar pressure-solution foliation that is defined by millimetre- to centimetre-scale seams of fine micaceous minerals that display increased spacing in the more siliceous units (e.g., Murphy, 1998).

Folds in the vicinity of the deposit are generally southwest verging, tight, and ‘S’ shaped when viewed to the northwest along the fold axes. These folds range from drill-core to outcrop scale and likely are related to similarly shaped kilometre-scale folds mapped in the Grass Lakes succession by Murphy (1997). The southwest vergence indicates that the Wolverine deposit is on the western limb of an open, upright, structure (D.C. Murphy, pers. comm., 2000). The relative lack of fold hinges and overturned limbs permits the correlation of units, some only one metre in thickness, between drill holes on the same cross-section (i.e., on the scale of about one half kilometre). Correlation between adjacent drill cores in certain cross-sections indicates some changes in thickness, and/or structural repetition of units near fold hinges. In rare cases, where primary compositional layering is visible, the intersection of the S_1 foliation with bedding (S_0) forms a lineation that parallels the orientation of the fold hinges. The compositional layering and S_1 foliation essentially are parallel except near the vicinity of fold hinges.

Layer-parallel (i.e., parallel to foliation) shearing has resulted in extensive gouge zones in the more ductile rocks (e.g., argillite) and intense fracturing in the more brittle rocks (e.g., rhyolite). Faulting is present to some degree throughout the entire Wolverine stratigraphy, although significant offset (>1 m) has not been identified in the cross-sections. Rootless folds are present locally. Most faults in the Wolverine stratigraphy are attributed to the same major deformational event.

STRATIGRAPHY

Despite greenschist-grade metamorphism and a high degree of deformation, it is possible to recognize volcanic, volcaniclastic and sedimentary protoliths at Wolverine.

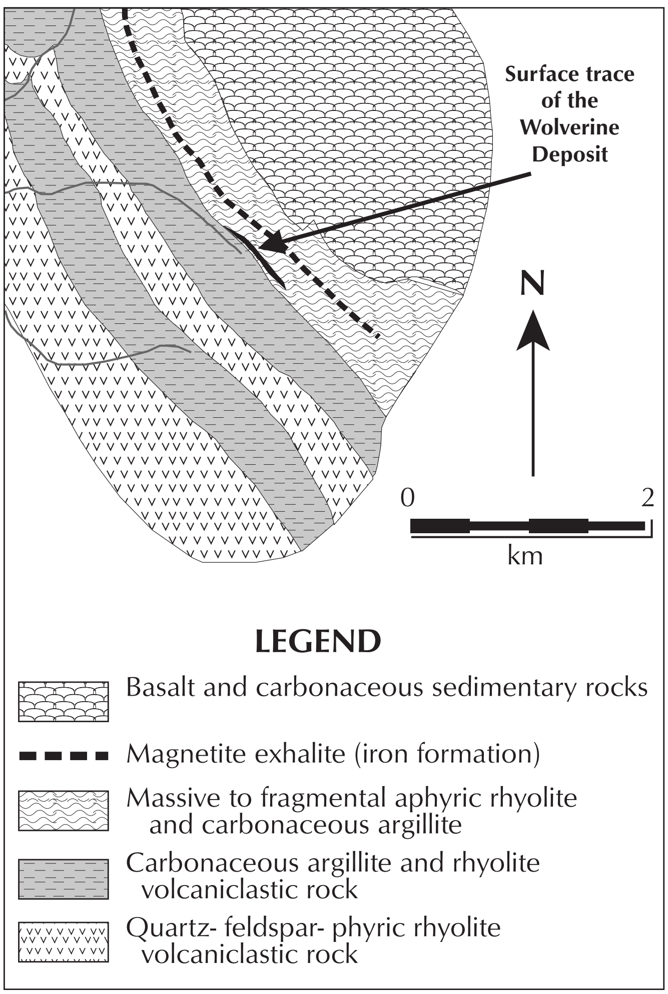

Figure 4. *Local geology of the Wolverine deposit (modified from an unpublished map by Expatriate Resources Limited). The arrow points to UTM coordinate 440000E, 6811000N (NAD 27).*

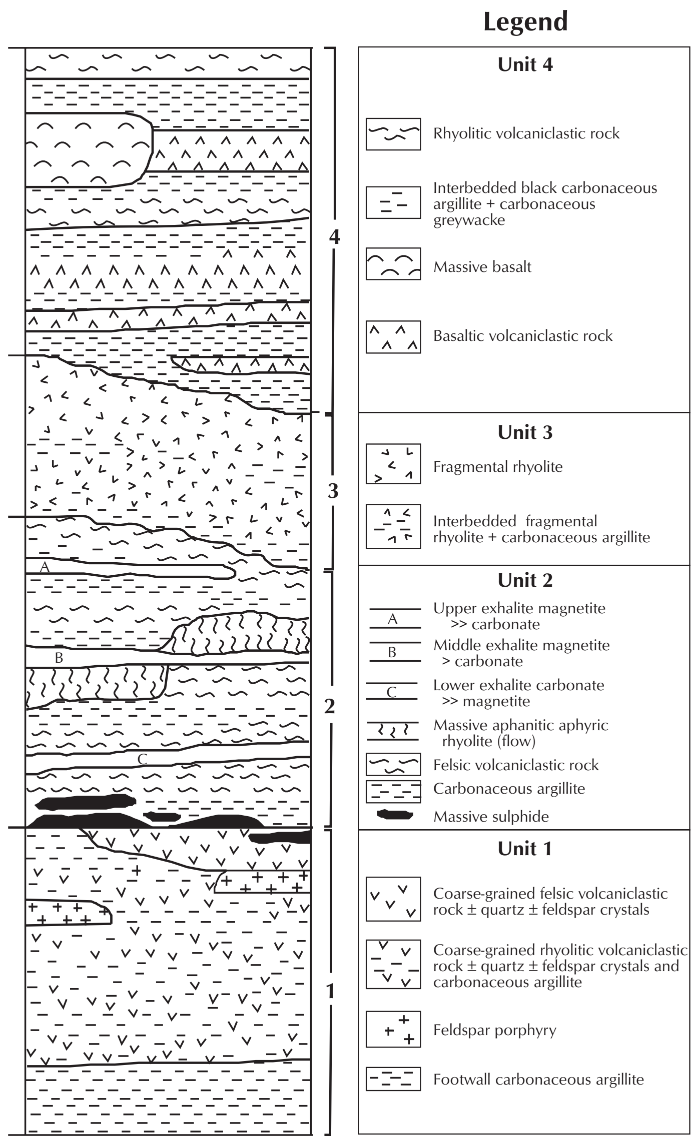

Figure 5. *Generalized stratigraphic column for the Wolverine deposit. Constructed from detailed geological mapping of drill core, drill logs, and cross-sections supplied by Expatriate Resources Limited.*

In this paper, the Wolverine stratigraphy has been divided into four successive units, each of which consists of several different lithologies. The units are described below (from oldest to youngest) and illustrated in Figures 5, 6, 7 and 8a-d. Importantly, exhalative lithologies, which include massive sulphides, are restricted to Unit 2. The Wolverine stratigraphy appears to be upright and not overturned, such as at the Kudz Ze Kayah deposit (e.g., Schultze, 1996).

Unit 1 - Footwall Volcaniclastic, Carbonaceous Sedimentary and Porphyritic Intrusive Rocks

(1) *Green to grey quartz- and feldspar-crystal-bearing rhyolite volcaniclastic rock with variable amounts of interbedded carbonaceous argillite*. Flattened, fine- to coarse-grained fragments of rhyolite are abundant in this lithology, which also contains up to several volume percent (vol. %) K-feldspar and quartz crystals although either, or both, may be absent. Potassium feldspar crystals are subhedral to euhedral in shape and range from 1 to 5 mm in diameter, whereas similarly sized greyish-blue quartz 'eyes' have rounded outlines. The relative abundances of feldspar crystals, quartz eyes and rhyolite fragments in this lithology vary significantly throughout the deposit.

(2) *Black to grey, fine-grained, carbonaceous, tuffaceous argillite*. This rock commonly contains several vol. % grey tuff as layers or clasts, and up to several vol. % rounded blue quartz eyes ranging up to 1 mm in diameter. This footwall argillite is similar to the

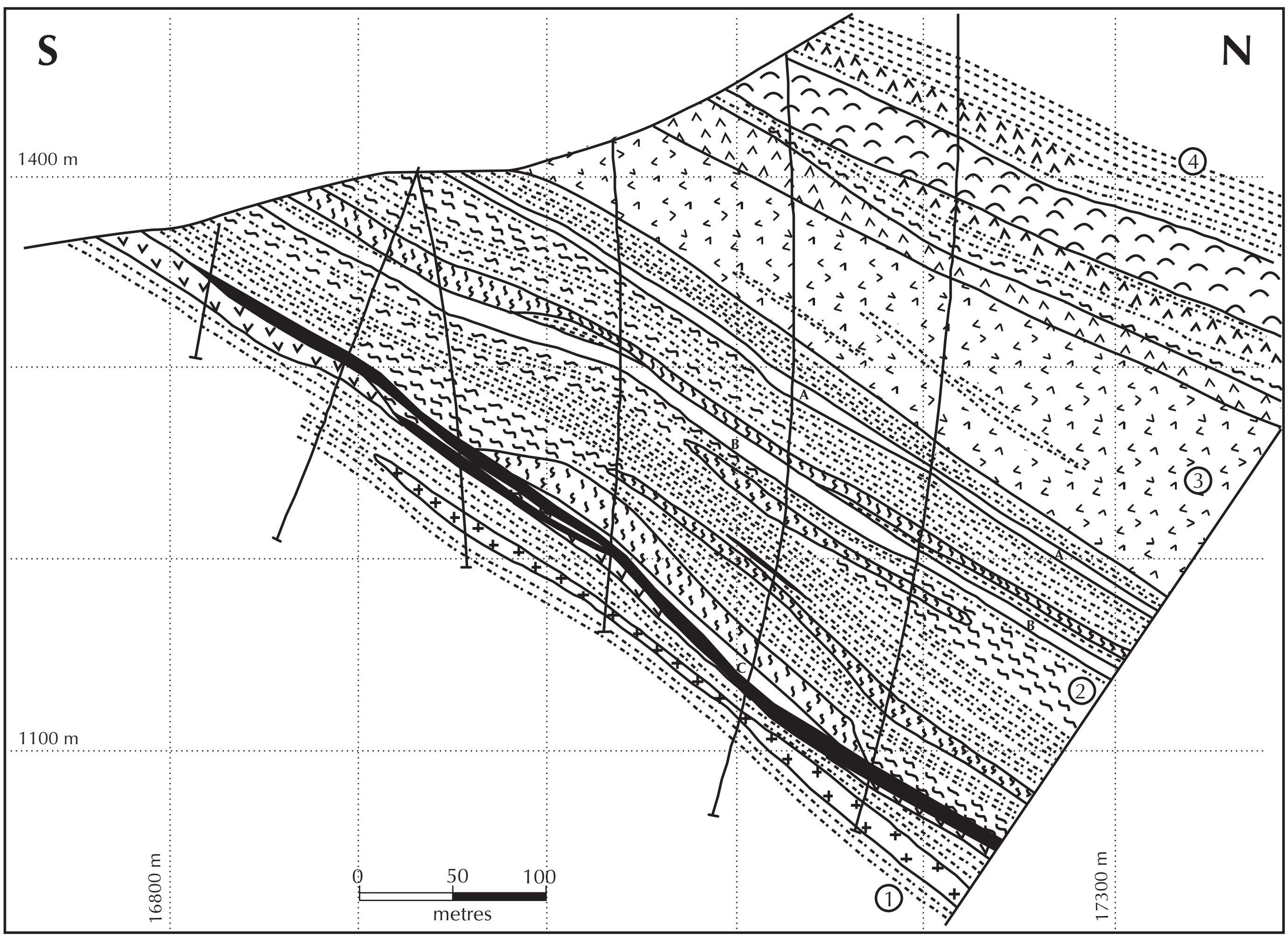

Figure 6. Geological cross-section 16250E through the Lynx zone of the Wolverine deposit. The location of this cross-section is shown on Figure 9. Constructed from detailed geological mapping of drill core, drill logs and cross-sections supplied by Expatriate Resources Limited. Coordinates (in metres) are from the property grid (Fig. 9). Unit numbers and patterns shown in Figure 5.

carbonaceous argillite in the hanging wall but is locally distinguished by a slightly coarser grain size, lighter colour, and the presence of quartz eyes in the former.

(3) *Grey, weakly foliated, K-feldspar-phyric rhyolite porphyry* (Fig. 8a). This intrusive lithology contains 5 to 10 vol. % K-feldspar phenocrysts up to 5 to 10 mm in diameter, in a grey, aphanitic, siliceous groundmass. Grey quartz eyes are rare.

The massive sulphide lens typically lies immediately above or, in some areas, within the felsic volcaniclastic rocks, which range from 1 to 60 m in width. The 30- to 50-m-thick carbonaceous argillite in the footwall marks the base of the volcano-sedimentary sequence, which hosts the mineralization. The 6- to 15-m-thick K-feldspar-phyric porphyries occur at an average distance of 20 m below the base of the massive sulphide horizon and are interpreted to be intrusive sills. The porphyry contains sulphide veins in at least one drill hole, which suggests emplacement was prior to mineralization. Piercey et al. (2001, this volume) describe the nature and occurrence of this lithology in more detail.

Unit 2 – Interbedded Argillite, Rhyolite and Magnetite-Carbonate-Pyrite Exhalites

(1) *Grey, massive to flow-banded, aphanitic to very fine-grained, aphyric rhyolite*. This rock is composed of alternating domains of aphanitic rhyolite with sub-millimetre to centimetre-thick micaceous partings

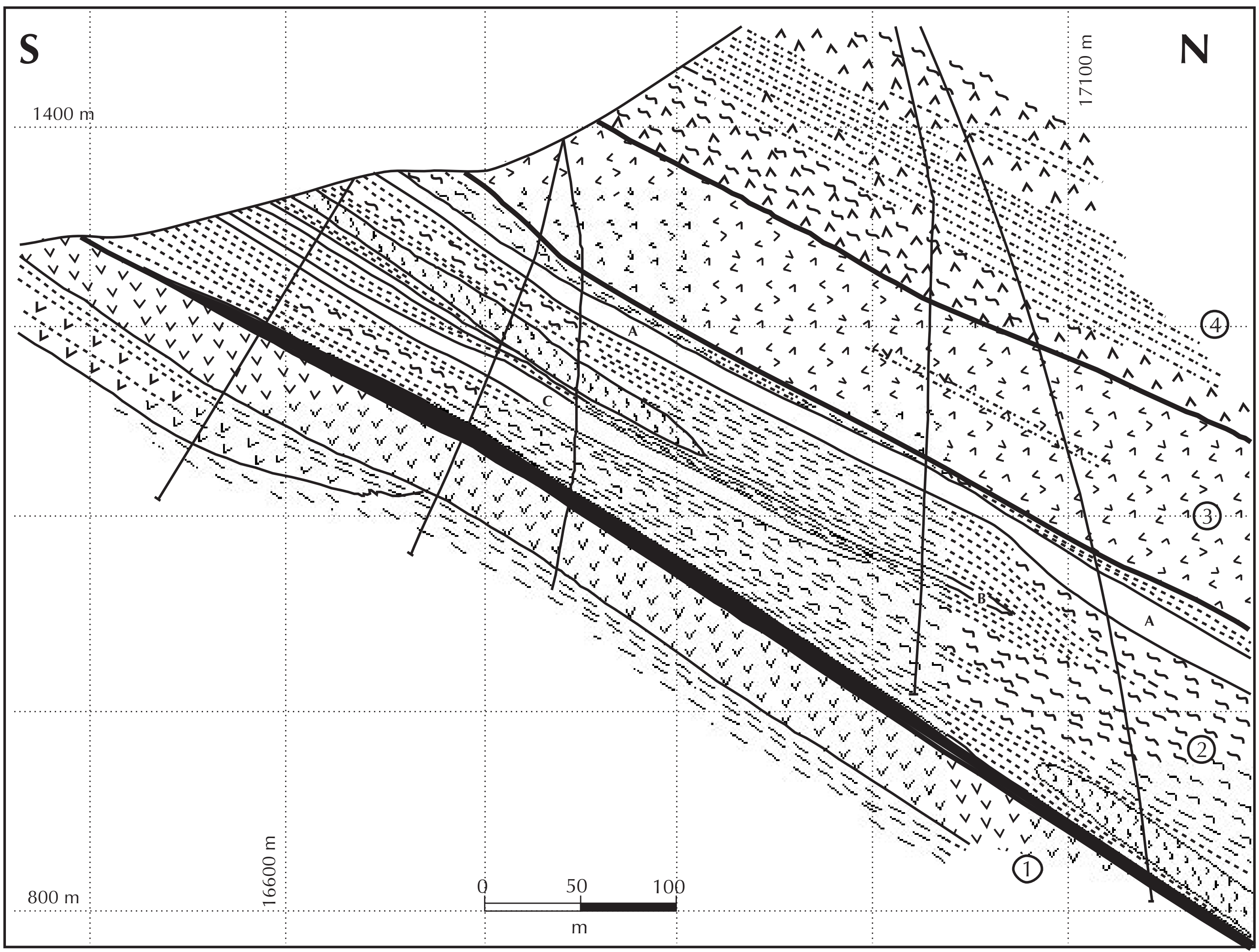

Figure 7. *Geological cross-section 16700E through the Wolverine zone of the Wolverine deposit. The location of this cross-section is shown on Figure 9. Constructed from detailed geologic mapping of drill core, drill logs and cross-sections supplied by Expatriate Resources Limited. Coordinates (in metres) are from the property grid (Fig. 9). Unit numbers and patterns shown in Figure 5.*

oriented parallel to the dominant S_1 foliation. The rhyolite domains commonly contain minute K-feldspar (?) microlites.

(2) *Black, finely laminated, carbonaceous argillite*. This rock commonly contains several vol. % grey tuff layers or clasts. A strongly siliceous variant contains abundant flattened and sheared veins of quartz and pyrite.

(3) *Grey to black, magnetite-predominant exhalite (iron formation;* Fig. 8b). This rock contains 5 to 60 vol. % disseminated to massive layered magnetite with lesser carbonate, chlorite, quartz, and sericite. The layering is interpreted to be a primary feature and where present, commonly assumes the form of millimetre-scale monomineralic bands of magnetite interbedded with layers of mixed silicates and carbonates.

(4) *Grey to white, carbonate-predominant exhalite* (Fig. 8c). This exhalite contains up to 90 vol. % patchy to massive fine carbonate (calcite > ankerite > siderite) with lesser magnetite, chlorite and pyrite. These rocks only rarely exhibit fine laminations; field relations suggest that the layers have responded in a ductile manner to deformation and primary sedimentary textures are now transposed.

(5) *Fine-grained, polymetallic, massive sulphides*. The types and styles of mineralization present in Unit 2 are described separately in the following section.

The immediate host-rock sequence to the massive sulphide mineralization ranges from 85 to 160 m in thickness and includes four distinct exhalative lithologies (not all of which are present in each drill hole). The uppermost two are commonly magnetite-predominant exhalite (A and B), the middle is a carbonate-predominant exhalite (C), and the lowermost is a pyrite-predominant exhalite (massive sulphide; see Figs. 5 and 7). The

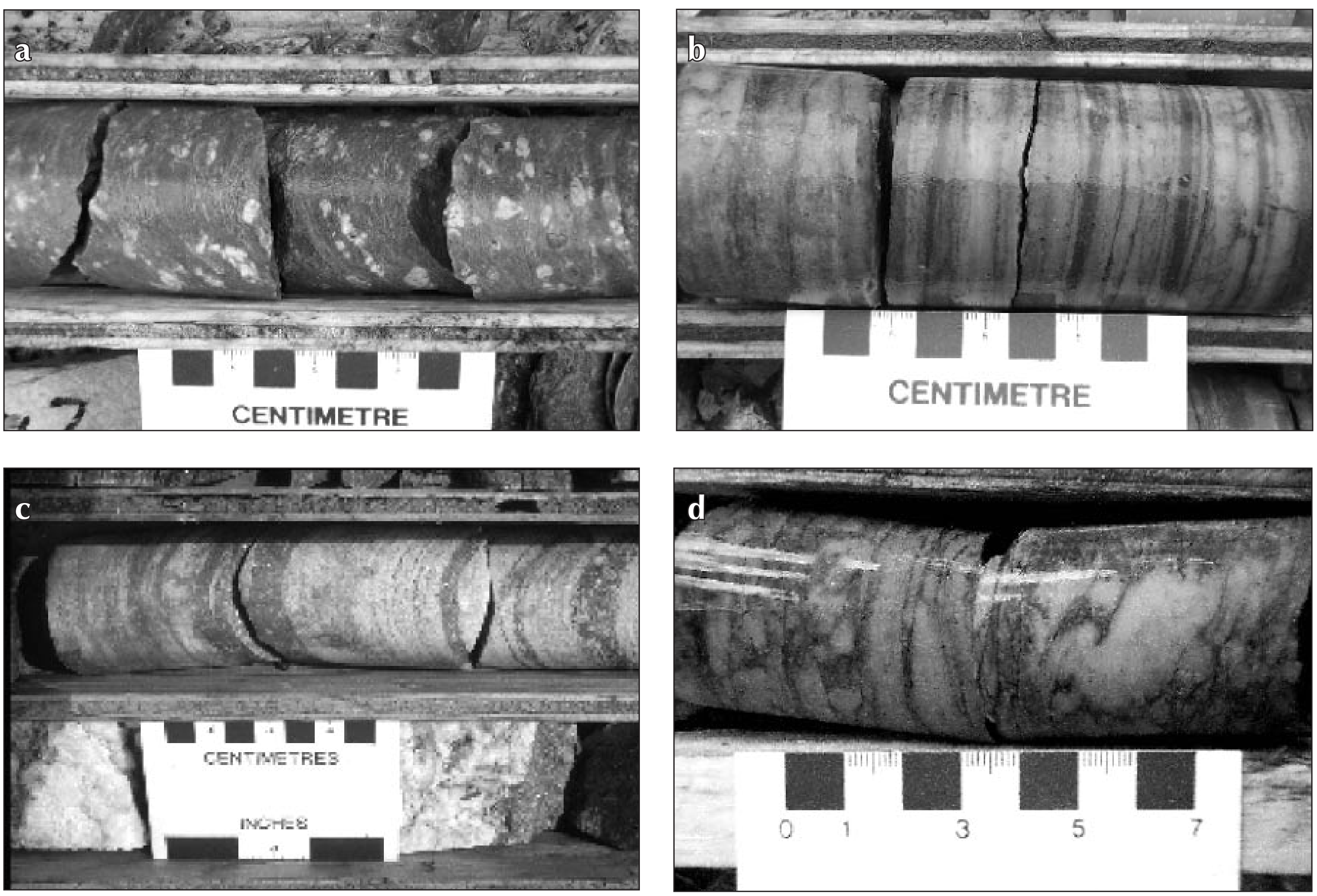

Figure 8. *Photographs of host-rock lithologies: (a) K-feldspar–phyric rhyolite porphyry of Unit 1; (b) magnetite exhalite (iron formation) of Unit 2; (c) carbonate-pyrite exhalite of Unit 2; and (d) fragmental rhyolite of Unit 3.*

thickness of the individual exhalites ranges from less than 1 m up to 10 m. The magnetite-rich exhalites are laterally extensive with strike lengths in excess of 12 km. All exhalites are separated by mixed sequences of interbedded argillite and rhyolite, which are commonly interbedded on the scale of a centimetre. The thickness of individual rhyolite and argillite horizons is extremely variable at the scale of the deposit. Both massive rhyolite and carbonaceous argillite may attain widths of up to 30 m. Some massive rhyolite intervals have a fine-grained base, which grades upward into feldspar-microlite-bearing rhyolite and subsequently into a rhyolite breccia (a flow-top breccia?). Collectively, these features suggest emplacement as flows.

Unit 3 – Fragmental Rhyolite

(1) *Grey fragmental rhyolite* (Fig. 8d). This rock is characterized by wispy, sub-millimetre, dark green to black, anastomosing micaceous bands, which separate centimetre-sized felsic aphanitic volcanic rock fragments. These fragments are sub-angular to sub-rounded, irregularly shaped and possess ragged boundaries. A variant of this unit has a distinctive greenish hue and contains 1 to 2 vol. % disseminated magnetite, which may be a product of weak semi-conformable (?) chloritic alteration.

(2) *Grey to black fragmental rhyolite and black carbonaceous argillite*. Rhyolite fragments (50 to 90 vol. %) are generally centimetre-sized, ovoid, and flattened into the plane of foliation. This lithology is similar to the fragmental rhyolite described above but may be distinguished from it by its greater proportion of argillite.

This unit occurs above the mineralized sequence and its base is marked generally by the presence of the uppermost exhalite. The thickness of this unit is fairly constant throughout the deposit, averaging about 80 m.

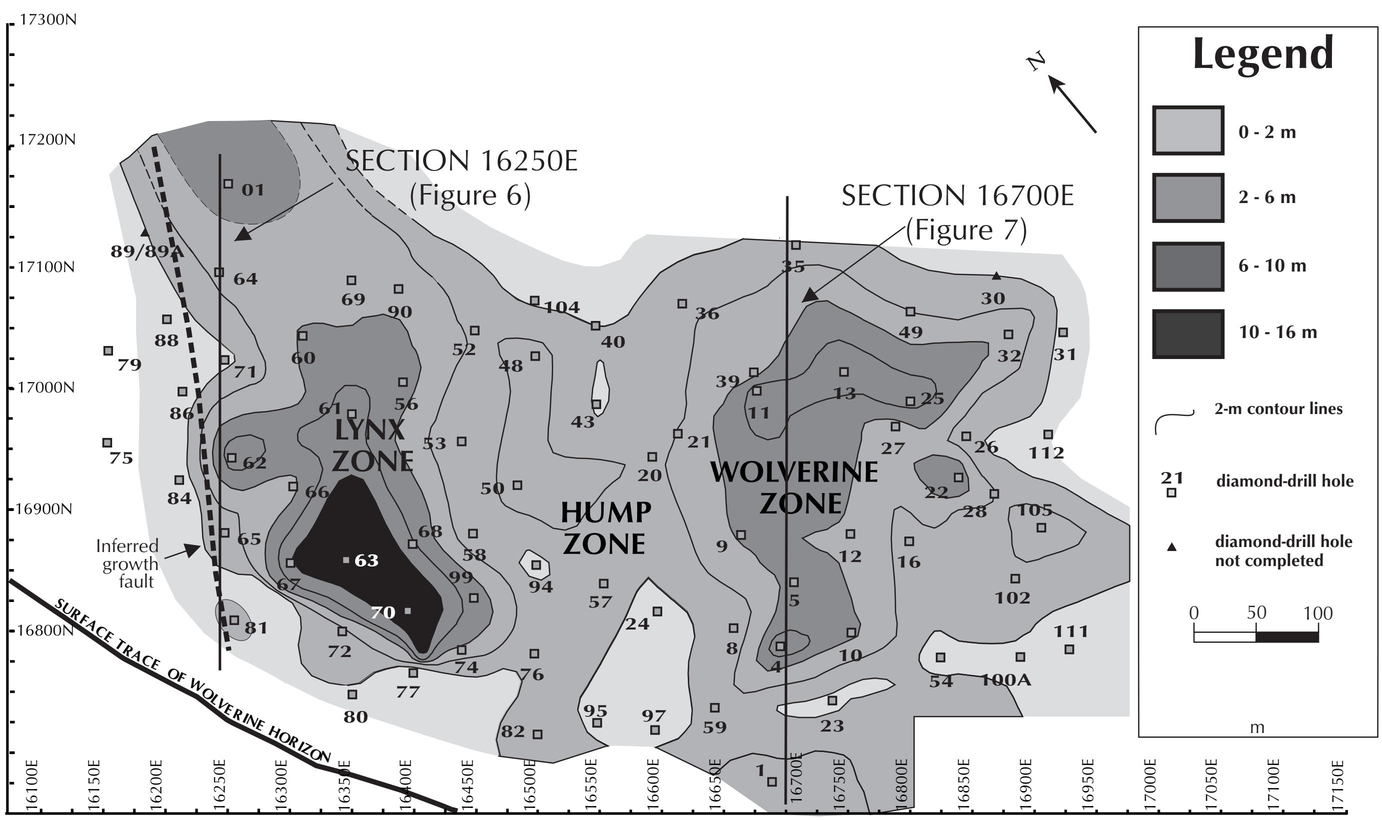

Figure 9. *Contours of true thickness of massive sulphide mineralization projected to the surface. Figure illustrates the morphology of sulphide mineralization associated with the Wolverine, Lynx, and Hump zones. The locations of the individual drill holes are projected to the base of the massive sulphide intersection. Coordinates (in metres) are from the property grid. Modified from Expatriate Resources Limited (2000). Property grid shown – grid number 16900N, 16650E equals approximately 440000E, 6811000N (UTM coordinates, NAD 27).*

Unit 4 – Interbedded Carbonaceous Argillite and Greywacke, with lesser Basalt and Rhyolite

(1) *Medium-green, massive, fine-grained basalt with biotite and minor epidote on partings*. These rocks are interpreted as flows where massive and homogeneous. They are likely volcaniclastic in origin where interbedded and layered with carbonaceous sedimentary rocks.

(2) *Interbedded black carbonaceous argillite and grey to black, medium-grained greywacke*. These rocks contain minor beds of felsic volcaniclastic rocks that are similar in appearance to the fragmental rhyolite of Unit 3 described above.

This uppermost sequence probably represents the transition from the Wolverine stratigraphy to the overlying basaltic flows and volcaniclastic rocks of the Campbell Range succession. The upper limit to this unit is unknown, but its thickness is at least 200 m. The basalts and the carbonaceous sedimentary rocks are mostly interbedded on a centimetre scale, although individual massive basalt (flows?) and carbonaceous sedimentary sequences can reach up to 40 m and 30 m in thickness, respectively. The base of this unit is defined by the first occurrence of green basaltic volcaniclastic rock.

MINERALIZATION

Massive sulphide mineralization occurs most commonly at or near the contact between units 1 and 2, where the transition from interbedded, massive, aphyric rhyolite and carbonaceous argillite to more coarsely grained and quartz- and K-feldspar-phyric rhyolitic volcaniclastic rock is located. The immediate hanging wall to the massive

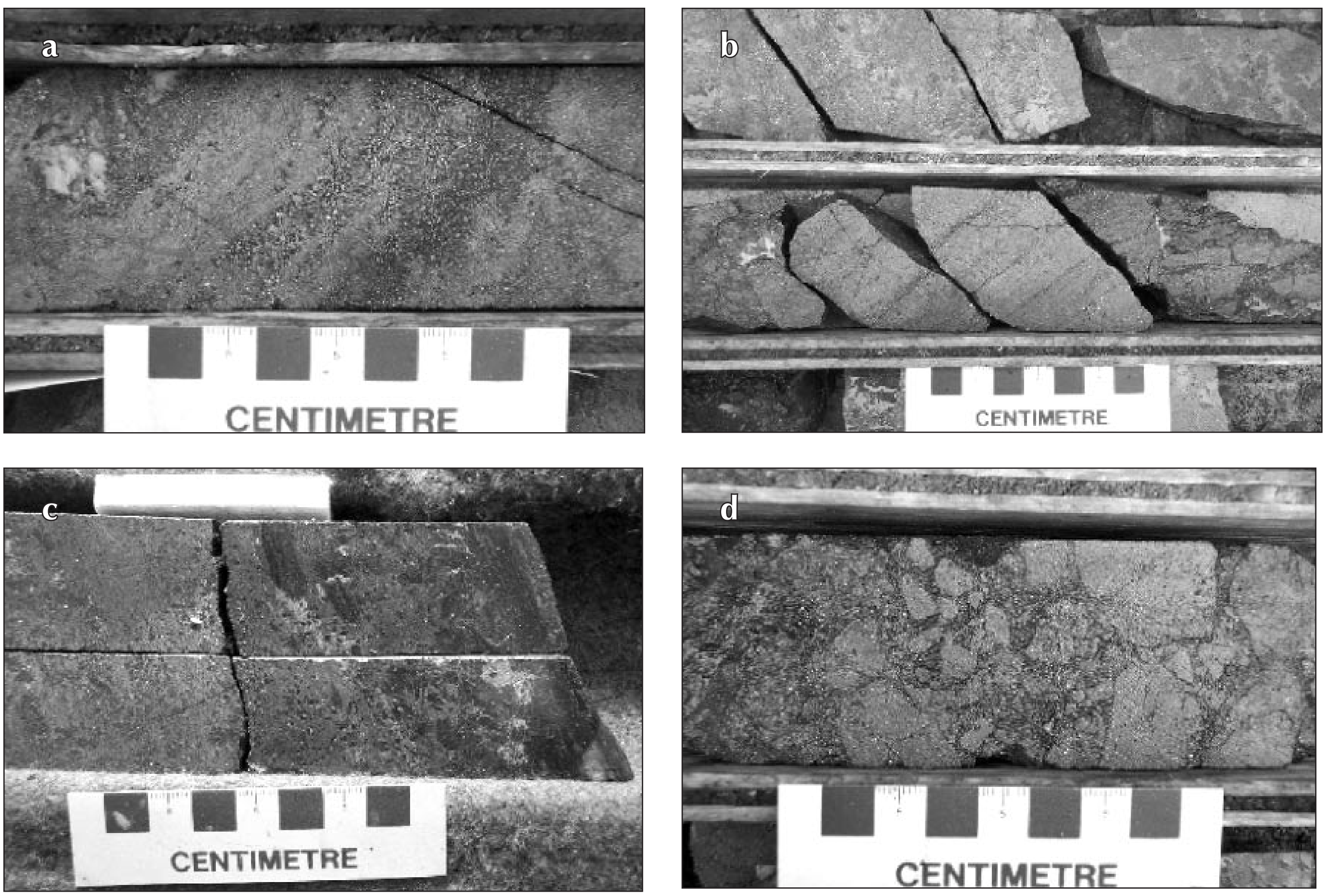

Figure 10. *Photographs of massive sulphide mineralization: (a) layered, massive pyrite and sphalerite, with lesser disseminated euhedral 'buckshot' pyrite; (b) large, angular, breccia fragment composed of layered (possibly laminated) pyrite and sphalerite; (c) pyrrhotite-chalcopyrite-chlorite altered/replaced rhyolite at the base of the massive sulphide intersection; and (d) sulphide breccia with angular to subrounded fragments of pyrite set in a medium-grained pyrite matrix.*

sulphide mineralization is typically black, graphitic argillite of unit 2.

On the basis of style and mineralogy, the sulphide mineralization at Wolverine has been divided into three predominant types: (1) massive stratiform, (2) semi-massive replacement, and (3) sulphide stringer veins. Examples of these rocks are shown in Figure 10. The distribution of the mineralization is illustrated in Figure 9, which contours the surface projection of the true thickness of the massive sulphide intersection in each drill hole. The true widths of the sulphide mineralization shown in Figure 9 represent a combination of massive stratiform (including multiple lenses if present), semi-massive replacement, and sulphide stringer veins.

(1) MASSIVE STRATIFORM SULPHIDES

Most of the mineralization occurs in tabular, homogeneous massive sulphide lenses composed of pyrite and sphalerite with lesser amounts of pyrrhotite, chalcopyrite, galena, tetrahedrite-tennantite and arsenopyrite. Other trace minerals identified in previous studies include marcasite, native gold and native silver (Expatriate Resources, unpublished data, 1996). Meneghinite ($Pb_{13}CuSb_7S_{13}$) is the predominant lead sulfosalt mineral. It is distributed locally together with lesser bournonite ($PbCuSbS_3$), boulangerite ($Pb_5Sb_4S_{11}$), and miargyrite ($Ag_2SSb_2S_3$; Expatriate Resources, unpublished data, 1996). Common gangue minerals are quartz, calcite, dolomite, ankerite, siderite, chlorite and

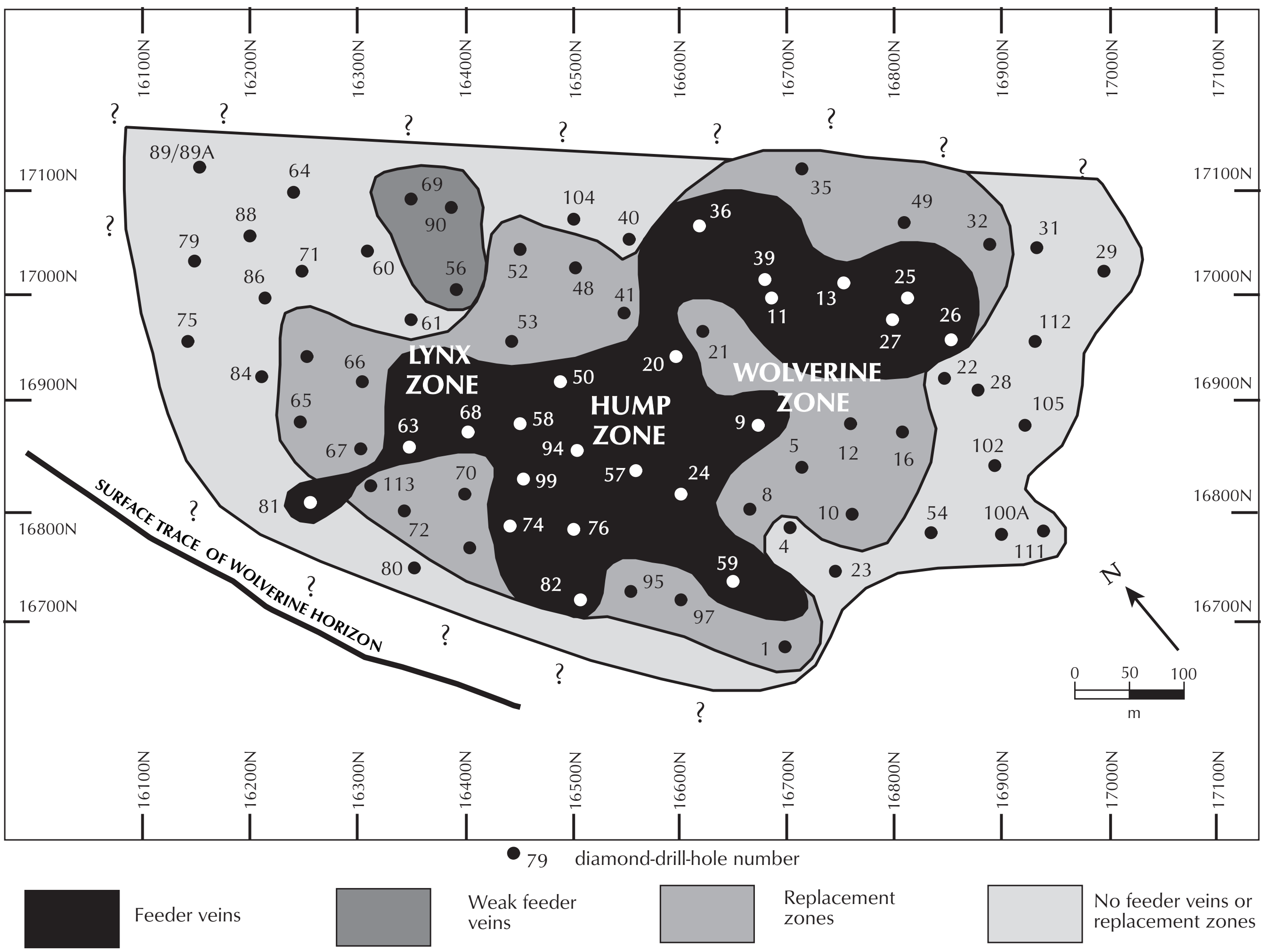

Figure 11. *Plan map of the Wolverine deposit showing the distribution of stringer veins ('feeder veins') and replacement-style mineralization. The locations of the individual drill-holes are projected to the base of the massive sulphide intersection. Coordinates (in metres) are from the property grid (J. Peter and S. Paradis, unpublished data, 2000). See Figure 9 for UTM coordinates of property grid.*

sericite. These minerals occur interstitial to the sulphide minerals and commonly form either very fine-grained masses or irregular blebs. Gangue minerals typically comprise less than 5 vol. % of the mineralized zones.

The two 'lens-like' areas where the accumulation of massive sulphides is thickest are termed the Wolverine zone and the Lynx zone (Fig. 9). These zones are separated from one another by an area of non-stratiform, semi-massive replacement sulphide mineralization and sulphide-stringer vein mineralization, which occurs at or near the same stratigraphic horizon as the massive sulphide lenses. This area is termed the Hump zone.

The sulphide lenses range in thickness from less than 1 m near the fringes of the deposit to 9.8 m in the Wolverine zone. In some localities, such as in the thickest sections of the Lynx zone, there are multiple sulphide lenses separated by up to 8 m of argillite or rhyolite. These multiple lenses may represent distinct exhalative horizons (i.e., stacked sulphide lenses), or may be the result of structural repetition due to folding or structural dismemberment. Examples of the stratiform massive sulphide mineralization, and the different textures they exhibit, are discussed below and shown in Figures 10a-d.

(2) SEMI-MASSIVE REPLACEMENT SULPHIDES

Figure 11 is a plan view of the deposit illustrating the distribution of the sulphide stringer vein and semi-massive replacement-type sulphide mineralization. Replacement zones are those areas of mineralization where sulphide minerals have partly to completely replaced host rocks. This has resulted in discrete, fine-grained, semi-massive sulphide zones ranging in thickness from several centimetres up to one metre. Replacement-type mineralization is most common in the Hump zone, but it also forms in the immediate footwall to the stratiform massive sulphide lenses in the Wolverine and Lynx zones. Here, it is associated with strongly chloritized and/or carbonatized rhyolite and argillite.

Replacement-type mineralization generally surrounds and occurs above and outboard of the stringer vein mineralization. Sphalerite is the most common replacement sulphide mineral and it occurs as either massive layers or irregular blebs and disseminations together with subordinate pyrite. Semi-massive pyrite and sphalerite replacement-type mineralization hosted by chloritized and carbonatized rhyolite and argillite in the Hump zone reaches up to 13 m in thickness. Semi-massive pyrite and sphalerite replacement-type mineralization in the footwall of the stratiform massive sulphide in the Wolverine zone ranges from 6 to 8 m in thickness. Chalcopyrite commonly forms small, semi-massive replacement zones in the immediate footwall to the sphalerite-rich massive stratiform sulphide mineralization. Chalcopyrite replacement zones typically have well defined upper and lower boundaries, are on the order of 30 cm thick, contain 60 to 80 vol. % massive to interstitial chalcopyrite with minor pyrrhotite, and are associated with intense and pervasive chloritic alteration of the host rocks.

(3) SULPHIDE STRINGER VEINS

Sulphide stringer vein zones are strongly developed in several areas of the deposit. Stringer vein mineralization is developed most strongly beneath, and intermixed with, massive replacement-type sulphide mineralization in the Hump zone. It is also prevalent in the immediate footwall to the thickest stratiform, and semi-massive replacement-style mineralization in the Wolverine zone. Well mineralized zones of this type comprise 5 to 10 vol. % of the rock and consist of randomly oriented, 2- to 3-cm-wide veins of quartz, pyrite and sphalerite. An envelope of silicification commonly surrounds individual veins. These areas of strong vein development are interpreted as up-flow conduits or pathways for hydrothermal fluids that precipitated the overlying massive stratiform sulphide mineralization. Thus, sulphide stringer veins are tentatively identified as the 'feeder zones' to massive sulphide mineralization. Where well developed, such as in the Wolverine zone, stringer vein mineralization ranges in thickness from 1 to 4 m. Weakly developed stringer vein mineralization is much more widespread, however, and it consists of 5- to 10-mm-wide quartz-sulphide veins that lack significant alteration envelopes. In the Wolverine zone, weakly developed quartz-chalcopyrite stringer veins extend approximately 10 m into the chloritized footwall.

SULPHIDE TEXTURES

Stratiform sulphide lenses are generally fine grained and homogeneous, although millimetre- to centimetre-scale layering is locally common. Pyrite is the principal sulphide mineral throughout the deposit and it typically occurs as very fine-grained, anhedral masses. Pyrite also forms more coarsely grained porphyroblasts (termed 'buckshot' pyrite), which are set in a matrix of finer grained pyrite and/or sphalerite (Fig. 10a). Abundant, fine-grained, reddish brown (i.e., iron-rich) sphalerite forms delicate, wispy, sub-millimetre- to centimetre-scale layers. These layers are largely responsible for the bedded appearance of the massive sulphide mineralization (Fig. 10b). In most places, layers are parallel to the S_1 foliation and are likely a result of deformation, although there are primary sedimentary features preserved in places. Some sphalerite also occurs as very small grains interstitial to massive pyrite.

Galena, tetrahedrite-tennantite, and arsenopyrite are all common sulphide minerals in the massive sulphide lenses, although they are difficult to distinguish from one another in hand specimen. They typically occur together as fine-grained, anhedral aggregates within sphalerite-rich layers. Tetrahedrite-tennantite also occurs as very fine grains interstitial to pyrite, although this is difficult to identify due to the fine-grained nature of the mineralization. Chalcopyrite is rare within the stratiform sulphide lenses. It occurs almost exclusively as remobilized medium-grained masses on the edges of large patches of quartz gangue or wall-rock fragments (Fig. 10c).

Breccia textures are preserved on the eastern flank of the Lynx zone, where they occur both at the top of the massive sulphide lens and within it. Breccias are composed entirely of sulphide minerals and are classified into two types: (1) matrix-supported breccia with 3- to 5-mm-diameter rounded clasts of fine-grained pyrite set in a matrix of similarly fine-grained pyrite comprising 20 to 30 vol. % of the rock; and (2) clast-supported 'jigsaw' breccia with angular clasts of pyrite and sphalerite, ranging from one up to several centimetres in diameter, set in a pyrite matrix comprising 5 to 20 vol. % of the rock (Fig. 10d). Both types of breccia are interpreted as primary features associated with the formation of the massive sulphide on the sea floor. Their nature and distribution are the subject of further investigation.

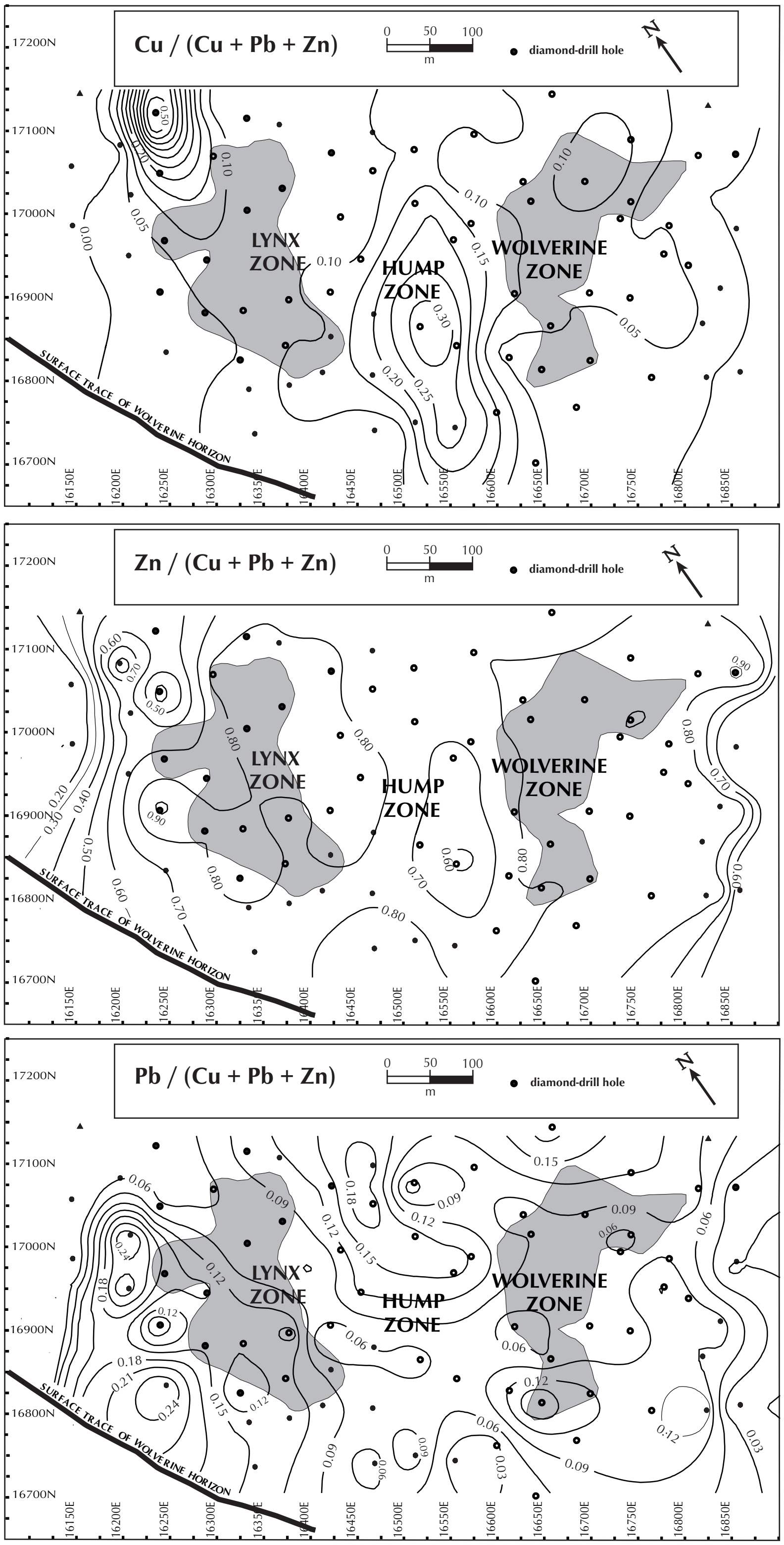

Figure 12. *Contours of (a) Cu / Cu + Pb + Zn, (b) Zn / Cu + Pb + Zn, and (c) Pb / Cu + Pb + Zn that illustrate the lateral zonation of copper, lead, and zinc in the Wolverine deposit. Note the correspondence of elevated copper values to the location of the Hump zone. The positions of the individual drill-holes are projected to the base of the massive sulphide intersection. Plots are generated from data provided by Expatriate Resources Limited. See Figure 9 for UTM coordinates of property grid.*

MINERAL AND METAL ZONATION

Figures 12a-c illustrate the lateral zoning of copper, zinc, and lead, respectively. The combined metal grades used to generate the contours represent, in most cases, a combination of massive stratiform mineralization and semi-massive replacement/sulphide stringer vein mineralization (where the latter has significant grade). The distribution of copper (Fig. 12a) is controlled by chalcopyrite, which is located mainly in the central part of the deposit in footwall stringer and replacement mineralization. Conversely, zinc and lead occur in the greatest concentration in the massive stratiform sulphides on the fringes of the deposit (e.g., Figs. 12b,c) outboard, and stratigraphically above, the sulphide stringer vein and replacement zones. Structural dismemberment and remobilization of sulphides during deformation, however, likely have disrupted much of the original metal and mineral zonation in the deposit.

Little zoning is evident within the pyrite- and sphalerite-dominant stratiform massive sulphide lenses. Sphalerite-rich mineralization with associated galena and tetrahedrite-tennantite occurs throughout the sulphide lenses in the Lynx and Wolverine zones, as centimetre- to metre-thick zones of poor definition, which alternate with pyrite-dominant massive sulphides. In most places, the entire sulphide interval contains abundant sphalerite, although distribution of the extremely sphalerite-rich zones is erratic. Chalcopyrite distribution is strongly zoned because it is the principal sulphide mineral in massive replacement-type and stringer vein-type mineralization in the footwall. Elsewhere, chalcopyrite is only a very minor constituent of the overlying stratiform sulphide lenses. Consequently, areas of the deposit, which lack sulphide stringer vein or massive replacement-type mineralization do not contain signifcant chalcopyrite. A notable exception occurs in massive stratiform sulphide

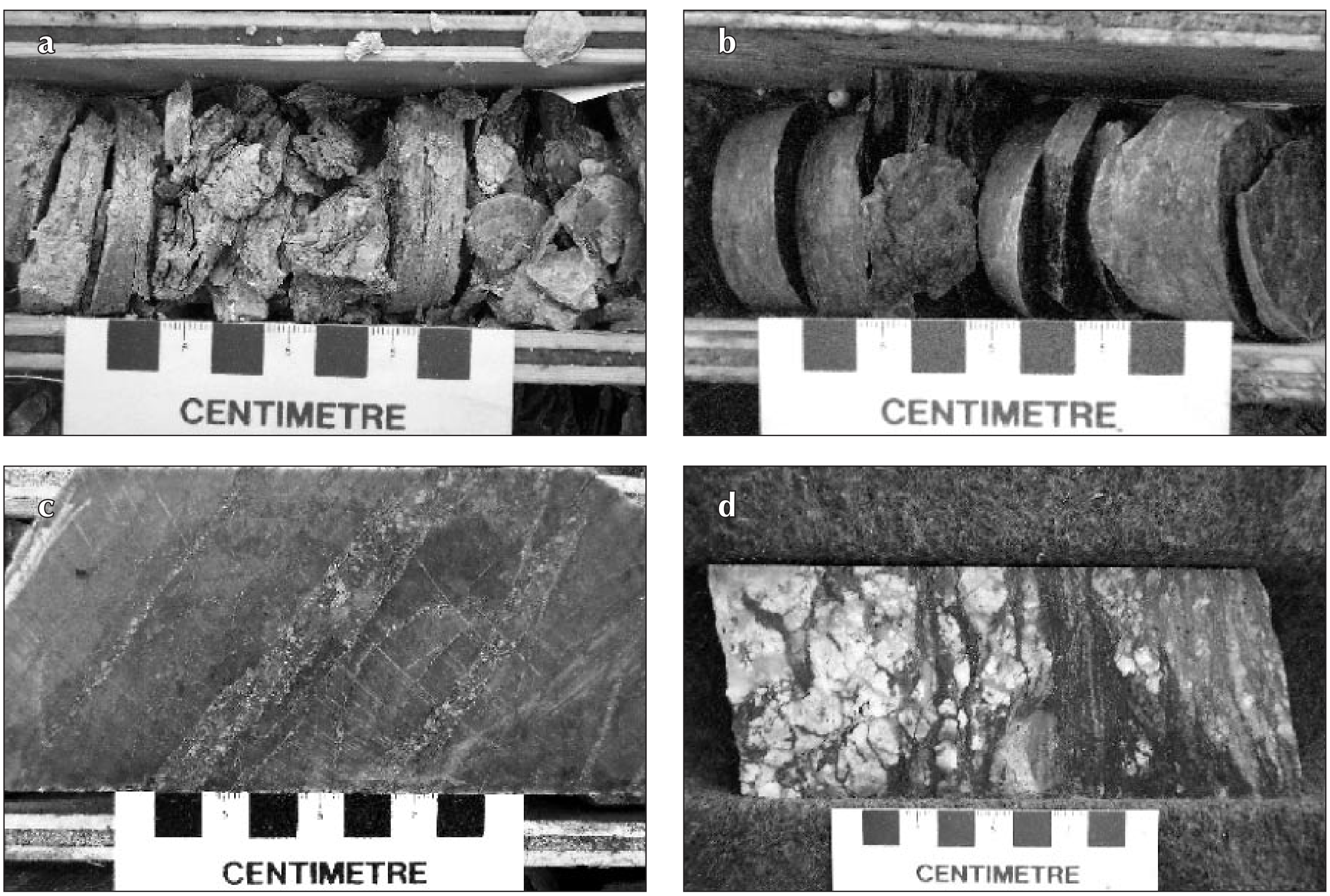

Figure 13. *Photographs of alteration styles: (a) strongly sericitized rhyolitic volcaniclastic rock; (b) chloritized rhyolitic volcaniclastic rock; (c) strongly silicified and sulphide stringer-veined (pyrite and sphalerite) rhyolitic volcaniclastic rock; and (d) carbonatized rhyolitic volcaniclastic rock.*

mineralization forming the northwest portion of the Lynx zone. Here, a 1.3-m-thick zone of chalcopyrite-rich sulphide mineralization forms the base of the massive sulphide lens. This area of elevated copper values is related spatially to an inferred north-northwest-trending growth fault, which may have localized the ascent of mineralizing fluids. The location of this fault is based on the extreme variations in sulphide thickness mapped over short distances. Its position is illustrated in Figure 9.

HYDROTHERMAL ALTERATION

Hydrothermally altered rocks are found predominantly in the immediate footwall to the massive sulphide mineralization, where permeable felsic volcaniclastic rocks have been preferentially altered. Four main styles of hydrothermal alteration are intimately associated with mineralization at the Wolverine deposit (e.g., Figs. 13a-d). The alteration types, in order of decreasing abundance, are (1) sericite, (2) chlorite, (3) silica (quartz), and (4) carbonate. The main features of each are discussed below.

(1) Sericite alteration (Fig. 13a) is characterized by moderate to pervasive development of sericite in fine- to coarse-grained felsic volcaniclastic rocks. Sericite alteration is stratabound and occurs throughout the deposit, both within, below, and lateral to (or outboard of) the zone of chlorite alteration, but occurs most commonly in the footwall to massive sulphide mineralization. Sericite-altered volcaniclastic rocks are intensely foliated (likely due to a ductility contrast with adjacent unaltered rocks?) and contain 40 to 60 vol. % sericite. In the most strongly altered zones, all minerals excluding quartz are completely replaced. Sericite alteration is the most extensive and widespread alteration type, reaching a thickness of 50 m where best developed in the Hump and Wolverine zones. There is a gradual decrease in the intensity of sericite alteration moving laterally away from these zones. Sericite alteration is locally well developed in the Lynx zone, but not as extensively as elsewhere, possibly because there is more variation in the footwall lithologies. Sericite alteration is locally mapped in rocks of the hanging wall, especially on the eastern fringe of the deposit where the stratiform massive sulphide mineralization occurs within rhyolitic volcaniclastic rocks of Unit 1. It should be noted that it is difficult, in places, to distinguish hydrothermal sericite alteration from that which formed in the felsic rocks in response to regional metamorphism and deformation, particularly where the former is only weakly developed. There may be a compositional difference between sericite forming the two types and this is under current investigation.

(2) Chlorite alteration (Fig. 13b) is characterized by the intense development of chlorite in fine- to coarse-grained, felsic volcaniclastic rocks. The result is a dark green chloritized rock with moderately to coarsely flattened felsic volcanic rock fragments with, or without quartz and feldspar crystals. Chlorite alteration is most strongly developed in the Wolverine zone where it occurs in the immediate footwall to the massive sulphide mineralization and is up to 30 m thick. It is widespread in the Hump zone, where it is associated with carbonate alteration and massive sulphide replacement-style mineralization. In most localities where chlorite alteration is present, there is a gradual transition in alteration-types from chlorite-dominant to sericite-dominant with increasing distance from the massive sulphide lens. This zonation can be ascribed to the twin influences of decreasing heat and fluid flow in those areas distal to the main zone(s) of hydrothermal activity (e.g., Lydon, 1988).

(3) Silica alteration (Fig. 13c) is characterized by the pervasive development of fine-grained quartz in rocks immediately adjacent to quartz–sulphide (pyrite >sphalerite >>chalcopyrite) veins. This alteration-type is rare and may be confined to narrow zones associated with hydrothermal fluid conduits. Silica alteration is particularly strong in drill hole WV-97-81, where it extends 5 m below the massive stratiform mineralization (see location on Fig. 9). Here, rhyolite tuff is intensely silicified and contains 3 to 5 vol. % quartz-pyrite-sphalerite veins ranging up to 3 cm in width. In most other localities, sulphide stringer veins are narrower and lack associated silica alteration. In Unit 2, carbonaceous argillites in the hanging wall are locally strongly silicified and contain narrow veins of quartz and pyrite. Petrochemistry of the aphyric rhyolite in the hanging wall indicates that they contain significantly higher SiO_2 than that found in typical rhyolite (S.J. Piercey, unpublished data, 2000). These possible hanging wall alteration phenomena are currently under investigation.

(4) Carbonate alteration (Fig. 13d) is characterized by the development of varying amounts of white calcite, orange-brown ankerite and brown siderite. This alteration-style is commonly associated with chlorite alteration. Carbonate minerals commonly occur as large porphyroblasts ranging up to 2 cm in diameter, which may occupy 20 to 30 vol. % of the rock. This alteration-style occurs with massive sulphide replacement and sulphide-stringer mineralization both in the Hump zone and in the immediate footwall to the massive sulphide mineralization in the Wolverine zone. This unique texture is intimately associated with mineralization, and may have formed by the precipitation of carbonate, which was scavenged from the underlying sediments by hydrothermal fluids. The exact distribution of carbonate alteration is poorly understood at the present time, but widths of individual zones rarely exceed 2 m.

DISCUSSION

The field data presented in this paper, particularly the spatial and temporal association of the sulphide mineralization with felsic volcanic rocks, demonstrate that the Wolverine deposit shares many features with the Kuroko deposits of the Hokuroku district, Japan (e.g., Ohmoto, 1996). The petrochemistry of the felsic volcanic rocks in the Wolverine succession is consistent with formation in an ensialic back-arc basin (Piercey et al., 2000). The ensialic back-arc basin setting and the close association of the sulphide mineralization with black carbonaceous shales and felsic volcanic rocks places the Wolverine deposit in a group of rather unique VHMS deposits, which include those of the Bathurst camp in New Brunswick (e.g., van Staal et al., 1991; McCutcheon, 1992; Goodfellow and Peter, 1996).

In order to gain a better understanding of the volcanic environment in which the Wolverine deposit was generated, further study of the nature and distribution of the host rocks is necessary. Petrographic studies may be used to reveal whether the volcaniclastic rocks of Units 1 and 2, and the fragmental rhyolite of Unit 3, are mass flow deposits (i.e., epiclastic) or pyroclastic in origin. Changes in the thickness of these rocks over the entire deposit may correspond to the location of a volcanic centre. The presence of graphitic argillite in the immediate hanging wall, and extensive carbonaceous argillite in the footwall, implies that starved, anoxic conditions may have prevailed at or near the time of sulphide deposition, and may have had a strong influence on the mineralization process (e.g., Eastoe and Gustin, 1996; Goodfellow and Peter, 1996, 1999). Chemical analyses of the Wolverine shale will be used to investigate this possibility.

A conspicuous feature of the Wolverine massive sulphide mineralization is the lack of a classic 'carrot-shape' copper-rich feeder zone, which typically extends far below the base of the massive sulphide deposit (e.g., Lydon, 1984). Although this is likely due in part to the effects of post-mineralizaton deformation, the relatively large amount of semi-massive replacement-type mineralization is evidence that the footwall volcaniclastic rocks and sediments were sufficiently permeable (unlithified?) to inhibit the formation of fracture-controlled fluid pathways. Rather, fluids selectively mineralized and altered chemically and physically favourable host-rock sequences. This sub-seafloor replacement-style of mineralization is similar to that of the Rosebery deposit, which is hosted in the Cambrian Mount Read 'Volcanics' of Tasmania (e.g., Green, et al., 1981).

To completely understand how the massive stratiform sulphide mineralization formed requires further study of sulphide textures and, in particular, identification of whether the layering in the sulphides is primary (i.e., bedding), or the result of remobilization and recrystallization associated with later tectonism. Preliminary field evidence suggests that the layering may be primary in places, implying that the sulphides likely were resedimented from the edges of a sulphide mound on the sea floor. The presence of primary sulphide breccia (Fig. 10d) provides further evidence for the formation and collapse of a sulphide mound on the ancient sea floor (Lydon, 1988).

FUTURE WORK

Research on the Wolverine deposit is only in its preliminary stages. Future research includes continued petrographic studies of the sulphide mineralization, host rocks, and hydrothermal alteration in combination with isotopic and geochemical characterization of the mineralization and the hydrothermally altered and unaltered host rocks. These studies will define further the temporal and spatial nature of alteration and massive sulphide mineralization. Acquisition of such data will permit the quantification of the physico-chemical conditions of ore formation and place constraints on material transfer processes accompanying hydrothermal alteration. The ultimate aim of the project is to produce a genetic model for formation of the Wolverine deposit and develop exploration criteria that may be applied to the search for further VHMS deposits in the Finlayson Lake district and elsewhere.

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REFERENCES

Eastoe, C.J. and Gustin, M.M., 1996. Volcanic hosted massive sulfide deposits and anoxia in the Phanerozoic oceans. Ore Geology Reviews, vol. 10, p. 179-197.

Goodfellow, W.D. and Peter, J.M., 1996. Sulphur isotope composition of the Brunswick No. 12 massive sulphide deposit, Bathurst Mining Camp, New Brunswick: Implications for ambient environment, sulphur source, and ore genesis. Canadian Journal of Earth Sciences, vol. 33, p. 231-251.

Goodfellow, W.D. and Peter, J.M., 1999. Reply: Sulphur isotope composition of the Brunswick No. 12 massive sulphide deposit, Bathurst Mining Camp, New Brunswick: Implications for ambient environment, sulphur source, and ore genesis. Canadian Journal of Earth Sciences, vol. 36, p. 127-134.

Green, G.R., Solomon, M. and Walshe, J.L., 1981. The formation of the volcanic-hosted massive sulphide deposit at Rosebery, Tasmania. Economic Geology, vol. 6, p. 304-338.

Lydon, J.W., 1984. Volcanic hosted massive sulphide deposits. Part 1: A descriptive model. Geoscience Canada, vol. 11, p. 195-202.

Lydon, J.W., 1988. Volcanic hosted massive sulphide deposits. Part 2: genetic models. Geoscience Canada, vol. 15, p. 43-65.

McCutcheon, S.R., 1992. Base-metal deposits of the Bathurst-Newcastle district: Characteristics and depositional models. Exploration and Mining Geology, vol. 1, p. 105-119.

Mortensen, J.K., 1992. Pre-mid-Mesozoic tectonic evolution of the Yukon-Tanana Terrane, Yukon and Alaska. Tectonics, vol. 11, p. 836-853.

Murphy, D.C., 1997. Preliminary geological map of Grass Lakes area, Pelly Mountains, southeastern Yukon (105G/7). Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Open File 1997-3, 1:50 000 scale.

Murphy, D.C., 1998. Stratigraphic framework for syngenetic mineral occurrences, Yukon-Tanana Terrane south of Finlayson Lake: A progress report. *In:* Yukon Exploration and Geology 1997, C.F. Roots and D.S. Emond (eds.), Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 51-58.

Murphy, D.C. and Timmerman, J.R.M., 1997. Preliminary geology of the northeast third of Grass Lakes map area (105G/7), Pelly Mountains, southeastern Yukon. *In:* Yukon Exploration and Geology 1996, Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 62-73.

Murphy, D.C. and Piercey, S. J., 1999a. Finlayson Project: Geological evolution of Yukon-Tanana Terrane and its relationship to Campbell Range belt, northern Wolverine Lake map area, southeastern Yukon. *In:* Yukon Exploration and Geology 1998, C.F. Roots and D.S. Emond (eds.), Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 47-62.

Murphy, D.C. and Piercey, S.J., 1999b. Geological map of Wolverine Lake area (105G/8), Pelly Mountains, southeastern Yukon. Exploration and Geological Services Division, Yukon, Department of Indian and Northern Affairs Canada, Open File 1999-3 (1:50 000 scale).

Murphy, D.C. and Piercey, S.J., 1999c. Geological map of Finlayson Lake area, southeast quarter (105G/7, 8 and parts of 1,2 and 9), southeastern Yukon. Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Open File 1999-4 (1:100 000 scale).

Murphy, D.C. and Piercey, S.J., 2000. Syn-mineralization faults and their re-activation, Finlayson Lake massive sulphide belt, Yukon-Tanana Terrane, southeastern Yukon. *In:* Yukon Exploration and Geology 1999, D.S. Emond and L.H. Weston (eds.), Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 55-66.

Ohmoto, H., 1996. Formation of volcanic hosted massive sulphide deposits: The Kuroko perspective. Ore Geology Reviews, vol. 10, p. 135-177.

Piercey, S.J. and Murphy, D.C., 2000. Stratigraphy and regional implications of unstrained Devono-Mississippian volcanic rocks in the Money Creek thrust sheet, Yukon-Tanana Terrane, southeastern Yukon. *In:* Yukon Exploration and Geology 1999, D.S. Emond and L.H. Weston (eds.), Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 67-78.

Piercey, S.J., Murphy, D.C., Mortensen, J.K. and Paradis, S., 2000. Arc-rifting and ensialic back-arc basin magmatism in the Northern Canadian Cordillera: Evidence from the Yukon-Tanana Terrane, Finlayson Lake region, Yukon. *In:* Slave-Northern Cordilleran Lithospheric Experiment (SNORCLE) - Lithoprobe Report No. 72, p. 129-138.

Piercey, S.J., Peter, J.M., Bradshaw, G.D., Tucker, T.L. and Paradis, S., 2001 (this volume). Geological attributes of high-level subvolcanic porphyritic intrusions in the Wolverine Zn-Pb-Cu volcanic-hosted massive sulphide deposit, Finlayson Lake district, Yukon, Canada. *In:* Yukon Exploration and Geology 2000, D.S. Emond and L.H. Weston (eds.), Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 335-346.

Schultze, H.C., 1996. Summary of the Kudz Ze Kayah project, volcanic hosted massive sulphide deposit, Yukon Territory. *In:* Yukon Exploration and Geology 1995, Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 29-31.

Thompson, R.I., Nelson, J.L., Paradis, S., Roots, C.F., Murphy, D.C., Gordey, S.P. and Jackson, L.E., 2000. Ancient Pacific Margin NATMAP Project, year one. Geological Survey of Canada, Current Research 2000-A1, 8 p. (online; http://www.nrcan.gc.ca/gsc/bookstore).

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.

van Staal, C.R., Winchester, J.A. and Bédard, J.H., 1991. Geochemical variations in Middle Ordovician volcanic rocks of the northern Miramichi Highlands and their tectonic significance. Canadian Journal of Earth Sciences, vol. 28, p. 1031-1049.