VOLCANIC-HOSTED MASSIVE SULPHIDE DEPOSITS OF THE FINLAYSON LAKE DISTRICT, YUKON

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Abstract

The Finlayson Lake District (FLD) is a crescent-shaped 300 km long, and 50 km wide area within southeastern Yukon Territory. It comprises part of the Yukon-Tanana Terrane, one of the innermost terranes of the Canadian Cordillera that underlies much of the central Yukon and parts of Alaska and British Columbia, and part of the Slide Mountain Terrane. The FLD is consists of several fault- and unconformity-bound groups and formations of early Mississippian to early Permian metamorphosed plutonic, volcanic, and sedimentary rocks. The rocks were formed in a variety of tectonic settings, including rifted frontal arc, continental back-arc, and oceanic back-arc that range in age from 365 to 275 Ma. The FLD hosts numerous base metal sulphide deposits that collectively contain in excess of 30 Mt. The Fyre Lake Cu-Co is a Besshi-type deposit containing 15.4 Mt grading 1.2% Cu, 0.8% Co, and 0.46 g/t Au that occurs at the transition from mafic volcanic rocks to overlying turbiditic sedimentary rocks in a fore-arc setting. The Kudz Ze Kayah Zn-Pb-Cu and GP4F Zn-Pb Kuroko-type deposits are hosted by felsic volcanic and volcaniclastic rocks in the immediate wallrock whereas the Wolverine Zn-Pb-Cu deposit is hosted by graphitic shales and felsic volcanic and volcaniclastic rocks and is best classified as a volcanic-sediment-hosted massive sulphide (VSHMS) deposit. These latter three deposits are thought to have formed in ensialic back-arc rift or back-arc basin environments. The deposits have strongly hydrothermally altered rocks in the stratigraphic footwalls, with alteration styles varying from chlorite (Fyre Lake, Kudz Ze Kayah, Wolverine, Ice), sericite (Kudz Ze Kayah, GP4F, Wolverine), silica/quartz (Kudz Ze Kayah, Wolverine), carbonate (Wolverine) and albite (Kudz Ze Kayah). Feeder zones/stringer veins are present at the Fyre Lake, Kudz Ze Kayah, Wolverine and Ice deposits. Hanging-wall alteration is present at Fyre Lake (weak chlorite) and Wolverine (weak sericite). Wolverine has a laterally extensive (>10 km strike length) chemical exhalative sedimentary iron formation horizon in the hanging wall that is not present at Kudz Ze Kayah or GP4F. Much of the Kudz Ze Kayah deposit likely formed as a mound on the seafloor, as did at least some of the Wolverine deposit. However, subsurface replacement was important at Wolverine, and likely was entirely responsible for the formation of GP4F. The Kudz Ze Kayah deposit contains an inferred geological resource of 13 Mt at 5.55% Zn, 1.00% Cu, 1.30% Pb, 125 g/t Ag, and 1.2 g/t Au. GP4F contains an inferred resource of 1.5 Mt grading 6.4% Zn, 3.10% Pb, 0.10% Cu, 89.7 g/t Ag, and 2.0 g/t Au. Wolverine has measured and indicated reserves of 4.51 Mt grading 12.04% Zn, 1.15% Cu, 1.57% Pb, 351.5 g/t Au, and 1.2 g/t Au. The Ice Cyprus-type deposit is a massive sulphide deposit formed by mafic volcanic rocks at the transition from underlying brecciated pillow basalt to overlying massive basalt and is thought to have formed in a back-arc basin/ocean basin setting. The geological resource at Ice is 4.56 Mt grading 1.48% Cu; some intervals contain about 1% Zn, but a Zn resource has not been calculated.

There are numerous other showings and prospects that require additional exploration work. The relatively nascent level of exploration in the FLD suggests that prospecting, coupled with traditionally successful exploration methods, such as surficial geochemistry, and airborne and ground geophysics (magnetics, EM) focused on the prospective rock units, are likely to result in new discoveries in the coming years.

Résumé

Le district de Finlayson Lake (DFL) est une étendue falciforme longue de 300 km et large de 50 km dans la partie sud-est du Yukon. Elle se compose d’un segment du terrane de Yukon-Tanana, l’un des plus intérieurs des terranes de la Cordillère canadienne qui s’étend à une bonne partie du centre du Yukon et à des parties de l’Alaska et de la Colombie-Britannique, et d’un segment du terrane de Slide Mountain. Le DFL comprend plusieurs groupes et formations limités par des failles ou des discordances qui se composent de roches plutoniques, volcaniques et sédimentaires métamorphisées datant du Mississippien précoce au Permien précoce. Ces roches se sont formées entre 365 et 275 Ma dans toute une gamme de cadres tectoniques, dont des arcs frontaux en distension, des arrière-arcs continentaux et des arrière-arcs océaniques. Le DFL recèle de nombreux gisements de sulphures de métaux communs qui renferment
ensemble plus de 30 Mt de minerai. Le gisement de Cu-Co de Fyre Lake est un gîte de type Besshi renfermant 15,4 Mt de minerai titrant 1,2 % de Cu, 0,8 % de Co et 0,46 g/t de Au. Ce gisement se présente à la transition entre un empiement de roches volcaniques maﬁques et une succession sus-jacente de roches sédimentaires turbiditides dans un cadre d’avant-arc. Les gisements de Zn-Pb-Cu de Kudz Ze Kayah et de Zn-Pb de GP4F, des gisements de type Kuroko, sont encaissés dans des roches volcaniques et volcanoclastiques felsiques tout au sommet de l’empiement volcanique, alors que le gisement de Zn-Pb-Cu de Wolverine est encaissé dans des shales et des roches volcaniques et volcanoclastiques felsiques et s’insère mieux dans la catégorie des gîtes de sulfures massifs dans des roches volca-no-sédimentaires. On pense que ces trois derniers gisements se sont formés dans des milieux ensialiques de rift d’arrière-arc ou de bassin d’arrière-arc. Ils présentent aux éponthes stratigraphiques inférieures des roches ayant subi une intense altération hydrothermale, dont les styles variés sont caractérisés par la présence de chlorite (Fyre Lake, Kudz Ze Kayah, Wolverine, Ice), de séricite (Kudz Ze Kayah, GP4F, Wolverine), de silicate/quartz (Kudz Ze Kayah, Wolverine), de carbonates (Wolverine) et d’albite (Kudz Ze Kayah). Des zones nourricières/filoniennes sont présentes aux gisements de Fyre Lake, de Kudz Ze Kayah, de Wolverine et d’Ice. Il y a altération dans l’éponte supérieure aux gisements de Fyre Lake (faible chloritisation) et de Wolverine (faible séricitisation). Le gisement de Wolverine présente dans son éponte supérieure un horizon latéralement étendu (~10 km d’étendue longitudinale) de formation de fer chimique d’origine exhalative qui est absent des gisements de Kudz Ze Kayah et de GP4F. Le gisement de Kudz Ze Kayah s’est en grande partie vraisemblablement formé sous la forme d’un monolithe sur le fond marin, comme, à tout le moins en partie, le gisement de Wolverine. Cependant, le remplACEMENT en subsurface a été important au gisement de Wolverine et il est vraisemblablement entièrement responsable de la formation du gisement de GP4F. Le gisement de Kudz Ze Kayah renfermerait des ressources présumées de 13 Mt titrant 5,55 % de Zn, 1,00 % de Cu, 1,30 % de Pb, 125 g/t de Ag et 1,2 g/t de Au. Au gisement de GP4F, les ressources présumées s’élèveraient à 1,5 Mt renfermant 6,4 % de Zn, 3,10 % de Pb, 0,10 % de Cu, 89,7 g/t de Ag et 2,0 g/t de Au. Au gisement de Wolverine, les ressources mesurées et indiquées s’établissent à 4,51 Mt titrant 12,04 % de Zn, 1,15 % de Cu, 1,57 % de Pb, 351,5 g/t de Ag et 1,68 g/t de Au, avec des ressources présomées additionnelles s’élevant à 1,69 Mt renfermant 12,16 % de Zn, 1,23 % de Cu, 1,74 % de Pb, 385,1 g/t de Ag et 1,71 g/t de Au. Le gisement d’Ice, de type Chypre, est encaissé dans des roches volcaniques maﬁques à la transition entre une succession inférieure de basaltine en coussins bréchifié et une succession supérieure de basalte massif, et il se serait formé dans un cadre de bassin d’arrière-arc/bassin océanique. Au gisement d’Ice, les ressources minérales sont de 4,56 Mt renfermant 1,48% de Cu; certains intervalles renferment environ 1% de Zn, mais les ressources en Zn n’ont pas été calculées.

De nombreux autres indices minéralisés et prospects doivent faire l’objet de travaux d’exploration additionnels. Le niveau d’exploration relativement embryonnaire du DFL suggère que la prospection associée aux méthodes classiques éprouvées d’exploration comme la géochimie des matériaux superficiels et les levés géophysiques aériens et au sol (magnétiques, EM) focalisés sur les unités lithologiques prometteuses permettront vraisemblablement de nouvelles découvertes au cours des années à venir.

**Introduction**

The discovery of a number of volcanic-hosted massive sulphide (VHMS) deposits in the Finlayson Lake District (FLD) within a relatively short timespan since 1995 facilitated the need to understand the stratigraphy and tectonic history of the region. Until recently, the age, stratigraphy and tectonic settings of the known VHMS deposits were poorly constrained, and this hindered exploration efforts in this part of the North American Cordillera. Recent work has provided much new information on the geology (Murphy and Timmerman, 1997; Murphy, 1998, 2001; Murphy and Piercey, 1998, 1999a,b,c, 2000a,b, 2002; Piercey and Murphy, 2000, 2001; Murphy et al., 2002, 2006), paleotectonic settings and metallogeny (Piercey, 2001; Piercey et al., 1999, 2001a,b,c, 2002a,b, 2003, 2004, 2006, in press), and the geology and origin of VHMS deposits (Bradshaw et al., 2001, in press; Layton-Matthews et al., 2001, in press; Boulton, 2002; Bradshaw, 2003; Layton-Matthews, 2005). This paper summarizes current knowledge of the massive sulphide deposits since the seminal in-depth report of Hunt (2002). The paper focuses discussion of the five largest and best known deposits in the area: 1) Fyre Lake, 2) Kudz Ze Kayah, 3) GP4F, 4) Wolverine, and 5) Ice.

**Tectonic Setting**

Pericratonic terranes contain elements of the continental margin that are of uncertain paleogeography (Wheeler and McFeely, 1991). Until a few years ago, the belt of pericratonic terranes, which lies between autochthonous miogeocli-
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Central margin of North America (Paradis et al., 1998; Nelson et al., 2002, 2006; Colpron et al., 2006a; Mortensen et al., 2006; Piercey et al., 2006). It has been suggested that the Yukon-Tanana Terrane was perhaps at one time linked to other similar terranes found in the Cordillera, such as the Kootenay Terrane in south central British Columbia, as part of an extensive single arc and arc/basement assemblage, which has now been broken apart and displaced by transcurrent faults such as the Tintina Fault (Mortensen, 1992b; Colpron et al., 2006a; Nelson et al., 2006).

The Slide Mountain Terrane in the FLD comprises Mississippian to Lower Permian basinal clastic rocks, and chert and mafic and felsic volcanic rocks of the Carboniferous Fortin Creek Group that have been deposited on oceanic crust in the Yukon-Tanana Terrane back-arc region. These rocks are cut by ca. 273 to 274 Ma intrusions that are likely comagmatic with Campbell Range Formation volcanic rocks. Basalt and chert of the Lower Permian Campbell Range Formation, assigned to the Slide Mountain Terrane, unconformably overlap rocks of the Yukon-Tanana Terrane, the Fortin Creek Group, and the terrane boundary between Yukon-Tanana Terrane and Slide Mountain Terrane. The FLD is juxtaposed against Proterozoic and Paleozoic strata of the ancient North American continental margin along the Tintina Fault to the southwest, and to the northeast the Inconnu Thrust separates the combined Yukon-Tanana and Slide Mountain terranes from North America (Mortensen and Jilson, 1985; Plint and Gordon, 1996, 1997; Tempelman-Kluit, 1979; Fig. 2).

**Stratigraphy**

The FLD forms a crescent-shaped area approximately 300 km long and 50 km wide that extends from Ross River in the north to Watson Lake in the south (Fig. 1), and comprises Devonian-Mississippian volcanic, intrusive, and sedimentary rocks. The FLD is juxtaposed against Proterozoic and Paleozoic strata of the ancient North American continental margin along the Tintina Fault to the southwest, and to the northeast the Inconnu Thrust separates the combined Yukon-Tanana and Slide Mountain terranes from North America (Mortensen and Jilson, 1985; Plint and Gordon, 1996, 1997; Tempelman-Kluit, 1979; Fig. 2). The Jules Creek Fault separates the Yukon-Tanana Terrane from the Slide Mountain Terrane in the FLD. The FLD is contiguous with the main part of the Yukon-Tanana Terrane, which underlies most of west central Yukon, after restoration of 425
**Figure 2. A)** Geology map of the Finlayson Lake District and environs.
km of Late Cretaceous right-lateral, strike-slip movement on the Tintina Fault (e.g. Mortensen, 1992b).

Rocks of the FLD comprise several fault- and unconformity-bound groups and formations of early Mississippian to Early Permian metamorphosed plutonic, volcanic, and sedimentary rocks (i.e. Cleaver Lake, Money Creek, and Big Campbell thrust sheets; Murphy et al., 2006; Fig. 3). Massive sulphide deposits occur solely within the Big Campbell thrust sheet (Fig. 2) (with one exception, the Ice Cu-Au-Co deposit, which is hosted by metabasalts of the Campbell Range Formation of the Slide Mountain Terrane). Rocks of the Big Campbell thrust sheet include Pre-Late Devonian quartz-rich metasedimentary rocks of the North River Formation, which are the structurally deepest rocks of the Yukon-Tanana Terrane; mafic and felsic volcanic, and carbonaceous metaclastic rocks of the Upper Devonian Grass Lakes Group; Late Devonian to Early Mississippian granite metaplutonic rocks of the Grass Lakes plutonic suite; carbonaceous metaclastic and mafic and felsic volcanic rocks of the Lower Mississippian Wolverine Lake Group; and carbonaceous metaclastic rocks and chert of the Lower Permian Money Creek Formation (Murphy et al., 2006) (Fig. 3).

The Grass Lakes Group consists of strongly foliated and lineated layered metasedimentary and volcanic rocks that crop out in a roof setting above and between bodies of Early Mississippian granitic orthogneiss and weakly foliated mid-Cretaceous granite (Murphy, 1998). The Grass Lakes Group has been subdivided into three formations, from oldest to youngest, the Fire Lake, Kudz Ze Kayah, and Wind Lake formations. The Upper Devonian (ca. 365 Ma) Fire Lake Formation is a mafic volcanic sequence composed mainly of chloritic phyllite with some carbonaceous phyllite and rare muscovite-quartz phyllite of probable felsic volcanic protolith. Intrusions and sills of mafic and serpentinized ultramafic plutonic rocks occur within the Fire Lake Formation. Stratigraphically overlying the Fire Lake Formation is the Kudz Ze Kayah Formation, which is a Late Devonian (ca. 360-356 Ma) sequence dominated by felsic volcanic and volcaniclastic and sedimentary rocks. It consists predominantly of feldspar-muscovite-quartz phyllite and augen phyllite of probable felsic volcanic and volcaniclastic origin, and lesser fine-grained carbonaceous and siliciclastic sedimentary rocks. The Wind Lake Formation forms the uppermost unit of the Grass Lakes Group and consists of carbonaceous phyllite, quartzite, and chloritic phyllite of probable alkalic mafic volcanic and intrusive protolith.

Coeval with the Kudz Ze Kayah and Wind Lake formations are the peraluminous meta-plutonic granitoids of the Grass Lakes Suite. These granitoids are the subvolcanic intrusive equivalents to the felsic volcanic host rocks to the Kudz Ze Kayah deposit, and are as old as 363 ± 3.3 Ma (Mortensen, 1992b). These plutonic rocks are deformed and were themselves re-intruded by younger, late-kinematic plutonic rocks before deposition of the Wolverine Lake Group.
The Grass Lakes Group is unconformably overlain by rocks of the Wolverine Lake Group and consists of a basal unit of conglomerate, grit, sandstone, and carbonaceous argillite, a middle unit of quartz-feldspar phytic felsic volcanic rocks, rare chert and sandstone, and an upper unit of aphyric rhyolite, argillite, magnetite iron formation, and mafic volcanic and intrusive rocks (Murphy et al., 2006). A second unconformity separates the Wolverine Lake Group from the overlying carbonaceous metaclastic rocks (carbonaceous phyllite, chert-pebble conglomerate, quartzofeldspathic sandstone to pebble conglomerate, and locally, matrix-supported diamictite) and dark grey to black chert of the Lower Permian Money Creek Formation. Both the Grass Lakes Group and Wolverine Lake Group occur in the footwall of the Money Creek thrust and record two cycles in the evolution of a Late Devonian to early Mississippian ensialic back-arc (Murphy and Piercey, 2000a; Piercey et al., 2001a, 2006). These groups are separated by an unconformity marking a period of deformation, uplift, and erosion.

Uranium-Pb geochronology places an upper age limit of 356.9 ± 0.5 Ma for the host rocks to the Wolverine Deposit and other zones (see below) (Mortensen, 1992b; Piercey et al., in press), and the immediate stratigraphic hanging wall is dated at 346 ± 2.2 Ma (Piercey, 2001), indicating that Wolverine is younger than Kudz Ze Kayah.

The Campbell Range Formation, which unconformably overlies rocks of the Wolverine Lake Group (Fig. 3), is a mafic-dominated sequence consisting of basalt, chert, and argillite (Fig. 2). The age of this assemblage is Pennsylvanian to Permian, based on radiolarians and ca. 273 to 274 Ma U-Pb ages on gabbros and plagiogranites (Murphy et al., 2006). These rocks are the youngest strata hosting VHMS deposits in the FLD.

Petrochemistry and Chemostratigraphy

The mafic metavolcanic rocks that host the Fyre Lake deposit are strongly depleted in the light rare earth elements (LREE) and high field strength elements (HFSE), have elevated Mg, Ni, and Cr contents, and chemically are similar to boninites present in some suprasubduction zone ophiolites (Sebert and Hunt, 1999; Sebert et al., 2004). Boninites are typically thought to originate as melts from a depleted mantle in rift, forearc, and arc- rift settings. The presence of continentally derived clastic sedimentary rocks intercalated with these boninites, as well as a LREE- and HFSE-enriched transitional subalkaline basalt immediately beneath the deposit, and the presence of mafic volcanic rocks with distinctive arc signatures (Ta, Nb, and Ti depletions) in the area, indicate that the deposit formed in an evolved island arc setting (Piercey et al., 2001c, 2004). At Fyre Lake, boninites are overlain by N-MORB to transitional sub-alkaline basalts (Sebert et al., 2004).

The felsic volcanic rocks that host the Kudz Ze Kayah deposit have elevated HFSE and REE (Zr>500 ppm; Ti/Sc=313-345; Zr/TiO₂=630-2,185; Zr/Sc=15.3-190.3; Zr/Y=3.3-17.7; Nb/Ta=11.6-15.8; Nb/Y=0.4-1.1; Piercey et al., 2001a). They plot in the fields for within-plume, crustally derived, A-type felsic rocks and are interpreted to represent evolving products of an ensialic back-arc rift or back-arc basin (Piercey et al., 2001a, 2006, and references therein). The mafic volcanic rocks of the Wind Lake Formation are weakly alkaline with chemical signatures similar to ocean island basalts (Piercey et al., 2002a).

The host rocks to the GP4F deposit are of similar geochemical composition to the nearby Kudz Ze Kayah deposit. The felsic flows and tuffs that host the GP4F deposit are of rhyolitic composition and fall within the transitional alkaline and subalkaline fields, they have high HFSE and REE contents, high HFSE ratios (e.g. avg Ti/Sc=325; Zr/TiO₂=1157; Zr/Sc=62), and within-plate (A-type) signatures. Their Nb/Ta ratios (8.5-16.4; avg. 13.5) are similar to rocks derived from the continental crust (~11-12), which suggests that the GP4F felsic rocks are derived by melting of continental crust (Boulton, 2002). Mafic dykes are of intermediate to basaltic composition and alkaline in character (Boulton, 2002) and resemble ocean island basalts (OIB) contaminated by continental crust; their composition is similar to mafic flows of the Wind Lake Formation (Piercey et al., 2002a). On the basis of the geochemical similarities of the felsic and mafic volcanic host rocks to those of Kudz Ze Kayah, the GP4F deposit is thought to have formed in a similar paleotectonic environment.

The felsic rocks from the stratigraphic footwall to the Wolverine deposit also have elevated HFSE and REE contents (Ti/Sc=248-417; Zr/TiO₂=559-1,220; Zr/Sc=40.4-84.7; Zr/Y=3.4-14.7; Nb/Ta=10.4-17.1; Nb/Y=0.5-1.1) and their composition is consistent with formation in an ensialic back-arc setting (Piercey et al., 2001a). Feldspar porphyritic rhyolites in the immediate footwall have even higher HFSE and REE contents (avg. values, n=24: Ti/Sc =302; Zr/Ti=0.21; Zr/Sc=61.6; Zr/Y=9.9; Nb/Ta=16.5; Nb/Y=0.67; Piercey et al., in press). Aphyric rhyolites in the hanging wall of the deposit, however, have low HFSE contents. The Wolverine Lake Group rocks are capped by MORB-type basalt indicative of transition to true back-arc spreading and ocean crust formation (Piercey et al., 2002b). The presence of an unconformity between carbonaceous phyllites of the Wind Lake Formation and overlying Wolverine Lake Group rocks indicates uplift, then resumption of ensialic back-arc magmatism and evolution to a spreading ridge, as evidenced by the presence of basaltic mafic volcanic rocks in the uppermost part of the Wolverine Lake Group (e.g. Murphy et al., 2006).

Basalts that host the Ice deposit display homogeneous MORB signatures with a possible influence from subcontinental lithospheric mantle in the lowermost basalts (Piercey et al., 1999). A permissible interpretation is that the deposit was formed in a back-arc basin/ocean basin setting (Piercey et al., 1999). The footwall basalts to the Money (Julia) prospect, 5 km east of Wolverine (see Money (Julia) Prospect below), have an E-MORB signature (Piercey et al., 1999).

Deformation and Metamorphism

In the Fire Lake area, host to the Fyre Lake deposit, the presence of biotite and garnet in the metasedimentary and metavolcanic rocks indicate upper greenschist metamorphic conditions (Sebert et al., 2004). Rocks in the vicinity of the deposit have been gently folded along a northerly trending anticlinal to monoclinal structure. Rocks have a strong F1 schistosity parallel to compositional layering, and there is a
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FIGURE 3. Structural and stratigraphic relationships in the Finlayson Lake District (modified from Murphy et al., 2006). Abbreviations are as follows: FC=Finlayson Creek limestone; KA=King Arctic Formation; KMC=Klatsa metamorphic complex; NR=North River Formation; WF=Whitefish limestone; WL=White Lake Formation. Timescale is from Okulitch (2002).
strong L1 mineral lineation trending 120 to 140º and plunging shallowly to the southeast in the plane of the F1 foliation. The host rocks and the Fyre Lake deposit have been deformed in Permian, Cretaceous, and Mississippian times. At Kudz Ze Kayah, the rocks and mineralization have undergone upper greenschist to lower amphibolite facies metamorphism and have been intensely deformed. At least three phases of deformation are recognized (Murphy and Timmerman, 1997). The deposit lies within an F1 fold, has been thickened by F2 folds, and imbricated by F3 deformation. D1 deformation was intense and penetrative, resulting in an S0-S1 composite fabric (Schultze, 1996). F1 folds are isoclinal and recumbent, and accompanied by attendant limb thrust faulting.

At GP4F, the mineralization and all host rocks, except the mafic dykes, have been metamorphosed to upper greenschist facies and have been intensely deformed. At least three phases of deformation are recognized (Murphy and Timmerman, 1997). The deposit lies within an F1 fold, has been thickened by F2 folds, and imbricated by F3 deformation. D1 deformation was intense and penetrative, resulting in an S0-S1 composite fabric (Schultze, 1996). F1 folds are isoclinal and recumbent, and accompanied by attendant limb thrust faulting.

At GP4F, the mineralization and all host rocks, except the mafic dykes, have been metamorphosed to upper greenschist facies, as evidenced by the presence of garnet, biotite, chlorite, albite, and titanite. However, the sulphides at GP4F are significantly less recrystallized than at Kudz Ze Kayah due to a lower metamorphic overprint. The GP4F deposit contains trace to minor gahnite, and this mineral is believed to have formed by desulphidation of sphalerite during metamorphism (Spry and Scott, 1986) A major deformation event in the region has obliterated most primary volcanic and sedimentary features in the rocks. The sequence is strongly foliated with one dominant S2 foliation (MacRobbie and Holroyd, 2000).

The immediate host rocks to the Wolverine deposit are less strongly metamorphosed and deformed than those at Kudz Ze Kayah, and metamorphic grades at Wolverine are middle greenschist based on the mineral assemblage of actinolite, albite, chlorite, and biotite. A major deformational event is recorded as a prominent S1 foliation that trends northwest and dips gently to the northeast. F1 folds in the vicinity of the deposit verge to the southwest, indicating that the Wolverine deposit is on the eastern limb of an open, upright antiform. Deformation has resulted in extensive gouge zones in ductile rocks such as argillite and intense fracturing in brittle rocks including rhyolite.

**Volcanic-Hosted Massive Sulphide Deposits**

**Grade and Tonnage**

To date, forty-one VHMS deposits and occurrences have been discovered at different stratigraphic levels within the FLD, and about 34 Mt of massive sulphides have been delineated since the district was recognized in the mid-1990s. The combined resource of Kudz Ze Kayah, Wolverine, and GP4F, the polymetallic massive sulphide deposits with the greatest economic potential, is 21.5 Mt grading 8.2 % Zn, 0.97 % Cu, 1.7 % Pb, 203 g/t Ag, and 1.6 g/t Au.

The Fyre Lake deposit has resources of 15.4 Mt at 1.2% Cu, 0.8% Co, and 0.46 g/t Au using the kriging method and a cut off of 0.5 % Cu, or 8.2 Mt at 2.1 % Cu, 0.11 % Co, and 0.73 g/t Au using a sectional block method and cut off of
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In late 2004, Yukon Zinc Corporation drilled two holes into the Fisher zone (see below), and drillhole WV95-06 intersected 2.2 m of massive sulphide with an average grade of 2.8% Zn, 1.4% Pb, 0.12% Cu, 62 g/t Ag, and 0.14 g/t Au. However, a resource has not been calculated for this zone.

The Ice deposit has an indicated resource of 4.56 Mt grading 1.48% Cu, including 3.4 Mt open pittable mineralization at 1.48% Cu (Expatriate Resources Ltd., 1999). The massive sulphide body is overlain by Cu-oxide mineralization for which there is insufficient data to estimate a geological resource; however, 2.7 Mt of this fall within the open pittable resources (Expatriate Resources Ltd., 1999; Hunt, 2002, Yukon Zinc Corporation, 2006b). There are also some Zn-rich (~1%) massive sulphide zones, but the Zn resource has not been quantified.

The Skyblaze zone on the Goal Net North property contains 16 m of greater than 1% Zn and 0.73 m of semi-massive sulphide mineralization grading 3.0% Zn, 1.85% Pb, 0.14% Cu, 63 g/t Ag and 0.2 g/t Au (Yukon Zinc Corporation, 2005). There are currently too few drillholes to calculate a resource. Although a resource for the Thunderstruck zone has not been calculated, drill intercepts over a thickness of 0.30 m reportedly grade 13.4% Zn, 5.07% Pb, 0.34% Cu, 40.7 g/t Ag, and 0.04 g/t Au with low Se contents (Yukon Zinc Corporation, 2004b, 2005).

The major (significant) massive sulphide deposits of the district occur at different stratigraphic levels within the FLD stratigraphy (Fig. 3; Murphy and Piercey, 1999a,b,c, 2000b; Hunt, 2002). Below are descriptions of each of these VHMS deposits.

Fyre Lake Deposit

The Fyre Lake deposit (also referred to as Kona) is located about 160 km northwest of Watson Lake and 140 km southeast of Ross River. The Fyre Lake deposit occurs within the ca. 365 Ma Fire Lake Formation of the Grass Lakes Group (Fig. 4). The Fire Lake Formation consists of a metamorphosed volcanic sequence composed mainly of chloritic phyllite with some carbonaceous phyllite, and rare muscovite-quartz phyllite of probable felsic volcanic origin (Figs. 4, 5). The Fire Lake Formation lies on clastic rocks of the North River Formation (Fig. 5).

The immediate host rocks to the deposit are chlorite-quartz and chlorite-actinolite-quartz schists (mafic volcanic and volcaniclastic rocks; Fig. 6A), and turbiditic sedimentary rocks form the immediate stratigraphic hanging wall (Fig. 6B). The metamorphosed sedimentary rocks are predominantly finely laminated carbonaceous phyllite and these overlie the volcanic rocks (Figs. 4, 5). Intercalated quartz-biotite schists (mafic volcaniclastic) and chlorite-mica-

![Figure 5. Generalized stratigraphic section of the Fyre Lake deposit area depicting the spatial relationships of the major rock units (from Sebert et al., 2004); legend as in Figure 4.](479)
quartz schists (wackes) occur at the base of the sedimentary sequence and grade upwards into the carbonaceous sedimentary rocks.

The Fyre Lake deposit consists of three parallel, northwest-trending tabular, sheet-like massive sulphide horizons that are grouped into two zones, termed the East Kona (Upper and Lower horizons) and West Kona zones (Fig. 7A-C). The zones are separated by an inferred, steeply dipping, reverse fault that down-drops the west side by about 100 m (Fig. 7A; Foreman, 1998).

East Kona consists of an upper and a lower horizon, each with an average thickness of 8 to 12 m and an average width of 100 to 125 m (Fig. 7B). The upper horizon occurs at the contact between the underlying volcanics and overlying sedimentary rocks. The lower horizon occurs 40 to 70 m stratigraphically beneath the upper horizon, within mafic volcanic rocks (Fig. 7B). East Kona massive sulphides are composed primarily of massive pyrite, with lesser pyrrhotite, chalcopyrite, sphalerite, and local lenses of massive magnetite (Fig. 6C).

FIGURE 6. Photographs of Fyre Lake deposit host rocks and mineralization. (A) Footwall mafic volcaniclastic rocks. (B) Hanging-wall intercalated mafic volcaniclastic and sedimentary rocks. (C) Chalcopyrite-rich massive sulphide from East Kona zone (Hunt, 2002). (D) Fine- to medium-grained bledby to disseminated pyrite with interstitial chalcopyrite in a matrix of grey, quartz-rich (silicified wall rock) matrix, West Kona zone. (E) Foliation-parallel quartz-sulphide-magnetite bands interpreted to be stringer veins from feeder zone that have been tectonically transposed parallel to F_{1} foliation, immediately below West Kona zone (DDH 97-115; 746.8 m). (F) Fine-grained magnetite fragments in matrix of pyrite-pyrrhotite-chalcopyrite-quartz from West Kona zone (DDH 97-95; 331 m). (G) Patchy to discontinuously banded pyrite-quartz crosscutting fragmental, fine-grained magnetite, West Kona zone (DDH 97-95; 341.8 m). (H) Wispy, banded magnetite (dark grey), chlorite (dark green), and semimassive sulphide (pyrite-chalcopyrite) with notable absence of chlorite, from immediately below the upper horizon of the East Kona zone (DDH 96-35; 67.8 m). (I) Finely bedded to laminated magnetite iron formation horizon from immediately below massive sulphide, lower horizon of East Kona zone (DDH 96-34; 72.3 m). Unless stated, the locations of individual samples are not specified. Images C, E, F, G, H, and I are from Sebert et al. (2004). The diameter of the core in photos (C) to (H) is 4.5 cm.
The West Kona zone has a strike length of 1,500 m, dips gently to the northeast, and remains open at both ends along strike (Fig. 7C). Although the massive sulphide lenses are elongated parallel to the local lineation, an inferred step fault with a facies change across it separates the East and West Kona zones; this fault is suggested to be synvolcanic in origin and may have served as the conduit for the mineralizing fluids (Sebert et al., 2004).

In general, the massive sulphides are zoned, with pyrite±sphalerite commonly occurring at the top part of the lenses, and pyrrhotite and chalcopyrite being more common in the lower parts of the lenses as well as comprising a significant portion of semimassive and disseminated mineralization that lies stratigraphically beneath the lenses. West Kona massive sulphides are dominated by magnetite-pyrite-chalcopyrite in a grey siliceous matrix in the east, and transitioning to pyrite-chalcopyrite (Fig. 6D) going westward, and massive pyrrhotite in the western-most part.

The semimassive and disseminated mineralization contains chlorite and quartz. Quartz-rich bands within mineralization (e.g. Fig. 6E) are interpreted to be stringer veins of a footwall feeder zone that have been tectonically transposed parallel to the prominent foliation, with the chlorite representing altered wallrock (Sebert et al., 2004).

A unit of fine-grained chert with a few percent sulphides (chalcopyrite, pyrite) and magnetite locally marks the top of massive sulphide lenses of the West Kona zone and the lower horizon of the East Kona zone (Fig. 6I). This unit, typically 15 to 40 cm thick, but ranging to several metres, is thought to be an exhalative sediment (Columbia Gold Mines Ltd., 1999; Sebert et al., 2004).

Although there have been several microscopic investigations of the Fyre Lake mineralization, the origin of the magnetite remains unclear and enigmatic. The high degree of deformation of the deposit indicates that the present textural association of magnetite with other sulphides and alteration minerals may largely be due to deformational processes. Textural relationships in Figure 6G and H indicate that magnetite predates sulphide, and sulphides have brecciated and partly replaced magnetite, with subsequent deformation imparting a crudely banded texture of alternating magnetite- and sulphide-rich layers.

Kudz Ze Kayah Deposit

The Kudz Ze Kayah deposit occurs within a sequence of predominantly felsic volcanic and volcaniclastic rocks, and minor metasedimentary rocks of the Kudz Ze Kayah Formation (Fig. 8). The felsic volcanic and volcaniclastic rocks are generally fine-grained, though centimetre-sized clasts occur in some intervals. Schultze (1996), in a brief early report of the deposit indicated that the rocks were emplaced as flows, and lapilli and ash tuffs. Limited petrographic studies of these rocks by company personnel note the presence of embayed feldspar crystal fragments in some porphyritic samples (e.g. Fig. 9A,D), quartz phenocrysts or phenoclasts in others, and quartz and feldspar in others, indicative of a tuffaceous origin. However, an epiclastic origin cannot presently be ruled out, and further work is needed to unambiguously ascertain the volcanic setting and mode of emplacement of these rocks. The host-rock sequence is stratigraphically overlain by carbonaceous sedimentary rocks (argillite) and alkalic mafic volcanic rocks of the Wind Lake Formation (Fig. 8). A biotite-chlorite-calcite schist (Fig. 9E) is interpreted to be a strongly deformed mafic intrusive body that was emplaced as a sill or dyke after formation of the deposit.

The main part of the Kudz Ze Kayah deposit, termed the ABM zone (Fig. 8), is a 500 m long, isoclinally folded lens of massive to semimassive sulphide (Figs. 10, 11) that occurs within a syncline that is overturned to the south and is half of a south-vergent anticline-syncline pair. The mineralization extends down dip about 400 m, averages 18 m thick, and reaches a maximum thickness of 34 m at the nose of the fold. The smaller southern part of the mineralization, referred to as the Fault Creek zone, has been downdropped by faulting (Fig. 8).

The stratigraphic sequence in the upper limb of the syncline is overturned, and hydrothermally altered rocks in the stratigraphic footwall now form the structural hanging wall to the deposit (Fig. 10). Both stratigraphic footwall and hanging-wall contacts comprise volcaniclastic rocks (Fig. 9A-D) and what are interpreted to be rhyolite flows. The most
strongly hydrothermally altered rocks are situated near the fold axis. Nearly symmetric base-metal zoning within the two limbs of the folded sulphide body supports the interpretation that the deposit is overturned. Figure 11A is a representation of the present, post-deformational configuration of the Kudz Ze Kayah deposit, including the location of the feeder zone and the adjacent mafic intrusive body, and Figure 11B presents the interpreted predeformational configuration.

The mineralogy of the sulphide bodies is dominated by pyrite (e.g. Fig. 9F,G), followed by sphalerite, pyrrhotite, galena, chalcopyrite, and trace arsenopyrite, tetrahedrite-tennantite, boulangerite, and electrum. Gangue minerals include chlorite, magnetite (e.g. Fig. 9F,G), quartz (e.g. Fig. 9H), Fe-carbonate, sericite, albite, and barite (Fig. 9I). Where present, barite is generally concentrated in the stratigraphic upper parts of the sulphide lens. In places, the sulphides have been strongly deformed and recrystallized, and many primary textures obliterated due to a strong foliation (e.g. Fig. 9F,G).

**GP4F Deposit**

The GP4F deposit is located over 5 km southeast of the Kudz Ze Kayah deposit (Fig. 8). The deposit is within the same package of Late Devonian-Early Mississippian rocks as Kudz Ze Kayah and is hosted by a sequence of alternating aphyric and porphyritic felsic volcanic rocks and felsic volcaniclastic rocks (collectively 90 vol.%) that is crosscut by mafic dykes (10 vol.%). Mineralization at GP4F occurs in an overturned homoclinal sequence as a single semimassive to massive sulphide lens up to 3.2 m thick that dips to the north at 30 to 35° N (Fig. 12), has a strike length of 200 m, extends 350 m down dip, and remains open to the northeast and east (MacRobbie and Holroyd, 2000; Boulton, 2002).

The aphanitic, aphyric felsic volcanic rocks are white to cream coloured and composed of subangular aggregates of quartz and interstitial muscovite in a cryptocrystalline albite-quartz matrix (Fig. 13A). Based on the presence of flow contacts in places, these rocks were likely emplaced predominantly as coherent rhyolite flows.

Felsic volcaniclastic rocks are fine- to medium-grained, grey, equigranular, and composed of quartz, muscovite, and chlorite with minor disseminated tourmaline (Fig. 13B). Some intervals contain abundant sub-centimetre- to centimetre-sized clasts of fine-grained felsic rock fragments (e.g. Fig. 13C). The volcanic setting and emplacement mechanism of the volcaniclastic rocks has not been determined.

Immediately below the massive sulphide lens is a massive, homogenous, foliated quartz-feldspar porphyry (Fig. 12) with 5 to 10% slightly bluish 2 to 5 mm quartz phenocrysts, 15 to 20% 3-12 mm feldspars in a fine-grained matrix of quartz-feldspar-sericite and muscovite (Fig. 13D). Other porphyritic intervals contain only feldspar phenocrysts (2-3%, 1-3 mm) in a quartz-feldspar-muscovite-biotite matrix or only bluish grey quartz phenocrysts (10-15% 1-4 mm) in a matrix of feldspar-biotite-sericite with trace quantities of disseminated tourmaline. The mode of emplacement of the porphyritic felsic rocks has not been determined; however, these relatively little-deformed, blue quartz-phryic porphyries yielded ages of 347 to 345 Ma (Murphy et al., 2006), suggesting that they are intrusive and part of the Wolverine suite.
Mafic dykes are dark grey/brown, fine- to medium-grained, and consist of quartz, biotite, sericite, calcite (in veinlets), and minor titanite; they are the most unaltered rock type present and display no obvious foliation.

The GP4F mineralization is relatively Cu-poor and Pb-rich in comparison to Kudz Ze Kayah (see Grade and Tonnage section above). Mineralization is crudely banded and consists of medium- to coarse-grained buckshot pyrite.
J.M. Peter, D. Layton-Matthews, S. Piercey, G. Bradshaw, S. Paradis, and A. Boulton

(50–60 vol.%) in a matrix of sphalerite, pyrrhotite, galena, magnetite (locally) and trace chalcopyrite (Fig. 13E–H). Gangue minerals are quartz, feldspar, chlorite, carbonate, sericite, and/or biotite.

A ‘marker tuff’ unit occurs almost universally in the structural hanging wall and is a light to medium grey/beige colour, homogenous, finely banded, fine-grained rock with a strong sericite – and lesser biotite – dark green chlorite-quartz-rich (± tourmaline and garnet) matrix and 10 to 30% disseminated to blebby pyrite, pyrrhotite, sphalerite, chalcopyrite, and gahnite (Fig. 13G, H). Mineralization in the marker tuff formed by partial replacement of the original host rocks.

The Wolverine deposit is hosted by rocks of the Wolverine Lake Group, dominated by felsic volcanic and volcaniclastic and carbonaceous sedimentary rocks and capped by mafic volcanic rocks (Fig. 14). The Wolverine Lake Group has a lower conglomerate with fragments of the Kudz Ze Kayah Formation within it and unconformably overlies the Kudz Ze Kayah Formation (Murphy and Piercey, 1998, 1999a).

The host-rock sequence (Fig. 15; Bradshaw et al., 2000) consists of black to dark grey, fine-grained carbonate argillite, fine- to coarse-grained, ± quartz-feldspar-phyric volcaniclastic rocks (Fig. 16A); K-feldspar-phyric porphyry (Fig. 16B); and massive flow-banded aphanitic, aphyric rhyolite (Fig. 16C); fine-grained felsic volcaniclastic rock with abundant centimetre-sized flattened clasts of aphyric rhyolite (Fig. 16D); and felsic volcaniclastic rock with abundant centimetre-sized flattened clasts of rhyolite and argillite (Fig. 16E). The volcanic setting and mode of emplacement of the felsic volcanic and volcaniclastic rocks has not been studied in detail. Also, within the host sequence are two intervals of magnetite iron formation (Fig. 16F) and a narrow discontinuous interval of carbonate exhalite (Fig. 16G); these are discussed further below.

Mineralization at Wolverine occurs as two steeply dipping coalesced, elongate to tabular, massive and semmassive sulphide lenses named the Lynx and Wolverine zones (Figs. 17, 18). The deposit has a strike length of approximately 750 m, dips steeply to the north, and remains open down-dip to the northeast where it crosses onto claims owned by Teck Cominco Ltd. The massive sulphides are up to 16 m thick (Figs. 17, 18). Stringer veins in the stratigraphic footwall beneath the massive sulphides (Fig. 18) demarcate fluid
upflow zones and define the feeder system that channeled the mineralizing fluids. Deformation has modified the original morphology of the Wolverine deposit, but the overall metal zoning and relationships between the lenses and their feeder zones (Fig. 18) suggest that much of the original deposit architecture remains intact. Thicker sulphide intersections are underlain by felsic volcaniclastic rocks (Fig. 16A,B,D,E). These rocks commonly contain extensive footwall replacement mineralization (Fig. 16K-M) and alteration (Fig. 16P-S) and/or stringer mineralization of pyrite, sphalerite, chalcopyrite, and galena (Fig. 16N,O).

According to Bradshaw et al. (in press) there are three types of mineralization: 1) banded/layered massive sulphides (Fig. 16I); 2) semimassive replacement-style sulphides (Fig. 16K-M); and 3) stringer sulphide veins (Fig. 16N,O). The massive sulphides are predominantly pyrite and sphalerite with minor pyrrhotite, chalcopyrite, galena, trace tetrathedrite and arsenopyrite, and rare marcasite, meneghinite (Pb13CuSb7S13), boulangerite (Pb5Sb4S11), bournonite (PbCuSbS3), miargyrite (Ag2Sb2S3), native Au, and electrum. Sulphides are generally fine grained and recrystallized in response to deformation and metamorphism. However, in a few places, colloform and framboidal pyrite textures are preserved, particularly in the uppermost parts of the sulphide lenses near the contact with hanging-wall argillite. A zone of replacement-style semimassive mineralization less than 3 m thick consists of sulphide minerals (chalcopyrite, pyrrhotite, sphalerite) that have partly to completely replaced permeable felsic volcaniclastic host rocks in patches that range from several centimetres to 1 m in diameter. This style of mineralization occurs immediately adjacent to stringer vein zones and extends up to about 100 m laterally outward from the periphery of the massive sulphide lenses (Fig. 18). Stringer vein zones, up to 25 m wide, consist of millimetre to 25 cm wide veins of pyrite, sphalerite, and lesser chalcopyrite, pyrrhotite, and arsenopyrite, together with common gangue minerals quartz, calcite, dolomite, ankerite, siderite, chlorite, biotite, and muscovite (Fig. 16N,O).

Within the Wolverine deposit there is no well preserved vertical base metal zoning from footwall to hanging-wall contacts, likely due to the deformational effects. However, high Cu areas dominated by chalcopyrite are confined predominantly to the base of the massive sulphide lenses within massive and replacement-style mineralization (e.g. in the area between the Lynx and Wolverine zones; Fig. 19A). High Zn and Pb areas are in the massive sulphides at the outer fringes of the deposit (Fig. 19B,C). Silver resides mostly within tetrahedrite.

Ice Deposit

The Ice deposit is located in the northern part of the FLD (Fig. 2) about 60 km east of Ross River. Host rocks to the deposit are basalts, cherts, and mudstones (Figs. 20, 21, 22) of the Campbell Range Formation. The immediate host rocks to the deposit are massive basalts, porphyritic-pilowed basalts (Fig. 23A) and variably autobrecciated pillow basalts that are plagioclase porphyritic immediately below the deposit (Fig. 23B,C) (Becker, 1997, 1998; Eaton and Pigage, 1997; Pigage, 1997). These are interbedded with black, grey, green, and red ribbon cherts (e.g. Fig. 23D), and minor greywackes and carbonaceous mudstones.

The massive sulphide lens at Ice is up to 28 m thick (Fig. 20), and is underlain by a zone of stringer sulphide veins (Figs. 22, 23E). Primary features and textures are much better preserved at Ice than in the Kudz Ze Kayah, GP4F, and Wolverine deposits. The lens comprise a Cu-rich basal core of chalcopyrite, bornite, and Cu-rich sphalerite (e.g. Fig. 23F) that is situated stratigraphically directly above the stringer vein zone. The basal Cu-rich sulphides are surrounded by thinner, lower grade Cu mineralization. Stringer sulphide
vein mineralization is locally present within the footwall-breciated, porphyritic basalt. Stringer veins are predominantly pyrite-quartz-chalcopyrite and specular hematite. The massive sulphides are largely overlain by a thin (~5 cm - 0.5 m) siliceous hematitic chert unit that passes upwards into a hanging wall of massive basalt flows and interlayered chert. The massive sulphide mineralization consists of low Pb, and very low As, Sb, Hg, and Se contents, consistent with a setting dominated by mafic volcanic host rocks.

Secondary mineralization is confined to the zone of near surface weathering that typically ranges between 5 and 50 m below surface, and extends to almost 80 m depth along fractures. Secondary mineralogy includes minerals that have wholly or partially replaced primary sulphide minerals and others that were precipitated from groundwater.

**Fisher Zone**

The Fisher Zone, discovered in 1995 by Westmin Resources Ltd., is located some 8 km northwest of the Wolverine deposit, and on the same apparent stratigraphic horizon, referred to as the Wolverine Belt (Fig. 14). The Fisher zone consists of numerous narrow bands or lenses of sphalerite-pyrite-galena within sericite-quartz±chlorite
altered felsic volcanic and volcani-
clastic rocks (Tucker, 1999). In the
footwall, there is a K-feldspar ±
quartz porphyry that is similar in
appearance and composition to that
in the Wolverine and Lynx zones
(Piercey et al., 2001b). This por-
phyry has been dated at 346.0 ± 2.2
Ma, similar to the 347.8 ± 1.3 Ma
age for Wolverine (Piercey et al., in
press). The area contains a mag-
netite iron formation that has been
thickened due to repetition by fold-
ing.

Sable Zone

The Sable Zone is located 1.6
km southeast of and along strike
from the Wolverine deposit, along
the Wolverine Belt (Fig. 14). Min-
eralization consists of thin
intersections of high-grade massive
sulphide and strongly silica-pyrite
and Fe-carbonate-altered rhyolite.
A K-feldspar-quartz porphyry in
the footwall has been dated at 352.4
± 1.5 Ma (Piercey et al., in press).

Puck Zone

Puck is located 2 km southeast
of the Wolverine deposit along the
Wolverine Belt (Fig. 14) and con-
sists of sphalerite±galena±chal-
copyrite stringer veinlets in vari-
ably sericite-altered quartz-phric
felsic volcanic rocks. In places,
there is a well developed calcte-
pyrite exhalite, magnetite iron for-
mination, and barite. There is a
narrow (6.1 m) interval of K-
feldspar-quartz porphyritic rocks
in the footwall, similar to that at the
Wolverine deposit and the Fisher
zone (Piercey et al., 2001b), and
this has been dated at 356.9 ±
0.5 Ma (Piercey et al., in press).

Goal Net Property

The Goal Net property of Yukon
Zinc Corporation is a 10 by 6 km
block of claims within rocks of the
Grass Lakes Group situated
equidistantly between the Fyre
Lake deposit to the south and the
GP4F deposit to the north (Murphy
and Piercey, 1999b,c) (Fig. 24).
The Goal Net property contains at
least twelve exploration targets,
only several of which have been
tested. In the Goal Net North area,
Zn-Pb-Cu semimassive sulphides

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**FIGURE 14.** Surface geology map of the Wolverine Belt and Wolverine deposit area (modified from Murphy et al., 2006; Bradshaw et al., in press; Expatriate Resources Ltd., unpub. data). Also shown is the cross section line for Figure 15.

**FIGURE 15.** Cross-section 16250E through the Wolverine deposit (modified from Expatriate Resources Ltd., unpub., 2001; Bradshaw et al., 2001).
FIGURE 16. Photographs of Wolverine deposit host rocks, mineralization, and hydrothermal alteration. (A) Footwall quartz-phyric felsic volcaniclastic (DDH WV97-102). (B) Footwall feldspar-porphyritic rhyolite. (C) Aphyric rhyolite forming the immediate hanging wall. (D) Hanging-wall felsic volcanioclastic with rhyolite breccia clasts (DDH WV97-112). (E) Hanging-wall rhyolite and argillite clast breccia. (F) Magnetite iron formation, from stratigraphic hanging wall to Wolverine Zone. (G) Calcite-pyrite exhalite that forms the immediate hanging wall to the massive sulphides in places. (H) Chalcopyrite-pyrrhotite-rich sulphides from base of massive sulphide lens (DDH WV00-120). (I) Banded, sphalerite-rich massive sulphides from upper part of massive sulphide lens.
FIGURE 16 CONTINUED. Photographs of Wolverine deposit host rocks, mineralization, and hydrothermal alteration. (J) Possible primary massive sulphide breccia, with pyrite-rich clasts in a sphalerite-rich matrix (DDH WV95-12). (K) Chalcopyrite-rich replacement-style mineralization from immediately below the massive sulphide lens (DDH WV95-21). (L) Chalcopyrite-rich replacement-style mineralization from immediately below the massive sulphide lens, with abundant silver-grey chlorite (DDH WV96-56; 333 m). (M) Replacement-style mineralization from immediately below the massive sulphide lens, with dark green porphyroblasts in a matrix of light grey felted chlorite (DDH WV96-71). (N) Sphalerite-chalcopyrite-pyrite-quartz stringer veins crosscutting felsic volcaniclastic, from feeder zone; note silicified vein margins (DDH WV95-25). (O) Sphalerite-chalcopyrite-pyrite-quartz stringer veins in graphitic argillite, from feeder zone; veins have been transposed parallel to prominent foliation (DDH WV96-25). (P) Intensely silicified felsic volcaniclastic with deformed pyrite-quartz veinlets. (Q) Strongly chloritized felsic volcaniclastic (DDH WV96-27). (R) Fe-carbonatized felsic volcaniclastic. (S) Strongly sericitized felsic volcaniclastic (DDH WV96-39). Unless stated, the locations of individual samples are not specified.
and disseminated sulphides are associated with pyritic sericite-altered felsic volcanic and volcanioclastic rocks (interpreted to be rhyolite tuff and quartz porphyry rhyolite, respectively), as well as disseminated pyrite-chalcopyrite with biotite-chlorite alteration. Low-grade stratiform Zn mineralization also occurs over 16 m in flat-lying argillaceous felsic volcaniclastic rocks within the Skyblaze zone. In the Goal Net South area, the Thunderstruck zone, 4.3 km south of Skyblaze (Fig. 24), is a gently southerly dipping continuous sheet of thin, high-grade pyrite-pyrrhotite-sphalerite-bearing semimassive to massive sulphides in chlorite-sericite-altered felsic schist that extends from outcrop down-dip for over 550 m (Yukon Zinc Corporation, 2004b, 2005). The zone is thought to be located at the same time stratigraphic position as both the Kudz Ze Kayah and GP4F deposits, within the basal portion of the Kudz Ze Kayah Formation.

**FIGURE 17.** Geological plan of the Wolverine deposit depicting the two thickened zones of massive sulphide (Lynx and Wolverine zones), diamond drillhole collars, and contours of massive sulphide thickness (Yukon Zinc Corporation, 2004a).

**FIGURE 18.** Geological plan of the Wolverine deposit depicting the distribution of feeder zone (as defined by the presence of stringer veins) and replacement-style mineralization/alteration; also shown are 6 to 10 m and 10 to 16 m massive sulphide thickness contours (for comparison with Fig. 17). Inset shows an idealized, schematic section. Figure constructed from J. Peter (unpub. data, 2001).
The Money (also referred to as Julia) prospect is located about 5 km east of the Wolverine Deposit in a thick sequence of pillowed and pillow breccia basalts intercalated with mudstone and chert of the Campbell Range Formation (Hunt, 1998). The deposit consists of a tabular lens of massive banded and siliceous pyritic sulphides that has a strike length of at least 53 m, extends down dip for at least 130 m, and averages 1 m in thickness. The footwall host rocks include pillow basalt, pillow basalt breccia with maroon mudstone matrix, chert, mudstone, and maroon shale (Baknes, 1997). The basalt and basaltic tuff have been hydrothermally altered to quartz-sericite-pyrite.
In addition to the deposits and occurrences described above, there are a number of others that have been recognized in the FLD. Details on these properties that include the Pack (or Pak), Blueline, Pneumonia (Mony), Akhurst (Expo), Ant (Hat Trick), Red Line, Cobb, League, and Nad properties within the Grass Lakes Group, the Hoo (Argus), El (Tin), and Eldorado properties in North River Formation rocks, are given by Hunt (2002).

Deposit Classification

Host rocks, and metal association and tenor (Cu-Co-Au), indicate that the Fyre Lake deposit is a Besshi-type VHMS deposit (e.g. Fox, 1984; Slack, 1993). A hallmark of Besshi-type deposits is that sedimentary rocks are a significant component of the host stratigraphy in addition to mafic volcanic rocks. Such deposits are also typically enriched in Co and Au.

The Kudz Ze Kayah deposit can be classified as a Kuroko-type deposit that formed as a mound on the paleoseafloor. At least part of the deposit likely formed by subsurface replace-
ment of host strata (e.g. albite-altered rocks and mineralization).

The GP4F deposit, only 5 km away from Kudz Ze Kayah, is also best classified as a Kuroko-type VHMS deposit and is genetically related to rift-related felsic volcanism within a back-arc basin as suggested by Piercey et al. (2001a) for the nearby Kudz Ze Kayah deposit. GP4F has no feeder zone characterized by stringer quartz-sulphide veins and associated intense hydrothermal alteration, and this indicates that the preserved portions of the deposit are the distal part of the seafloor hydrothermal system (perhaps with subsurface replacement), with the proximal Cu-rich mound and feeder zone eroded away.

The Wolverine deposit has many characteristics of a polymetallic Kuroko-type deposit, but with some characteristics common to SEDEX deposits. In this respect, Wolverine also has many geological, geochemical, and metallogenic similarities with the world-class Brunswick No. 12, No. 6, and Heath Steele deposits in the Bathurst Mining Camp of northern New Brunswick (see Goodfellow and McCutcheon, 2003). Among these similarities are 1) felsic volcaniclastic and black shale host rocks; 2) relatively Zn-rich (up to 30 wt.% in some intersections); and 3) presence of spatially associated and laterally extensive iron formations. Although the term “Bathurst-type” deposit has been coined previously, Goodfellow (2001) argued that volcanic-sediment-hosted massive sulphide (VSHMS) is a more meaningful classification, and we also favour such a moniker.

The Ice deposit, together with the Money occurrence, are the only known Cyprus-type (Cu-Zn) VHMS deposits in the FLD; distinguishing criteria for this deposit-type are the pillow to mafic volcanic host rocks, and the Cu-rich and Pb-Zn-poor nature of the mineralization.

**Alteration Mineralogy and Lithogeochemistry**

The VHMS deposits of the FLD are associated with hydrothermally altered host rocks. In the stratigraphic footwalls, alteration styles vary from chloride (Fyre Lake, Kudz Ze Kayah, Wolverine, Ice), sericite (Kudz Ze Kayah, GP4F, Wolverine), silica/quartz (Kudz Ze Kayah, Wolverine), carbonate (Wolverine) and albite (Kudz Ze Kayah). Feeder zones/stringer veins are present at the Fyre Lake, Kudz Ze Kayah, Wolverine and Ice deposits. Hanging-wall alteration is present at Fyre Lake (weak chlorite) and Wolverine (weak sericite).

At Fyre Lake, the mafic volcanic rocks stratigraphically beneath and peripheral to the massive sulphides have been hydrothermally altered to chloride and quartz (Sebert et al.,...
The hanging-wall mafic volcanic rocks have also been weakly chloritized (Sebert et al., 2004). In general, Sebert et al. (2004) indicate that there is a greater Mg content in altered rocks relative to unaltered rocks.

At the Kudz Ze Kayah deposit, structural hanging-wall (stratigraphic footwall) rocks have been hydrothermally altered to sericite, chlorite, and albite, and distributed in discrete zones; hydrothermal alteration intensity increases with proximity to sulphides. The most proximal alteration at the immediate base of the massive sulphides is dominated by albite (Fig. 9L), presumably because of intense replacement of detrital sedimentary and volcaniclastic rocks. This gives way to Fe chlorite-dominated alteration (Fig. 9J) that is commonly associated with chalcopyrite and pyrrhotite blebs and disseminations, and pyrrhotite→chalcopyrite→pyrite→ sphalerite→galena veins in the feeder zone. This, in turn gives way to a more distal sericite-dominated (=disseminated pyrite and/or pyrrhotite) alteration in the outermost zones (Fig. 9K). Silicification is developed only locally in a few places in the chlorite zone associated with sulphide replacement and feeder veins. Ankerite and siderite are ubiquitously developed in almost all of the host rocks in and around the deposit and occurs as Fe carbonate disseminations that have preferentially replaced felsic clasts in volcaniclastic rocks (Fig. 9M). Structural footwall (stratigraphic hanging-wall) rocks, however, are not visibly hydrothermally altered.

At GP4F, there is a narrow zone of sericite-chlorite hydrothermal alteration within felsic rocks immediately adjacent to (structurally above) the massive sulphides in the stratigraphic footwall (so-called marker tuff) (Boulton, 2002). The alteration intensity is weaker than is observed at Kudz Ze Kayah and is characterized by the destruction of feldspars. Quartz-feldspar porphyry occurs (with one exception) structurally below or stratigraphically above the massive sulphide lens. Stratigraphically below the lens, feldspars phenocrysts in porphyritic rocks have been completely
altered to sericite or secondary albite, resulting in a rock containing only quartz phenocrysts.

At Wolverine, hydrothermal alteration effects are largely confined to the permeable felsic volcaniclastic rocks that are the immediate footwall of the massive sulphide lenses, though they extend (in the footwall) to the periphery of the massive sulphide lenses and to a lesser extent the hanging wall. Four hydrothermal alteration styles are recognized (Fig. 25A-D; Peter, 2001; Bradshaw et al., in press): silicic alteration (Fig. 16P; distribution is not shown but restricted to close proximity to the feeder zone—see Fig. 18), carbonate alteration (Figs. 16R, 25A), chlorite alteration (Figs. 16Q, 25B), and sericite alteration (Figs. 16S, 25C,D).

Stringer sulphide veins typically have a 5 to 10 cm wide quartz alteration selvage (Fig. 16N,P). Zones of silicified rocks also extend up to 20 m below the base of sulphide lenses. Chalcopyrite-and pyrrhotite-rich semimassive replacement-style mineralization has attendant chlorite and Fe-carbonate, and more sphalerite-rich, semimassive replacement-style mineralization has associated sericite and ankerite alteration of the host rocks.

Carbonate alteration consists of various carbonates, ranging from creamy white calcite to orange-brown ankerite to brown siderite. The carbonate, comprising up to 30 vol.% of the rock, consists of porphyroblasts up to 2 cm in diameter. Carbonate alteration associated with replacement-style mineralization consist of 1 to 2 m wide zones, is most prevalent beneath the Lynx zone lens (Fig. 25A). This carbonate is generally ankeritic with up to 38 mole% Mg, whereas carbonate gangue within massive sulphide is generally end-member siderite although it can contain up to 26 mole% Mg (Bradshaw, 2003). Carbonate in sericite-altered rock is generally calcite. Chlorite alteration zones consist of abundant fine-grained chlorite (up to 50 vol.%) in coarse-grained volcaniclastic rocks. They generally flank silicic alteration zones and can extend up to 30 m below the base of the sulphide lenses. There is commonly a transitional change from chlorite-dominant to sericite-dominant alteration mineralogy. Electron microprobe analyses of chlorite show two compositional varieties: 1) dark green magnesian clinohlochlore, which forms fine-grained, massive aggregates; and 2) less common ferroan clinohlochlore, which forms local clots in carbonate altered rocks (Bradshaw et al., in press).

Sericite altered rocks occur within stratabound zones in the footwall up to 40 m wide and are generally peripheral to and below chlorite altered rocks. Sericite altered footwall rocks typically contain 40 to 60 vol.% sericite, with the abundance of the mineral decreasing with increasing distance from the sulphide lenses. Sericite alteration is developed best in the Wolverine zone and in the area between the Wolverine and Lynx zones (Fig. 25C). Minor sericite alteration occurs in hanging-wall rocks at the western, eastern, and up-dip edges of the sulphide lenses (Fig. 25D). Electron microprobe analyses indicate that the sericite is Ba-rich phengite (Bradshaw et al., in press).

Lithogeochemical indicators of footwall hydrothermal alteration at Wolverine are elevated Al₂O₃/Na₂O ratios, and low Na₂O on both a regional and local scale (G. Bradshaw, 2003, unpub. data; S. Piercey, unpub. data). Locally, the rocks at Wolverine and also Kudz Ze Kayah and GP4F have elevated K₂O due to the presence of abundant sericite, MgO-FeO due to chlorite and Fe carbonates, and CO₂-LOI (loss on ignition) due to the presence of Fe-carbonate, sericite, and chlorite.

At the Ice deposit, hydrothermal alteration is restricted to the stringer zone, where the rocks are dark green and intensely chlorite altered. Only a few metres from the stringer zone, the rocks are relatively unaltered (Becker, 1997, 1998; Eaton and Pigage, 1997; Pigage, 1997). To date

FIGURE 26. Age distribution for VHMS and VSHMS deposits in the FLD. Also shown are ages for other deposits in the Yukon-Tanana Terrane, and VHMS and SEDEX deposits from the Kootenay Terrane and the North American miogeocline, and globally significant (>50 Mt) VHMS and SEDEX deposits/camps that formed during the Devonian-Mississippian (modified from Piercey et al., in press and Nelson et al., 2002).
there has been no systematic study of the hydrothermal alteration associated with the Ice deposit, but a reconnaissance study of basalt samples from the stringer zone indicates that they exhibit typical Na2O and CaO depletions with enrichments in Fe2O3 and K2O (S. Piercey, unpub. data).

Exhalites

The narrow (15-40 cm wide), fine-grained chert with a few percent sulphides (chalcopyrite, pyrite) and magnetite that locally marks the top of massive sulphide lenses of the Fyre Lake deposit (Fig. 6I) is thought to be an exhalative sediment (Columbia Gold Mines Ltd., 1999; Sebert et al., 2004). However, the horizon does not appear to extend significantly beyond the mineralization. At the Ice deposit, red hematitic cherts occur at the mineralized horizon as narrow horizons and as interpillow sediment (Fig. 23F). As in other Cyprus-type deposits, these exhalites are generally of restricted areal extent (e.g., Peter, 2003).

In the FLD, exhalites of widespread areal distribution are only known to be associated with deposits in the area extending from the Fisher zone to the Sable zone, the Wolverine deposit, and the Puck Zone, referred to informally as the Wolverine Belt. There are three exhalite horizons in the vicinity of the Wolverine deposit: a narrow (less than 1 m wide) grey to white carbonate-predominant rock consisting of up to 90 vol.% patchy to massive carbonate (calcite>ankerite-siderite) with lesser magnetite, chlorite, and pyrite (Figs. 14, 16G) that locally overlies the massive sulphides, and two horizons up to several metres wide of a grey to black, magnetite-predominant iron formation contain 5 to 60 vol.% of disseminated to massively layered magnetite with lesser carbonate, chlorite, quartz, and white mica (Figs. 14, 16F). The layering is interpreted to be primary bedding. Monominerallic magnetite layers are interleaved with other minerals on a millimetre-scale. This magnetite-predominant iron formation occurs 80 to 100 m stratigraphically above the Wolverine massive sulphides and is laterally extensive with a strike length in excess of 12 km. It displays mineralogical and geochemical similarities with iron formations of the Heath Steele Belt in the Bathurst District, New Brunswick (Peter, 2003; Peter et al., 2003a,b).

It is important to note that the Kudz Ze Kayah and GP4F deposits, with many characteristics similar to Wolverine, have no associated exhalites.

Metallogeny

Within the pericratonic terranes along the western North American margin from Alaska to southern British Columbia, VHMS mineralization is associated with Devonian-Mississippian arc magmatism and associated back-arc basins. The episode(s) of extension within the arcs, ensialic back-arc basin formation, and felsic magmatism coincided with VHMS deposits in the FLD and elsewhere in the Yukon-Tanana Terrane (Fig. 26; Mortensen 1992a; Piercey et al. 2001a, 2002a, 2006; Dusel-Bacon et al. 2006; Nelson et al., 2006) and the initial opening of the Slide Mountain Ocean between the pericratonic terranes and the North American continent at about the Devonian-Mississippian boundary (Nelson, 1993; Nelson and Bradford 1993; Creaser et al. 1999). This period of arc and back-arc rifting and felsic to intermediate volcanism in the pericratonic terrane is also coeval with extension, alkalic magmatism, and VHMS and SEDEX deposit formation in rocks of the North American miogeocline during the mid-Paleozoic (e.g. Paradis and Nelson 2000; Nelson et al. 2002; Nelson and Colpron, 2007). The metallogenic evolution of the FLD is outside the scope of this paper, and the reader is referred to Piercey et al. (2001a, 2002a, 2006) and Nelson et al. (2002, 2006) for more detailed discussions.

Genetic Models

Hydrothermal Fluid Characteristics

Fluid Temperatures

The presence of hydrothermal sericite at Kudz Ze Kayah, GP4F, and Wolverine indicates that the mineralizing fluids were moderately acidic, and the Cu-sulphide mineralogy for Kudz Ze Kayah and Wolverine is consistent with precipitation from high-temperature (~350°C) fluids. Homogenization temperatures for primary two-phase fluid inclusions in quartz from quartz-sulphide stringer veins at Wolverine give temperatures of 235 to 353°C (Bradshaw et al., in press). This range is similar to geothermometric estimates for hydrothermal alteration chloride that yields formation temperatures of 273 to 288°C, and arsenopyrite geothermometric estimates of 215 to 336°C (Bradshaw et al., in press). The presence of sphalerite-galena-chalcopyrite stringer veinlets in variably sericite-altered quartz-phycolic felsic volcanic rocks at the Puck zone 2 km southeast of Wolverine suggests that this area was the locus of high-temperature upflow.

The paucity of Cu at GP4F indicates that this deposit likely formed at lower temperatures than Kudz Ze Kayah, based on the solubility considerations of Cu, Pb, and Zn as chloride complexes (Hannington et al., 1999a). Further, no feeder zone characterized by thinner quartz-sulphide veins and associated intensely altered rocks have been identified, and this suggests that the deposit is the distal part of a seafloor hydrothermal system.
Based on Cu solubility considerations, the Cu-rich nature of portions of the Ice and Fyre Lake deposits indicate that the Cu-rich portions of these deposits formed at temperatures of about 300 to 350°C (Crerar and Barnes, 1976). However, fluid inclusion homogenization studies have not been done on either of these deposits.

Fluid Salinities and Behaviour

Primary fluid inclusions in quartz from stringer veins at Wolverine contain low-salinity (2.1-8.5 wt.% NaCl equivalent; mean 6.0) fluids, indicating that the mineralizing fluids are predominantly hydrothermally modified seawater (Bradshaw et al., in press). The fluid inclusions show no evidence of fluid boiling and indicate that the deposit formed at a water depth of at least 1000 m. Based on temperature-density considerations of fluids of various salinities (Turner and Campbell, 1987), the venting mineralizing fluids behaved buoyantly at the seafloor. There are no other direct measurements of fluid salinities from other deposits in the FLD, but fluids are not expected to have been highly saline and have formed a brine pool as has been suggested for some VHMS deposits.

Fluid Redox and Evolution

The mineral zonation of the massive sulphides at Fyre Lake (basal pyrrhotite, upward to pyrite-chalcopyrite, and uppermost magnetite-pyrite) is likely a primary feature
related to redox variations attendant with the evolution of the primary sulphide mound in response to zone refining, with the magnetite deposited late in the paragenetic history of the deposit as the (originally reduced) fluids became more oxidizing. This interpretation, however, contradicts that of Sebert et al. (2004) who suggest that the intercalations of magnetite and sulphides are the result of multiple cycles of fluid evolution from oxidizing to reducing.

The coexistence of pyrite, pyrrhotite, and chalcopyrite and the preservation of Fe-rich sphalerite near the bases of the massive sulphide lenses in the Kudz Ze Kayah, GP4F and Wolverine deposits indicates a predominantly low and narrow range of log $f_{O_2}$ (-35 to -43) and log $f_{S_2}$ (-8 to -13) conditions within the sulphide mounds and replacement zones (Toulmin and Barton, 1964; Barton and Toulmin, 1966; Helgeson, 1969; Barton, 1978; Barton et al., 1979; Bowers et al., 1985; Hannington et al., 1999a). The absence of pyrrhotite and chalcopyrite, and the presence of Fe-poor sphalerite near the tops of the polymetallic sulphide deposit mounds in the FLD suggest a somewhat higher log $f_{O_2}$ (-35 to -30) and lower depositional temperatures (<250°C).

The presence of magnetite-bearing exhalite (Fig. 16F) along the Wolverine Belt, extending from the Fisher to the Puck zones (a distance of over 14 km; Fig. 14) indicates that these rocks are largely the product of hydrothermal plume fallout and widespread settling on the seafloor. However, geochemical data indicate that these rocks were formed from lower temperature fluids than the massive sulphides (Peter, 2003), following massive sulphide deposition.

At the Ice deposit, field identification of paragenetic sequences (L. Pigage and S.J. Piercey, unpub. data) and preliminary reflected light microscopy (S.J. Piercey, unpub. data) show complex paragenetic relationships between sulphide minerals and a changing fluid history through the evolution of the deposit. The deposit was likely formed as a pyrite-rich mound on the seafloor, but zone refining during fluid circulation through the mound and venting of high-temperature hydrothermal fluids resulted in the replacement of the core of the mound pyrite by chalcopyrite (and quartz), and finally bornite-sphalerite (=magnetite). The presence of specular haematite within the stringer veins also indicates that the hydrothermal fluids from which the massive sulphides were precipitated evolved from reducing and high temperature, to oxidizing and lower temperature (Barton, 1984).

Duration of Hydrothermal Activity

The age and composition of igneous rocks suggest that high heat flow existed within the greater FLD from 365 to 346 Ma, a 19 million year time span (e.g. Piercey et al., 2006). Zircon saturation temperatures indicate that the footwall porphyritic rhyolites at Wolverine were the products of high temperature (>900°C) partial melting of continental crust (Piercey et al., in press) and this high heat flow was responsible for initiating and maintaining the Wolverine deposit hydrothermal circulation system. Magmatic heat was present beneath the basin during formation of the Wolverine deposit from at least 352 to 346 Ma (Piercey et al., in press).

Because of the low sedimentation rate for graphic shales (e.g. 0.4-13 cm per 1,000 years; Goodfellow and Jonasson, 1987; Goodfellow and Turner, 1989) that form the immediate hanging wall to massive sulphides in parts of Wolverine (e.g. see Fig. 15), the cessation of hydrothermal activity is estimated to be on the order of 400,000 to several million years after Wolverine was formed and prior to resumption of hydrothermal activity marked by the iron formations.

Sources of Sulphur; Lead, Selenium, and Other Constituents

Sulphur isotope values ($\delta^{34}$S) have been used extensively to discern the source(s) of S in sulphides and sulphates in VHMS deposits (e.g. Ohmoto, 1996, and references therein). Possible sources include 1) abiogenic S reduced from seawater, whose S isotope composition varies through time, but is strongly positive, e.g., $\pm$20 per mil at present (Claypool et al., 1980); 2) igneous rocks - close to 0‰ for MORB to -8‰ for rhyolite (Ohmoto and Rye, 1979); 3) biogenically reduced from seawater - typically strongly negative (Saelen et al., 1993). In most modern seafloor sulphide deposits, seawater is entrained, downdrawn and heated, and seawater sulphur is largely removed by precipitation of anhydrite in the subsurface (Seyfried and Bischoff, 1981), such that vent fluids largely contain minimal seawater sulphate (Shanks and Seyfried, 1987). In sedimented seafloor hydrothermal environments, biogenic reduction of seawater sulphate can be a major source of S, and this process can cause strong excursions in the isotopic composition of the ambient seawater sulphate, particularly in restricted anoxic basins (Saelen et al., 1993).

To date, there are 37 bulk S isotope analyses of bulk sulphide, barite, and host lithologies from the Fyre Lake, Kudz Ze Kayah, GP4F, and Wolverine deposits. The data for sulphides range from $\delta^{34}$S$_{CDT}$ 0.5 to 25‰ (Fig. 27; Layton-Matthews, 2005; J. Peter, unpublished data). Additionally, there is a dataset of 86 laser spot analyses of sulphides from 15 samples from the Wolverine deposit (Bradshaw, 2003; Bradshaw et al., in press) obtained using the technique of Beaudoin and Taylor (1994); however, these are not shown in Figure 27.

Fyre Lake deposit sulphides range from $\delta^{34}$S$_{CDT}$ 0.5 to 5.1‰ ($n=3$). These values reflect derivation of S largely from igneous sources, likely by leaching of magmatic sulphides within the host mafic volcanic rocks, together with a small amount of reduced seawater sulphate.

The GP4F deposit exhibits a relatively narrow range for massive sulphides and host rocks of $\delta^{34}$S$_{CDT}$ 11.1 to 14.6‰ ($n=8$). For the Kudz Ze Kayah deposit, there is a much wider overall range of 9.8 to 25.0‰, with the sulphides ranging from 9.8 to 13.0‰ ($n=11$), barite within the massive sulphide ranging from 23.7 to 20.0‰ ($n=2$); barite from the stratigraphic upper part of Kudz Ze Kayah has a $\delta^{34}$S$_{CDT}$ value of 21.9‰ ($n=1$), and argillite ranges from 13.6 to 25.0‰ ($n=5$), with one outlier of 3.8‰. At the time of formation of Kudz Ze Kayah in the lower Mississippian (Tournaissian), the S isotopic composition of seawater is estimated to have been $\pm$22‰ (Claypool et al., 1980), and the analyses of Kudz Ze Kayah barite are in close agreement with this value. The ranges for GP4F and Kudz Ze Kayah sulphides are relatively narrow and suggest derivation of S from partial reduction of seawater sulphate and S leached from volcanic rocks (e.g. Ohmoto and Goldhaber, 1997).
Sulphur isotope compositions of sulphides (bulk and laser) from Wolverine give $^{34}$S_CDT values of 4.9 to 18.4‰. Black shale from the Sable prospect located along strike and to the west of Wolverine has a bulk $^{34}$S_CDT value of 20.4‰, similar to estimates for seawater at that time (Claypool et al., 1980). However, Bradshaw (2003) and Bradshaw et al. (in press), found that pyrite within hanging-wall argillite analyzed by laser has a negative value (-5.7‰). This indicates that the heavy bulk value may reflect hydrothermal modification/introduction and may not be of sedimentary (likely negative) origin through biogenic sulphate reduction (e.g. Ohmoto and Goldhaber, 1997). However, in situ microanalyses of isolated pyrite grains can give unrepresentative analyses, and more work needs to be done to resolve these questions. Nevertheless, the wide range of sulphur isotope compositions for Wolverine mineralization, with lighter values from the tops of the lenses, and heavier values in the lower parts and in the stringer veins indicates multiple sources. Sulphur in sulphides from the tops of the lenses was likely derived mainly from bacterial reduction of seawater sulphate, whereas sulphur in the stringer veins and at the base of the lenses was likely derived from the inorganic reduction of seawater sulphate in the subsurface.

Lead Isotopes

Lead isotopes have long been used as a tracer of Pb and, by inference other metals, in VHMS deposits (e.g. Doe and Zartman, 1979). The small size of VHMS circulation cells and total fluid fluxes (in comparison to SEDEX deposits) dictates that the Pb isotopic ratios of the sulphides are sensitive to the isotopic compositions of the various lithologies in the subsurface reaction zone. There are three possible sources of Pb in the FLD VHMS deposits: 1) mantle and mantle-derived mafic rocks (basalts, gabbros); 2) sedimentary sources of Pb; and 3) crustally-derived volcanic and igneous rocks.

Mortensen et al. (2006) report four Pb isotope analyses for each of the Fyre Lake and Ice mafic-hosted VHMS deposits, and one and two analyses for each of the felsic-hosted Wolverine and Kudz Ze Kayah VHMS deposits, respectively. Layton-Matthews (2005), Layton-Matthews et al. (in press), and J. Peter (unpub. data) provide data for GP4F and have conducted additional Pb isotope analyses for the Fyre Lake, Kudz Ze Kayah, and Wolverine deposits to examine within-deposit Pb isotope variability. Figure 28A-C presents the lead isotope analyses for the Fyre Lake, Wolverine, Kudz Ze Kayah, and GP4F deposits, and the data of Mortensen et al. (2006) for the Ice deposit. For comparison the shale growth curve of Godwin and Sinclair (1982) is given. Figure 28A plots the lead isotope compositions in $^{207}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb space for FLD sulphides determined by Mortensen et al. (2006) and various other SEDEX and VHMS deposits from the northern Cordillera of similar age (see figure caption for details).

The Fyre Lake deposit gives the least radiogenic ratios in comparison to the felsic-hosted VHMS deposits (Fig. 28B). The mafic volcanic rocks that host the Fyre Lake deposit are interpreted to be derived by partial melting of the mantle (Piercey et al., 2001c), and the low Pb isotopic ratios for the sulphides reflect a mixed source of mantle-derived magmatic and crustal Pb (either from sedimentary rocks in the subsurface, or magmatic rocks that have been contaminated by continental crust) (Layton-Matthews, 2005). The Ice analyses range from very non-radiogenic (n=2), reflecting mantle-derived lead, to more radiogenic values (n=2) (Fig. 28C; Mortensen et al., 2006). The deposit and its host volcanic rocks are interpreted to have formed in a back-arc basin that developed between the Yukon-Tanana Terrane and the North American Miogeocline (Murphy et al., 2006), but this basin is thought to have been geographically close to sources of continent-derived detritus from the Yukon-Tanana Terrane on the west (Patchett and Gehrels, 1998; Murphy et al., 2006; Nelson et al., 2006; Piercey et al., 2006). Therefore, Mortensen et al. (2006) concluded that at least a minor amount of Pb in the sulphides was derived from relatively Pb-rich continental sediments, and the Pb isotopic compositions of Ice mineralization reflect a mixing line between primitive mantle and a much more radiogenic Yukon-Tanana Terrane.

Lead isotope ratios of Wolverine sulphides lie on the shale growth curve at ca. 350 Ma and trend toward much more radiogenic values than the field for felsic-hosted VHMS
deposits of the FLD (Mortensen et al., 2006; hatched field shown in Fig. 28A,B). This likely reflects Pb derived from volcanic and intrusive rocks that originated from the melting of old radiogenic crustal rocks at Wolverine. For the Kudz Ze Kayah and GP4F deposits, the Pb isotopic data do not intersect the shale curve but form a cluster over a wide range of $^{207}$Pb/$^{204}$Pb and narrow $^{206}$Pb/$^{204}$Pb that falls above the shale curve. As pointed out by Layton-Matthews (2005) and Layton-Matthews et al. (in press), the differences between the highest $^{207}$Pb/$^{204}$Pb ratios for Wolverine and Kudz Ze Kayah are statistically significant and outside analytical error. This is likely due to sourcing of greater amounts of radiogenic lead from sedimentary rocks that are present in abundance in the vicinity of Kudz Ze Kayah and GP4F.

Modeling of the Kudz Ze Kayah and GP4F data using a two-stage growth curve of Stacey and Kramers (1975) indicates a $\mu$ value of 11 and extraction ages of 3.14 Ga. This implies that the Pb in these deposits is very old and was likely sourced from intrusive and extrusive felsic rocks that formed by partial melting of 3.1 Ga crust. Detrital zircons of this or similar age (3.34 Ga) have been noted in the Coast Mountains of southeastern Alaska, rocks that are thought to be the basement for Yukon-Tanana Terrane (Gehrels and Kapp, 1998; Gehrels, 2002). Also, Devine et al. (2006) have found 2.82 Ga inherited zircon ages in the Klatsa metamorphic complex (Yukon-Tanana Terrane), about 50 km south of Kudz Ze Kayah. Further, Archean Nd-Hf depleted mantle model ages for the Snowcap assemblage that underlies and forms the basement to the Yukon-Tanana Terrane (Piercey and Colpron, unpublished data) indicate Archean age crust that is likely of detrital origin and derived from the Slave craton.

Similar modeling for Wolverine suggests a different and less radiogenic reservoir ($\mu=12$, extraction age of 1.7 Ga; Layton-Matthews, 2005; Layton-Matthews et al., in press). Thus, hydrothermal fluids predominantly sourced Pb from younger, ca. 1.7 Ga rocks. These results are in agreement with detrital zircon ages for rocks thought to represent the Yukon-Tanana Terrane basement (e.g. Gehrels and Kapp, 1998; Gehrels, 2002) and with the detrital zircon attributes of Yukon-Tanana Terrane (Colpron et al., 2006b; Murphy et al., 2006), with a main peak at ca. 1.8 to 1.7 Ga Wopmay age, and lesser peaks at older ages. Additionally, Nd model ages of granites and felsic rocks are largely Paleoproterozoic (ca. 1.8-1.6 Ga; Piercey et al., 2003) also indicating melting of a mixed 1.8 Ga crust and Archean sedimentary basement.

Selenium

The three polymetallic deposits (Kudz Ze Kayah, GP4F and Wolverine) are variably enriched in Se, with Wolverine being the most enriched (1,100 ppm average), Kudz Ze Kayah having intermediate enrichments (210 ppm weighted average), and GP4F (8 ppm average) having the lowest contents (Layton-Matthews, 2005; Layton-Matthews et al., in press). This attribute is relatively uncommon for VHMS deposits (e.g. Huston et al., 1995; Hannington et al., 1999b; Layton-Matthews et al., in press). Selenium in these deposits is resident within clathralite (PbSe), galena, chalcopyrite, sphalerite, pyrite, and pyrrhotite.

Selenium isotope ratios ($^{82/76}$Se$_{MERCK}$) for Kudz Ze Kayah, GP4F, and Wolverine sulphides indicate that Se originated by magmatic degassing of SeO$_4$, rapid reduction to H$_2$Se, entrainment in the mineralizing fluid, mixing with Se leached from felsic volcanic rocks (for Kudz Ze Kayah) and graphic shales (for Wolverine), and deposition at high temperatures ($\sim$350°C) (Layton-Matthews, 2005). Selenium in the deposits is mobilized and transported under high-temperature conditions as H$_2$Se and concentrated in the Cu-rich portions of deposits; mixing of high-temperature fluids with ambient seawater in the brecciated margins of the mounds causes ore fluid oxidation and can also result in a clathralite-pyrite-barite and Se-rich matrix to the breccia clasts at Kudz Ze Kayah. Recrystallization of pre-existing mineralization during zone refining by a high Se/S ore fluid results in increased selenium tenor of all sulphides. Generally, with decreasing ore fluid temperature, there is a decrease in $\Sigma$Se/Se and Se concentration in the ore fluid. Mass balance considerations indicate that the Kudz Ze Kayah and Wolverine deposits require a large Se reservoir in addition to that from magmatic degassing and the felsic volcanic rocks, and this Se was probably provided by leaching from contemporaneous volcanic rocks and graphic shales hosting the Kudz Ze Kayah and Wolverine deposits, respectively.

Ambient Seafloor Environment

The FLD VHMS deposits show a wide variety of characteristics reflective of deposition under widely different redox conditions. The relatively low $\delta^{34}$S values for Fyre Lake sulphides, together with the presence of abundant disseminated magnetite of likely primary origin in the mineralization indicate that this deposit was formed under oxic ambient conditions. Similarly, the presence of a narrow hematite-quartz rock immediately overlying the mineralization at Ice indicates that this deposit was formed under similarly oxic ambient conditions.

The presence of black carbon-rich graphic shales suggests that the ambient bottom water in the basin in which the Wolverine deposit formed may have been anoxic. Heavy sulphur isotopic values of the Wolverine mineralization and of graphic shales (argillite) far away from the influence of the mineralizing processes (Fig. 27) provide supporting evidence that anoxic bottom waters at the site of massive sulphide deposition may have controlled the sulphur isotopic composition of the sulphides (Eastoe and Gustin, 1996). Seawater sulphate was organically reduced to sulphide in the water column and this was then fixed with venting metals.

Throughout Paleozoic time, there are several periods of time where the World’s oceans were anoxic. H$_2$S in a reduced water column has been shown to be a critical requirement for the formation of SEDEX deposits (Fig. 29; e.g., Goodfellow and Jonasson, 1984; Goodfellow, 1987; Shanks et al., 1987; Goodfellow et al., 1993) and some VHMS (e.g. some deposits in the Bathurst Mining Camp, northern New Brunswick: Goodfellow and Peter, 1996). Of note is the close relationship of other so-called VHMS to periods of global anoxia (e.g. Iberian Pyrite Belt, Spain and Portugal). Wolverine, and perhaps Kudz Ze Kayah and GP4F, was also formed within a period of global anoxia, and the relatively heavy sulphur isotope compositions of the sulphides (Fig. 27) might be explained by such a source.

Further evidence for anoxia comes from the iron formations at the Wolverine deposit. The absence of bedded barite
and the occurrence of Ba in carbonates, stilpnomelane, sericite, and biotite in laminated iron formations that overlie and are lateral to massive sulphides (J. Peter, unpub. data) indicate that Ba was introduced into the basin by hydrothermal fluids but was not precipitated as barite. Since Ba forms an insoluble sulphate (Blount, 1977), the lack of barite probably reflects very low sulphate contents in the ambient seawater at the site of venting. Such a low-sulphate environment may represent ambient marine conditions where bacterial sulphate reduction went to completion, or a low-sulphate environment.

Graphitic shales are not present in the immediate footwall to the Kudz Ze Kayah and GP4F deposits, but they are present in the hanging wall at the former where they are part of the Wind Lake Formation. The strongly positive sulphur isotope values for mineralization at Kudz Ze Kayah and GP4F would also suggest that anoxia may have played an important role in the mineralizing processes there also.

Deposit Morphologies and Architecture

The sulphide lens morphologies together with mineral textures at Kudz Ze Kayah, GP4F, Iice, and Fyre Lake indicate that these deposits were principally formed as discrete mounds on the paleoseafloor. Some mineralization occurs as replacements of volcanioclastic rocks in the shallow subsurface in and around the fluid upflow zones (e.g. Kudz Ze Kayah, GP4F, and Wolverine). The Fyre Lake, Wolverine, Kudz Ze Kayah, and Iice deposits have well preserved though deformed feeder vein zones (e.g. Figs. 6E, 16N,O, 23E). At Wolverine, the distribution of these veins, as well as replacement style mineralization, indicate that the Lynx and Wolverine zones likely represent two coalesced seafloor mounds (Fig. 18, inset). At Wolverine, in thinner mineralized intersections on the fringes of the Lynx and Wolverine zones, carbonaceous argillite forms the immediate footwall (Fig. 15), implying either contemporaneous onlapping by sulphide mass wasting, hydrothermal plume fallout over a protracted period of sedimentation, or subseafloor replacement (Bradshaw et al., in press). The semimassive replacement style mineralization is thought to have formed very near the paleoseafloor where the fluids were unfocused and where the rocks were not indurated.

Exploration Methods

Historical

The Fyre Lake deposit was discovered by Cassiar Asbestos Corporation in 1960 during follow-up work to locate the source of massive sulphide float boulders. Exploration efforts have included prospecting, geologic mapping, horizontal loop (Max-Min) and ground magnetics and electromagnetic (EM) surveys, and soil and silt geochemistry. Twenty-three shallow packsack (224 m) and 20 AX (1423 m) drillholes were completed between 1960 and 1991 by various companies. In 1996 and 1997, Pacific Ridge Explorations Ltd. (formerly Columbia Gold Mines Ltd.) drilled 115 holes (23,200 m), upon which the current resource is based.

The Fetish claims were staked in the Wolverine deposit area in 1973 by the Finlayson Joint Venture (Chevron Canada Ltd., Union Oil Company of Canada Ltd., and Marietta Resources International Ltd.). The exploration syn-

dicate discovered numerous multi-element geochemical anomalies in soils over a gossanous area during a grid soil sampling survey, and conducted mapping and trenching that year. The company drilled 2 short holes and intersected low-grade Cu and Zn-sulphide mineralization. However, these claims lapsed in 1982, whereupon they were restaked by Archer, Cathro, and Associates (1981 Ltd.), and further ground magnetic and Max-Min EM surveys were conducted that year.

In 1993, Equity Engineering Ltd. conducted exploration in the Wolverine deposit area (Fig. 14) after concluding that the region held promise for hosting VHMS-style mineralization. On behalf of Atna Resources Ltd., Equity staked claims over the Fetish sulphide mineralization and carried out an exploration program that consisted of geological mapping, prospecting, and rock/soil geochemistry. In 1995, the property was optioned from Atna by Westmin Resources Ltd. and by the end of that year Westmin had earned a 60% interest in the project and entered into a joint venture with Westmin as operator. The latter undertook an exploration program of detailed geological mapping, systematic grid soil geochemistry, and diamond drilling. This fieldwork led to the identification of several additional multi-element geochemical anomalies, and the intersection of massive sulphide mineralization in the Wolverine Zone. The first follow-up drillhole intersected 8.4 m of massive sulphide grading 7.63 g/t Au, 1,358.3 g/t Ag, 0.56% Cu, 3.45% Pb, and 14.22% Zn. This was followed by additional drilling in the period 1995 through 1997.

In 1996, Westmin carried out metallurgical testing on the Wolverine deposit. Results confirmed the presence of unusually high levels of Se (average of 1035 ppm Se, Expatriate Resources Ltd., 2000, unpub. data), a deleterious contaminant that could significantly impact the value of mineral concentrates. In 1997, recognition of hydrothermal alteration in drill core led to the discovery of the Sable Zone 1.6 km to the southeast of Wolverine. In early 1998, Boliden Ltd. acquired the assets of Westmin Resources Ltd. and, following the takeover, Expatriate concluded a letter of agreement to purchase Boliden’s interests in the Wolverine Project; by June 1999 a new Wolverine Joint Venture (Expatriate Resources Ltd. and Attna Resources Ltd.) conducted metallurgical and marketing investigations of the ore. Drilling programs by Expatriate in 2000 expanded the existing resource and further defined the known mineralization on the Wolverine property. In 2005, Expatriate Resources (now Yukon Zinc Corporation) constructed a decline into the massive sulphides and undertook a test mining program. Further, they completed an infill drilling program on the Wolverine deposit. Currently, the company intends to bring the deposit into production in the near future.

Cominco Ltd. originally carried out a surficial geochemical survey in the vicinity of the Kudz Ze Kayah deposit in 1977 and anomalous base metal anomalies in a subsequent Geological Survey of Canada regional geochemistry silt survey (Hornbrook and Friske, 1988) attracted their attention. Prospecting by Cominco led to the discovery of a cobble of massive sulphide float and felsic volcanic rocks. In 1994, the geo-
physical anomaly was drilled and the first hole intersected 22.5 m of massive sulphides in two zones. This outlined mineralization at Kudz Ze Kayah was named the ABM zone in recognition of A.B. Mauer, the discoverer of the mineralized cobble. That year, Cominco completed 52 diamond drillholes (8500 m) and flew 15,000 km of airborne geophysical surveys. In 1995, intensive exploration was done, which included 15,000 m of diamond drilling in 120 holes, engineering and environmental studies, and the construction of an approximately 20 km long access road to the Robert Campbell Highway. During 1996 and 1997, Cominco drilled-tested airborne geophysical targets in the Kudz Ze Kayah area. To the end of 1997, 168 exploration drillholes, totaling 24,663 m, were drilled. In 1998, Cominco carried out geological work and diamond drilling in and around Kudz Ze Kayah. In 1994 a number of geophysical anomalies were identified during a regional airborne geophysical survey. Follow-up drilling in 1998 of geophysical anomaly ‘4F’ led to the discovery of the GP4F deposit.

The Ice deposit was the first to be discovered in the Campbell Range Formation. High-grade oxide Cu mineralization was discovered in 1996 and claims were staked by Archer, Cathro, and Associates Ltd. Geological mapping, grid and reconnaissance soil geochemistry, and airborne and ground magnetic and electromagnetic surveys were conducted in 1996 and 1997. Thirty-four diamond drillholes (2,704 m) were completed in 1996 and 87 holes (7,880 m) were completed in 1997. No exploration work has been carried out since 1997. The deposit is now owned by Yukon Zinc Corporation.

In the Goal Net North area, soil geochemical surveys by Expatriate Resources Ltd. in 1998 and 1999 identified localized strong multi-element anomalies that coincided with induced polarization chargeability anomalies. Semimassive sulphides were discovered in 1999 in surface pits and this discovery was followed up by diamond drilling in 2000 and 2001 that helped to delineate the extent of mineralization. Further drilling in 2004 identified massive sulphide mineralization of the Skyblaze zone. The Thunderstruck zone in the Goal Net South area was discovered by Yukon Zinc Corporation, the successor to Expatriate Resources Ltd., during property mapping.

The Money prospect was discovered by the recognition of ferricrete and Cu-Zn-Au-Ag-bearing massive sulphide boulders in creeks.

Prospecting

The geological and regional stratigraphic framework has been vastly improved over the last few years through the work of Murphy and coworkers (e.g. Murphy et al., 2006, and references therein), and this will enable effective prospecting and exploration on a regional scale outside of the known areas of mineralization. Much exploration for VHMS deposit in the FLD remains to be done by prospecting for outcropping mineralization or associated hydrothermally altered rock. This is because the area has received relatively little exploration attention to date in comparison to the mature base metal mining camps of Canada. The initial staking rush in the mid 1990s generated by the discovery of the Kudz Ze Kayah deposit resulted in relatively few companies staking large blocks of ground. The limited resources available to these companies caused them to focus their efforts on property scale exploration, and grassroots work was curtailed. Grassroots exploration should utilize lithogeochemical methods to recognize geochemically favourable volcanic rocks (petrochemistry and chemostratigraphy), hydrothermally altered volcanic, volcanioclastic and sedimentary rocks, and exhalites.

Petrochemistry and Chemostratigraphy

VHMS deposits of then FLD are known to occur at lithological contacts between rocks of markedly different character (e.g. volcanic and sedimentary facies) or composition (e.g. rhyolite basalt). Within the FLD, rocks favourable for hosting VHMS deposits include those formed within an arc rift, back-arc rift, or at the transition from arc to back-arc magmatism.

Exploration for Cyprus- and Besshi-type deposits should be focussed on areas of high-temperature mafic magmatism as defined by lithogeochemistry. In the FLD, the presence of boninitic rocks is an indication of a depleted mantle source typical of nascent to back-arc regimes (e.g. Piercey et al., 2001c). Such rocks require high-temperature melting that is capable of initiating a stable, long-lived hydrothermal system. Boninites of the Fire Lake Formation are host to the Fyre Lake deposit in the FLD. Depleted arc tholeiites, mid-ocean ridge basalts, (MORB) and back-arc basin basalts (BABB) are also favourable high-temperature mantle melt targets (Swinden 1991, 1997; Syme et al., 1999; Wyman et al., 1999; Piercey et al., 2004). MORB can form not only at mid-ocean ridges but also in back-arc basins, and these rocks have flat REE patterns with low Nb and Th contents (Ewart et al., 1994; Hawkins and Allan, 1994; Hawkins, 1995). BABB are chemically similar to MORB but have minor negative Nb anomalies (Ewart et al., 1994; Hawkins and Allan, 1994; Hawkins, 1995) and are formed within back-arc basins.

For the polymetallic Kuroko-type VHMS and VSHMS deposits, the felsic magmas emplacement at high levels in the crust provided the magmatic heat source that initiated hydrothermal convective circulation, making high-temperature felsic volcanic rocks the best targets. Such rocks typically fall in the within-plume, A-type fields on discrimination plots and are characterized by very high HFSE (Nb, Zr > 300 ppm, Y), REE, high Zr/Si, and negative chondrite-normalized Eu anomalies: (La/Yb)n < 7, (Gd/Yb)n < 2, and Y/Zr < 7. They also have higher Zr saturation temperatures than rhyolites that are not associated with the VHMS deposits (e.g. Barrie, 1995) (FLD range 750-1000°C; mean 899°C; n=55 (Piercey et al., 2001a, 2006; S. Piercey, unpub. data, 2002).

Felsic or felsic-sedimentary rock sequences underlain by continental crust typically have alkalic and MORB mafic rocks associated with felsic volcanic rocks. Although the VHMS deposits are commonly hosted by the high-temperature felsic and sedimentary rocks, they are usually overlain by alkalic basalts and MORB. Such an evolution from felsic to mafic magmatism is attributed to the onset of decompression melting of the mantle following thinning, rifting, and partial melting of the overlying crust (e.g. Piercey et al., 2002a). Alkalic basalts have high Nb, Th, and LREE, and are
the product of lithospheric mantle melting induced by rifting, whereas MORB formed from upwelling asthenosphere due to basin opening. Within the FLD, alkaline rocks of the Wind Lake Formation crosscut and overlie the Kudz Ze Kayah and GP4F deposits (Piercey et al., 2002a). Similarly, at the Wolverine deposit, rocks of the uppermost part of the Wolverine Lake Group are basaltic flows and sills with E-MORB to BABB affinities (Piercey et al., 2002b).

**Hydrothermal Alteration**

The recognition of proximal focused hydrothermal upflow-related siliceous, chloritic, and sericitic alteration can further focus exploration. Both regional and local hydrothermal alteration effects can be recognized using mineral assemblage identification by X-ray diffraction, short-wavelength infrared spectrometry, conventional whole rock lithogeochemistry, and oxygen isotope mapping.

Hydrothermally altered rocks generally have high LOI, \( \text{H}_2\text{O}, \) and \( \text{CO}_2 \) contents, due to the presence of hydrated alteration minerals such as chlorite and sericite, and/or carbonates. The formation of alteration minerals typically involves reactions in which \( \text{Al}_2\text{O}_3 \) is conserved, whereas other elements such as \( \text{Na}_2\text{O} \) are lost to the hydrothermal fluids (e.g. Date et al., 1983). Unaltered rocks typically have \( \text{Na}_2\text{O} \) contents of 2 to 5 wt.%, and those with less than 2 wt.% are altered by feldspar destruction; those with more than 5 wt.% \( \text{Na}_2\text{O} \) are characterized by albite or paragonite alteration and \( \text{Na}_2\text{O} \) addition (e.g. Giorgetti et al., 2003). For these reasons, the \( \text{Al}_2\text{O}_3/\text{Na}_2\text{O} \) index of Spitz and Darling (1978) is an effective indicator of hydrothermal alteration in a sample. Typically, rocks that have been strongly hydrothermally altered rocks have very high \( \text{Al}_2\text{O}_3/\text{Na}_2\text{O} \) ratios (50-100) and indicate a loss of alkali elements and a residual gain in \( \text{Al}_2\text{O}_3; \) unaltered rocks have ratios that are typically less than 10. Anomalously high \( \text{MgO}, \text{Fe}_2\text{O}_3, \) and \( \text{FeO} \) contents in felsic rocks commonly reflect the addition of these elements via chlorite and pyrite alteration (e.g. Hajash and Chandler, 1981). A useful graphical tool to recognize hydrothermal alteration in rocks is the alteration box plot of Large et al. (2001), because this plot indicates where least altered rocks should plot and also provides fields and vectors for altered variants. The presence of high contents of metals (Cu, Pb, Zn, Au, Ag, Co, Se, etc.) in rocks relative to unaltered equivalents suggest that the rocks are hydrothermally altered.

**Exhalites**

Distal hydrothermal sediments (exhalites) composed of finely layered quartz, magnetite, chlorite, carbonate, and trace sulphides are direct products of seafloor hydrothermal activity (e.g. Spry et al., 2000; Peter, 2003). These rocks are typically formed during the nascent and/or waning stages of hydrothermal venting in ancient hydrothermal systems and can be used as vectors toward mineralization (e.g. Peter and Goodfellow, 1996, 2003). Some exhalites display mineralogical and geochemical zonation around known associated VHMS deposits (see Peter, 2003, and references therein). Minerals indicative of close proximity to mineralization include magnetite, siderite, ankerite, calcite, dolomite, stilpnomelane, apatite, and pyrite. Elements that are indicative of close proximity to mineralization include Fe, Mn, Cu, Pb, Zn, Ag, Au, As, Bi, Cd, Se, Hg, Sb, Sn, In, and Ti, and others. Certain elements (e.g. Ti, Al) are indicative of detrital input, and the ratio of hydrothermal to detrital element (e.g. Fe/Ti) can provide a simple indicator of proximity to a hydrothermal vent. High hydrothermal:detrital ratios signal a close proximity to the vent. Combinations of these elements, perhaps given different weightings of importance, can be arranged to give an index that may be more effective than individual elements or ratios (e.g. Peter, 2003; Peter and Goodfellow, 2003).

**Geophysics**

The high magnetic susceptibility of some massive sulphide deposits (e.g. Fyre Lake - abundant pyrrhotite; Ice - abundant magnetite), imparted by the presence of pyrrhotite and magnetite indicates that ground and airborne electromagnetics would be highly effective exploration methods in the FLD. The Kudz Ze Kayah deposit is indicated by both a strong magnetic and electromagnetic anomaly (Holroyd and Klein, 1998) although the Wolverine deposit does not have a strong magnetic response. However, the iron formations that extend from the Fisher zone southeast to Wolverine and beyond have a strong magnetic signature that is readily identified by airborne surveys (Yukon Zinc Corp., unpub. data, 2000; R. Shives, pers. comm., 2007). Further, altered hanging-wall rocks at Wolverine are identified by radiometric techniques. The disseminated to massive nature of the sulphides suggests that induced polarization methods should be effective.

**Surficial Geochemistry**

The original Fetish claims (now the Wolverine deposit) and the Fisher Zone were found using soil geochemistry, and the Kudz Ze Kayah deposit area was outlined by a stream sediment Pb-Zn anomaly in a geochemical survey undertaken by the GSC (Hornbrook and Friske, 1988). The GP4F deposit has been metamorphosed to higher metamorphic grade and is known to contain gahnite that probably have formed by desulphidation of sphalerite during metamorphism (Spry and Scott, 1986). Drift prospecting for gahnite and other diagnostic minerals may therefore be effective in focusing exploration efforts in the FLD. A regional till geochemistry survey and Quaternary geology investigations by Bond and Plouffe (2002) showed ice flow patterns during glacial maxima in the FLD trend towards the west-northwest. Basal till is widespread across plateau surfaces and glaciofluvial sand and gravel dominate in low-lying areas. Multi-element anomalies are present in till near known mineralized zones, and till down-ice from the Kudz Ze Kayah is enriched in Pb and Zn. In addition, they found base metal anomalies northwest of Wolverine Lake and southwest of Finlayson Lake where no mineral occurrences are known.

**Knowledge Gaps**

Although there has been a plethora of new knowledge gained on the tectonic setting, geological setting, and genesis of the VHMS deposits of the FLD, there are a number of unresolved questions. 1) What are the volcanic and sedimentary settings of the deposits? Detailed reconstructions of the volcanic stratigraphy are needed. 2) What is the exact nature of the long time span between Kudz Ze Kayah aged mineralization (ca. 362 Ma) and Wolverine aged mineralization?
tion (ca. 346 Ma)? Recent age dating in the Wolverine area indicates that hydrothermal circulation was active during this time span within a condensed stratigraphic section (Piercey et al., in press). 3) What role did anoxia play in the formation of the polymetallic VHMS and VSHMS deposits of the FLD? 4) What role did magmatic fluids and volatiles play in the development of these deposits? Did they contribute metals to the ore-forming system? 5) Additional information is needed on the nature and extent of regional scale hydrothermal alteration in the FLD, particularly detailed studies of alteration associated with the hydrothermal upflow zones associated with different VHMS deposits. An understanding of the three-dimensional distribution and timing of alteration is needed along with the isotopic and geochemical attributes of this alteration. 6) What is the exact nature and distribution of Se enrichment in polymetallic VHMS deposits in FLD, and how does this relate to such events responsible for the enrichment of Se in base metal deposits in the Selwyn Basin (e.g. Wolf deposit)? 7) Finally, the applicability and effectiveness of unconventional surgical methods (e.g. heavy minerals in tills, mobile metal ions, enzyme leaches, and partial extractions) in exploration need to be evaluated.

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References


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Hanington, M.D., Blecker, W., and Kjarsgaard, I., 1999a, Sulfide mineralogy, geochemistry, and ore genesis of the Kidd Creek Deposit; Part I, North Central and South orebodies: Economic Geology, Monograph 10, p. 163-224.

Hanington, M.D., Blecker, W., and Kjarsgaard, I., 1999b, Sulfide mineralogy, geochemistry, and ore genesis of the Kidd Creek Deposit; Part II, The bonite zone: Economic Geology, Monograph 10, p. 225-266.


--- 1999b, Geological map of Wolverine Lake area (105G/8), Pelly Mountains, southeastern Yukon: Indian and Northern Affairs Canada, Open File 1999-3 (1:50 000 scale).

--- 1999c, Geological map of Finlayson Lake area, southeastern Yukon (105G/8 and parts of 1.2 and 9), southeastern Yukon: Indian and Northern Affairs Canada, Open File 1999-4 (1:100 000 scale).

--- 2000a, The Money Creek Thrust, Yukon-Tanana Terrane, southeastern Yukon; intra-terrane shortening by thrust re-activation of a syn-depositional fault, in Abstracts with Programs: Geological Society of America, Cordilleran Section and associated societies, 96th annual meeting; Geological Society of America, v. 32, p. 57.


Volcanic-Hosted Massive Sulphide Deposits of the Finlayson Lake District, Yukon


Piercey, S.J., Peter, J.M., Mortensen, J.K., Paradis, S., Murphy, D.C., and Tucker, T.L., in press, Geological, geochemical and U-Pb age constraints on the origin of footwall porphyritic rhyolites from the Wolverine volcanic-hosted massive-sulfide (VHMS) deposit, Finlayson Lake District, Yukon, Canada: Economic Geology.


——— 2006b, Ice deposit (website). Available at: http://www.yukonzinc.com/ice.htm