VOLCANOGENIC MASSIVE SULPHIDES OF THE SOUTHERN TULKS VOLCANIC BELT, CENTRAL NEWFOUNDLAND: PRELIMINARY FINDINGS AND OVERVIEW OF STYLES AND ENVIRONMENTS OF MINERALIZATION

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ABSTRACT

The Tulks Volcanic Belt of the Victoria Lake Supergroup, central Newfoundland, is dominated by quartz ± feldspar porphyritic felsic volcaniclastic rocks and lesser amounts of mafic volcanic rocks and intercalated sedimentary rocks. The belt has traditionally been viewed as a single stratigraphic sequence of ca. 498 Ma age, but recent geochronological studies imply that it may be a composite, and include rocks as young as 453 Ma.

The southern portion of the belt is host to three important clusters of VMS deposits known as the Tulks East, Tulks Hill, and Boomerang deposits, as well as a number of smaller sulphide prospects. The major deposits are characterized as "replacement-style" massive sulphides, hosted by felsic pyroclastic and volcaniclastic rocks. In contrast, the Curve Pond and Dragon Pond showings are more typical classic exhalative-type sulphide mineralization associated with exhalative horizons and regional iron formations. As such, the southern Tulks Volcanic Belt contains a continuum of VMS deposit types. The recent discovery of the high-grade polymetallic Boomerang deposit cluster, coupled with additional exploration data, resulting in higher grades and improved understanding of the Tulks East and Tulks Hill deposit clusters highlights the exploration potential of the belt. It has been suggested that the Boomerang mineralized horizon occurs within a younger stratigraphic panel than that of the Tulks East and Tulks Hill deposit clusters. Geochronological studies have been initiated to test this hypothesis, the results of which may have significant implications for exploration.

VMS deposits in the southern Tulks Volcanic Belt are interpreted to have formed in volcaniclastic and sediment-rich basins during transitional tectonic regimes as conditions changed from convergent (e.g., active-arc environment) to extensional (e.g., back-arc or arc-rift). The change from compressional to extensional regimes would allow for active rifting, conduit formation, and high levels of focused heat flow, which are ideal conditions for the development of large and productive hydrothermal systems.

INTRODUCTION

Field work in 2006, focused on both the more important deposits and the smaller prospects that may have exploration potential within the southern portion of the Tulks Volcanic Belt (TVB). This study relies heavily on the examination of archived and recent exploration company drill-core samples and reviews of outcrops, where available.

The objectives for this project are to document the stratigraphy and styles of mineralization and alteration associated with volcanogenic massive sulphide (VMS) deposits and prospects within the TVB of the Victoria Lake Supergroup (Figure 1). The 2006 program focused on the southern portion of the belt, extending from the southern tip of Red Indian Lake south to the Pat's Pond area. This portion

of the belt is host to significant VMS mineralization at the Tulks East and Tulks Hill deposit clusters, and the Boomerang deposit cluster (Boomerang–Domino–Hurricane sulphide lenses), as well as numerous smaller VMS occurrences.

This paper provides a review of the main VMS deposits and some of the smaller prospects, and presents initial thoughts regarding the style of alteration, type of mineralization, and environments of VMS formation. Much of the paper is a synthesis of earlier work with the addition of new thoughts and observations gleaned from fieldwork undertaken during the 2006 field season. Petrographic, geochemical and other aspects of research are ongoing, and should provide further insights into these issues.
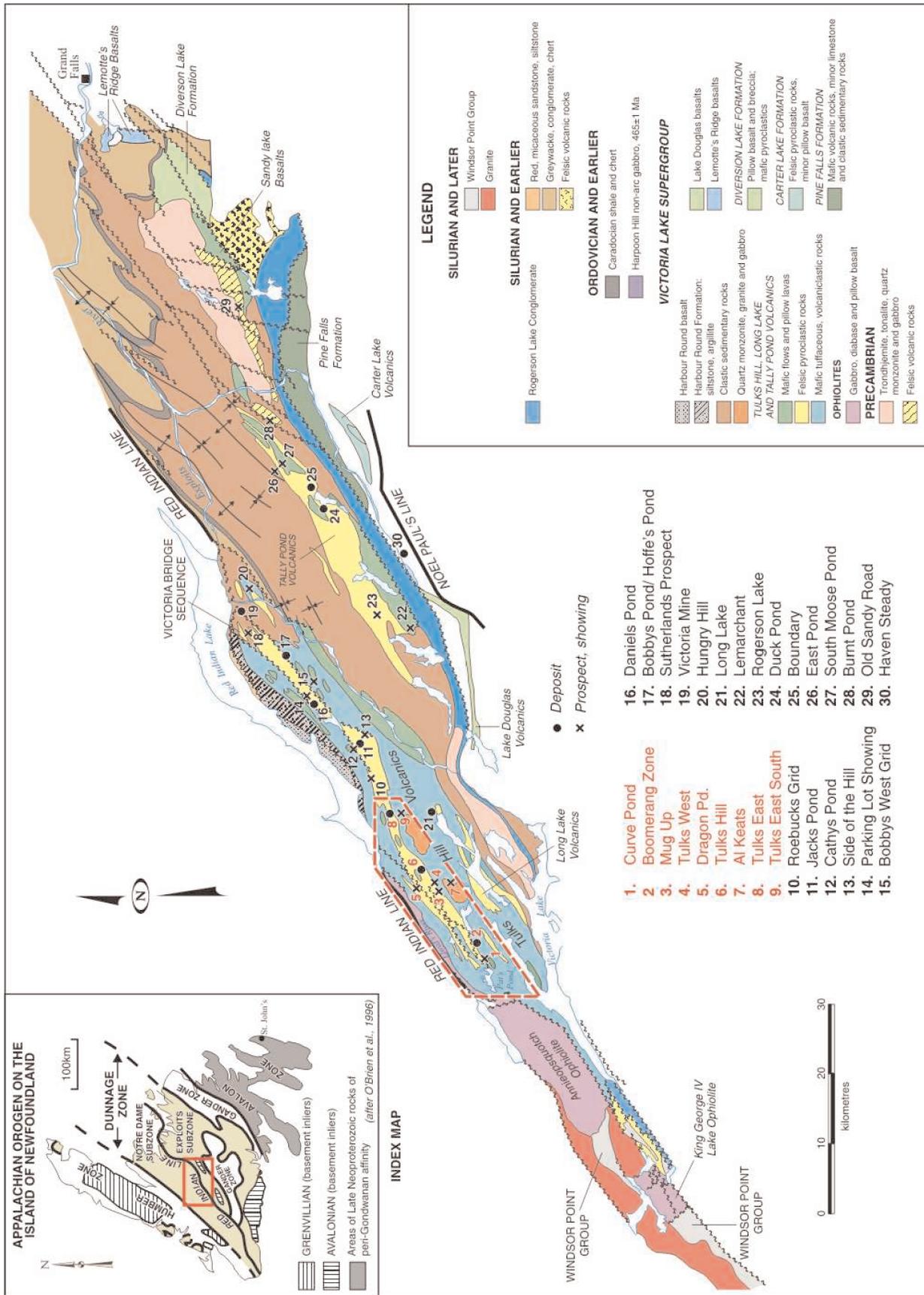
Figure 1. *Simplified geology map of the Victoria Lake Supergroup showing the location of the TVB and associated volcanogenic massive sulphide occurrences. Note the southern TVB and its mineral occurrences outlined in red (modified after Evans and Kean, 2002).*

PREVIOUS WORK

This study is not the first investigation into the VMS potential and mineralized environments of the TVB. The first regional mapping was conducted by Riley (1957), followed by Williams (1970), and then more detailed mapping by the Newfoundland Department of Mines and Energy (Kean, 1977, 1979a, b, 1982, 1983; Kean and Jayasinghe, 1980, 1982; Kean and Mercer, 1981; Evans *et al.*, 1994a, b, c). The name Victoria Lake Group was proposed from the early work of Kean (1977). A recent summary of the geology, geochemistry, tectonic setting, and VMS mineralization of the Victoria Lake Supergroup (VLS; Evans and Kean, 2002) provides the most current regional synthesis and was a valuable source of information for this report. Evans and Kean (2002) also provide detailed lists of all previous work conducted in the area.

There have been many exploration projects in the area, many of which were brought to the advanced exploration stage with diamond-drilling programs. One of the first exploration programs that consisted of prospecting, and stream and soil sampling by Asarco, led to the discovery of the Tulks Hill deposit in 1961. Asarco conducted detailed evaluation work on the prospect, eventually outlining a geological resource for the deposit. Abitibi-Price commenced exploration in the area surrounding the southern end of Red Indian Lake in the 1970s. During follow-up work associated with the Tulks Hill discovery, Abitibi-Price discovered the Tulks East prospect in 1977, and outlined three massive sulphide lenses (*e.g.*, *see* Barbour and Thurlow, 1982). Following lake-sediment surveys and detailed airborne EM surveys, Abitibi-Price discovered a large zone with anomalous gold at the Midas Pond–Glitter Pond location. In 1985, BP Canada Ltd. acquired Abitibi-Price's land holdings and in 1989, following additional exploration, BP Canada Ltd., discovered the "Green Zone" at the southern end of the TVB. This zone is now referred to as the Curve Pond prospect. Noranda Mining and Exploration worked in the southern TVB from 1993 to1998 and later completed additional geophysical surveys, mapping, surficial geochemistry and lithogeochemistry. They further evaluated the Tulks East prospect and the Curve Pond prospect with diamond drilling, which defined additional massive sulphides at Tulks East. Interestingly, Noranda also examined the Boomerang alteration zone (*see* below) and drilled several holes in this area. After discovering interesting alteration and stringer sulphides, they finally intersected massive sulphides grading 0.46% Cu, 2.63% Pb, 7.4% Zn, 76.5 g/t Ag, and 0.67 g/t Au over 1.8 m (true thickness) in Hole GA-97-05 (Banville *et al.*, 1997; Noranda, 1998). This intersection is actually part of the Domino VMS deposit subsequently discovered by Messina Minerals in 2006. From 1999 to 2006, the southern TVB was explored by several companies: Tulks Resources (1999-2000), Windarra Resources (2001), Mishibishu Gold Corporation (2002-2003), and finally Messina Minerals Inc. (2004-present). During this period, significant work was completed on the Tulks East and Curve Pond prospects, in addition to the Midas Pond gold prospect. In December, 2004, Messina Minerals Inc. discovered the Boomerang VMS deposit and subsequent work has delineated two associated VMS deposits termed Domino and Hurricane. Presently, Messina Minerals Inc. continues to explore the area in search of additional resources.

The numerous industry reports prepared over the years on the southern TVB were invaluable sources for preparation of this review. It should be noted that the reference to Noranda (1998) includes data derived from many of the earlier company assessment reports. A recent NI 43-101 technical report of the Tulks South Property for Messina Minerals Inc. (Dearin, 2006) provides an additional excellent overview of the geology and mineral occurrences in the southern portion of the belt.

REGIONAL GEOLOGY

The Dunnage Zone of the Newfoundland Appalachians (Figure 1) represents the vestiges of Cambro-Ordovician continental and intra-oceanic arcs, back-arc basins, and ophiolites that formed in the Iapetus Ocean (Kean *et al.*, 1981; Swinden, 1990; Williams, 1995). The zone is divided by an extensive fault system (the Red Indian Line) into a western peri-Laurentian segment (Notre Dame and Dashwoods subzones), and an eastern peri-Gondwanan segment (Exploits Subzone). In the study area, the Red Indian Line separates the Buchans Group Belt, which formed on the North American side of the Iapetus Ocean, from the VLS, which formed on the Gondwanan side of Iapetus. The deformation associated with final closure of the Iapetus Ocean culminated during the Silurian (Colman-Sadd *et al.*, 1992), at which time, thrusting and folding juxtaposed these initially geographically distinct volcanic belts. The two main subzones of the Dunnage Zone are differentiated based on stratigraphic, structural, faunal, and isotopic characteristics (Williams *et al.*, 1988).

The TVB (*see* Figures 1 and 2) forms part of the Exploits Subzone and represents the remnants of one of several bimodal Cambrian to Ordovician volcanic-arc sequences. Together with adjacent volcanic and sedimentary belts of variable tectonic affinities, it belongs to the informally defined VLS (Evans and Kean, 2002). Evans and Kean (2002) subdivide the VLS into the TVB (ca. 498 Ma), the Long Lake Volcanic/Volcaniclastic Belt (ca. 505 Ma), and the Tally Pond Volcanic Belt (ca. 515 Ma). In addition to these age differences, lithogeochemical studies indicate
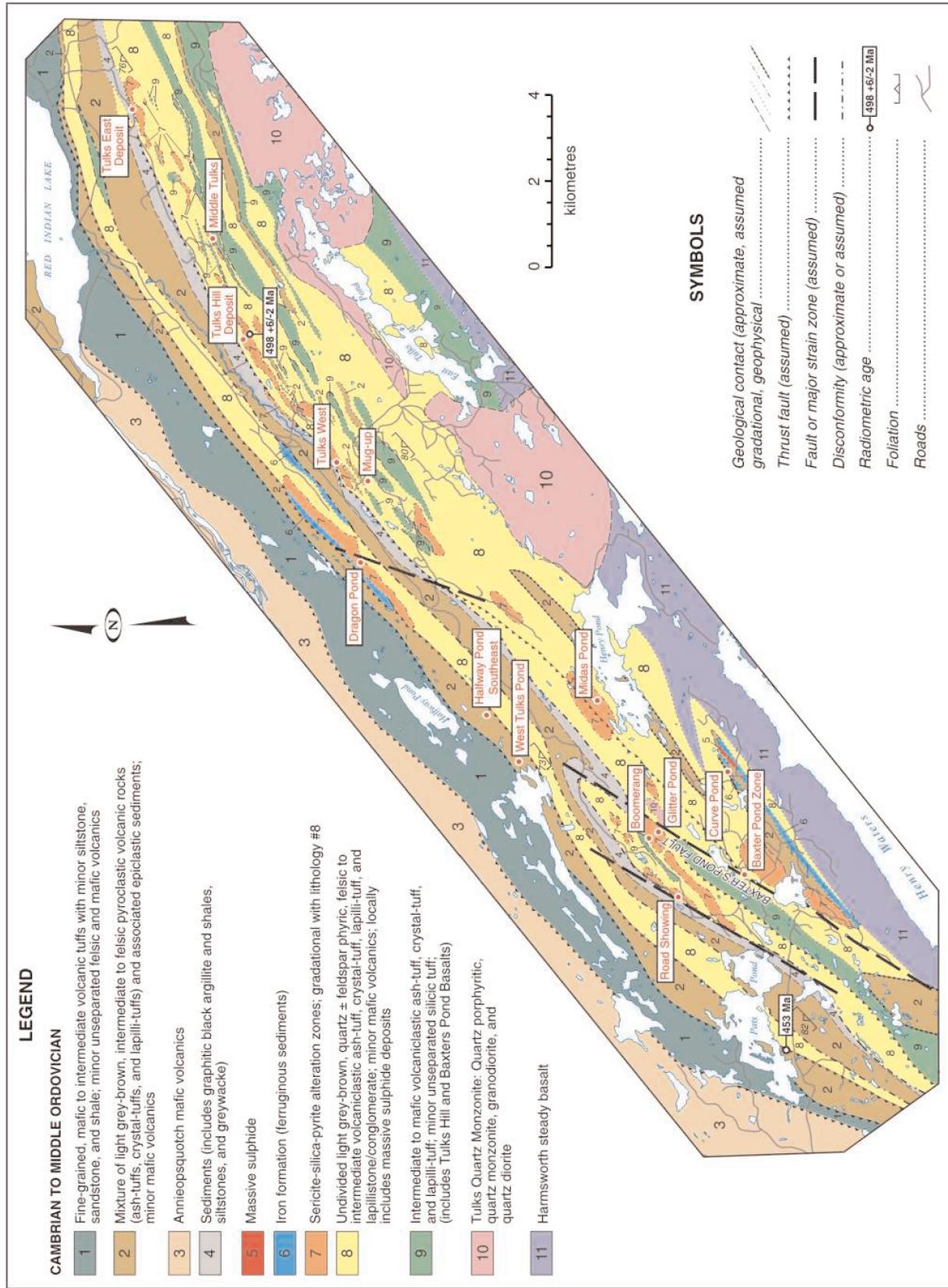
Figure 2. *Geology map of the southern TVB illustrating the various rock types and the VMS deposits, prospects, and showings. Note that the map is not intended to distinguish the various groupings defined by van Staal et al. (2005). (Partly modified and compiled from industry sources (e.g., Noranda, 1998) and government publications (e.g., Kean, 1982; Evans et al., 1994; Evans and Kean, 2002; van Staal et al., 2005).*
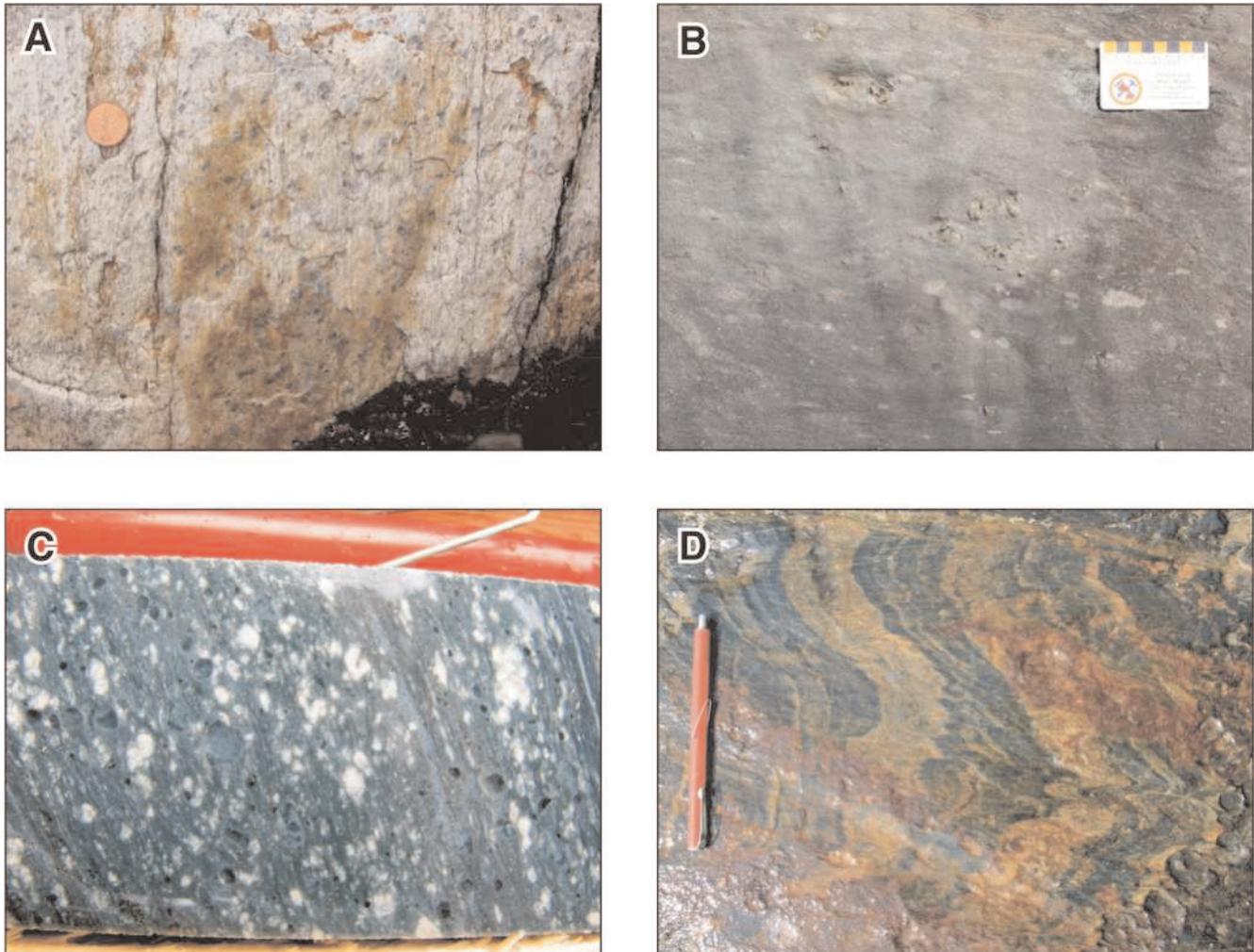
Plate 1. *Regional rock types: A) quartz porphyritic felsic volcanic, B) amygdaloidal basalt, C) quartz and feldspar porphyritic felsic volcanic, and D) interbedded sediments.*

that the VLS is composed of distinct chemical groupings representing different tectonic environments (*e.g.*, active arc, arc-rift, back-arc, and mature arc; *see* Swinden *et al.*, 1989; Evans and Kean, 2002).

Evans and Kean (2002) divide the VLS into two main terrains, separated by the Rogerson Lake Conglomerate, termed the northern and southern terrains. The TVB is part of the northern terrain, where it is bounded to the north by the Red Indian Line and the sedimentary and volcaniclastic rocks of the Harbour Round Belt, and to the south by a regionally extensive magnetic anomaly separating the Tulks Volcanics from the Long Lake Belt.

The TVB covers an area of approximately 65 by 8 km, trending from northeast–southwest. It is a bimodal belt dominated by felsic volcanic rocks and variable amounts of intermixed mafic volcanic rocks, felsic pyroclastic rocks, and volcaniclastic and sedimentary rocks. The age of the

TVB was constrained by a U–Pb age of 498 +6/-4 on a small, subvolcanic porphyry near the Tulks Hill VMS deposit (Evans *et al.*, 1990). However, recent age dates provided by the Geological Survey of Canada (GSC; van Staal *et al.,* 2005) suggest that portions of the TVB are actually much younger (*see* below), and this necessitates some revision of stratigraphy.

The most common rock types of the TVB consists of light-grey to white, quartz ± feldspar porphyritic pyroclastic rocks, felsic ash tuffs through to tuffs and lapilli tuffs, breccias (locally bimodal), and local subvolcanic porphyries (Plate 1). Mafic volcanic rocks are subordinate and are dominated by tuffs, lapilli tuffs, breccias, and local pillow lavas (Plate 1).

The TVB hosts several significant VMS deposits and numerous other prospects and showings. The scope of this report is confined to the southern portion of the belt, as indi-
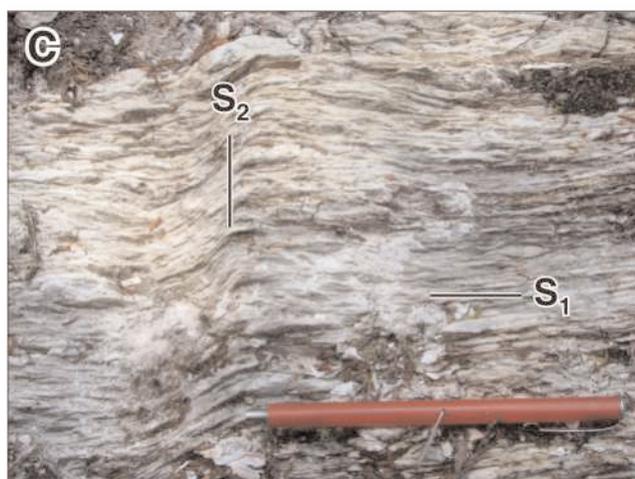
Plate 2. *A) Folding in an outcrop of sedimentary rocks at the Al Keats occurrence, B) Z, M and S folds in drillcore from the Tulks West occurrence, and C) S_1 and S_2 foliations in altered felsic volcanic rocks.*

cated in Figure 1. The geology of this area is shown in more detail in Figure 2.

GEOLOGY AND MINERALIZATION

LOCAL GEOLOGY

The southern TVB consists of various felsic, intermediate and mafic pyroclastic rocks (ash tuffs through to lapillistone/agglomerates), high-level (locally amygdaloidal) dykes and sills, sedimentary rocks (black shales, graphitic argillites and greywacke), thin iron formations, and subvolcanic intrusions. The belt experienced greenschist-facies metamorphism and moderate to strong deformation. Folding is common at the small scale (Plate 2), but the lack of outcrop impedes identification of large fold structures. Primary textures are usually obliterated by well-developed, bedding-parallel foliations (S_1 and S_2; Plate 2). Stratigraphy typically strikes steeply to the northeast and dips northwest, and the prominent regional foliation is defined by alignment of chlorite and sericite. The belt is transected by late shear zones and faults.

All rocks within the 2006-2007 study area were originally considered to be part of the TVB and of similar age, dated at 498 +6/-4 Ma (Evans *et al.*, 1990). However, recent Tulks Group (ca. 498 Ma) mapping and geochronological studies by the GSC, have revised stratigraphic nomenclature to define a series of generally westward-younging tectono-stratigraphic units including the the Pats Pond Group (ca. 487 Ma), the Sutherlands Group (ca. 462 Ma; Dunning *et al.*, 1987), and the Wigwam Brook Group (ca. 453 Ma; van Staal *et al.*, 2005; Zagorevski *et al.*, 2003). Whereas the Wigwam Brook Group has been dated from a sample of quartz and feldspar-phyric tuff immediately south of Pat's Pond, the Pats Pond Group age-date is from a sample of bimodal breccia that occurs south of Victoria Lake in the Burgeo Highway area. From an exploration perspective, due to the structural complexities within the southern TVB and that various VMS deposits discussed below fall into different tectonostratigraphic subdivisions, there is an obvious need for more geochronological study to clarify the relationships between mineralization and stratigraphy.

VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS

Massive sulphide deposits in the southern TVB are characteristically associated with felsic volcanic rocks (quartz ± feldspar ash-crystal tuffs) hosted within sequences of volcaniclastic and sedimentary rocks. Abundant bimodal sills are associated with synchronous volcaniclastic sedimentary rocks (argillite/wacke) within the mineralized sequences, suggesting a possible arc-rift or back-arc basin tectonic environment for massive sulphide formation. As currently interpreted, the deposits plunge to the northeast, and their geometry is controlled by later deformation.

Three known VMS-deposit clusters occur in the study area, as well as numerous prospects and zones of alteration. From north to south, the VMS deposits are the Tulks East, the Tulks Hill, and the recently discovered Boomerang-Domino-Hurricane deposit clusters. Mineralization is associated with intense sericite–silica–pyrite and locally chloritic alteration and is interpreted to have formed in sub-seafloor replacement environments (*see* discussion below). Some of the prospects are associated with intense chlorite alteration and exhalative horizons (*e.g.*, iron-formations). Excluding the map staked licence surrounding the Tulks Hill deposit, which is held by Buchans River Ltd. and optioned to Prominex Resources Corp., the bulk of the southern TVB and most of the VMS deposits are held by Messina Minerals Inc.

Tulks East Deposit

The Tulks East deposit is hosted by a series of sericite–silica–pyrite and, locally, chlorite–carbonate altered felsic tuffs/lapilli tuffs (Figures 2 and 3, Plate 3). Both the hanging wall and footwall have experienced hydrothermal alteration and contain stringer mineralization (Figure 3, Plate 3). The alteration envelope associated with the massive sulphides extends approximately 1600 m along strike, 200 m across strike, and to at least 400 m deep (McKenzie *et al.*, 1993; Noranda, 1998). The footwall stratigraphy consists mainly of felsic crystal and lapilli tuffs, and minor conglomerate and lapillistone, mafic tuffs, and intermediate to mafic amygdaloidal sills. Mineralization occurs toward the top of this package, which is overlain by a thick sequence of intercalated graphitic argillite and mafic to intermediate high-level sills and dykes. The Tulks East fault is developed within this relatively incompetent sequence, and is a zone about 20 to 30 m thick. The positioning of the fault in this sequence is not always discernable. However, in certain instances observed in drill core, the footwall to hanging-wall stratigraphy is still intact, and it is herein interpreted that the footwall and overlying graphitic argillite represent a primary stratigraphic succession. The hanging wall above the graphitic argillite consists predominantly of mafic to inter-

mediate sills and lesser amounts of quartz-phyric felsic volcanic rocks.

To date, this deposit represents the largest accumulation of mineralization in the TVB with three massive sulphide lenses (the A, B, and C zones) totalling ~5.6 million tonnes (Barbour and Thurlow, 1982); all three lenses are tabular in shape and remain open at depth. The lenses were originally determined to dip 70° to the northwest and plunge 45° to the north (*e.g.*, Barbour and Thurlow, 1982). However, recent diamond drilling by Messina Minerals Inc. suggests that the A Zone actually lies much closer to the surface than would be expected by such geometry (Messina Minerals Inc., Press Release, October 26, 2006).

The massive sulphides consist of medium- to coarse-grained pyrite, intergrown with lesser amounts of pyrrhotite, sphalerite, galena and chalcopyrite (Plate 3). Gangue minerals are dominated by quartz and lesser amounts of sericite, chlorite and carbonate. The A-Zone lens is the largest accumulation of sulphide with ~ 4.5 million tonnes of massive sulphide (~ 2% base metals (Zn+Cu+Pb)), but the smaller B Zone (~0.23 million tonnes) has higher grades (~ 8.7% Zn, 0.66% Cu, 1.26% Pb, 58.7 g/t Ag, and 0.14 g/t Au; Barbour and Thurlow, 1982). The C Zone contains ~1 million tonnes of lower grade pyritic massive sulphide.

Although Tulks East was historically inferred to be dominated by low-grade, uneconomic pyritic sulphides, recent work indicates exploration potential for the downplunge extension of the A-Zone lense (*e.g.*, Tallman, 2000; Messina Minerals Inc., Press Releases, October 27, 2005 and August 1, 2006). Structural reinterpretations of the ore-horizon stratigraphy by Messina Minerals Inc. suggest that the B Zone (which typically sits ~15 m above the A Zone) is a fault offset of the downplunge extension of the A Zone (Messina Minerals Inc., Press Release, October 27, 2005). Additionally, similar hanging-wall and footwall stratigraphies of both sulphide lenses, as observed through detailed drill-hole relogging during this project, support the notion that they are structural repetitions of one another. The A Zone has good potential for higher grade base metals at depth, as indicated by the fact that both base-metal contents and the intensity of chloritic alteration increase downplunge (*e.g.*, to the northeast). For example, DDH TE-05-86, a 100 m step-out from previous drilling, intersected 7 m of 6.2% Zn, 0.4% Cu, 0.3% Pb, 19 g/t Ag, and 0.3 g/t Au (Messina Minerals Inc., Press Release, October 27, 2005). The deeper portions of the A Zone may thus be closer to a vent complex. Mineralization within the downplunge extensions of the A Zone appears to display typical VMS base-metal zonation with a massive pyritic upper blanket close to surface, Zn- and Cu-bearing sulphides in the core of the sulphide lens, and a lower pyritic keel at depth. This pattern is illus-
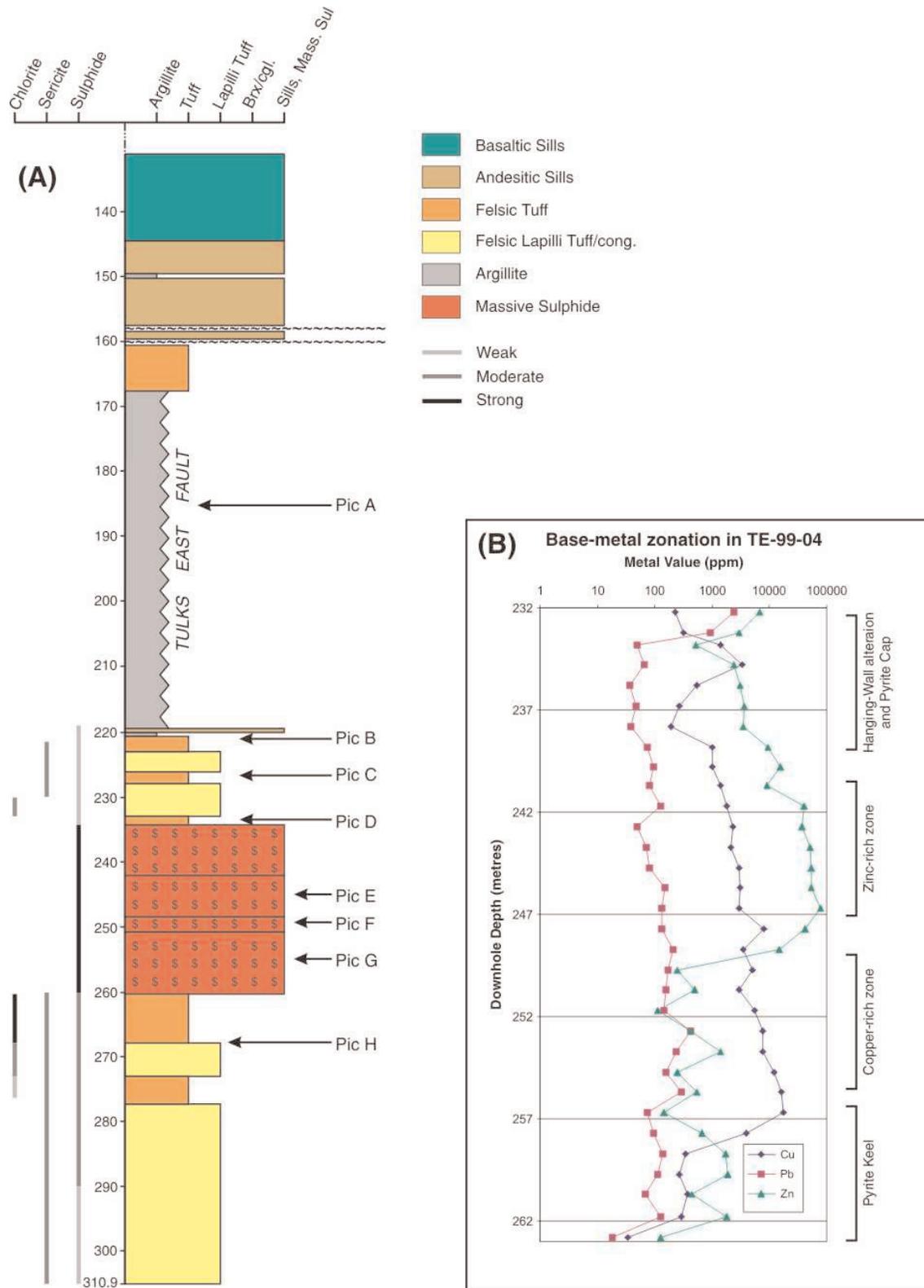
Figure 3. *A) Schematic drillhole stratigraphic column for DDH TE-99-04 from the Tulks East deposit. The hole intersected the A-Zone massive sulphide lense. Note the presence of alteration in both the footwall and hangingwall and also the metal zonation in the sulphide lense. References to pictures correspond with Plate 3. B) Graph illustrating base-metal zonations within the massive sulphide lense (modified from Tallman, 2000).*
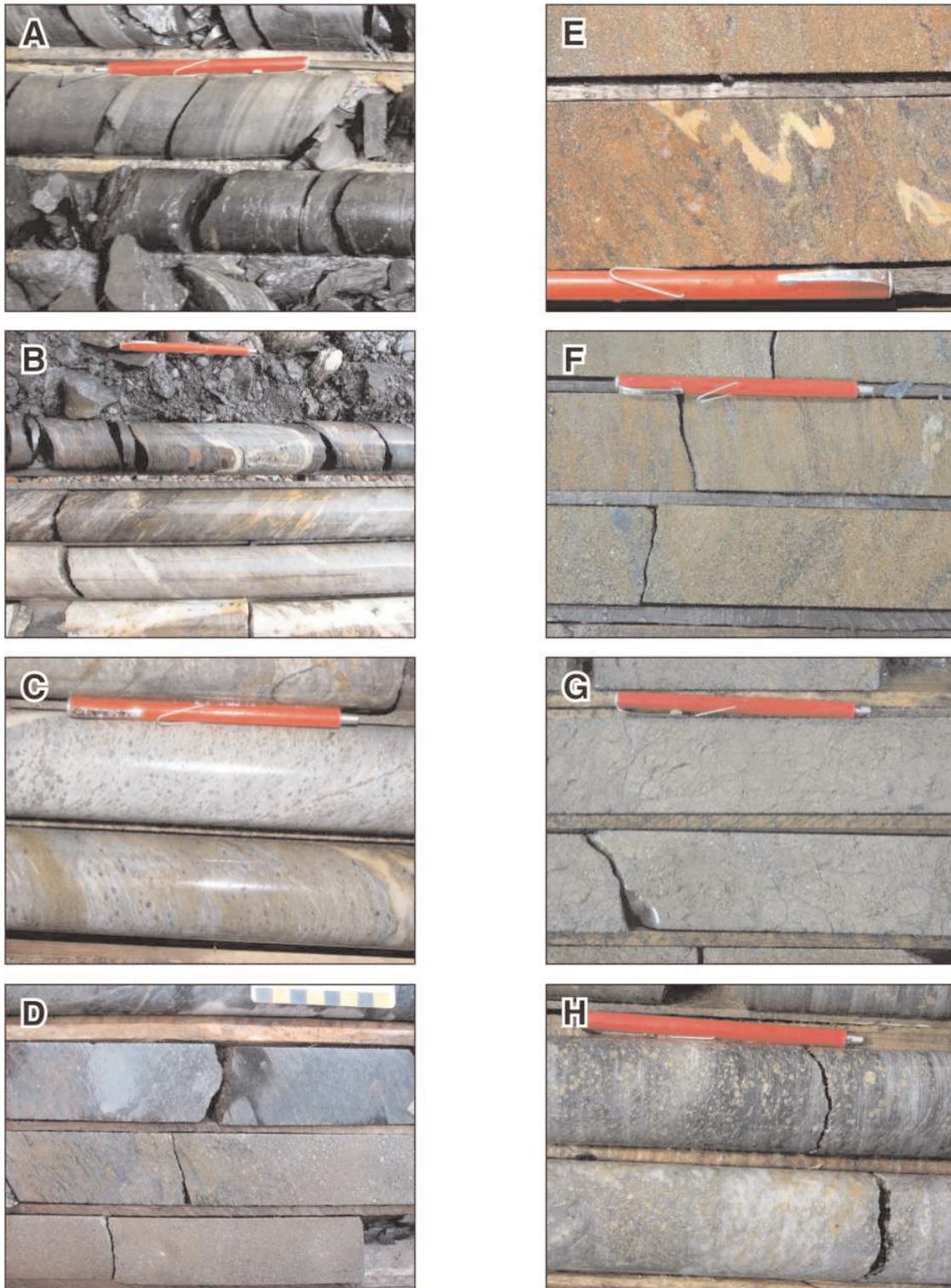
Plate 3. *Photographs of rock types, mineralization, and alteration at the Tulks East deposit. A) Banded greywacke and black argillite (locally graphitic), B) Contact of graphitic argillite (note Tulks East Fault) with felsic volcanics, C) Hangingwall quartz-eye phyric felsic tuff. Note intense sericite/pyrite alteration, D) Hanging-wall felsic volcanics. Note intense pyrite/sericite/chlorite alteration, E) Zn-rich ore. Note relict quartz-crystals and post-mineralization folding, F) Cu-rich Tulks East ore, G) Pyritic keel to Tulks East A-Zone ore body, H) Intense chlorite/sericite/pyrite alteration of footwall felsic volcanics.*

trated well by a geochemical profile through the sulphide zone in Hole TE-99-04, shown in Figure 3b (after Tallman, 2000).

Tulks Hill Deposit

The Tulks Hill deposit occurs at a similar stratigraphic horizon as the Tulks East deposit and is hosted by a similar series of altered felsic volcanic rocks, dominated by a blue quartz ± feldspar phyric (locally lapilli-rich) tuff (Figure 4). The deposit can be seen outcropping as a rusty zone on the side of Tulks Hill from the Tulks river valley (Plate 4). Substantial work was done on the deposit by Moreton (1984), Jambor and Barbour (1987), and exploration companies. The deposit was explored through an adit, which extends some 175 m into the hillside for the purposes of bulk sampling. The property is currently held by Buchan's River Ltd., and has been optioned to Prominex Resources Corp., who are currently carrying out a diamond-drilling program.

The deposit consists of four massive sulphide lenses (termed T1 to T4) collectively containing 720,000 tonnes of massive sulphide grading 5.6% Zn, 1.3% Cu, 2.0% Pb, 41 g/t Ag and 0.4 g/t Au (Jambor and Barbour, 1987; Figure 4). The lenses are tabular in shape and dip approximately at 70° to the northwest. Metal zonations have been observed in outcropping sulphides as well as in the underground workings and in drill sections (Jambor and Barbour, 1987). The first three lenses (T1, T2 and T3) outcrop on surface and are marked by heavily gossaned areas, whereas the T4 lense occurs at depth (Plate 4). Isoclinal folding in the area suggests that some of the lenses may represent structural repetitions of the same horizons (Moreton, 1984; Saunders, 1999). As the T1, T2 and T3 lenses locally contain high-grade, banded massive sulphides on surface (Plate 4), they are possible sources for the anomalous sulphide boulders discovered in the southern Tulks Volcanic Belt. In addition to pyrite and base metals, significant magnetite also occurs within the T1 and T2 lenses, which serves to discriminate the ore from other massive sulphide bodies in the area. It is uncertain if this different mineralogy of magnetite-rich sulphides is simply a function of localized late deformation and alteration or if it indicates that the deposit does not correlate with the Tulks East and surrounding deposits.

Prominent sericite, chlorite, pyrite, and silica alterations are observed within a felsic quartz-eye tuff in proximity to the sulphide lenses, and the alteration and related stringer mineralization are present in both the hanging wall and footwall, as pointed out by Kean and Evans (1986) for the T3 lens (Plate 4). Alteration associated with the sulphide lenses can be observed over a 2000-m-long zone (McKenzie *et al.*, 1993). In addition to the felsic tuffs, the stratigraphy also contains mafic sills, black argillite and shale, and intermedi-

ate volcanic rocks. The rock types and stratigraphy appear very similar to those observed at the Tulks East deposit.

Drilling conducted in 2006 by Prominex Resources Corp. has successfully intersected high-grade base-metal sulphides in the T3 and T3a massive sulphide lenses (Prominex Resources Corp., Press Release, November 20, 2006). During this drilling program, intended to re-evaluate earlier exploration in the area, Prominex intersected intervals of 13.5 % Zn over 4.6 m and 9.3 % Zn with 1.0% Cu over 6.1 m in the T3 lense. These encouraging results have led to plans for a more extensive drilling campaign in 2007.

Boomerang Deposit Cluster

The recently discovered Boomerang–Domino–Hurricane VMS deposit cluster is located in the southern portion of the TVB in the vicinity of Pat's Pond, ~17.5 km southwest of the southern tip of Red Indian Lake (Figures 1 and 2). Prior to the discovery of Boomerang in December of 2004 by Messina Minerals Inc., this area was recognized as a zone with good VMS potential based on alteration characteristics and the occurrence of high grade stringer sulphides in footwall rocks (Noranda, 1998). Messina Minerals Inc. discovery hole, GA-04-11, intersected 13.9 m of 0.7% Cu, 4.0% Pb, 13.6% Zn, 102 g/t silver and 1.0 g/t gold massive sulphides at a vertical depth of ~240 m on the Boomerang horizon (Messina Minerals Inc., Press Release, December 10, 2004). This deposit is the best known of the three sulphide deposits and is therefore focused on, with only brief descriptions provided of the Domino and Hurricane massive sulphide zones. The size and distribution of the three massive sulphide zones, as currently defined, are illustrated in a longitudinal section in Figure 5.

Boomerang Deposit

The stratigraphy within the Boomerang deposit consists of a series of felsic volcanic rocks (ash-crystal (quartz ± feldspar) tuffs, lapilli tuffs, coarse-grained volcaniclastic rocks (conglomerate and breccia)), sedimentary rocks (black argillite, siltstone, chert and black shales), felsic, and amygdaloidal mafic sills, and intermediate dykes (Plate 5). Based on observed interfingering textures, the bimodal sills are considered to be synchronous with the volcanosedimentary rocks (Plate 5). Well-defined fining-upward sedimentary sequences (*e.g.*, turbiditic sequences) are commonly observed in drill core, and along with the bimodal sills may suggest an arc-rift type environment (Figure 6, Plate 5). All these rock types, with the exception of some of the late sills, are overprinted by strong northwest-dipping foliations. The observation that some sills are foliated whereas others are massive with little to no foliation implies different ages for the sills. Although the lack of available outcrop hinders
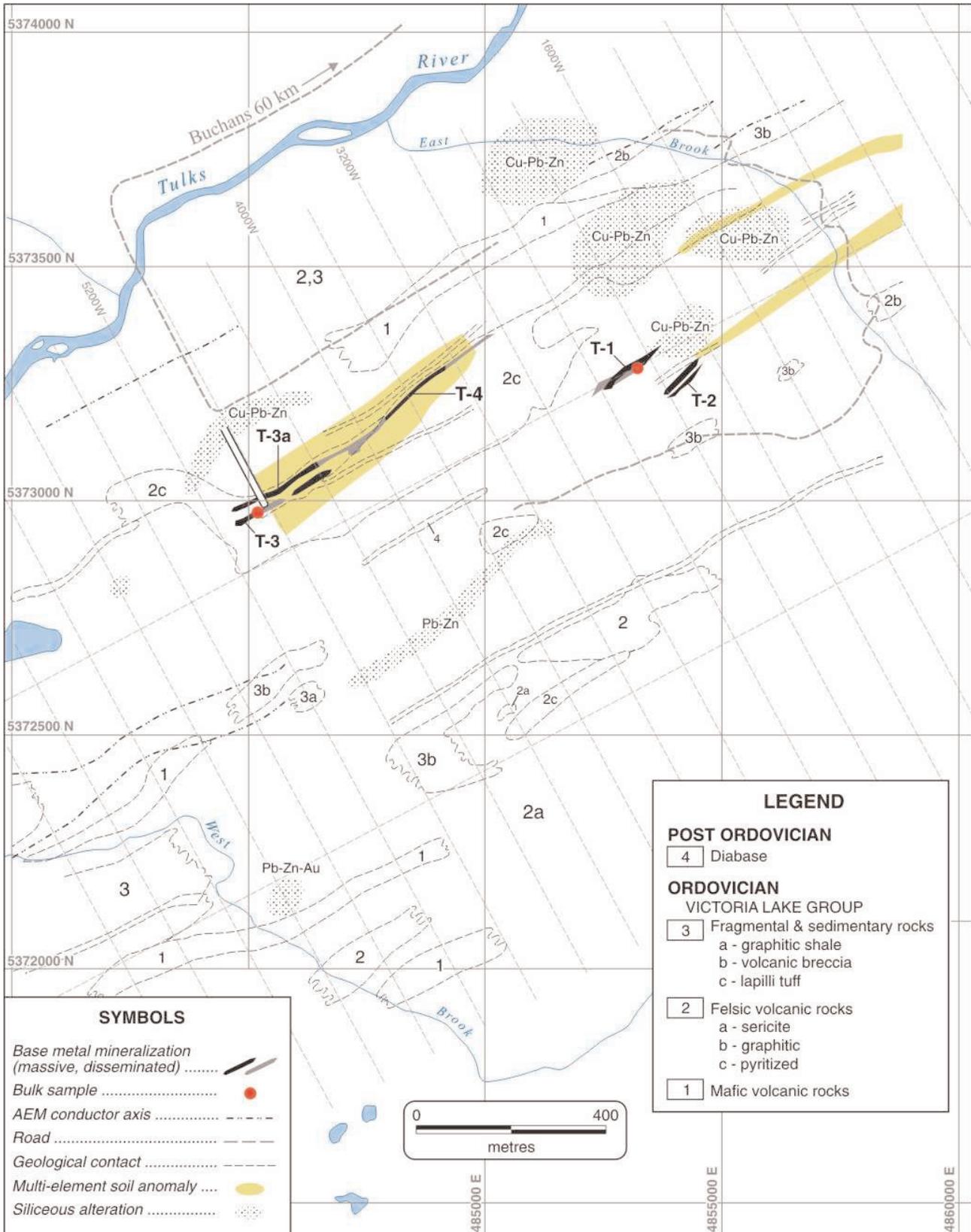
Figure 4. *Simplified geology map of the Tulks Hill deposit area illustrating rock types and alteration patterns. (From Prominex Resources Corp. website; geology compiled after United Bolero).*
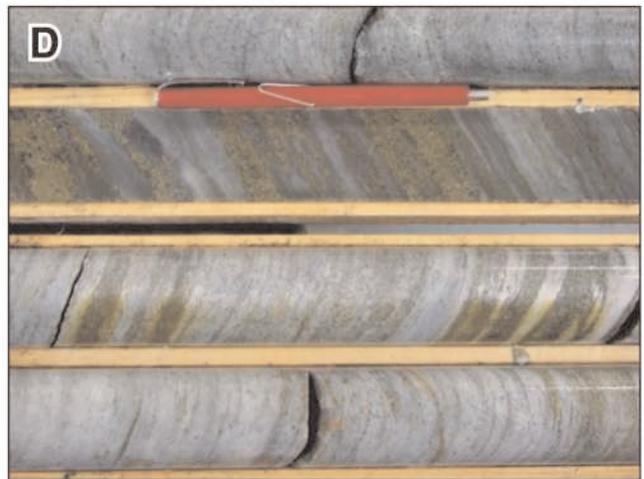
Plate 4. *Photographs of Tulks Hill deposit: A) adit into the T3 lense, B) schistose felsic volcanics, C) footwall alteration in felsic volcanics, D) sulphide-stringers in footwall alteration zone, E) high-grade massive sulphide sample from the T1 lense.*

observation of large-scale folding, small-scale isoclinal folding is commonly observed and may provide an explanation for some of the pinching and swelling of the massive sulphides as indicated by varying thicknesses of massive sulphide intersections (Plate 5).
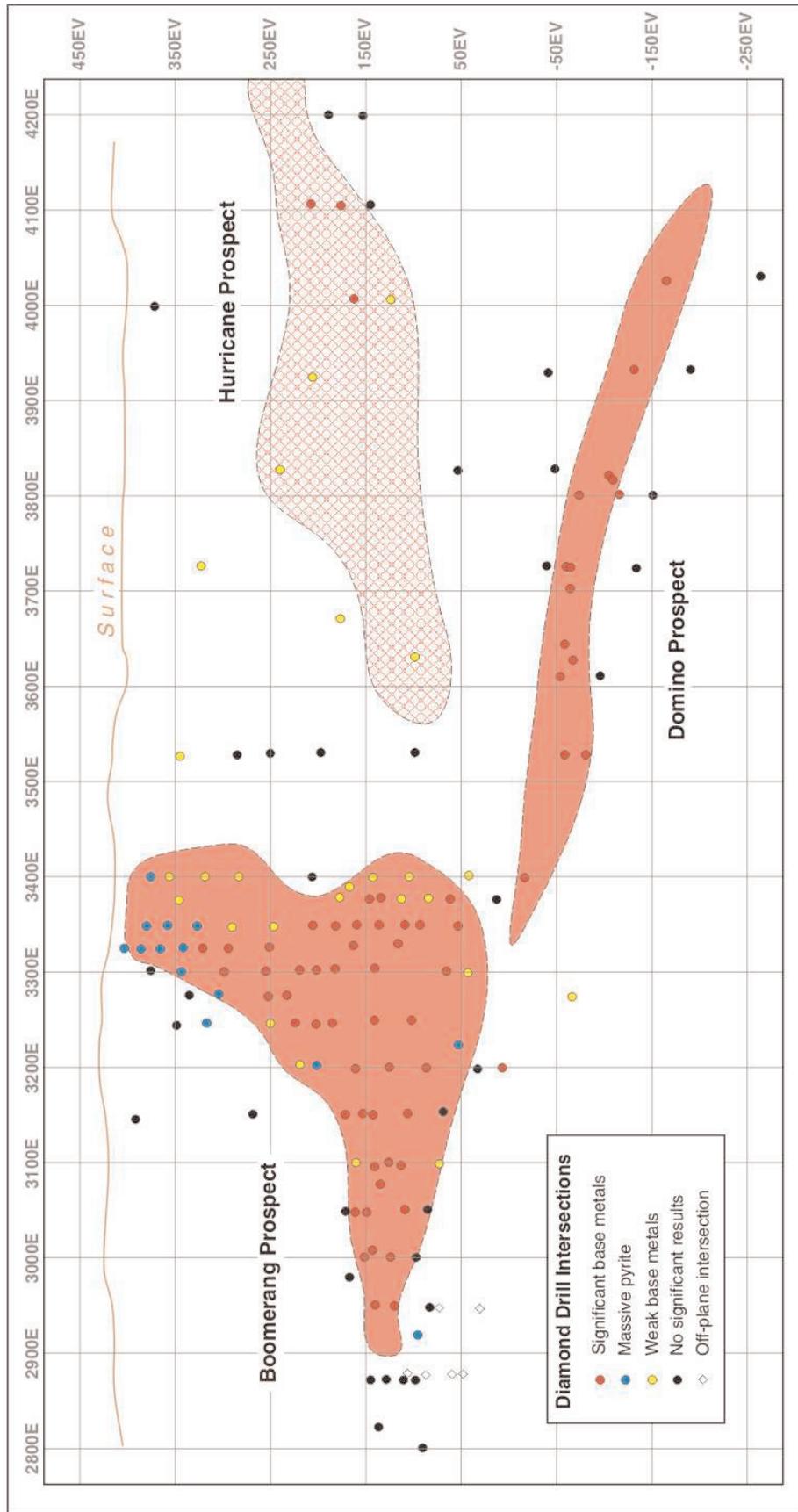
Figure 5. *Longitudinal section illustrating the size and distribution of the Boomerang, Domino, and Hurricane massive sulphide lenses (after Messina Minerals Inc. website 2006).*
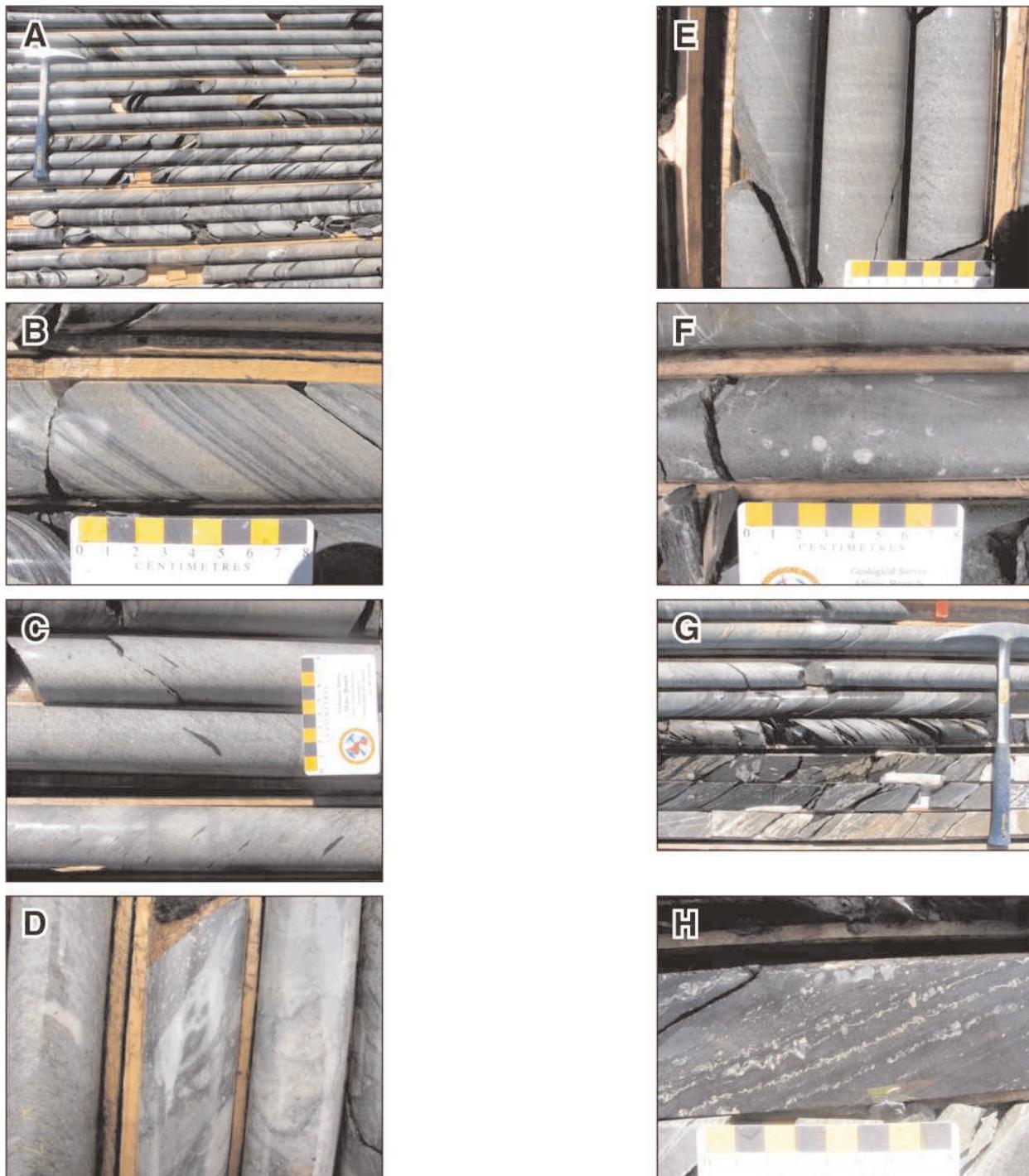
Plate 5. *Photographs of Boomerang–Domino stratigraphy, mineralization and alteration: A) Intercalated felsic tuffs and black argillite (locally sulphide-bearing). Note the rip-up clasts of the argillite in the tuffs, B) Finely inter-laminated black argillite/greywacke and felsic ash-tuff. Note abundant overprinting pyrite, C) Pyroclastic felsic tuff with rip-up clasts of black argillite, D) Heterolithic volcanoclastic breccia/conglomerate. This lithology is common within the stratigraphy and typically displays fining-upward relationships where it grades into felsic tuff, E) Light grey, medium-grained felsic sill. The sills occur in both the hanging wall and footwall to the deposit and locally cut the massive sulphides, F) Amygdaloidal basaltic sill. Amygdales (filled with calcite) occur toward the tops of the sills suggesting a high-level of emplacement. The sills have chilled lower contacts, G) Intercalated felsic tuff and black argillite immediately overlying the ore horizon, H) Blow-up of mineralized black argillite from photograph G.*
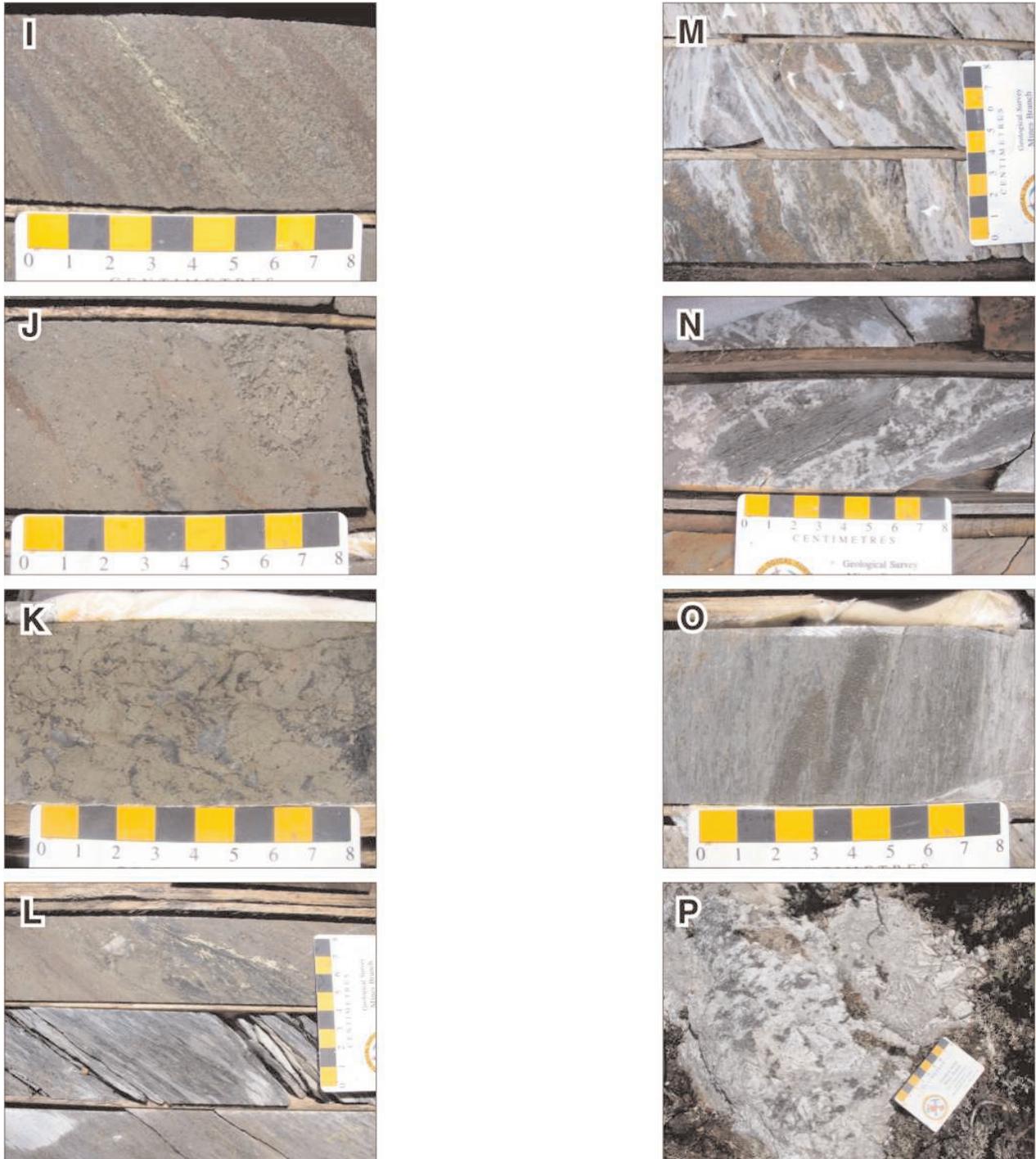
Plate 5 continued. *I) High-grade, massive sulphides (Zn–Pb–Cu). Note the abundant relic quartz crystals and preserved layering suggesting that the sulphides invaded and replaced a sandy crystal-rich tuff, J) Massive sulphides with coarse-grained blebby pyrite interpreted to have formed through recrystallization processes, K) Pyritic massive sulphides with quartz gange, the sulphides are interpreted to have totally replaced the protolith, L) Massive sulphide replacing the heterolitic felsic lapilli tuff footwall, M) Intensely sericitized felsic tuff in a stringer zone directly underneath the massive sulphide horizon. Note the base-metal-rich composition of the stringers, N) Chaotic carbonate alteration in footwall rocks, O) Sericitized and pyritized footwall felsic sandy tuff. Note the isoclinal folding in the pyrite stringer suggesting post-mineralization structural overprinting. P) Outcrop of massive barite (locally replaced by silica). The location of this outcrop in the footwall to the deposit suggests possible influences by large scale tectonics.*
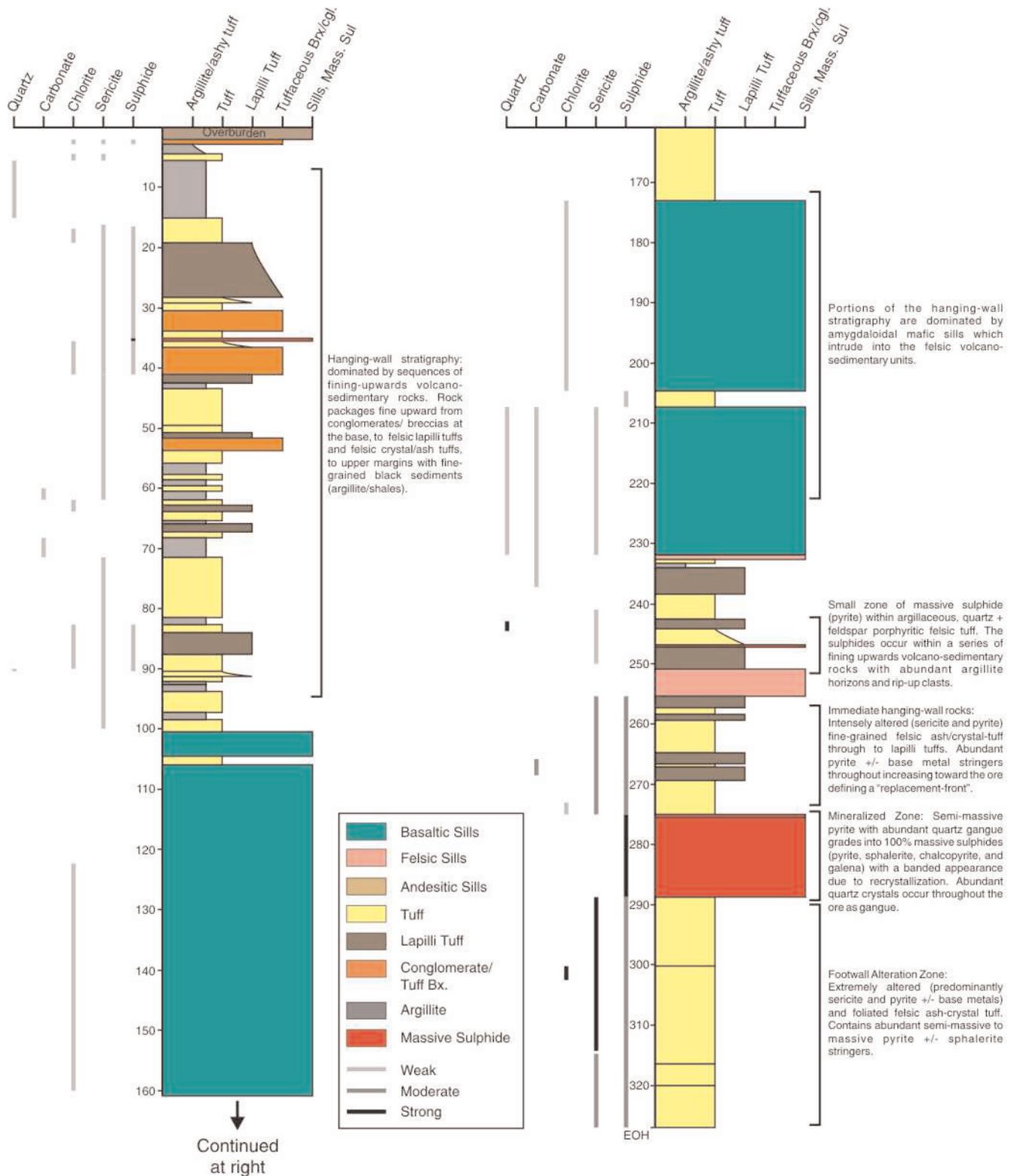
Figure 6. *Schematic drillhole stratigraphic column for DDH GA-04-11 (discovery hole) from the Boomerang deposit illustrating rock types and relations and alteration patterns.*
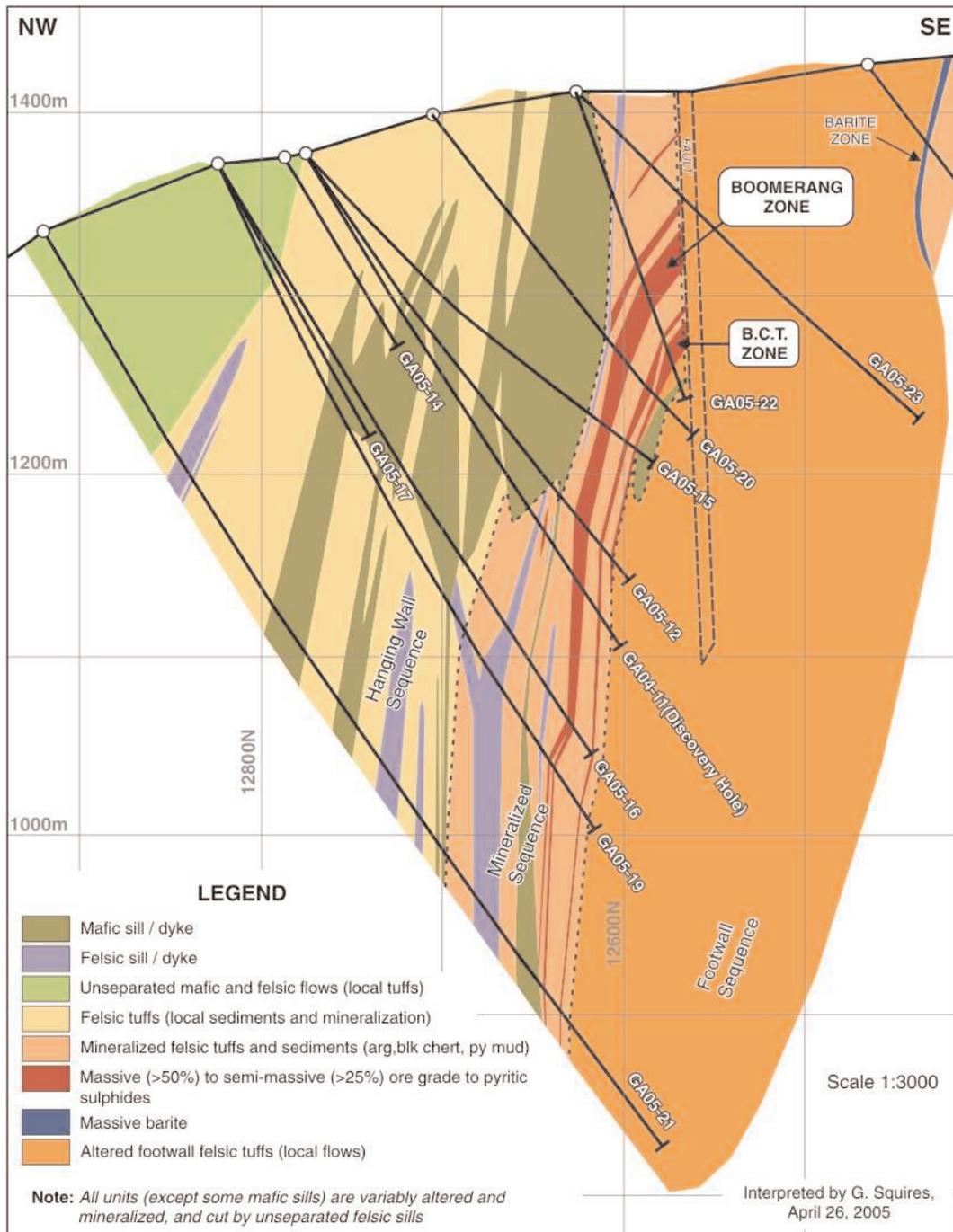
Figure 7. *Cross-section of the discovery section (3300E) on the Boomerang deposit illustrating the rock types and relationships of the footwall, mineralized, and hanging-wall sequences. (After Messina Minerals Inc. website 2006).*

The stratigraphy of the deposit is divided into the hanging-wall sequence, the mineralized horizon, and the footwall sequence, as shown in Figures 6 and 7 and described by Squires *et al.* (2005a,b) and Dearin (2006). The hanging-wall sequence consists of undifferentiated, locally fining upward, felsic volcanic rocks dominated by quartz ± feldspar crystal-ash tuffs, fine-grained sedimentary rocks (black shales/ argillite/greywacke/chert), volcaniclastic conglomerate/ breccia, and bimodal sills (Figure 6). Footwall rocks consist of strongly sericitized felsic volcanic rocks (dominated by fine-grained, pyroclastic crystal-ash tuffs) that have common base-metal stringer sulphides (Plate 5). The rocks are extremely sericitized and display an intense foliation and a local crenulation cleavage (Plate 5). An out-

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crop of massive barite, known from the early days of exploration, has also been mapped in the "footwall" of the Boomerang massive sulphide deposit (Plate 5). However, its location below the main ore zone is peculiar and suggests that it is either structurally juxtaposed, or that it represents another favourable exploration horizon at a lower stratigraphic level. The co-existence of black shales, presumably associated with a reduced and anoxic environment, with barite, presumably formed in an oxidized environment, adds to the problematical nature of the barite. The mineralized horizon of the Boomerang deposit consists of strongly altered fine-grained pyroclastic felsic volcanic rocks (ash-crystal tuffs), as well as sedimentary rocks (black shales, chert and argillite), which are intimately associated with massive sulphide mineralization (Plate 5). The intercalation of volcanic, pyroclastic and sedimentary rocks may have provided a favourable environment for the formation of the Boomerang massive sulphide lense via replacement (*see* below).

Hydrothermal alteration, predominantly sericite–silica–pyrite, and, locally, minor chlorite and carbonate, and stringer base-metal sulphides, occur in both the hanging wall and footwall of the massive sulphide lense. However, the intensity of the alteration is higher in the footwall to the deposit (Figure 6). The hanging-wall stratigraphy also displays minor intervals of sulphide-bearing exhalative (?) sedimentary rocks (Plate 5).

As of November, 2006, the Boomerang massive sulphide lens had a defined horizontal strike length of 500 m, a vertical extent between 25 and 275 m (average ~100 m), and a thickness varying between 5 to 20 m (average ~10 m); (Messina Minerals Inc. website, 2006, and Dearin, 2006). Geometrically, the sulphide lense dips approximately 85° to the northwest and has slight plunge from 0 to 15° southwest. In contrast to the medium- to coarse-grained massive sulphides associated with the Tulks Hill and Tulks East deposits, sulphides in the Boomerang deposit are dominated by fine- to medium-grained, banded and wispy sphalerite–galena–chalcopyrite–pyrite intergrowths (Plate 5). Metal zonation is apparent because the margins of the massive sulphide lenses are dominated by pyrite, the base of the deposit is enriched in Zn and Cu, and the top of the deposit consists of a gold-enriched pyritic cap (Messina Minerals Inc. website, 2006; Tallman, 2006). Local concentrations of arsenopyrite and a silver mineral (tetrahedrite?) are associated with some of the high-grade silver and gold intervals; an association also observed at the Domino lens.

Domino Deposit

The Domino massive sulphide lense, discovered by Messina Minerals in February, 2006, is located approxi-

mately 200 m northeast of, and approximately 100 m deeper than, the Boomerang deposit (Figure 5). The stratigraphy is very similar to that described above for the Boomerang lense. Messina Mineral Inc. "discovery hole" DDH-GA-06-96 intersected 10.58 m of massive sulphides grading 0.5% Cu, 5.5% Pb, 7.3% Zn, 128 g/t Ag and 1.0 g/t Au, including 3.63 m grading 0.5% Cu, 7.4% Pb, 12.1% Zn, 219 g/t Ag and 1.4 g/t Au. The massive sulphide lense extends over at least 500 m strike length, is 1 to 5 m in true thickness, and has a vertical extent of approximately 30 to 70 m (Messina Minerals Inc., Press Release, August 10, 2006). It is now known that the massive sulphide intersection made by Noranda in DDH GA-97-05 (Banville *et al.*, 1998) was actually part of the Domino lense.

Hurricane Deposit

The Hurricane massive sulphide lense represents the third significant discovery by Messina Minerals Inc. in this area. The sulphide zone is located approximately 700 m to the northeast of the Boomerang deposit. Although in the early stages of exploration, results to date indicate that the Hurricane massive sulphide lense contains high polymetallic grades (*e.g.*, between 20 and 31.3% combined Zn–Pb–Cu), which have been intersected over 100 m of strike length and at least 70 m of vertical extent (Messina Minerals Inc., Press Release, November 8, 2006).

Other VMS Deposits

In addition to the above described massive sulphide deposits, numerous other VMS prospects and areas of favourable VMS-style alteration occur throughout the southern TVB (Figure 2). The prospects can be divided into three main groups based on observed characteristics:

1) Coarse-grained, disseminated to semi-massive pyrite (with lesser base metals) associated with chloritized felsic/intermediate (?) volcanics (*e.g.*, Middle Tulks prospect, Al Keats prospect, and a portion of the Curve Pond prospect).

2) Chlorite, sericite, silica, and pyrite altered felsic (intermediate?) volcanics containing chalcopyrite and pyrite stringers and anomalous arsenopyrite (*e.g.*, Tulks West and Mug-up prospects).

3) Massive sulphides (locally base-metal enriched and locally anomalous in (secondary?) arsenopyrite) associated with exhalative ferruginous sediments in the form of iron formations (*e.g.*, the main Curve Pond prospect (formerly the Green Zone) and Dragon Pond).

Group 1

This group includes the Middle Tulks and Al Keats prospects, and a portion of the Curve Pond prospect. The zones of mineralization and alteration consist of intensely chloritized felsic to intermediate volcanic rocks and coarse- (*e.g.*, "Buck-shot type") to fine-grained disseminated pyrite and lesser base-metal sulphides (Plate 6). Silica–sericite alteration is developed on a local scale.

The Middle Tulks prospect (Figure 2, Plate 6) alteration zone, discovered by Messina Minerals Inc. during 2005, is located between the Tulks East and Tulks Hill deposits. Although predominantly pyritic, selective grab samples have assayed 0.3% Cu, 0.6% Pb, 1.9% Zn, 47 g/t Ag and 0.3 g/t Au (Messina Minerals Inc., Press Release, October 27, 2005). The intense chloritic alteration and disseminated (to semi-massive) pyrite is visually identical to the Al Keats prospect located to the south. The Al Keats prospect contains abundant sedimentary rocks (inter-bedded black argillite and greywacke; Plate 1) associated with mineralization (up to 4.68% Zn and 1.5% Cu in grab samples, 0.3% Zn over a 2 m channel (*e.g.*, Noranda 1998)). The similarities in alteration and mineralization, along with the locations of the prospects, suggest that they may represent a common prospective stratigraphic horizon, possibly lower than that hosting the Tulks Hill and Tulks East deposits.

Group 2

Prospects within this group include the Tulks West and Mug-up prospects. The Tulks West prospect was discovered by Asarco through follow-up work after the Tulks Hill discovery, whereas the Mug-up prospect was discovered by D. Evans and B. Kean during mapping in 1988. Both are predominantly composed of chlorite, sericite, silica, and locally carbonate altered felsic to intermediate (?) volcanic rocks associated with stringers and disseminations of pyrite, chalcopyrite, arsenopyrite, and local sphalerite and galena (Plate 7). Diamond drilling within the Tulks West area, intersected footwall stockwork sulphide mineralization associated with minor occurrences of base metals. The enrichment of As (*e.g.*, presence of arsenopyrite), along with the relatively high Cu grades, may suggest direct input of magmatic hydrothermal fluids from a proximal vent system (*e.g.*, Franklin *et al.*, 2005).

Group 3

Prospects included in this group consist of the "exhalative-type" Curve Pond and Dragon Pond VMS prospects. Unlike most of the other deposits described above, these have ferruginous sedimentary horizons (*e.g.*, iron-formations) associated with massive sulphides (Plate 8). This spa-

Plate 6. *Heavy chlorite alteration with semi-massive pyrite at the Middle Tulks VMS showing. Note the variable habit of the pyrite (*e.g., *coarse cubes versus fine-grained semi-massive disseminations). Host rock is interpreted to be intermediate volcanics.*
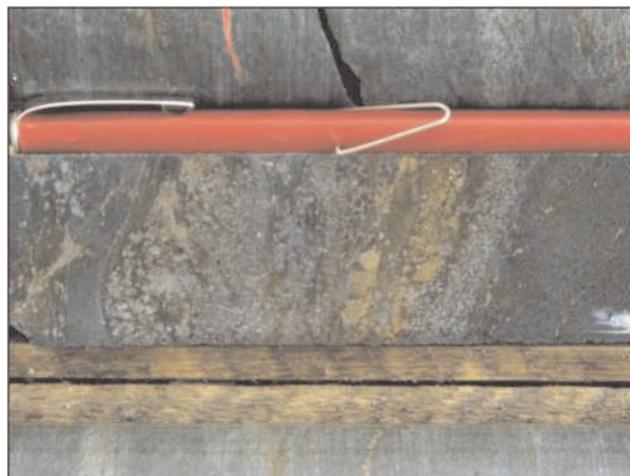
Plate 7. *Stringer of semi-massive arsenopyrite, chalcopyrite and pyrite in felsic-intermediate volcanics of the Tulks West Showing.*

tial association likely indicates a genetic link between the two.

The Curve Pond prospect, discovered in 1990 by BP geologists following detailed mapping and exploration, is located southeast of the Boomerang deposit (Figure 2). Iron formation associated with the Curve Pond VMS horizon has been traced, in outcrop and drill core, for approximately 10 km, and has been intersected over thicknesses of a few metres to 70 m (Noranda, 1998, Messina Minerals Inc., Press Release, September 18, 2006). The iron formation directly overlies the VMS horizon, which is about 4 m thick and has been traced for approximately 130 m. Intensely
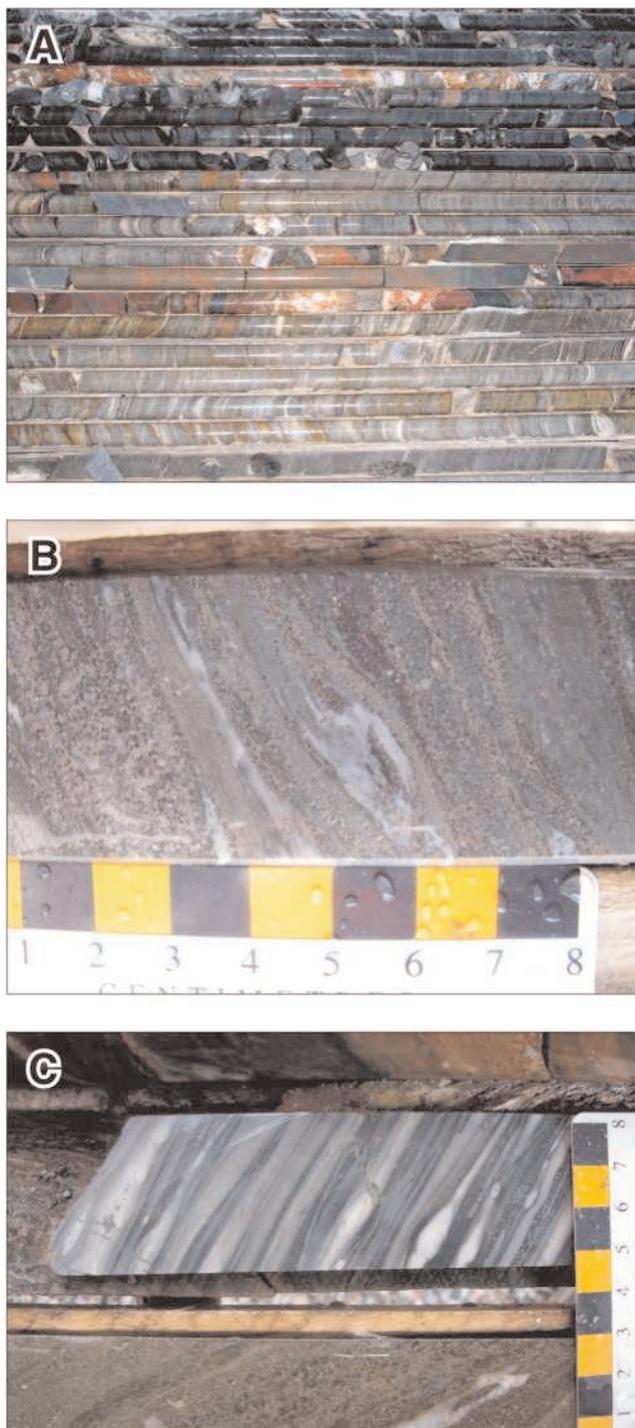
Plate 8. *A) Dragon Pond mineralized horizon. Note the change in rock types down-hole from black shales/argillite, into felsic lapilli-tuff, into iron-formation, down into sericitized felsic lapilli-tuff, B) Banded massive sulphides (Zn–Pb–Cu) from the Curve Pond Showing. Note the abundant quartz crystals and fragments in the ore, C) Massive pyrite and pyrrhotite at the Curve Pond Showing. Note the banded greywacke and chert, which may be analogous to the iron-formation unit mapped in the field.*

altered (sericite–silica) quartz-feldspar phyric felsic volcanic rocks comprise the footwall to the mineralization. Grab samples by Noranda in 1993 from the main part of the showing returned assays up to 26% Zn and 1.2% Pb. Sulphides vary from massive pyrite ± pyrrhotite to "layered" pyrite with lesser pyrrhotite, chalcopyrite, sphalerite, and galena (Plate 8). The prospective horizon has been the focus of previous drilling programs by BP, Noranda and Mishibishu Gold Corp., most of which intersected favourable alteration and/or massive sulphides. The area is currently being actively explored and evaluated by Messina Minerals Inc.

The Dragon Pond massive sulphide horizon was discovered by diamond drilling by Noranda in 1995. The favourable horizon is sandwiched between altered (sericite, silica, and pyrite) footwall quartz-feldspar felsic volcaniclastic rocks and overlying, locally ferruginous, sedimentary rocks (Plate 8). This prospect occurs along a favourable horizon that is clearly distinct from that hosting the Tulks Hill and Tulks East deposits. It is yet uncertain if the Boomerang deposit sits along the same horizon. Although no significant base-metal values have been discovered, the large footprint of favourable alteration, in addition to the associated iron-formation, suggests further exploration potential for the area.

The presence of these mineralized horizons in association with exhalative ferruginous sediments at Curve Pond and at Dragon Pond is very significant in that the geological environment is analogous to that which hosts massive sulphide deposits of similar age in the Bathurst VMS camp in New Brunswick (*e.g.*, Goodfellow and McCutcheon, 2003, and references therein).

ALTERATION

Alteration associated with VMS mineralization in the southern TVB is dominated by stratabound sericite–silica–pyrite alteration zones. The alteration is widespread throughout the belt and is identifiable in both the field and in diamond-drill core (Plates 3-8). Less evident in the field are the minor amounts of chlorite and carbonate alteration that are locally observed in drill core in the footwall alteration systems of many of the deposits. Chlorite alteration, where present, typically occurs with stringer mineralization in the footwall sequences of deposits (*e.g.*, Tulks East deposit, Plate 3) or with heavily disseminated pyrite in felsic to intermediate volcanic rocks (*e.g.*, Middle Tulks, Al Keats prospects, Plate 6). Hydrothermal carbonate alteration locally occurs as spots and semi-massive accumulations. Vein-like or chaotic net-textured carbonate suggests that it formed as a replacement alteration product rather than by precipitation on the seafloor (*e.g.*, Domino footwall rocks,

Plate 5). In general, the strength of the alteration increases with proximity to sulphide-bearing horizons.

An important feature of most VMS deposits in the southern TVB is that they are hosted by what are interpreted as originally porous and permeable felsic volcaniclastic rocks (*e.g.*, crystal-ash tuffs). These host-rock characteristics apparently influenced the distribution and extent of hydrothermal fluid flow, and therefore the distribution of hydrothermal alteration and mineralization.

DISCUSSION

STYLE OF VMS MINERALIZATION AND DEPOSIT TYPES

Mechanisms for the formation of VMS deposits are commonly described in terms of two main processes: 1) exhalative or supra-seafloor sulphide accumulation (*e.g.*, chimney-growth process or precipitation from a brine-pool), or 2) sub-seafloor replacement and associated sulphide accumulation (*e.g.*, Doyle and Allen, 2003; Franklin *et al.*, 2005). The recognition and understanding of the second process is relatively new and it has implications for the deposits in the southern TVB as suggested by Squires *et al.,* 2005a, b; G. Squires, personal communication, 2006.

Doyle and Allen (2003) describe three main criteria that are diagnostic of sub-seafloor massive sulphide deposits: 1) the massive sulphides are enclosed within rapidly emplaced volcanic or sedimentary facies (*e.g.*, pyroclastic or tuffaceous rock types, mass-flow deposits), 2) the massive sulphides preserve some relicts of the host rocks, and 3) replacement fronts can be observed between the massive sulphide and the host rocks. Other characteristics that may suggest replacement of the host rocks include discordance between mineralization and bedding, and the presence of strong hydrothermal alteration in the hanging-wall sequence.

The VMS deposits at Tulks East, Tulks Hill, Boomerang and Domino display many of these characteristics. In all the cases, hydrothermal fluids infiltrated favourable horizons of unconsolidated (?), porous, and permeable felsic volcaniclastic rocks resulting in variable degrees of replacement of the original rock types and associated accumulation of massive sulphides. The mixing of upwelling hydrothermal fluids with cooler inter-pore fluids and seawater would result in the formation of a strata-bound massive sulphide lens, which is enclosed within a halo of hydrothermal alteration (*e.g.*, Gibson, 2005). The three deposits also show evidence of relict host rock types (felsic crystal-ash tuffs) within the ore in the form of relict quartz crystals (Plate 5), and they locally preserve bedding; they all display hydrothermal alteration and stringer mineralization, in both the hanging-wall and footwall sequences (Figures 3 and 6, Plate 3). In addition, all three deposits also contain fine-grained sedimentary rocks either in the mineralized horizon, or directly above it, which may have acted as a physical barrier to fluid migration and trapped the metalliferous fluids in the prospective horizons.

As outlined by Franklin *et al.* (2005) and Doyle and Allen (2003), in order for a sub-seafloor, replacement-style deposit to form there must have been upward and outward movement of extremely large volumes of hydrothermal fluids. Most VMS deposits are associated with rifting of arcs in extensional tectonic regimes, which promotes development of large-scale structures. Consequently, it is likely that some of the upwelling hydrothermal fluids would reach the seafloor to vent and produce potentially metalliferous exhalative horizons. In the southern TVB, the exhalative, sulphide-bearing horizons at the Dragon Pond and Curve Pond prospects, and sulphide-bearing exhalative (?) sediments in the hanging wall to the Boomerang and Domino deposits may record venting of fluids. The peculiar presence of arsenopyrite associated with many of the VMS occurrences may suggest that a significant proportion of magmatic fluids were involved in ore deposition in both types of environments (*e.g.*, *see* Franklin *et al.*, 2005 and references therein).

As such, the southern TVB contains deposits that form a continuum from classic exhalative VMS deposits that formed on the seafloor (*e.g.*, Curve Pond and Dragon Pond) through to replacement-style deposits such as Boomerang, Tulks East, and Tulks Hill (Figure 8).

The classification of Barrie and Hannington (1999) and Franklin *et al.* (2005) typically shows that the VMS deposits in the southern TVB fit into the bimodal felsic subdivision because their host sequences are dominated by >50% felsic volcanic rocks and/or 35 to 70% felsic volcaniclastic rocks, they have ~10 to 15% siliciclastic rocks in the host stratigraphic succession, and mafic volcanic and intrusive rocks form the remainder. As observed in the Tulks deposits, such environments commonly produce Zn-rich ore systems. However, it should be noted that some deposits (e.g., Tulks East, Dragon Pond) contain local abundances of sediment and siliciclastic rocks that have proportions nearing those of the associated felsic and mafic volcanic rocks. As such, these deposits may be better classified as ranging from bimodal felsic to bimodal siliciclastic. Although the deposits in the southern TVB share some similarities with the Duck Pond and Boundary deposits in the Tally Pond Volcanics, in that they are dominated by replacement-style mineralization (Squires *et al.*, 2001; Squires and Moore, 2004),
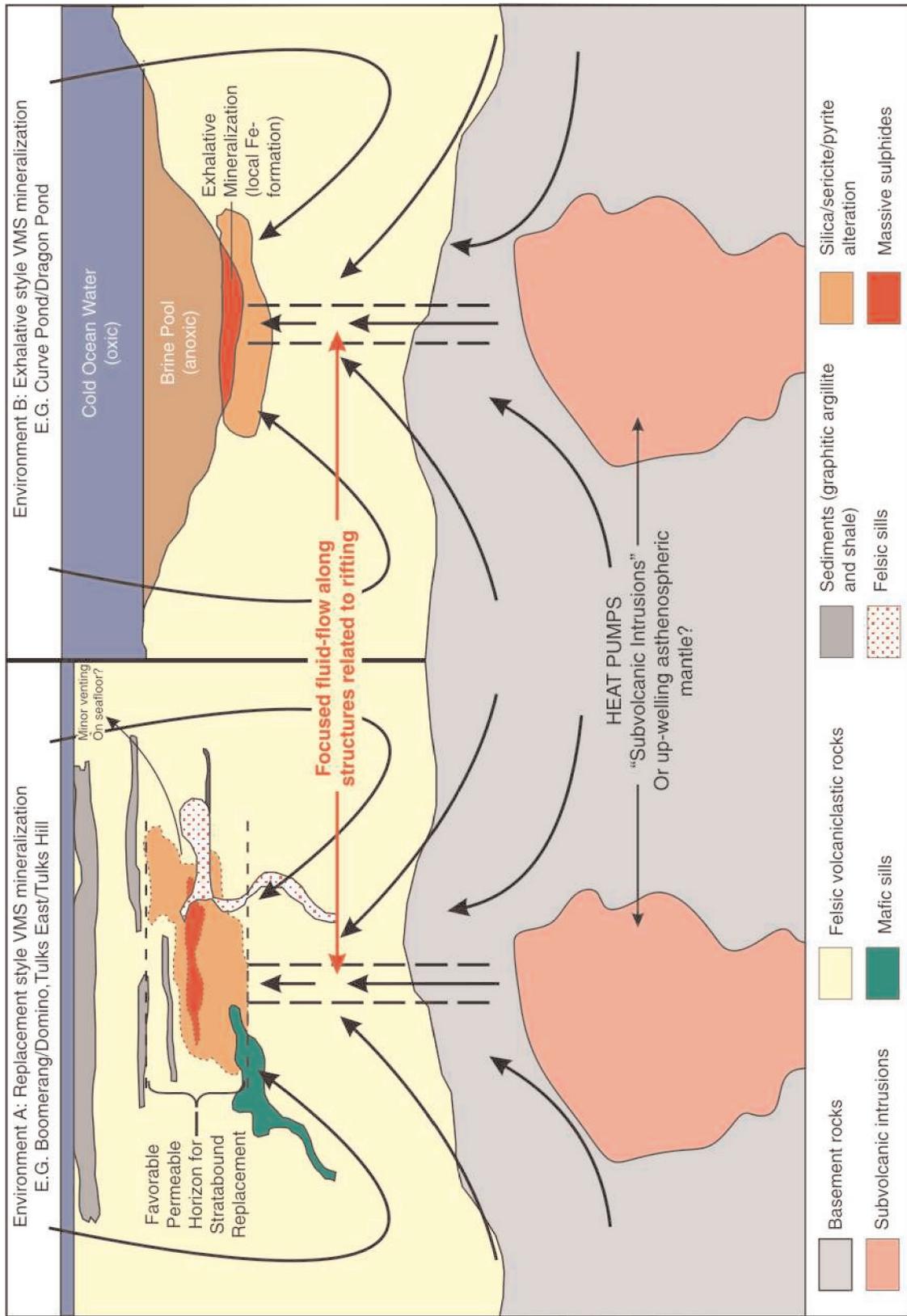
Figure 8. *Schematic diagram illustrating the two types of VMS forming environments observed in the southern TVB. Note that the two environments may be locally related and form a continuum.*

they differ in that the Tally Pond deposits are associated with felsic volcanic rocks that commonly display coherent flow-banding and form rhyolite domes, whereas deposits in the southern TVB are associated with volcaniclastic felsic successions and sedimentary rocks, and lack a clear association with flows or domes.

FACIES ARCHITECTURE: INITIAL OBSERVATIONS, GEOCHRONOLOGICAL IMPLICATIONS, AND INFLUENCE ON VMS POTENTIAL

Lithostratigraphic units mapped from surface outcrops and diamond-drill cores provide a framework for understanding the facies architecture of the southern TVB. Volcanic, volcaniclastic, and sedimentary facies are dominated by: 1) thick, massive to graded beds of felsic volcaniclastic rocks ranging from fine volcaniclastic sediments (black shales and argillites), ash-crystal tuffs, and volcaniclastic conglomerate/breccia; 2) thick homogenous sections of crystal (quartz ± feldspar) rich tuff and sandstones; 3) massive to laminated sediments (shales/mudstones); 4) bi-modal sills; and 5) mafic volcanic rocks.

Preliminary investigations indicate that there are broad regional facies variations throughout the belt. The north-eastern portion of the belt (*e.g.*, area of Tulks Hill and Tulks East deposits) is dominated by massive quartz–porphyritic felsic tuffs in the footwall and mineralized horizons, with increasing amounts of volcaniclastic (?) sedimentary rocks and mafic volcanic rocks in the hanging wall. The southern portion of the southern TVB is dominated instead by inter-calated felsic volcaniclastic rocks (quartz + feldspar felsic tuffs, volcaniclastic breccias and conglomerates), turbiditic sedimentary rocks (black shales, siltstones, cherts, greywacke), and abundant bimodal sills. Finally, the western margin of the belt is dominated by intercalated quartz + feldspar felsic tuffs and thick successions of fine-grained volcaniclastic (?) sedimentary rocks including turbidites. These broad facies variations correspond to the recent mapping conducted by the GSC (van Staal *et al.*, 2005; Zagorevski *et al.*, 2003) that subdivided the belt into the Pats Pond, Wigwam Brook, and Tulks groups. Coupled with the U–Pb data suggesting that these have contrasting ages, this supports the concept that the southern TVB is a composite sequence.

Observed volcanic facies range from being syn-eruptive, such as the homogeneous quartz ± feldspar phyric tuffs and sandstones formed by submarine coeval explosive volcanism, to post-eruptive, dominated by volcaniclastic conglomerate and breccias, with local rounded clasts and rip-up clasts of black shales. The fragmental nature of the latter, with clasts of fine-grained sediments, suggests that they formed after being temporarily stored in the volcanic envi-

ronment. The sedimentary rocks provide direct field evidence for the importance of mass flows and turbidity currents. Graded bedding (conglomerate through to shales and mudstones) also suggests that these sequences developed in post-eruptive environments.

Due to the lack of outcrop in the area, many gaps and uncertainties remain in our knowledge of detailed stratigraphic correlations within, and between, these facies assemblages. This is particularly important in the area of the recently discovered Boomerang VMS cluster. As currently mapped by van Staal *et al.* (2005), the deposits are interpreted to occur within the ca. 487 Ma Pat's Pond Group, which is ca. 11 Ma younger than the Tulks Group, which hosts the Tulks East and Tulks Hill deposits. However, the U–Pb site from which this correlation is drawn lies about 35 km along strike to the southwest. If this interpretation is correct, it argues against earlier interpretations that VMS mineralization within the southern TVB is hosted by a single stratigraphically restricted felsic volcanic package (*e.g.*, Evans *et al.*, 1990; Noranda, 1998). Two geochronology samples have thus been collected from the main Boomerang mineralized horizon to test this concept. The results of this work may have important implications if they support the existence of a second, younger prospective volcanic horizon within the TVB.

VOLCANIC ENVIRONMENTS AND TECTONIC SETTINGS FOR VMS MINERALIZATION: PRELIMINARY THOUGHTS

The VMS deposits of the southern TVB typically occur in thick successions of felsic volcaniclastic rocks (crystal-ash tuffs) intercalated with varying amounts of sedimentary rocks (black shales, cherts, greywackes). Fining-upward turbiditic sequences are commonly observed in the mineralized packages of rocks. Bimodal volcanic sills occur syngenetically with the volcaniclastic and sedimentary rocks (Plate 9). Many of the basaltic sills are amygdaloidal at their tops and have chilled lower margins. These relationships suggest that the VMS systems formed in an environment of active volcanism and synchronous sedimentation, most likely within a rifted basin, possibly of back-arc affinity.

Such an environment is supported through lithogeochemistry conducted as part of previous investigations in the area (*e.g.*, Swinden *et al.*, 1989; Evans and Kean, 2002 and references therein; Rogers, 2004; Zagorevski, 2006). Although mainly dealing with mafic volcanic rocks, these studies documented a change in chemical signatures within the belt suggesting a transition in tectonic setting from an active arc environment to a non-arc or back-arc rifting environment. The upper basalts of Swinden *et al.*, 1989 have a LREE-enriched trace-element pattern, lack a Nb depletion,

Plate 9. *Interfingering contact relationship between felsic tuff (left) and an intermediate to mafic dyke (right) suggesting that both were emplaced synchronously.*

which, in addition to supporting a non-arc environment, suggests high heat-flow regimes (*see* Figure 13a of Evans and Kean, 2002). This transition from an island-arc (convergent regime) to an arc-rift or back-arc (extensional regime) environment is important as such transitions and extensional environments are considered important for VMS formation. The combination of active progressive rifting and high heat-flow allows conduits to form and focus both upward hydrothermal fluid flux as well as downward movement of seawater into the hydrothermal system (*e.g.*, Lesher *et al.*, 1986; Lentz, 1998; Piercey *et al.*, 2001). The heat pump for the hydrothermal system may be related to subvolcanic intrusions and/or upwelling hot asthenospheric mantle in a back-arc rift-environment. Franklin *et al.* (2005) also point out that the bimodal magmatism that accompanies rifting (such as that observed in the southern TVB) also facilitates high geothermal gradients. The presence of such high heat-flow, accompanied by the emplacement of shallow plutons, could also provide potential sources of magmatic fluids.

CONCLUSIONS AND FUTURE WORK

The main focus of 2006 was to examine the known VMS deposits and prospects to gain an understanding of: 1) the regional and local stratigraphy of the southern TVB, 2) the alteration styles associated with mineralization, and 3) the nature and style of the massive sulphide mineralization.

Volcanic lithofacies were investigated and classified to aid in ongoing lithogeochemical studies. Preliminary results suggest that there are a number of distinguishable volcanic facies amongst the variable felsic pyroclastic and volcaniclastic rocks that host mineralization across the belt. This observation had been invoked by earlier workers (*e.g.*, Evans *et al.*, 1994 a, b, c; Kean, 1982) and it is supported by

more detailed work under this project. The facies variations are generally consistent with proposed subdivisions of the southern TVB (van Staal *et al.*, 2005). The Tulks East and Tulks Hill deposit clusters occur within the Tulks Group (ca. 498 Ma), whereas the Boomerang deposit cluster appears to be hosted by the younger Pats Pond Group (ca. 487 Ma). This study suggests that there are important contrasts in the stratigraphy between these two sequences. The correlations will be tested by U–Pb geochronology.

Two main types of VMS mineralization occur within the southern TVB: 1) replacement-style mineralization at the Tulks East, Tulks Hill, and Boomerang deposit clusters, and 2) classic exhalative-style mineralization at the Curve Pond and Dragon Pond prospects. Each type shares some similarities with world-class deposits. The replacement-style deposits, especially the Boomerang deposits, display many similarities to deposits such as the Rosebery Deposit in the Cambrian Mount Read Volcanics of Australia. Similarities include the sheet-like replacement style of mineralization, the high Zn–Pb metal content and similar host rocks and alteration styles (*e.g.*, Large *et al.*, 2001). The exhalative-style mineralization has affinities to the world-class deposits of the Bathurst mining camp in New Brunswick (*e.g.*, Goodfellow and McCutcheon, 2003). These similarities include similar ages, the presence of bimodal volcanics associated with volcano-sedimentary sequences, and association with regional-scale ferruginous sediments (iron formations). Regional geological and geochemical data suggest that most of the VMS mineralization within the southern portion of the belt developed within an extensional tectonic regime, likely associated with a transition from an active arc to an arc-rift or back-arc environment.

Several follow-up research studies have now been initiated. Lithogeochemical sampling has been completed on all stratigraphic units within the southern TVB, using outcrops and diamond-drill core. Results will hopefully aid in identification and characterization of prospective VMS horizons for future exploration. Isotopic studies have also been initiated to see if such data support the observed variations in prospective VMS environments.

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