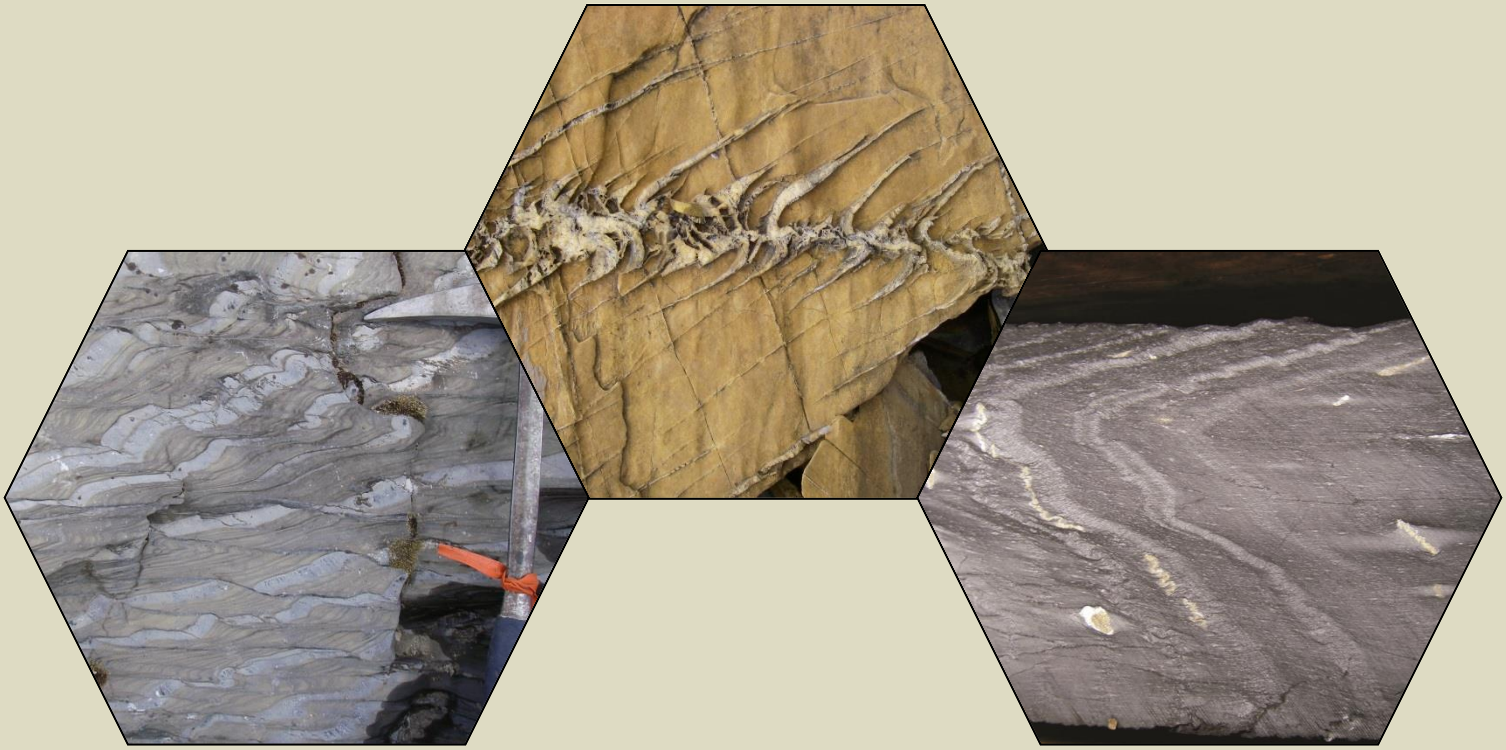

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The Structural Model for Howard’s Pass Pb-Zn District, Northwest Territories: Grounds for Re-Interpretation

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Northwest Territories Industry, Tourism and Investment

NORTHWEST TERRITORIES GEOLOGICAL SURVEY

NWT Open File 2015-01

The Structural Model for Howard's Pass Pb-Zn District, Northwest Territories: Grounds for Re-Interpretation

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Cover photos (left to right)

- *Light grey limestone and yellowish-brown silty limestone beds of the Rabbitkettle Formation displaced along black pressure solution seams.*
- *Sigmoidal tension gashes filled with quartz in silicic-baritic mudstone of the Steel Formation.*
- *Folded sulphide-bearing calcareous mudstone of the Duo Lake Formation. Note the axial-planar pressure solution cleavage, diffraction of the cleavage in light grey beds, the folded quartz-calcite veins, and pressure shadows filled with quartz-calcite.*

ABSTRACT

Since the late 1970s discovery of Pb-Zn mineralization in the Silurian shale of the Selwyn Basin at Howard's Pass, additional mineralization has been identified and define a 40-km-long Pb-Zn district of 15 deposits (NTS 105I). Mineralization was initially discovered at the XY showing in the Yukon followed by the discovery of additional mineralization at XY Nose and CMC in the NWT by Cominco. The currently defined Howard's Pass district is mostly in the Yukon Territory where most recent exploration has been undertaken. The CMC area in the NWT has not seen additional exploration since its initial discovery. In order to improve the geological framework, the Northwest Territories Geoscience Office conducted field work in the CMC area during the summers of 2009 and 2011.

The published structural model for the Howard's Pass district holds that syngenetic mineralization was deformed while sediments were still water-saturated, during a period of compressional tectonism in the prevailingly extensional regime of the Silurian. This early deformation was followed by Devono-Mississippian and late Cretaceous deformation of the Cordilleran orogeny that produced further folding, faulting, low-grade metamorphism and minor remobilization of pyrite along slaty cleavage, but did not significantly affect stratigraphy or the texture and distribution of sulphide minerals. New insights from recent property-scale surface bedrock mapping by Selwyn Resources Ltd. (Hodder and Bain, 2005-2012; unpublished internal reports, Selwyn Resources Ltd.) and the Northwest Territories Geoscience Office indicate that an alternative interpretation is required to explain the newly identify distribution of the strata and mineralization.

We propose that the map pattern of rock types is primarily controlled by thrusting, forming a duplex structure, not simply by folding. Imbricated thrusts are proposed to root into a flat-lying detachment surface, termed the Howard's Pass décollement, which forms the floor thrust of a duplex. The Howard's Pass décollement displays significant ductile strain. Above the décollement, a series of imbricated thrust faults disrupt mineralization and stratigraphic succession. Sulphides (galena, sphalerite, and pyrite) are concentrated and remobilized along a pressure solution cleavage, which is well developed in zones of high strain. The duplex is capped by a flat-lying detachment surface that is the roof thrust of the duplex and above which less shortening has been accommodated. We suggest that the duplex and associated fabrics (pressure solution cleavage, transposition, folds and faults) formed 250-300 Ma after deposition of sediments, during the Cordilleran orogeny, and significantly affected the distribution of the mineralization. Herein, we document the structural style that defines the Howard's Pass district and discuss the presence of imbricate thrusts, multiple levels of décollement, duplex structure, ductile shear fabrics, and transposition. We propose an alternative structural interpretation where layer-parallel shortening during Jura-Cretaceous orogenesis resulted in a regional-scale duplex structure.

Keywords: Howard's Pass Pb-Zn district, SEDEX, Selwyn Basin, Cordilleran orogeny, deformation, tectonic, structural style, detachment, décollement, duplex, high-strain zone, transposition, NTS 105I

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INTRODUCTION

The Howard's Pass Pb-Zn district encompasses 15 deposits hosted in the stratigraphy of the Selwyn Basin (Fig. 1) and extends for over 40 km (Fig. 2). The deposits have been classified as Sedimentary Exhalative (SEDEX) and contain more than 154 Mt of indicated resources grading 5.35% Zn and 1.86% Pb (Kirkham et al., 2012). As summarized by Goodfellow and Lydon (2007), SEDEX deposits are typically tabular bodies composed predominantly of Zn, Pb, and Ag bound in sphalerite and galena that occur interbedded with iron sulphides and basinal sedimentary rocks. They were deposited on the seafloor and in associated sub-seafloor vent complexes by hydrothermal fluids vented into mostly reducing environments, such as restricted sedimentary basins in continental rift settings.

The Howard's Pass district has been extensively drilled (more than 1000 drill holes), but until recently no systematic detailed bedrock geological or structural mapping have been conducted. Hodder et al. (2014) released a simplified interpretive structural geology map of the district. During our limited field work, we carried out structural mapping at 1:10,000 scale around the CMC claims, and south to the March fault (map area outlined in Figure 2), exclusively on the NWT portion of the district. In spite of the extensive drilling in the district, no drilling has been recorded for the map area, although two drill pads are present. Previous exploration, consisting of 12 trenches excavated by Cominco Ltd. (Pride, 1973; Olfert, 1982), has also been identified. The results of the fieldwork conducted by the Northwest Territories Geoscience Office (NTGO) in the CMC area was incorporated in the Hodder et al. (2014) map published at 1:50,000 scale (Fig. 3). A more detailed version of the field work is provided here (Fig. 4). Our interpretation of the structural geology is consistent with observations made by Hodder and Bain (2005-2012, unpublished internal reports, Selwyn Resources Ltd.). However, no attempt has been made yet to correlate the subsurface geology with the surface geology. In this report, the "Howard's Pass district" refers to the area that encompasses the 15 Pb-Zn deposits (Fig. 3) outlined in green in Figure 2. The "map area" refers to the area of detailed mapping (Fig. 4) outlined in red Figure 2. "District-scale" refers to features observed within the Howard's Pass district as defined above, and "regional-scale" (or the term "regionally") refers to features documented within the Nahanni map area (NTS 105I) and adjacent NTS map sheets (Fig. 5). We present a regional geological framework and a review of the currently accepted model for the Howard's Pass district, followed by new observations and interpretations, based on field mapping. From these observations a preliminary structural model for the deposit is presented.

REGIONAL GEOLOGICAL FRAMEWORK

Neoproterozoic to Paleozoic slope-to-basin facies continental margin strata underlie an area ~770 x 200 km that lie across central Yukon Territory, Canada, and collectively define the Selwyn Basin (Mair et al., 2006). The Selwyn Basin strata are generally considered to represent an off-shelf succession of siliciclastic and slope carbonate rocks deposited along the northwestern margin of ancestral North America. The Selwyn Basin stratigraphy was first described by Gabrielse (1967) and subsequently documented by various authors (Blusson, 1976; Tempelman-Kluit, 1977; Tempelman-Kluit, 1981; Abbott, 1982; 1983; Fritz, 1985; Gordey and Anderson, 1993; Cecile, 1982; 2000; Norris, 1997; Murphy, 1997; Gordey, 2008).

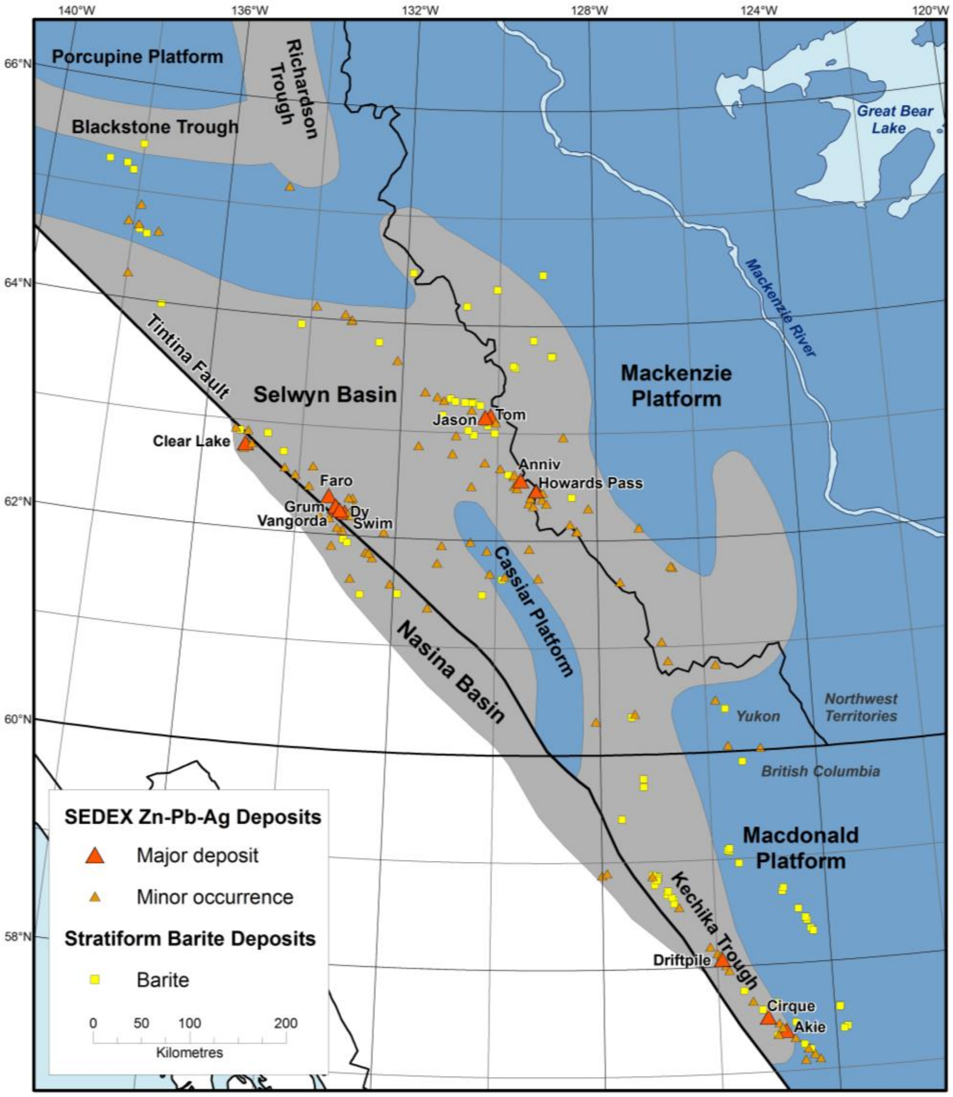


Figure 1. Map showing location of the Selwyn Basin (grey), Mackenzie Platform (blue), and major Pb-Zn and Ba deposits. Modified from Goodfellow and Lydon (2007).

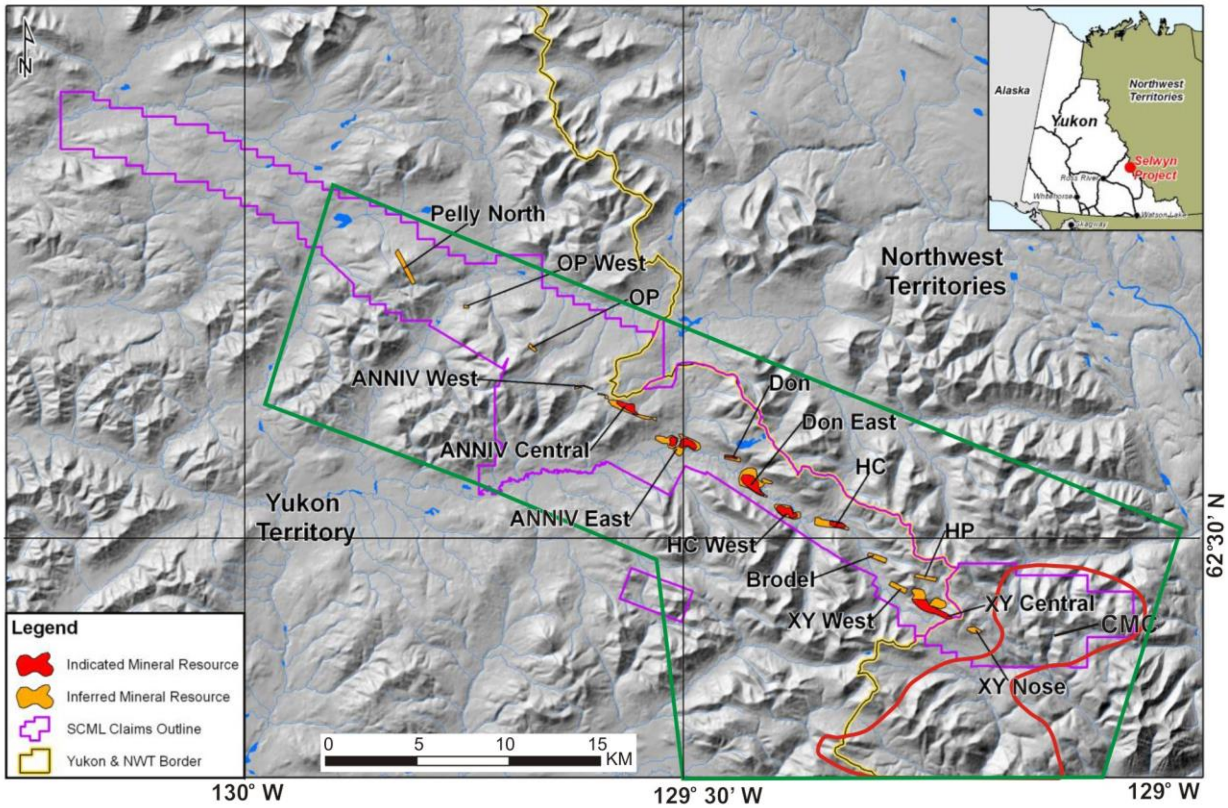


Figure 2. Map (shaded digital elevation model) showing location of the Howard's Pass district with deposit names, claims outline in purple, Howard's Pass district outlined in green (map of Hodder et al., 2014; Fig. 3), and map area of Figure 4 outlined in red. SCML: Selwyn Chihong Mining Ltd. Modified from Kirkham et al. (2012).

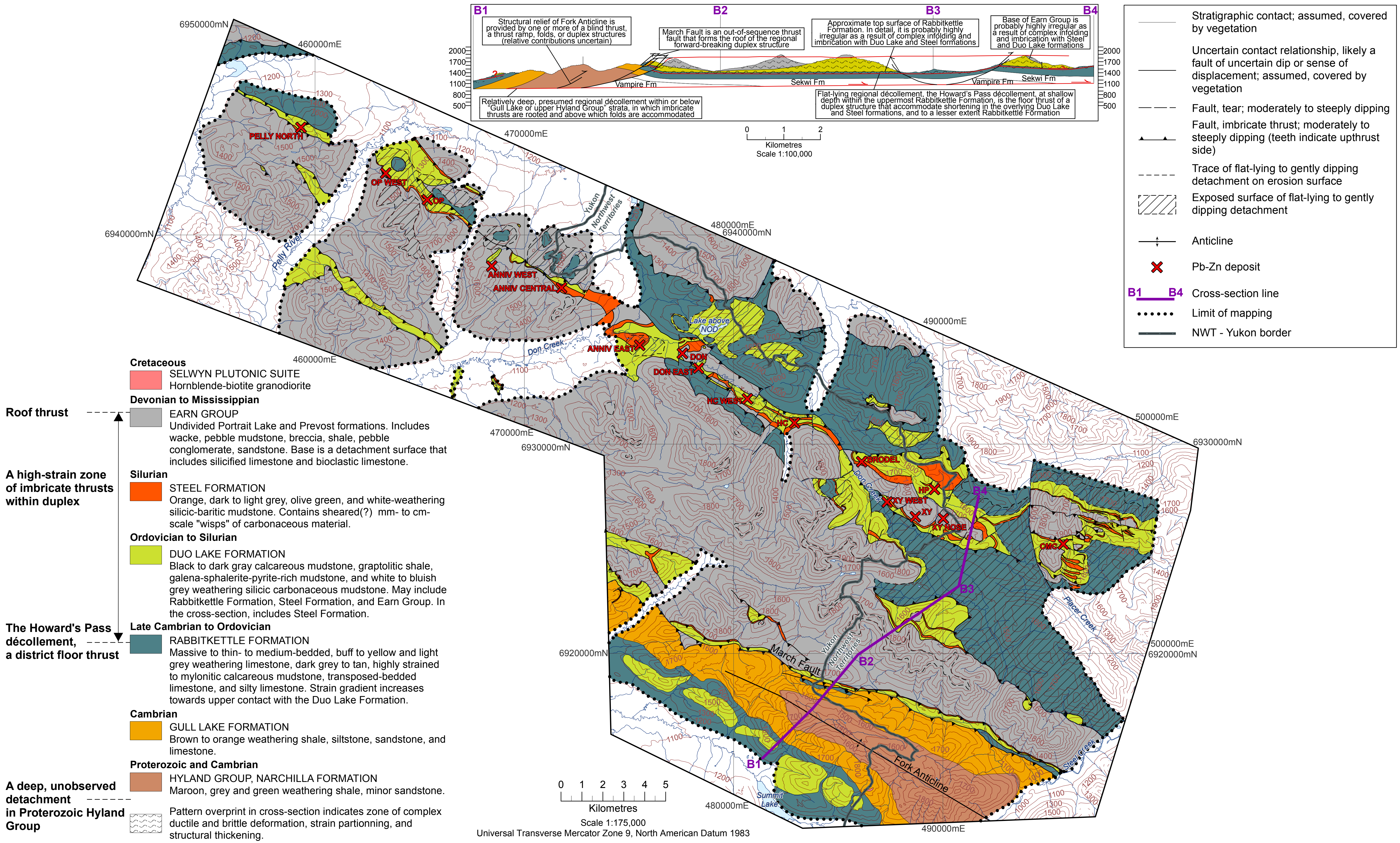


Figure 3. Simplified district-scale interpretative structural geology map and cross-section B1-B2-B3-B4. Adapted from Hodder et al., 2014.

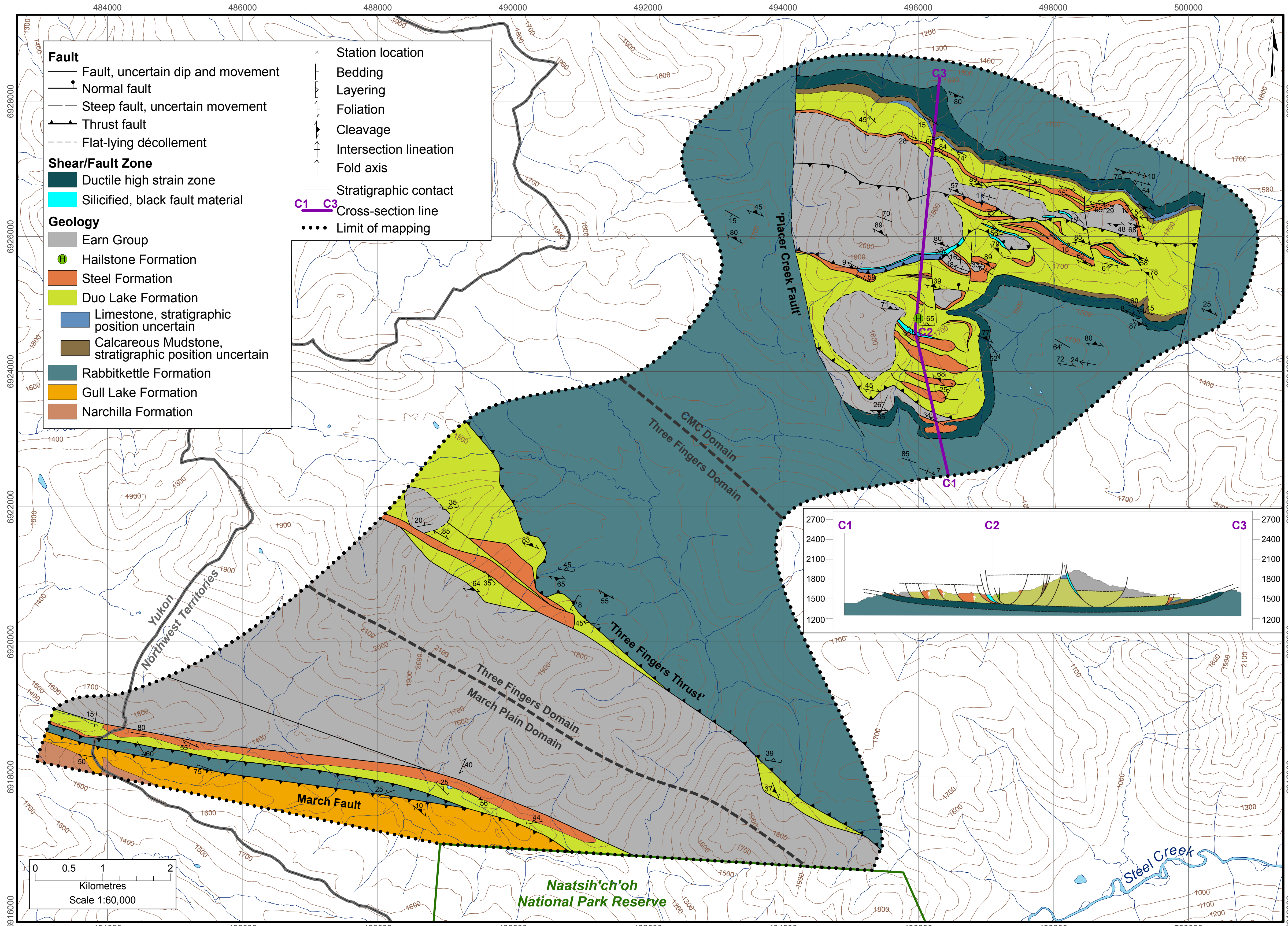


Figure 4. Simplified geology map of the study area which is subdivided into 3 domains; CMC domain, Three fingers domain and March plain domain. Only selected structural measurements are shown. Cross-section C1-C2-C3 of the CMC area is interpretative, as most contacts and faults have uncertain dip.

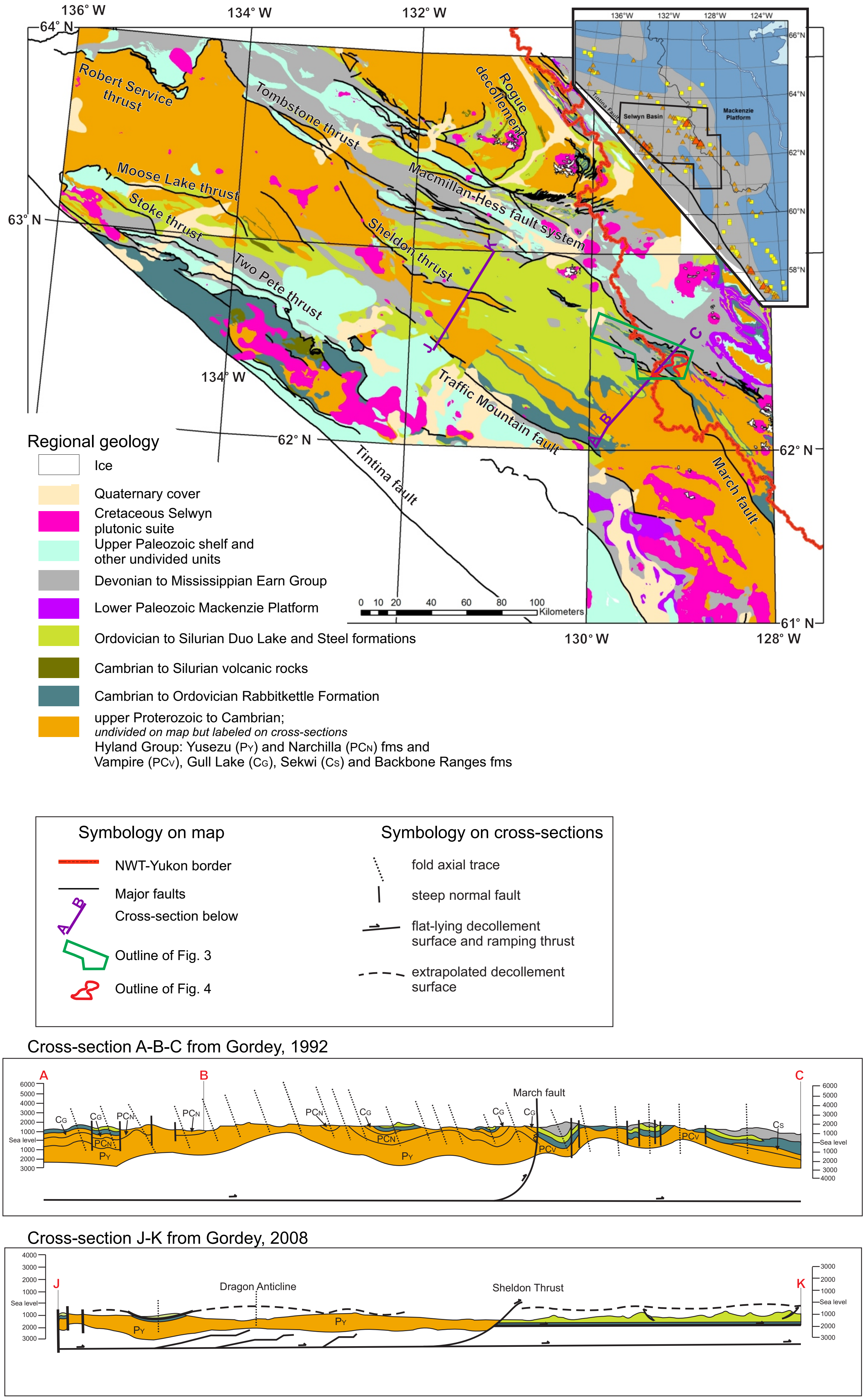


Figure 5. Simplified geology map of the east-central part of the Selwyn Basin showing major faults. Compiled and adapted from Abbott (1982), Gordey (1992), Gordey and Makepeace (2003), Cecile (2000) and Gordey (2008). The cross-sections show differing interpretations of structural style of deformation. Cross-section A-B-C of Gordey (1992) and cross-section J-K of Gordey (2008) are both adapted for this publication.

The rheological contrast between the shale-dominated strata of the Selwyn Basin and the carbonate-dominated competent strata of the Mackenzie Platform to the northeast led to differences in structural styles. In a Cordilleran framework, the Selwyn Basin strata form a strongly deformed and thrust-faulted package, referred to as the Selwyn fold and thrust belt (Gabrielse, 1991). The belt is located between the Mackenzie foreland fold and thrust belt to the east, and the accreted terrane and displaced elements of the ancient North American continental margin to the west. Ductile deformation and fabric development within the thrust imbricate sheets, chevron-type folds, and transposition fabrics of the Selwyn Basin contrast with the broad concentric folds and associated brittle thrust faults, and lack of internal deformation fabrics, of the Mackenzie fold and thrust belt (Gabrielse, 1991; Gordey and Anderson, 1993). The following summary follows Gordey and Anderson (1993), Mair et al. (2006) and Gordey (2008), and focuses on the stratigraphy preserved in the Howard's Pass district and deformation and metamorphism that affected the area.

Late Precambrian to Middle Devonian: Selwyn Basin strata

Extension in the late Proterozoic that resulted in the rifting of Laurentia persisted until the Devonian and led to the formation of the Selwyn Basin on the rifted margin. The Selwyn Basin was a depocenter for Neoproterozoic to Middle Devonian slope and basinal strata. Paleozoic deformation resulted from intermittent crustal extension and block faulting, rather than compressional deformation, and is recorded by thick clastic successions of the late Proterozoic Hyland Group (Yusezyu and Narchilla formations), Cambrian strata (Gull Lake and Rabbitkettle formations), Ordovician-Silurian strata (Duo Lake and Steel formations) and Devono-Mississippian strata (Hailstone Formation). The term Road River Group is not used in this paper since a common single usage has not been formally defined. In this report, the "Selwyn Basin strata" is used to refer to the Proterozoic to Middle Devonian succession described above. The Selwyn Basin strata are considered the offshelf facies of the Mackenzie Platform, deposited in relatively deeper water and generally consist of shale, siltstone, sandstone, limestone, chert and conglomerate.

The boundary between shelf facies of the shallow Mackenzie Platform and the offshelf facies of the deeper Selwyn Basin migrated through time across a northwest trending zone 50 km wide where stratigraphy representative of the two facies is interstratified (Gordey and Anderson, 1993; Cecile, 2000). It is noteworthy that the Howard's Pass district is paleogeographically very proximal to the basin-to-platform transition.

Middle Devonian to early Mississippian: Earn Group strata

In the Middle Devonian, the depositional setting changed abruptly from a relatively passive and quiescent one, to one influenced by tectonic activity. This shift is recorded as a regional marine transgression, modified by local, repeated uplift and subsidence during which detritus sourced from various locations to the west and north were deposited. This siliciclastic basin which consists of turbiditic marine shale, sandstone and conglomerate overlaps both the Selwyn Basin and the Mackenzie Platform.

In northern Yukon, compressional deformation produced folds, an angular unconformity, and uplift that resulted in a south-prograding clastic succession, and corresponds to the widespread Ellesmerian orogeny (Gordey, 1988). In south-central Yukon (which includes the Howard's Pass district), Devonian-Carboniferous tectonism was extensional and produced block faulting, local felsic volcanism and numerous barite-base metal SEDEX deposits. This extensional phase has been related to rifting and separation along the outer continental margin; the separated piece(s) forming the basement of terranes that eventually returned to collide with the margin in the Mesozoic (Tempelman-Kluit, 1979; Nelson et al. 2006). Just how the compression in the north and extension in the south were linked along the margin is unclear (Gordey et al., 2011a, and references therein).

In the Howard's Pass district, the associated strata are assigned to the Earn Group (Portrait Lake and Prevost formations). Definition of the Earn Group varies across Selwyn Basin, but current use of the term follows Gordey and Anderson (1993) where the Earn Group is divided into two mapable units separated by an unconformity: the Lower to Middle Devonian chert and shale Portrait Lake Formation, and the overlying Upper Devonian to Mississippian coarse siliciclastic Prevost Formation. The Earn Group strata are correlative with the marine siliciclastic units that transgressed to the east across the Mackenzie Platform which include the Misfortune, Thor Hills, Hare Indian, Canol and Imperial formations to the east (Gordey, 2008; Martel et al. 2011).

Mesozoic (Jura-Cretaceous) northern Cordilleran orogeny

All pre-Mesozoic events in the study area and surroundings are inferred to result from crustal extension. It is not until the Mesozoic (Jurassic, Cretaceous, and Paleocene) that a compressional regime prevailed. The Selwyn Basin and Earn Group strata were deformed by eastward migrating collision driven by accretion of exotic terranes (Mair et al. 2006 and references therein). The northern Cordilleran orogeny commenced in the Jurassic as exotic elements of the composite Yukon-Tanana terrane overrode the ancient continental margin (Staples et al., 2014 and references therein). The northeasterly-directed compression is believed to follow a thin-skinned detachment model (Mair et al., 2006 and references therein). The age of final deformation of Selwyn Basin strata is late early Cretaceous (100 Ma), based on folding of locally preserved late early Cretaceous strata (Gordey et al., 2011a) and cross-cutting of structures by mid-Cretaceous plutonic rocks (Gordey and Anderson, 1993). This commonly accepted interpretation has been partly challenged based on paleomagnetic data and tectonic reconstruction (Johnston 2001; 2008; Irwin and Wynne, 1991). These studies suggest that parts of the Selwyn Basin formed thousands of kilometres south relative to the autochthonous ancestral North America.

Structural style of Jura-Cretaceous deformation

According to Gordey and Anderson (1993), deformation during the northern Cordilleran orogeny produced the Selwyn fold and thrust belt with northwest plunging open to locally tight folds and associated axial planar slaty cleavage with a maximum amount of shortening estimated to be about 30%. Subsequently, Gordey (2008) suggests that deformation resulted in large, gently-dipping, northeast-verging thrust faults and buried detachments, whose hanging wall strata were mildly to severely imbricated and folded, with an estimated shortening of about 50%.

The major difference between these interpretations lies principally around the structural style created during thin-skinned Mesozoic collisional Cordilleran deformation. In the first interpretation, the deformation accommodated above a single regional detachment produced open folds with only a few thrusts present (Fig. 5; Gordey, 1992). In the latter interpretation, the collisional thin-skinned deformation created a series of flat-lying detachments and imbricated thrusts, where thrusting dominated over folding (Fig. 5; Gordey, 2008).

The currently accepted structural model of the Howard's Pass district, depicting a broad open fold, is primarily based on regional interpretation of Gordey and Anderson (1993), and is not constrained by drill core or structural property-scale mapping. Additionally, the open fold geometry is inconsistent with Gordey's (2008) interpretation of the structural style of deformation of rocks continuous with the western part of the Howard's Pass district (Fig. 5). According to Gordey (2008), the collisional thin-skinned Jura-Cretaceous deformation created a series of imbricated thrusts of incompetent Ordovician to Lower Devonian shale and chert that are complexly deformed and severely shortened above a flat-lying regional detachment (floor thrust) near the top of the Rabbitkettle Formation in the NTS map sheet immediately to the west of Howard's Pass (Fig. 5). The package of complexly deformed and structurally thickened (chevron folded, isoclinally folded and imbricated) Duo Lake and Steel formations is constrained upwards by a kinematically-related upper detachment (roof thrust) presumed to be at the base of the Earn Group. Together these kinematically-related structures form a regional scale duplex (Gordey, 2008). Between the floor and the roof thrusts, Gordey (2008) observed homoclinal successions of frequently alternating Duo Lake and Steel formations, which persist for up to 10 km across strike. It is difficult to determine if the structural repetition, internal to the regional duplex, results from thrust imbrication, isoclinal folding, or a combination of both, as there is poor exposure, lack of marker horizons, and absence of fold hinges and facing indicators (Gordey, 2008).

The extensive regional duplex structure is warped (Dragon anticline; Fig. 5; Gordey, 2008) and broken by subsequent thrusts (Sheldon thrust; Fig. 5; Gordey, 2008). These structures must have merged into a deeper buried detachment within or below the Proterozoic Hyland Group. Ultimately, all the above structures must root into a basal detachment that extends across the entire Cordilleran orogeny. Gordey (2008) concludes that the duplex, lower buried detachments and associated fabrics formed as a result of collisional compression during Jura-Cretaceous Cordilleran orogeny. As these conclusions apply to the map sheets surrounding the Howard's Pass area, it is not unrealistic to consider their applicability to the study area.

Late Cretaceous and Paleogene transcurrent and normal faulting

Jura-Cretaceous compressional deformation was followed by a late Cretaceous (post-85 Ma) dextral transcurrent regime, which laterally displaced elements of the newly assembled continental margin along the orogen-parallel Tintina fault (Fig. 1). Steep normal faults are documented in the Selwyn Basin strata but their timing is poorly constrained. In the western Selwyn Basin, Mair et al. (2006) recognized otherwise poorly documented sinistral movement on brittle faults that postdates the mid-Cretaceous period of magmatism. They suggest that some extensional deformation possibly occurred as a result of orogenic collapse prior to the more pervasive north-south oriented dextral movement induced by northward movement of the Kula Plate (Engebretson et al., 1985).

Metamorphism

In the Howard's Pass district, regional metamorphic grade is sub-greenschist facies, but metamorphic temperatures and pressures have been poorly documented. Temperatures of 300-325 °C are estimated based on the Conodont Alteration Index CAI of conodonts and graptolites (Gordey, 2008; this study) and >200 °C based on breakdown of organic matter (Macqueen and Barker, 1981). Maximum pressure based on depth of burial (maximum overlying stratigraphy) is estimated to be less than 2.8 kb, or less than 3.2 kb if we account for probable overthrusting during early Cretaceous deformation (Gordey and Anderson, 1993). Regionally, the metamorphism is interpreted to be associated with syn- to post-deformation heat flow related to the regional Jura-Cretaceous orogeny and, locally, to the Cretaceous intrusions (Gordey and Anderson, 1993; Gordey, 2008). Kawasaki and Symons (2012) inferred that peak metamorphism occurred during the Middle Jurassic (170 +/- 20 Ma) based on paleomagnetic age determination. Alternatively, Goodfellow and Jonasson (1986) inferred that the Paleozoic sedimentary rocks of the Selwyn Basin were subjected to lower greenschist metamorphism during extensional events contemporaneous with the Antler orogeny and the Ellesmerian orogeny (Middle Devonian to Mississippian).

GEOLOGY OF THE HOWARD'S PASS PB-ZN DISTRICT

Established model for evolution of the district

The Howard's Pass Pb-Zn district is viewed as a classic example of a SEDEX deposit formed in a euxinic basin (Goodfellow and Lydon, 2007). The host rock is Silurian-aged black shale of the Howard's Pass formation. The ore consists of sphalerite, galena, and pyrite. The current model proposes that mineralization is stratiform, and deformation is syndepositional with further deformation a result of local compression speculated to have occurred just after deposition of the sediments, while they were still water-saturated. Subsequent deformation led to the development of a broad syncline during Jura-Cretaceous northeast-directed collisional Cordilleran orogeny, but did not significantly affect the distribution of the metals (Jonasson and Goodfellow, 1986).

It is relevant to point out that the SEDEX model was developed for stratiform, pyritic bodies in siliciclastic rocks of intracontinental fault-controlled basins. However, Howard's Pass is stratabound, not particularly pyritic, and located within calcareous mudstone of a Phanerozoic marginal basin that does not appear to be fault-controlled (Hodder and Bain; 2005-2012, unpublished internal reports, Selwyn Resources Ltd.).

Below, we provide a review of the stratigraphy of the area (Fig. 6). We reinterpret the timing and role of deformation in the formation and subsequent modification of the deposit.

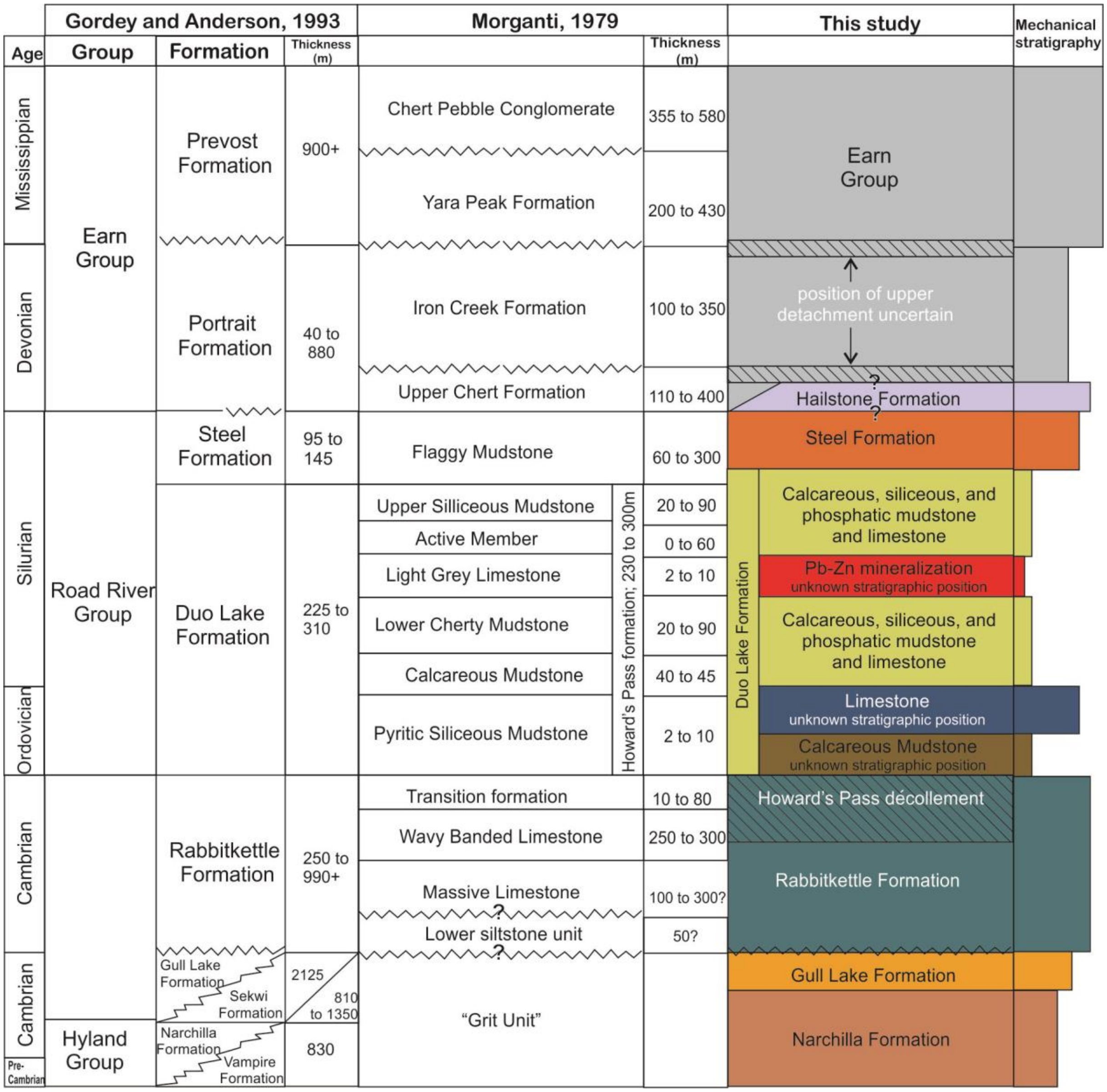


Figure 6. Table of stratigraphic nomenclature utilized at the regional scale (Gordey, 2008), at the district scale (Morganti, 1979), and in this study. No biostratigraphic data was collected in the Duo Lake Formation in this study and therefore the stratigraphic position of distinctive units of the Duo Lake Formation is uncertain. Color-coding of nomenclature used in this study refers to legend of Figure 3. The column on the right is a mechanical stratigraphy section and the width of the column represents the estimated relative competency of the units based on field observations.

Stratigraphy

The stratigraphy of the Howard's Pass district has been documented in detail by Morganti (1979) based on 1:30,000 scale mapping and drill core logging. He assigned informal names of formation and member rank (Fig. 6), and this terminology is used for exploration purposes. The nomenclature used in this report and on our geological map (Fig. 4) is shown in Figure 6 and follows Gordey and Anderson (1993).

Rabbitkettle Formation

Regionally, the Rabbitkettle Formation (Gabrielse et al., 1973) varies in thickness, facies, and textures based on its paleogeographic location. In the vicinity of the Howard's Pass district, Gordey and Anderson (1993) described the unit as mainly fine-crystalline, nodular limestone and massive to thinly-bedded, argillaceous to silty limestone. Sandy dolostone, quartz sandstone, intraformational limestone conglomerate, and green volcanic tuff have been documented locally. Most of the conodont age dating of Rabbitkettle Formation in the vicinity of the Howard's Pass district returned Middle Ordovician ages, which is younger than elsewhere in the Selwyn Basin (Gordey and Anderson, 1993). Thickness variation is extreme, from 250 to over 1000 m. The base of the formation rests unconformably above various older units (Vampire, Gull Lake and Narchilla formations).

At the district scale, Morganti (1979) subdivided the "Cambrian Limestone", now known as the Rabbitkettle Formation, into four informal formations (Lower Siltstone unit, Massive Limestone Formation, Wavy Banded formation and Transition formation; Fig. 6). Of particular interest, the Transition formation is described as a thinly laminated calcareous mudstone and intercalated limestone in gradational contact with the Wavy Banded limestone below, and Howard's Pass formation above (Fig. 6). Pride (1973) refers to a finely laminate dolomitic siltstone, and puts it at the base of the "Ordovician-Silurian shale package". The nature of the "Transition zone" is a key element in elucidating the structural style of Howard's Pass district. Our observations and insights, which suggest a tectonic character for the "Transition zone", are described below (see "Nature of contacts between formations").

Duo Lake Formation

Regionally, the Duo Lake Formation was first described by (Cecile, 1982) and comprises recessive black siliceous graptolitic shale and chert with minor limestone (Gordey and Anderson, 1993). The maximum thickness in the region of this poorly exposed unit is estimated to be about 300 m. However, the lithofacie variations and thickness estimates are poorly constrained as they are occasionally based on observation of rock chips from scree in ground squirrel holes (e.g. section 9 of Gordey and Anderson, 1993). The unit's age ranges from early Ordovician to late Silurian regionally (Gordey and Anderson, 1993), but in the Howard's Pass district only early to mid-Silurian ages have been documented (Norford and Orchard, 1985).

Morganti (1979) adopted the name "Howard's Pass formation" to represent the sequence of mudstone, chert and limestone, 230 to 300 m thick, present in the Howard's Pass district, which Gordey and Anderson (1983) included as part of their regionally extensive Duo Lake Formation. Morganti (1979) noted an atypically large amount of thickening in the base of the Howard's Pass formation, which he tentatively explained by a poorly documented platform-marginal tectonic setting inferred for the deposition of the sediments compared to a more typical intracontinental setting. Alternatively, the thickening could be caused by the presence a fault-bounded trough, although no evidence for a fault-bounded sub-basin has been found (Morganti, 1979).

Morganti (1979) describes the Howard's Pass formation as moderately homogeneous, consisting mostly of carbonaceous and siliceous mudstones. He subdivided the formation into six members (Pyritic and Siliceous Mudstone, Calcareous Mudstone, Lower Cherty Mudstone, Light Grey Limestone, Active, and Upper Siliceous Mudstone; Fig. 6). The presence of concretions and quartz and/or calcite veins (referred to as pseudo-bedding by Morganti, 1979) is documented throughout most of the Howard's Pass formation. The formation contains units that are laminated, thinly bedded or massive, and commonly shows evidence of folding and faulting. The Active Member is distinctive as it is a heterogeneous unit and contains all the Pb-Zn concentrations in the district – some mudstone contain up to 50% Zn+Pb (Morganti, 1979). The Active Member is described in more details below (see Morganti (1979) for full description of other members of the Howard's Pass formation).

Active Member

The Active Member is described as a heterogeneous unit of carbonaceous mudstone, cherty mudstone, chert and limestone which hosts the Pb-Zn mineralization (Morganti, 1979). It is rarely exposed and, in drill core, shows considerable variations in thickness, ranging from zero to greater than 60 m. As summarized in Kirkham et al. (2012), the Active Member comprises nine subunits consisting of heterogeneous intercalation and repetition (cycles) of one or more of the following: light grey limestone facies, graded limestone facies, dark grey to medium grey calcareous mudstone facies, thin-bedded calcareous mudstone facies, cherty mudstone facies, rhythmite facies, thin-bedded cherty mudstone facies, whitish grey zinc-lead mudstone (sulphidite) facies, and grey chert facies. Within some subunits there are thin framboidal pyrite beds, soft sediment deformation features, and sphalerite and galena grains. The sulphide minerals are either conformable with bedding and sedimentary textures or found along cleavage planes.

Steel Formation

The Howard's Pass formation is overlain by the orange-weathering Flaggy Mudstone formation (Fig. 6), correlative to the regionally documented Steel Formation (Gordey and Anderson, 1993). This unit consists of orange, grey, green and white-weathering silicic mudstone, which commonly contains wispy laminations thought to be caused by disruption of bedding by burrowing organisms (Gordey and Anderson, 1993). The estimated maximum thickness present at the regional scale is about 150 m. At the district scale a range of 60 to 300 m in thickness is documented (Morganti, 1979). The age of this unit is mid- to late-Silurian and a single collection of graptolites in the Steel Formation returned an early late Silurian (Ludlow) age (Gordey and Anderson, 1993).

Earn Group

Rocks assigned by Morganti (1979) to the Backside Siliceous Mudstone, Iron Creek formation, Yara Peak formation and Chert Pebble Conglomerate correspond to the regionally defined Earn Group first proposed by Campbell (1997). The Earn Group strata consist of turbiditic siliciclastic rocks that conformably to unconformably overlie the Steel Formation (Gordey and Anderson, 1993; Gordey and Roots, 2011). The lower and upper Earn Group strata (Portrait Lake and Prevost formations, respectively) are separated by an unconformity. At the district scale limestone, carbonaceous shale, siltstone, sandstone, chert and conglomerate are included in the Earn Group (Fig. 6). The unit's thickness varies considerably, from less than 1000 m to over 2000 m, and total thickness is unknown as the base and top of the Prevost Formation are not exposed at a single locality. The Earn Group is Lower Devonian to early Lower Mississippian (Gordey and Anderson, 1993 and references therein). In the Howard's Pass district, Norford and Orchard (1985) interpret the age of the Earn Group, based on conodonts collection, to range from Upper Silurian to Middle Mississippian.

Deformation history

The deformation history of the Howard's Pass deposits has been documented by Morganti (1979), Goodfellow et al. (1983), Jonasson and Goodfellow (1986), Goodfellow and Jonasson, (1986) and is summarized in Goodfellow and Lydon (2007). McClay (1991) provides an alternative interpretation. Gordey and Anderson (1993) provide a regional-scale deformation history based on 1:250,000 bedrock mapping of map sheet 105I (Gordey, 1992), which contains the Howard's Pass deposits. Gordey (2008) provides a revised deformation history, based on 1:250,000 bedrock mapping (105J and K) which includes the western continuation of the shale succession that hosts Pb-Zn mineralization in the Howard's Pass district (Fig. 5).

Timing of deformation

The presence of deformation and associated fabrics has been acknowledged in the literature, but the timing of fabric development is debated. Some authors attribute most structures and fabrics to syndepositional Ordovician-Silurian extensional deformation rapidly followed by local mid-Silurian compressional deformation during diagenesis, while others consider them to form mainly during the Jura-Cretaceous compression of the Cordilleran orogeny. Below we describe the two models, and argue in favour of a Jura-Cretaceous deformation.

Syndepositional and lithification deformation model: Silurian deformation and associated fabrics

Morganti (1979), Goodfellow et al. (1983), Jonasson and Goodfellow (1986), Goodfellow and Jonasson (1986) and as summarized in Goodfellow and Lydon (2007), favour a model where the bulk of the fabrics were formed synchronous with deposition during extension and/or during diagenesis during local compression. In these papers, the main deformation of host sediments (Howard's Pass formation) is speculated to have occurred during a period of compressional tectonism, which produced buckle folding soon after mid-Silurian deposition of mud and metals, and burial of the deposit. The deposit is believed to have been water-saturated at the onset of deformation. The stratigraphy which hosts the mineralization is interpreted to now be folded into a broad syncline based on regional mapping by Gordey and Anderson (1993). Disharmonic folds, truncation of beds, boudinage, quartz calcite dilation veins, distortion of graptolite fossils, stylolites, crenulation cleavage, pressure shadows, pressure solution cleavage, isoclinal folding, shearing along spaced cleavage, ptygamatic folding of earlier veins, transposition, rod-shaped boudins, and bedding plane detachment are all elements believed to have formed during compressional Silurian deformation of these water-saturated sediments. High interstitial water content is considered mandatory to account for the extent and intensity of deformation. Because buckle folding is observed in Llandovery to Wenlock age upper Duo Lake Formation but is uncommon in the overlying Ludlow age Steel Formation, Jonasson and Goodfellow (1986) concluded that deformation ended prior to the deposition of the Steel Formation (in Wenlock time). Jonasson and Goodfellow (1986) infer that the horizontal compression responsible for the early deformation of the deposit was caused by a brief period of uplift during the otherwise subsiding basin. This speculative compressional event has not been documented elsewhere in the Selwyn Basin. In this model, later Devono-Mississippian and late Cretaceous deformation produced further folding, faulting, low grade metamorphism and minor remobilization of pyrite along slaty cleavage, but did not significantly affect sulphide textures and distribution.

The veracity of the model assembled by Jonasson and Goodfellow (1986) where a localized compressional event occurred in mid- to late-Silurian has been questioned by McClay (1991) and is re-examined in this study.

Post-lithification deformation model: Jura-Cretaceous deformation and associated fabrics

McClay (1991) provides an alternative interpretation on timing and cause of deformation. His work on deformation of stratiform Pb-Zn deposits in the northern Canadian Cordillera focused on the Tom, Howard's Pass, Cirque, and Driftpile Creek deposits (Fig. 1). He proposes that relicts of primary depositional/diagenetic structures are preserved in the orebodies (commonly in pyrite and very rarely in the galena and sphalerite). However, the pressure solution cleavage, presence of multiple cleavages, bedding transposition along shear fabrics and associated remobilization and concentration of the ore minerals, and cataclasite and brecciation, are all results of Jura-Cretaceous (late Jurassic to mid-Cretaceous) regional deformation and low grade metamorphism produced by collisional Cordilleran orogeny. McClay (1991), in his Figure 13, shows that the pressure solution cleavage and transposition of earlier fabrics can develop even though stress levels required for deformation are extremely low. McClay (1991) argues that fine grained sulphides, especially pyrite and galena, will act ductilely under low grade metamorphism and be easily affected by pressure solution. He concludes that the most significant deformation mechanism of the mineralization in his study is that of pressure solution of silicates, carbonates, barite and fine-grained pyrite, in contrast to the relative insolubility of sphalerite and carbonaceous material under these conditions. The most intense cases of pressure solution can result in complete transposition of primary structures and concentration of sphalerite and carbonaceous material in the solution seams. According to McClay (1991), these seams have been previously mistakenly interpreted as primary bedding. In deposits studied by McClay (1991) low grade regional metamorphism and penetrative deformation have overprinted, transposed and in some cases obliterated many of the primary depositional and diagenetic features.

Although the Howard's Pass deposits are interpreted to be folded into an open syncline, no detailed systematic property-scale structural mapping has been carried out to support this interpretation (McClay, 1991). This study, in combination with the extensive field work conducted by Hodder and Bain (2005-2012, unpublished internal reports, Selwyn Resources

Ltd.) are the first attempts to remedy that dearth and elucidate the structural history of the Howard's Pass district.

Mineralization

Since 2005, Selwyn Resources Ltd. and Selwyn Chihong Mining Ltd invested over 250 million dollars in the Howard's Pass Pb-Zn district. Geological resources (drill indicated and inferred), as of September 2012, are summarized in Table 1 and the locations are shown in Figure 2.

Table 1. Total indicated and inferred resources for the Howard's Pass deposits, as of September 2012. Blbs: billion pounds. GG: gigagrams. Sourced from NI43-101 compliant report by Kirkham et al. (2012).

Resource Class	Tonnes	Zn (%)	Pb (%)	Zn (Blbs/GG)	Pb (Blbs/GG)
Indicated	185,573,200	5.2	1.79	21.26/9643	7.31/3311
Inferred	237,856,900	4.47	1.38	23.44/10618	7.21/3266

Ore body

According to Morganti (1979) the Zn-Pb ore forms complex saucer shaped bodies containing laminated to massive sulphides, which include very fine grained stratiform sphalerite, galena and pyrite. Morganti sub-divided the mineralization into six textural types:

1. laminated sulphide-rich carbonaceous mudstone;
2. type 1 with abundant open to closed fold hinges where galena is concentrated in fractured fold hinges;
3. laminated sulphides with intense folds. Massive sulphides located in flow folds are not associated with laminae;
4. a: laminated sphalerite and galena in siliceous laminated mudstone, and
   b: massive sphalerite and galena in dewatering structures and later cleavage that is cross-cutting laminations;
5. massive sphalerite, galena and pyrite, and
6. isolated sphalerite and/or galena spatially associated with pyrite concretions, micro fault planes or stylolite seams.

In the literature, descriptions of mineralization at Howard's Pass are frequently generalized as stratiform, fine grained and concordant with lamellas. However, as detailed by Morganti (1979) and others, a significant amount of sphalerite and galena grains are coarse and are located in structures discordant with bedding (McClay, 1991; Cleland, 2008). The coarse sulphides are described as filling diagenetic structures such as water escape, faults, stylolites, fractures, concretions and fold hinges, or a later tectonic cleavage (Morganti, 1979; Jonasson and Goodfellow, 1986; McClay, 1991; Cleland, 2008; this study). Sphalerite and pyrite are also found replacing and infilling spherical microfossils and fragments of sponge spicules (Jonasson and Goodfellow, 1986).

Metallogenesis

The Howard's Pass deposits are interpreted as SEDEX deposits. In idealized SEDEX deposits the exhalative fluids are channelled by syn-sedimentary faults and precipitate on the sea floor. The Howard's Pass deposits are interpreted to have formed at relatively low temperature (<220°C) from metalliferous brines discharged at the seafloor. Sulphur is thought to be derived from the water column (Goodfellow, 1987). Deposits are usually hosted in fine-grained siliciclastic rocks in linear second- or third-order euxinic sediment-starved anoxic deep water basins (Morganti, 1979).

The syndepositional tectonic model for SEDEX deposits of the Selwyn Basin (including Faro, Howard's Pass and Tom/Jason) invokes three episodes (Cambrian, Silurian and Devonian) of stratiform mineralization (vent distal or vent proximal) that result from three distinct hydrothermal venting events located along extensional faults that bound third-order basins and restricted basins. At Howard's Pass though, unlike other deposits, no vent complex, feeder zone, or extensional Silurian growth fault (basin-bounding structures) have been identified. According to Goodfellow and Jonasson (1986) minor slump folds and pronounced thickening of mineralized and overlying units are the only evidence for assuming the presence of an unrecognized growth fault and associated subsidence at the Howard's Pass (XY) deposit (Fig. 2).

Recent research on various Pb-Zn and Barite deposits of the Selwyn Basin (Cousens, 2006; Hodder and Bain, 2005-2012, unpublished internal reports, Selwyn Resources Ltd.; Leach et al., 2005; 2010; Paradis et al., 2013; Gadd et al., 2013; Gleeson et al., 2013; Johnston et al., 2014), and other clastic-hosted Pb-Zn deposits worldwide (De Vera et al., 2004; Slack et al., 2004a,b), provides new data to interpret the genesis of these deposits. Some of these authors suggest a model where some shale-hosted Zn-Pb deposits would be best described as clastic-dominated shale-hosted Pb-Zn mineralization with perhaps less syngenetic mineralization and more diagenetic and epigenetic components, where the bulk of the metals were not deposited by sedimentary exhalation of metals into the seafloor of a deep restricted anoxic/euxinic basin. In one model, it is suggested that the tectonic setting would be in an environment where the presence of upwelling centres along a basin margin leads to the deposition of biogenic precipitants forming calcareous, carbon-rich sediments. At Red Dog (Alaska) for instance, the mudstone that hosts Zn-Pb mineralization was deposited in an oxygenated environment, off the slope from the carbonate platform (Slack et al., 2004). The abundance of biogenic silica, organic matter, carbonate and phosphate in some of these host rocks reflects great biogenic productivity in a coastal upwelling of nutrients to the surface waters, of which there are both ancient and modern examples. An organic carbon-rich, iron-poor, phosphatic mudstone would have acted as the reducing agent for deposition of sulphides, during diagenetic sub-seafloor hydrothermal replacement of carbon with mineralizing fluids travelling up faults to precipitate along favourable lamination by replacement at depth (Leach et al., 2005, 2010; Hodder and Bain, 2005-2012, unpublished internal reports, Selwyn Resources Ltd.).

Recent preliminary studies on deposits of the Selwyn Basin (i.e. Tom, Nidd, Jason, Howard's Pass) suggest there is little evidence for exhalation; and the bulk of the Pb-Zn sulphide minerals precipitated below the seafloor (Gadd et al., 2013; Gleeson et al., 2013; Hodder and Bain, 2005-2012, unpublished internal reports, Selwyn Resources Ltd.). Others suggest that, based on paleoenvironmental proxies such as Fe speciation, S isotopes, and Fe/Al and Mo/TOC ratios, some proxies indicate that exhalation in anoxic conditions of extreme basin restriction occurred (Johnston, 2014). The contrasting results of these new studies highlight the need to re-examine certain aspects of the currently accepted model for the district, as well as for other 'SEDEX' deposits in the Selwyn Basin.

Timing of mineralization

Although Morganti (1979) sub-divided the mineralization into six textural types, two broad types are present; fine-grained sulphides in lamination concordant with bedding and fine-to-coarse-grained sulphides in structures discordant with bedding. An attempt at directly dating the concordant mineralization was made by Kelley et al. (2011). They have measured the Re and Os isotope abundances in pyrite from two drill holes in the DON and XY Central deposits (Fig. 2). From these analyses they calculated an isochron age of 442+/- 14 Ma, early Silurian, comparable to the age of graptolite and conodont fossils identified at Howard's Pass (Norford and Orchard, 1985).

The discordant, coarse sphalerite and galena documented by Morganti (1979) in fractures, dewatering structures, flow-fold hinges, pyrite concretions, micro fault planes or stylolite seams, and by Cleland (2008) in cleavages planes, differ from the fine-grained sphalerite and galena spatially associated with lamellae. Whether the later discordant mineralization is: (1) syngenetic ore partly remobilized during diagenesis and concurrent dewatering of the host rock; (2) syngenetic and/or diagenetic ore remobilized during Cordilleran fold and thrust belt formation and associated metamorphism; or (3) truly epigenetic mineralization introduced by metamorphically-derived fluids is debated. Jonasson and Goodfellow (1986) favour model (1) where coarse sphalerite and galena are spatially associated with the discordant fabrics formed during diagenesis in the early Silurian. On the other hand, Cleland (2008) demonstrates at least partial remobilization and recrystallization of laminated sphalerite-galena mineralization into discordant structures occurred, and favours model (2), concluding that cleavage-related "veins and shears" occurred by hydrothermal fluid circulation produced by regional Jura-Cretaceous deformation. Kawasaki and Symons (2012) interpret the results of paleomagnetism to indicate that the coarse-grained Pb-Zn mineralization in fine fractures that cut the laminated mineralization was formed by remobilization during metamorphism as in model (2). They conclude that the minimum age for metamorphism is Middle Jurassic. According to Gadd et al. (2013), petrography, EPMA and LA-ICP-MS data reveal textural controls on trace element distributions and contents in morphologically variable pyrites, and suggest that model (1), (2) and (3) are likely all components of the mineralization at Howard's Pass.

OBSERVATIONS AND INTERPRETATIONS: STRUCTURAL GEOLOGY OF THE FIELD AREA

Our observations are based on structural mapping of bedrock exposures, and examination of talus slope, and frost heaved blocks and chips around CMC, Three Fingers and March plain domains on the Northwest Territories side of the district (Fig. 4). We also have visited some key locations in the Yukon Territory, and looked at a limited number of drill cores and samples collected from the "ore pile", which is a collection of broken ore-bearing rocks from various deposits amassed near the XY Central deposit (Fig. 2).

Fabrics and structures

A description of tectonic fabrics observed in each formation is provided below. Several types of ductile and brittle fabrics were observed in the field. Primary and diagenetic structures are observed but are generally obliterated as a result of recrystallization, shearing, transposition and dissolution. A detailed characterization of the fabrics and how strain was partitioned in the field area has not yet been completed.

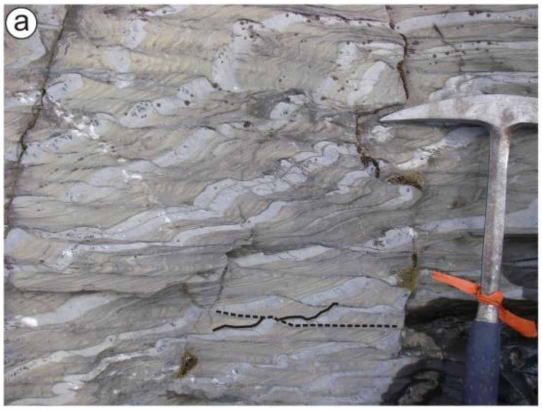
Rabbitkettle Formation

The Rabbitkettle Formation mm-, cm-, and m-scale bedding ranges from undeformed, to folded, cleaved, foliated, or partially to completely transposed along a planar fabric (Fig. 7). This planar fabric is a dissolution cleavage (pressure solution) defined by mm-scale black seams of insoluble material (Fig. 7a). In limestone of the Rabbitkettle Formation, these seams are oriented either parallel or oblique to bedding, and are axial planar to folds. Bedding is commonly partly (Fig. 6a) to completely (Fig. 7b) transposed along these seams. Several overprinting fabrics can be present (Fig. 7c) but their relationships are difficult to assess because of the lack of exposures in place. Most exposures are large boulders as shown in Figure 7g. S-C fabrics and C' shear bands are commonly observed (Fig. 7d). An intense stretching lineation is marked by cigar- or rod-shaped stretched limestone beds (Fig. 7e). Kink bands, chevron-type folds (Fig. 7f) and concentric folds (Fig. 7g) are locally observed. The fabrics in the Rabbitkettle Formation change in intensity and style depending on proximity to the contact with the overlying Duo Lake Formation. The strain gradient variation will be discussed in section "Nature of contacts between formations" below. The wavy appearance, resulting from the presence of S-C fabrics and C' shear bands, has been interpreted by previous workers as primary. Likewise, the cigar- or rod-shaped stretched limestone beds have been previously interpreted as primary nodules or nodular bedding, but are interpreted here as a result of transposition (dismembered beds by pressure solution cleavage).

Duo Lake Formation

Outcrop observations

Most outcrops of the Duo Lake Formation shale show two planar fabrics with an intersection lineation (Fig. 8a). It is not a slate in which you can see a fabric that intersects bedding. The intersection is of two tectonic fabrics. Pencil shaped partings are commonly observed. The presence of two intersecting fabrics is one feature that is used to distinguish Duo



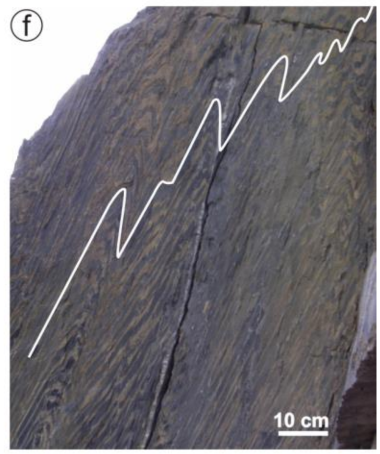


Figure 7. Photos of fabrics observed in the Rabbitkettle Formation. Photo captions are on the following page.

Figure 7. Photos of fabrics observed in the Rabbitkettle Formation. (a) Light grey limestone and yellowish-brown silty limestone beds (solid black line) displaced along black pressure solution seams (dashed black line). (b) Bedding transposed into near parallelism with shear fabric. Note presence of kink bands. (c) Outcrop of limestone showing at least three planar fabrics (marked by three pencils). (d) Thin yellowish-brown silty limestone beds wrapping around light grey limestone "lenses". The wavy appearance is caused by dragging along shear bands and is not primary in origin. (e) Elongated and flattened light grey limestone "lenses" represent rod shaped limestone beds dismembered along a shear fabric (f) Chevron-type folds of transposed limestone beds (white line) that were subsequently buckled. (g) Typical exposures of Rabbitkettle Formation at Howard's Pass. Blocks of folded limestone beds with a strong axial planar cleavage.

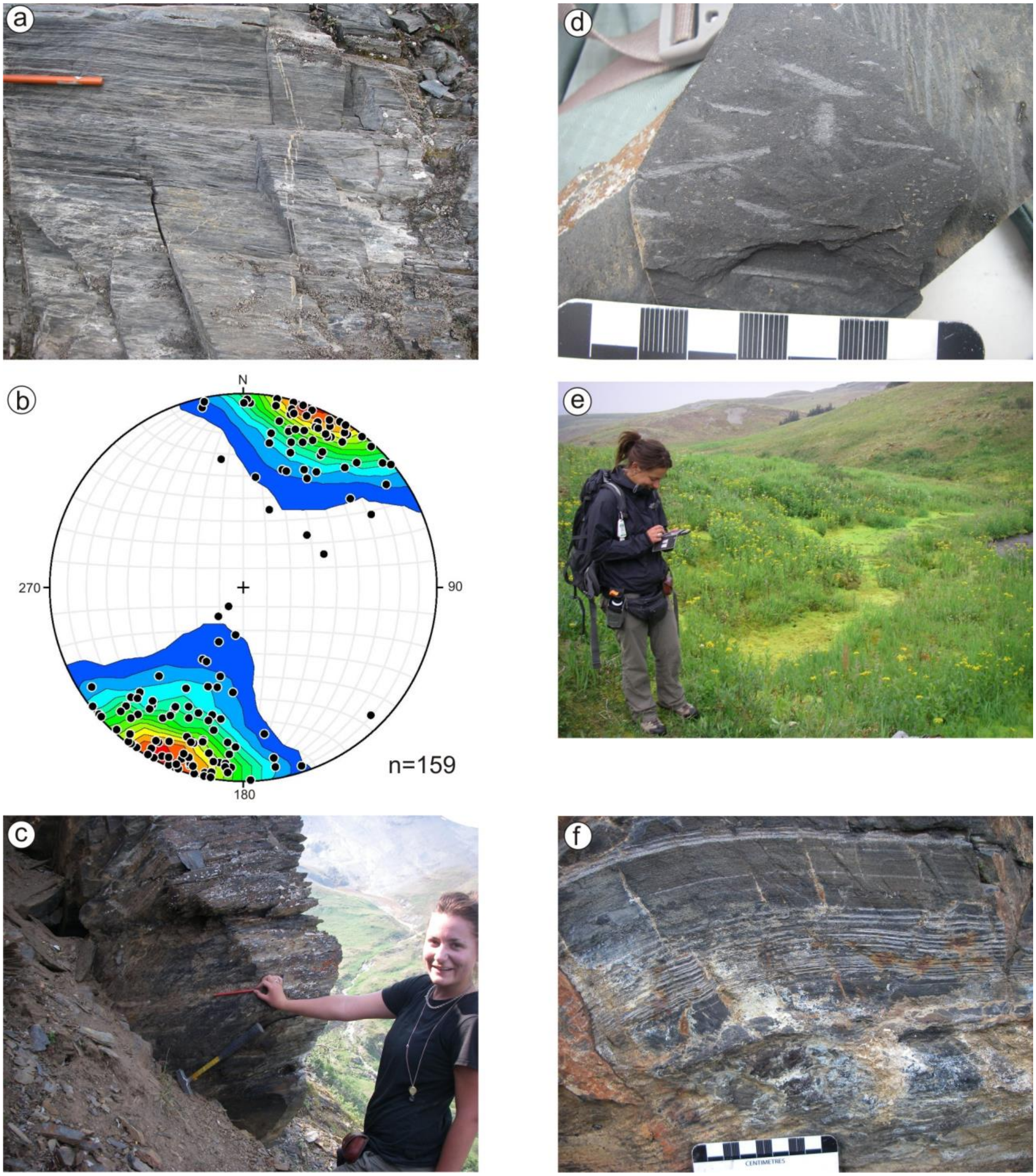


Figure 8. Photos of fabrics observed in outcrops of Duo Lake Formation. (a) Sub-horizontal intersection lineation of two cleavages. (b) Outcrop showing sub-horizontal colour banding overprinted by a moderately dipping cleavage. (c) Graptolite imprints preserved along slaty cleavage plane. (d) Outcrop of light grey and dark grey layering of the Active member at Anniv deposit. See Figure 3 for location. (e) Bright green moss informally referred to as "zinc moss" found in vegetated areas thought to overgrow nearby mineralized strata.

Lake Formation from the Earn Group slate (see Figure 10d below). One fabric is a penetrative slaty cleavage, that strikes 300°, dips steeply to the north (Fig. 8b), and has been informally termed the "regional cleavage" (Hodder and Bain, 2005-2012, unpublished internal reports, Selwyn Resources Ltd.). The other fabric is a spaced dissolution cleavage (pressure solution) defined by mm-scale black seams of insoluble material, which is rarely observed in outcrop but is evident in core and cut hand samples. The spaced pressure solution cleavage has been previously interpreted as dewatering (water escape) structures that formed during diagenesis (Morganti, 1979; Goodfellow and Jonasson, 1986). Bedding is often hard to identify since it is overprinted by two fabrics. When the slaty cleavage is oriented sub-parallel to mm-spaced pressure solution cleavage, which is defined by black dissolution seams in black shale, it is impossible to distinguish them. Colour or compositional banding is commonly observed but whether it represents primary bedding, a tectonic banding or is a result of alteration is uncertain (Fig. 8c). Outcrop-scale folds are locally present in what looks like decimetre-thick bands of chert or silicified mudstones. Graptolites have been identified on the steep "regional cleavage" plane (Fig. 8d), which implies that the cleavage must have developed parallel to bedding. Therefore, bedding was, at least locally, re-oriented from horizontal to steeply dipping prior to the formation of the "regional cleavage". The mineralized unit (Active Member) is not exposed in the map area, but zinc moss is observed in some areas (Fig. 8e), commonly in old trenches. The Active Member is rarely exposed in the district, but outcrops at the Anniv deposit (Figs. 2 and 8f). Fabrics from the mineralized unit are best recognized in samples from drill core and from the ore pile.

Drill core and ore pile

Some key features were observed in drill core and samples collected from the ore pile located near the XY camp, just south of XY nose (Fig. 2). The pressure solution cleavage is defined by seams of insoluble material like carbon (Fig. 9a), galena (Fig. 9b) and sphalerite (Fig. 9c; Cleland, 2008). Similar-type folds of beds and bedding-parallel veins with an axial planar fabric are common (Fig. 9a). Quartz-calcite veins are folded, and show feather structures on the inside of folds, indicating folding occurred after quartz and calcite grained were crystalized (Fig. 9d). Chaotic sheath folds are observed (Fig. 9e). Sheath folds are interpreted to form during progressive shearing (Cobbold and Quinquis, 1980). Fold limbs are commonly sheared out, (or possibly dissolved during pressure dissolution and associated volume loss) leaving fold noses of more competent lithologies, some of which may have been misinterpreted as primary nodules or concretions. Pressure shadows are present around pyrite grains and are filled with quartz-carbonate (Fig. 9a). Kink bands are observed in outcrops but much more readily seen in drill core (Fig. 9f). The kink bands and kinematically related pressure solution cleavage have been interpreted as diagenetic and were commonly termed dewatering (or water escape) structures. We interpret these structures as dissolution cleavage and kink bands formed during deformation and metamorphism. Undeformed beds are also present (Fig. 9g). The development of fabrics in this unit varies in intensity and likely depends on mineralogy and grain size.

Steel Formation

The very fine grained silicic-baritic mudstone does not exhibit a pressure solution fabric, but has a strong penetrative planar fabric, typically, but not always, parallel to the cm- to m- scale

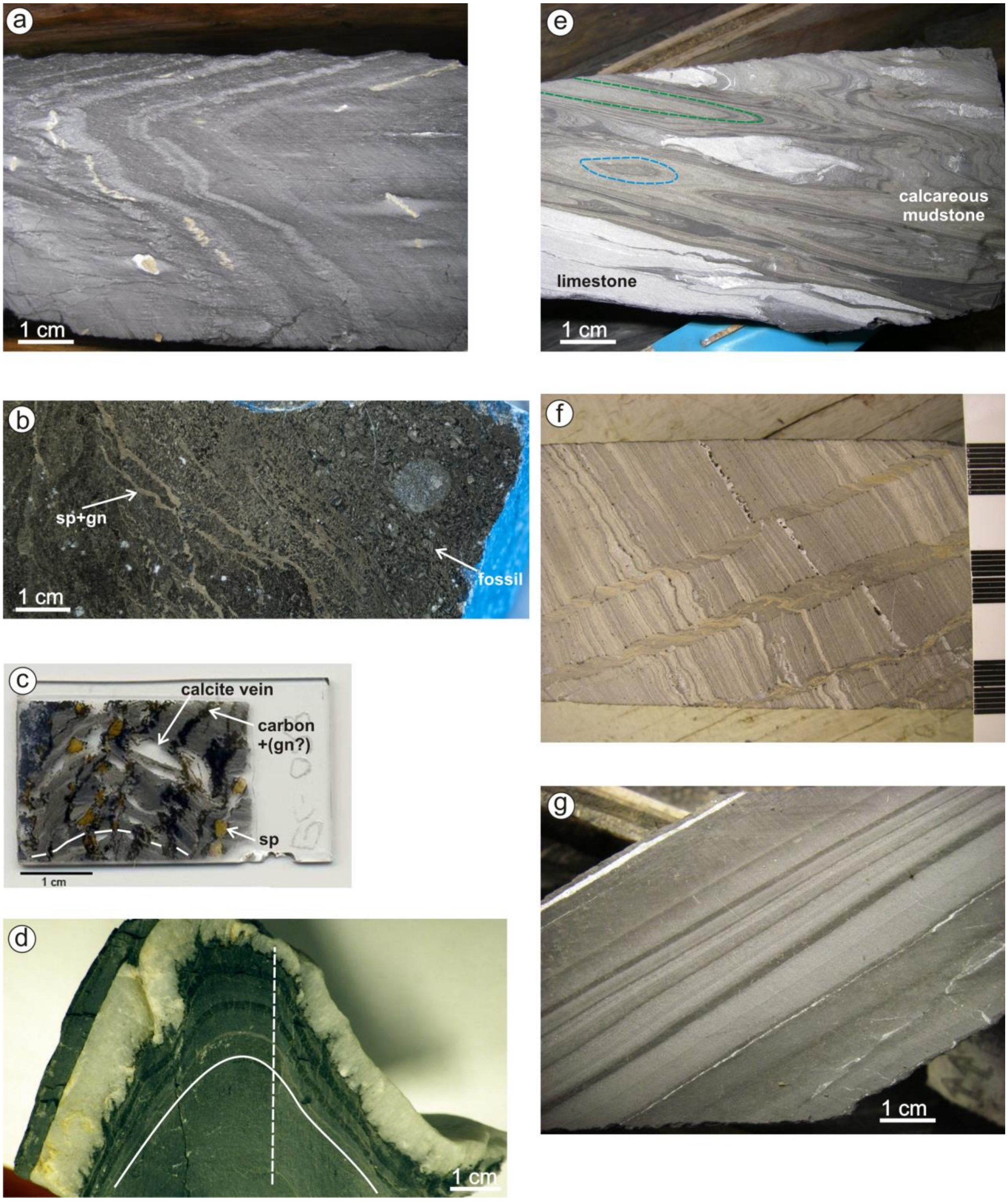


Figure 9. Photos of fabrics observed in mineralized samples from core and from the ore pile. Photo captions are on the following page.

Figure 9. Photos of fabrics observed in mineralized samples from core and from the ore pile. (a) Folded medium and dark grey sulphide-bearing calcareous mudstone. Note the axial planar pressure solution cleavage, diffraction of the cleavage in light grey beds, the folded quartz-calcite veins, and pressure shadows filled with quartz-calcite. (b) Pressure solution seams filled with sphalerite (sp), galena (gn) and carbonaceous matter in a bioclastic limestone. Note that the seams cut unclassified macrofossils replaced by sphalerite, galena, and calcite. The light grey circle on the right side is an acid drop mark. (c) Photograph of a thin section from Cleland (2008) showing coarse sphalerite grains (yellow) concentrated along pressure solution seams of insoluble carbonaceous matter and possibly galena (black). Seams are axial planar to folded bedding (white line) and bedding-parallel calcite veins. (d) Folded mudstone beds (solid white line) and bedding-parallel quartz-calcite vein with an axial planar cleavage (dashed white line) that crenulates an earlier bedding-parallel fabric. Note feathered texture on the inside of the folded vein. (e) Calcareous mudstone beds folded into sheath folds (dashed blue line) and similar-type (green dashed line). Light grey is unit are dismembered limestone beds. (f) Kink bands perpendicular to bedding. Note the displacement

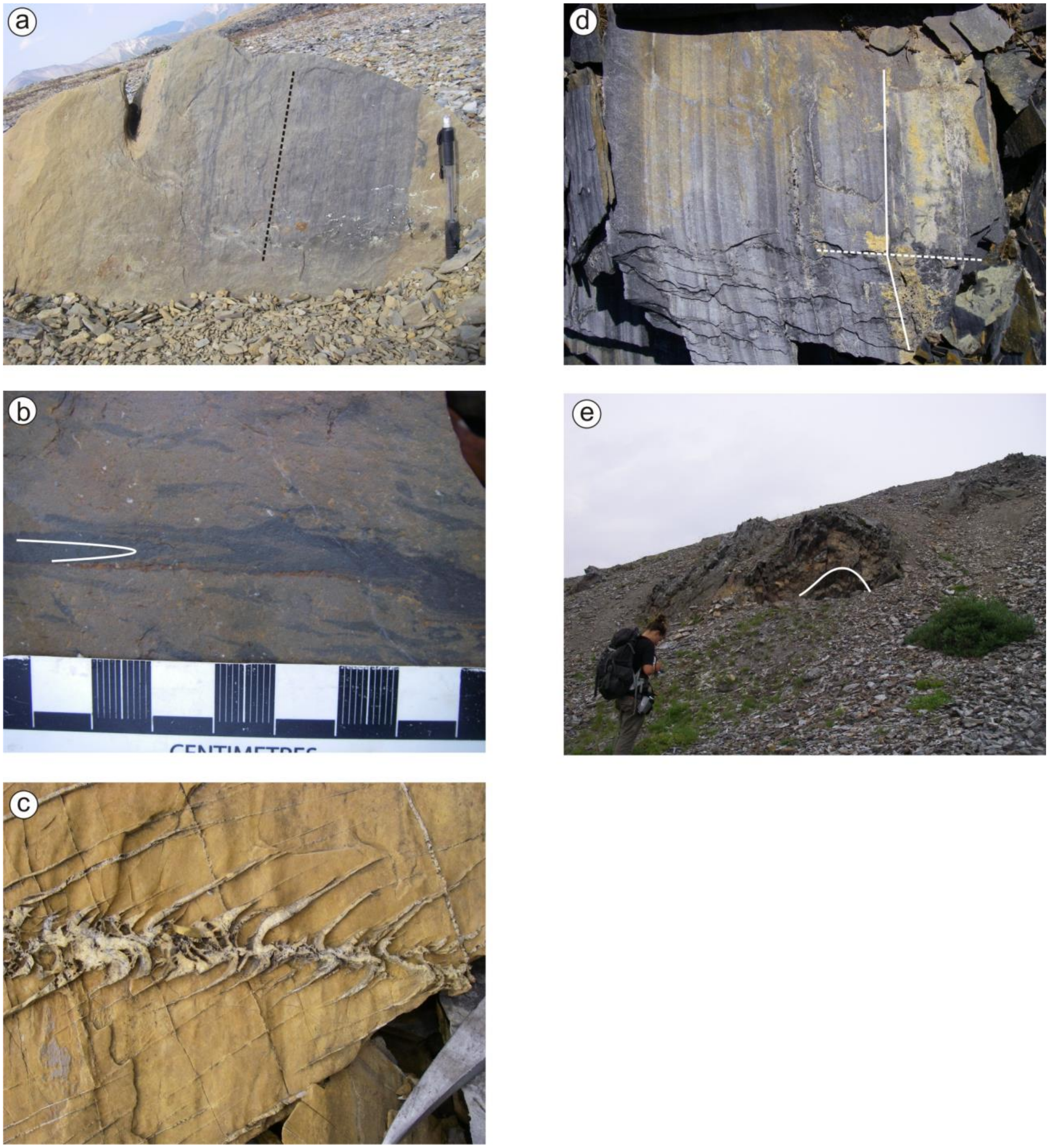


Figure 10. Photos of fabrics in the Steel Formation and Earn Group rocks. (a) Orange weathering and grey weathering siliceous mudstone of the Steel Formation with cleavage-parallel wispy features. (b) Isoclinal fold (solid white line) of carbonaceous material defining the cleavage-parallel wispy features (dashed black line). (c) Sigmoidal tension gashes filled by quartz. Photograph of a boulder; actual sense of shear is uncertain. (d) Light grey and medium grey thinly bedded slate of the Earn Group siliciclastic rocks. Note the slaty cleavage (dashed black line) at high angle to bedding (solid black line). (e) Folded beds (solid white line) of the Earn Group strata. Fold axis dips moderately towards the west.

colour-banding (Fig. 10a). The fabric is defined by strained and recrystallized quartz crystals and by carbonaceous matter. The discontinuous carbonaceous matter is informally referred to as "wispy" features, interpreted to be caused by disruption of bedding by a burrowing organism (Gordey and Anderson, 1993). The wispy features are generally aligned with the foliation and locally show isoclinal folding (Fig. 10b). Folds of beds at the outcrop or map-scale are rare in the map area but have been documented elsewhere in the district (Gordey and Anderson, 1993; Hodder and Bain (2005-2012, unpublished internal reports, Selwyn Resources Ltd.). Quartz-filled sigmoidal tension gashes are present (Fig. 10c). The fabrics in the Steel Formation have similar orientations and style than the ones in the Duo Lake Formation.

Earn Group

The slate and coarser siliciclastic rocks of the Earn Group show the best preserved primary bedding, and the least amount of strain. Bedding in the slate is mm- to cm-scale and locally graded. It is overprinted by one planar fabric. The fabric is a penetrative slaty cleavage usually at a high angle to bedding (Fig. 10d). The massive conglomerate units are weakly foliated and the foliation is defined by flattened clasts. This fabric most likely corresponds to the "regional cleavage". Folds are locally observed at outcrop scale (Fig. 10e). Limited mapping was conducted over the Earn Group rocks during this study, but one obvious observation is that some of the Earn Group rocks are less deformed than the Duo Lake and Steel formations.

The limited amount of field work conducted in the study area did not allow for characterization of fabrics. Several cleavages, dissolution fabrics, folds, shear fabrics, stretching and intersection lineations are observed, but their orientation and relative timing, proximity to high strain zones, and genetic relationships are poorly constrained. Strain partitioning is evident, where zones of intense shearing and fabric development are separated by weakly strained zones. Primary bedding and fossils such as graptolites, crinoids, and burrows are preserved in weakly deformed rocks.

Deformation mechanism

The presence of pressure solution cleavage, transposition, chevron folds, sheath folds, concentric folds, kink bands, tension gashes, S-C fabrics, pressure shadows, and ductile high strain zones are all indicative of stress-induced ductile progressive shearing and pressure solution mass transfer. Pressure solution cleavage forms by stress-induced solution transfer, during diagenesis or post-lithification metamorphism (Davis and Reynolds, 1996)

McClay (1991) argues that fine-grained sulphides, especially pyrite and galena, will act ductilely under stress and associated low grade metamorphism and be easily affected by pressure solution. He concludes that the most significant deformation mechanism of the mineralization at Howard's Pass (and other Pb-Zn +/- Ba of the Selwyn Basin) is that of stress-induced dissolution of soluble silicates, carbonates, barite and fine-grained pyrite and the concentration of relatively insoluble sphalerite and carbonaceous material under these conditions. The most intense cases of pressure solution involve complete transposition of primary structures and concentration of sphalerite and carbonaceous material in the solution seams, as observed at Howard's Pass (Fig. 9c). The strain is spatially partitioned which results in the presence of high strain zones and zones that have not experienced deformation. The zones of high strain are localized within incompetent strata, or where there is a mechanical competency contrasts. The high strain zones are also preferentially developed where there are concentrations of soluble silicates, carbonates, fine-grained sulphides.

The fabrics and structures and the presence of strain partitioning observed at Howard's Pass are interpreted to be the product of progressive shearing (Ramsay and Graham, 1970) and pressure solution during layer-parallel shortening through time. Folds develop first during 10 to 30% layer-parallel shortening. When over 30% of shortening occur, strain exceeds what can be accomplished by folding. The rocks begin to shorten thereafter by movement on detachment surfaces and cleavage planes, as well as by pressure solution and associated loss of material (Davis and Reynolds, 1996). It is uncertain if all fabrics formed during post-lithification deformation or if some formed during diagenesis. This uncertainty will be discussed in section "Timing of deformation" below.

Nature of contacts between formations: stratigraphic or structural?

Rabbitkettle - Duo Lake formations contact ("Transition zone")

The contact between Rabbitkettle and Duo Lake formations was previously interpreted as gradational from limestone to shale, marked by the presence of a transitional unit termed the "Transition zone or formation" (Morganti, 1979). Because this unit was observed everywhere in drill core at the same apparent stratigraphic level, it was given an informal 'formation' status.

The contact is ultimately marked by a unit of millimetre- to centimetre-sized thinly colour-banded rock with alternating orangey-grey bands and medium to dark grey bands (Fig. 11a). The rock is very fine grained and mostly siliceous to dolomitic. Below the contact, as you go down stratigraphy into the underlying Rabbitkettle Formation, the thinly colour-banded rock alternates with thicker (1 to 5 cm) light grey limestone "beds" or "lenses" (Fig. 11b). Between the thinly colour-banded unit and the underlying, undeformed thin to medium bedded silty limestone of the Rabbitkettle Formation (Fig. 11f), is the Wavy Banded and nodular limestone (Figs. 11c, d and e), assigned to the Rabbitkettle Formation by Morganti (1979). Contrary to Morganti (1979) we consider the contact between the Rabbitkettle and Duo Lake formations to show structures that are tectonic – not primary – in origin. Most outcrops show a dissolution cleavage with partial to complete transposition of primary bedding and earlier fabrics (Figs. 11a to e).

Thin sections observations show that 'primary laminations' are in fact S-C fabrics developed in a ductile high strain zone – primary bedding is not preserved (Fig. 12a). Recrystallization and both lattice- and shaped-preferred orientation of quartz and calcite mineral grains are evident in the microlithons between the pressure solution cleavage planes (Fig. 12b). We suggest that the top of the Rabbitkettle Formation previously interpreted as a stratigraphic unit by Morganti (1979) is a tectonic unit which represent a layer-parallel high strain zone. It is a fine-grained mylonite probably derived from a silty limestone of the Rabbitkettle Formation. We believe the "laminations" are transposed bedding and/or earlier cleavage.

There is evidence of deformation from outcrop-scale to micro-scale. The "gradual" change from lower to uppermost Rabbitkettle Formation is marked by variations in the intensity of ductile shearing, and is not a primary lithological change. It demarks a strain gradient (Fig. 11). Figure 11 shows the structures developed as one gets closer to the Duo Lake Formation which are

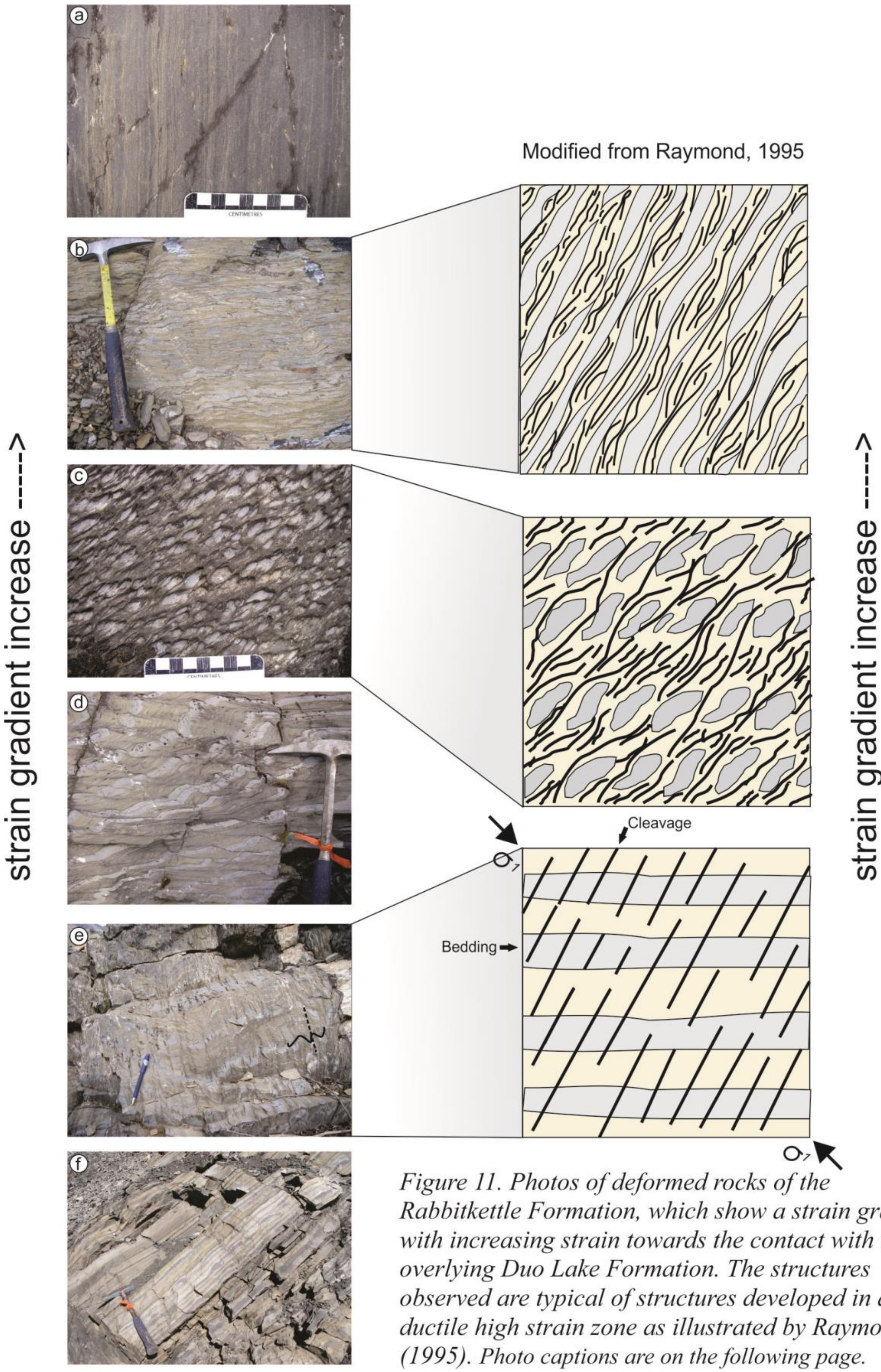


Figure 11. Photos of deformed rocks of the Rabbitkettle Formation, which show a strain gradient with increasing strain towards the contact with the overlying Duo Lake Formation. The structures observed are typical of structures developed in a ductile high strain zone as illustrated by Raymond (1995). Photo captions are on the following page.

Figure 11. Photos of deformed rocks of the Rabbitkettle Formation, which show a strain gradient with increasing strain towards the contact with the overlying Duo Lake Formation. The structures observed are typical of structures developed in a ductile high strain zone as illustrated by Raymond (1995). (a) Undeformed thin to medium bedded limestone and silty limestone for reference. Photo is from outside of the Howard's Pass district as no undeformed Rabbitkettle Formation is observed in map area. Photo location is from southwest quadrant of NTS 105P. (b) Spaced pressure solution cleavage (dashed black line) perpendicular to bedding (solid black line) defining tight, upright sub horizontal. (c) Further up section (i.e. higher strain); light grey limestone and yellowish-brown silty limestone beds displaced along black pressure solution seams (d) Elongated and flattened light grey limestone "lenses" represent rod shaped limestone beds dismembered along a shear fabric. Note the similarity between this photo and the second cartoon from Raymond (1995). (e) Bedding transposed into near parallelism with shear fabric and subsequently kinked. Note the similarity between this photo and the third cartoon from Raymond (1995). (f) Typical appearance of unit previously called "Transition zone" defined as a thinly laminated mudstone in gradational contact between Rabbitkettle and Duo Lake formations. Interpreted here as a high strain zone where all structures (primary and tectonic) are transposed into parallelism with high strain zone margin. This is the shear zone termed the Howard's Pass décollement that marks the contact between the Rabbitkettle and the Duo Lake formations.

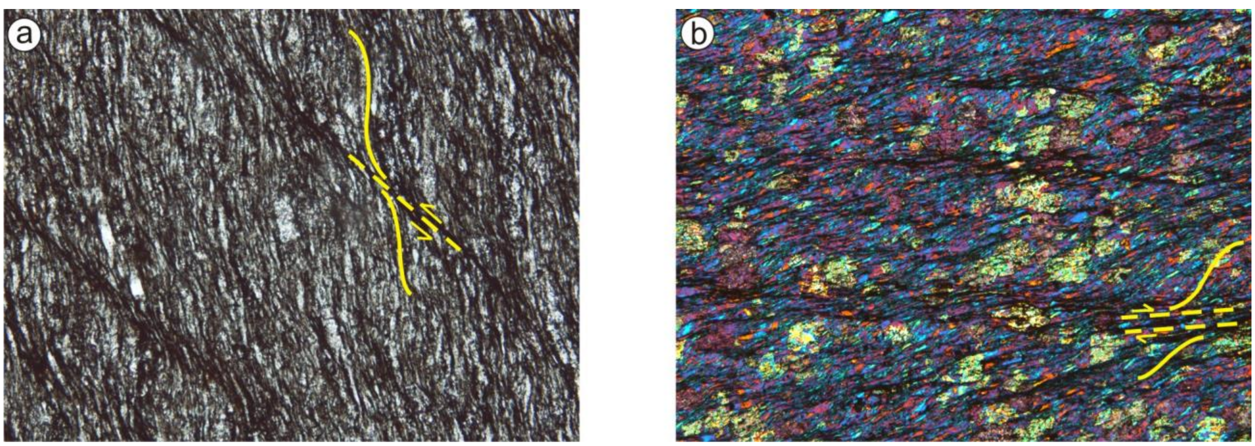


Figure 12. Microphotographs of thin section from hand sample from a boulder of the high strain zone of the Howard's Pass décollement (Fig. 10a). No primary structure such as bedding is preserved. (a) S-C fabric where the "C" shear bands (dashed yellow line) and the "S" foliation (solid yellow line) developed as a result of progressive shear in a high strain zone. (b) Microphotograph with the gypsum plate under cross-polarized light shows the Lattice Preferred Orientation (LOP) of the deformed and recrystallized quartz grains between the "S" foliation planes.

remarkably similar to structures expected to develop in theoretical models for high-strain zones (Raymond, 1995). The dark blue polygon (ductile high-strain zone) on Figure 4 marks the highest strain rocks of the Rabbitkettle Formation only. All other exposures of the Rabbitkettle Formation in the map area show some degree of strain, from partially transposed, folded, to weakly to strongly foliated (Figs. 7 and 11). Figure 11f is a photo of undeformed Rabbitkettle Formation taken outside of the Howard's Pass district (NTS 105P).

The Transition zone and the Wavy Banded limestone subdivisions of Rabbitkettle Formation of previous workers (Fig. 6) are therefore interpreted here as highly strained Rabbitkettle Formation, and the high-strain zone is concordant with the top of the Rabbitkettle Formation throughout the Howard's Pass district (Hodder et al., 2014; this study). It is located there because of the mechanical strength differences between the formations (Fig. 6).

Within the map area (Fig. 4), the layer-parallel high-strain zone here referred to as the Howard's Pass décollement consistently defines the contact between the Rabbitkettle and Duo Lake formations. It is exposed at an elevation between 1500 and 1600 m. The constant elevation of the décollement exposures shows that it is a horizontal to shallowly south-dipping structure (about 10°-30°). Only along the northern most extent of the map area does it steepen to about 40° (Fig. 4). On the west and east sides of the CMC domain (Fig. 4), the décollement is offset by north-south trending faults. The décollement is also truncated by the March fault and raised by out-of-sequence thrusts and back thrusts (see "Faults" section below).

Duo Lake – Steel formations contact

The contact of the Duo Lake Formation with the overlying Steel Formation is commonly marked by a meter-wide zone of black silicified blocky and crumbly rocks of uncertain protolith (Fig. 13). It best described as fault material ("silicified, black fault material" in Fig. 4). The map pattern in the CMC and Three fingers domains shows clear recurrent repetition of the Duo Lake and Steel formations strata of which the contact is marked by faults (Fig. 4). As mentioned above, homoclinal successions of frequently alternating Duo Lake and Steel formations have been documented extensively by Gordey (2008) and have been reported by Gordey and Anderson (1993) but not illustrated on maps. Because of the presence of fault material between the repeated strata and the absence of fold hinges, we suggest that the repetition is mainly caused by thrust imbrication.

Steel Formation - Earn Group contact

The nature of the contact between the Steel Formation and the Earn Group is enigmatic. It is unknown if the basal contact observed in the map area is an unconformable stratigraphic contact, or if it is faulted. If it is faulted, it remains unknown if parts of the lower Earn Group (perhaps the entire Portrait Lake Formation) have been removed by faults resulting in the juxtaposition of the Prevost Lake Formation on Duo Lake and Steel formations. Our current field observations indicate a faulted contact, discussed below.

Regionally, the Earn Group overlies the Steel Formation in what is documented as a conformable to unconformable relationship (Gordey and Anderson, 1993; Fig. 6). At the district scale, Morganti (1979) places an unconformity below the lowest member of the strata he correlates with Earn Group (Iron Creek formation). However, based on our mapping, the Earn Group is in direct contact, sometimes with an angular relationship, with both the Steel and Duo Lake formations (Fig. 3), and locally with even the Rabbitkettle Formation (Figs. 3 and 4; Hodder et

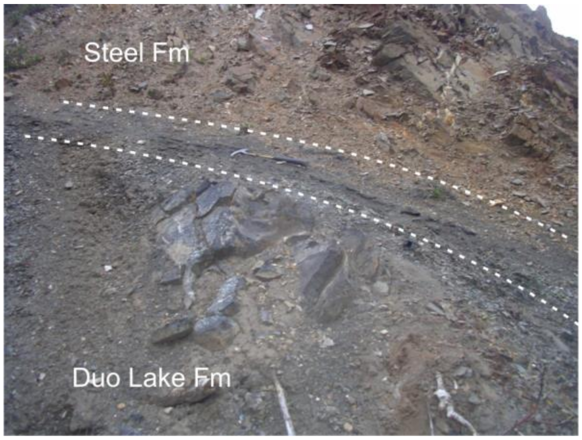


Figure 13. Contact between the Steel Formation and the Duo Lake Formation is marked by a 30 cm wide zone of black crumbly silicified mudstone interpreted as a brittle fault zone. Hammer circled for scale.

al., 2014). In addition, in the CMC and Three fingers domains, the Earn Group has a flat-lying lower contact that truncates the thrust-imbricated Duo Lake and Steel formations (Fig. 4). Hence, if the contact is an unconformity, pre-Earn Group deformation and subsequent erosion must be invoked to explain the underlying imbricated rocks. However, this is not likely as the timing of thrusting is almost certainly post-Earn Group. Therefore, in localities where the base of the Devonian Earn Group is truncating slices of repeated Steel and Duo Lake formations that were thrust-imbricated during the Jura-Cretaceous, the base must have been faulted after its deposition. If the base of the Earn Group was an unconformity, it would need to be younger than the thrusting, which is not the case. However, where the strata underlying the base of Earn Group are not clearly thrust-imbricated, invoking a fault is less obvious since the younger Earn Group strata lie stratigraphically above the underlying formations.

Younger rocks overlying older rocks along a fault are not uncommon in thrust systems, especially along the roof thrust of a duplex or triangle zone (Billings, 1933; McClay, 1992 and references therein). Moreover, folded or corrugated roof thrusts have segments of the fault with a reverse sense of displacement, while others have an apparent normal sense of displacement (McClay, 1992 and references therein). These relationships could explain unintuitive map patterns (e.g. thrusted younger over older relationships) observed in Howard's Pass district. We favour an interpretation in which a shallowly dipping detachment surface defines the base of Earn Group in the map area. Whether the faulted lower contact is the base of the Portrait Lake Formation or the Prevost Lake Formation, or somewhere else in the succession, is unknown.

Faults

Out-of-sequencethrusts and back thrusts

Many faults in the area have unknown dips and sense of movement as a direct result of poor outcrop exposure. However, in some localities key thrust fault relationships are observed. For instance, Hodder et al. (2014) show the Rabbitkettle Formation thrust on top of the Duo Lake

Formation along a moderately south dipping thrust just south of the XY deposit (Figs. 3 and 14a; Hodder et al., 2014)

In the Three Fingers domain of our map area (Fig. 4), we observed the Rabbitkettle Formation overlying both the Earn Group and Duo Lake Formation rocks above a north dipping thrust (Figs. 4 and 14b). The underlying rocks are strongly deformed and chaotically folded into isoclinal folds. We interpret this structure as a back thrust, informally termed here the "Three Finger thrust", which likely cuts through the Howard's Pass décollement and roots into a lower detachment. A steep fault, of uncertain dip, cuts through the CMC domain of our map area (Fig. 4) where the Earn Group is juxtaposed to the Duo Lake Formation, Steel Formation and Earn Group strata. It is uncertain if this fault is a simple north-dipping normal fault, a south-dipping forward breaking (out of sequence) thrust, or a complexly reactivated north-dipping (possibly back) thrust that puts younger rocks on top of older rocks.

Hodder et al. (2014) demonstrated that the Rabbitkettle Formation overlies the Duo Lake Formation along a flat-lying detachment surface, in the Nod Lake area (north of the Don deposit; Fig. 3), and is eroded to provide a window of the Duo Lake Formation through the Rabbitkettle Formation. This relationship has also been identified in drill core around the Don deposit (Selwyn Resources Ltd., Unpublished internal reports).

West of the study area, Gordey (2008) diagrammatically illustrates in cross-section forward breaking thrusts and back thrusts of the Rabbitkettle Formation onto the Duo Lake Formation (Fig. 5) to explain similar complex relationships observed immediately west of Howard's Pass district. Gordey (2008) also illustrates in cross-section a south-dipping out-of-sequence thrust, termed the Sheldon thrust, which cuts through the floor thrust (near contact between the Duo Lake and Rabbitkettle formations) of his duplex (Fig. 5). The March fault south of the Howard's Pass district is a similar structure (Figs. 3 and 4; Hodder et al., 2014).

March fault

The March fault is located in the southern part of the map area (Fig. 4). Outcrops on either side of the fault were briefly visited during our field work. Further detailed mapping along the fault is required to elucidate a potentially complex and protracted movement history.

The March fault was first mapped by Gordey (1992) as a south dipping thrust that juxtaposes the Narchilla, Gull Lake and Yusezu formations against the Duo Lake, Rabbitkettle and Vampire formations. Its extension to the south in the Frances Lake map area (NTS 105H) was not reported on Blusson's (1966) map, although Proterozoic brown, grey and maroon and green shale (Blusson's unit 1 now known as the Narchilla Formation) is in direct contact with middle and late Cambrian argillaceous silty limestone (Blusson's unit 9 now known as Rabbitkettle Formation). Hart and Lewis (2006) mapped in the Hyland Valley and extended the trace of the March fault from the Nahanni map sheet (Gordey, 1992) south for over 50 km, where the fault juxtaposes the Yusezyu and Narchilla formations with the Vampire, Rabbitkettle and Sekwi formations.

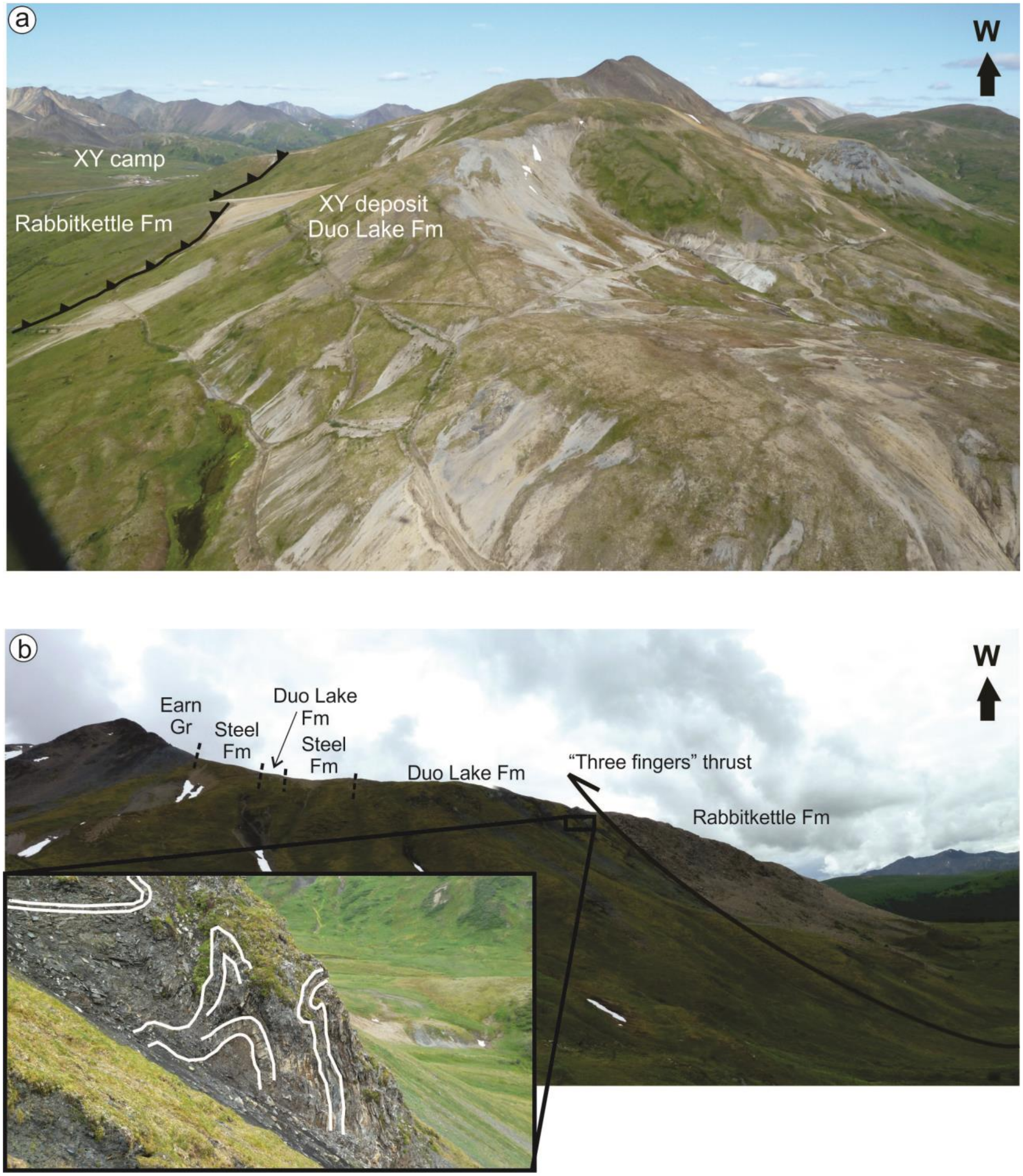


Figure 14. East-west striking thrusts in the map area. (a) Rabbitkettle Formation thrust on top of the Duo Lake Formation along a moderately south dipping, northeast-verging thrust just south of XY deposit (outside of map area, see Fig. 3; Hodder et al., 2014). (b) The “Three Fingers” thrust is a north dipping back thrust which puts Rabbitkettle Formation on top of strongly folded Duo Lake and Steel formations. Inset shows folded strata of mudstone and chert of Duo Lake Formation in the footwall of the thrust.

Gordey and Anderson (1993), Hart and Lewis (2006) and Barnes (2011) made four key observations and documented stratigraphic, structural, plutonic and metamorphic differences across the fault. First, there is an abrupt facies change in the Precambrian Hyland Group from the Narchilla Formation to the Vampire Formation that apparently occurs right across the March fault. Second, the Gull Lake Formation is present on the southwest side of the March fault but is absent on the northeast side. The time-equivalent Sekwi Formation is missing immediately northeast of the fault. Gordey and Anderson (1993) provided two potential explanations to account for this geometry; both involve pre-Rabbitkettle Formation and post-Gull Lake Formation movement (see their Figure 65). However, no evidence for disturbance during that time period has been recognized elsewhere in the Selwyn Basin or in the time equivalent units of the carbonate platform (Gordey and Anderson, 1993). Third, along the Hyland Valley, the Highland plutonic suite rocks (~ 106 Ma) are exposed on the southwest side of the fault, whereas the Tungsten plutonic suite rocks (~ 97 Ma) are exposed on the northeast side (Hart et al., 2004a, b; Heffernan, 2004; Rasmussen, 2013). The style of emplacement of nearly coeval plutonism is different on either side of the fault. The occurrence of Highland plutonic suite rocks as thick flat concordant sheets suggests that they were emplaced at mid-crustal levels (~10-15 km). Whereas the Tungsten plutonic suite rocks have steep sides and flat tops, and were likely emplaced in the upper crustal levels (5-7 km). Finally, differences in style of deformation, intensity of fabric development and grade of metamorphism on either side of the fault show a component of southwest side up displacement (Hart and Lewis, 2006; Barnes, 2011). Hodder et al., 2014 interpreted the March fault as an out-of-sequence thrust that breaks the Howard's Pass décollement.

Based on initial field observations in the map area (Fig. 4), the March fault appears to put the Gull Lake Formation on top of the Rabbitkettle Formation, and in turn the Rabbitkettle Formation on top of Duo Lake and Steel formations (Fig. 15). The rocks in the footwall are tightly folded. Based on the interpreted map pattern, it is likely that the fault has splays (Fig. 4). It is difficult to distinguish the Gull Lake Formation from the Steel Formation, as both units can display a grey-orange weathering colour with dark grey "wispies" and decimetre- to meter-wide light grey limestone beds. Dips of foliation and/or bedding in the vicinity of the March fault vary from steeply north-dipping along the westernmost portion of the March fault in the map area, to steeply south-dipping along the easternmost portion, just off the map area (Fig. 4).

We suggest that the March fault is kinematically related to, and likely continuous with, the Sheldon thrust of Gordey (2008), which puts the Proterozoic Yusezyu Formation of the Hyland Group over the severely shortened Ordovician-Silurian Duo Lake Formation. The Sheldon thrust cuts through a flat-lying detachment above which shortening of the Duo Lake/Steel/upper Rabbitkettle formations was accommodated (Gordey, 2008). This detachment is interpreted here to be continuous with the Howard's Pass décollement floor thrust mapped in the Howard's Pass district. The Sheldon thrust also cuts through an upper detachment presumed to be at the base of the Earn Group below which shortening was accommodated. This roof thrust may be within the

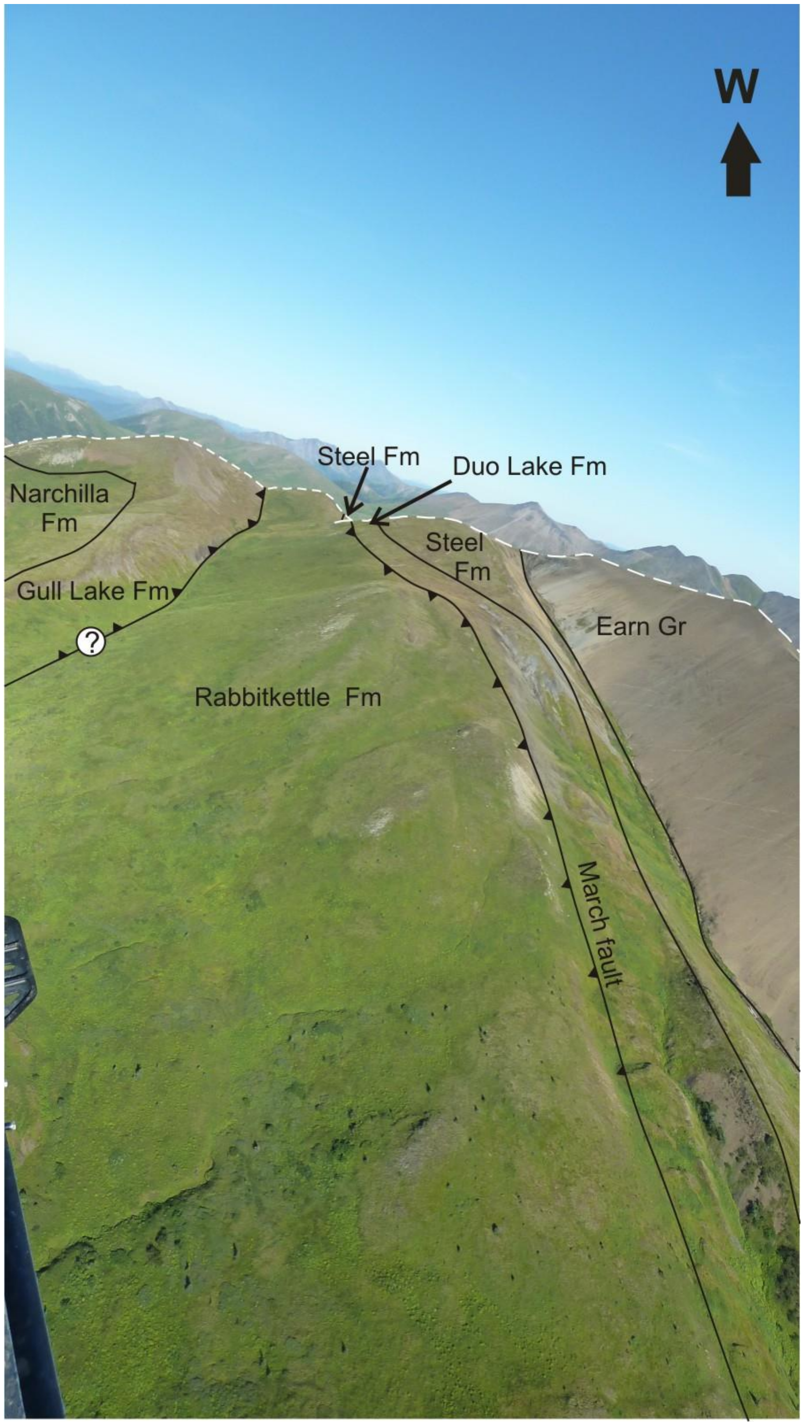


Figure 15. Photo of the March fault placing Rabbitkettle Formation on top of Steel and Duo Lake formations along a south-dipping thrust that likely roots within or below the Hyland Group succession. The presence of splays and likelihood of multiple reactivations renders the complete movement history of the fault difficult to assess. White dash line which marks the top of the ridge line is the Northwest Territories-Yukon border; for location see map of Fig. 4 where March fault intercepts border.

Earn Group in the Howard's Pass district, and is interpreted to be continuous with Gordey's (2008) upper detachment.

The observations stated above all lead to a model where the March fault was active in the Proterozoic and reactivated, possibly multiple times, prior to and during Jura-Cretaceous orogenesis and later transcurrent motion. It repeatedly influenced patterns of sedimentation, igneous activity, faulting and likely mineralization. The March fault may have influenced the formation of non-magmatic Au mineralization (Hart and Lewis, 2006) and the presence of Li-rich pegmatitic dykes (Barnes, 2011) in the Hyland Valley. Whether the March fault has played a role in the Pb-Zn mineralization is uncertain and needs to be assessed.

North-south faults

Two steeply-dipping and north-trending faults are mapped (Fig. 4). The 'Placer Creek fault" shows apparent west-side up displacement, and the unnamed fault (northeast of the map area; Fig.3) shows apparent east-side up displacement. These faults offset the flat-lying detachment surfaces of the Howard's Pass décollement and the lower Earn Group. The faults could be interpreted as post-thrusting normal faults, or alternatively tear faults or lateral ramps commonly developed as part of a thrust system (Dixon and Pratt, 2004). Tear faults are oriented parallel to the thrust transport direction and separate thrust sheets where each part behaves independently and can have different amounts of displacement along the imbricate thrusts (McClay, 1992). Tear faults are common in the Howard's Pass district (Fig. 3; Hodder et al., 2014). In the map area, the two steeply dipping and north trending faults (Fig. 4) have been interpreted as tear faults that displace the duplex.

Newly recognized Lower Devonian bioclastic limestone

An outcrop of bioclastic limestone containing ossicles of crinoids with twin axial canals was mapped during this study and recognized for the first time in the Howard's Pass district (Fig. 16). Its stratigraphic relationship to adjacent units is not exposed, but appears to be intercalated with Silurian Duo Lake Formation strata (green circle labelled "H" on Fig. 4). The unit has been dated as Emsian Lower Devonian (McCracken, 2013). This Lower Devonian-aged unit might be assigned to the slope facies Hailstone (Cecile, 2000) or Natla (Gabrielse et al., 1973; Gordey and Anderson, 1993) formations. The Hailstone and Natla formations contain, where mapped north and east of Howard's Pass, calcareous black shale, thin-bedded limestone and bioclastic limestone. In the Howard's Pass district, it is possible, even likely, that some shale and limestone have been assigned the Duo Lake Formation or the Portrait Lake Formation, but are actually Lower Devonian equivalents of Hailstone or Natla formations (Fig. 3). It is uncertain if Lower Devonian-aged slope facies shale and limestone are more extensive and have not been recognized in the district because the paucity of visible fossils and the lack of biostratigraphy, or if it is a single slice structurally emplaced. The presence of this slope facies unit indicates the proximity to a carbonate platform at that time. The CAI of the bioclastic limestone found at Howard's Pass is 5, indicating burial temperature over 300°C.

Figure 16. Photo of bioclastic limestone containing ossicles of crinoids with twin axial canals, dated during this study as Esmian - Lower Devonian (McCracken, 2013). See location "H" on Figure 4.

PRELIMINARY STRUCTURAL MODEL

Based on our observations, observations documented by Hodder and Bain (2005-2012, unpublished internal reports, Selwyn Resources Ltd.), and extrapolations with cross-sections, maps and reports from Gordey (2008), we have conceptually developed a simplified schematic diagram showing the structural style of deformation in the Howard's Pass district (Fig. 17).

The key elements in the proposed Howard's Pass thrust system are the floor and roof thrusts which bound an internally complex duplex structure, as well as the inferred buried detachment(s) above which out-of-sequence thrusts and back thrusts break through the duplex (Fig. 18).

Levels of detachment

Four levels of regional scale detachments are present in our model and affected the geometry of the Howard's Pass district. The highest detachment is inferred to be at the base or within the Earn Group (possibly at the base of the Prevost Formation), and forms the roof thrust to the duplex. It has not been observed during this study but is interpreted to be correlative with the detachment postulated at the base of the Earn Group by Gordey (2008) and observed by Hodder et al. (2014) within the Earn Group. The middle detachment is observed near or at the top of the Rabbitkettle Formation, and is termed the Howard's Pass décollement (Fig. 17). It forms the floor thrust to the duplex which involves imbricated thrust sheets of the Duo Lake and Steel formations, and likely some of the upper Rabbitkettle Formation and lower Earn Group. The third, deep detachment (circled P on Figure 17) is inferred to be within or below Precambrian Hyland Group strata. An additional and even deeper "master" detachment (labelled B on Figure 17) has been postulated by Gordey (2008) to account for thin-skinned shortening underneath the entire Cordilleran fold and thrust belt.

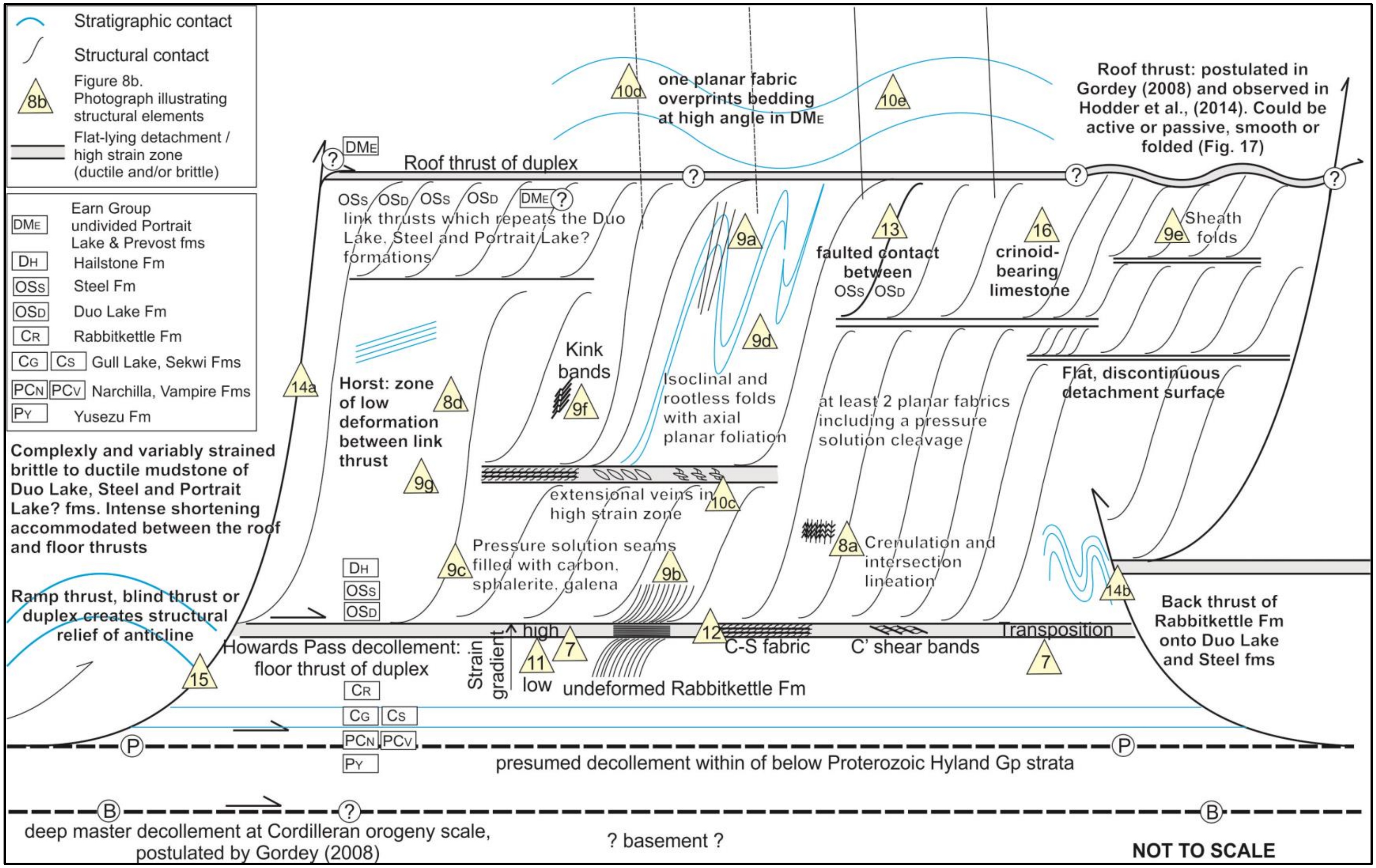


Figure 17. Schematic, simplified diagram of structural style of deformation in the Howard's Pass district showing observed and inferred structural elements present within the complex duplex structure formed as a result of severe layer-parallel shortening. Observed structural elements (yellow triangle) are shown in photographs from Figures 7 to 16. Circled letter P: presumed décollement within or below the Proterozoic Hyland Group. Circled letter B: deep master décollement at Cordilleran orogeny scale, postulated by Gordey (2008).

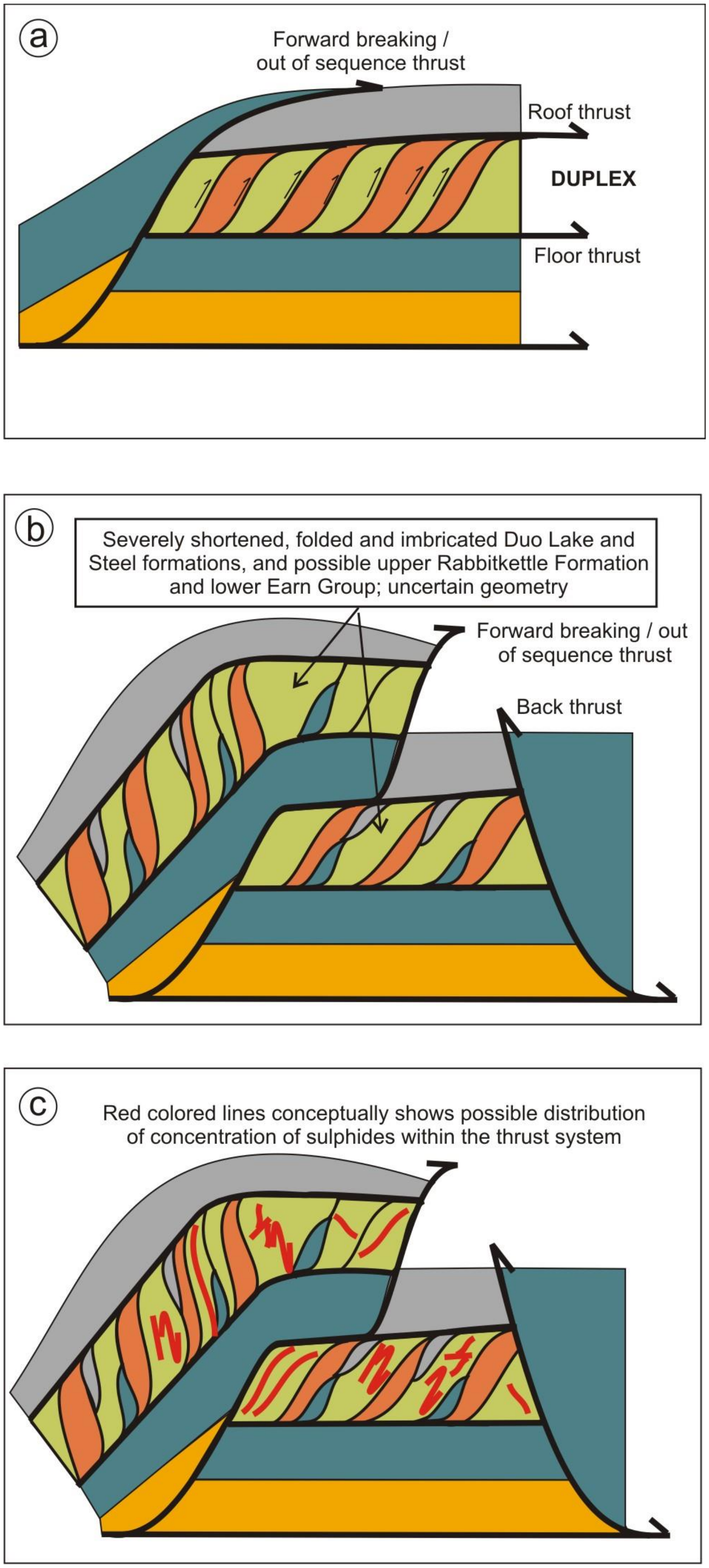


Figure 18. Schematic illustrations representing the conceptual model developed for the structural evolution of the Howard's Pass district. Colours refer to Figure 4. (a) Basic key elements of the thrust system. (b) Model showing some of the complexities. (c) Model illustrating the possible distribution of mineralization within the thrust system.

Earn Group upper detachment (roof thrust)

Based on mapping in our map area, some of the shale, sandstone and conglomerate of the Earn Group (undivided Portrait Lake and Prevost formations; Fig. 4) display only one planar fabric, which is defined by a slaty cleavage generally at a high angle to the primary bedding. The limited amount of mapping carried out in the Earn Group impedes a thorough interpretation, but based on the obvious differences in structural style between the Duo Lake and Steel formations and the Earn Group; we suggest that some of the Earn Group strata sit on the thrust-imbricated Duo Lake and Steel formations along a detachment surface. This detachment is postulated to be the upper detachment (roof thrust) of a large-scale regional duplex structure. The presence a roof thrust to a duplex has been postulated by Gordey (2008) and by Hodder et al. (2014). Because some strata of the Earn Group appear to be involved in the thrust imbrication (Fig. 4) it is likely that the detachment is partly within the Earn Group (possibly between Portrait Lake and Prevost formations), and not at the base. On our map, the flat-lying upper detachment is present at an elevation of about 1600 m in the CMC domain and at 1800 m in the Three Fingers domain, where it puts the Earn Group strata on top of the thrust-imbricated Duo Lake and Steel formations (Fig. 4).

The Howard's Pass décollement (floor thrust)

The structural style of folds and thrust faults within thin-skinned thrust belts is considered to be a function of the state of stress and the mechanical stratigraphy (e.g. Jamison, 1992). At Howard's Pass district, the pre-existing flat-lying stratigraphic contact between Rabbitkettle and Duo Lake formations is interpreted to have taken most of the strain along a regional detachment surface. This surface (previously referred to as the Transition zone; Fig. 6) is mapped throughout the Howard's Pass district (Fig. 3; Hodder et al., 2014) and extends to the west of the district as far as the western edge of the Tay River map sheet (longitude 134°W in Fig. 5; Gordey (2008)). It is also presumed to be present north of the district, in NTS 105P (Gordey et al., 2011b). This décollement is therefore at least 250 km in length along its strike and is exposed or shallowly buried across strike for at least 95 km. It is ultimately defined by a mylonite at or near the contact between the Rabbitkettle and Duo Lake formations, and a strain gradient can be observed from the less deformed lower Rabbitkettle Formation to the highly strained uppermost Rabbitkettle Formation (Figs. 11 and 12).

Deep, inferred detachments

A deep buried detachment is inferred to reside within or below the Hyland Group rocks (labelled P on Figure 17). This detachment would be the root for the ramping thrusts that break through the Howard's Pass décollement (floor thrust of the duplex) such as the March fault (Hodder et al. 2014) and the Sheldon thrust (Gordey, 2008), and blind thrusts responsible for the structural relief of the Fork anticline (Hodder et al. 2014) and the Dragon anticline (Gordey, 2008). An additional and even deeper "master" detachment (labelled B on Figure 17) has been postulated by Gordey (2008) to account for shortening underneath the entire Cordilleran fold and thrust belt.

Within the duplex

Between roof and floor thrusts, a series of imbricate and/or link thrusts disrupt the variably penetratively strained stratigraphy (shale and mudstone). The floor thrust is the surface above which shortening and structural thickening is accommodated by faulting and folding, and where strain partitioning is observed. The complex geometry of structures above the décollement (Fig. 17) is attributed to the contrasting mechanical properties of the shale and mudstone of the Duo Lake and Steel formations compared to the underlying limestone and overlying coarser siliciclastic rocks. Our observations are consistent with Gordey (2008) who stated: "[…] the structure can be complex at a local scale, particularly in strata of the Road River Group [Duo Lake Formation]. At a larger scale however, […] structure is dominated by a few shallow-dipping thrust faults and buried detachments across which the more complex deformation was accommodated."

Thrust panels have been mapped in the Howard's Pass district but because the dominant lithology is black mudstone, thrust faults are difficult to recognise and to delineate without very detailed biostratigraphic control. The identification of thrust faults is particularly where shales are tightly folded and penetratively deformed (e.g. McClay, 1983; McClay et al., 1988, 1989; Gordey, 2008; this study). In drill holes, several faults have been identified and repetition of units is common. For instance, the pre-2011 drill hole log database (Selwyn Resources Ltd., Unpublished data) shows that the mineralization (logged as Active Member) has been intersected more than once, and up to five times, in a single drill hole in over 50 drill holes in various deposits (XYC, XYN, ANE, ANC, Don). Without biostratigraphy, it is challenging to provide a robust model for stratigraphy and subsequent deformation within the duplex. Similarly at the regional scale, Gordey (2008) stated: "In these areas [within duplex] formational identity of strata (Duo Lake, Steel, or Portrait Lake formations) can be ambiguous and the amount and manner of structural repetition unclear." Adding to this challenge is the presence of previously unrecognized limestone and shale of the Lower Devonian Hailstone Formation (mentioned above).

The term "shale belt" is used to described deformed shale packages in fold and thrust belts. Also, the term "Mushwad" has been applied to a duplex structure where incompetent strata are deformed between a floor thrust and a roof thrust (Thomas, 2001). In an example from the Appalachian, Thomas (2001) shows structurally thickened thrust imbricated sheets of shale below a raised roof thrust of more competent conglomerate units.

Based on available data, thickness variations in some formations of the Selwyn Basin are extreme and most frequently explained by syndepositional growth faulting and/or by movement (faulting and/or uplift) followed by erosion beneath unconformities (Gordey and Anderson, 1993; Goodfellow and Jonasson, 1986) or simply remain unexplained. Our observations suggest that, in addition to pre- and syndepositional faulting and unconformities, some of the thickness variation likely result from unrecognized post-depositional thrust imbrication (stacking), folding, transposition, and mylonitization during the Jura-Cretaceous northeast-directed collision of accreted terranes onto ancestral North America.

TIMING OF DEFORMATION

Deformation during Jura-Cretaceous Cordilleran orogeny at Howard's Pass was previously thought to not have significantly affected the distribution of the strata and ore, and that deformation was mostly Silurian in age and had ceased prior to deposition of the Steel Formation (Jonasson and Goodfellow, 1986). In contrast, our observations show that both the Duo Lake and Steel formations were involved in concurrent thrust imbrication and that the associated fabrics are present in both formations. The two formations are observed in steep to moderately dipping homoclinal sequences that can only be explained by tight to isoclinal folds or thrust-imbricated sheets. As mentioned above, the main mechanism of deformation of mineralization and host strata is that of layer-parallel stress-induced dissolution. The pressure solution seams are developed in Rabbitkettle, Duo Lake and Steel formations. They are not developed in siliciclastic rocks of the Earn Group primary because most Earn Group strata are above the roof thrust of the duplex where little shortening (less strain) has been accommodated. However, even in the Earn Group strata that appear to be involved in the thrust imbrication, because of the high silica content of the unit there is very little insoluble material present to be concentrated in pressure solution seams.

Gordey (2008) interprets the formation of the regionally extensive duplex structure and associated elements such as the floor thrust, imbricated thrust sheets, and the proposed roof thrust to have occurred concurrently, during the formation of the Selwyn fold and thrust belt, sometime between early Jurassic and mid-Cretaceous (Gordey et al., 2011a). As the thrust system progressed, the related regional stress, heat and confining pressure led to fabric development and re-orientation during progressive deformation.

We support this interpretation and suggest that, at Howard's Pass, the duplex and associated tectonic fabrics such as folding, transposition, pressure solution seams, penetrative slaty cleavage, recrystallization and plastic deformation shown by both shape and lattice preferred orientation, all formed during the Jura-Cretaceous orogeny, and not the Silurian deformation. These structures and fabrics are geometrically and kinematically related to the thrust system and developed concurrently with the formation of the duplex. The fact that no evidence of Silurian compressional deformation has been documented outside of the Howard's Pass (as per Jonasson and Goodfellow, 1986) supports our interpretation.

While our interpretation does not preclude the presence of a diagenetic pressure solution cleavage, there is no evidence for two generations of overprinting pressure solution cleavages. Thus, it is suggested that all the pressure solution is related to the tectonic deformation. Moreover, the regional stress caused by collisional deformation and the regional heat flow that produced metamorphism at >300°C would provide ideal conditions to have dissolved or re-mobilized the sulphides, carbonates, and silicates, especially in areas of high strain partitioning.

Our observations and interpretations are consistent with the structural style documented throughout a large portion of the Selwyn Basin (Fig. 5), and in other "SEDEX" deposits (Cirque, Driftpile, Tom; Fig. 1; McClay, 1991), which resulted from the northeast-directed collision driven by accretion of exotic terranes into ancestral North America during the Cordilleran orogeny.

IMPLICATIONS FOR ORE DISTRIBUTION

The re-interpretation of the structural style at Howard's Pass has important implications on the distribution of the mineralization. The fine-grained stratabound ore is deformed, and partly remobilized along pressure solution cleavage, during the Jura-Cretaceous Cordilleran orogeny and associated metamorphism. The conceptual duplex model of Figure 18 illustrates diagrammatically how the mineralization could be repeated by thrust imbrication and folding within the duplex. The sulphides are also remobilized and concentrated as coarse to fine sphalerite and galena in pressure solution cleavage. The pressure solution cleavage is most intensely developed in zones of high strain. These high-strain zones are likely preferentially focused where sulphides are abundant and along existing weaknesses such as competency contracts and pre-existing structures. Therefore, understanding the distribution of strain and orientation of high-strain zones within the Howard's Pass thrust system is essential in efforts to correlate high grade intervals in drill core.

In addition to repeating and concentrating the ore within the duplex, the duplex itself can be repeated by out-of-sequence thrusts and back thrusts (Figs. 17 and 18). Map patterns documented during this study, by Gordey (2008) and Hodder et al. (2014) as well as relationships observed in drill core, where Rabbitkettle Formation and older units overlie the Duo Lake Formation and younger units, support this interpretation. The new structural interpretation documented here opens up opportunities to intersect mineralization within the Duo Lake Formation below the first intersection of Active Member, but also below the Rabbitkettle Formation.

To understand and predict the geometry of the thrust system, one needs to recognize shear fabrics (S-C fabrics and C' shear bands) and transposition in the context of the main sense of shearing during progressive deformation (Ramsay and Graham, 1970). It is critical for connecting assayed intervals from drill hole to drill hole. Strict adherence to a hypothetical stratigraphy and wholly syngenetic mineralization therein, ignores structural controls on late coarse mineralization attendant to deformation.

SUMMARY

The geology of the Howard's Pass Pb-Zn district has been reassessed based on new mapping. The most significant points of our new perspective are that:

- Pressure solution cleavage and kink bands, folds, transposition, S-C fabric, detachment surfaces and thrust imbrication are all the result of layer-parallel shortening during Jura-Cretaceous deformation and metamorphism, although no observations preclude the presence of fabrics developed during diagenesis.
- The "Transition zone or formation" is a tectonic entity, here termed the Howard's Pass décollement, not a stratigraphic unit.
- Howard's Pass décollement displays ductile deformation (S-C fabrics) and defines a flat-lying regional-scale detachment surface at the top of the Rabbitkettle Formation.
- The internal stratigraphy of the Duo Lake and Steel formations has been extensively but heterogeneously dismembered along thrust-imbricated faults and folds to accommodate

shortening between floor and roof thrusts of a duplex structure. Undeformed rocks and zones of brittle to ductile deformation are present due to strain partitioning.

- Earn Group strata (perhaps only the Prevost Lake Formation) are structurally above the roof thrust of the duplex and accommodated less shortening than strata within the duplex.
- A newly recognized bioclastic limestone found intercalated with mudstone currently mapped as Ordovician-Silurian in age has been dated as Lower Devonian (slope facies unit of Hailstone or Natla formations). The presence of slope deposits indicates the proximity to a coastal environment. These slopes facies strata are regionally known to have a significant mudstone component, suggesting some mudstone interpreted as Duo Lake Formation or Earn Group strata may be incorrectly assigned. This discovery reinforces the need for a detailed biostratigraphic framework.
- Fine-grained stratabound ore has been partly remobilized and re-deposited as coarse sphalerite and galena along pressure solution cleavages and kink bands which develop in zones of high strain. The sulphides are therefore concentrated in zones of high strain.
- The sulphides are therefore not only in a single time-dependent stratigraphic unit (Active Member). The presence of sulphides does not qualify for assigning the host rock to the "Active Member". The nature and heterogeneity of the so-called "Active Member" and the presence of remobilized sulphides in discordant dissolution cleavage support diagenetic replacement and later remobilization of sulphides.
- The mineralization is repeated by thrust imbrication within the duplex and the duplex itself is repeated by out-of-sequencethrusts and back thrusts. Understanding the effects of deformation during Cordilleran orogeny is imperative in predicting the geometrical distribution of the ore.
- The March fault may have similarities with the better documented Dawson thrust. The Dawson thrust is believed to be responsible for localization of structurally controlled gold deposits (Rackla Gold trend and Tombstone Gold trend). Likewise, the March fault has been attributed to have played an important role in localization of non-magmatic Au mineralization in the Hyland Valley (Hart and Lewis, 2006). These faults are interpreted as early deep, and subsequently re-activated, structures along which metalliferous fluids were repeatedly transported and deposited along structure and favourable lithologies. The implications of the potentially comparable early structure on the deposition of base metals Howard's Pass are uncertain, and need further investigation.

CONCLUSIONS

Most structural elements formed as a result of thin-skin layer parallel shortening during Jura-Cretaceous northeast directed collision of accreted terranes onto ancestral North America, which deformed the syn- to diagenetic mineralization and host rock in a duplex and resulted in remobilization of some of the ore along pressure solution cleavage. Multiple levels of décollement, at both deep and shallow levels, in the Selwyn Basin have been observed and inferred. We believe that Howard's Pass is an exceptional opportunity to observe a flat-lying décollement exposed at, or just below, current erosional levels. This décollement extends and correlates with the décollement documented to the west of Howard's Pass (Gordey, 2008;

Hodder et al., 2014). Ductile deformation including shear fabrics (e.g. mylonitization), recrystallization, pressure solution cleavage, kink bands, transposition, folding and thrusting are observed in this regional duplex bounded by a floor thrust (near the top of Cambrian Rabbitkettle Formation) and an inferred roof thrust (at the base or within the Upper Devonian Earn Group). Thrust imbrication within the duplex involves the upper portion of the Rabbitkettle Formation, Duo Lake Formation, Steel Formation, and possibly the lower part of Earn Group. This interpretation is valid at the regional scale. At the district scale, the application of this simple interpretation is challenging because of the difficulty in correctly assigning rock types into a stratigraphy (i.e. unrecognized faults within the currently accepted stratigraphy, lack of systematic biostratigraphy, recognition of a shale unit (Hailstone Formation)). Also, the fact that some primary features have been obliterated during deformation makes it hard to know the manifestation of earlier pre-collisional deformation features (facies variations, syndepositional faulting, slump folding, and dewatering structures) on the current geometry.

We disagree with previous interpretations that Cordilleran deformation did not significantly affect the distribution of the ore. The thickest and highest grade drill core intersections of the resource are where thrusting has repeated the stratigraphic section, and where high (possibly syngenetic to diagenetic) stratabound metal concentrations are coincident with high remobilized metal concentrations in zones of high strain and coincident pressure solution cleavage. Acknowledging the structural controls on mineralization at Howard’s Pass is imperative in defining the distribution of zone with greatest ore concentration.

CONSIDERATIONS FOR FUTURE WORK

- A detailed biostratigraphy needs to be conducted, especially in strata of Duo Lake Formation, Steel Formation and Earn Group, to provide a framework to elucidate the effect of faulting and folding on the strata and mineralization.
- There is a paucity of in situ structural measurements of planar and linear fabrics (orientation of cleavages, shear planes, crenulations, fold axis, lineations, etc). A detailed structural analysis of fabrics in bedrock, ideally in situ, and in oriented drill core would be an invaluable addition to any structural interpretation of the Howard’s Pass district.
- The Earn Group rocks are generally better exposed than the older strata. Detailed stratigraphic and structural mapping of this unit would be instrumental in determining the structural style and postulated presence of an upper detachment at the base (or within) the Earn Group, above the strongly but heterogeneously deformed and thrust-imbricated Duo Lake and Steel formations.
- A detailed study on the nature and deformation of the silicic-barite mudstone of the Steel Formation would also be very beneficial to the understanding of the depositional environment, diagenetic processes and deformation of the Howard’s Pass deposit.
- The mapping conducted by the NTGO and the Selwyn Resources Ltd. (Hodder and Bain, 2005-2012, unpublished internal reports, Selwyn Resources Ltd.) has focused on the Howard’s Pass Formation, Steel Formation, and the uppermost Rabbitkettle Formation. Similarly, most drill holes were stopped when they intersected Rabbitkettle Formation. Therefore little is known about the Rabbitkettle Formation. Interestingly, drill hole 09 in

the Don deposit encountered a second horizon of mineralization (logged as Active Member) underneath the Rabbitkettle Formation (logged as Cambrian Limestone). A systematic approach to mapping and measuring sections of the Rabbitkettle Formation would be essential to understand the subsurface distribution of rock types.

- The concept of a duplex structure is proposed but the details need to be worked out. How many thrust sheets are identifiable within the duplex? Where is roof thrust? How was it deformed? What are the effects of strain partitioning? Where is the remobilized mineralization focused within the duplex? Where are the leading and trailing thrusts of the duplex?
- Surface bedrock geology correlation with oriented drill core logging is essential in order to provide an accurate 3D model for the district. Because of the abundance of mudstone of various compositions and the amount of strain partitioning present, the stratigraphy is difficult to identify in drill core. It is also complicated by the presence of ductile shear zones and brittle fault zones, partial to complete transposition of bedding and earlier fabric, and the presence of virtually undeformed horsts. There is a need to relog the core with a regional and structural perspective and a robust biostratigraphic framework.
- Ar-Ar radiometric age dating of muscovite in samples of the Howard's Pass décollement was attempted but not successful. Another method for dating the timing of shearing and fabric development would be beneficial to better constrain the timing of deformation and redistribution of the ore along related structures.
- Re-Os geochronology of various generations of pyrite interpreted to be temporally associated with sphalerite and galena could provide information on whether there was a single mineralizing event, or multiple ones.
- A reconnaissance-scale attempt at fission track thermochronology is currently underway. The objective of this study is to better constrain the time-temperature history of the rocks on either side of the March fault. Seven samples will be analyzed by apatite and zircon fission track thermochronology, and apatite and zircon (U/TH)/He thermochronology in order to determine exhumation history of each samples. The pattern on exhumation will constrain the displacement history across the March fault, helping to understand the latter's role in the deformation history of the Howard's Pass district, and the distribution of the rocks hosting Pb-Zn mineralization. If results are conclusive, a more systematic approach should be used to define the thermochronology of the March fault, and determine its prolonged movement history and potential role in the Pb-Zn mineralization, as well as Au mineralization along its southern extension in the Hyland Valley.

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