The geometry and kinematic history of Cordilleran deformation at the Howard's Pass shale-hosted massive sulphide deposit, Yukon: 1st year progress report

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Abstract

The shale-hosted massive sulphide Zn-Pb deposits of Howard's Pass were deposited during the Silurian and subsequently deformed during the Cretaceous Cordilleran orogeny. A recent model proposes that the deposits are hosted within a regional thrust duplex with strong transposition of bedding. This study aims to test this model and is focused on the XY group of deposits. Lithostratigraphic mapping and structural observations indicate one main phase of folding, F_1, and the XY group of deposits is located on the southern limb of a macroscopic F_1 syncline. F_1 folds are steeply inclined and gently plunging to the WNW–NW. A regionally developed, steep, NE dipping, cleavage, S_1, is axial planar to the F_1 folds across Howard's Pass. S_1 manifests as a slaty cleavage comprising pervasively developed dissolution seams. WNW and NNE striking extensional faults overprint F_1 folds. No shear fabrics or evidence for transposition of bedding were identified.

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Introduction

Shale-hosted massive sulphide (SHMS) Zn-Pb-Ag deposits account for 40% of Zn and 60% of Pb reserves globally (Goodfellow, 2004; Hoggard et *al.*, 2020). They also supply more than 25% of global production of these metals. In the past, SHMS deposits have been more commonly referred to as sedimentary exhalative, SEDEX, deposits. However, at several locations globally, there is evidence that such deposits do not form exclusively by hydrothermal exhalative processes on the seafloor, but can also be a product of replacement by infiltrating hydrothermal fluids in the subsurface during sedimentation, diagenesis, or early basin inversion (*e.g.*, Perkins, 1997; Kelley et *al.*, 2004; Leach et *al.*, 2010; Magnall et *al.*, 2016). They are usually deposited in tabular or lenticular stratiform sulphide bodies containing sphalerite, galena, pyrite, ± barite (McClay, 1991; Goodfellow and Lydon, 2007; Emsbo et *al.*, 2016). SHMS deposits form within intracontinental rifts and failed rifts, passive margins, and back-arc basins (Leach et *al.*, 2005; Goodfellow and Lydon, 2007). They are typically hosted within reduced sag-phase sedimentary units and form during periods of reactivated extensional faulting or, in some cases, during early basin inversion (Leach et *al.*, 2005; Goodfellow and Lydon, 2007; Gibson et *al.*, 2017). Sedimentary basins hosting SHMS deposits commonly undergo inversion and internal deformation during subsequent periods of crustal shortening and orogenesis (Bell and Hickey, 1998; De Vera et *al.*, 2004; Leach et *al.*, 2010; Gibson et *al.*, 2017), with many deposits being incorporated into foreland fold and thrust belts (*e.g.*, Red Dog; De Vera et *al.*, 2004).

The Selwyn basin, located in the Canadian Cordillera across central Yukon and western Northwest Territories, is host to several world-class Zn-Pb deposits (Fig. 1; Goodfellow, 2004; Goodfellow, 2007). These include the Devonian age Tom and Jason deposits of the Macmillan Pass district, the Cambrian age deposits of the Anvil district (*e.g.*, Faro, Grum, DY), and 15 Silurian age deposits that together comprise the Howard's Pass district in eastern Yukon, adjacent to the border with the Northwest Territories (Fig. 1; Goodfellow, 2004; Goodfellow, 2007). The latter group of deposits represents one of the largest undeveloped Zn-Pb resources in the world with an estimated 400 Mt grading 4.5% Zn and 1.5% Pb (Kirkham et *al.*, 2012). The Howard's Pass orebodies comprise bedded sulphide laminae hosted within Ordovician to Silurian siliceous and phosphoritic shales of the Duo Lake Formation (Morganti, 1979; Goodfellow and Jonasson, 1986; Goodfellow, 2007; Slack et *al.*, 2017). No vent complexes have been identified, and the deposits are generally considered to be examples of distal exhalative sulphide deposition, where mineralization was emplaced below the sediment–water interface as a dense, acidic, metalliferous brine percolated down into sulphidic muds during early diagenesis (McClay, 1991; Goodfellow, 2007; Gadd et *al.*, 2016, 2017; Slack et *al.*, 2017). During the Cretaceous Cordilleran orogeny, the rocks of the Selwyn basin underwent regional shortening and were incorporated into a foreland fold and thrust belt

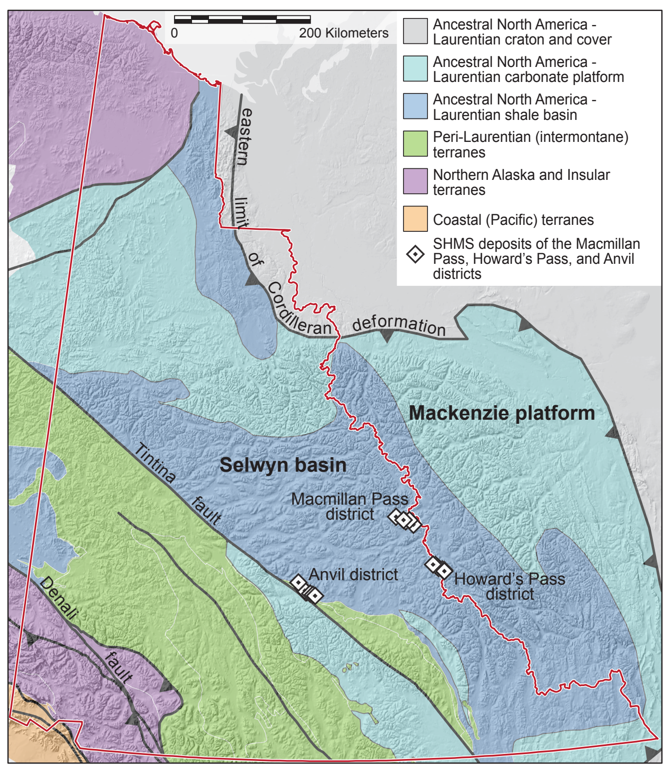


Figure 1. *SHMS Zn-Pb deposits of the Macmillan Pass, Anvil and Howard's Pass districts in the Selwyn basin of central Yukon. Geological terranes of the Canadian cordillera are grouped by paleogeographic affinities as described by Nelson et al. (2013). Geological data from Yukon Geological Survey (2020).*

to the east of the orogenic core (Gordey and Anderson, 1993; Mair *et al.*, 2006; Staples *et al.*, 2016). The region containing the Howard's Pass deposits has been affected by thin-skinned deformation forming relatively tight upright folds within wide, thrust-separated, fault panels (Gordey and Anderson, 1993; Gordey, 2013). The orebodies themselves are folded and have been locally remobilized into dissolution cleavages (McClay, 1991), although the intensity of deformation and the timing of deformation, Silurian *vs.* Cretaceous, have been subject of some debate (Goodfellow and Jonasson, 1986; Jonasson and Goodfellow, 1986; McClay, 1991; Martel, 2017; Slack *et al.*, 2017). Most previous workers agree, however, that the spatial distribution of the ore is largely unaffected by the deformation at the deposit to district scale.

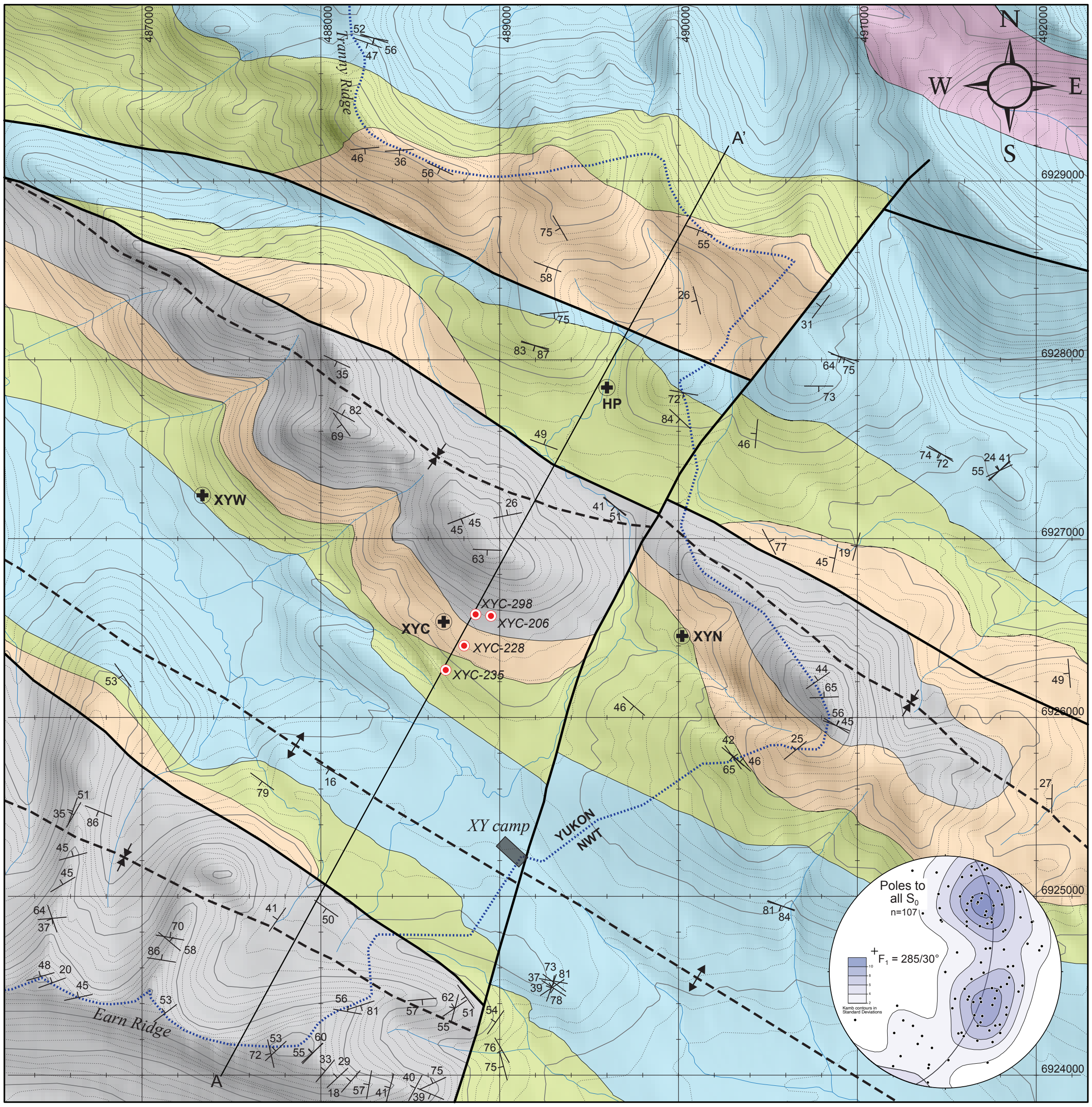
Recently, Hodder *et al.*, (2014) and Martel (2017) proposed that the ore horizons and their host stratigraphy in the Howard's Pass district lie within a regional-scale Cordilleran-age duplex structure with complex internal folding and imbricate thrusting between a mylonitic basal thrust (the Howard's Pass décollement) and an upper roof thrust. The duplex is described as having significant internal ductile deformation within steeply dipping thrust-bounded fault blocks, with Martel (2017) noting that zones of intense foliation development and transposition of bedding alternate with other zones that are only weakly to moderately strained. Hodder *et al.* (2014) and Martel (2017) suggest that the orebodies have been extensively imbricated by thrusting and accompanying tight folding. The sulphide minerals were remobilized and concentrated along pressure solution cleavage that is attributed to high-strain within the duplex rather than regional folding. Contrary to the previous geometric interpretations of Howard's Pass, the duplex model suggests that imbricate thrusting, folding, and bedding transposition rather than stratigraphic position are the main control on the distribution of SHMS ore at the deposit to district scale (Hodder *et al.*, 2014; Martel, 2017). The duplex model is a radical reinterpretation of the geometry and kinematic history of the Howard's Pass SHMS deposits. It has significant implications for the first-order controls on the spatial distribution of ore and the premise of stratigraphic control that underpins exploration for this deposit type (Martel, 2017).

Here we present preliminary results from a structural study of deformation in and around the XY group of deposits at the eastern end of the Howard's Pass district: XY Central (XYC), XY West (XYW), XY Nose (XYN), and the HP deposit (Fig. 2a). The goals of the study are to: (i) test the geometric and kinematic validity of the duplex model presented by Hodder *et al.*, (2014) and Martel (2017); (ii) assess how deformation history of the host rock package affected the sulphide orebodies; and (iii) determine the scale at which the distribution of ore is controlled by deformation. The data presented below represent the results of our initial, 2020, summer field season. The main focus of this field work was 1:10 000 scale lithostratigraphic and structural mapping in the XY area. A new geological map and section based on this mapping is shown in Figure 2. In addition, 1500 m of drill core was logged across 7 holes with 4 holes (XYC-206, XYC-228, XYC-235, XYC-298) located on Cross Section A-A' (Fig. 2b). Within some holes, only the mineralized portion was logged owing to time constraints. Logging focused on checking lithostratigraphic contacts and assessing structure in all lithostratigraphic units. This included documenting bedding-cleavage relationships, microfolding, veins, boudins, concretions, sulphide textures and all their overprinting relationships.

Geologic Setting

The Selwyn basin was initiated in the Neoproterozoic and sedimentation continued into the Mesozoic. The basin fill comprises rift (Neoproterozoic–Cambrian), continental margin (Cambrian to Mid-Devonian and Mississippian to Mesozoic), and backarc basin sediments (Mid-Devonian to Mississippian; Gordey and Anderson, 1993; Nelson *et al.*, 2013). Plate convergence on the northwestern margin of ancestral North America initiated in the Triassic and culminated in the Mid-Cretaceous Cordilleran orogeny (Gordey and Anderson, 1993; Mair *et al.*, 2006; Staples *et al.*, 2016; Monger and Gibson, 2019). During this orogeny the rocks of the Selwyn basin underwent significant shortening and now form a foreland fold-and-thrust belt that is wedged between the Mackenzie foreland fold-and-thrust belt and accreted exotic terranes along

a



Legend

0 — 1,000 Metre

Devonian

Earn Group
Undifferentiated mudstone and sandstone. Dark to light grey finely laminated mudstone with <5 mm grey-black silty layers. Weathered outcrops show distinct maroon bands. Interbedded with cherty lenses 1-20 cm and silty limestone up to 1 m. Often forms shale when breaking along dense cleavage planes. Mudstone is variably calcareous. Sandstone is fine-grained with small, rounded chert and quartz granules. Matrix is beige-yellow with orange weathering and consists of subrounded chert clasts and lithic fragments. Seen as piles of rubble and not *in situ*. Massive sandstone blocks are cut by large quartz veins. Poorly sorted conglomerate is seen just outside of the field area.

Silurian to Early Devonian

Steel Formation
Medium to dark grey mudstone with strong orange weathering strongly expressed in outcrop and in talus. Small, <1 cm dark grey silty layers show "wispy" texture that does not weather as strongly. Associated with weathered pyrite cubes with quartz-calcite pressure shadows. Contains coarse, crystalline limestone concretions ranging from 1 cm up to 2 m. Concretions exhibit a strong, fetid odor when a fresh surface is exposed.

Early Ordovician to Silurian

Duo Lake Formation
Dark grey to black, recessively weathering, mudstone. Fine-grained, carbonaceous and locally calcareous. Interbedded with thin <1 cm dark grey silty bands, chert lenses up to 1 m and limestone beds from 1 cm to 2 m. Contains 1 cm blue bands of phosphate. Very fissile and forms pencil cleavage in outcrop. Locally graptolitic towards the top. Mineralization is hosted within the "Active Member" and sulphides (sphalerite, galena, pyrite) are seen in sedimentary beds and in spaced, sulphide rich dissolution seams that are axial planar to folds.

Cambrian to Early Ordovician

Rabbitkettle Formation
Dominantly fine-grained, crystalline light grey limestone layers up to 5 cm with a "wavy" texture interbedded in a rusty orange silty, argillaceous matrix with visible quartz and feldspar. Matrix is variably dolomitic. Different varieties show much thinner layers with laminae thickness <1 cm and no dolomite. Local layers of massive crystalline limestone with no internal textures.

Cambrian

Vampire Formation
Recessive weathering, dark grey to brown, mudstone, siltstone and interbedded sandstone. Not mapped as part of this study, but compiled from Gordey and Anderson, (1993)

XYC — Pb-Zn deposit

XYC-228 — Drillhole

84 — Bedding, S_0

Contact

Fault

Trace of S_1 axial plane cleavage (cross section)

F_1 synform

F_1 antiform

AM — Active member of Duo Lake (on cross section)

Universal Transverse Mercator Projection, Zone 9N. North American Datum 1983.

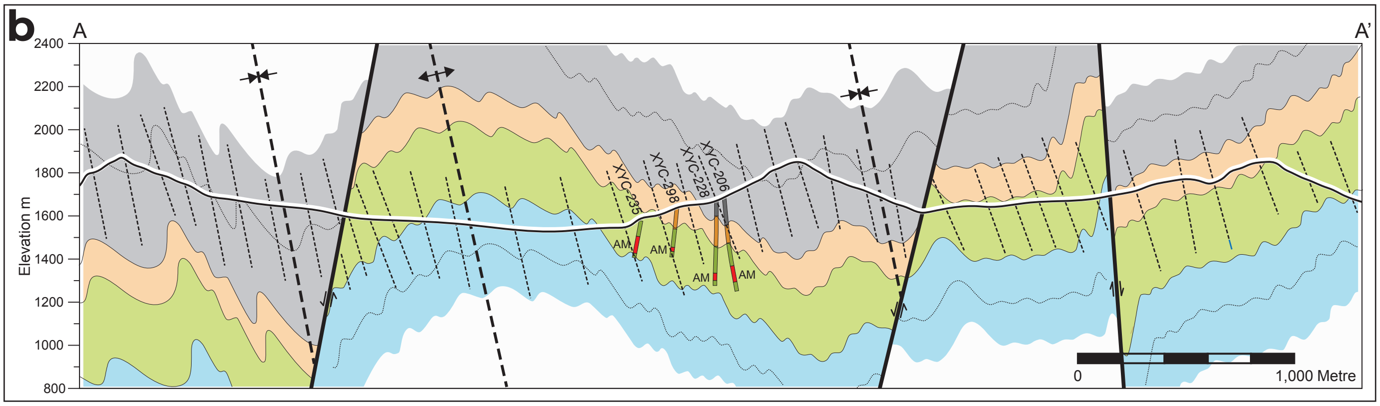


Figure 2. ***(a)*** *Geologic map of the 2020 field area with major fold axial traces, faults and cross section line shown. Stereonet of all bedding data collected in mapping area is shown in lower right (lower hemisphere projection, equal area).* ***(b)*** *Cross section A-A' through the XYC Deposit.*

the ancestral North American continental margin (Mair et al., 2006; Staples et al., 2016). Following regional deformation, the Selwyn basin was intruded by mid-Cretaceous granitoid rocks (Gordey and Anderson, 1993; Mair et al., 2006).

The oldest rocks within the Selwyn basin are the sandstone, shale and carbonate rocks of the Hyland Group which underlie the western Selwyn basin (Gordey and Anderson, 1993; Mair et al., 2006). These are constrained to the Neoproterozoic to early Cambrian age. The transition from carbonate platform sediments of the Mackenzie platform to basin facies occurs across a series of NW–SE to E–W trending normal faults (Eisbacher, 1981). The Hyland Group is overlain by a thick package of Cambrian to Middle Devonian strata that includes siltstone of the Cambrian Vampire Formation, shale of the Lower to Middle Cambrian Gull Lake Formation, siliceous limestone and calcareous shale of the Late Cambrian to Early Ordovician Rabbitkettle Formation, and carbonaceous shale, chert and mudstone of the Road River group, which comprises the Early Ordovician to Silurian Duo Lake Formation and Silurian to Early Devonian Steel Formation (Gordey and Anderson, 1993; Turner et al., 2011). Finally, the Earn Group was deposited during the Early to Middle Devonian and is characterized by a stratigraphically complex package of black siliceous shale, chert, mudstone, quartz-arenite, and conglomerate with unconformities and sharp variations in thickness and facies (Garizone et al., 1997). Regional metamorphic grade in the Howard's Pass region is constrained to sub-greenschist facies as estimated by Gordey and Anderson (1993).

The stratiform orebodies at Howard's Pass district comprise 15 separate Zn-Pb deposits distributed along a 40 km-long NW–SE trending corridor adjacent to the Yukon-Northwest Territories border. All the deposits of Howard's Pass are hosted in the Duo Lake Formation, which Morganti (1979) subdivided into four separate members that from bottom to top are: the Pyritic Siliceous Mudstone (PSMS), the Calcareous Mudstone (CCMS), the Active Member (ACTM), and the Upper Siliceous Mudstone (USMS). A Lower Cherty Mudstone was also broken out but is now combined with the CCMS. The Active Member is defined by the presence of fine-scale, bedding parallel, laminae of sphalerite, galena and pyrite and is the host for mineralization. In a recent study, Kelley et al., (2017) reported a Re-Os isochron age of 442 ± 14 Ma for 12 pyrite separates from the Don and XYC deposits at Howard's Pass. The textures of the pyrite are interpreted as being indicative of coeval deposition with sphalerite, and mineralization is considered to have occurred during the early Silurian, concurrent with sedimentation or early diagenesis.

Much of the stratiform ore at Howard's Pass exhibits hand specimen-scale tight folding of sulphide laminae with spaced sulphide-rich seams that crosscut the laminae at a high angle (Morganti, 1979; McClay, 1991; Jonasson and Goodfellow, 1986; Kelley et *al.*, 2017; Gadd et *al.*, 2016; Martel., 2017; Slack et *al.*, 2017). Jonasson and Goodfellow (1986) attribute the folding to Silurian tectonic deformation during compaction and dewatering of the sediments. Some of the crosscutting sulphide seams are attributed to dewatering and the formation of sulphide "concretionary pillars", while others are recognized as dissolution cleavage related to folding (Jonasson and Goodfellow, 1986). In the latter case dissolution has removed almost all of the quartz and/or carbonate to leave a very high concentration of sulphide and carbonaceous matter (McClay, 1991). The folding and pressure solution cleavage are now generally considered to be a product of Cordilleran rather than Silurian deformation (McClay, 1991; Gadd et *al.*, 2016, 2017; Martel, 2017).

Lithostratigraphy

The following section provides a brief description of the lithostratigraphic units within the mapped area shown in Figure 2. From oldest to youngest, these are: the Vampire, Rabbitkettle, Duo Lake, and Steel formations, and rocks of the Earn Group. The descriptions combine field observations made during this study with those of previous workers (Gordey and Anderson, 1993; Martel et *al.*, 2011; Gordey, 2013). The Vampire Formation was not mapped during this field season and is not described below.

Rabbitkettle Formation

The Rabbitkettle Formation is a thick package of limestone interbedded with shale that overlies the Vampire Formation around the XY deposits. Rabbitkettle comprises three lithofacies: wavy banded limestone, massive limestone and the transition zone (Fig. 3). The wavy banded limestone is the most common of the lithofacies in the study area. It consists of 1–5 cm thick crystalline limestone beds embedded in a rusty brown-orange, variably dolomitic and argillaceous matrix. Original descriptions by Morganti (1979) describe the "wavy" texture as nodular limestone. Wavy banded limestone outcrops display well-developed mesoscopic folding and good exposures are seen in the valley near the XY Camp. Massive Rabbitkettle limestone was only observed as large talus boulders at Tranny Ridge (Fig. 2a). This unit lacks compositional layering and comprises massive, grey, fine-grained crystalline limestone. The transition zone forms the top of the Rabbitkettle Formation and underlies the Duo Lake Formation. It is similar in composition to the wavy banded limestone but the laminae occur on the <1 cm scale (Fig. 4). The orange-brown layers are fine-grained argillaceous siltstone that contain variable amounts of dolomite.

Pratt (1992) correlated trilobite ages of the Late Cambrian (NTS 105P and NTS 105I). Gordey and Anderson (1993) reported a mid-Ordovician conodont age for the Rabbitkettle Formation in contact with Duo Lake Formation at Howard's Pass. Within the study area it is estimated to have a minimum thickness of between 650 and 700 m.

Duo Lake Formation

The Duo Lake Formation, part of the Road River Group, conformably overlies the Rabbitkettle Formation and is predominantly a dark grey to black, recessively weathering, shale (Fig. 5). The uppermost USMS Member of the Duo Lake is a siliceous, non-calcareous, massive, carbonaceous mudstone interbedded with light grey cherty mudstone and limestone up to 2 m thick. Graptolites are found in the upper 15 m of the unit. The unit shows abundant crystalline limestone concretions up to 1 m in diameter. Zones with cherty texture show strong conchoidal fracturing. Small blue bands <5 cm thick have been interpreted to be phosphatic by Slack et *al.*, (2017). Galena and sphalerite occur locally near the contact with the underlying Active Member, which is host to the mineralization at Howard's Pass. The Active Member is a 20 to 80 m thick repetitive sequence of carbonaceous mudstones, chert, limestone and economically significant Zn-Pb mineralization. Sphalerite and pyrite occur in planar laminae that are <0.5 cm thick. Within the laminae, pyrite is fine-grained and has a framboidal habit. Sphalerite is fine-grained and beige with a dull luster. In the diamond drill core examined in this study,

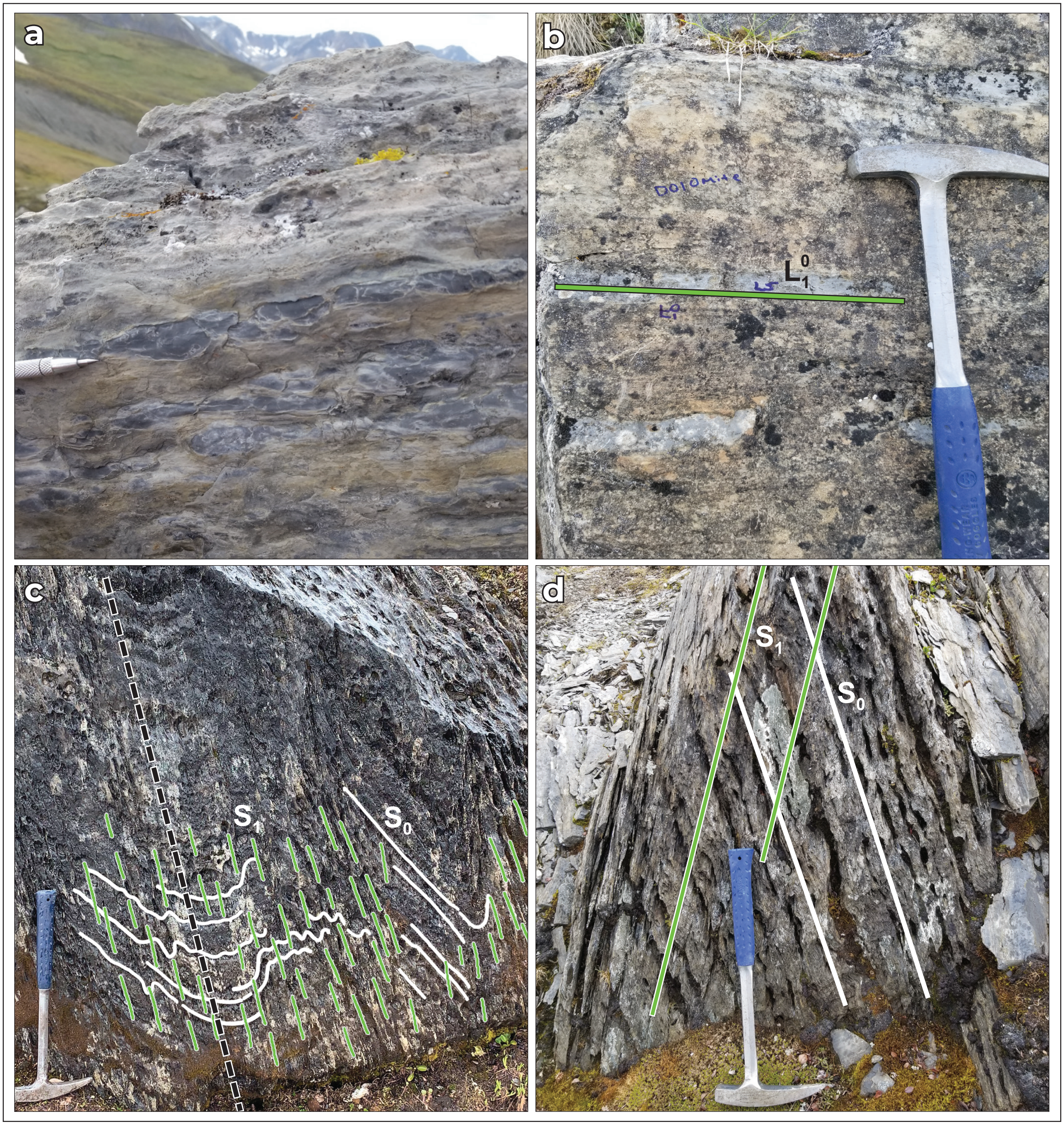


Figure 3. *Rabbitkettle Formation.* ***(a)*** *Wavy banded limestone interbedded with orange weathering silty mudstone.* ***(b)*** *Grey planar limestone beds within thicker dolomitic layers. The exposed face of the outcrop is parallel to S_1 and the trace of bedding defines the intersection lineation, L_1^0 (green line).* ***(c)*** *Mesoscopic folding within the Rabbitkettle limestone. Axial planar cleavage (S_1) shown by short green lines. Folded bedding S_0 are highlighted by white lines. The black dashed line defines the axial plane of the synform, 285/76°NE.* ***(d)*** *Rabbitkettle limestone with the S_1 cleavage indicated by green line and bedding, S_0, by white lines. Asymmetry indicates direction to nearest antiform is to the left of the image. Hammer and scribe for scale.*

galena was rarely observed in sulphide laminae. The CCMS Member is characterized by a lack of Pb and Zn mineralization. It is a massive, calcareous, carbonaceous, dark grey to black mudstone. Calcite occurs as cement within the mudstone or as small, <1 cm concretions. As the unit is massive, primary bedding is hard to identify. The lowermost PSMS Member is a massive, carbonaceous black mudstone with 1 to 10 mm long lenticular pyrite concretions. The PSMS Member is not present everywhere in the stratigraphic sequence and in places the CCMS Member is in conformable contact with the underlying Rabbitkettle Formation.

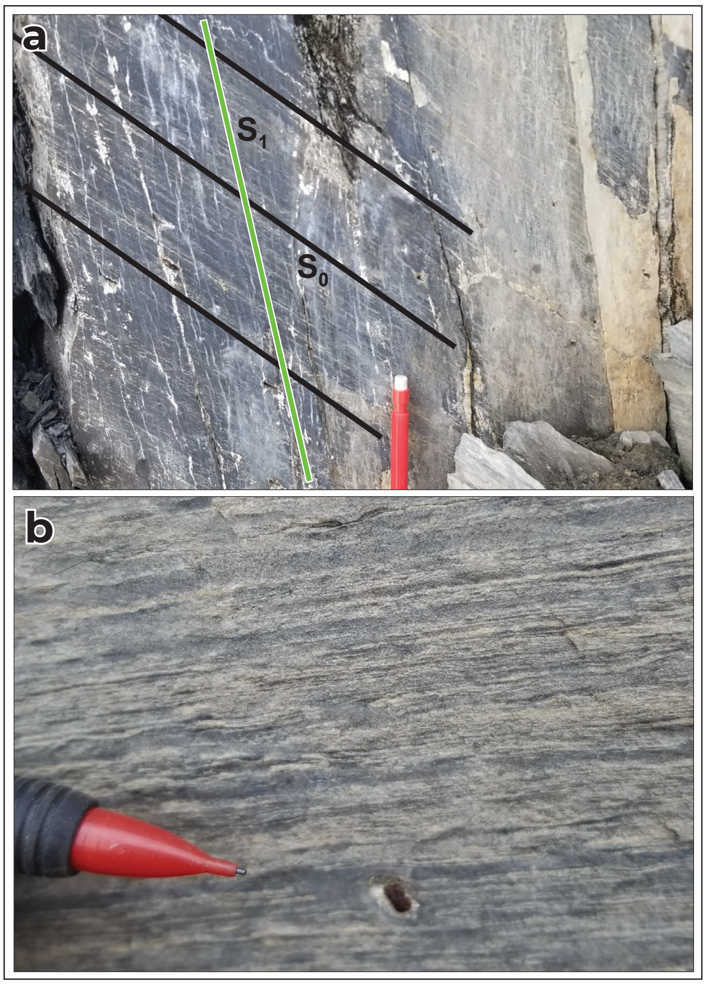


Figure 4. *Rabbitkettle Formation transition zone.* ***(a)*** *Thin (mm-thick) limestone layers (grey) with interbedded mudstone. Black lines highlight bedding,* S_0*. The green line highlights* S_1*.* ***(b)*** *Close up of (a) with pencil for scale. Weathered pyrite cube has a narrow calcite pressure shadow.*

Owing to the recessive nature of the Duo Lake members and the predominance of massive, black mudstone, it is hard to identify which members are exposed at surface unless visible sphalerite or galena is present which indicates the Active Member. The formation is well exposed around XYC, XYW, and XYN. It typically weathers grey-orange, but around the XY deposits, it bleaches to a yellow colour along cleavage planes. Conodont and macrofossils constrain the age of the Duo Lake Formation to be mid-Ordovician to Silurian (Cecil, 1982; Kelley et *al*., 2017). The Duo Lake Formation has a total thickness of up to 300 m.

Steel Formation

The Steel Formation, also part of the Road River Group, overlies the Duo Lake Formation across a sharp, conformable boundary. The Steel Formation is an orange-weathering mudstone whose diagnostic colour provides a useful marker horizon in the district. Outcrops of Steel mudstone are relatively common in the XY area, most notably around the deposits at XYW, XYC, and XYN. Contacts between Steel and other units are well exposed in ridge facies and talus slopes. Fresh rocks of the Steel Formation are a light grey mudstone interbedded with dark grey carbonaceous layers that show a “wispy” texture (Fig. 6). The wispy bedding does not weather orange like the rest of the rock but becomes a light grey. Different workers have attributed wispy bedding to bioturbation by microorganisms (Gordey and Anderson, 1993). Weathered cubic pyrite grains with distinct pressure shadows of quartz and calcite are seen in both core and outcrop. Limestone concretions are abundant and can be up to 2 m in diameter (Fig. 6b). Concretions give off a strong fetid odor when broken. The unit’s age is poorly constrained, but conodont assemblages provide a tentative range of Silurian to Upper Devonian (Gordey and Anderson, 1993). The Steel Formation has an estimated thickness of 100 to 150 m in the XY area.

Figure 5. *Duo Lake Formation.* ***(a)*** *Outcrop of Duo Lake black mudstone with distinct orange weathering from the south side of the XY Nose.* ***(b)*** *Weathered Duo Lake showing oblong blocks caused by preferential parting along S_1 (subvertical dip to right) and S_0 (gentle dip to left).* ***(c)*** *Diagnostic black cherty mudstone of Duo Lake Formation (Upper Siliceous Mudstone member). White fracture fill is probably clay minerals. Hammer and notebook for scale.*

Figure 6. Steel Formation. ***(a)*** Outcrop north of XYC (looking 270) with well-developed cleavage-bedding asymmetry. S_1 is 255/79°N and indicated by green line. Bedding, S_0, (white line) is 110/58°S. Cleavage-bedding asymmetry indicates antiform to the right of the image. ***(b)*** Fetid limestone concretion. Found from the cm scale up to >1 m. Orange weathering talus that is diagnostic of Steel Formation litters the ground around the concretion. ***(c)*** Intersection lineation (L_1^0) of bedding on S_1 cleavage surface (green line). Characteristic bioturbated "wispy" bedding is prominent in this outcrop. ***(d)*** Similar to (c), with L_1^0 intersection lineation (green line) of bedding on weathered S_1 cleavage face. Hammer and pencil for scale.

Earn Group

The Earn Group is the youngest unit exposed in the field area and consists of finely laminated mudstone interbedded with fine-grained sandstone. Just outside the field area in the south and west, large ridges of poorly sorted pebble conglomerate dominate. The Earn mudstone is medium to dark grey, with maroon laminae up to 5 cm thick (Fig. 7). The mudstone is typically interbedded with thin, <1 cm silty layers and cherty beds up to 1 m thick. The unit breaks readily along cleavage planes where they are well-developed in outcrop (Fig. 7a). Bedding is generally planar. The Earn sandstone is fine to medium grained with small, well-rounded chert and quartz grains. It is beige-yellow with orange weathering. Outcrops of sandstone are rare and it is rarely seen *in situ*. Gordey and Anderson (1993) have mapped the Earn Group rocks in the field area as the Portrait Lake Formation and give its age as Early to Late Devonian.

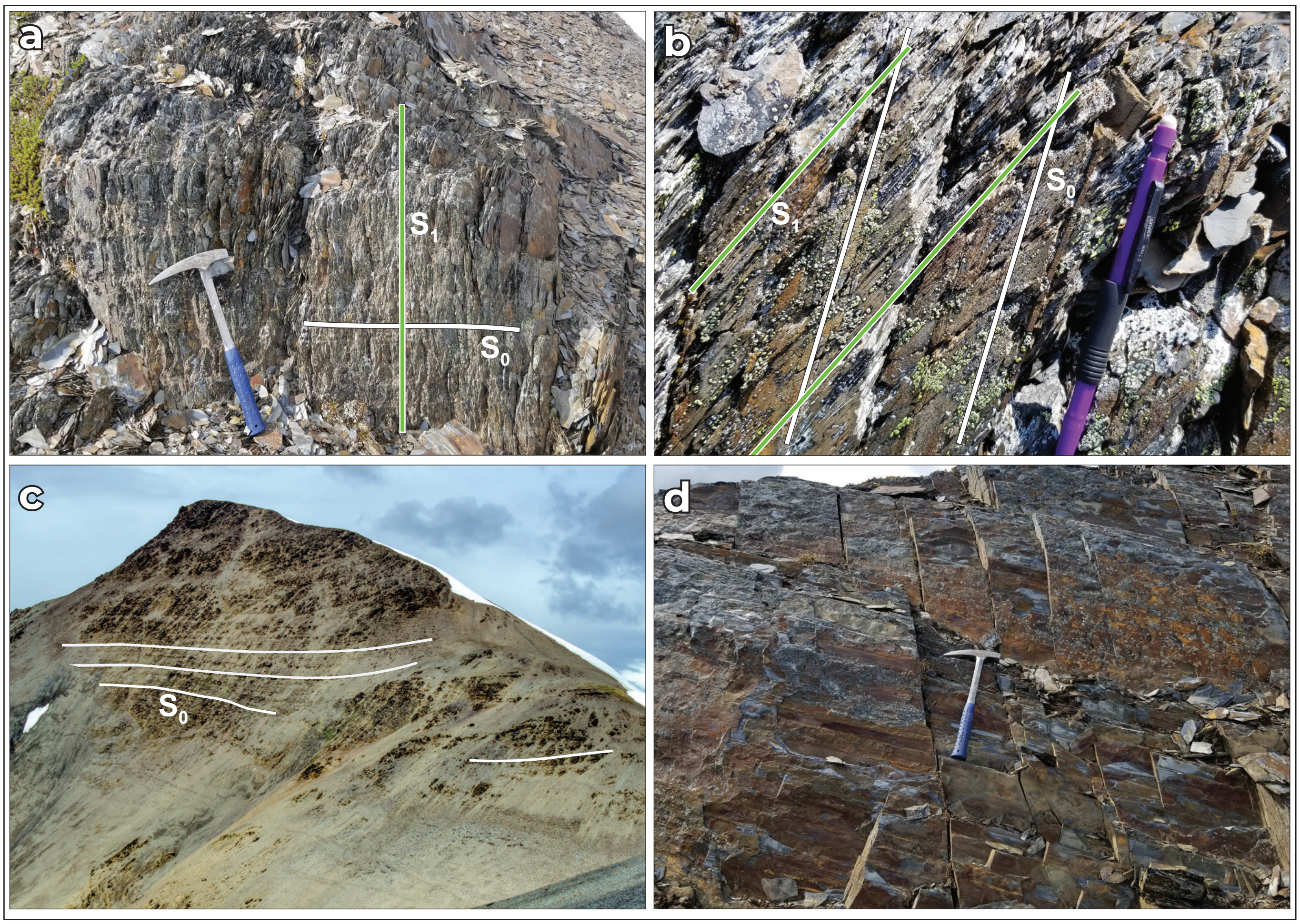


Figure 7. *Earn Group.* ***(a)*** *Highly fissile Earn mudstone with S_1 slaty cleavage (green line) perpendicular to bedding, S_0 (white line) in hinge zone of F_1 fold.* ***(b)*** *Well-developed cleavage-bedding relationship. The S_1 cleavage (green line) is 310/58°NE and bedding, S_0 (white line), is 293/75°NE. Asymmetry indicates antiform to the left of the image.* ***(c)*** *Bedding, S_0, dipping moderately into the ridge face on south limb of the XY Syncline.* ***(d)*** *Blocky Earn Group strata with distinct maroon weathering. Hammer and pencil for scale.*

Structure

Methodology

Structural mapping focused on determining the geometric relationship of primary compositional layering, bedding (S_0), relative to the dominant foliation developed at the hand specimen to outcrop scale. The goal was twofold: firstly, to use bedding-cleavage asymmetry at the mesoscopic scale to determine the direction to antiform (vergence; Figs. 3d, 6a, 7b) and map out the geometry of folds at the macroscopic scale (e.g., Bell and Hickey, 1998; Hickey and Bell, 2001). Secondly, to evaluate the evidence for the transposition of bedding within a duplex structure and any fabrics indicating significant non-coaxial shear attributed to intense ductile deformation by Martel (2017).

Bedding was readily identified in most outcrops across the study area. It is discernable from the hand specimen scale to the macroscopic scale; being evident on mountain sides (Fig. 7c) and in satellite imagery of the whole XY region. In units of the Rabbitkettle Formation, bedding is most commonly manifested as interlayered, variably dolomitized, limestone bands and argillaceous silt layers (Figs. 3a,b and 4). Within Duo Lake Formation mudstones, bedding is defined by thin, <1 cm, bands of siltstone. In the more siliceous sections of the Duo Lake Formation, careful inspection is needed to identify such siltstones in individual outcrops. Bedding in the Steel Formation is evident as bioturbated silt layers (Fig. 6a,c,d). In the Earn Group rocks, bedding is most readily visible as mudstone interbedded with laminae and thin beds of siltstone (Fig. 7a,b). In more massive, coarse-grained, sandstone and conglomeratic units of the Earn Group, bedding planes are less obviously discernable at the outcrop scale.

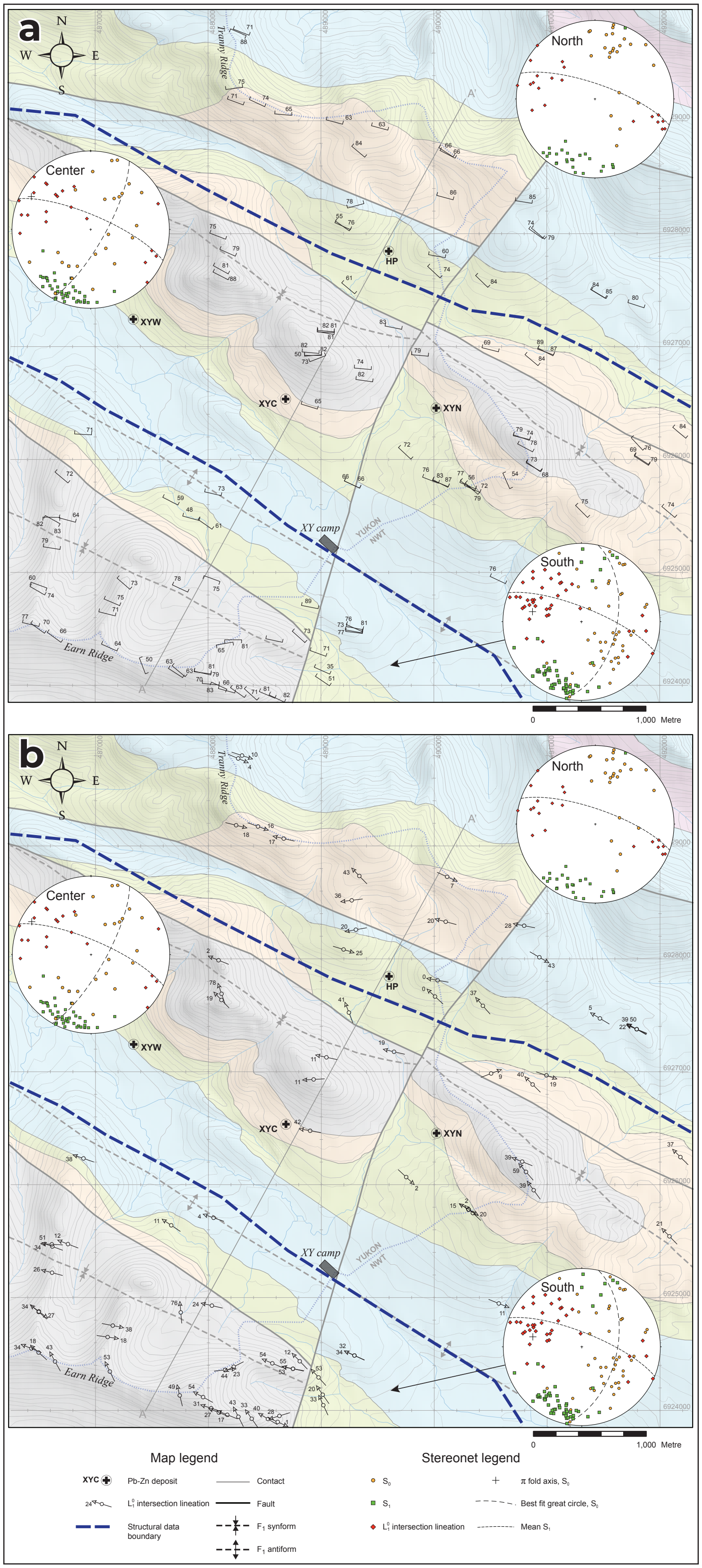
F_1 Folding

Figure 8 presents a summary of structural data collected across the XY area during the 2020 field season. Our structural mapping is consistent with the XY area having been affected by one main phase of folding, F_1. Folds are developed at all scales with a well-developed axial planar foliation, S_1. The best examples of mesoscopic F_1 folds occur in wavy banded units of the Rabbitkettle Formation (Fig. 3c), but they are developed in all stratigraphic units. F_1 folds are upright (Fig. 2b) and S_1 has a subvertical to steep NNE dip (Fig. 8a). L_1^0 intersection lineations have a horizontal to gentle WNW plunge (Fig. 8b).

S_1–S_0 asymmetry (vergence) identified three macroscopic steep, NNE dipping, F_1 folds in the XY area (Figs. 2 and 8): a synform centered on the Earn Ridge south of the XY Camp with an approximate trend and plunge of 299/30°; an antiform that passes through the area of the XY Camp immediately south of the deposit with a trend and plunge of approximately 300/20°; and another synform along the topographic ridge immediately northeast of XY and XYN with an approximate trend and plunge of 300/20°. Outcrops northeast of the central synform have a consistent S_1–S_0 asymmetry indicating the presence of another macroscopic antiform somewhere to the northeast of the study area (Figs. 2a and 8b). Although F_1 folds at the outcrop scale can be open to close in terms of interlimb angle (Fleuty, 1964), the macroscopic F_1 folds have an open geometry with wavelengths and amplitudes of ~4 km and ~700 m respectively (Fig. 2b). The study area was split into three separate zones (south, central and north) based on the density of data points gathered during the field season. Structural data for each of these zones are presented on stereonets in Figure 8.

S_1 Cleavage

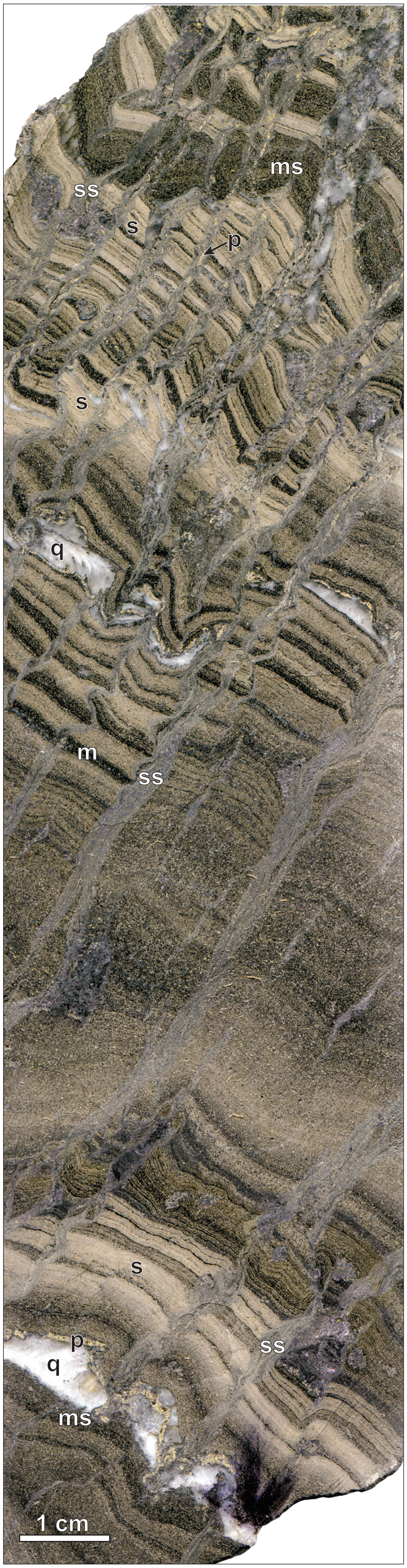
In all lithostratigraphic units except the Active Member of the Duo Lake Formation, S_1 is typically manifested as a well-developed slaty cleavage comprising penetrative dissolution seams that are axial planar to F_1 folds at all scales (Fig. 9). S_1 was the only penetrative foliation observed in the XY area. No evidence was found for an earlier foliation at a low angle or subparallel to S_0, and S_1 was not observed to transpose S_0 to any significant extent. Variable degrees of S_1 refraction across bedding contacts is common in the limbs of mesoscopic F_1 folds (Fig. 10a,b), especially in Rabbitkettle Formation and Earn Group units and this can decrease the cleavage-bedding obliquity in less competent units. However, at the outcrop scale S_0 has an enveloping surface that is always oblique to S_1 and changes in cleavage-bedding asymmetry reflect a switch in vergence across F_1 fold hinges.



Sulphide Seams

Mineralized laminae intersected in drill core through the Active Member at XYC are commonly crosscut by sulphide-rich seams that are up to 0.5 cm wide (Fig. 9). In areas of high Zn + Pb grade (~30% Zn, 15% Pb) the seams have a spacing of about 1 cm, and are typically at a high angle to bedding laminae. Sphalerite and pyrite are common within the laminae and seams. Where present, galena tends to be concentrated more in the sulphide seams. Pyrite, sphalerite and galena are coarser grained within the seams than the laminae they cut across (Fig. 10c,d). Sulphide grain size is finer on the edge of the seam than the center (coarse grains are up to 3 mm). The sulphide seams also contain a high amount of carbonaceous material. Sphalerite often occurs as inclusions within larger pyrite grains. Sphalerite shows a lighter colour within the sulphide seam and a darker colour in the laminae when viewed in plane polarized light. Locally, sulphide seams transition along their length into spaced dissolution cleavage with a more stylolitic texture in intervening layers of carbonaceous mudstone, chert or limestone. These dissolution cleavages are axial planar to microfolds and are interpreted as being S_1. In the core we have logged to date, no evidence has been found to suggest that the sulphide seams are a different generation to S_1 in the intervening layers (no significant obliquity and no overprinting relationships). Consequently, the sulphide seams are considered to be an expression of S_1 in sulphide-rich laminae.

Figure 8. ***(a)*** *Overlay map of S_1.* ***(b)*** *Overlay map of L_1^0 intersection lineation. The mapping area has been subdivided into three structural zones based on data density: North zone (north of the XY deposits); Center zone (centered on the XY deposits); and South zone (south of XY camp). Structural data for each zone is presented on a separate stereonet (lower hemisphere projection, equal area). See Figure 2 for explanation of geological units.*



S_k Kinks

A set of kink bands, S_k, that overprint S_0 and S_1 are developed in Earn Group mudstones and Rabbitkettle wavy banded limestone at a limited number of locations across the study area (Fig. 11). The kink bands have moderate to subvertical dip and a NNW to NNE strike. An area with well-developed S_k, is developed in Earn Group rocks spatially adjacent to the trace of a steep, NW–SE striking, fault on the southern limb of the antiform just south of the XY deposits (Fig. 11a), suggesting the kinks may be linked to movement on that structure. This is also exhibited in the northwestern part of the field area where kinks in the Rabbitkettle wavy banded limestone (Fig. 11b) are observed directly adjacent to a NNE–SSW extensional fault.

Faults

Several WNW and NNE striking faults that postdate F_1 folding occur in the study area. Mapping constraints on their trace across topography indicate that they are steeply dipping structures. Relative displacement of folds and stratigraphic contacts suggest predominantly normal dip-slip movement. In the southern part of the mapping area, a steeply SW dipping fault SW of the XY Camp omits a thin layer of Steel Formation and juxtaposes younger Devonian rocks of the Earn Group against the older Silurian Duo Lake Formation. Just north of XYC and XYN, rocks of the Earn Group are juxtaposed against Duo Lake Formation across a steep SW dipping fault. Farther to the east and west, Steel wraps around topography on the northern limb of the synform that hosts the XY deposits. Between the two deposits, there is no Steel Formation exposed and Earn Group is in contact with Duo Lake Formation across the fault, indicating a normal sense of displacement. A NNE–SSW striking extensional fault is mapped down-dropping rocks of the Steel Formation against Rabbitkettle Formation. These faults are not well exposed at surface.

Figure 9. *Drill core through a deformed section of the Active Member at the XYC deposit. Sulphide-rich and mudstone laminae are crosscut at a high angle by sulphide seams. The sulphide-rich laminae and the sulphide seams are largely made up of sphalerite and pyrite. Galena was rarely identified and is concentrated in the seams rather than the laminae. m = mudstone; ms = mudstone with disseminated sulphide; s = sulphide-rich laminae; p = pyrite; ss = sulphide seam; q = extensional quartz veinlets. Core is from XYC-235 at 86.70 m.*

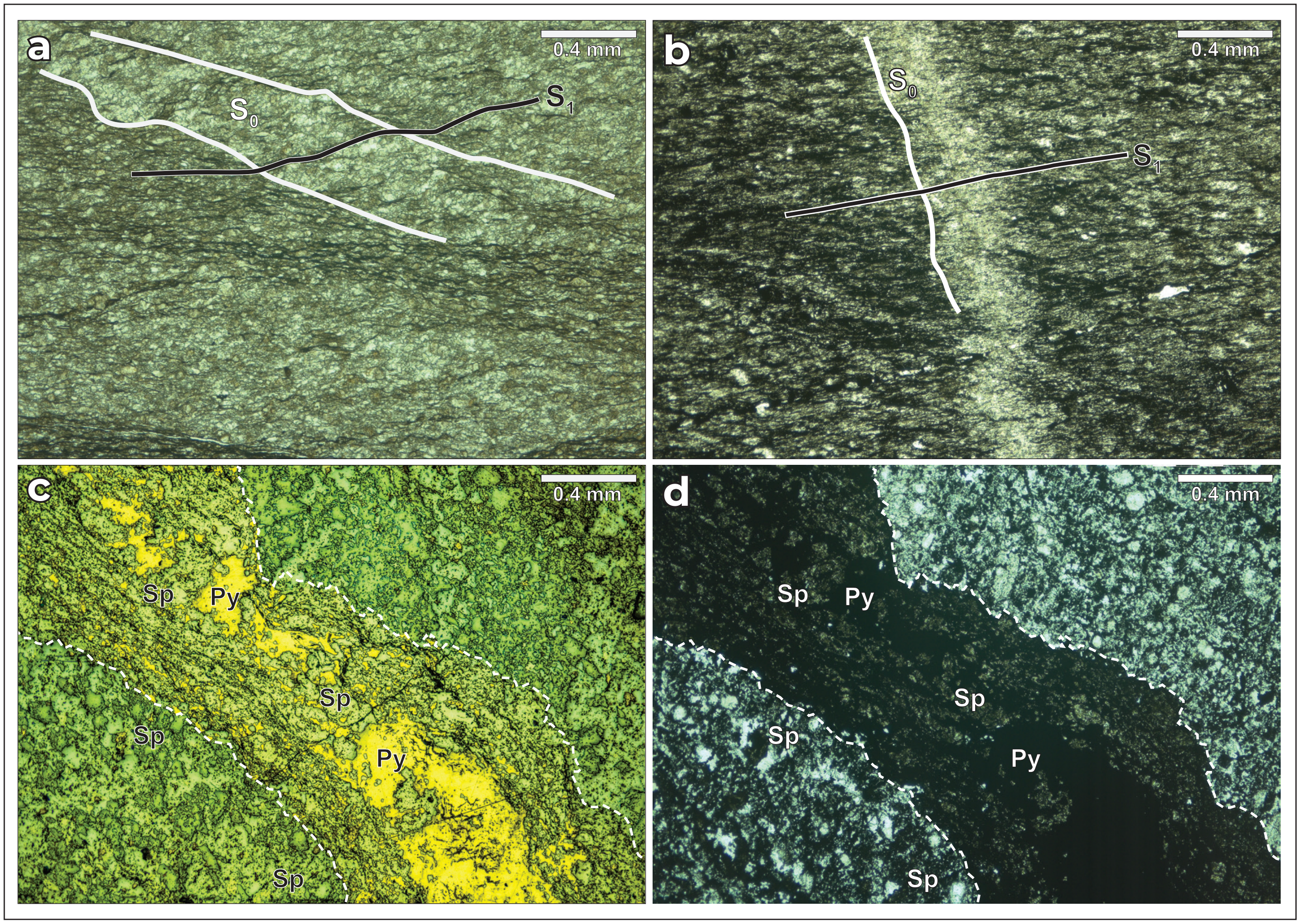


***Figure 10. (a)** PPL image of bedding, S_0 (white line), and S_1 slaty cleavage (black line) within Rabbitkettle wavy banded limestone. S_1 refracts slightly across bedding laminae. **(b)** PPL image of bedding, S_0 (white line), and S_1 slaty cleavage (black line) within the USMS Member of the Duo Lake Formation. S_1 is at a high angle to S_0 indicative of an F_1 hinge zone. **(c)** Reflected light image from the Active Member of the Duo Lake Formation. Sulphide-rich seam (highlighted by dashed white lines) crosscuts sulphide-rich laminae making up the wall rock. Coarse-grained pyrite fills the center of the sulphide seam. Sphalerite occurs in the sulphide seam and in the surrounding wall rock. Sphalerite is lighter coloured in the seam than in the wall rock. **(d)** Same image in plane polarized light (PPL). Pyrite is opaque. Sphalerite is slightly anisotropic. Sp = sphalerite; Py = pyrite. Scale bar is 0.4 mm on all images.*

Although most of the faults identified in this study are thought to be normal faults, a steep fault with an apparent backthrust geometry is exposed in Earn Group rocks just W of the SW corner of the mapping area (Fig. 12). Bedding on the south side dips approximately 50° NNW. Across the fault, bedding is rotated to a steeper, subvertical dip.

Discussion

Our first season of mapping indicates that the cluster of XY deposits at Howard's Pass has been affected by one main deformation event that folded the host sedimentary strata into a series of upright to steeply NNE dipping, gently WNW to NW plunging folds (Figs. 2 and 8). These folds are part of a regional Cordilleran fold set that are extensively developed along the northeastern half of the Selwyn basin (Gordey and Anderson, 1993). The axial planar cleavage, S_1, is

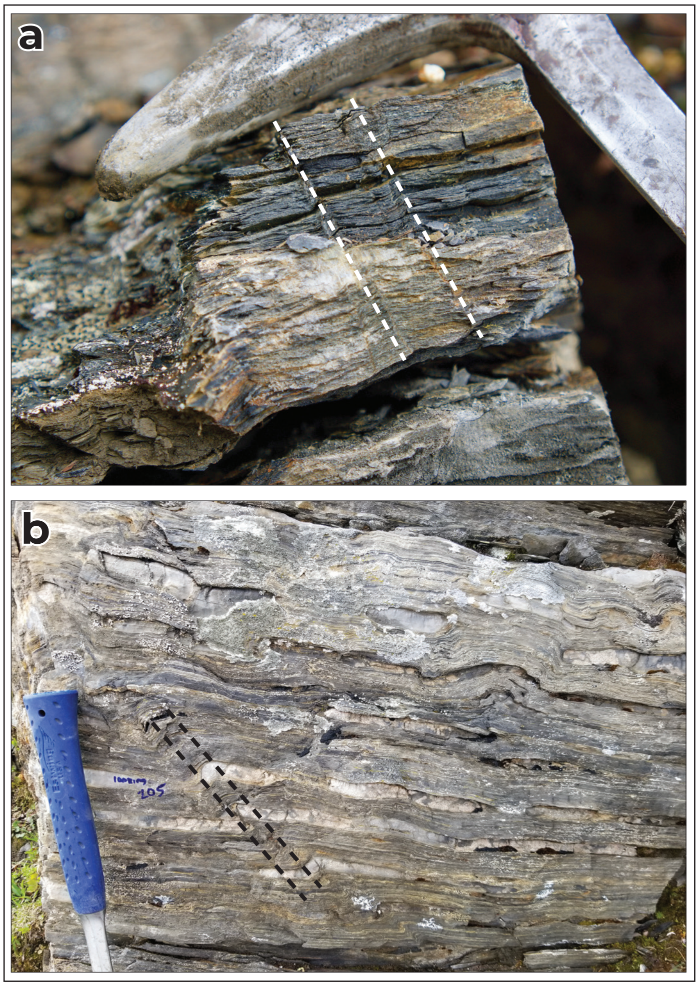


Figure 11. (a) *Kink banding (white dashed lines) within the Earn Group mudstone in the southern field area (NAD83/UTM9N, 486612 E, 6925420 N).* ***(b)*** *Kink banding (black dashed line) within Rabbitkettle limestone adjacent to normal fault at 490924 E, 6928012 N (NAD83/UTM9N).*

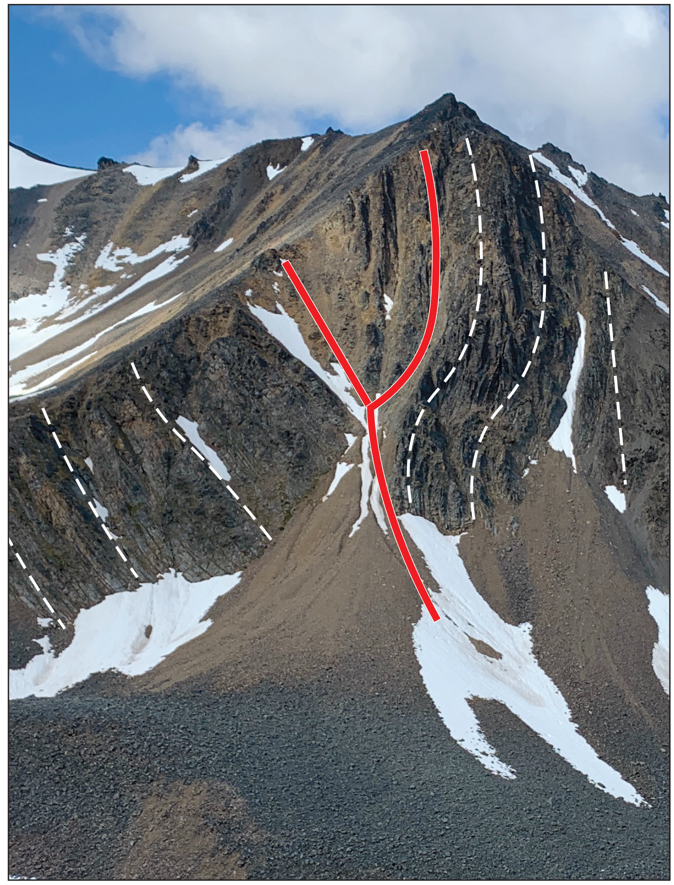


Figure 12. *Backthrust in Earn Group rocks just outside the SW corner of the mapping area (at NAD83/UTM9N, 485625 E, 6924848 N). Bedding appears to be dipping ~50° NW and is rotated to subvertical across the trace of the thrust. White dashed lines highlight bedding. Red lines highlight the thrust trace.*

also regionally developed (McClay, 1991; Gordey and Anderson, 1993). The distribution of host rock units in the XY region and the mapped changes in vergence determined from bedding-cleavage asymmetry and minor fold asymmetry are consistent with a conformable, folded, stratigraphic sequence. There are no mapped stratigraphic relationships identified to date that require the presence of significant thrusts to explain the geometry of mapped lithostratigraphic units. In that respect, our results are at odds with Martel (2017) who suggests that thrusts are needed to explain the geometry of lithostratigraphic units in the Howard's Pass district. Similarly, we did not observe any structural evidence for the thrust duplex proposed by Hodder et al., (2014) and Martel (2017). The steeply dipping S_1 slaty cleavage is well developed in almost every rock type and is kinematically linked to the development of F_1 folds at all scales. No other mylonitic foliation was observed and there is no evidence for extensive transposition of bedding prior to the development of S_1. The transition zone at the top of the Rabbitkettle Formation has been described as a mylonitic basal thrust by Martel (2017), but in outcrops visited as part of this study S_1 is the only foliation present and its angular relationship to S_0 is a function of its relative location across an F_1 fold.

It is possible that there are some thrusts present in the XY area, and one possible backthrust exposed in Earn Group rocks (Fig. 12) is supportive of that possibility. However, it is unlikely that any such thrusts have significant displacement across them. Smaller scale thrusts might be an explanation for multiple intersections of the Active Member of the Duo Lake Formation in several drillholes at XY (Martel, 2017), although tight F_1 folding might be more likely. At the deposit to district scale, our mapping is consistent with the distribution of ore being primarily a stratigraphic control (the Active Member) with local reconcentration of sulphides in dissolution cleavages (the sulphide seams) occurring at the hand specimen to microscopic scale (Figs. 9 and 10c,d).

A post-folding series of steeply dipping, WNW and NNE striking faults overprint the regional F_1 folds, and an observed kink fabric, S_k, may be associated with movement on these structures. As the timing on these faults are poorly constrained, it is possible that they have been reactivated several times in the past and that the current apparent displacement may be a product of more than one period of movement. Although no feeder structures for the mineralization have been identified at Howard's Pass, it is possible that one of the mapped faults might represent a Silurian structure that controlled the upwelling of hydrothermal metalliferous fluid. Cordilleran reactivation of such faults might make it difficult to identify them as feeder structures.

Future Work

The work presented in this report is based on one, initial season of mapping at Howard's Pass. Additional microstructural analysis of oriented samples and of drill core collected as part of that fieldwork will be undertaken to evaluate the kinematic evidence for significant non-coaxial shear as proposed by Martel (2017). Next year, additional mapping around the XY region will be focused on understanding the geometry of the faults mapped this year and evaluate evidence for the sense of slip across them. Detailed mapping of lithofacies on either side of the faults will help determine if any of these faults were active at the time of sedimentation. Additionally, the mapping area will be extended to the south to compare and integrate the regional structure into our interpretation of the geometry at Howard's Pass and see how structural complexity changes across regional structures.

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