



**NWT Open File 2017-02**

**Carlin-type gold and clastic-dominated zinc-lead potential  
of the Misty Creek Embayment region, Mackenzie  
Mountains, Northwest Territories**



B.J. Fischer

**NORTHWEST TERRITORIES  
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**Northwest Territories**

*Cover Image:*

*A towering cliff of planar-bedded Devonian carbonate rocks overlies a narrow, recessive, brown band (volcanogenic bioclastic sandstone of the Late Silurian or Early Devonian Lower member of the Tsetso(?) Formation), which in turn overlies a succession of dark lime mudstone belonging to Silurian Cloudy Formation. The thick, resistant band near the top of Cloudy Formation (and in the foreground) is an interval of thin-bedded lime mudstone with lenses and nodules of secondary black chert. Looking west-northwest from about 130° 10' W, 64° 3' N.*



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**NWT Open File 2017-02**  
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**Carlin-type gold and clastic-dominated zinc-lead potential of the Misty Creek Embayment region, Mackenzie Mountains, Northwest Territories**

**Gisement potentiel d'or de type Carlin et de minerais de plomb-zinc à dominante clastique dans la région du rentrant de Misty Creek, Monts Mackenzie, Territoires du Nord-Ouest**

\* Le présent document contient la traduction française du sommaire.

**B.J. Fischer**

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*Distributed by:*

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*Recommended Citation:*

*Fischer, B.J., 2018. Carlin-type gold and clastic-dominated zinc-lead potential of the Misty Creek Embayment region, Mackenzie Mountains, Northwest Territories; Northwest Territories Geological Survey, NWT Open File 2017-02, 90 pages.  
DOI: 10.13140/RG.2.2.14299.72480*

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## Résumé

La région du rentrant de Misty Creek (RMC) dans la partie nord-ouest des monts Mackenzie des Territoires du Nord-Ouest est une zone insuffisamment explorée susceptible de renfermer des gisements d'or de type Carlin, similaires à ceux découverts dans le champ de Rackla, qui se trouve 60 km à l'ouest de là, et des dépôts de minerais de plomb-zinc (PZ) à dominante clastique semblables à ceux du gisement géant de Howards Pass, qui se trouve 200 km plus au sud. La zone présente plusieurs caractéristiques communes avec les champs d'or de type Carlin du nord-est du Nevada, notamment les principaux éléments d'histoire tectonique considérés comme essentiels à la formation d'un grand champ d'or de type Carlin, à savoir une marge de divergence près d'une écorce continentale fine, de grandes failles lithosphériques, une phase d'évolution prolongée de la marge de divergence comprenant une extension épisodique, suivie d'une période d'orogénèse par contraction, puis une phase tardive d'extension modérée. De plus, les strates du RMC comprennent plusieurs horizons de calcaire silteux perméable et de débris carbonatés semblables à ceux abritant la plus grande part des gisements d'or de type Carlin au Nevada. L'architecture structurelle de la région du RMC comporte plusieurs configurations susceptibles d'avoir constitué des pièges à fluides minéralisateurs, comme les strates perméables au cœur des anticlinaux couvertes de schiste ou de dolomie massive et imperméable. La région se caractérise aussi par la présence de schiste argileux riche en matières organiques réduites et de mudstone avec des sulfures synsédimentaires à plusieurs niveaux stratigraphiques, une caractéristique importante à la fois pour les gisements d'or de type Carlin et ceux de minerais de zinc-plomb à dominante clastique. Le RMC est adjacent à une plateforme carbonatée contenant des évaporites à plusieurs niveaux, il a été dolomitisé régionalement et renferme des centaines de gisements de minerais de zinc-plomb encaissés dans des roches carbonatées. Or, tous ces facteurs indiquent la possibilité d'une dominante clastique dans le bassin adjacent. Le RMC est un bassin de deuxième ordre, avec des signes de développement de bassins de troisième ordre du Dévonien inférieur et du Dévonien moyen en son sein. Ailleurs dans le monde, ce type de configuration tectonique est associé aux champs de minerais de zinc-plomb à dominante clastique. Les sédiments exhalatifs (mudstone barytique, phosphorites) se trouvant à plusieurs niveaux stratigraphiques pourraient indiquer la présence de métaux exhalatifs à proximité. Les limons de cours d'eau présentent des anomalies pour plusieurs métaux caractéristiques de l'or de type Carlin (Sb, As, Au, Tl, Hg) et les gisements de métaux à base à dominante clastique (Pb, Zn, Fe, Sb, As, Tl), et les données lithogéochimiques disponibles sont encourageantes.

La région du RMC présente plusieurs indicateurs de présence potentielle de minéralisation de zinc-plomb à dominante clastique et d'or de type Carlin. La cartographie du substratum rocheux est suffisamment détaillée pour confirmer la présence des éléments fondamentaux de la configuration tectonique requis pour chaque type de gisement et celle des roches hôtes et des structures propices. Les données géochimiques des limons de cours d'eau enregistrent des niveaux anormaux d'indicateurs géochimiques pour chaque type de gisement. Des perspectives considérables s'ouvrent à des programmes de prospection régionaux ciblés qui pourraient délimiter et mettre en valeur des zones de production possible d'or de type Carlin et de minerais de zinc-plomb à dominante clastique.

## Abstract

The Misty Creek Embayment (MCE) area in the northwestern Mackenzie Mountains of the Northwest Territories is an underexplored area with potential to host Carlin-type gold deposits similar to those already discovered in the Rackla district 60 km to the west, and clastic-dominated (CD) zinc-lead deposits similar to those in the giant Howards Pass district 200 km to the south. The area shares a number of characteristics with the Carlin-type gold districts in northeastern Nevada, including the key elements of a tectonic history thought to be essential to development of a major Carlin-type gold district: a rifted-margin setting near the edge of thinned continental crust, through-going lithospheric faults, a protracted rifted-margin phase of evolution that included episodic extension, a subsequent period of contractional orogeny, and a late phase of mild extension. Additionally, the strata of the MCE include numerous horizons of reactive, permeable silty limestones and carbonate debrites similar to those hosting the bulk of the Carlin-type gold deposits in Nevada. The structural architecture of the MCE area includes a number of settings that could have provided traps for ore fluids, such as permeable strata in the cores of anticlines capped by shale or by massive, impermeable dolostone. The MCE area includes reduced, organic-rich shale and mudstone with synsedimentary sulfides at a number of stratigraphic levels, a feature important to both Carlin-type gold and CD zinc-lead deposits. The MCE is adjacent to a carbonate platform that contains evaporites at multiple levels, has been regionally dolomitized, and is host to hundreds of carbonate-hosted zinc-lead deposits, all of which factors are indicative of CD potential in the adjacent basin. The MCE is a second-order basin with evidence of Early or Middle Devonian development of third-order basins within it. Such a tectonic setting is associated with CD zinc-lead districts around the world. Exhalative sediments (baritic mudstone, phosphorites) at a number of stratigraphic levels might be indicators of exhalative metals nearby. Stream silts are anomalous in a number of metals characteristic of Carlin-type gold (Sb, As, Au, Tl, Hg) and CD base-metal deposits (Pb, Zn, Fe, Sb, As, Tl), and the available litho-geochemical data are encouraging.

The MCE area displays multiple indicators of its potential for both Carlin-type gold and CD zinc-lead mineralization. Bedrock mapping is detailed enough to confirm the fundamentals of the tectonic setting required for each deposit type and the presence of the appropriate host rocks and structures. Stream-silt geochemistry data record anomalous levels of marker elements for each deposit type. There is considerable scope for both regional and detailed programs of exploration to identify and develop both CD zinc-lead and Carlin-type gold prospects.

## Introduction

The Misty Creek Embayment (MCE) area is an underexplored part of the northwestern Mackenzie Mountains that is highly prospective for Carlin-type gold and for clastic-dominated (CD) zinc-lead deposits (also called SEDEX deposits; Leach *et al.*, 2010). During most of the Early Paleozoic, the MCE was a depocenter on the edge of the Selwyn Basin

(Cecile, 1982), and the Selwyn Basin itself was a large embayment into the western (present-day direction) margin of ancestral North America, or Laurentia. The MCE, Selwyn Basin, and adjacent platforms were succeeded in Late Devonian time by a distal back-arc basin (Nelson *et al.*, 2013) that endured until Mesozoic orogeny, when compressive forces thrust the basinal strata over the platforms, and platformal strata over the craton, creating northeast-verging folds and thrusts in the MCE region. The deposits of both basins, the Lower Paleozoic MCE and the Upper Paleozoic “post-Selwyn basin”, are of interest for their potential metal endowments. This report focusses on the Carlin-type gold and CD zinc-lead prospectivity of an area between about 63°N and 64°50'N at about 130°W (Figure 1), covered by part of National Topographic System (NTS) mapsheets 106B, 1050, and 105P. This area encompasses most of the exposed strata of the MCE as well as some of the post-Selwyn basin. The stratigraphy, structure, and geochemistry of this area are reviewed as they relate to its Carlin-type gold and CD zinc-lead potential, and the features that make the MCE area prospective for both deposit types are summarized.

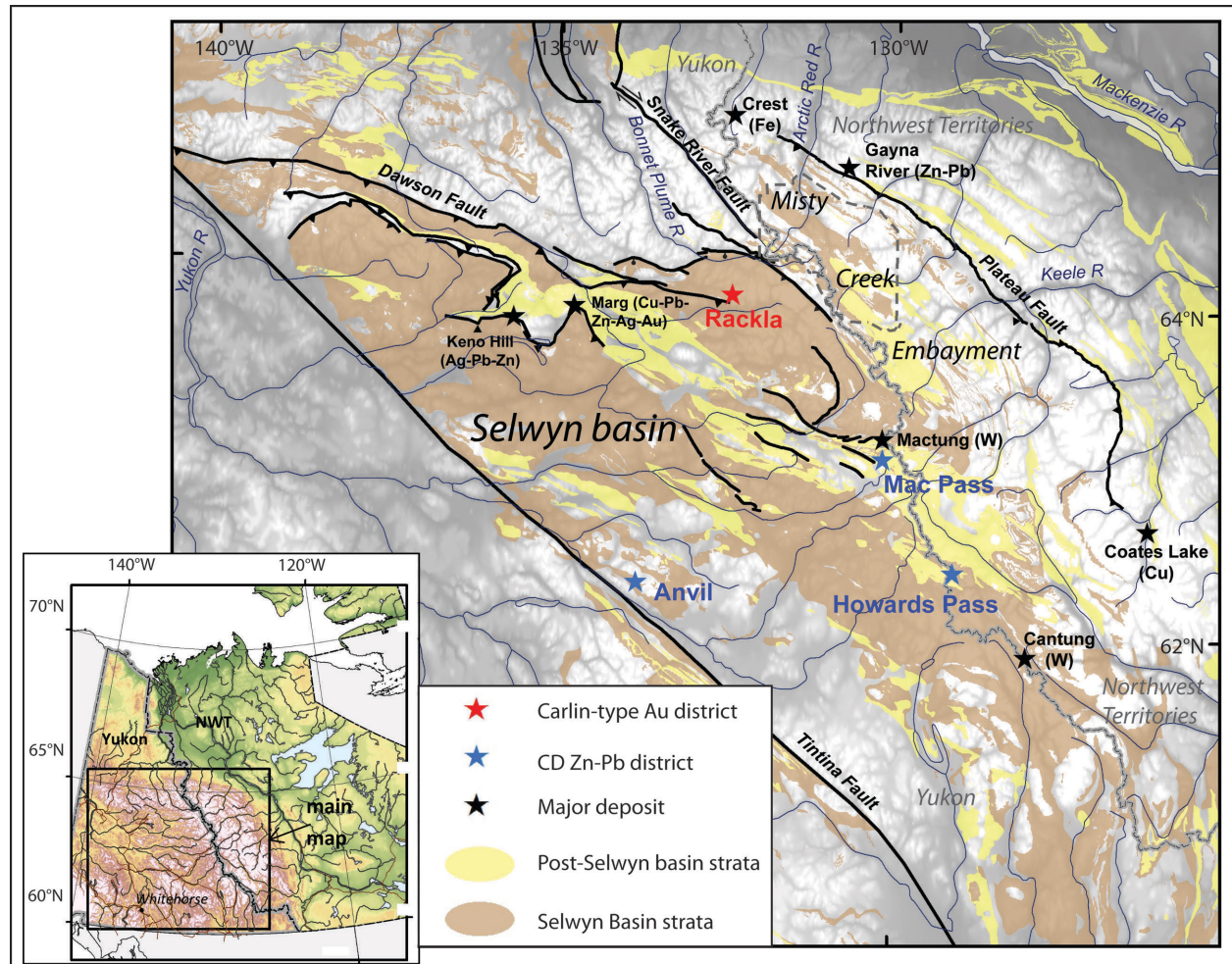


Figure 1. Locations of the Selwyn Basin, Misty Creek Embayment, main districts of clastic-dominated zinc-lead and Carlin-type gold, and other major deposits in the northwest Mackenzie Mountains. Black lines are major faults, teeth on down-dip side. Dashed line is the footprint of the Selma mapping project.

Geology was generalized from Okulitch and Irwin (2014) and Yukon Geological Survey (accessed 2017), on shaded topographic relief from Natural Resources Canada. Projection is Universal Transverse Mercator Zone 9 based on North American Datum 1983. Location map shows colored topographic relief (high to low elevation: white, pink, yellows, greens, dark green).

In this report, the key features of both Carlin-type gold and CD zinc-lead deposits are described. Parallels are drawn between the tectonic history of the MCE area and the Carlin-type gold district of Nevada. Time periods are discussed that would have been ideal for the formation of Carlin-type gold or CD zinc-lead deposits in the MCE area. When the paleo-emplacement is being referred to, the term MCE is used, whereas when reference is being made to the geographic area in which rocks of the MCE are found, the term MCE area (limited to the immediate area) or MCE region (including surrounding areas) is used. All mapsheet references in this report refer to the NTS.

## Previous Work

Strata of the Selwyn Basin host a number of important zinc-lead districts defined by clusters of CD zinc-lead deposits. The giant Howards Pass district, 130 km south of the heart of the MCE, is the largest of these (Goodfellow and Lydon, 2007). The MCE area and surrounding region were explored for CD zinc-lead and carbonate-hosted (Mississippi Valley-Type or MVT) zinc-lead deposits by a number of companies in the 1970's and 80's. Records of these explorations are archived at the Northwest Territories Geological Survey<sup>1</sup> (NTGS) and the Yukon Geological Survey (YGS). Poulsen (1996) pointed out the parallels between the geological environments of the Nevada district and the Selwyn Basin, and suggested the potential for Carlin-type gold in the parts of the Selwyn Basin affected by Mesozoic plutonism.

In 2005, the NTGS, in collaboration with the Geological Survey of Canada (GSC), conducted stream-sediment geochemical surveys across mapsheets 105P and parts of 105O (Day *et al.*, 2005), and in 2007 and 2008, across mapsheets 106A, B, and parts of C (Falck and Day, 2008; Day *et al.*, 2009). These surveys were part of a major, multi-year effort to systematically analyze stream waters and sediments throughout the Mackenzie Mountains, where such data had been lacking. The surveys revealed a number of metal anomalies in stream silts in the MCE area, as well as gold grains without an apparent source, in heavy mineral concentrates of stream sediments (Falck *et al.*, 2012).

Existing bedrock geology maps (Blusson, 1974 and the digital compilation of Gordey and Makepeace, 2003) were of insufficient detail to serve as a base for targeted exploration or geological interpretation of the area. Therefore, the NTGS initiated a regional geological mapping and compilation study known as the Selma project (SELwyn-MACKenzie shale basins) in 2009, to upgrade the bedrock geology map in areas dominated by basinal units,

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<sup>1</sup> The original assessment reports for the NWT can be downloaded from [www.nwtgeosciences.ca](http://www.nwtgeosciences.ca).

follow up on the geochemical results, and investigate the mineral potential of the basal rocks in the MCE area.

The Selma project began with a brief reconnaissance in 2009 and continued in 2011 with work carried out by a two-person crew over four weeks, in 2012 with a four-person crew over seven weeks, and in 2013 with one week of spot checks. Mapping focused on the basal strata in the southeast quadrant of mapsheet 106B, although other areas were examined as well. Academic partners conducted stratigraphic studies (Chevrier and Turner, 2013a, b), and an airborne radiometric and magnetic survey was flown over part of mapsheet 106B (Fortin *et al.*, 2012). The field observations and geophysical information were combined with pre-existing data from a variety of sources and some concurrently obtained industry data (Vivian and White, 2013) to produce a revised, 1:100 000-scale map of parts of mapsheet 106B (Fischer, 2016).

The current report makes use of knowledge gained during the Selma project to illustrate the prospectivity of the MCE area for CD zinc-lead and Carlin-type gold. The independent discovery in 2010 of the Rackla district of Carlin-type gold showings in Yukon, 60 km southwest of the MCE, vindicated the focus of the Selma project. The Rackla showings were discovered by follow-up of stream-sediment arsenic anomalies (Arehart *et al.*, 2013; Tucker *et al.*, 2013; Yukon Minfile, accessed 2015).

## Metallogeny of the Selwyn Basin region

Numerous deposit types have been found in rocks of the Selwyn Basin and co-eval Mackenzie Platform, as well as in both older and younger units in the region (Figure 2). The symbols referred to in brackets below are those in Figure 2. From oldest to youngest, the main deposit types in the region are:

- **Iron Oxide-Copper-Gold (IOCG)** showings of iron, copper and uranium (red squares) are hosted by hydrothermal breccias in Paleoproterozoic sedimentary rocks of the Wernecke Supergroup. These Wernecke breccias are known to have formed in the Mesoproterozoic, but their mode of formation is debated (Laughton *et al.*, 2005).
- **Sediment-hosted copper** deposits (Kupferschiefer or red-bed type; orange squares) are present in late Neoproterozoic rift-phase strata of the lowermost Windermere Supergroup (Martel *et al.*, 2011), which are preserved in the hangingwall of the Plateau fault, east and southeast of the MCE area. The host carbonate rocks overlie red-bed sandstones and conglomerates. Mineralization was late diagenetic to epigenetic (Milton, 2015; Chartrand and Brown, 1985).
- Neoproterozoic **stratiform iron formation** in the northwestern Mackenzie Mountains (Crest deposits, green squares) consists of hematite-jasper rhythmites

within a glacio-marine succession of diamictites and mudstones belonging to the lower part of the Windermere Supergroup (Baldwin *et al.*, 2012; Yeo, 1986).

- Early Paleozoic syngenetic to diagenetic, **CD zinc-lead** ( $\pm$ barium, silver, gold) deposits (blue squares) are hosted by Selwyn-basin strata in the Cambrian Anvil district, the giant, Silurian Howards Pass district, and the Devonian Macmillan Pass (Mac Pass) area (Goodfellow, 2007).
- Syngenetic and diagenetic **barite** (light blue squares) is present as nodules and laminations in Middle Devonian mudstone of the post-Selwyn Basin. Barite-rich horizons are developed intermittently along a strike length of 80 km. Some horizons are over 600 m long and over 70 m thick (Fernandes *et al.*, 2017; Cecile, 2000; Fischer, 2016).
- A few **volcanic-hosted massive sulfide** (VMS) deposits (red crosses) are within the region. The Marg deposit is in a predominantly siliciclastic setting of the northern post-Selwyn Basin, hosted by Late Devonian(?), felsic volcanoclastic rocks and associated with silica, ferroan carbonate, and muscovite (Holbek *et al.*, 2001). The deposit is a Kuroko-type Zn-Pb-Cu deposit with resources of Zn-Pb-Cu-Ag-Au (Yukon Minfile, accessed 2015). The other VMS showings are minor Kuroko or indeterminate types, mostly in unidentified metamorphosed host rocks (Yukon Minfile, accessed 2015).
- **Carbonate-hosted (MVT) lead-zinc** ( $\pm$ copper, silver) deposits (blue circles, orange circles) formed over a wide geographic area in platformal strata of Proterozoic and Lower Paleozoic ages (Martel *et al.*, 2011). Mineralization is structurally controlled, epigenetic, and of at least two ages, including a Late Devonian to Early Carboniferous event and a Late Cretaceous to Early Tertiary event (Fischer, 2012; Wallace, 2009; Paradis, 2007), although some deposits (e.g., Prairie Creek) include syngenetic mineralization (Paradis, 2007).
- A single known occurrence of **Columbian-style (schist-hosted) emerald** (horizontal green diamond), in veins cutting Neoproterozoic siliciclastic rock, is interpreted to be Late Devonian to Middle Mississippian in age and unrelated to intrusions (Hewton *et al.*, 2012).
- A number of deposit types are associated with Cretaceous granitic plutons of the NNW-trending Tombstone-Tungsten belt, which lies southwest of the MCE area:
  - **skarns** (down-pointing triangles) can be grouped into tungsten-dominated (most notably the Cantung mine; Figure 1), copper-dominated, lead zinc-dominated, and antimony-rich (Rasmussen *et al.*, 2007a). The tungsten-dominated skarn deposits may contain copper, zinc, bismuth, gold, or molybdenum, whereas silver may be found in the lead-zinc skarns and lead in the antimony-rich skarns;
  - **intrusion-related gold** (left-pointing triangles), including gold-dominated skarns, gold-bearing quartz veins and stockworks within intrusions and adjacent hornfelsed zones, disseminated-sulfide replacements of carbonate rocks, and other showings associated with plutons (Hart *et al.*, 2004; Hart,

2007; Rasmussen *et al.*, 2007a; NORMIN, accessed 2013; Yukon Minfile, accessed 2015);

- **porphyry-related gold** showings (right-pointing triangles) contain gold-silver±copper, either in sulfide-tourmaline-quartz-feldspar veins cutting porphyritic granitic to syenitic stocks or plutons and the surrounding sedimentary rocks, or associated with disseminated sulfides in the same host rocks (Yukon Minfile, accessed 2015);
- **emerald** and other varieties of beryl in quartz veins (vertical green diamonds; NORMIN, accessed 2013);
- **lithium±(niobium-tantalum, gemstones)** in pegmatites (horizontal colorless diamonds). Gems are typically semi-precious tourmaline (elbaite; NORMIN, accessed 2013; Barnes *et al.*, 2007);
- **polymetallic replacement** deposits, including mantos, and **polymetallic vein** deposits (green triangles with dots), mainly of lead-zinc±silver (NORMIN, accessed 2013, Rasmussen *et al.*, 2007a).
- **Orogenic gold** showings (yellow circles) associated with north-trending faults, west and south of Cantung (Nelson *et al.*, 2013; Hart and Lewis, 2006)
- Sedimentary rock-hosted or **Carlin-type gold** (yellow diamonds) in the Rackla district (Arehart *et al.*, 2013; Yukon Minfile, accessed 2015).

These deposit types are arranged spatially in a manner that corresponds broadly to the arrangement of major geological settings. The IOCG, sediment-hosted copper, and iron-formation deposits are restricted to Proterozoic exposures in the northwest of the region and along the Plateau Fault. Carbonate-hosted zinc-lead (MVT) deposits occur in Proterozoic and Paleozoic platformal carbonate hosts, which form a northwest-trending belt west of the Plateau Fault. Clastic-dominated zinc and lead, exhalative and replacive barite, VMS base metals, and Carlin-type gold all lie in a broad belt of basinal rocks west of the co-eval carbonate belt, corresponding to the Selwyn and post-Selwyn basins. These showings are, broadly speaking, concentrated near the transition between the basinal and platformal belts. Other gold showings, skarns, gems, and rare earths associated with intrusions are localized along the trend of the Tombstone-Tungsten plutonic belt, which roughly parallels the northern and eastern edges of the Selwyn Basin, offset to the basinal side (Figure 3; Hart *et al.*, 2004).

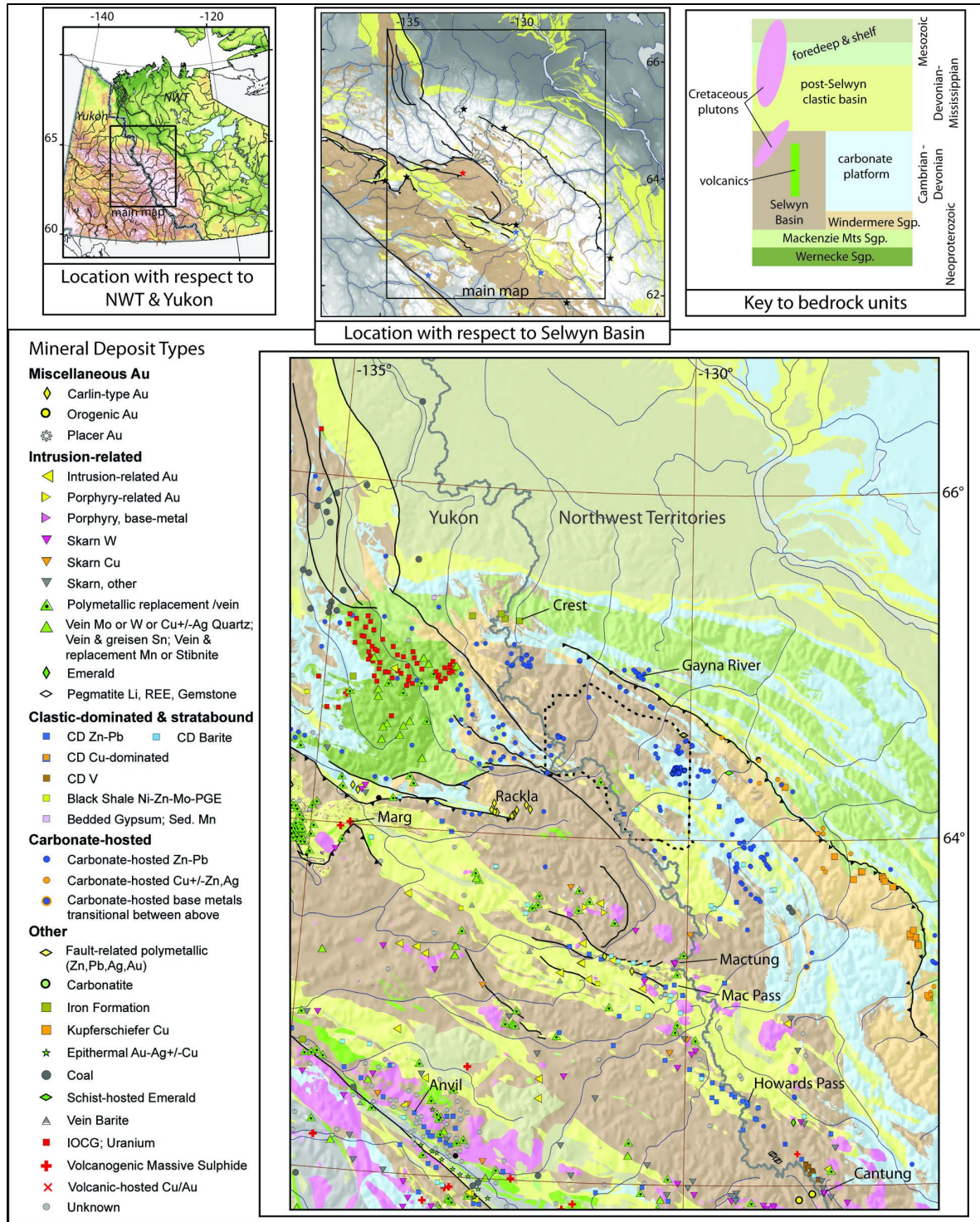


Figure 2. Mineral showings in the Misty Creek Embayment and surrounding regions, with major deposits/districts labelled. Black lines are faults, teeth on the down-dip side. Dashed line is the footprint of the Selma mapping project. Key to location maps is as for Figure 1. Bedrock geology was generalized from Okulitch and Irwin (2014) and Yukon Geological Survey (accessed 2017), on shaded topographic relief from Natural Resources Canada. Projection is Universal Transverse Mercator Zone 9 based on North American Datum 1983.

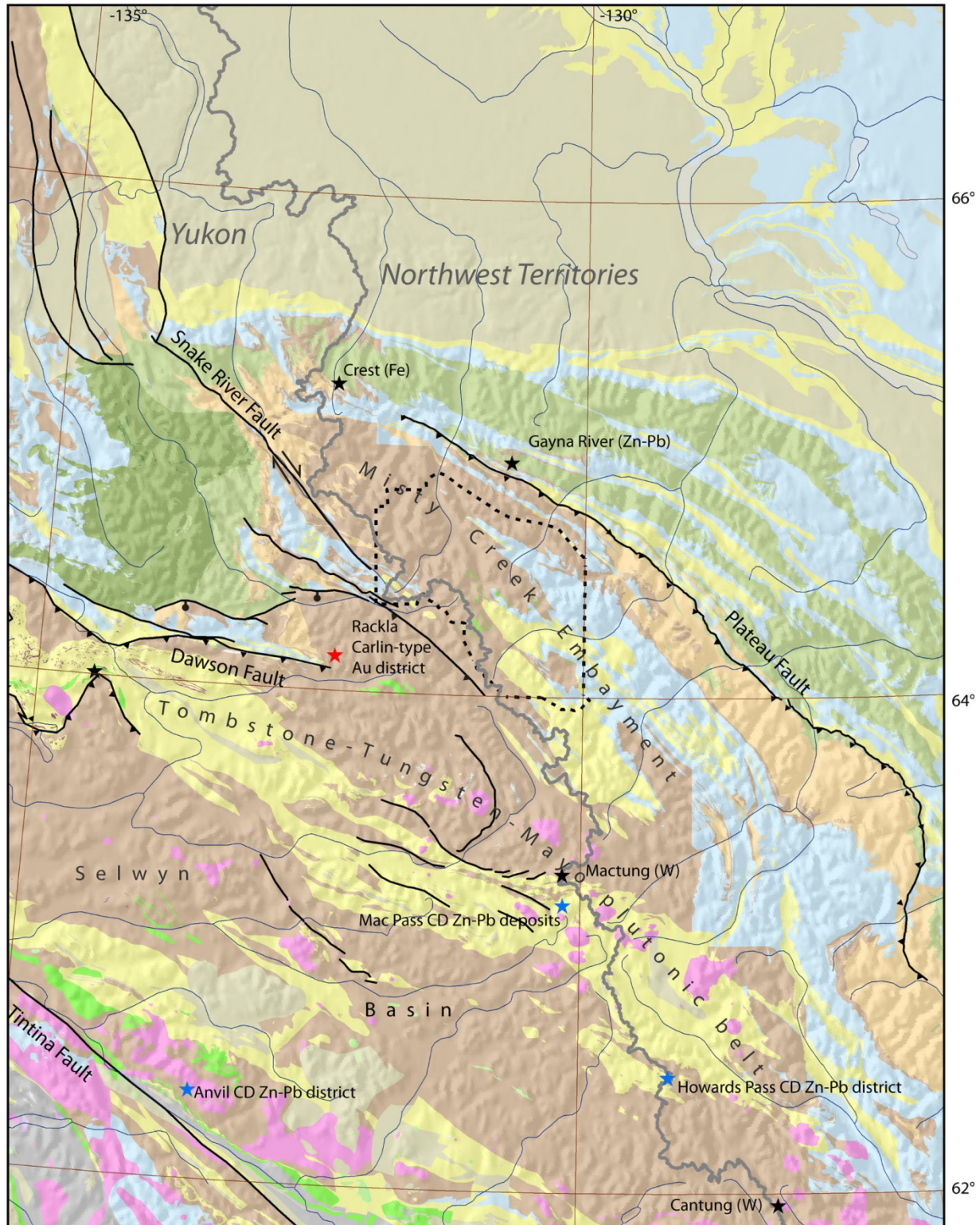


Figure 3. Major tectonostratigraphic packages and faults in the Misty Creek Embayment and surrounding regions. Location and key to bedrock units is as in Figure 2; a detailed key is in Figure 4. Dashed outline is the Selma project area. Blue stars are clastic-dominated Zn-Pb districts and the red star is a Carlin-type Au district. Sources of background data and projection are as for Figure 2.

# Tectonic History of the Misty Creek Embayment Area

The tectonic history of the Carlin-type gold district in Nevada is thought to have been key to its formation (below), therefore the tectonic history of the MCE area is relevant to its prospectivity. The major tectonostratigraphic packages of the Selwyn Basin in the Mackenzie and Selwyn Mountains are illustrated in Figures 3 and 4. The two oldest packages are the Paleoproterozoic Wernecke Supergroup and the late Mesoproterozoic to early Neoproterozoic Mackenzie Mountains Supergroup. The former is a succession of dominantly sedimentary rocks deposited on a passive margin resulting from the breakup of the supercontinent Columbia (Furlanetto, 2015). The latter is a succession of dominantly sedimentary rocks deposited in an epeiric sea that developed along the margin of the North American craton over a failed rift (Long *et al.*, 2008). These packages may have been the source of metals for later mineralization events, but are otherwise not relevant to our discussion. Thus, this review begins with rifting in the late Neoproterozoic.

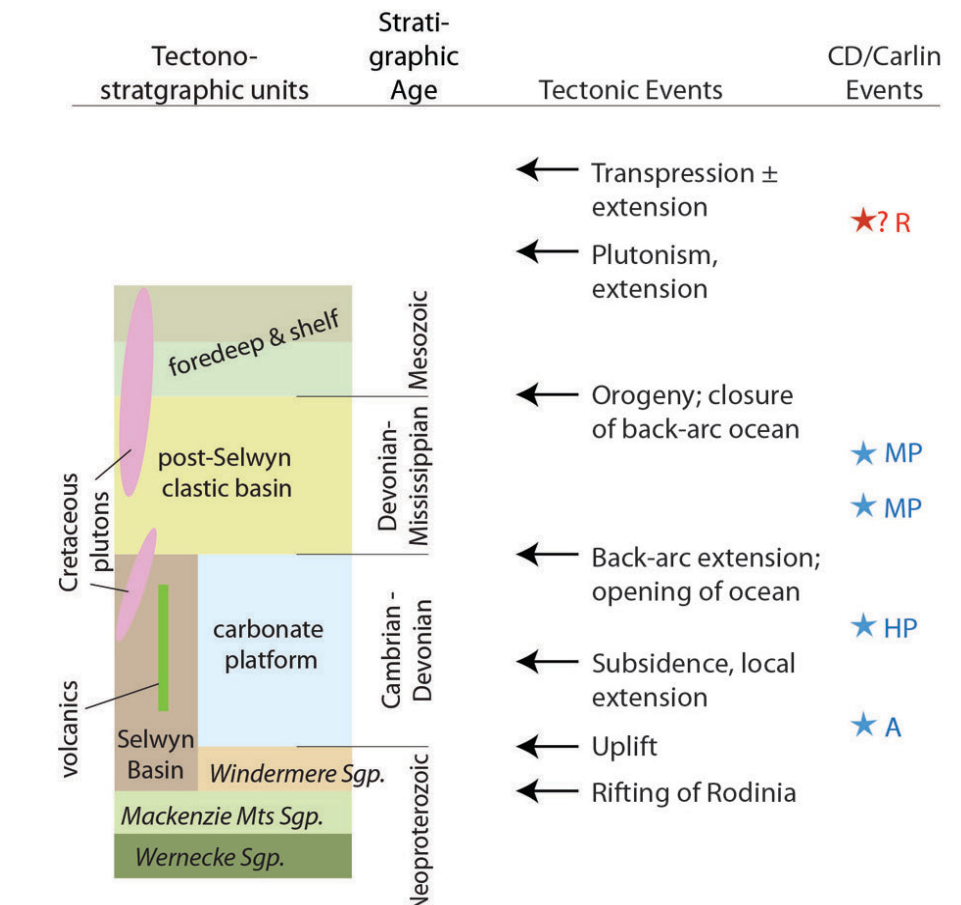


Figure 4. Major tectonostratigraphic packages in the Misty Creek Embayment and Selwyn Basin region, indicating main tectonic events and relevant mineralizing events. Clastic-dominated events are indicated by blue stars and Carlin-type events by red stars. A = Anvil district, HP = Howards Pass district, MP = MacMillan Pass district, R = Rackla district (age uncertain).

## Neoproterozoic rifted margin

Deposition of the Windermere Supergroup, which is the third major tectonostratigraphic package in the MCE region, began with rifting of the supercontinent Rodinia in latest Neoproterozoic time (Ross, 1991). This rifting event determined the character of different segments of the continental margin, and thereby affected their subsequent metallogenic history in profound ways.

The North American Cordillera is divided into major blocks or segments by a number of northeast-trending linear features that have been interpreted as the expressions of ancestral transfer faults (Cecile *et al.*, 1997; Lund, 2008). The northern Canadian Cordilleran segment, which includes the Selwyn Basin and MCE, is interpreted to have been the lower-plate margin of an asymmetric rift system (Lister *et al.*, 1986), in which the parent plate, prior to rifting, was thinned by slip along a shallowly west-dipping detachment (Figure 5). This asymmetric detachment would have allowed the part of the crust beneath the detachment – the lower plate – to rise and bend upward as the weight of the upper plate was removed, with eventual rifting along the locus of the upward culmination. The lower plate became the western margin of Laurentia, and the upper plate became the margin of an unidentified continent to the present-day west (e.g., Li *et al.*, 2008).

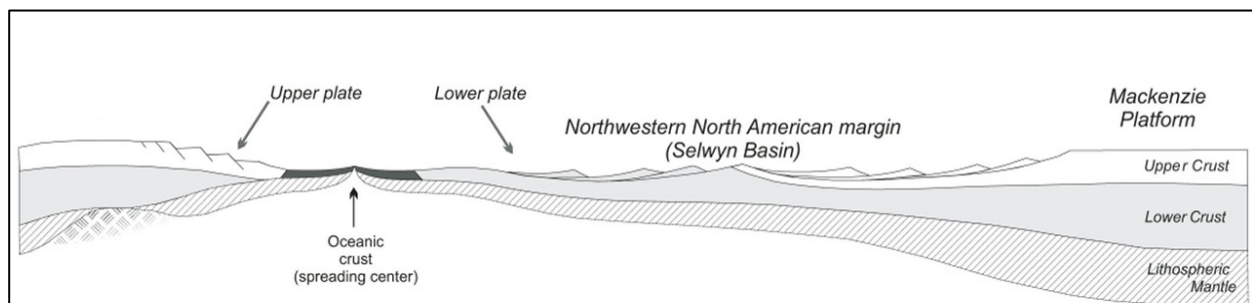


Figure 5. Schematic cross-section looking north at the early Selwyn Basin shortly after rifting, assuming an asymmetrical rifting model. Listric fault-bounded sub-basins and the associated large rotations of fault blocks on the lower-plate margin (right-hand side) contribute to its structural complexity. This margin will become stratigraphically more complex than the upper-plate side as the basin fills. Modified from Mair *et al.* (2006).

This simple rifting scenario is complicated by the existence of transfer faults, which are zones of strike-slip that are orthogonal to the line of rifting. Transfer faults develop on rifted margins to accommodate differential displacements between extending segments of crust. The sense of dip of the master detachment fault can change across a transfer fault. Where this happens, the rifted margin that eventually develops will change, along its length, from lower-plate type to upper-plate type (Lister *et al.*, 1986).

The western margin of Laurentia is thought to have formed by asymmetric rifting in which the dip of the detachment fault changed sense across two major transfer-fault zones, the

Liard line in northern Canada, and the Snake River fault zone in west-central USA (Figure 6; Lund, 2008; Cecile *et al.*, 1997). North of the Liard line and south of the Snake River fault zone (USA)<sup>2</sup>, the continental margin is a lower-plate margin. The intervening segment is an upper-plate margin.

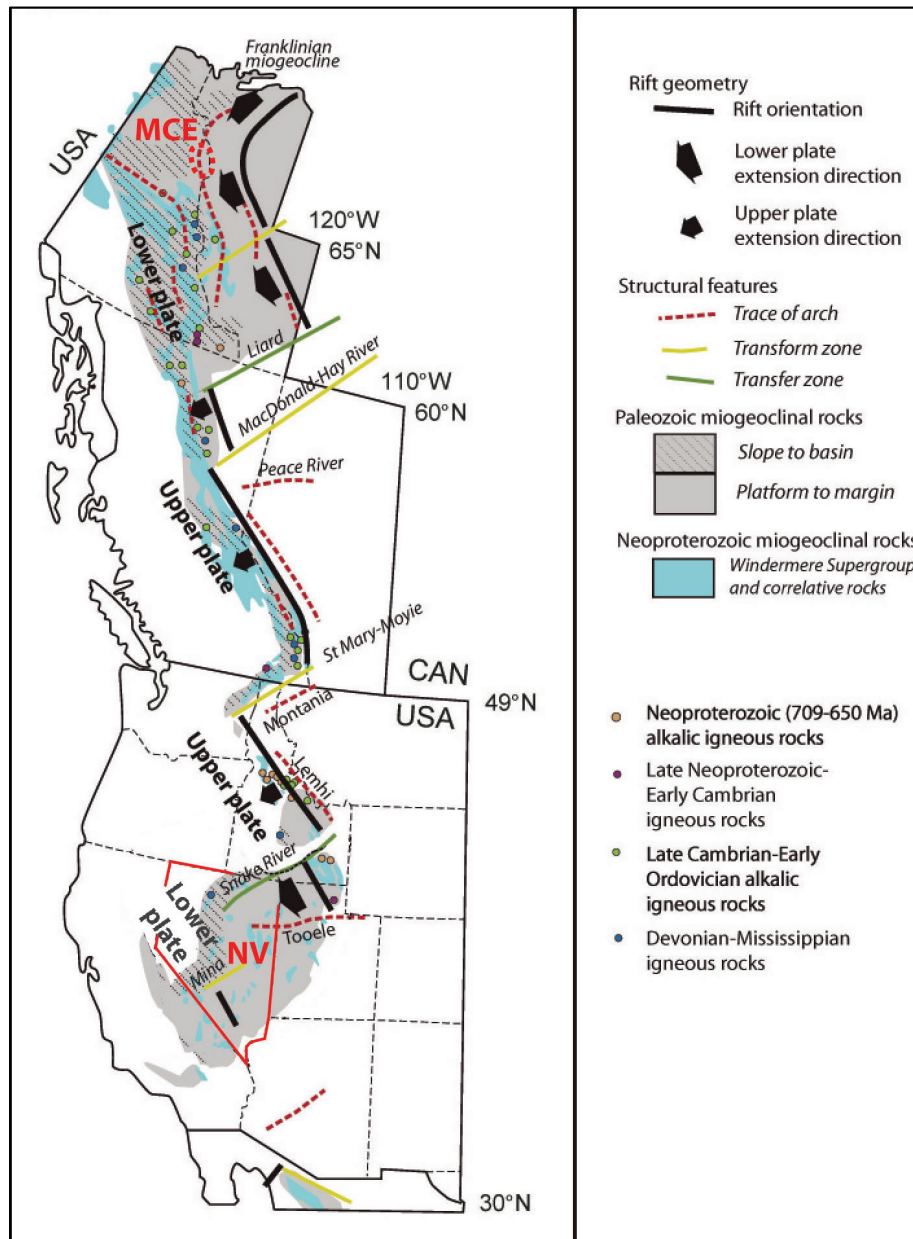


Figure 6. The western margin of North America (in its present orientation) with interpreted upper-plate and lower-plate segments of the margin separated by transfer faults. The Misty Creek Embayment area

<sup>2</sup> There is a Snake River Fault along the northeast edge of the Selwyn Basin. To circumvent any confusion that may be caused by the coincidence of names, the faults will be referred to as the Snake River fault zone (USA) and the Snake River Fault (Canada).

in northern Canada (MCE; outlined by a dashed red line), and the state of Nevada (NV; solid red line) are both on lower-plate segments. Modified from Lund (2008).

Lower-plate sides of asymmetrically rifted margins have greater structural and stratigraphic complexity than upper-plate sides: more fault-bounded sub-basins, more-varied sedimentation, greater permeability, and more rheological contrasts during later deformation. These factors make lower-plate margins more prospective for mineral deposits than upper-plate ones (Cecile *et al.*, 1997; Lund, 2008). The MCE is on the northern lower-plate segment of the North American margin, and the Carlin district is on the southern lower-plate segment (Figure 6).

The stratigraphic deposits of the rifting and subsequent Proterozoic phases of passive-margin development on the western margin of Laurentia are collectively known as the Windermere Supergroup (Ross, 1991). This Supergroup is typical of such successions, consisting of thick, basal, syn-rift, siliciclastic rocks with minor intercalated, mafic igneous rocks, overlain inboard by platformal, carbonate-dominated rocks and outboard by deep-water strata. The latter include terrigenous turbidites of the Proterozoic Hyland Group deposited in the earliest Selwyn Basin (Figure 3), and carbonate units deposited on the coeval platform to its east. Windermere deposition was terminated at the end of the Neoproterozoic by a brief period of uplift in the northern Canadian Cordillera, recorded by fluvial sandstones (MacNaughton *et al.*, 2000; Martel *et al.*, 2011).

Major, lithospheric, basin-bounding faults are thought to be important to the development of Carlin-type gold districts. The northern edge of the Selwyn Basin is marked by the Dawson Fault, a major basin-bounding structure that probably formed during the late Neoproterozoic rifting (Mair *et al.*, 2006; Murphy, 1997). The eastern terminus of the Dawson Fault is about 60 km west of the MCE area. The northeastern margin of the Selwyn Basin is a poorly understood, SE-striking fault or fault system that changes character from normal in the north to reverse in the south (Figures 1 and 3; Blusson, 1974; YGS, accessed 2017), and may link, through the Snake River Fault (Canada), with the Richardson Fault Array, a system of crustal-scale faults that have been intermittently active since the Proterozoic (Thorkelson, 2000; Norris, 1997). The Snake River Fault (Canada) is a SSE-trending, dextral strike-slip fault that coincides roughly with part of the southwestern boundary of the northern MCE. This fault is also thought to be a deep, basement structure that has been re-activated more than once since the late Neoproterozoic (Thorkelson, 2000; Eisbacher, 1981).

## Early Paleozoic rifted margin

The brief period of uplift at the end of the Neoproterozoic that terminated Windermere deposition was followed by renewed subsidence that lasted approximately 150 million years, until the end of the Early Paleozoic. Carbonate-dominated platforms (the Mackenzie Platform in the east and Ogilvie Platform in the north) dropped off westward and southward (respectively) into the Selwyn Basin (Fritz *et al.*, 1992; Martel *et al.*, 2011), which received, during this time period, mostly fine-grained, thin-bedded, siliciclastic and

carbonate sediments, and chert. These Lower Paleozoic basinal sedimentary rocks in the MCE have been mapped as the Road River Group (Blusson, 1974; Gordey and Makepeace, 2003), an ill-defined designation that will be avoided in this report (see Cecile, 1982 for a discussion).

Restricted parts of the western rifted margin of Laurentia were affected by transient extensional episodes throughout the Early Paleozoic. Some of these were accompanied by mafic alkaline magmatism (Figure 7; Goodfellow *et al.*, 1995; Fritz *et al.*, 1992). The MCE formed as the locus of at least two such episodes of extensional faulting, in the Middle Cambrian and Middle Ordovician (Cecile, 1982). Both are recorded by rapid increases in unit thickness toward the axis of the paleo-embayment and thinning towards its margins, suggesting deposition in a steep-sided basin that was rapidly deepening. The Ordovician pulse of extension was accompanied by mafic alkalic volcanism at two centers in the study area (Cecile, 1982; Fischer, 2016). Additional pulses are suggested by the presence of volcanic rocks overlying Early and Middle Devonian carbonate rocks at two locations (Goodfellow *et al.*, 1995; Fischer, 2016). The Early Paleozoic phase of rifted-margin sedimentation in the MCE ended in the late Middle Devonian (Cecile, 2000; Selma project unpublished data).

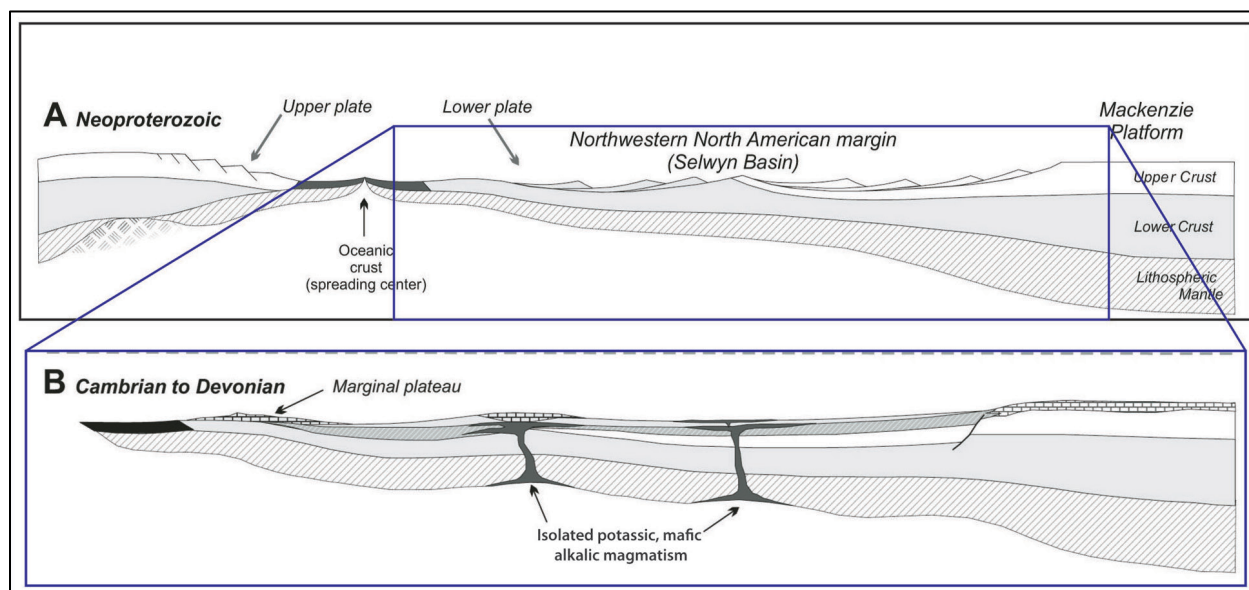


Figure 7. Schematic cross-section of the northern North American margin, looking north. [A] Latest Neoproterozoic formation of the Selwyn Basin by asymmetric rifting (same as Figure 5). [B] Selwyn-Basin side of the rift in Cambrian to Devonian time. The localized mafic alkalic magmatism shown in the cross-section was accompanied by extensional faulting (not shown). Modified from Mair *et al.* (2006).

The entire period of time from the Middle Cambrian until the Middle Devonian, with repeated extension and magmatism, would have been ideal for precipitation of CD base metal mineralization in the MCE. Indeed, two episodes of such mineralization are known from this period in the main Selwyn Basin: the Cambrian event that formed the Anvil

district and the Silurian event that formed the Howards Pass district (Figures 3 and 4; Goodfellow, 2007).

## Late Paleozoic distal back-arc and the post-Selwyn basin

At the end of the Early Paleozoic, global shifts in plate motions were caused by the closure of the Iapetus Ocean along the eastern edge of ancestral North America. These shifts initiated subduction of oceanic crust beneath the western margin of the continent, which was about 700 km southwest of the MCE at the time, and development of a volcanic arc over the subducting plate (Nelson *et al.*, 2006, 2013). Relative plate motions were such that an extensional regime prevailed behind the arc, where active faulting eventually culminated in rifting and the formation of the Slide Mountain Ocean (Figure 8; Nelson *et al.*, 2013). Meanwhile, to the north, the Ellesmerian orogeny caused uplift and erosion in northernmost Yukon (Gordey and Anderson, 1993; Murphy, 1997).

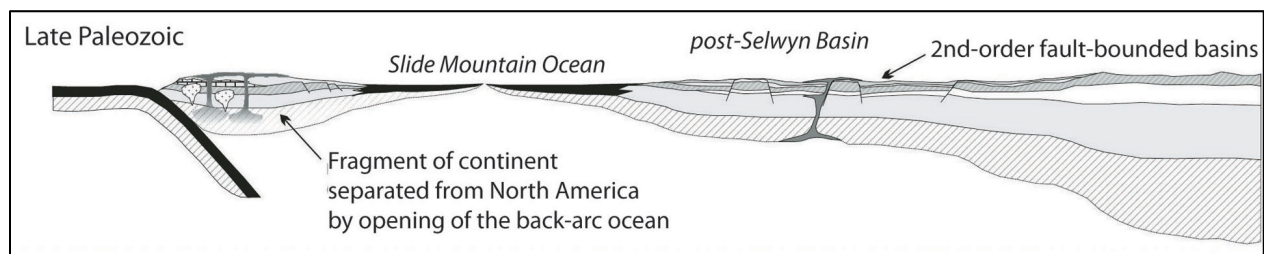


Figure 8. Schematic cross-section of the Laurentian margin in the Late Paleozoic, after initiation of east-dipping subduction and opening of a back-arc basin that became the Slide Mountain Ocean. The Selwyn Basin region was under extension during this time, and sub-basins were created by faulting. Modified from Mair *et al.* (2006).

In this way, the Lower Paleozoic passive margin was succeeded by an Upper Paleozoic basin with characteristics of both a foredeep and a back-arc basin. This post-Selwyn basin was a depocenter for terrigenous detritus derived from the orogen to the north and from elevated fault blocks of older Selwyn Basin strata to the west (Gordey and Anderson, 1993). The Late Devonian tectonic regime in the region of the former Selwyn Basin, MCE, and Mackenzie Platform was dominantly extensional or transtensional (Gordey and Anderson, 1993; Murphy, 1997), with active faulting, and deposition of coarse, siliciclastic submarine fans and siliceous muds of the Earn Group and the Imperial assemblage. In the MCE area, these deposits are preserved as the Middle to Late Devonian Horn River and Imperial formations, which consist of turbiditic shale and siltstone with subordinate amounts of sandstone.

During the Mississippian, a stable shelf developed in the region that endured throughout the Permian (Nelson *et al.*, 2006; Cecile, 1982). A change in plate motions initiated closure of the Slide Mountain Ocean in the Middle Permian (Nelson *et al.*, 2013), though it was some time before this affected sedimentation patterns to the east. In the MCE area, deposition during the Mississippian was dominated by the fine sandstone, siltstone and

shale of the Hawthorne Creek and younger formations (Cecile, 2000). No Permian or younger rocks are preserved in the MCE area.

Active faulting and deep-basinal sedimentation made the Devonian to Mississippian period an ideal time during which to form CD zinc-lead deposits. The Macmillan Pass CD zinc-lead deposits (Tom, Jason) formed at this time in the Selwyn Basin (Figures 3 and 4; Goodfellow, 2007).

## **Mesozoic to modern orogeny**

Shifting tectonic relationships at distant plate edges continued to control sedimentation in the MCE area throughout the Mesozoic and Cenozoic (Figure 4). The continental fragment that had been separated from Laurentia by the Slide Mountain Ocean, along with its associated arc and subduction complex, were re-united with the continent in a series of accretionary events during the Triassic and Jurassic (Nelson *et al.*, 2013). In the Late Jurassic or Early Cretaceous, Selwyn Basin strata were thrust northward over broadly coeval platformal units along the re-activated Dawson Fault and two overlying thrust faults (Mair *et al.*, 2006). The Cordilleran orogen advanced inland, north- and northeastward, throughout the Mesozoic. Folding and thrusting caused over-thickening, which in turn led to melting, plutonism, and localized extension (Poulsen *et al.*, 1997; Hart *et al.*, 2004; Nelson *et al.*, 2013).

Structural preparation of the ground is important in Carlin-type gold systems. The directions of major stresses influence the orientations and displacements of faults. Until the Early Cretaceous, convergence of the outboard terranes with North America was oblique, the oceanic plates rotating clockwise with respect to the North American craton. This led to sinistral displacements on major fault systems within the Cordillera (Nokleberg *et al.*, 2005). The direction of plate convergence shifted from oblique to orthogonal late in the Early Cretaceous, initiating a period of intense orthogonal compression during which the Proterozoic and Paleozoic continental-margin rocks of the Selwyn Basin and Mackenzie Platform were thrust over the craton (Gabrielse and Yorath, 1992). The less-competent basinal rocks were intensely folded against the more competent rocks of the carbonate platform and older Proterozoic basement. The Dawson Fault was reactivated in a reverse sense, and numerous shallow, north- and northeast-directed detachments developed in the Paleozoic cover (Martel *et al.*, 2011; Mair *et al.*, 2006; Gabrielse and Yorath, 1992).

The direction of plate convergence shifted again in the Late Cretaceous, to oblique with reverse rotation, leading to a transpressive regime that continues today (Nokleberg *et al.*, 2005). Slip on major faults has been dextral in response to the transpressive regime. The Rackla Carlin-type gold deposits probably formed during the latest Cretaceous or early Paleocene, post-dating deformation (Arehart *et al.*, 2013).

## Continental crust

The nature of the basement is relevant to development of Carlin-type gold districts. Geophysical and isotopic evidence suggest that the basement beneath the MCE area consists of extended continental crust. Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of Mesozoic granitoid plutons are greater than 0.706 throughout the northern Canadian Cordillera east of the Tintina Fault (Armstrong, 1988). Values of 0.706 and higher can be taken to indicate assimilation of continental Precambrian lithosphere into the granitoid melt (Kistler and Peterman, 1978). Seismic reflection and refraction profiles from a transect that crossed the southern end of the MCE show that Mesoproterozoic cratonic rocks underlie the Cordillera from as far east as the deformation front to west of the Tintina Fault (Lithoprobe project, Cook and Erdmer, 2005). Teleseismic studies have shown that the asthenosphere rises to <100 km deep beneath the northern Cordilleran mobile belt (Frederiksen *et al.*, 1998), and seismic studies show that the Moho is also shallow there (Cook and Erdmer, 2005). These results emphasize that the continental crust has been thinned beneath the northern Cordillera.

## Carlin-type Gold Deposits

The type area for Carlin-type gold deposits is in Nevada, USA (Figure 9). Although there are a few districts of Carlin-type deposits in other parts of the world, most notably in southern China (Zhang *et al.*, 2003; Su *et al.*, 2009) and the recently discovered Rackla district in northern Canada (Arehart *et al.*, 2013), no other district has yet proven to be as large as the type Carlin district in Nevada. An understanding of the characteristics of Carlin-type deposits in their classic setting and in the Rackla district will allow us to understand the criteria that will be most useful in guiding exploration in the MCE area.

Nevada is well-endowed with a variety of mineral-deposit types. Both Carlin-type gold and CD barite-(zinc-lead) deposits are related to the Paleozoic continental margin, and therefore overlap in space. A number of deposit types are related to the Mesozoic-Cenozoic plutonism that affected the continental margin, including: gold-bearing skarn, porphyry copper-gold, gold-bearing vein and replacement, distal disseminated silver-gold, and reduced intrusion-related gold (Poulsen, 1996; John *et al.*, 2003; Nutt and Hofstra, 2007). Other gold-deposit types in the district are epithermal gold, orogenic gold, and even gold-bearing CD deposits (John *et al.*, 2003; Emsbo *et al.*, 2006). Some types of gold mineralization overprint others in the same deposits (Emsbo *et al.*, 2003, 2006; Breit *et al.*, 2005).



Figure 9. [A] Locations of the Northwest Territories and Nevada in North America. The locations in northern Canada of the Rackla district of Carlin-type gold and the Misty Creek Embayment area (MCE) are indicated by arrows. [B] The Mega pit at the Twin Creeks mine in Nevada. [C] The Betze-Post pit at the Goldstrike mine in Nevada.

## Ore and ore bodies

The defining characteristics of Carlin-type deposits are that they are extremely fine-grained, sedimentary rock-hosted, epigenetic gold deposits without obvious genetic relation to igneous bodies (Cline *et al.*, 2005). The geometry of Carlin-type ore bodies varies according to the permeability characteristics of the host rocks. One of the most remarkable features of the deposit type is the profound lack of visual distinction between ore and unmineralized rock, which compels the mine geologist to use assays to delimit ore on pit faces (Zohar, 2013). Carlin-type gold occurs in very fine-grained to microscopic arsenian pyrite, typically in arsenian rims on pre-existing pyrite. The gold is present as submicron particles or, more commonly, in solid solution with the pyrite (Arehart *et al.*,

1993a; Cline *et al.*, 2005). The fine grain size of the pyrite imparts a dark, sooty appearance to the rock.

## Host rocks

The most common host rock of Carlin-type gold deposits in Nevada is thin-bedded, silty limestone, but dolostone, calcareous siltstone, and even igneous rocks are known to host ore. The key requirements are that the host rock has high reactivity and high initial permeability (Hofstra and Cline, 2000). Reactivity implies a high proportion of components that are soluble in the ore fluid and will react with it to precipitate gold; such components are usually carbonate minerals. There may be another requirement, for a high initial content of reactive (non-sulfide) iron; for example, iron in ferroan calcite, dolomite, or silicate minerals. This is discussed further in the section on Alteration (below).

Permeability can be primary, or enhanced by diagenesis, deformation, or hydrothermal reactions. One of the most important means of developing permeability in the Nevada district was by differential dissolution of a calcareous host rock with mineralogical or grain-size heterogeneities; for example, carbonate debrite, skeletal grainstone, or silty limestone (*e.g.* Jory, 2002). The matrix or cement of these rocks will dissolve while the less-soluble clasts, skeletal grains, and terrigenous silt grains remain to form a permeable framework, preventing the collapse that would affect a homogeneously soluble rock (Figure 10). A small grain size in these heterogeneous rocks will further enhance permeability, and a high density of bedding planes can as well, especially after deformation involving bedding-plane slip (Hofstra and Cline, 2000; Breit *et al.*, 2005). A low feldspar content is important because feldspar can be altered during hydrothermal events to smectite, whose swelling properties can plug permeability (Hofstra and Cline, 2000; Emsbo *et al.*, 2003).

Most igneous and contact-metamorphic rocks in the Nevada district were non-reactive aquitards and are therefore unmineralized (Bettles, 2002). However, a variety of igneous rock types carry gold grades in Nevada deposits, including: felsic dykes and small plutons, mafic flows and tuffs, ultramafic sills, and lamprophyre dykes (Jory, 2002; Ressel *et al.*, 2000; Hall *et al.*, 2000; Smith *et al.*, 2013a; Zohar, 2013). Many such igneous bodies are mineralized only at their contacts or where fractured, faulted, or brecciated. Certain lamprophyre dykes, however, are homogeneously mineralized at a higher grade than the surrounding sedimentary ore (Emsbo *et al.*, 2003). This is attributed to an initial 10-20% carbonate minerals, which dissolved to allow penetration by the ore fluid, and a high initial reactive-iron content. Pre-ore alteration of an igneous or contact-metamorphic rock to a sericite-chlorite assemblage may be important to maintaining its permeability by using up the feldspar that might otherwise have formed smectite (Hofstra and Cline, 2000).

Carlin-type ore in Nevada formed in host units of various ages, from Cambrian to Permian (Cline *et al.*, 2005). The same holds true in the Rackla district, where carbonate hosts of Proterozoic and Paleozoic ages have been identified (Colpron *et al.*, 2013). Although the age of the host is not a controlling factor, its sequence-stratigraphic position is (Cook, 2015). Lowstands of sea level allow karst formation on exposed portions of platforms, and wave

erosion of the margins of shallow platforms. Eroding margins shed turbidites, debris flows, and slumps onto the adjacent slope and into deep-water settings at the base of the slope and in the basin. Favorable host lithologies are the carbonate debrites, turbidites, and slumps, as well as the coeval karst facies. Strata, such as calcareous siltstone and siliciclastic shale, deposited during subsequent transgressions onto the karsted platform can be good hosts if they are iron-rich or fractured (Cook, 2015).

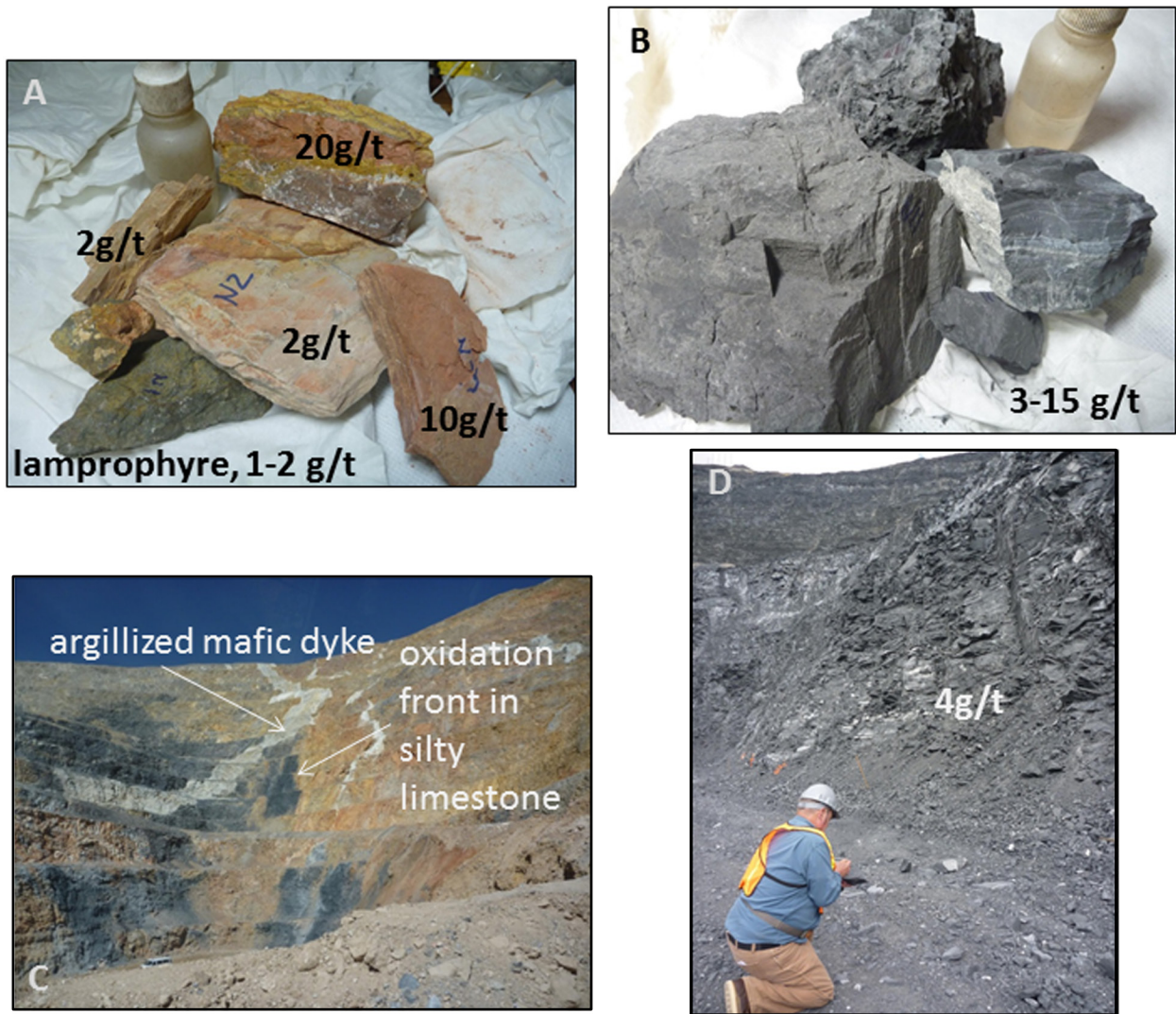


Figure 10. Host rocks of Carlin-type ore from various deposits in Nevada, showing grades of gold in grams/tonne. [A] Oxidized, de-carbonatized silty limestone and a piece of lamprophyre dyke from the Long Canyon deposit. [B] De-carbonatized silty limestone from the Mega pit of the Twin Creeks mine. [C] Sharply delimited zone of oxidation in the Cortez Hills pit of the Cortez mine. [D]) Dark grey, carbonaceous silty limestone in the Betze-Post pit at the Goldstrike mine.

## Alteration

Carlin-type ore formation was accompanied by dissolution of carbonate minerals, argillization of silicate minerals, sulfidation of iron-bearing minerals, and silicification of limestone (Hofstra and Cline, 2000). The type of alteration that dominated in any given rock was determined by that rock's composition (*i.e.*, whether it was a pure or impure limestone, igneous, or iron-rich). Igneous rocks were affected by argillic alteration, as were the terrigenous minerals in carbonate rocks. Products of argillic alteration were illite and kaolinite, as well as minor montmorillonite, smectite, dickite, and sericite (Hofstra and Cline, 2000; Teal and Jackson, 2002).

Impure limestones experienced calcite-selective decarbonatization<sup>3</sup>, which is the most obvious and common alteration in the Nevada district (Figure 10). Decarbonatization increases porosity and exposes hydrothermal solutions to iron in the residue of dolomite and terrigenous minerals (Kuehn and Rose, 1992; Cline *et al.*, 2005). Calcite-selective decarbonatization leaves a dark grey, friable, porous rock that consists mainly of insoluble matter, such as terrigenous silt and organic carbon, with or without dolomite and ore-stage pyrite (*e.g.*, Poulsen, 1996; Hall *et al.*, 2000; Emsbo *et al.*, 2003; Breit *et al.*, 2005; Cline *et al.*, 2005; Jackson *et al.*, 2010). Complete decarbonatization (the removal of all carbonate species) is common along feeder zones in the footwall of deposits, where the rock affected is not usually well mineralized (Dave Groves, personal communication). However, at one deposit, complete decarbonatization of a dolomitized heterolithic breccia produced a friable, delicate intergrowth of ore-stage pyrite and insoluble residues that contained up to 190 g/t Au (Emsbo *et al.*, 2003).

Silicification affected pure carbonates more than those with a terrigenous component, and limestones more than dolostones. Locally, however, decarbonatized rocks were silicified (Hofstra and Cline, 2000). Silicification is most intense along faults that served as fluid conduits (Teal and Jackson, 2002). Although silicified zones typically contain chemically anomalous amounts of gold, they are not usually ore (Poulsen, 1996). The timing of silicification with respect to ore formation is not always clear, however where it is discernable, it varies among deposits, and pre-, syn-, and post-ore silicification may be present at a single deposit (Teal and Jackson, 2002).

Sulfidation of iron carbonates and iron silicates affected all rock types that contained reactive iron minerals, and is believed to have been the principle control on gold precipitation (Hofstra and Cline, 2000). Reactive iron can be mobilized during fluid events, and thereby made available for sulfidation, in which hydrogen sulfide is removed from the ore fluid and bound with iron to form pyrite. The loss of H<sub>2</sub>S from the fluid reduces the solubility of gold, forcing gold to precipitate with the pyrite (Stenger *et al.*, 1998; Hofstra and Cline, 2000; Emsbo *et al.*, 2003). Notwithstanding this, some deposits may have formed

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<sup>3</sup> Decarbonatization means the removal of carbonate minerals. In Nevada, much of the decarbonatization is selective for calcite, leaving dolomite unaffected. Some authors (*eg.* Peters *et al.*, 1998) have used the term decalcification to try to portray this, but that usage leads to confusion with the established use of decalcification to mean loss of calcium ions. Here the term calcite-selective decarbonatization is used.

by introduction of both iron and sulfur, though the iron probably hadn't moved very far from its source (Kesler *et al.*, 2003; Hofstra and Cline, 2000).

There is a lack of any regional-scale zoning around Carlin-type deposits, and many lack a deposit-scale zoning that is visible to the naked eye. However, in some deposits the intensity of decarbonatization increases toward the presumed fluid conduit (Teal and Jackson, 2002), and in many deposits, there is a halo of calcite veining around the unveined ore zone that is believed to result from the short-distance movement of calcium carbonate into the surrounding rocks during decarbonatization (Cline *et al.*, 2005). A halo of depleted and variable  $\delta^{18}\text{O}$  in carbonate rocks extends 3-4 km from a deposit known as Screamer (Barker *et al.*, 2013). The halo is more intense along faults and permeable horizons that served as fluid conduits. Also at the Screamer deposit, kaolinite coats fractures within the rock volume influenced by the Carlin-type hydrothermal system, whereas fractures are free of kaolinite outside this zone (Ye *et al.*, 2003). A mineralogical zoning of clay species around presumed fluid conduits has been noted in many of the Carlin-type deposits in Nevada. For example, proximal kaolinite grades to distal smectite in dykes of various compositions at the Jerritt Canyon, Chimney Creek, and Beast deposits (Hofstra and Cline, 2000), and proximal dickite-muscovite grades through kaolinite-sericite to distal smectite-illite in calcareous siltstone and silty limestone of the Long Canyon deposit (Smith *et al.*, 2013a). More examples are described by Kuehn and Rose (1992) and Arehart (1993b).

Much of the ore in the Carlin district has been oxidized to depths of up to several hundred meters, far deeper than the extent of oxidation in the surrounding, unmineralized rock (Phillips, 2005; Zohar, 2013). Because of the initial abundance of pyrite in the ore, the oxidized zones are brick red. Oxidation fronts can be quite sharp; an example of this is shown in the photo of the Cortez Hills pit in Figure 10. Gold extraction from oxidized ore is simple and is commonly carried out using heap-leach methods. Non-oxidized ore is refractory and requires oxidation, which is typically done in an autoclave, or in a roaster if the ore is very carbon-rich, prior to leaching (Heitt, 2002; Hofstra and Cline, 2000).

## Ore fluids

Fluid-inclusion and isotope studies in conjunction with petrography, geochemical modelling, and other geological observations indicate that the ore-forming fluids were at low temperature and of low to moderate salinity, and were probably weakly acidic (Hofstra and Cline, 2000; Cline *et al.*, 2005; Emsbo *et al.*, 2006). Their source, and the source of the gold, is more controversial, but there is general agreement that at most deposits, fluids were meteoric, low temperature (150-250°C), of low (to moderate) salinity, and weakly acidic. At some deposits, however, there is evidence of a deep-sourced fluid that was either metamorphic or magmatic (Cline *et al.*, 2005).

Most genetic models propose that gold was either scavenged from the host succession or leached from the underlying Proterozoic clastic sedimentary strata (Cline *et al.*, 2005). Some of the Devonian CD zinc-lead deposits in Nevada are rich in gold, which has led to the proposal that these pre-existing concentrations of CD gold were scavenged to form the

Eocene Carlin-type gold deposits in the same district (and locally, in the same mine; Emsbo *et al.*, 2003). Genetic models for Carlin-type deposits are discussed in greater detail by Muntean *et al.* (2004) and Cline *et al.* (2005).

## Deposit-scale controls

Individual Carlin-type deposits in Nevada vary widely in the details of their lithology and structure. Despite this, there is, for the most part, agreement regarding the key deposit-scale controls, which are:

1. **Reactive, permeable host rocks.** Silty limestone, for example, is more permeable after decarbonatization than pure limestone due to the framework of insoluble material left behind. The two predominant hosts of Carlin-type deposits in the northern Carlin trend are the Popovich and Roberts Mountain formations, both of which consist largely of siliciclastic-silty lime mudstone or lime siltstone that is planar laminated or wispy laminated/bioturbated (Jory, 2002). The generalized long-section in Figure 11 illustrates the strong stratigraphic control on ore localization by the Popovich Formation.

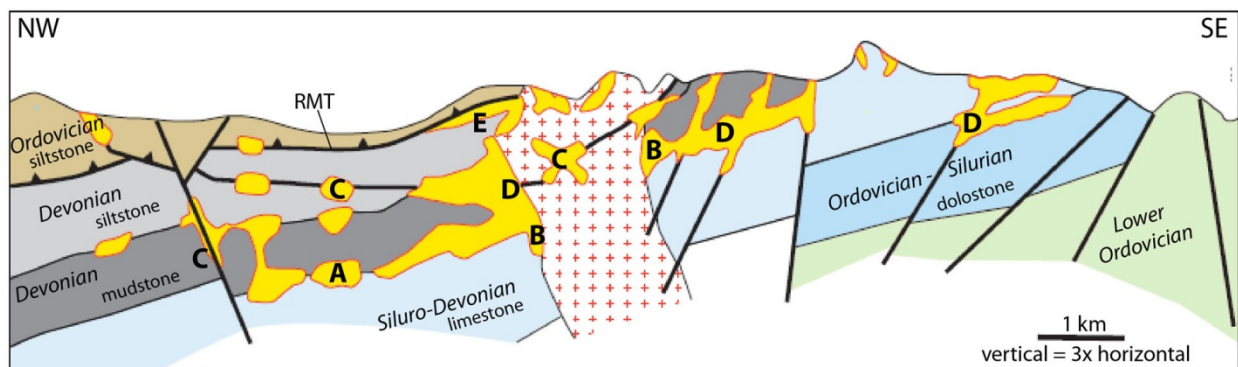


Figure 11. Schematic long section looking southeast through the northern Carlin trend, illustrating some of the deposit-scale controls on Carlin-type ore. Various ages of sedimentary rocks (green, blue, grey) are invaded by a Jurassic stock (red cross pattern), cut by numerous faults, and overthrust by shaley strata (brown) along the Roberts Mountain thrust (RMT). The dark grey Devonian mudstone is the Popovich Formation. Ore (yellow) is concentrated along stratigraphic contacts (A), the edges of the stock (B), faults (C), fault-fault and fault-contact intersections (D), and below the overthrust siliciclastic strata (E). Modified from Hofstra and Cline (2000).

2. **Fluid conduits.** Structural complexity, especially within and flanking anticlines and horsts, creates conduits that permit movement of large volumes of fluid. The presence of such conduits is essential to all deposits (Figure 11; Cline *et al.*, 2005; Jory, 2002; Zohar, 2013; Kuehn and Rose, 1992). Fluid conduits include not only faults, but also contacts and permeable horizons such as carbonate debrites, bioclastic beds, and, in some cases, mafic sills (Breit *et al.*, 2005). Fluids typically access non-fault conduits by following a fault conduit.

The presence of the appropriate host rocks and fluid conduits may have been sufficient to form some deposits (Jory, 2002), but in other cases a third control was necessary:

3. **A structural trap** that physically blocks the flow of ore fluids or changes their physico-chemical state in a way that forces precipitation (Figure 11). This is either:
  - a) **A layer or zone of impermeable rock** that blocked the upward or lateral flow of mineralizing fluids, such as:
    - i. A thrust-emplaced cap of impermeable shale over permeable host rocks (the most common trap),
    - ii. A stratigraphic barrier, where mineralization is trapped in a reactive limestone unit beneath a younger, impermeable shale or tight lime mudstone (Jory, 2002; Smith *et al.*, 2013b), and
    - iii. An impermeable stock, sill or dyke (Hofstra and Cline, 2000; Bettles, 2002);  
or
  - b) Places of **structural or lithological heterogeneity**, such as the edges of igneous bodies or deformation-associated damage zones (Cline *et al.*, 2005; Hofstra and Cline, 2000). Such zones have enhanced permeability (lower effective mean stress) which leads to lower pore-fluid pressure than in the surrounding rocks. A fluid entering one of these zones will experience changes in its physico-chemical state, possibly triggering precipitation of minerals from solution. Examples of zones of lower effective mean stress in places of structural or lithological heterogeneity include:
    - i. Permeable stratigraphic horizons within a low-permeability succession (Jory, 2002; Large *et al.*, 2011);
    - ii. Stratigraphic contacts (Figure 11; Large *et al.*, 2011; Jackson *et al.*, 2010), especially where displacement during deformation has been dominantly contact-parallel (Jory, 2002; Rhys, 2013);
    - iii. The edges of stocks (or, in some cases, of their associated metamorphic aureoles). Deformation around rheologically competent bodies that are surrounded by rocks of lower competence results in inhomogeneous strain and localized damage zones around the body (Figure 11; Large *et al.*, 2011; Cline *et al.*, 2005);
    - iv. The intersections of faults with other faults, folds, lithological contacts, or permeable lithologies (Figure 11; Jory, 2002; Johnston *et al.*, 2008; Large *et al.*, 2011; Rhys, 2013), including permeable fracture networks such as flower structures in dilational jogs, extensional horsetail splays, *en echelon* fractures, and sets of minor, shallowly or moderately dipping faults that are conjugate to a major, steep fault (Rhys, 2013; Cline *et al.*, 2005; Hofstra and Cline, 2000); and
    - v. Structures within anticlinal culminations (Figure 12; Hofstra and Cline, 2000; Jory, 2002; Rhys, 2013). Localized extension within regional-scale anticlinal culminations is accommodated by conjugate faults and other steep structures of limited extent, which can become conduits for ore fluids. The overarching control remains the hinge zone of the regional-scale antiform. In northern Nevada, the hinges of east-verging regional folds control ore placement in a number of subdistricts (Hall *et al.*, 2000; Teal and Jackson, 2002; Johnston *et*

*al.*, 2008; Rhys, 2013). An anticlinal control may also have been active in the Rackla district, where the Osiris, Isis East, and Conrad deposits lie in the core zones of anticlines (Figure 13; Tucker *et al.*, 2013; Arehart *et al.*, 2013).

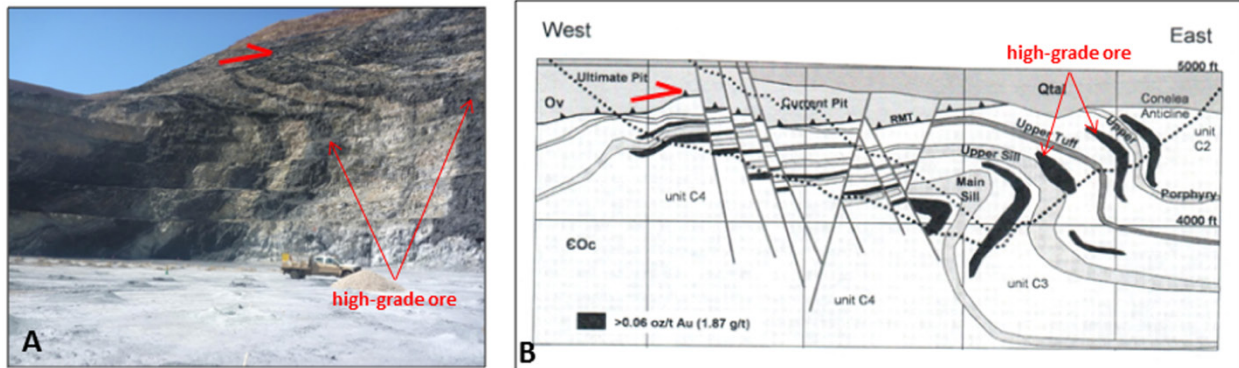


Figure 12. Anticlinal control in the Mega pit at Twin Creeks mine, Nevada. [A] Folds are traced on the pit wall by dark, decarbonatized silty limestone (ore) alternating with light bands of greenish grey, argillized, volcanoclastic strata and white quartz-porphry sills (low-grade ore). The highest-grade ore is at the anticlinal culminations. Red half-arrow marks the Roberts Mountain Thrust, which truncates the folded strata. Truck for scale. [B] Diagrammatic representation of almost the same part of the pit (Modified from Breitt *et al.*, 2005). Dark grey zones locate the high-grade ore (>1.87 g/t).

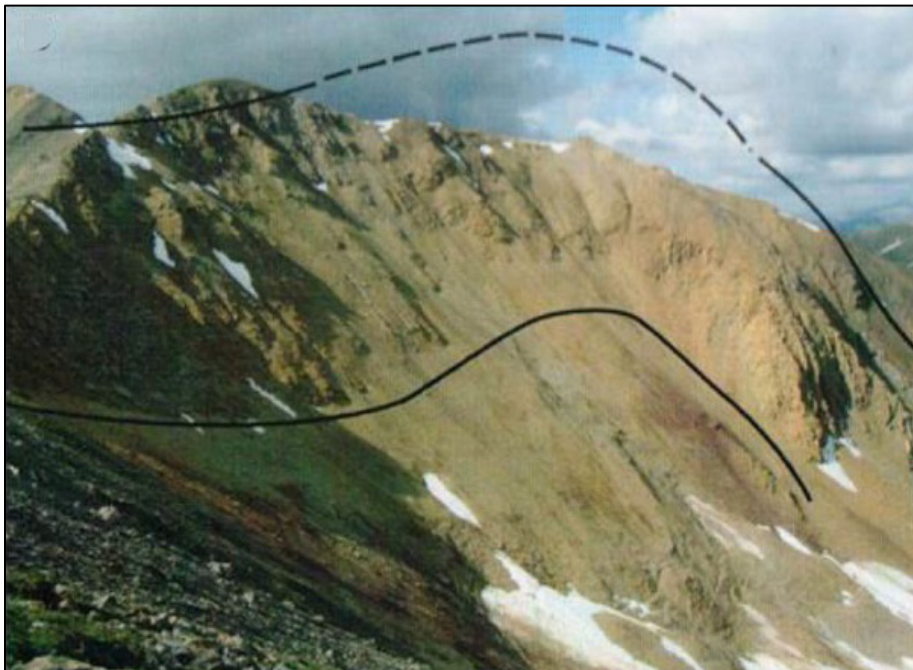


Figure 13. The anticlinal structure that hosts the Osiris Carlin-type deposit in the Rackla district. Modified from Arehart *et al.* (2013).

## Vectors to ore

Most of the Nevada deposits don't have a characteristic geophysical signature, but geochemistry of stream silt, soil, soil gas, vegetation, and groundwater can be useful. The most consistently introduced elements in Nevada deposits, besides gold, are arsenic, mercury, antimony, thallium, and locally, tellurium (Cline *et al.*, 2005; Hofstra and Cline, 2000; Muntean *et al.*, 2011). Not all of these are consistently or individually useful as exploration tools. Regional-scale arsenic anomalies can be useful in selecting regions of interest, but since all of northern Nevada is anomalous in arsenic, the element is not as useful for targeting individual deposits, which are only roughly associated with the highest arsenic anomalies (Patterson and Muntean, 2011). At some deposits, antimony in soil is not associated in any consistent way with gold ore, but antimony in vegetation is (Muntean and Taufen, 2011). Zinc anomalies in soil and vegetation are spatially related to underlying ore at some deposits (Muntean and Taufen, 2011), and zinc is elevated in bedrock in and around some orebodies (Peters *et al.*, 1998). Mercury in Nevada often has a smaller footprint than gold itself, and its association with gold ore can be erratic, which limits its usefulness in exploration (Muntean and Taufen, 2011; Albino, 1994; Brooks and Berger, 1978). In the Rackla district, the combination of As-Tl-Sb-Hg is regarded as a signature of Carlin-type systems (ATAC Resources Ltd., accessed 2017), and most deposits have been discovered by following discovery of regional stream-silt arsenic, gold, or thallium anomalies with detailed stream-silt and soil surveys that outlined some combination of As, Hg, Au, Sb, Tl and Ag anomalies (Yukon Minfile, accessed 2015; Tucker *et al.*, 2013; Arehart *et al.*, 2013). Both the Nevada and Rackla districts host abundant Paleozoic barite deposits, and Ba has a spatial association with ore, however its importance as a pathfinder element is uncertain (Arehart *et al.*, 2013).

The presence of abundant organic matter in the host basin may be a prerequisite for formation of Carlin-type gold, though the reason isn't clear (Hofstra and Cline, 2000; Large *et al.*, 2011). Some types of organic matter are sulfur-rich and can provide sulfur to form H<sub>2</sub>S, however, there is evidence that organic matter in the Nevada districts was sulfur-poor (Hofstra and Cline, 2000). Organic matter can also provide sulfur indirectly, by acting as the reductant for thermochemical reduction of barite or anhydrite. Most importantly, though, organic matter can buffer the oxygen fugacity of circulating fluids, keeping it low enough that the dominant sulfur species in the fluid is H<sub>2</sub>S (Hofstra and Cline, 2000). Gold can dissolve in H<sub>2</sub>S-rich (reduced) waters by forming bisulfide complexes, although it is poorly soluble to insoluble in oxygenated waters. When a reduced, gold-bearing fluid encounters reactive iron in the rock, H<sub>2</sub>S is removed from solution by sulfidation of the iron to form pyrite. As a result, the gold is no longer soluble, and precipitates along with the pyrite.

It has also been proposed that organic matter was an interim storage location for the gold. According to this proposal, gold was extracted from seawater and clay minerals, fixed to the organic matter of slope and basin deposits under reducing conditions during sedimentation or diagenesis, then re-mobilized during later diagenetic, hydrothermal, or hydrocarbon fluid-flow events (Large *et al.*, 2011). If this was the case, it would be important to have numerous permeable zones (coarser horizons of terrigenous clastic

rocks or carbonate debrites) interstratified with the black, organic-rich mudstones, in order to allow fluids to scavenge a larger volume of rock. Despite the district-scale importance of organic matter, at the deposit scale there is no consistent spatial correlation between rocks with high organic-carbon content and rocks that host gold ore (Hofstra and Cline, 2000).

## Tectonic controls on Carlin-type deposits

There are three key elements of tectonic history that are agreed to be necessary to form giant districts of sediment-hosted, Carlin-type gold, and a fourth that may be important (Figure 14; Grauch *et al.*, 2003; Groves *et al.*, 2005; Cline *et al.*, 2005; Emsbo *et al.*, 2006). The first required element of tectonic history is a setting near the edge of a long-lived, rifted continental margin (a so-called passive margin; Figure 14-1), which provides a diversity of rock types that create rheological and permeability contrasts (Groves *et al.*, 2005) and may also be the source of metals scavenged by circulating fluids (Ilchik and Barton, 1997; Emsbo *et al.*, 2003). This setting provides through-going lithospheric faults that originated during the initial rifting as well as later growth faults that developed as the margin underwent episodes of extension (Hofstra and Cline, 2000). These faults are important to subsequent movement of mineralizing fluids.

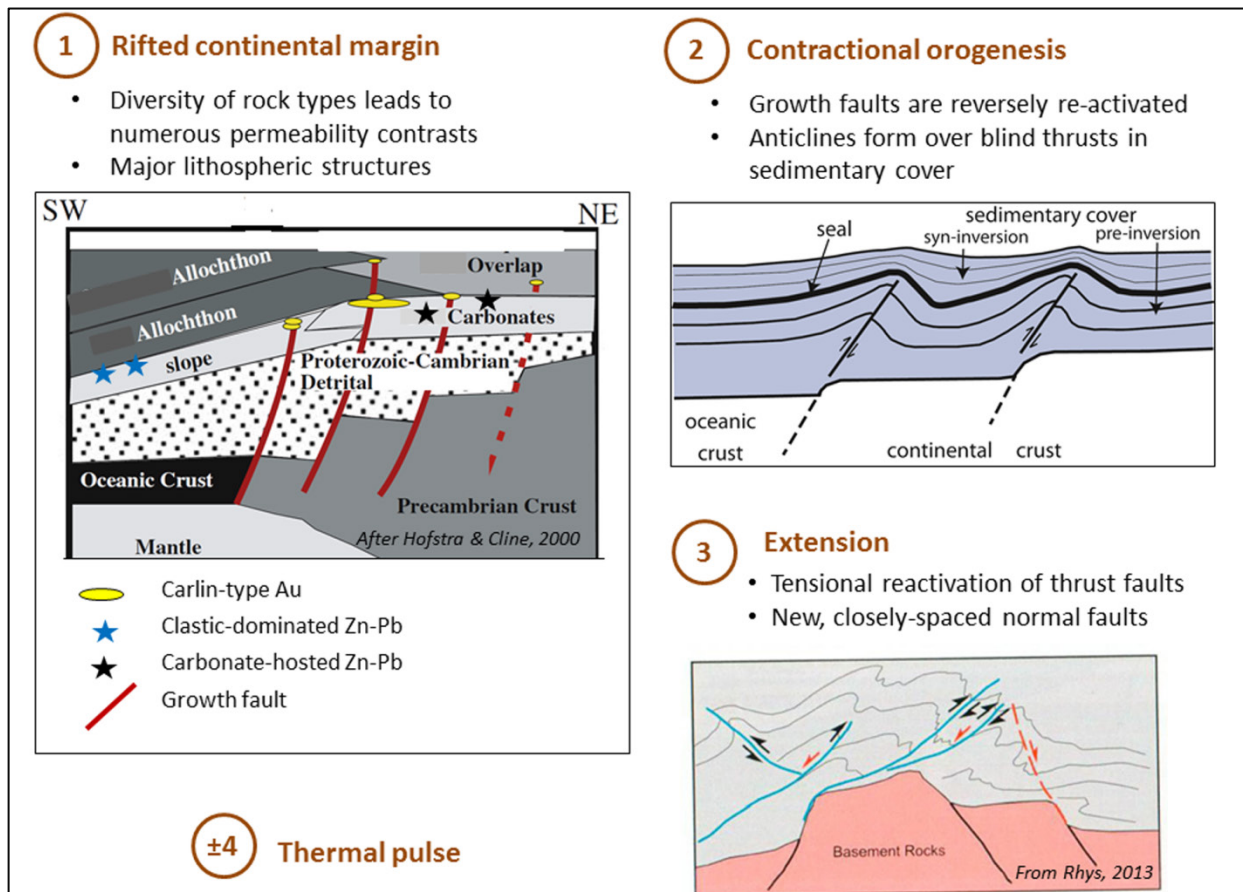


Figure 14. Tectonic controls on Carlin-type ore. (1) The first control, a rifted margin, provides both fluid conduits and rheological contrasts among a diversity of rock types. The generalized cross-section of the Carlin district in Nevada shows Precambrian crust (at right) that rifted in the Proterozoic, leading to formation of oceanic crust (at left). A typical rifted-margin succession has developed over the extended transitional crust and the oldest oceanic crust, and consists of a thick, basal layer of detrital sediments, overlain by a carbonate platform (right), debris flows and slope facies (left), and a deep basin (off the left side of the diagram). Modified from Hofstra and Cline (2000). (2) The second control, contractional orogeny, terminates the rifted-margin phase. The schematic cross-section shows sedimentary cover over a rifted crust during and after basin inversion. Originally-normal growth faults have been re-activated reversely as sedimentation continued, leading to asymmetric anticlines over blind thrusts. Underlying lithospheric faults have influenced the locations of later faults. (3) The third control is a late extensional phase. Some of the reverse faults (blue) that were active during contractional orogeny are re-activated as normal faults (red arrows), and new normal faults (red) form. Basement faults continue to exert control. From Rhys (2013). (±4) A thermal pulse associated with extension may be required.

The nature of the crust underlying the Nevada Carlin-type gold district, and the presence of structural breaks in it, have been inferred from isotopic and geophysical data (initial strontium isotope ratios and lead isotope ratios of granitoids, and gravity, magnetic and magnetotelluric data; Grauch *et al.*, 2003 and references therein). Most of the Carlin-type deposits in Nevada, including the largest, lie over oceanic or extended, transitional continental crust (Figure 15; Grauch *et al.*, 2003). They are concentrated along trends that reflect underlying deep-crustal structures that originated during the rifting of Rodinia and have been re-activated multiple times since then (Grauch *et al.*, 2003; Crafford and Grauch, 2002). Some of these structures coincide with the continental margin, which trends alternately NE and NNW, and others are at a high angle to it (Figure 15). The NE-trending segment of the continental edge, known as the Snake River fault zone (USA), is thought to have developed as a transfer fault, whereas the NW-trending structures were inherited from normal faulting that accommodated NE-SW extension early during continental rifting (Tosdal *et al.*, 2000; Lund, 2008). These basement structures ultimately controlled the regional location of Carlin-type ore deposits in Nevada by permitting the flow of hydrothermal fluids from depth, up to intersections with subordinate fluid pathways (faults or permissive strata; Cline *et al.*, 2005).

The second required element of tectonic history is a phase of compression and orogenesis that follows the long-lived rifted margin. The originally listric growth faults are re-activated under compression in a reverse sense, while sedimentation of a cover succession is taking place. This creates anticlines in the sedimentary cover over blind thrusts in the underlying rifted-margin succession (Figure 14-2; Bally, 1984; Yamada and McClay, 2004; Gibson *et al.*, 2017). These anticlines and related structural features become traps for later mineralizing fluids (Emsbo *et al.*, 2006). Another effect of orogenesis is the emplacement of allochthonous thrust sheets of basinal, shaley strata over the rifted-margin succession (Cline *et al.*, 2005; Groves *et al.*, 2005). Shale units within these allochthons are typically impermeable and may act as seals, trapping fluids in underlying reactive strata where the ore then precipitates (Hofstra and Cline, 2000). In Nevada, the compression and orogenesis that terminated the rifted-margin phase began in the Late Devonian, and allochthons were emplaced eastward or northeastward over the continental margin in the Late Devonian

and the Triassic (Figure 14-1). A series of compressional orogenic events continued throughout the Mesozoic.

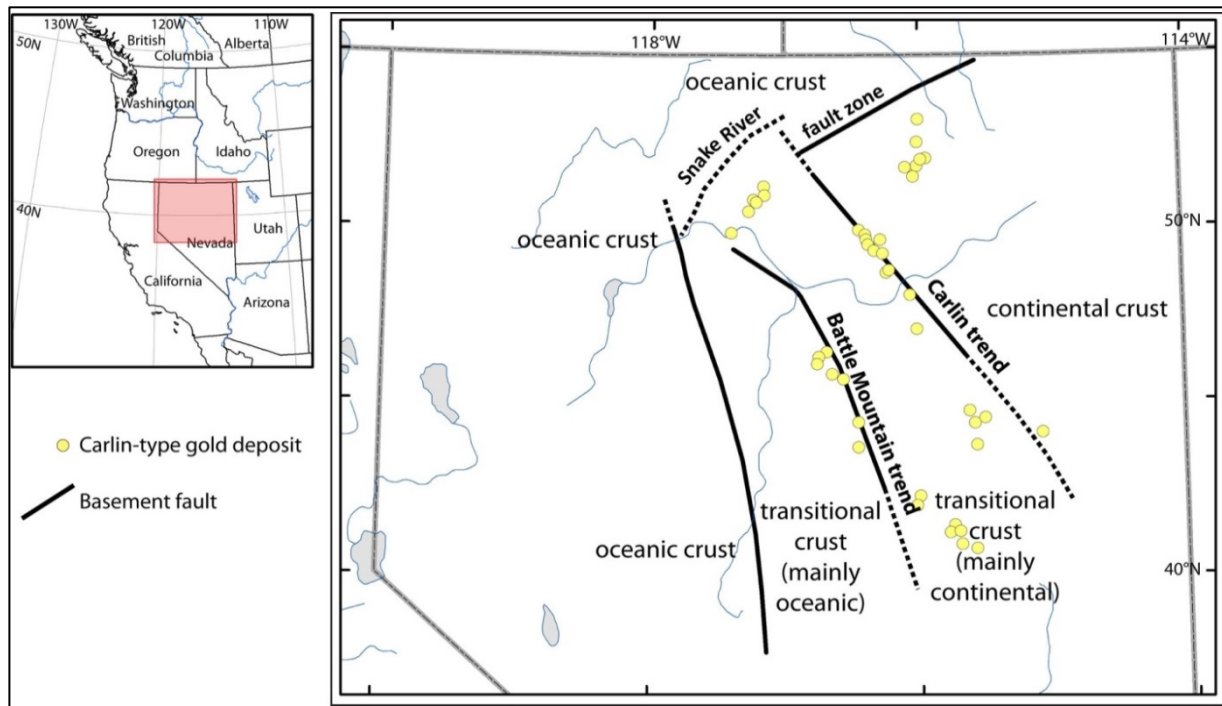


Figure 15. Lithosphere-scale basement structures in northern Nevada that controlled localization of Carlin-type ore. The nature of the underlying crust was inferred from geophysical and isotopic data. The dashed lines are not supported by as much data as the solid lines. The red box on inset shows location of main map. Large map has been modified from Grauch *et al.* (2003) and Crafford and Grauch (2002).

The third required element of tectonic history is a phase of extension that follows contractional orogeny (Cline *et al.*, 2005). The extension causes tensional reactivation of pre-existing thrust faults, which used to be normal and now become normal again, plus it creates many new, closely-spaced normal faults (Figure 14-3). The overall effect is to greatly enhance the permeability of the crust in the extending area, which allows for flow of mineralizing fluids into structural traps. The phase of extension is thought to be critical to the formation of giant districts of sediment-hosted, Carlin-type gold. In Nevada, Carlin-type deposit formation coincided with a mild Eocene extension that was related to the removal or steepening of the Farallon plate being subducted beneath western North America (Humphries, 1995). This phase of extension pre-dated the extreme extension of basin-and-range formation (Groves *et al.*, 2005; Cline *et al.*, 2005).

In Nevada, a regional crustal thermal event and related magmatic activity were caused by upwelling of the asthenosphere to the base of the crust after slab removal (Humphries, 1995). Such an event might be required to initiate and maintain the fluid circulation needed to form Carlin-type gold (Muntean *et al.*, 2004; Ressel and Henry, 2006). A thermal

event is the fourth element of tectonic history that may be necessary to formation of giant districts of Carlin-type gold.

## Clastic-dominated Zinc-Lead Deposits

The characteristic features of CD zinc-lead deposits and the problems inherent in classifying them have been discussed by Leach *et al.* (2005, 2010) and Emsbo *et al.* (2016). The body of knowledge on these deposits is large and the model is well known, hence only certain aspects of the CD zinc-lead deposit model that are particularly relevant to exploration in the MCE area are described here (Table 1; Figure 16). The classic setting of CD base-metal deposits, as for Carlin-type gold deposits, is a rifted-margin succession (Figure 14-1), but intracontinental and back-arc rift settings have been identified for some CD deposits (Leach *et al.*, 2010). Clastic-dominated zinc-lead deposits develop in basinal, slope, and outer shelf strata, either syn-depositionally or during diagenesis, according to the classic model (Leach *et al.*, 2005; Large *et al.*, 2005), or during basin inversion, according to a more recent model (Gibson *et al.*, 2017).

Table 1. Characteristics of clastic-dominated (CD) zinc-lead deposits that are useful as vectors to mineralization. Information is primarily from Leach *et al.* (2010) and Emsbo *et al.* (2016); exceptions are noted. MVT = Mississippi Valley-Type.

Type of characteristic	Characteristic	Details
Tectonic setting	First-order rifted basin	Rifted passive-margin basin. Examples: Howards Pass deposits of the Selwyn Basin, Canada (Goodfellow, 2007); Red Dog deposit, Alaska; Rammelsberg deposit of the Rhenohercynian basin, Germany. Intracratonic rift basin. Examples: deposits of the Mount Isa – McArthur basin system in northern Australia (Large <i>et al.</i> , 2005); Sullivan deposit in the Belt-Purcell Basin, Canada (Goodfellow and Lydon, 2007). Rifted back-arc basin. Example: MacMillan Pass deposits in the Selwyn Basin (Goodfellow and Lydon, 2007).
	Second- and third-order basins	Most CD deposits occur in areas affected by syn-depositional faulting related to sub-basin formation. Second-order basins (tens of kilometers) and some third-order basins (kilometers across) are created by syn-depositional, extensional faults believed to serve as ore-fluid conduits. Evidence of such faulting includes abrupt facies boundaries, abrupt changes in unit thickness, debrites, and intraformational breccias. Local evidence may include Fe- or Mn-carbonate alteration or silicification of wall rocks. Some third-order basins are bathymetric lows protecting low-energy, oxygen-poor bottom waters and organic-rich, pyritic muds that react with dense, bottom-hugging, metalliferous brines. Increasing thicknesses of debrites and pyrite and organic matter concentrations may point toward bathymetric lows.

(continued)

Table 1. (continued)

Type of characteristic	Characteristic	Details
Tectonic setting	Upper part of the basin fill	Rift basins are filled, broadly speaking, with a basal rift-phase succession dominated by terrigenous clastic sediments and/or volcanic deposits, and an upper sag-phase succession dominated by mud-grade terrigenous and carbonate sediments. Most CD deposits occur in the upper part. Since fluid temperatures of at least 100°C are required, at least 3 km of sediment fill should underlie the prospective horizons.
	Presence of thick rift-phase fill	The thick, oxidized, permeable lower part of the basin fill is believed to be essential: as the source of metals, to buffer ore fluids, and to allow movement of the fluids. The volume of fill should be mappable at the scale of the first-order basin.
	Presence of known CD deposits	All known basins with CD deposits contain multiple such deposits at multiple stratigraphic levels, thus the presence of already discovered CD occurrences makes a basin more prospective.
	Adjacent to a platform with evaporite rocks and MVT deposits	Since CD deposits are believed to form from saline residual brines, the prospective basin will be adjacent to a platform with evaporite rocks, salt-dissolution breccias, or regional dolostone facies. MVT deposits and high-temperature dolomite on the platform may point to CD deposits in the basin.
	Presence of sill/volcanic complexes	Volcanic or sill complexes may have provided a source of heat to drive fluid circulation (Goodfellow and Lydon, 2007).
Host succession	Fine-grained siliciclastic sediments deposited in deep water (below wave base)	The host succession was deposited below wave base on the outer shelf, on the slope or in the basin, typically with a low sedimentation rate. Although the host rock may be carbonate or (rarely) coarse siliciclastic rock, the succession as a whole is dominated by deep-water mudstone, shale and siltstone.
	Reduced sediments	The host succession contains abundant reduced sediments with at least 1% organic carbon. Increasing organic matter and pyrite within a prospective horizon may point toward ore.
	Debrisites	Slump breccias, turbidites and other debrisites are common in the ore-bearing successions at a number of deposits.
Distal exhalative sediments	Barite, apatite, Fe/Mn carbonate, silica, Fe sulfides, metalliferous shale	Bedded exhalative rocks distal to a deposit may contain iron and/or manganese carbonates, iron sulfides, barite, phosphates, or chert. None of these is necessarily present. Some may be present within the deposit, above it or below it, as well as lateral to it. Silica may be present as quartz in the vent complex and veins, as chert within the layered ore, and as siliceous shale and chert distal to the ore. Black, metalliferous shale may be a distal indicator of ore.

(continued)

Table 1. (continued)

Type of characteristic	Characteristic	Details
Alteration	Sericite, chlorite, Fe-sulfides, Fe-Mn carbonates, silica, (tourmaline)	Deposits hosted by carbonate-bearing sedimentary rocks ( <i>e.g.</i> northern Australia) tend to have halos of Fe-Mn carbonate alteration. Deposits hosted by siliciclastic rocks may have muscovite halos. Silicified wall rocks are common. Tourmaline alteration under the Sullivan deposit may pre-date the ore.
	Chemical halos (in rocks or stream silts) of Pb, Zn, Fe, Tl, $\pm$ Mn, ( $\pm$ As, Ba, Bi, Hg, Mn, P, Sb)	Although no single deposit has a halo of all trace elements, and no single element is associated with every deposit, most deposits have a halo of Pb, Zn, Fe and Tl enrichment. Most of those in carbonate-bearing sediments have a halo of Mn enrichment. The few deposits in which rare earth elements have been studied tend to show positive Eu anomalies. Halos of enriched $^{18}\text{O}$ and depleted $^{13}\text{C}$ have been noted around some deposits.
	Chemical zoning	Lateral zonation: Pb:Zn, Zn:Fe, Pb:Fe and Zn:Mn ratios increase toward ore and Ba:Zn decreases toward ore. Mineral populations are reduced close to ore (ferroan carbonate, iron sulfides) and oxidized distally (barite, calcic carbonate, iron oxides). Vertical zonation: Pb:Zn increases, Zn increases, and Ba:Zn decreases toward deposits.

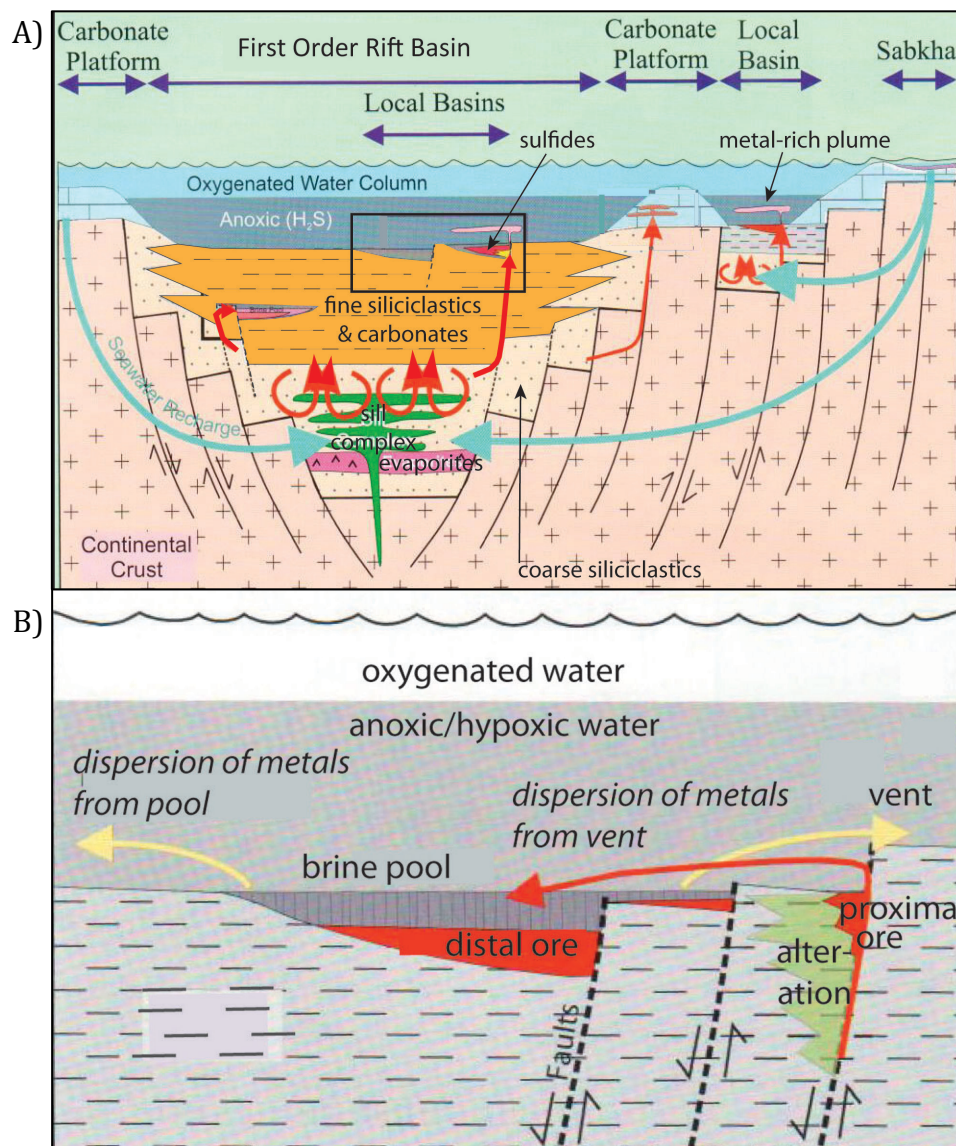


Figure 16. The classic model for clastic-dominated lead-zinc (CD) deposits. [A] The tectonic setting of CD deposits. A first-order rift basin is floored by thinned continental crust (pink). Mafic intrusive sills and dykes and evaporitic sediments may be present. Rift blocks of crustal rock are delimited by listric faults and overlain by coarse siliciclastic sediments, which themselves are overlain by fine grained, thin bedded siliciclastic and minor carbonate sediments. Carbonate platforms on uplifted fault blocks restrict circulation between the rift basin and the open ocean, or between local sub-basins. Although the upper layers of water are oxygenated, the restricted, lower layers are suboxic to anoxic. Red lines show flow of hydrothermal fluids. Blue-green lines show seawater recharging the hydrothermal reservoir. Sulfide minerals (red) replace sediments, or metal-rich fluids (pink) are exhaled to form plumes from which sulfides precipitate on the seafloor. Box shows general location of [B]. [B] A closer view of the seafloor adjacent to a number of faults, one of which is venting metalliferous fluids (red arrow). Metalliferous brine collects in pools (dark grey) from which sulfides precipitate at the bottom (red). Metals can disperse slowly from the pool into the surrounding water (yellow arrows). Drawings after Goodfellow and Lydon (2007).

## Local and district-scale controls

### Ore

Clastic-dominated zinc-lead deposits consist of multiple stacked, tabular bodies of stratabound ore, or discordant bodies that were feeders to stratabound ore (Leach *et al.*, 2005; Goodfellow and Lydon, 2007). The ore consists of laminated, massive or semi-massive sulfides that are commonly brecciated, but may include a significant component of sulfides in small, cross-cutting veins. The laminated sulfides are thought to be either sediment replacements, which formed as basinal brines percolated through sediments beneath the seafloor, or syn-depositional exhalative precipitates, which formed from basinal brines exhaled onto the sea floor (Figure 16). Brecciated ore formed in and near the vent for the hydrothermal fluids. Sphalerite, galena, and pyrite are the dominant sulfides. Commodities in economic concentrations are zinc, lead, and commonly silver, although gold or copper can be significant in some deposits. Carbonate minerals, barite, and silica (as chert or quartz) are the most common gangue minerals, but none of these is universally present (Leach *et al.*, 2005; Goodfellow and Lydon, 2007).

### Host rocks

The host succession of a CD zinc-lead deposit is usually dominated by reduced, fine-grained siliciclastic rocks that were deposited in deep water, below wave base (Leach *et al.*, 2005, 2010; Figure 16; Table 1). The actual host rock may be carbonate or even coarse siliciclastic rock, but the succession containing it is always dominated by reduced rocks, and the biggest deposits are hosted by reduced shale or mudstone. Although the cause of the high organic-carbon content of the succession is unknown for many districts, in others it was due to very low siliciclastic input, locally high biological productivity, and anoxic or dysoxic bottom water (for example, the Red Dog district in the Kuna Basin; Dumoulin *et al.*, 2004).

Sulfide minerals in CD zinc-lead deposits are commonly interstratified with other exhalative or near-seafloor replacive rocks, such as laminated barite, phosphorite, chert, or Fe-Mn carbonate. These related rocks may extend beyond the limits of the ore, making them useful as exploration tools — their presence in an area increases its prospectivity (Leach *et al.*, 2005; Goodfellow and Lydon, 2007; Table 1).

### Alteration and geochemical halos

Mineralogical alteration associated with CD zinc-lead ores is variable and not visually obvious in all deposits (Table 1). Enrichment in Fe-Mn carbonate is evident in carbonate hosts around some deposits (Leach *et al.*, 2010; Goodfellow and Lydon, 2007). In others, silica as chert or siliceous mudstone is associated with ore, but the age of silicification with respect to mineralization is often uncertain. Sericite, chlorite, and tourmaline have been introduced at various deposits (*ibid.*).

Geochemical halos tend to be more useful than mineralogical ones as vectors to ore. Manganese halos are present where the host succession contains carbonate rocks (Large and McGoldrick, 1998). Other elements that tend to be enriched around these deposits

include Pb, Zn, Fe and Tl, and less commonly or strongly, Sb, Hg, As, Ba, Bi, and P (and rarely Cd, Ge, Ni; Goodfellow and Lydon, 2007). Note that many of these (Tl, Sb, Hg, and As) are also enriched around Carlin-type gold deposits. Zoning of metal ratios is common (Table 1), and Pb:Zn ratios that increase toward ore have been detected up to 10 km from a deposit.

## **Tectonic setting of clastic-dominated zinc-lead deposits**

The tectonic setting of CD zinc-lead deposits is, grossly speaking, a rift basin (Leach *et al.*, 2010; Table 1; Figure 16). This includes the rifted margins of epicratonic basins (*i.e.*, passive margins), as well as intra-cratonic basins floored by thinned continental crust, and back-arc basins floored by continental crust. Basin fills in all three settings are typical of basins developed over rifted crust: a basal succession of coarse siliciclastic rocks and an upper succession of fine siliciclastic and carbonate rocks.

It is typically the upper part of the basin fill, thought to have been deposited during the post-rifting phase of thermal sag, that hosts CD deposits (Figure 16), although a few are hosted within the lower, rift-phase fill (Leach *et al.*, 2005, 2010). For certain basins, particularly those in northern Australia, the designation of successions as rift- or sag-phase is controversial, as is the origin of the basin itself in some cases (Leach *et al.*, 2010; Gibson *et al.*, 2017). Most deposits are localized in second- and third-order basins created by syn-depositional faults that are thought to have served as ore-fluid conduits (Large *et al.*, 2005; Leach *et al.*, 2005). The timing of ore formation is not always well constrained; although the classic model depicts syn-extensional mineralization, a more recent model proposes syn-inversion mineralization for some major districts (Gibson *et al.*, 2017). The presence of volcanic or sill complexes in the basin has been suggested to be important, since the magmatism may have provided a source of heat to drive circulation (Goodfellow and Lydon, 2007). Basins containing CD deposits have flanking carbonate platforms that contain evaporite rocks, salt-dissolution breccias, or regional dolostone facies, all of which are evidence of evaporation of large volumes of seawater. Such evaporation was essential to generate the residual, saline brines that formed the ore (Emsbo *et al.*, 2016). The margins of the platforms usually also host a number of MVT deposits and occurrences of high-temperature dolomite, which are thought to have been generated by the same fluid flow systems that generated the CD deposits (*ibid.*).

A prospective basin will therefore be a rift basin adjacent to a platform with known MVT deposits and evaporitic rocks or regional dolostone. The prospective parts of the basin will be those portions of its mid to upper levels where there is evidence of syn-sedimentary faulting (abrupt facies changes, abrupt changes in the thickness of a unit, or the presence of fault-scarp breccias or debrites). The most prospective higher-order basins will be those with a high proportion of carbonaceous, pyritic mudstone or shale.

# The Misty Creek Embayment Area

The remainder of this report describes the attributes of the MCE area that make it prospective for Carlin-type gold and CD zinc-lead deposits. The bedrock geology is taken from a recently published map, covering most of the MCE area, in which new mapping of the basinal rocks was compiled with pre-existing data from various sources (Fischer, 2016; Figure 17). For the southern reaches of the MCE, the latest available bedrock geology maps are from Gordey *et al.* (2012) and Cecile (1996). Source references for stratigraphic units are provided along with the unit descriptions below, or can be found in Martel *et al.* (2011).

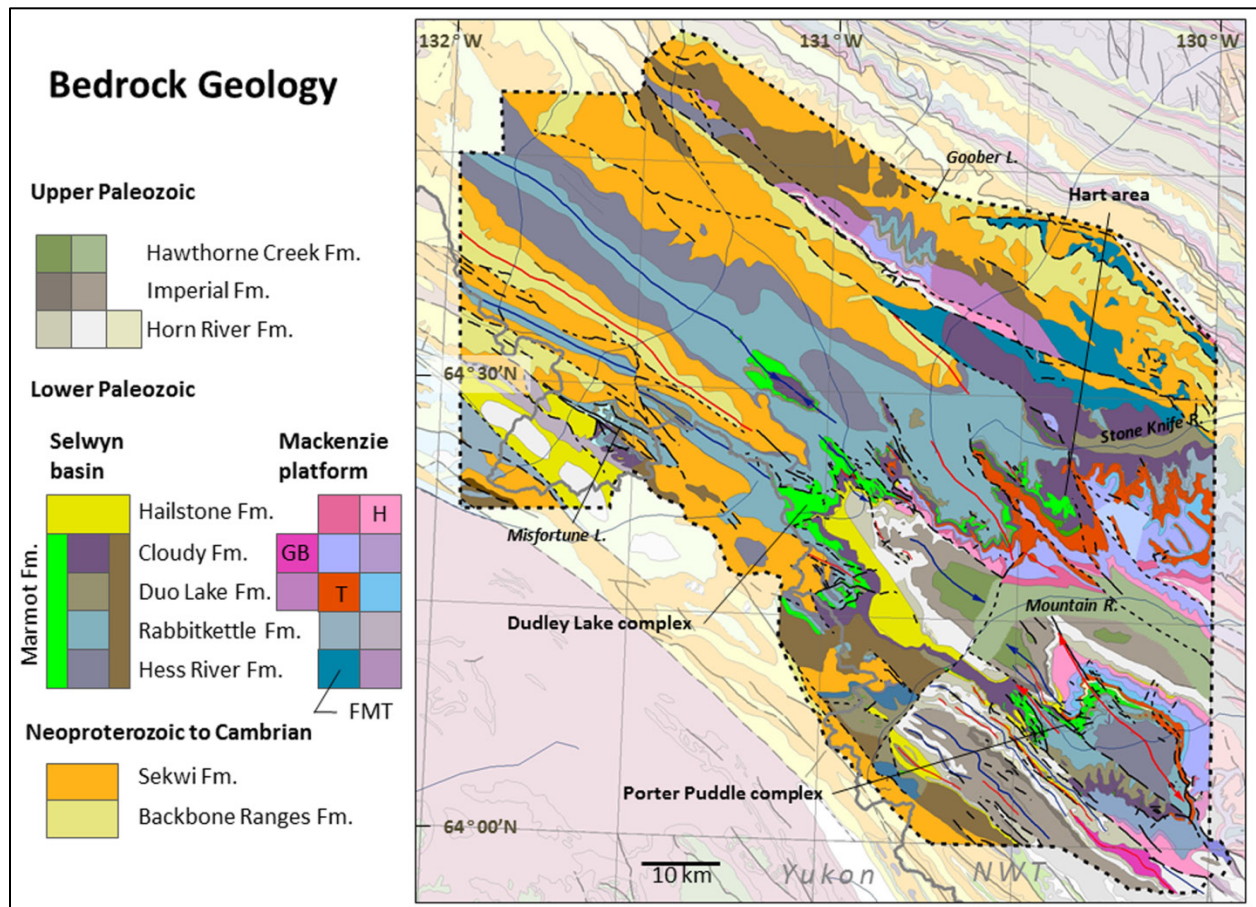


Figure 17. Bedrock geology of the Misty Creek Embayment in mapsheet 106B, simplified from Fischer (2016). The interpretation of bedrock geology is based partly on new mapping, which was concentrated in the southeast, and partly on the compilation of pre-existing data. Location of the map is shown in Figures 1 to 3. Red lines are axial traces of anticlines, blue lines of synclines; arrows indicate directions of fold plunge. Black lines are faults (solid = defined, dashed = approximate, short dash = inferred). The new map is shown in vivid colors with thick black, dashed outline. Background geology is generalized from Gordey and Makepeace (2003). Locations mentioned in the text are labeled. FMT = Franklin Mountain Transitional formation, GB = Grizzly Bear Formation, H = Hume Formation, T = Tsetso(?) Formation. Projection is Universal Transverse Mercator Zone 9 based on North American Datum 1983.

The MCE was adjacent to the Mackenzie Platform, which was a carbonate-dominated platform that endured from Early Cambrian until Middle Devonian time. Evaporitic units developed on the platform at a number of different times (Cambrian Saline River Formation; Early Devonian Camsell Formation, Middle Devonian Bear Rock Formation; Martel *et al.*, 2011). An extensive dolomitization affected many of the Devonian carbonate units (Morrow *et al.*, 1990).

## **Bedrock Geology**

The oldest rocks in the MCE area, deposited during the latest Neoproterozoic and Cambrian uplift, are mainly fluvial sandstone (Backbone Ranges Formation) overlain by an Early Cambrian unit that records a carbonate ramp evolving to a shelf (Sekwi Formation). This is, in turn, overlain conformably by five basinal units, from Middle Cambrian to Middle Devonian in age (Hess River, Rabbitkettle, Duo Lake, Cloudy, and Hailstone formations; Cecile, 1982, 2000), as well as volcanic rocks of the Ordovician-Silurian Marmot Formation (Cecile, 1982) and related intrusive rocks. These Early Paleozoic basinal strata, at one time mapped collectively as “Road River Group” (Blusson, 1974), record a range of basinal environments from deep water through slope to platform edge, and are dominated by calcareous sediments.

Overlying the Early Paleozoic succession is a second basinal succession, deposited in a distal back-arc setting during Late Paleozoic transgressive overlap, that covered both the Selwyn Basin and the adjacent carbonate platforms. Deposits of this basin are dominated by terrigenous shale and belong to the Devonian Horn River and Imperial formations (see Pugh, 1983 for a history of these names and their current definitions) and the Mississippian Hawthorne Creek Formation (Cecile, 2000). The stratigraphic units of both basins are described below, insofar as their potential to host Carlin-type or CD zinc-lead mineralization.

### **Potential hosts of Carlin-type gold mineralization**

Within the MCE area, almost all of the Lower Paleozoic basinal units and some of the platformal units have the characteristics required to be considered potential hosts of Carlin-type gold (Figure 18). Parts of the Backbone Ranges and Sekwi formations, most of the Hess River, Rabbitkettle, Cloudy, and Hailstone formations, and parts of the Tsetso(?), Grizzly Bear and Hume formations:

- are reactive (rich in carbonate minerals at least, and some are also rich in reactive iron, generally as ferroan dolomite);
- have components with contrasting dissolution potential (less-soluble silt grains, skeletal fragments, or breccia clasts in a more-soluble matrix), which can lead to enhanced permeability in the presence of fluids; and
- have fine grain size, which promotes dissolution by increasing reactive surface area, and/or thin bedding, which increases permeability along bedding planes, especially after deformation.

The Duo Lake Formation and other platformal carbonate units are not regarded as priority stratigraphic targets, although they should not be ruled out.

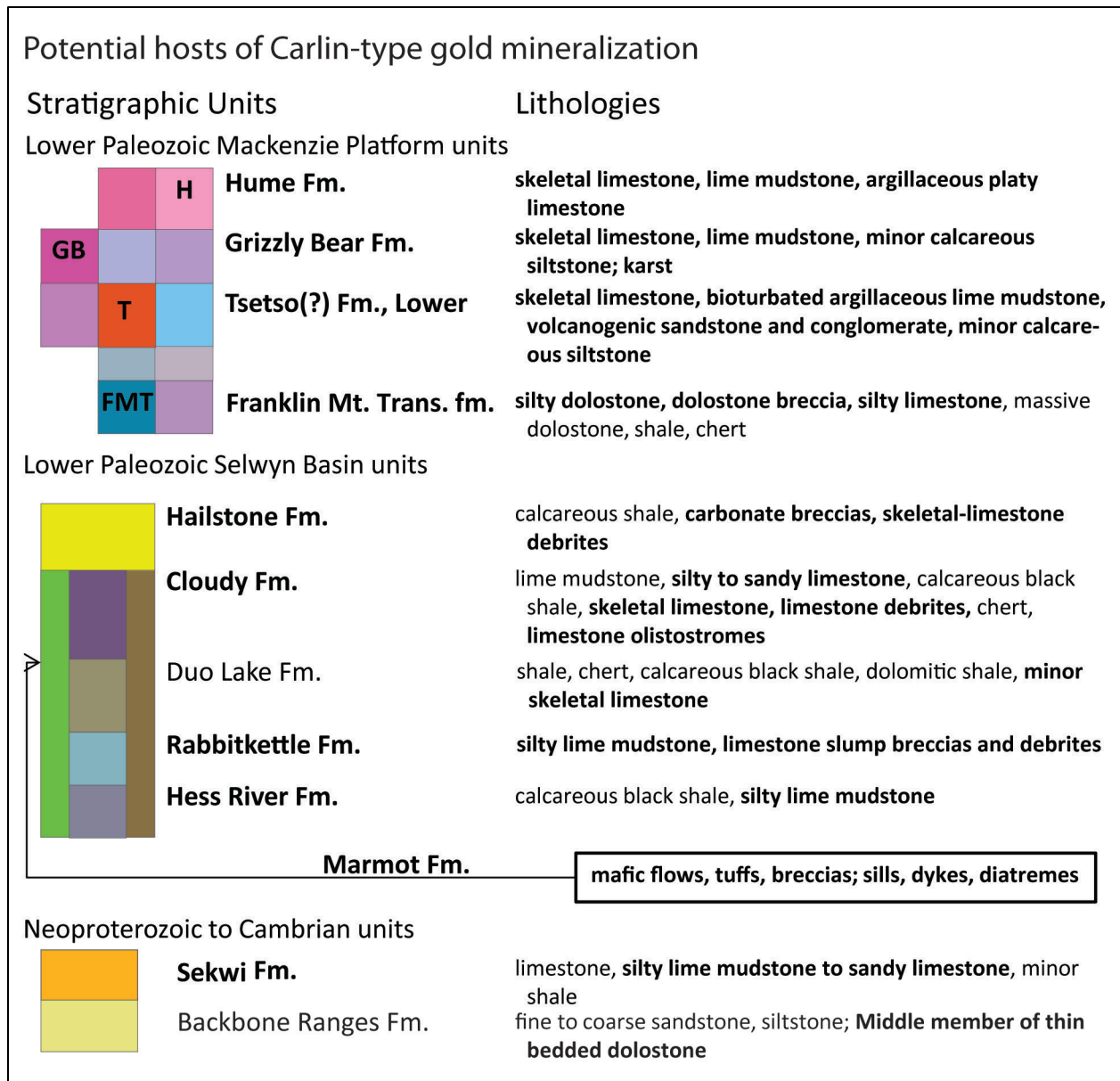


Figure 18. Bedrock geology legend from Figure 17, modified to show rock units of the Misty Creek Embayment area and the lithologies within them that are potential hosts of Carlin-type gold. Regular black font is used for units with low potential, and bold font is used for units and lithologies with good potential to host Carlin-type gold deposits.

### Potential hosts of clastic-dominated zinc-lead mineralization

The parts of the succession that are ideal hosts for CD deposits are the deep-water, below wave-base shales and mudstones with high organic-carbon content that were deposited in the upper parts of the basin during active extension (Figure 19). The Duo Lake and Hailstone formations, which are the uppermost units of the MCE, meet all of these criteria and are the most prospective hosts. The Hess River Formation of the MCE, and the Horn River Formation and parts of the Imperial Formation of the post-Selwyn basin, despite being the lowermost units of their respective basins, can also be regarded as prospective

CD hosts. The Mississippian Hawthorne Creek Formation is the uppermost exposed part of the post-Selwyn basin in the MCE area and includes deep-water, black shales and mudstones, but it was probably deposited during a tectonically quiet phase of the basin's development, without syn-depositional faulting. The regional tectonic history is not well-enough understood to completely rule out the Hawthorne Creek Formation as a potential host of CD mineralization, but it should not be regarded as a prime target horizon.

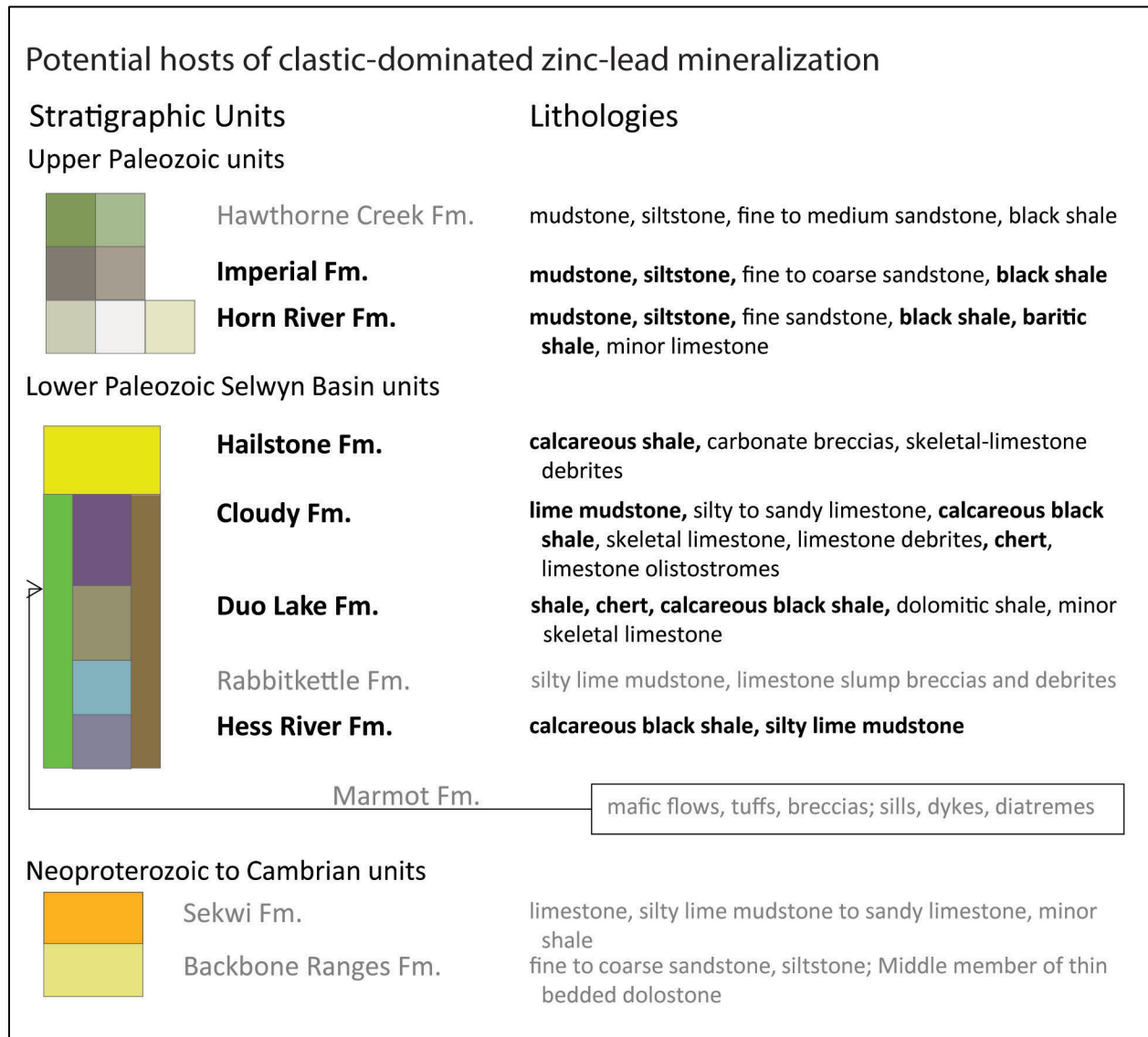


Figure 19. Bedrock geology legend from Figure 17, modified to show rock units of the Misty Creek Embayment area and the lithologies within them that are potential hosts of clastic-dominated (CD) zinc-lead deposits. Grey font is used for units that are not likely to host CD deposits. Bold font is used for units and lithologies that have the potential to host CD deposits.

## **Lower Paleozoic strata**

The Lower Paleozoic basal units of the MCE include the best potential host units of Carlin-type gold, as well as some potential hosts for CD zinc-lead deposits. In addition, there are some Lower Paleozoic platformal units that are of interest as potential hosts of Carlin-type gold. The oldest of these is the Cambrian Sekwi Formation, which is a complex, carbonate-dominated unit deposited on an Early Cambrian ramp that evolved to a shelf in the late Early Cambrian. In platformal areas to the southeast, east and northwest of the MCE, the Sekwi Formation consists of a basal second-order sequence and six overlying third-order sequences with local karst, limestone debrites and turbidites, and abundant skeletal and silty-limestone lithologies (Fischer and Pope, 2011). It has not been examined closely in mapsheet 106B.

### ***Hess River Formation***

The Middle Cambrian Hess River Formation (Cecile, 1982) is a potential host of both Carlin-type gold and CD zinc-lead mineralization. This unit is very recessive, very thin-bedded, and typically dark grey or black weathering (Figure 20). It consists of lime mudstone and lime siltstone with a variable terrigenous content, as well as lesser amounts of variably calcareous shale and siltstone, minor carbonaceous shale, and rare, very fine grained lithic sandstone. It contains a sandstone member over a kilometer thick in the northwestern part of mapsheet 106B (Cecile, 1982). Other than the sandstone member, the Hess River Formation is exposed only as rubble on ridges, and is best examined in gullies and stream cuts. It is interpreted as a turbidite deposited from dilute flow in deep water.

Phosphorite a few centimeters thick in a 97-m interval of phosphatic shale is present in the Hess River Formation near Goober Lake (Figure 17; Cecile, 1982). Just below the phosphorite is a 2-m thick interval of baritic limestone, consisting of scattered barite crystals in silty limestone, as well as some very thin beds of coarsely crystalline barite. Phosphorite in the Hess River Formation was also noted just south of the Selma project area (map sheet 1050; Cecile, 1982).

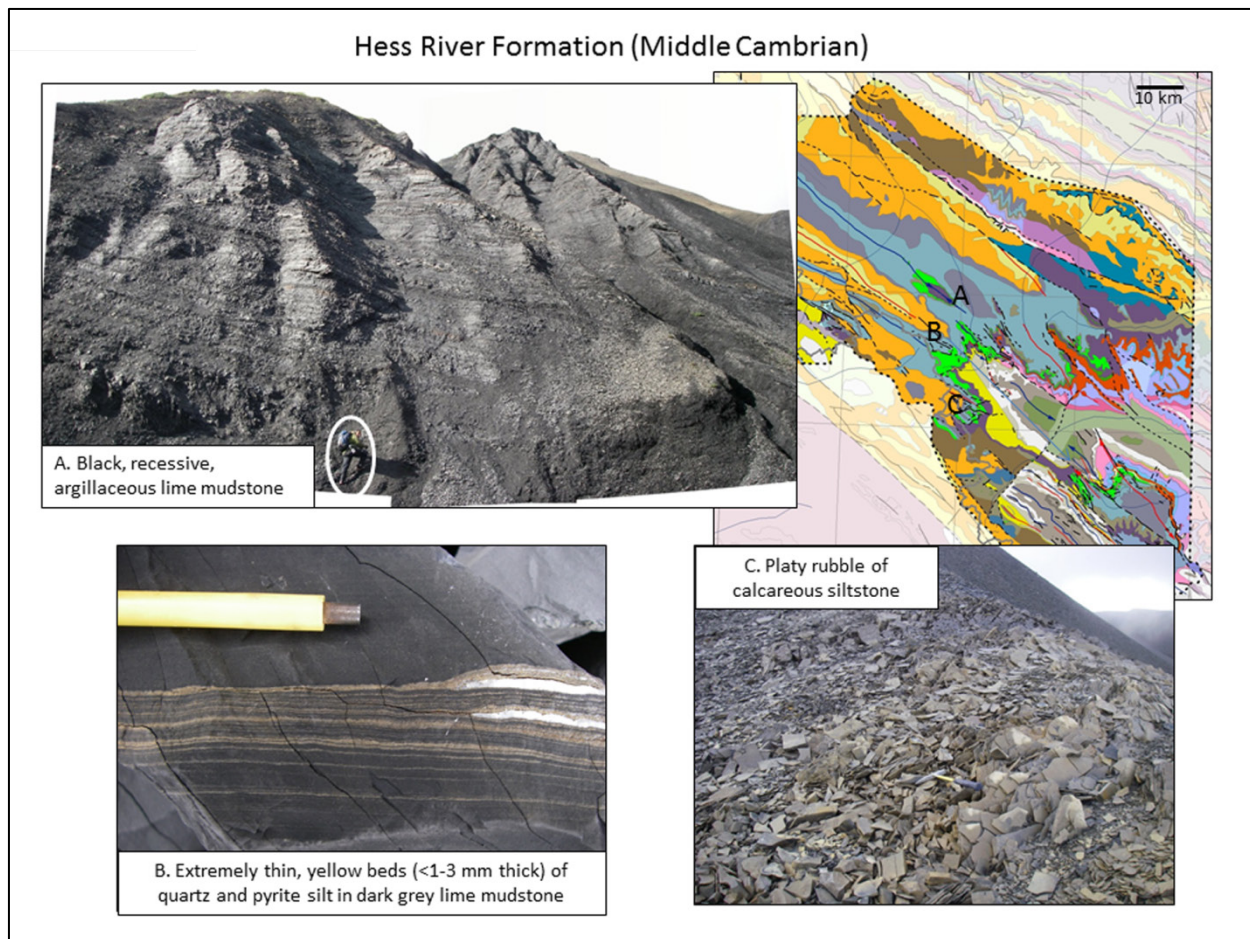


Figure 20. The Hess River Formation. The photo locations are shown on the map at upper right. [A] Black, recessive, thinly to very thinly bedded, argillaceous lime mudstone and minor calcareous shale, from the central part of the map area where the formation is thickest and the embayment was deepest. Person is circled for scale. [B] Dark grey lime mudstone with the yellow, millimeter-scale beds of quartz and pyrite silt that are typical of the Hess River Formation [C] Platy rubble of quartz-silty calcareous siltstone. Hammer is 40 cm long.

### ***Rabbitkettle Formation***

The Cambro-Ordovician Rabbitkettle Formation is a resistant unit of thin to medium bedded limestone and argillaceous limestone (Cecile, 1982; Figure 21) that may be prospective for Carlin-type gold. The Rabbitkettle Formation in mapsheet 106B has a characteristically striped or banded appearance at multiple scales: on mountainsides, in outcrops, and in hand specimens. This banded appearance is caused by the regular alternation of layers of different color or resistance. Light grey layers are commonly wavy or nodular and composed of diagenetically recrystallized calcite. Yellowish or orangey grey layers are limestone containing a significant component of siliciclastic silt or clay. Horizontal burrows, discontinuous wispy laminations, and current-ripple cross laminae defined by terrigenous silt are common sedimentary structures. Intraformational slump breccias and debrites with tabular clasts are a significant minor lithology, and form beds

that range from a decimeter to over 3 m thick. Rabbitkettle sediments include turbidites, tempestites, and tabular-clast debris, and were deposited on a slope prone to slumping and collapse.

On the Niddery High, a paleogeographic submarine high that separated the MCE from the Selwyn Basin (Cecile, 2000), there are two occurrences of phosphatic rock in the Rabbitkettle Formation. One is a 20-cm thick limestone conglomerate with phosphatic cement, and the other is a 10-m interval of limestone with phosphatic nodules and laminae (Christie and Sheldon, 1986).

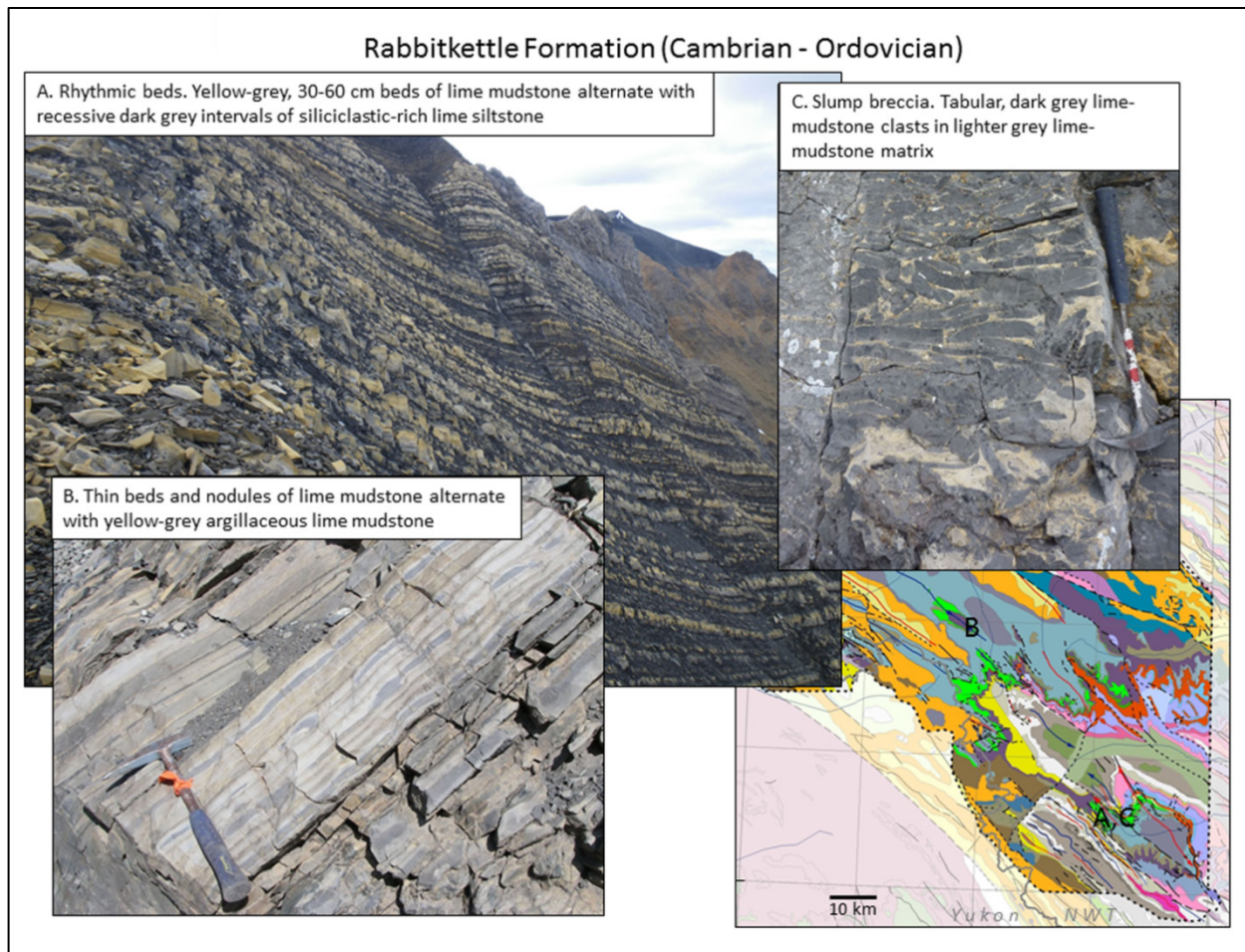


Figure 21. The Rabbitkettle Formation. The photo locations are shown on the map at bottom right. [A] Rhythmic alternation of medium-thickness beds of yellow weathering, very dark grey lime mudstone, and dark weathering, siliciclastic-silty to argillaceous lime mudstone-siltstone. [B] Thin, light grey, wavy to nodular beds of diagenetic calcite or lime mudstone, alternating with thin, yellow beds of siliciclastic-silty to argillaceous lime mudstone. [C] Slump breccia of intraclast rudstone, with dark, tabular clasts of lime mudstone in a light grey matrix of lime mudstone. Hammer in [B] and [C] is 40 cm long.

### ***Franklin Mountain Transitional formation***

The Cambro-Ordovician Franklin Mountain Transitional formation (FMT in Figure 17) was deposited in an environment that was transitional between platform and basin. It is laterally intergradational and intertongues with the platformal dolostone of the Franklin Mountain Formation to the east, and the Rabbitkettle Formation and parts of the Duo Lake Formation to the west (basinward; Cecile, 1982; Figure 17). The transitional formation comprises varying proportions of thin-bedded, siliciclastic-silty dolostone, siltstone, dolostone breccia, Franklin Mountain-like massive dolostone, Rabbitkettle-like limestone, siliciclastic-silty limestone, and shale, as well as Duo Lake-like shale, dolomitic shale, and chert. The transitional formation is understood only from a few measured sections (Cecile, 1982; Fischer, 2012). The unit includes lithologies that might be susceptible to mineralization in a Carlin-type system, such as silty limestone and silty dolostone. The unit was at least locally deposited on an unconformity at the top of the Sekwi Formation (Fischer and Pope, 2011) but, closer to the center of the embayment, was deposited conformably on the Hess River Formation (Cecile, 1982).

### ***Duo Lake Formation***

The Ordovician Duo Lake Formation. (Cecile, 1982) is a potential host of CD zinc-lead mineralization, and a less likely, possible host for Carlin-type gold. The unit consists of variably siliceous, calcareous, dolomitic, and carbonaceous siltstone and shale, plus minor chert, limestone, and volcanogenic sandstone. The limestone includes variably siliciclastic lime mudstone and thin skeletal beds. Graptolites are common in the mudstones. The Duo Lake Formation was deposited in deep, marine water that was generally quiet. Barite nodules have been identified in chert of the Duo Lake Formation near the Dudley Lake complex (Cecile, 1982).

### ***Cloudy Formation***

The Silurian Cloudy Formation (Cecile, 1982; Fischer, 2016) in the MCE is a potential host of Carlin-type gold. Intervals of black calcareous shale within the Cloudy Formation are prospective for CD zinc-lead as well.

The Cloudy Formation in the map area is a mixed unit of dark, platy, recessive limestone, lime mudstone, skeletal-limestone debrite, minor calcareous siltstone and chert, and rare small coral bioherms and pinnacle reefs (Figure 22). Terrigenous silt and sand are locally significant components of the lime mudstone and skeletal limestone. Skeletal beds are partly silicified. The formation typically has a black, recessive aspect, broken by a number of lighter colored, grey or yellow horizons representing the skeletal intervals.

Deposition of the Cloudy Formation took place in an open-marine setting on a lower slope. Kilometer-scale olistostromes and car-sized olistoliths (Cecile, 1982; Fischer, 2016) attest to significant slope instability, due to either concomitant tectonic activity (possibly Marmot Formation magmatism) or a nearby over-steepened platform margin. Along the northeastern edge of the embayment, coarse crystals of barite are scattered within limestone of the Cloudy Formation over a strike length of 1 km (Cecile, 1982).

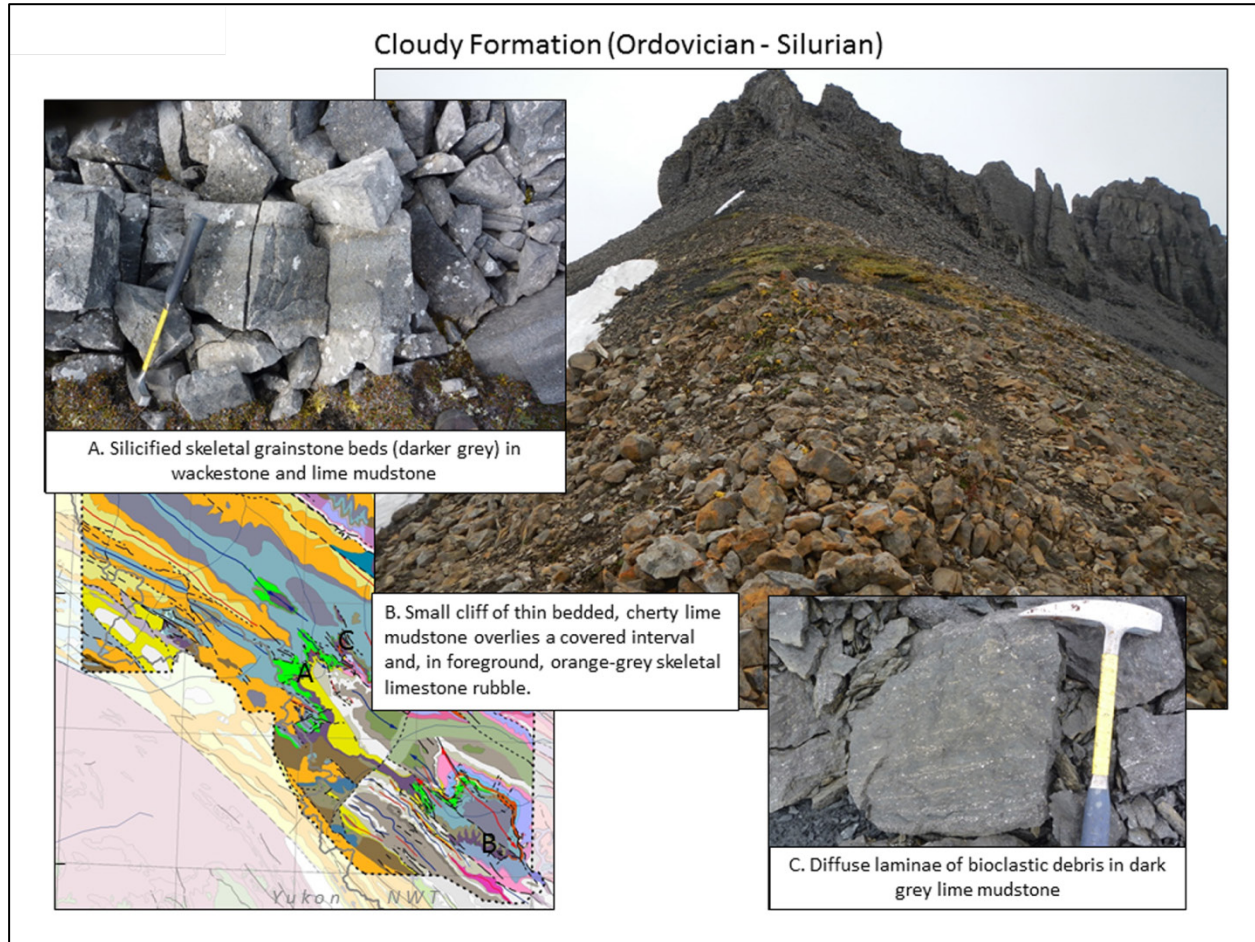


Figure 22. The Cloudy Formation. The photo locations are shown on the map at bottom left. [A] Silicified beds of skeletal grainstone (dark grey) in unsilicified skeletal wackestone and lime mudstone (light grey). Hammer is 40 cm long. [B] A dark cliff of thin-bedded, cherty lime mudstone overlies a covered interval and orangey grey weathering skeletal limestone that is exposed as rubble. [C] Diffuse, very thin beds of sand-sized bioclastic debris in a matrix of dark grey lime mudstone.

### ***Hailstone and Grizzly Bear formations***

The Early Devonian Hailstone Formation and laterally equivalent Grizzly Bear Formation (Cecile, 2000) have the potential to host Carlin-type gold. In addition, intervals of black calcareous shale in the Hailstone Formation are prospective for CD zinc-lead. Anomalous zinc has been detected in the upper part of the Hailstone Formation (Cecile, 2000).

The Hailstone Formation is the youngest unit of the Lower Paleozoic MCE. The Hailstone Formation overlies the Cloudy Formation and transitional Silurian platformal strata in the Misfortune Lake area; it unconformably to conformably overlies the Duo Lake and Cloudy formations in the central map area; and it overlies the Hume Formation conformably in the north of the Porter Puddle area and unconformably in the west of the same area. The Hailstone Formation is temporally equivalent to parts of the coeval platform, including the Hume Formation.

The Hailstone Formation is a recessive, black unit dominated by thin-bedded, black lime mudstone to calcareous siltstone, with subordinate skeletal limestone and rare limestone breccia and calcareous sandstone. Basinal facies and platform-proximal facies are recognized in the Hailstone Formation (Fischer, 2016; Figure 23). Near the base of the basinal facies in the Dudley Lake area, a 10m-thick bed of debrite composed of skeletal limestone clasts in a matrix of calcite cement and lime mudstone can be traced for 6 km. A similar limestone debrite 8 km away may be part of the same high-energy event. Sparsely distributed throughout the basinal facies are thin beds of normally graded skeletal packstone, interpreted as debrites. These become more abundant and thicker toward the paleo-platform. Small bryozoan mounds and meters-thick coral bioherms distinguish the platform-proximal facies (Figure 23-C).

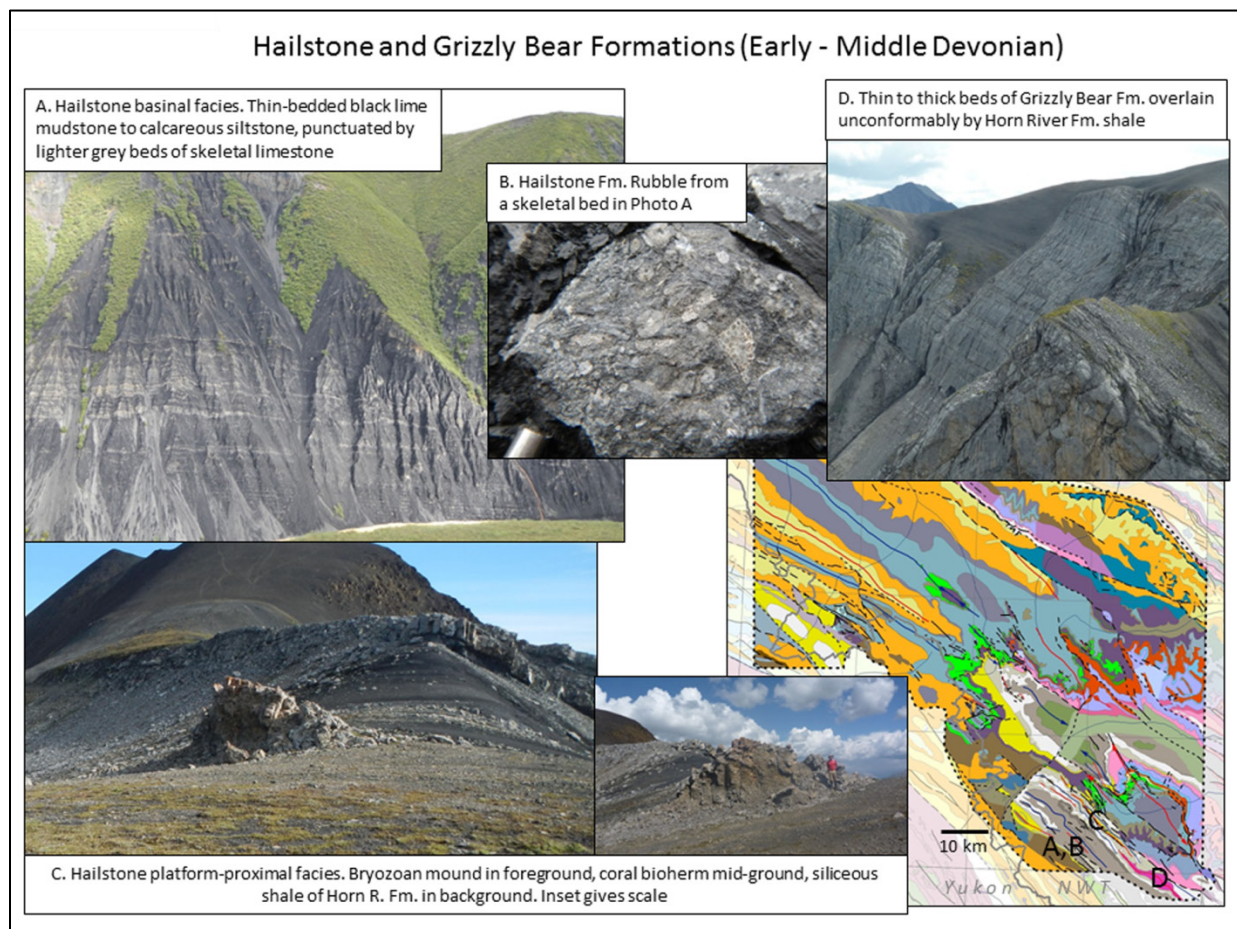


Figure 23. The Grizzly Bear and Hailstone formations. The photo locations are shown on the map at lower right. [A] Hailstone Formation, basinal facies. Thin-bedded, dark grey to black weathering lime mudstone to calcareous siltstone with minor thin beds of light grey, skeletal limestone. This photo was taken near the type section of Hailstone Formation (Cecile, 2000). [B] Rubble of skeletal limestone from one of the light grey beds in [A]. Tip of pen magnet is 5 mm across. [C] Hailstone Formation, platform-proximal facies. The bryozoan bafflestone mound in the foreground is 1-2 m high. The light grey, resistant horizon in mid-ground is part of a 5-m high, 2-km long coral-dominated reef. The rest of the

Hailstone Formation is recessive and calcareous. The brown hill in the background is the conformably overlying siliceous shale of the Horn River Formation. The inset shows the bryozoan mound with a person for scale. (D) Thin to thick, light grey, resistant limestone beds of Grizzly Bear Formation, showing a few meters of paleo-karst relief at the contact with the overlying siliceous shale of the Horn River Formation.

The Grizzly Bear Formation is a platformal facies that was partly contemporaneous with the Hailstone Formation. In the map area, the Grizzly Bear Formation is a resistant, light grey weathering unit that consists of heavily re-crystallized, medium to coarsely crystalline skeletal packstone to rudstone, wackestone grading to lime mudstone, and minor calcareous siltstone. Fossils in this unit are dominantly crinoid ossicles and coral fragments, and bedding tends to be obscured but ranges from thin to very thick (Figure 23). The top of the unit is karsted with a few meters of relief under siliceous shale of the Horn River Formation.

The Grizzly Bear Formation was deposited in shallow, open marine water on a platform or as talus against the platform edge. On the upper slope below the platform, small bioherms and beds of bioclastic debris and lime mud formed the platform-proximal facies of the Hailstone Formation. The basal facies of the Hailstone Formation was deposited lower on the slope, which was affected by episodic debris flows composed mainly of platformal detritus.

### ***Tsetso(?) Formation, Lower member***

The Tsetso Formation (Morrow, 1991) is a Siluro-Devonian platformal unit. A complex Lower member assigned tentatively to the Tsetso Formation (Fischer, 2016) has potential to host Carlin-type gold. This member includes a skeletal variant in the Porter Puddle area, and a volcanic-skeletal variant in the Hart area (locations in Figure 17). The Lower member of the Tsetso(?) Formation overlies, and its lower part may locally be laterally equivalent to, the Cloudy Formation. The skeletal variant (Figure 24-A) of the Lower member ranges from recessive to resistant, and from thin to thick bedded. It consists of variable proportions of fossiliferous, heavily bioturbated lime mudstone, skeletal limestone, pure to argillaceous lime mudstone, and calcareous siltstone. The volcanic-skeletal variant of the Lower member (Figure 24-B) consists of turbiditic, re-worked volcanogenic sandstone and conglomerate with locally abundant bioclastic fragments, finer volcanogenic epiclastic deposits, and patch reefs of skeletal limestone.

These variants of the Lower member of the Tsetso(?) Formation were deposited in a shallow subtidal setting during or shortly after contemporaneous volcanism. The volcanism may have contributed to proliferation of marine life by providing a shallow-water substrate for it to grow on.

## Tsetso Formation, Lower member (Silurian – Devonian)

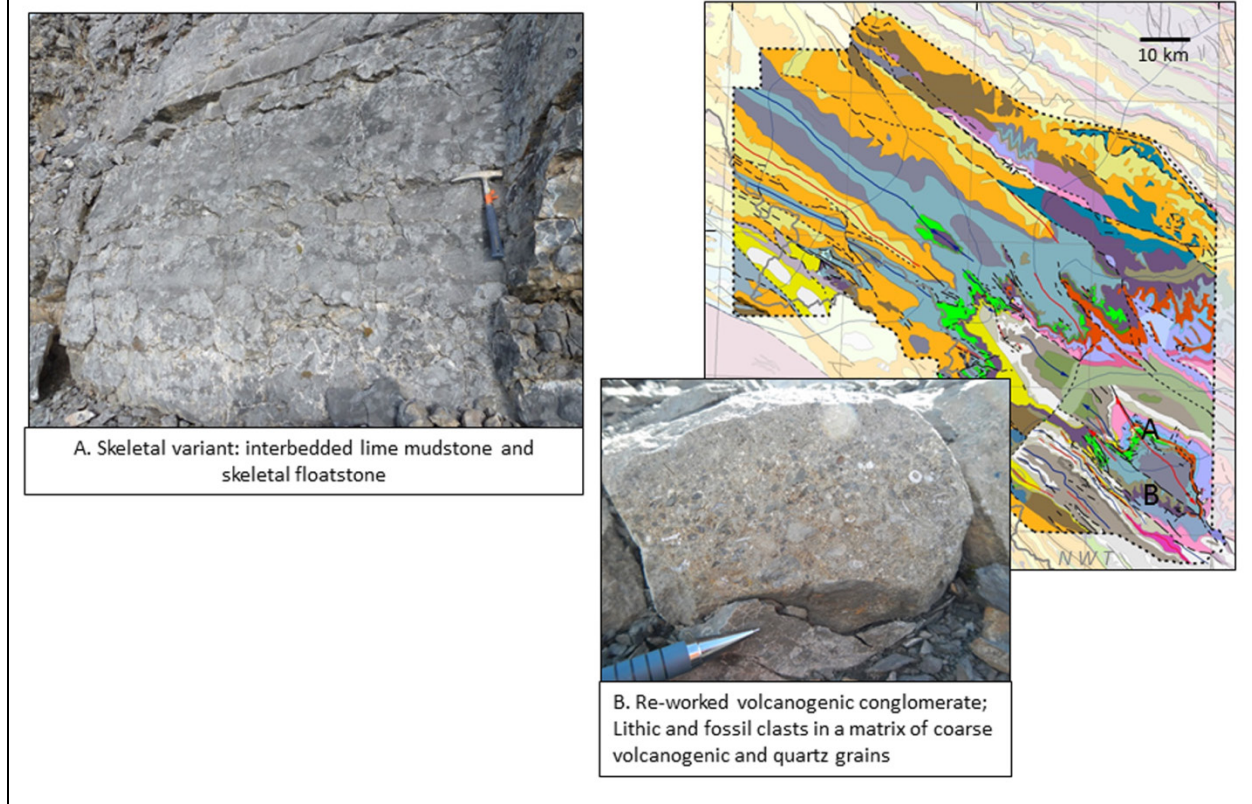


Figure 24. The Tsetso(?) Formation, Lower member. The photo locations are shown on the map at right. [A] Skeletal variant. Thinly interbedded lime mudstone and skeletal floatstone of the Skeletal variant of the Lower member. [B] Volcanic-skeletal variant. A re-worked volcanogenic conglomerate from the Volcanic-skeletal variant of the Lower member consists of pebble-sized fossil and lithic clasts in a moderately well-sorted, coarse sandstone matrix of quartz, feldspar(?), volcanic clasts, other lithoclasts, and sparse fossil debris.

### **Hume Formation**

The Early to Middle Devonian Hume Formation (*e.g.*, Morrow, 1991; Martel *et al.*, 2011) is the youngest unit of the platformal carbonate succession in the Mackenzie Mountains. In the map area, the Hume Formation is a resistant, planar-parallel bedded, light grey weathering skeletal limestone consisting of diverse lithologies (for example, brachiopod-crinoid floatstone with crinoid grainstone matrix, and coral rudstone with boulder-sized coral heads), and minor platy limestone (Figure 25; also Figures 28-A and -B). Beds are mostly medium to thick but become thinner toward the top of the unit, where shale interbeds appear. Limestone beds become thinner and shale intervals thicker as the Hume Formation grades into the Hailstone Formation or the Hare Indian Member of the Horn River Formation.

The Hume Formation was deposited on an open marine shelf that prograded westward (Morrow, 1991), probably during a sea-level highstand. The top contact of the Hume Formation is a transgressive surface.

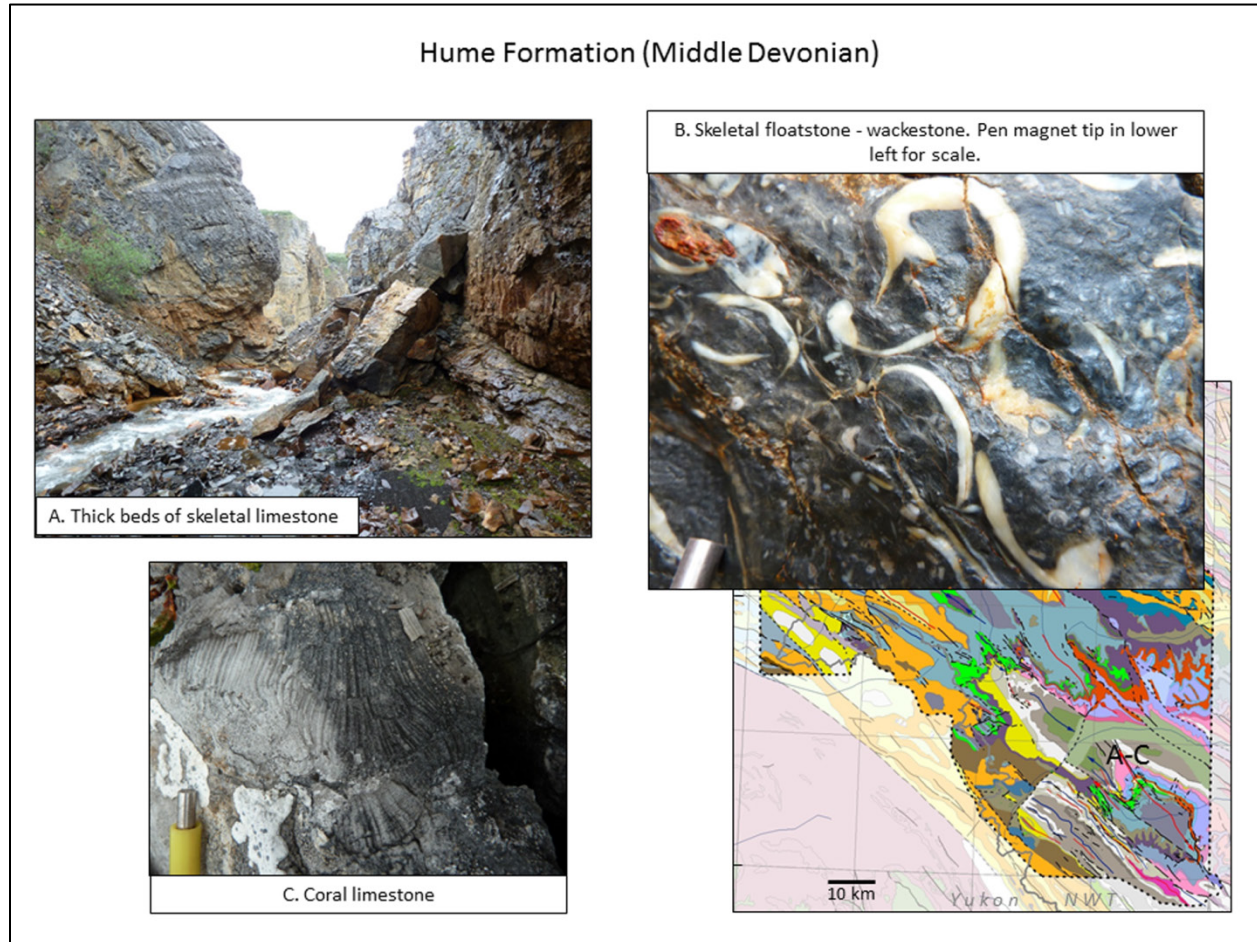


Figure 25. The Hume Formation. The photo locations are shown on the map at lower right. [A] Thick beds of skeletal limestone. [B] Skeletal floatstone with a wackestone matrix. [C] A head of coral in a coral rudstone. Tip of pen magnet in [B] and [C] is 5 mm wide.

### **Igneous rocks**

Although the role of magmatic processes in development of Carlin-type mineral deposits remains uncertain, it is clear that igneous rocks can react with ore fluids and become hosts of gold mineralization, or, in other cases, seals that block the passage of fluids. The presence of volcanic rocks, dykes, and sills in the MCE suggests that hydrothermal fluids were circulating at shallow levels in the crust, which enhances the prospectivity for contemporaneous CD zinc-lead deposits.

Most of the volcanic rocks and all of the so-far dated intrusive rocks in the MCE are Ordovician in age. In the Porter Puddle complex, volcanic strata record additional pulses of magmatism during the Silurian and the early Early Devonian, and a final pulse in the late

Early to early Middle Devonian. The early Early Devonian pulse is also present in the Hart area, and is assigned to the Lower member of the Tsetso(?) Formation (see above). The Ordovician pulses belong to the Marmot Formation (Cecile, 1982).

Mafic alkalic rocks of the Marmot Formation are distributed irregularly throughout the embayment (Figure 17; Goodfellow *et al.*, 1995; Leslie, 2009; Williams, 2013; Fischer, 2016). Two centers of volcanism, the Porter Puddle complex and the Dudley Lake complex, are located about 35 km apart. Outside of these centers, the Marmot Formation consists mostly of re-worked volcanogenic sediments. Within the centers are pillowed and amygdaloidal flows, phenocrystic flows or subvolcanic intrusions, and a wide range of fragmental rocks, both pyroclastic and reworked (Figures 26 and 27). There is evidence that a volcanic edifice grew at both of these places from submarine to subaerial (Cecile, 1982; Fischer 2016). Diatremes, sills, and dykes intrude the volcanic rocks and basinal strata as young as the Cloudy Formation (Figure 27). At least four diatreme pipes have been identified in and near the Porter Puddle complex, and others are scattered across the embayment (Copland, 1995a, b). Phenocrysts consist of phlogopite and altered pyroxene, olivine, and plagioclase. Sericite and chlorite alteration is common in both the volcanic and the intrusive rocks (Cecile, 1982).

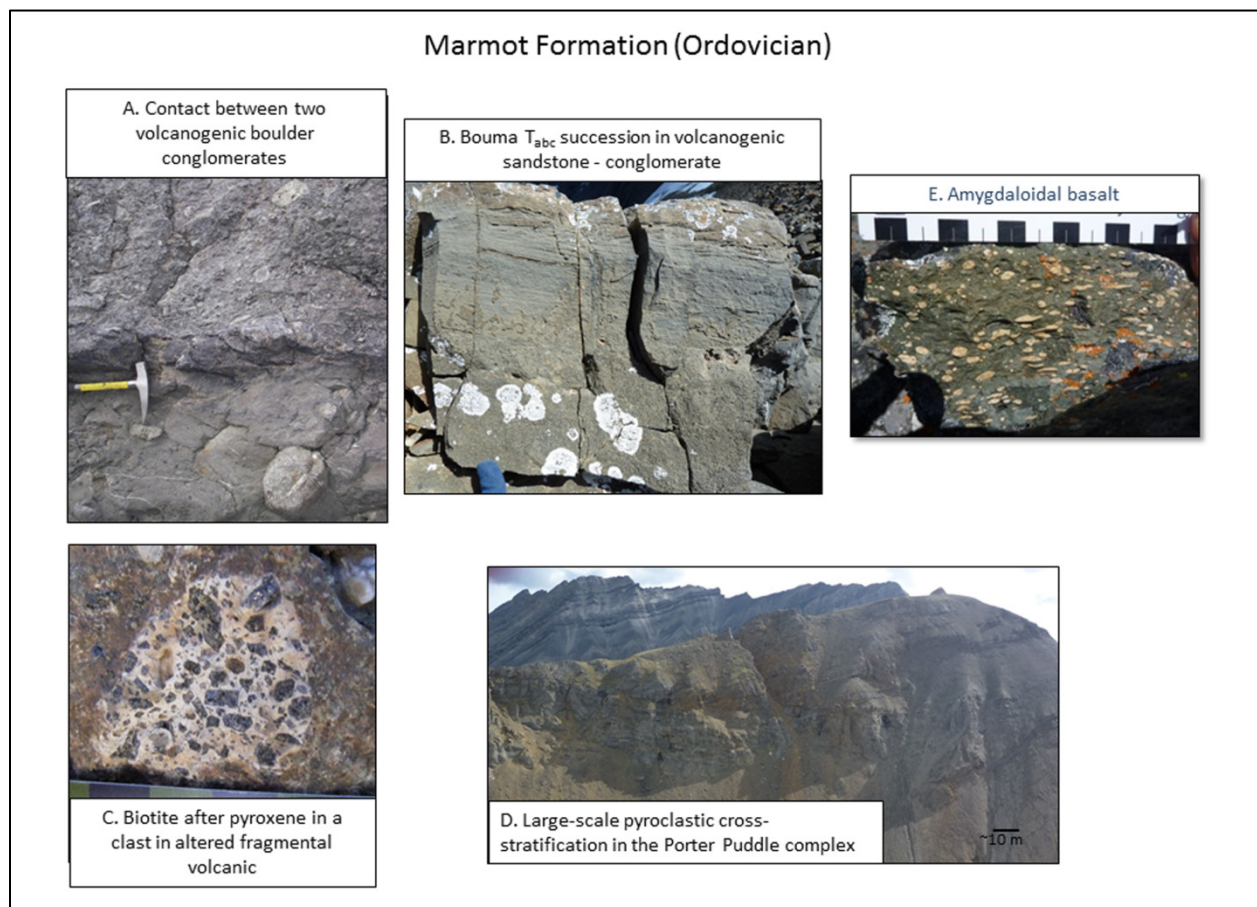


Figure 26. Marmot Formation. The photo locations are shown on the map in Figure 27. [A] The contact between two volcanogenic boulder conglomerates. Hammer at contact for scale. [B] An epiclastic volcanogenic sandstone showing Bouma turbidite divisions: the massive brown rock at the bottom, touched by a blue fingertip for scale; the grey laminated rock; and the brown, cross-laminated rock at the top. [C] A clast in an altered fragmental volcanic rock from the base of Marmot Formation. Large pyroxene crystals have been replaced by biotite. Divisions on scale card below the sample are 1 cm. [D] Large-scale pyroclastic cross-stratification in the Porter Puddle complex. The ridge in the background is made of platformal carbonate strata that overlie Marmot Formation. [E] Amygdaloidal basalt flow. Black and white divisions on scale card are 1 cm.

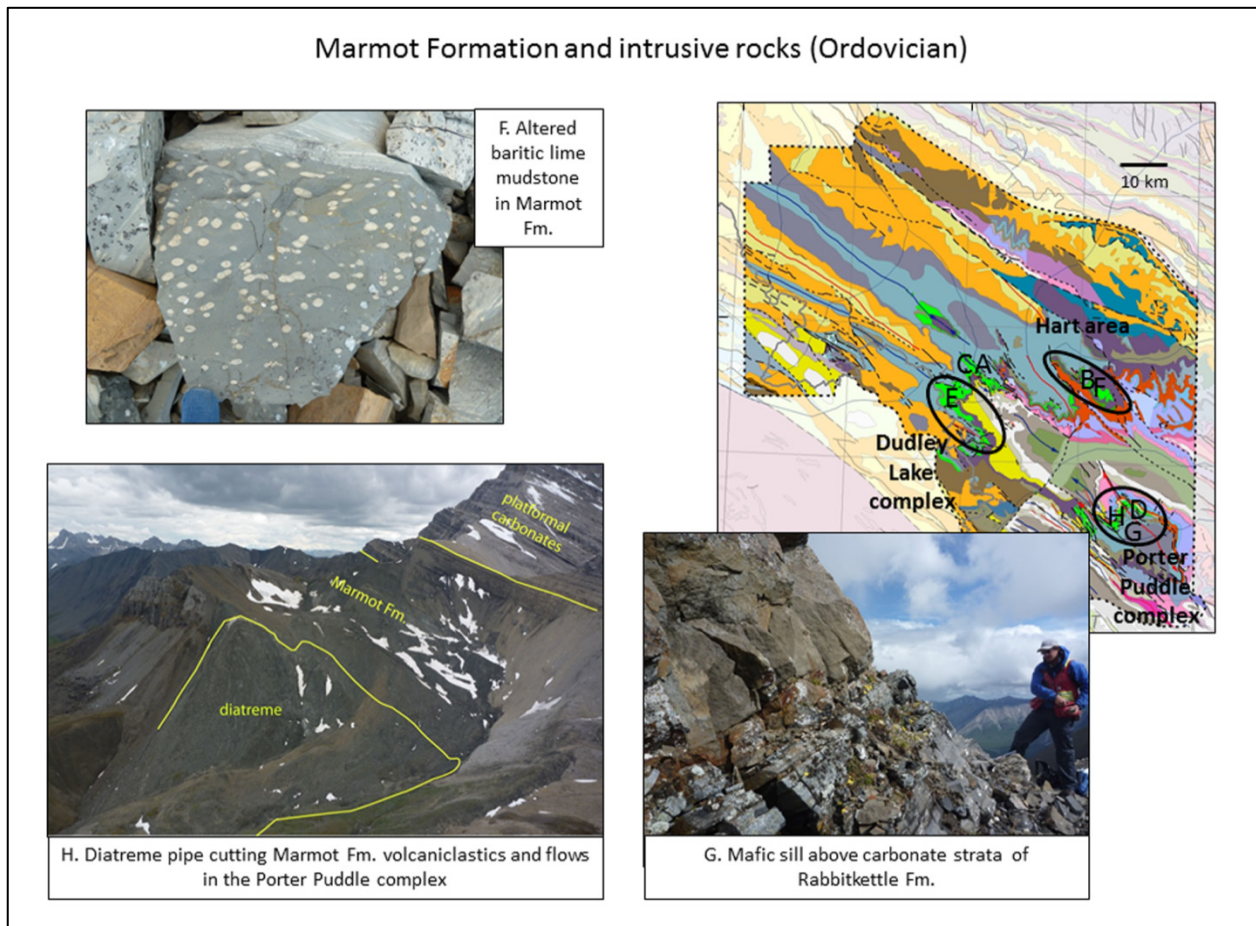


Figure 27. Marmot Formation (continued) and associated intrusive rocks. The photo locations are shown on the map at right. [F] Altered baritic(?) lime mudstone, in which barite (or possibly, phosphatic) nodules have been altered to clay(?) minerals. The sample is from a succession of epiclastic volcanogenic rocks in the Hart area. Blue-gloved fingertip for scale. [G] Mafic sill cutting thin-bedded limestone of the Rabbitkettle Formation. [H] A diatreme pipe in the Porter Puddle complex, approximately 300 m in diameter, intrudes Marmot Formation volcanoclastic and carbonate strata, and is overlain by the Tsetso(?) and Camsell formations (platformal carbonate).

The presence of baritic (?) mudstone in the Marmot Formation in the Hart area (Figure 27-F) is of interest as an indicator of hydrothermal exhalations onto or into the seafloor lime muds during Marmot time. The barite (?) has been replaced, possibly by clay minerals, which raises the possibility of an additional, later phase of hydrothermal fluid flow.

### **Devonian-Mississippian strata**

Strata of the younger, post-Selwyn basin are of interest as potential hosts of CD zinc-lead mineralization or, less attractively, of Carlin-type gold mineralization. They may also be of importance in forming seals to Carlin-type systems.

The Horn River Formation is a recessive, fissile, shale- and mudstone-dominated unit with minor siltstone and very fine sandstone (Figure 28) that is equivalent to the Hare Indian and Canol formations farther to the east (Pugh, 1983). Laminated barite and nodular baritic mudstone is developed intermittently in the upper Horn River and equivalent formations along at least 80 km strike length, and ranges up to 72 m thick (Fernandes *et al.*, 2017; Fischer, 2016; Cecile, 2000). In the southeast part of mapsheet 106B, the Horn River Formation is divisible into three members: a Lower member of black, silicified mudstone that weathers brown, an Upper member of black shale that weathers silvery grey, and locally, a Baritic member of light grey mudstone that weathers brown. The Baritic member, where it is present, lies above the Upper member at the top of the Horn River Formation, and contains barite nodules and laminations and thin beds of limestone (Fischer, 2016). In the northeast part of mapsheet 1050 and the northwest of 105P, the equivalent Canol Formation is variably siliceous, and consists of a lower section that is silty and recessive, and an upper, more-resistant section of baritic mudstone, mudstone, shale, calcareous nodules, and thin beds of limestone (Cecile, 2000; Martel *et al.*, 2011; Fernandes *et al.*, 2017).

Fossils in the Horn River Formation include vascular plant debris, spherical microfossils, and sponge spicules. A coquina of pelagic stylolinids and fine planar-parallel laminations indicate deposition under very low sedimentation rates, well below wave base. The high organic content combined with the strictly pelagic fauna suggest anoxic conditions (Muir and Dixon, 1984). The Horn River Formation represents the first deposits of the Middle Devonian transgression.

The Imperial Formation in the map area is a pinkish brown-weathering siltstone to fine grained sandstone with abundant sedimentary structures indicative of deposition by turbidity currents (Figure 28). The Horn River and Imperial formations are both recessive and weather into rounded hills; outcrop exposures are uncommon (Figure 29).

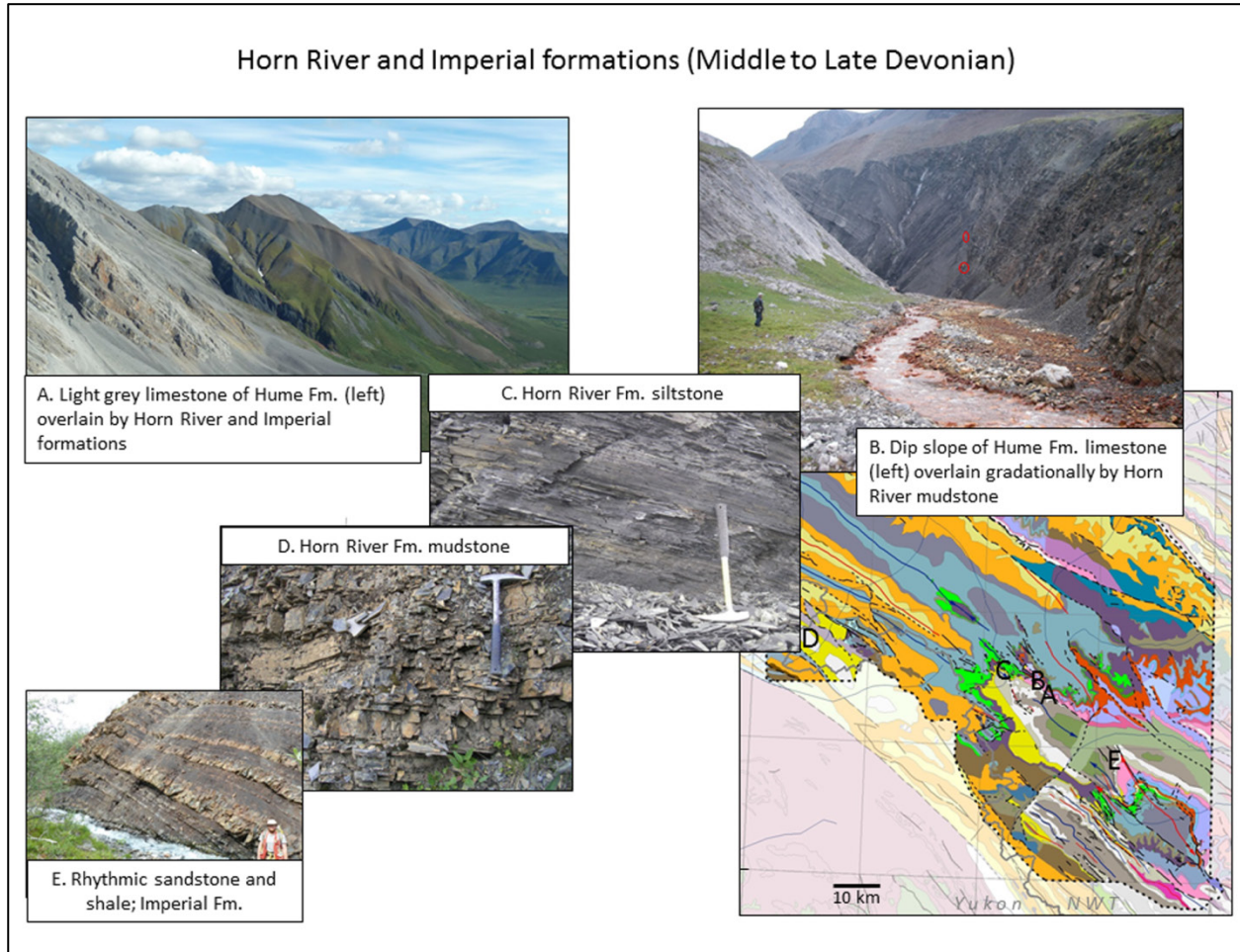


Figure 28. Horn River and Imperial formations of the post-Selwyn basin. Locations of photos are shown on the map at lower right. [A] Looking southeast at light grey, planar-bedded, skeletal limestone of the Hume Formation (left), overlain by the Horn River Formation (black and light grey) and Imperial Formation (brown). The Horn River Formation here is unusually thin because it is cut off by a fault that approximately follows the Hume - Horn River contact. [B] Looking northeast at the same succession as in [A], at a location where the Hume - Horn River contact is not faulted. The contact is interbedded and gradational, with the proportion and thickness of limestone beds decreasing upward. A minor stratabound zinc showing associated with a barite vein in mudstone of the Horn River Formation is being examined (small red circles around people). [C] Dark grey siltstone of the Horn River Formation. The siltstone is finely laminated and its bedding-plane surfaces weather a silvery blue-grey. [D] Orangey-brown weathering, dark grey mudstone of the Horn River Formation. [E] Imperial Formation. Sharp-based beds of fine grained lithic sandstone alternate with interbeds of shale in a rhythmically repeated succession.



Figure 29. Looking southwest (from star in Figure 30) along a ridge that shows the heavy weathering typical of the Middle to Late Devonian basinal succession. The dark brown and black in the foreground is siliceous shale of the Lower member of the Horn River Formation. Upsection, in the near midground, is silvery grey shale of the Upper member of the Horn River Formation, and light brown, locally baritic mudstone of the Baritic (uppermost) member of the Horn River Formation. On the farthest part of the ridge, the dark purplish brown color is fine grained sandstone of the Imperial Formation, Lower member, and the rosy brown hill in midground at right is siltstone and very fine grained sandstone of the Imperial Formation, Upper member.

### Structure

The structural pattern of the mapped area is dominated by northwest-trending faults and fold axes, but many structures trend north, northeast, and east (Figure 30). Many of the tighter, NW-trending folds in the central and western parts of the map area are associated with steep, small-displacement faults parallel to the axial planes. A broad synclinal structure, the Arctic Red Synclinorium, dominates the western part of the map. It has limbs of the Sekwi Formation and a core of Lower Paleozoic basinal and volcanic units, with a doubly plunging syncline at its center (circled in Figure 30). Additional major fold systems parallel the Arctic Red Synclinorium to the southwest.

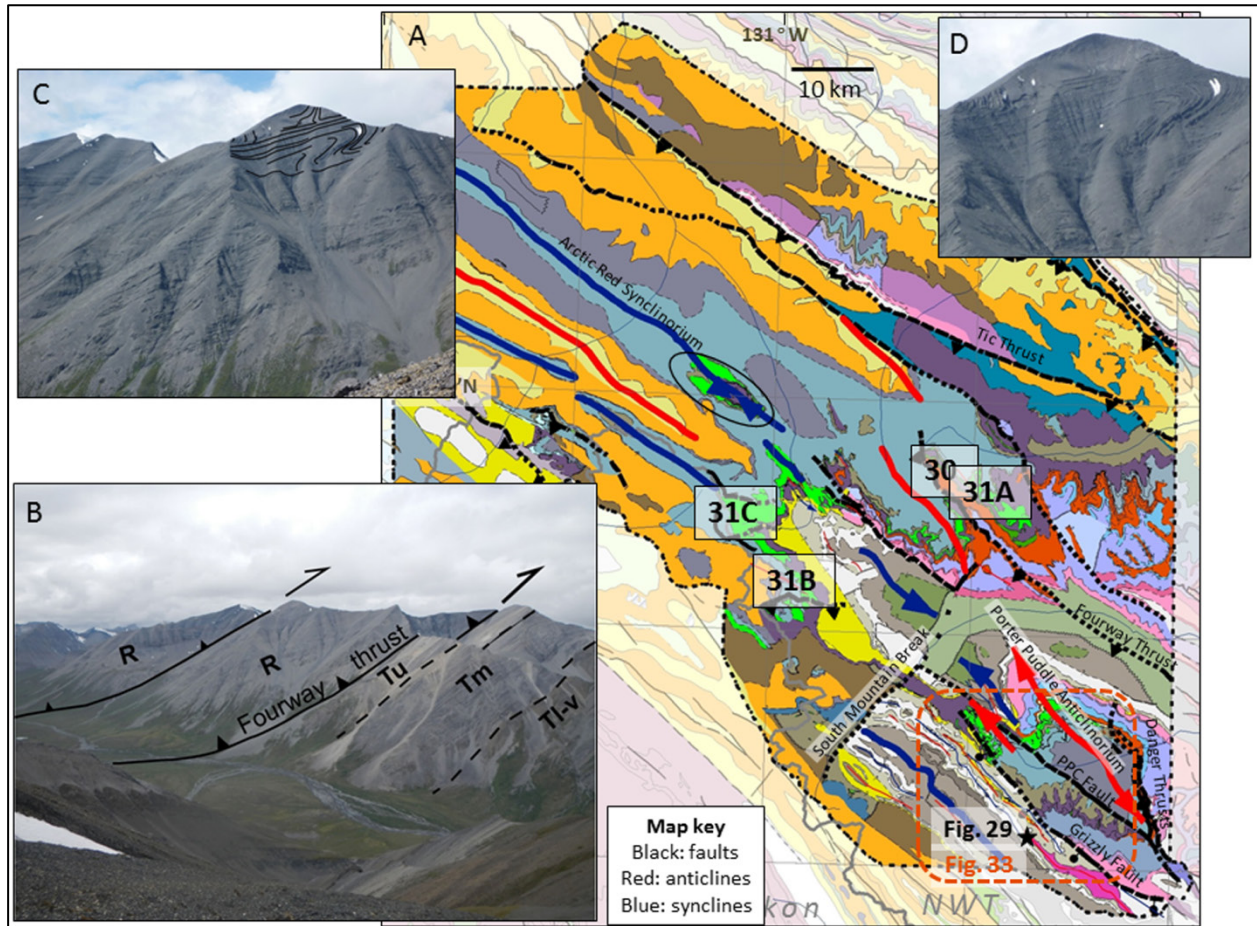


Figure 30. Structures in the northern Misty Creek Embayment area. [A] Bedrock geology map with the main structures labelled. The map legend is as for Figure 17. Photo locations are shown by figure numbers. The location of Figure 29 is shown by a star in the southeast part of the map. Red dashed box shows the location of Figure 33. [B] Looking west at the Fourway thrust zone, where the Cambro-Ordovician Rabbitkettle Formation (R) has been placed on top of the Upper (Tu), Middle (Tm), and Lower (volcanogenic variant; Tl-v) members of the Siluro-Devonian Tsetso(?) Formation. [C] A closer look at the zone of deformation in the hangingwall of the Fourway Thrust and footwall of the secondary thrust to its south (left). Bedding-plane traces have been accented to show the shapes of shear folds developed during the thrusting. [D] A closer look at the shear folds in [C].

The Porter Puddle Anticlinorium in the southeast part of the map area (Figure 30) is an open, doubly plunging anticlinal dome that exposes strata as old as the Cambrian Hess River Formation. It is paired with a broad, NW-plunging synclinorium that preserves strata as young as the Mississippian Hawthorne Creek Formation. The Porter Puddle Anticlinorium is cut at a shallow angle by the PPC Fault, whose displacement appears to have had both dip-slip and strike-slip components.

Major NW-trending faults include NE-verging thrusts, such as the Tic Fault in the north and the Fourway Fault in the central-east, and normal faults like the Grizzly Fault in the

southeast (Figure 30). Most of the NE-verging thrusts are broad zones of deformation whose traces are much wider than the lines shown on the map (Figures 30 and 31).

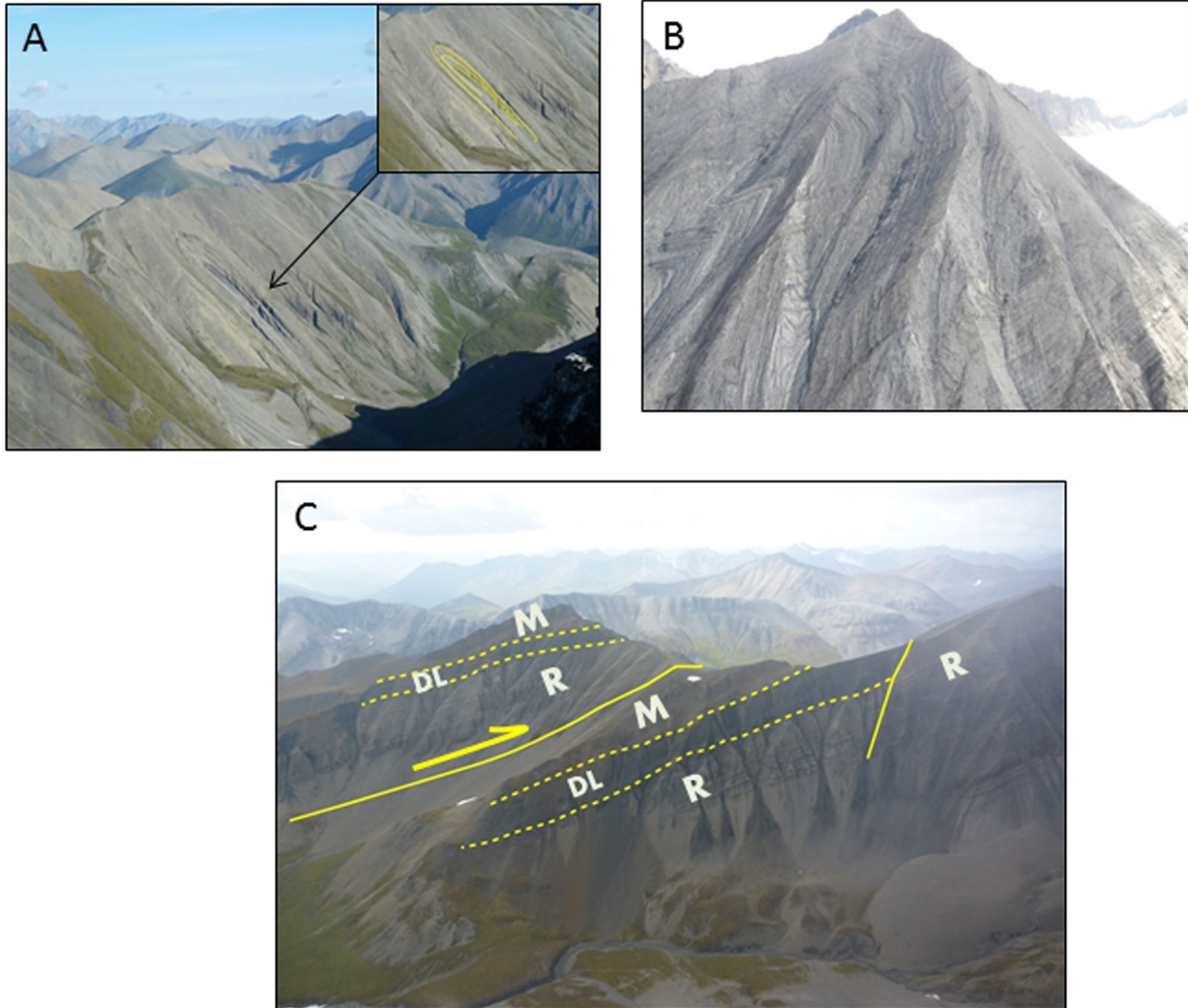


Figure 31. Structures in the northern Misty Creek Embayment area (continued). Locations of photos are shown by figure numbers on Figure 30-A. [A] Looking south-southeast at one of a number of sheath folds that have developed in the footwall zone of the Fourway Thrust. Bedding form lines are drawn in yellow on the inset to emphasize the shape of the fold. [B] Looking southwest at a zone of deformation in the Rabbitkettle Formation. This zone wraps the western edge of the Dudley Lake Complex. [C] Looking southwest at the Stewart Thrust, which repeats the Rabbitkettle (R), Duo Lakes (DL), and Marmot (M) formations at the southern end of the Dudley Lake complex.

The paired Danger thrusts trend north and verge east, in the far southeast of the map area (Figure 30). A NE-trending structural break is inferred to occupy the broad, covered valley of the southern tributary of the Mountain River, based on a profound stratigraphic mismatch across its southern end (Horn River Formation against Duo Lake Formation). However, the mismatch decreases and may even disappear to the north. East-trending faults

include the north-verging Stewart Thrust at the southern end of the Dudley Lake complex (Figure 31).

Mapping in the southeast of the mapsheet was more detailed than in other areas, and has revealed numerous, closely spaced, NW-trending folds and minor thrusts in the soft, easily deformed rocks of the Horn River and Imperial formations. This area is discussed below.

## **Settings for Carlin-type gold ore**

A number of settings in the MCE area are evaluated against the criteria, already discussed, that constrain the location and setting of Carlin-type ore deposits.

### **Stratigraphic traps**

Impermeable units that overlie units of permissive lithologies might together form a stratigraphic trap. The overlying unit functions as a seal, so that any gold-bearing fluids rising beneath it are trapped in the reactive unit, which encourages precipitation of gold. In addition, impermeable dykes can act as barriers to lateral fluid flow, trapping fluids in adjacent reactive strata.

The Duo Lake Formation, which is dominated by impermeable siliciclastic shale in most places, could trap fluids in underlying Rabbitkettle and Hess River strata (Figure 32, #1). The extents of the Franklin Mountain Transitional formation have not been mapped, but it might also make a good host to Carlin-type gold where it is overlain by the Duo Lake Formation. Narrow intervals of siliceous shale within the Rabbitkettle Formation could trap fluids in lower parts of the Rabbitkettle and Hess River formations (Figure 32, #2).

Perhaps the best potential traps exist where siliceous shales of the Canol Formation overlie permeable and reactive strata of the Hailstone, Grizzly Bear, and Hume formations (Figure 32, #3). The permeable and reactive strata of the Lower member of the Tsetso(?) Formation and, in the Porter Puddle area, the underlying Marmot Formation, are overlain by dolostone of the Middle member of the Tsetso(?) Formation (Hart area) or the Camsell Formation (Porter Puddle area; Figure 32, #4; Figures 26-D and -H). Although both the Middle member of the Tsetso(?) Formation and the Camsell Formation include vuggy horizons, they also contain non-porous horizons that could function as seals, as do the overlying dolostone formations. Dykes and sills related to the Marmot Formation that are scattered throughout the Lower Paleozoic strata of the embayment might also have acted as seals.

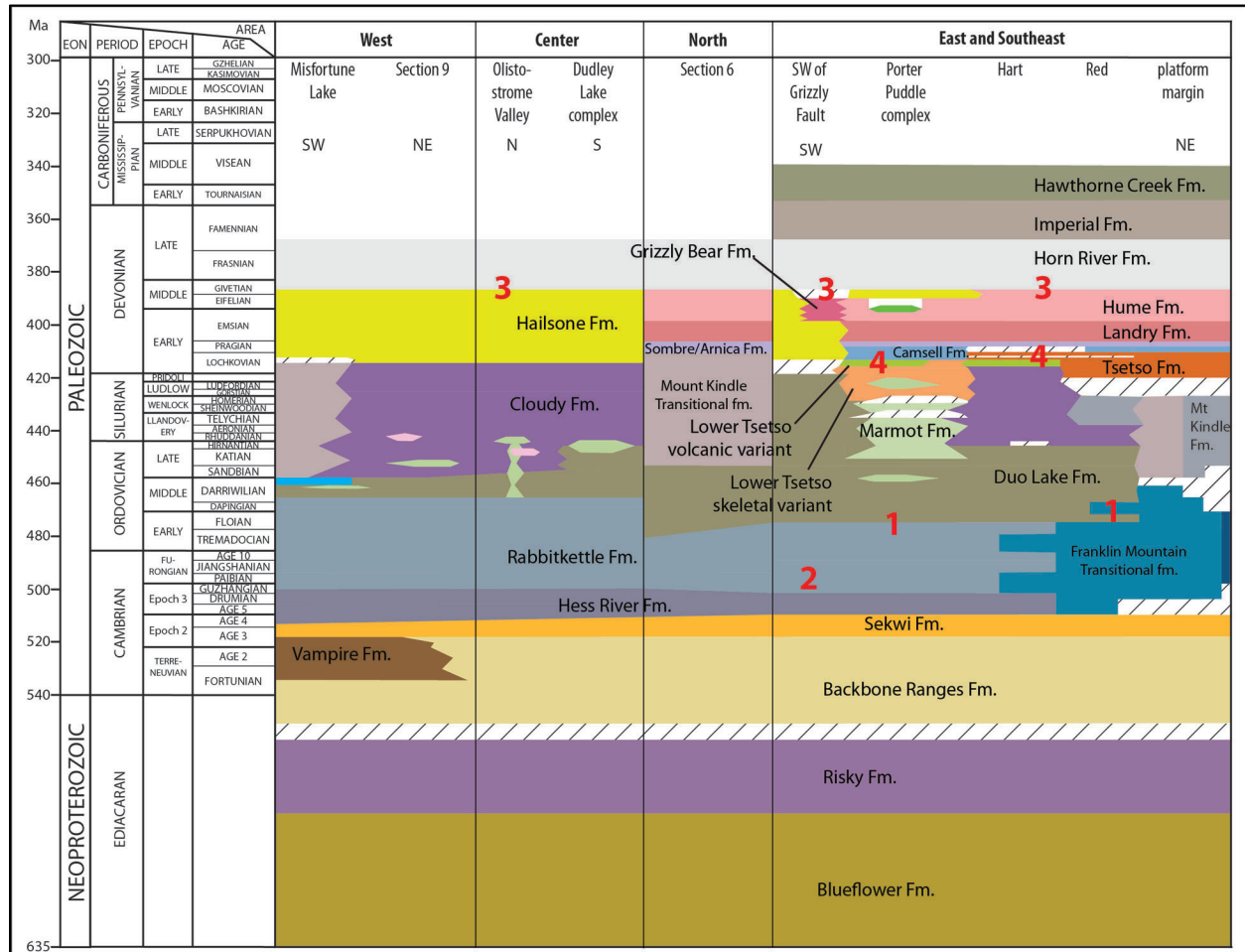


Figure 32. Schematic time-stratigraphic chart for the northern Misty Creek Embayment area, showing potential stratigraphic traps numbered in red: (1) Potential Duo Lake Formation seal over reactive strata in the Rabbitkettle Formation or Franklin Mountain Transitional formation; (2) Seals internal to the Rabbitkettle Formation might have trapped fluids in lower parts of the Rabbitkettle Formation and in the Hess River Formation; (3) Potential Horn River Formation seal over reactive strata in the Hailstone, Grizzly Bear, or Hume formations; (4) The Camsell Formation or the Middle member of the Tsetso(?) Formation might have formed seals over reactive rocks in the Tsetso(?) Lower member or the Marmot Formation. Not shown are potential seals formed by dykes or sills related to the Marmot Formation. After Fischer (2016).

### Hailstone anticline

The Middle Devonian strata in the southeastern part of mapsheet 106B are folded into a number of anticlines and synclines whose axial traces trend northwest. Exposure is poor, but distinctive weathering characteristics enable identification of members within the Horn River and Imperial formations (Figure 29), and the Hailstone Formation is clearly identifiable in the core of Hailstone Anticline (Figure 33).

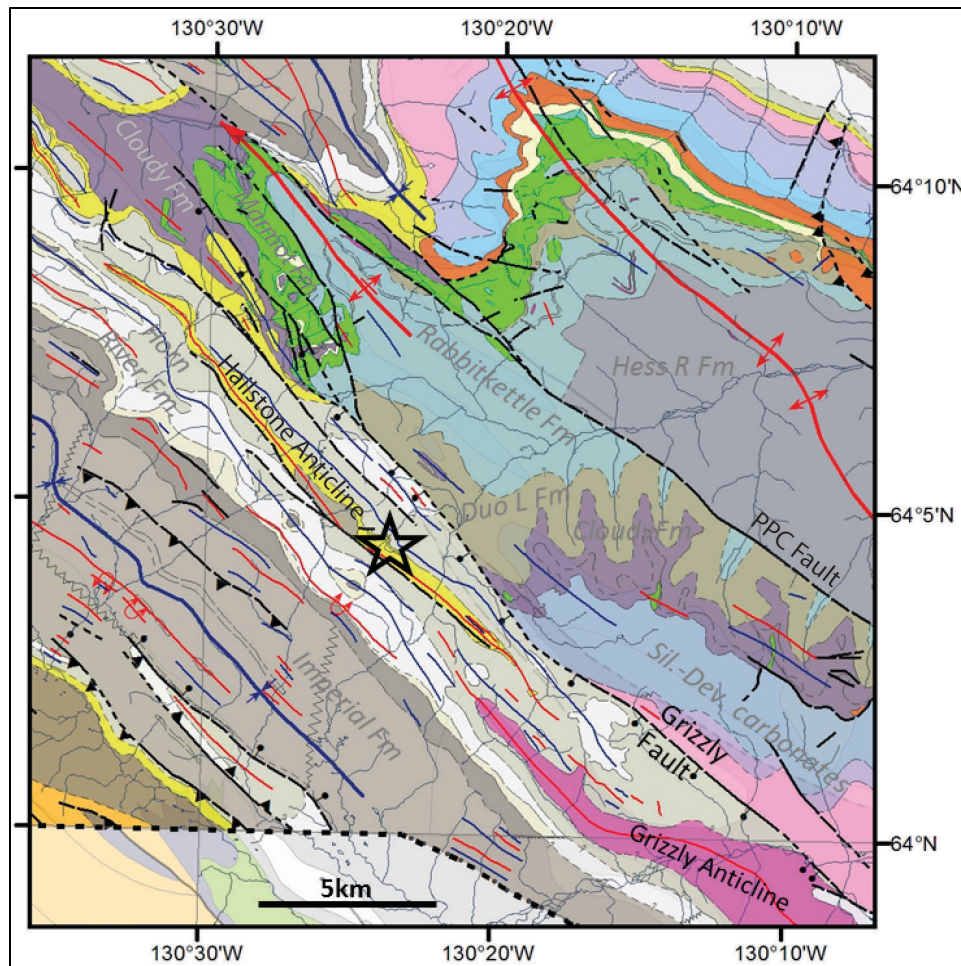


Figure 33. Map of the Hailstone Anticline area (location in Figure 29). Star shows the location of Figure 34. Yellow is the Hailstone Formation, brown in the core of the Hailstone Anticline is the Duo Lake Formation, deep pink in the core of the Grizzly Anticline is the Grizzly Bear Formation, and other relevant units are labeled. Unlabeled members of the Imperial and Horn River formations are dark greys and light greys, respectively. Thick red lines are anticlinoria, thick blue lines are synclinoria, and arrows show the direction of plunge. Thin red and blue lines are anticlines and synclines, respectively. Black lines are faults (solid for defined, dashed for approximate or inferred; teeth on the up-thrust side of reverse faults, ball ornaments on the down-dropped side of normal faults). After Fischer (2016).

The Hailstone Formation in the Hailstone Anticline is a recessive, carbonaceous, argillaceous limestone, except near the top of the unit, where a one to two meter-thick interval of laterally intermittent bryozoan framestone and a five meter-thick reef of medium- to thick-bedded coral rudstone, separated from each other by a few meters of recessive, calcareous strata, can be traced for 2 km (Figures 23-C and 34). The Hailstone Formation is overlain by siliceous shale of the Lower member of the Horn River Formation. The anticline is at least 15 km long (Figure 33). The resistant reef and rudstone intervals disappear to the northwest, as the unit transitions to basinal facies, but dominate the southeastern exposures in the anticlinal core.

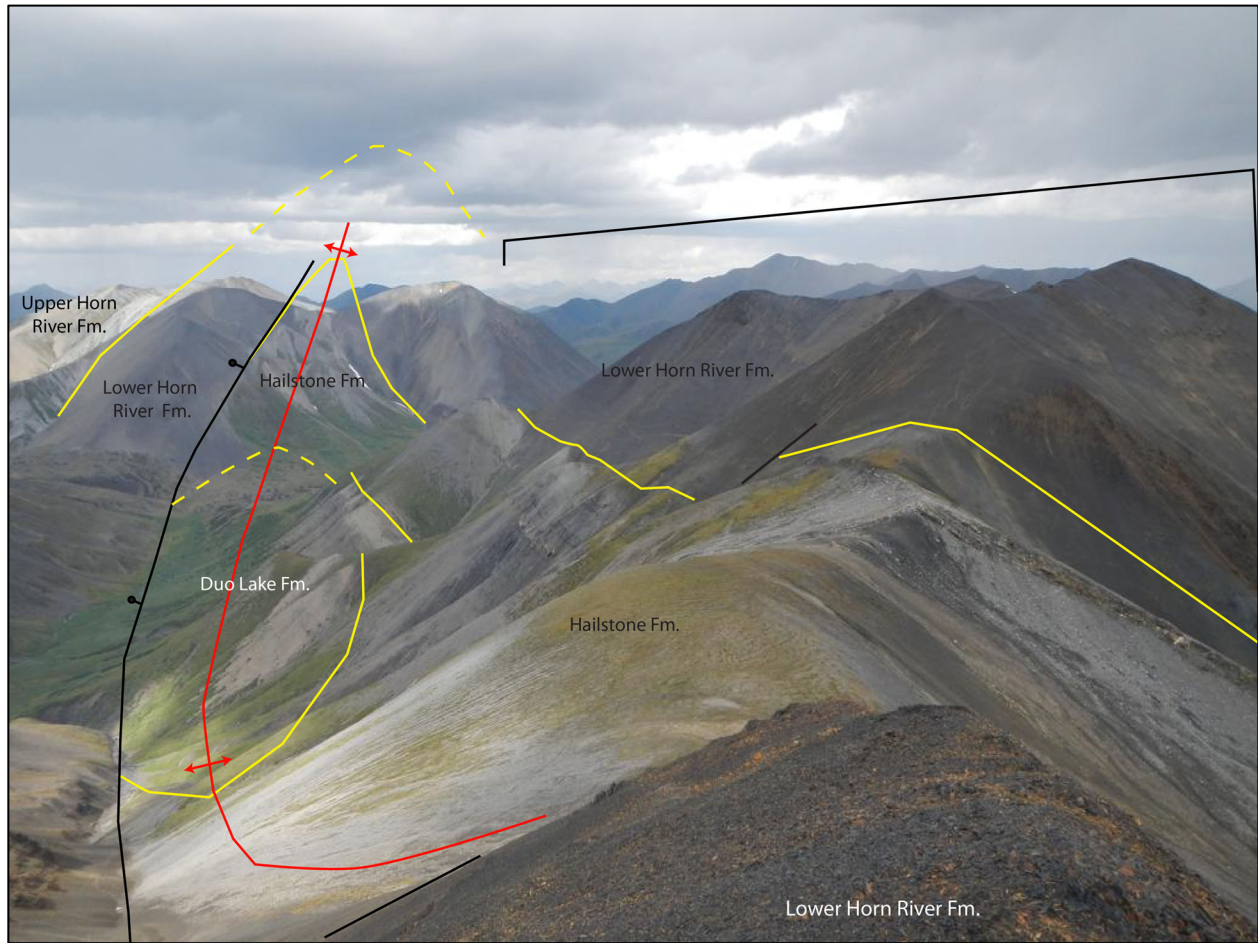


Figure 34. Looking northwest along the axis of Hailstone Anticline (red), from the star in Figure 33. Yellow lines are stratigraphic contacts. A minor normal fault (black line with ornaments on down-dropped side) closely parallels the fold axis (a common circumstance in the map area). The projected plane of a fault that is out of sight over the range of hills to the right is shown by black lines.

The Hailstone Formation in this anticline is an ideal Carlin-type host rock because it is a reactive unit with strong differential-dissolution potential, and it is in the core of an anticline, adjacent to a major fault, and underneath tight shales. This is the kind of structural trap that hosts gold ore in many of the classic deposits in Nevada, and may have played a role in the Rackla district as well.

### **Grizzly anticline – exposed and subsurface**

The Grizzly Anticline parallels the Hailstone Anticline to its southwest (Figure 33). The Grizzly Anticline is cored by mostly recrystallized skeletal limestone (rudstone to wackestone) and lime mudstone of the Grizzly Bear Formation, which represents the most platform-proximal stage in a lateral facies transition from basinal or toe-of-slope facies (Hailstone Formation), through upper-slope and reef-proximal facies (also Hailstone Formation), to platform-edge forereef facies (Grizzly Bear Formation). Skeletal limestones of the Grizzly Bear Formation, and perhaps recrystallized skeletal limestone, would have

had good potential for differential dissolution. The extents of this potential Carlin-type host in an anticlinal trap are therefore of interest.

The Grizzly Anticline might, at first glance, be thought to be the southeastern extension of the Hailstone Anticline, offset along a covered or cryptic fault (Figure 35). However, small outcrops of the Hailstone Formation suggest that the two anticlines overlap. Furthermore, the results of a radiometric survey conducted in 2011 (Fortin *et al.*, 2012) strongly suggest that the Grizzly Bear Formation in the anticline extends northwest under cover without any offset (Figure 35). Carbonate rock shows up as cyan hues on the ternary radioelement map (Figure 35-B). The Hailstone Anticline does not contain enough exposed carbonate rock to show up in this survey, however the core of the Grizzly Anticline is an intense greenish cyan, where the Grizzly Bear Formation is exposed. The same color extends northwest along strike from the exposed Grizzly Bear Formation (between the heads of the orange arrows on Figure 35-B), where siliceous shales of the Horn River Formation are the only exposed rocks. The radioelement response is interpreted to mean that the Grizzly Bear Formation plunges northwest underneath the Horn River Formation, close enough to the surface to dominate the radiometric signature. The volume of potential host rock in anticlinal traps is increased substantially by recognition of this possible buried extension of the Grizzly Bear Formation.

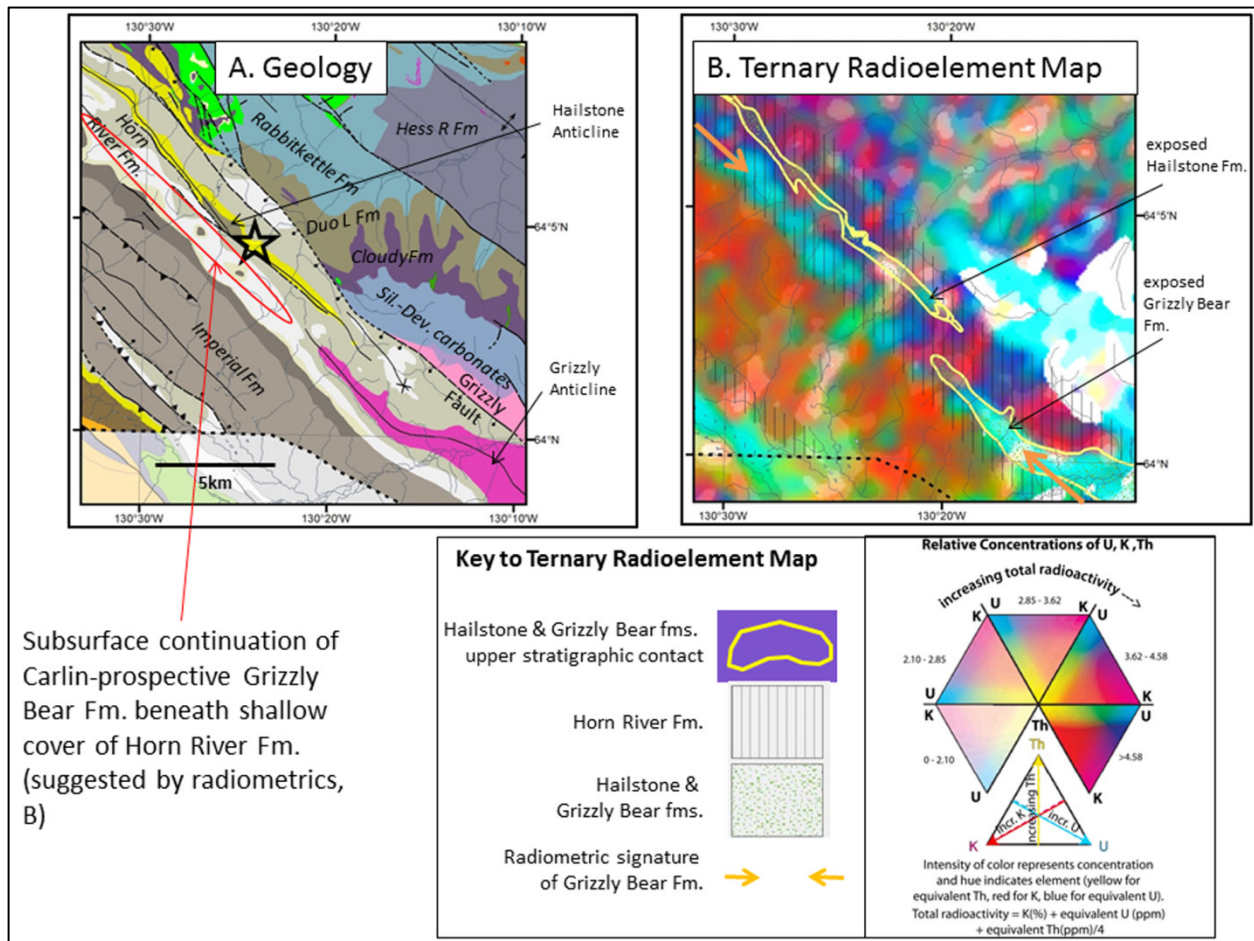


Figure 35. The Grizzly Anticline, a potential trap for Carlin-type gold. [A] Bedrock geology (after Fischer, 2016). The red oval outlines the area in which the Grizzly Bear Formation is suspected to lie beneath the surface, under a shallow cover of Horn River Formation strata. [B] Ternary radioelement map of the same area. Data are from a 2011 gamma-ray spectrometer survey with 500-meter line spacing (Fortin *et al.*, 2012). The relative concentrations of potassium, uranium, and thorium or their equivalents determine the hue, and the total radioactivity determines the saturation of the colors, as indicated in the key. Areas of exposed Hailstone or Grizzly Bear Formation, which are lateral facies equivalents, are outlined in yellow. Although the pattern of bedrock exposures suggests that the two anticlines may have originally been one, now segmented and offset by a fault, the ternary data belie this. Orange arrows point to either end of a distinctive greenish cyan anomaly interpreted to be the Grizzly Bear Formation exposed in the southeast and undercover in the northwest.

### **Structural or lithological heterogeneity**

When adjacent rock bodies with different rheological properties are deformed together, spaces will open up between them. These spaces are available for later fluid movement and ore deposition. In the MCE area, the two volcanic-intrusive complexes not only consist internally of rheologically diverse components, but also provide a rheological contrast to surrounding strata. These sites of heterogeneity and rheological contrast may have created localized zones of greater permeability, which would have lowered the effective stresses in migrating gold-bearing fluids, and potentially thereby caused precipitation of gold.

A rheological contrast also exists between permeable horizons of carbonate debrite and the shaley strata that enclose them in Cloudy and Hailstone formations. Structural and lithological complexity exists where thin-bedded, shaley strata, or rocks rich in terrigenous material, are in contact with tight carbonate strata, such as where the Duo Lake – Marmot – Cloudy ± Lower Tsetso(?) package has been deformed between the underlying carbonate Rabbitkettle Formation and the overlying Devonian carbonate units. Mafic sills and pipes intrude Cambrian and Ordovician units of contrasting rheology, especially in the Porter Puddle, Dudley Lake, and Hart areas. Intersections of faults with contacts, other faults, and folded strata abound. At any of these sites, rheological contrasts may have led to greater fracturing during deformation, and subsequent retention of an enhanced permeability. Migrating ore fluids, upon encountering these areas, would experience a change in their physico-chemical state that might initiate precipitation of ore.

### **Settings for clastic-dominated zinc-lead ore**

The most prospective basins for CD zinc-lead deposits, as reviewed above, are sub-basins that were actively faulting at the time of sedimentation, allowing faults to conduct mineralizing fluids into the accumulating basinal sediments. There are at least two places within the mapped area where there may be evidence of syn-depositional faulting (Figure 36-A). At both locations, a thick platformal-carbonate succession terminates abruptly against basinal rocks.

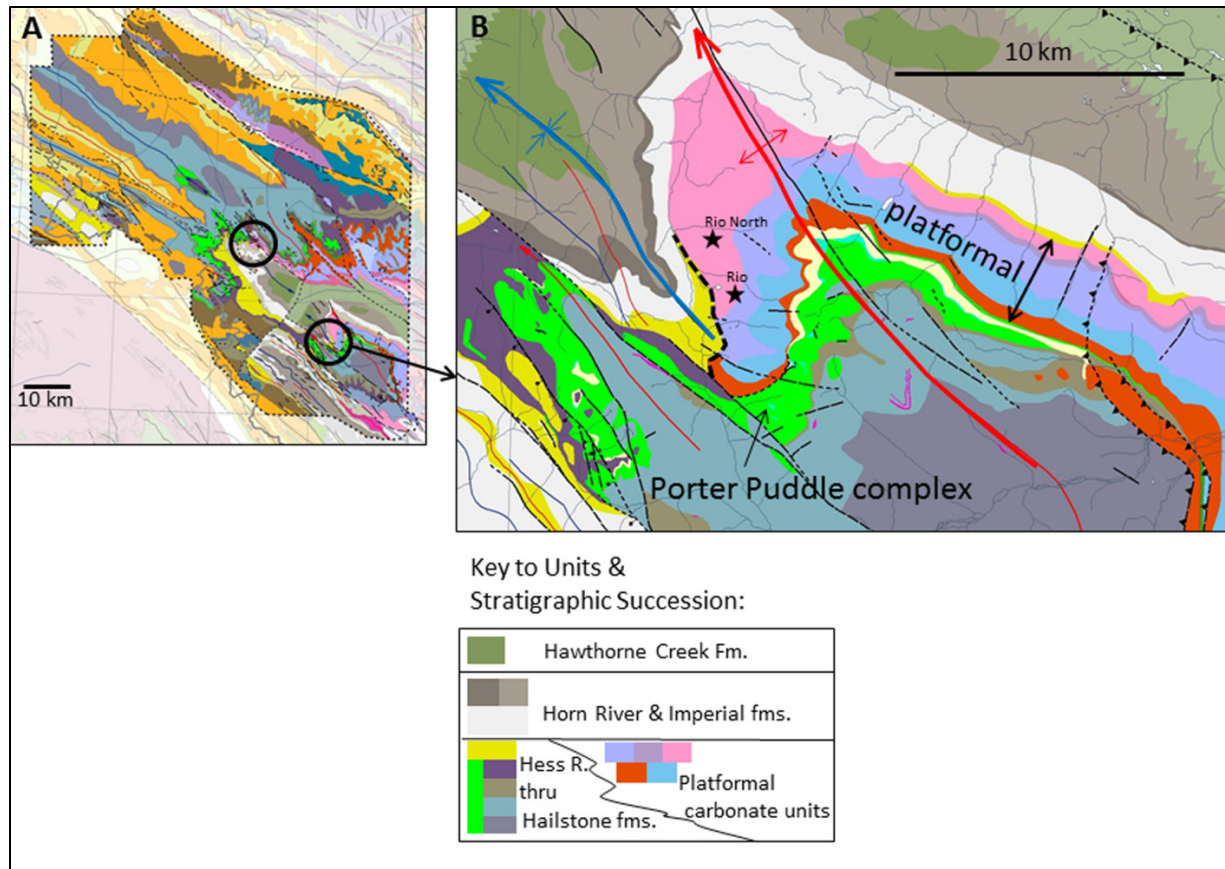


Figure 36. Areas of possible syn-depositional faulting with potential for clastic-dominated zinc-lead (CD Zn-Pb) deposits. [A] Two areas (circled) where possible Middle or Late Devonian faulting suggests the former presence of third-order basins and syn-depositional conduits for CD Zn-Pb fluids. Map legend is as for Figure 17. [B] Bedrock geology of the Porter Puddle area (southern circle in [A]). A thick, Early to Middle Devonian platformal succession transitions laterally, over a short distance, into deep basinal rocks (yellow; transition is marked with a thick, dashed black line). The transition is abrupt enough to suggest a structural break, and is overlain by an uninterrupted Late Devonian succession. The break, therefore, must be Early to Middle Devonian. Thin black lines are late faults, red and blue lines are anticlines and synclines, respectively, and black stars are minor carbonate-hosted zinc showings. Maps after Fischer (2016).

The southern of these two areas of possible syn-depositional faulting is adjacent to the Porter Puddle volcanic complex (Figure 36-B). The succession outward from the core of the Porter Puddle anticlinorium is well-exposed and continuous, from the Mid-Cambrian Hess River Formation (dull purple) through the Ordovician volcanic rocks of the Marmot Formation, that comprise the Porter Puddle complex (green), through a succession of Devonian platformal carbonate units, and into the Mid-Devonian siliciclastic strata of the Imperial Formation (brown). The succession in the adjacent syncline is not as well-exposed but also appears continuous, from basinal calcareous shale and black limestone of the Early to Mid-Devonian Hailstone Formation (yellow), through the shale and sandstone of the Horn River (off-white) and Imperial (brown) formations, into the siliciclastic strata of the Mississippian Hawthorne Creek Formation. (dark green). The lateral transition from

platformal carbonate to basinal calcareous shale of the Hailstone Formation (the postulated fault on the map) is too abrupt to be a normal facies transition, which suggests that there must be a structural break of some kind. The break, however, is overlain by a continuous layer of younger, Horn River strata (see the northwest end of the postulated fault). Therefore, the break pre-dated deposition of the Horn River Formation in the Late Devonian, and must have been a syn-depositional fault that terminated the platform laterally, allowing deep-water sediments to accumulate adjacent to platformal rocks. Such a fault would have been an ideal conduit for Devonian CD zinc-lead fluids.

Interestingly enough, there are zinc showings in the carbonate rocks near the postulated fault (Figure 36-B; NORMIN, accessed 2013; Darney and Ikona, 1975; Darney *et al.*, 1976). The Rio Main zinc showing (NORMIN identification number 106BSE0004) returned 6% Zn over a 50-foot (15 m) chip sample, but disappointing drill results. The Rio North zinc showing (106BSE0007) is defined by a grab sample with 9% Zn from a 250-foot (76-m) mineralized zone. Nelson *et al.* (2002) argued that subduction beneath the western margin of North America in the Late Devonian led to thermal convection, not only within the rifting back-arc basin, where focused discharge of mineralized brines along extensional faults created CD zinc-lead deposits, but also within the basinward parts of the adjacent carbonate platform, where discharge of the same mineralized brines led to formation of carbonate-hosted (MVT) zinc-lead deposits.

At the northern location in Figure 36-A, there is a small zinc showing in basal Horn River strata (Figure 28-B). In addition to the two areas of possible syn-depositional faulting shown in Figure 36-A, there is a limestone debris flow, 10 m thick and 15 km long, near the base of Hailstone Formation in the central part of the map area. This massive debrite in the midst of conformable deep-water strata may have been generated by syn-depositional faulting.

## **Geochemical data and known gold showings**

Stream-silt analyses for Pb, Zn, and Fe (Figure 37) and for Sb, As, Au, and Tl (Figure 38) were taken from a number of unlevelled datasets covering parts of the Yukon and Northwest Territories (Day *et al.*, 2005, 2009, 2012; Falck and Day, 2008; McCurdy *et al.*, 2007, 2009a, 2009b; Ozyer, 2010, 2012; Héon, 2003; YGS, 2011; Jackaman, 2012, 2015). The use of unlevelled data for this preliminary look is only somewhat ameliorated by the use of the same laboratories and protocols within a short span of time for the NWT surveys. There may be shifts in base level at survey boundaries, especially between the various older Yukon surveys. Because data have not been normalized with respect to the dominant background lithology of the catchment basin, some anomalies will reflect the background level in a certain rock unit of the element in question, as opposed to a concentrated deposit. Furthermore, gold values are difficult to interpret because the very low concentrations of interest combined with the small sample size leads to a “nugget effect”, that is, gold particles will be missed in many of the samples, while those that include a gold flake will have a higher than representative concentration of gold (*e.g.*, Radford, 1996). The use of a

cyanide leach on the clay-sized fraction of large samples would lead to data with better reproducibility (*e.g.*, Arne and Macfarlane, 2014).

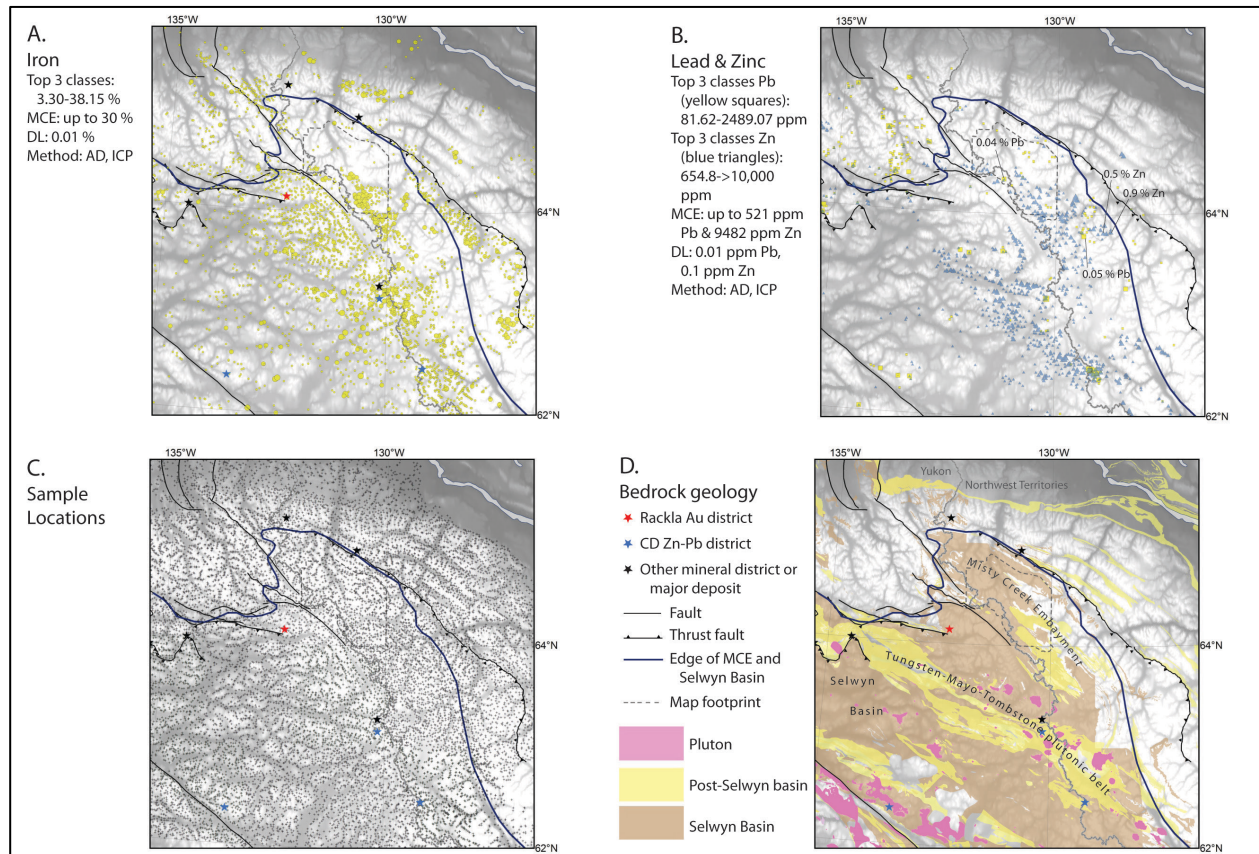


Figure 37. Stream-silt geochemistry of the Selwyn Basin region, showing major faults and mineral districts on a background of greyscale surface relief. Blue line is the approximate locus of the transition from Lower Paleozoic platformal strata in the east and north into basinal strata to the west and south, inferred from bedrock geology and Cecile (1982). Dashed grey outline is of the Selma project map (Fischer, 2016). Statistical treatments were made on unlevelled data. The creation of classes is explained in the text. [A] Iron. Each yellow symbol is a stream-silt sample that contained  $\geq 3.30\%$  Fe. [B] Lead and zinc. Each blue symbol is a stream-silt sample that contained  $\geq 654.8$  ppm Zn. Each yellow symbol is a stream-silt sample that contained  $\geq 81.62$  ppm Pb. [C] Stream-silt sample locations are represented by black dots. [D] Generalized bedrock geology of the area depicted in [A] to [C] and Figure 38. AD, ICP = acid digestion followed by inductively coupled plasma mass spectrometry. CD Zn-Pb = clastic dominated zinc-lead. DL = lower detection limit. INAA = instrumental neutron activation. MCE = Misty Creek Embayment. See text for data sources.

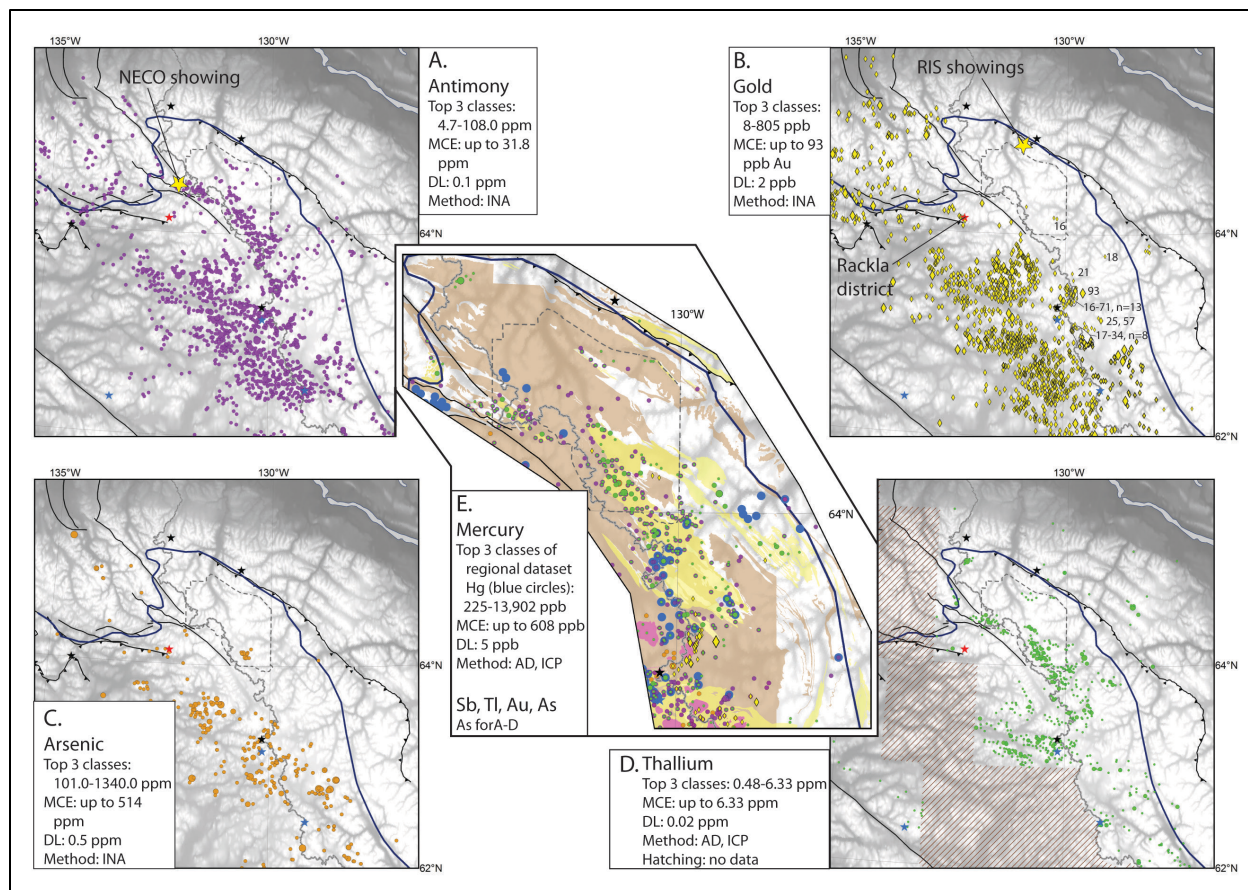


Figure 38. Stream-silt geochemistry of the Selwyn Basin region (continued). Sample locations, symbols, regional geology, sources, and abbreviations are as in Figure 37. [A] Antimony. Each purple symbol is a stream-silt sample that contained  $\geq 4.7$  ppm Sb. NECO is a Hg-Sb-Zn-Pb showing described in the text. [B] Gold. Each yellow diamond-shaped symbol is a stream-silt sample that contained  $\geq 8$  ppb Au. Labels are values  $\geq 16$  ppb Au for selected samples; n= refers to the number of samples whose Au values fall within the given range. The Rackla gold district is indicated. RIS is a group of Pb-Zn-Au showings described in the text. [C] Arsenic. Each orange symbol is a stream-silt sample that contained  $\geq 101$  ppm As. [D] Thallium. Each green symbol is a stream-silt sample that contained  $\geq 0.48$  ppm Tl. Hatching indicates areas for which stream sediments were not analyzed for Tl. (E) Mercury (blue symbols) and Sb, Tl, Au and As (colored as in [A] to [D]) for a portion of the area shown in [A] to [D], on a backdrop of generalized geology. Legend for the bedrock geology is as for Figure 37-D. Each blue circle is a stream-silt sample that contained  $>224$  ppb Hg. The top three classes for the wider area shown in [A] to [D] contain 225-13,902 ppb Hg. The top three classes for the smaller area shown in this figure contain 109-3018 ppb Hg, with the highest values associated with plutons in the southwest. Note the coincidence of Hg, Sb, Tl, and Au in some areas of the MCE south of  $64^{\circ}\text{N}$ .

The concentrations of each element across the illustrated area were divided into five classes, based on natural breaks in the data, using a GIS-software algorithm. Each map symbol in Figures 37 and 38 represents one stream-silt sample that had a value of the specified element within the top three classes. Symbols size increases with class value. Samples whose values fell within the lower two classes are shown only on the sample-

location map. Subtitles on each map show the range of values in the top three classes for the entire map, plus the maximum values in the MCE area.

This first-pass look at the unlevelled data suggests the presence of anomalous Pb, Zn and Fe in the MCE, especially along its southwestern margin, where up to 0.4% Zn and 0.05% Pb were detected in stream silts (Figure 37-B). For the elements Sb, As, Au, and Tl, the maps of unlevelled, classified data are not as informative, partly because Tl data are missing for a large swath of the Yukon (hatch marks in Figure 38), and partly because the Sb, As and Au signature of felsic plutons overwhelms the regional signal in the south and west of the illustrated area. Nevertheless, it can be seen that there are locally anomalous amounts of all four elements in the MCE by comparison with other pluton-free parts of the NWT. The latter areas are largely devoid of colored symbols in the maps of Figure 38 – that is, largely devoid of samples whose concentrations of those elements were high enough to fall within the uppermost three classes. Therefore, it would appear that the Sb, As, Au, and Tl anomalies in the MCE area derive from a non-plutonic source. Whether that source is a lithological unit or a concentrated mineral deposit cannot be determined from this simple visualization. Methods that should be applied to the data to help isolate anomalies caused by deposits include, at a minimum, levelling based on dominant watershed lithology/lithologies, and also, if warranted, corrections for differing erosion rates of each lithology and differing dilutions in watersheds of different sizes (Arne and Brown, 2015). All of the elements in Figure 38 – Sb, As, Au, Tl – are associated with Carlin-type gold districts. Sb, As and Tl are also markers for CD zinc-lead districts, as are Pb, Zn and Fe, so the elevated values of those elements in the MCE area are encouraging on two fronts.

Gold is present in stream silts in the MCE area in concentrations up to 93 ppb (Figure 38), as determined by Instrumental Neutron Activation Analysis on 30-gram aliquots of -80 mesh material from the dried sample. Anomalies in stream sediments as low as 3 and 4 ppb Au have been followed up to discover deposits in Nevada (Felder *et al.*, 2011); those anomalies were determined using a cyanide leach on specific size fractions of bulk samples (Bulk Leach Extractable Gold method) with a lower detection limit of 0.1 ppb Au. Mercury values up to 608 ppb were found in MCE stream silts (Figure 38-E), as single samples or clusters of a few samples. In Nevada, mercury anomalies tend to be smaller than the corresponding gold anomalies, and that would seem to be the case in the MCE as well.

There is an interesting cinnabar showing called NECO on the western edge of the embayment (Figure 38-A; Yukon Minfile #106B015). This showing consists predominantly of float with dolomite-sphalerite-(galena-barite) - filled veins and fractures that cut dolomitized limestone of the Sekwi Formation and chert-dolomite breccia of an overlying unit. There are also quartz (-stibnite) veins and calcite-sphalerite-cinnabar veins and lenses up to 1.5 m wide in the Sekwi Formation limestone. One patch of cinnabar measured 12 cm across. Selected samples returned assays up to 9.8% Hg and 8.1% Sb. The fractured, mineralized rock lies in a faulted, overturned anticline. Samples from NECO were not assayed for gold. The presence and style of sphalerite and galena suggest that this showing has at least a component of structurally controlled carbonate-hosted zinc-lead mineralization (Fischer, 2012). However, the structural setting and the concentrations of

Hg and Sb raise the possibility of overprinting of the base metal mineralization by a gold system, as has been noted in the Nevada district (*e.g.*, Emsbo *et al.*, 2006).

Another group of gold showings, the RIS group (Guild and Brock, 1974; NORMIN #106BNE0007), consists of a number of occurrences scattered along 700 m of a northwest-trending fault zone near the east edge of the embayment. Four lead-zinc-gold showings and three lead-zinc-silver showings consist of intensely silicified carbonate rock with disseminated and vein-hosted galena and sphalerite, and accessory pyrite, tetrahedrite, malachite, and hydrozincite. Gold values include 0.28 oz/ton across 11.5 feet (9.6 g/t across 3.5 m) and 0.38 oz/ton gold across 8 feet (13.0 g/t across 2.4 m) in chip samples. The silicified, mineralized zone forms the northeast limb of a small anticline in the footwall of a reverse fault that has anomalous sense (dips northeast; Guild and Brock, 1974). The mountain slope is actively eroding, as seen on a visit in 2017, and the showings have been buried in the 40 years since their discovery by upward growth of an apron of coalescing colluvial fans. The presence of tetrahedrite and malachite is not unusual in the carbonate-hosted zinc-lead showings of the Mackenzie Mountain (Martel *et al.*, 2011), whereas the presence of gold and intense silicification hint at overprinting by Carlin-type processes.

Minimal lithogeochemistry has been carried out in the MCE. Cecile (1982) sampled a vertical section of Cambrian to Silurian basinal strata. Carbonaceous shale intervals and chert intervals in the Hess River and Duo Lake formations contain concentrations of Zn, Ag, As, Hg and Sb that, although low, are anomalous relative to the other intervals sampled. A sample of the uppermost Hailstone Formation from another location contained 0.27% ZnO (Cecile, 2000). Scattered grab samples of various units in the MCE show that: the Marmot Formation contains elevated Hg (up to 368 ppm), Tl (up to 2.5 ppm), and in places, As (up to 40 ppm); the Duo Lake Formation is anomalous in Fe, Mn, Mg and P compared to the Horn River Formation; the Hailstone Formation has elevated Zn (up to 3800 ppm); and the basal part of the Horn River Formation contains slightly elevated Zn (up to 200 ppm; Fischer, 2014).

## **Summary of the Potential of the Misty Creek Embayment area**

The MCE area is prospective for both Carlin-type gold and CD zinc-lead deposits. The key features that reveal this prospectivity are summarized below.

### **Clastic-dominated zinc-lead potential**

The Selwyn Basin is well known as an important district for CD zinc-lead deposits, being host to multiple sub-districts that collectively record at least three major mineralizing events over 200 million years (Goodfellow, 2007). It is a first-order rift basin with over three kilometers of clastic, rift-phase fill (the Hyland Group; Gordey and Anderson, 1993) adjacent to a platform that experienced evaporative conditions at three separate times and

regional dolomitization (Martel *et al.*, 2011). Hundreds of MVT showings are present along the platform margins (*ibid.*; NORMIN, accessed 2013).

In exploring for new sub-districts of the Selwyn Basin, the MCE area is appealing, meeting each of the key exploration criteria described above (Table 2). The MCE itself is a second-order basin (Cecile, 1982), and there is possible evidence of third-order faulting within it. Deep-water, reduced shale and mudstone were deposited contemporaneously with sub-basin faulting during four separate periods of time (represented by the Hess River Formation, Duo Lake and Cloudy formations, Hailstone Formation, and Horn River Formation). Two volcanic complexes (Dudley Lake and Porter Puddle Complexes) and a number of sills and diatremes are present in the basin fill. Stratiform barite is present at three separate stratigraphic levels: the Hess River Formation., the Duo Lake / Cloudy formations, and the Horn River Formation. Phosphorite is present in the Hess River and Rabbitkettle formations, and siliceous shale or chert is present in the Hess River, Rabbitkettle, Duo Lake, Cloudy, and Canol formations (Fischer, 2016; Cecile, 1982). Sericite and chlorite alteration has affected the volcanic rocks of the Marmot Formation (Cecile, 1982). Finally, stream silts contain locally anomalous amounts of the metals typically associated with CD zinc-lead deposits, including Pb, Zn, Fe, Tl, As, and Sb (Day *et al.*, 2005, 2009; Falck and Day, 2008), and the available lithogeochemical data are encouraging (Table 2; Cecile, 1982, 2000; Fischer, 2014).

Table 2. Exploration criteria for clastic-dominated zinc-lead deposits, and how they are met in the Misty Creek Embayment area.

Type of criterion	Requirement / Characteristic	Misty Creek Embayment area
Tectonic setting	First-order rifted basin	Selwyn Basin was a rifted passive-margin basin.
	Second- and third-order basins	Misty Creek Embayment is a second-order basin. Possible evidence of syn-depositional faulting suggestive of third-order basins.
	Upper part of the basin fill	Misty Creek Embayment strata are typical of upper-basin fill (fine-grained siliciclastic and carbonate sediments).
	Presence of thick rift-phase fill	Proterozoic Hyland Group of Selwyn Basin is at least 3500 m thick.
	Presence of known CD deposits	Anvil (Cambrian), Howards Pass (Silurian), and MacMillan Pass (Devonian) districts. The giant Howards Pass district contains 15 significant deposits.
	Adjacent to a platform with evaporite rocks and MVT deposits	Mackenzie Platform has multiple levels of evaporite strata, an extensive dolomite facies, and hundreds of MVT showings.
	Presence of volcanic complexes or sills	Dudley Lake and Porter Puddle volcanic complexes, numerous sills and diatremes.
Host succession	Fine-grained siliciclastic sediments deposited in deep water (below wave base)	Carbonaceous shale and mudstone, variably pyritic and calcareous, of Hess River Formation, Duo Lake / Cloudy formations, Hailstone Formation, and Horn River Formation, representing four separate periods of time, were all deposited below wave base.
	Reduced sediments	
Distal exhalative sediments	Barite, apatite, Fe/Mn carbonate, silica, Fe sulfides, metalliferous shale	Stratiform barite at three separate stratigraphic levels (Hess River, Duo Lake / Cloudy, and Horn River formations). Phosphorite in Hess River and Rabbitkettle formations. Barite(?) in Marmot Formation. Siliceous shale or chert in the Hess River, Rabbitkettle, Duo Lake, Cloudy, and Horn River formations.
Alteration	Sericite/muscovite, chlorite, tourmaline, Fe-sulfides, Fe-Mn carbonates, silica	Sericite and chlorite alteration in the volcanic rocks of Marmot Formation.
	Chemical halos (in rocks or stream silts) of Pb, Zn, Fe, Tl, $\pm$ Mn, ( $\pm$ As, Ba, Bi, Hg, P, Sb)	Stream silts contain locally anomalous amounts of Pb, Zn, Fe, Tl, As, and Sb. Rocks of Hailstone and basal Horn River formations anomalous in zinc. Carbonaceous shale and chert intervals in Hess River and Duo Lake formations contain elevated Zn, Ag, As, Hg and Sb. Duo Lake Formation contains elevated Fe, Mn, Mg and P.
	Chemical zoning	Not known.

## Carlin-type gold potential

The tectonic setting of the MCE area shares certain key characteristics with the setting of the classic Carlin-type district in Nevada (Table 3). It overlies extended continental crust adjacent to lithosphere-scale faults. A rifted-margin succession developed on the extended crust subsequent to rifting, and endured for 150 million years while undergoing episodes of extension (Figures 4 and 32). This succession, as in Nevada, consists of basal Proterozoic terrigenous clastic and carbonate strata and overlying paired belts of Lower Paleozoic platformal carbonate units flanked by coeval basinal strata. The Lower Paleozoic units represent numerous depositional sequences.

The rifted-margin regime was terminated by contractional orogeny, beginning in the Jurassic in the MCE area, producing north- and northeast-vergent folds and thrusts. The relationship between mineralization and thrusting in the Rackla Carlin-type gold district to the west has not been clarified, but the district is near the exposed trace of the crustal-scale Dawson Fault and two overlying, thin-skinned thrusts that collectively accommodate more than 100 km of shortening (Mair *et al.*, 2006; Colpron *et al.*, 2013).

In the Carlin district in Nevada, mineralization was contemporaneous with mild extension in the Eocene. In the Rackla district of northwestern Canada, the age of Carlin-type gold deposition is known to be post-deformation and thought to be latest Cretaceous or early Paleocene (Arehart *et al.*, 2013). Local extension in the Selwyn Basin area was associated with mid-Cretaceous pluton emplacement (Poulsen *et al.*, 1997; Hart *et al.*, 2004; Nelson *et al.*, 2013), although there is no recognized extension associated with magmatism in the Rackla district. There may have been localized extension at step-overs and bends in the transpressive regime that followed plutonism (Nokleberg *et al.*, 1995, Cox *et al.*, 2001), however, regional-scale extension is not recognized. This apparent lack of a period of late extension is mitigated by the presence of actual Carlin-type gold deposits, 60 km to the west of the MCE area.

At local to district scales, the strata of the MCE area are dominantly calcareous, reactive, and amenable to Carlin-type mineralization; notably, silty lime mudstone, skeletal-limestone and limestone-breccia debrites, limestone turbidites, skeletal limestone, slumped limestone, karst, and calcareous volcanogenic sandstone. Structural preparation exists in the MCE area in the form of numerous intersecting structures, and potential traps include anticlinal traps, impermeable overlying strata, and areas of structural and lithological heterogeneity. Stream silts are enriched in Tl, Sb, As, and Au. Certain stratigraphic intervals are enriched in one or more of Hg, Tl, Sb, and As. In short, the MCE area has attributes suggestive of the existence of Carlin-type gold systems, as evidenced by the recent discoveries along the Rackla Belt in the adjacent Selwyn Basin of the Yukon.

Table 3. Exploration criteria for Carlin-type gold districts, and how they are met in Nevada and the Misty Creek Embayment area. MCE = Misty Creek Embayment.

Type of criterion	Requirement / Characteristic	Nevada district (well studied)	Misty Creek Embayment area (not well known)
Tectonic history	Rifted-margin (passive-margin) setting above oceanic or extended continental crust	Overlies extended continental and oceanic crust of the western margin of Laurentia created during rifting of Rodinia.	Overlies extended continental crust of the western margin of Laurentia created during rifting of Rodinia.
	Adjacent to crustal-scale faults	Deposit trends (Carlin trend, Battle Mountain – Eureka trend, Getchell trend) coincide with crustal-scale faults thought to be remnants of Neoproterozoic rifting and transfer faulting.	Snake River Fault (Canada) & Dawson Fault are crustal-scale faults that have been active intermittently since the Neoproterozoic.
	Long-lived, complex sedimentary succession	Succession consists of Neoproterozoic and Early Cambrian rift-related terrigenous clastic rocks, Lower Paleozoic carbonate ramps that evolved to rimmed platforms, and Lower Paleozoic basinal sediments.	Succession consists of Neoproterozoic Windermere Supergroup and Hyland Group rift-related terrigenous clastic rocks, overlain by Windermere Supergroup rifted-margin terrigenous and carbonate rocks, Cambrian fluvial and carbonate-ramp deposits (Backbone Ranges & Sekwi formations), and Lower Paleozoic rifted-margin strata (Cambrian to Devonian carbonate rocks of the Mackenzie Platform and latest Neoproterozoic to Devonian basinal strata of the MCE and Selwyn Basin).
	Contractional orogeny & terrane accretion	A succession of orogenies associated with terrane accretion and subduction on the western margin of Laurentia, beginning with Late Devonian orogeny and continuing intermittently through Late Cretaceous.	A succession of events associated with terrane accretion and subduction on the western margin of Laurentia, beginning with Late Devonian back-arc extension, and including Triassic thrusting and Jurassic-Cretaceous orogeny.
	Extension	Mild regional extension in the Eocene, linked to removal or steepening of a subducted slab from beneath western North America; coincident with formation of Carlin-type deposits.	Local Cretaceous extension associated with pluton emplacement; possible local extension during Paleocene or Eocene associated with transcurrent movement on the Tintina Fault.
	Thermal pulse accompanies extension	Crustal thermal event related to slab removal.	Local thermal aureoles associated with Cretaceous plutons. No evidence of regional thermal event.

(continued)

Table 3. (continued)

Basin-scale	Abundant reduced (organic matter - rich) sediments in the host basin	Abundant carbonaceous strata; past petroleum generation.	Hess River, Cloudy, Hailstone, Horn River and Hawthorne Creek formations, from Cambrian to Mississippian in age, contain carbonaceous strata; Horn River (Canol) Formation is a known petroleum source rock.
	Numerous permeable horizons; products of third- and lower-order sea-level lowstands in both deep water (mass-transport deposits) and shallow water (karsted platform).	Carbonate debrites, turbidites, slumps, slides and karst facies generated during lowstand exposure.	Carbonate turbidites and debrites in Cloudy and Hailstone formations (some in Duo Lake Formation), slumps in Cloudy and Rabbitkettle formations, karst in Grizzly Bear Formation, skeletal rudstone/ floatstone in Tsetso & Hume formations, calcareous sandstone in Marmot, Cloudy and Lower Tsetso(?) formations.
District-& deposit-scale	Heavily faulted ground, intersecting structures	Extension during the rifted-margin phase, thrusting and basin inversion during orogeny, extension during slab rollback; thrusts, steep faults at high angles to thrusts; conjugate faults in the footwalls of thrusts, closely spaced anticlines and synclines subparallel to and cut at shallow angles by thrusts.	Cambrian and Ordovician extensional faulting (creating the MCE), Devonian faulting as suggested by mapping, Mesozoic thrusts, back-thrusts, and steep faults in multiple orientations (mostly striking southeast, east, south); faults intersect sub-parallel folds at shallow angles; broad & open to closely spaced anticlines and synclines subparallel to thrusts.
	Anticlinal traps	Deposits are localized in permissive strata and second-order faults within the culminations of regional asymmetric anticlines.	Numerous anticlines formed during Mesozoic deformation; e.g. Hailstone Anticline, Grizzly Anticline.
	Seals / stratigraphic traps	Allochthonous shale over reactive limestones. Tight carbonate strata over reactive carbonate strata. Locally, impermeable dykes or sills adjacent to reactive strata.	Horn River shale over reactive Hailstone or Grizzly Bear strata, Devonian dolostone over volcanic or skeletal variants of Lower Testso(?) Formation, Lower Paleozoic shale intervals over older reactive calcareous strata.

(continued)

Table 3. (continued)

District-& deposit-scale	Sites of structural or lithological heterogeneity	Permeable stratigraphic horizons. Stratigraphic contacts. The edges of stocks, whose perturbation of the prevailing stress field created discrete areas around the stock margin of low effective mean stress (and preferred ore deposition). The intersections of faults with other structures, including permeable fracture networks. Structures within anticlinal culminations.	Grainstone horizons in shaley strata, terrigenous strata sandwiched between tight carbonate horizons, rheologically competent volcanic complexes surrounded by less-competent sedimentary rock, dykes and sills cutting carbonate strata, fault intersections, intersections of faults with other sites of lithological heterogeneity, anticlinal culminations.
Host rocks	Reactive, permeable hosts, typically calcareous, preferably also bearing non-sulfide iron.	Fine-grained, thin-bedded, calcareous rocks with terrigenous silt, <i>e.g.</i> , silty lime mudstone. Limestone debrite, skeletal limestone. Lamprophyre. Fractured felsic to mafic intrusive rocks, fractured siliceous or calcareous siltstone.	Parts of Sekwi Formation (calcareous, dolomitic, silty, skeletal), Hess River (calcareous, silty, thin-bedded, debrites, skeletal), Rabbitkettle (thin-bedded, silty), parts of Duo Lake (calcareous, dolomitic, thin-bedded, silty, skeletal), Cloudy (calcareous, skeletal, debrites, silty, thin-bedded, fractured silicified), Hailstone (calcareous, silty, thin-bedded, debrites, skeletal), and Grizzly Bear (calcareous, skeletal) formations, Lower member of Tsetso(?) Formation (calcareous, silty, sandy, skeletal), Marmot Formation and related intrusions (fractured, calcareous, iron-rich).
Vectors	Presence of known Carlin-type deposits	Numerous deposits	Rackla district 60 km to west; possibly NECO and RIS showings
	Geochemical anomalies	Au, As, As, Hg, Sb, Tl ± Te	Stream-silt anomalies of As, Sb, Tl, Au, Hg in MCE, elevated As, Hg, Sb in parts of Hess River and Duo Lake formations and Hg, Tl, ±As in Marmot Formation, and lithogeochemical anomalies of Sb, Hg at NECO

## **Conclusions**

The Misty Creek Embayment area is a greenfields target region with strong indicators of good potential for Carlin-type gold mineralization and clastic-dominated zinc-lead deposits. Bedrock mapping is not detailed, but sufficient to confirm the fundamentals of the tectonic setting required by each deposit model and the presence of the appropriate rock types and structures for each. Stream-silt geochemistry reveals anomalies of marker elements, including gold itself. There is considerable scope for both regional and detailed programs of exploration to identify and develop targets.

## **Acknowledgements**

This work benefitted from discussions with numerous geologists, including the Northwest Territories Geological Survey colleagues Hendrik Falck, Karen Gochnauer, and Edith Martel, and especially Dave Groves of East Mountain Exploration, LLC who directed me to papers I had missed and shared aspects of his experience with Carlin-type gold deposits. Special thanks to Moira Smith and David Rhys, who led a Society of Economic Geologists field trip through the Carlin district of Nevada in 2013, and to the many mine personnel who went out of their ways to accommodate us. I am grateful for the thoughtful reviews provided by Dave Groves and Hendrik Falck. Funding for field work was provided by the Government of the Northwest Territories and the federal Polar Continental Shelf Project.

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