Targeting carbonate-hosted Zn-Pb ore in the Mackenzie Mountains: where to look and why

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Summary

Numerous occurrences of carbonate-hosted (or Mississippi Valley-type) Zn±Pb mineralization are present in Neoproterozoic to Devonian rocks of the Mackenzie Mountains zinc district (Northwest Territories, Canada). Detailed stratigraphic and petrographic studies of showings in the Early Cambrian Sekwi Formation, a preferred host of mineralization, have allowed us to identify major controls on localization of sphalerite, galena, and subordinate ore minerals. Microthermometry of fluid inclusions in sphalerite and Sr, C, O, and S isotopic analyses of sphalerite, barite and dolomite have revealed the involvement of hotter fluids that rose from deeper sources than hitherto suspected.

A first-order control is proximity to faults. Rock types that are preferentially mineralized are those with mm- to cm-scale variations in mineralogy or texture, such as ooid grainstone or burrow-mottled dolostone with variable organic or siliciclastic content. This lithologic control is third-order, subordinate to a second-order stratigraphic control such that the structurally lowest susceptible rocks in the local succession are preferentially mineralized. The age of mineralization is Cretaceous-Tertiary, based on its association with late faulting.

At least two fluids participated in mineralization. A shallow fluid, which may have been a saline connate fluid or seawater, equilibrated with marine carbonate rock (perhaps Sekwi Formation) at 150ºC. A deep fluid rose along steep faults from a crystalline basement reservoir during Late Cretaceous orogeny, leaching metals from the overlying sedimentary pile, and equilibrated thermally with its surroundings at 250-350ºC as it traversed a Neoproterozoic evaporite horizon along a major detachment 7 km deep. Thermochemical reduction of evaporitic sulfate produced H_2S, leading to metal-sulfide precipitation in hydrothermally enhanced pores of the Sekwi Formation.

This deposit model can be applied throughout the Mackenzie Mountains. Carbonate-hosted Zn±Pb deposits should be sought near ramping thrusts or their splays, preferably in upper Sekwi Formation where it has been dolomitized and disrupted by multiple steep faults. The most prospective horizons are the structurally lowermost local occurrences of susceptible rock types.

Introduction

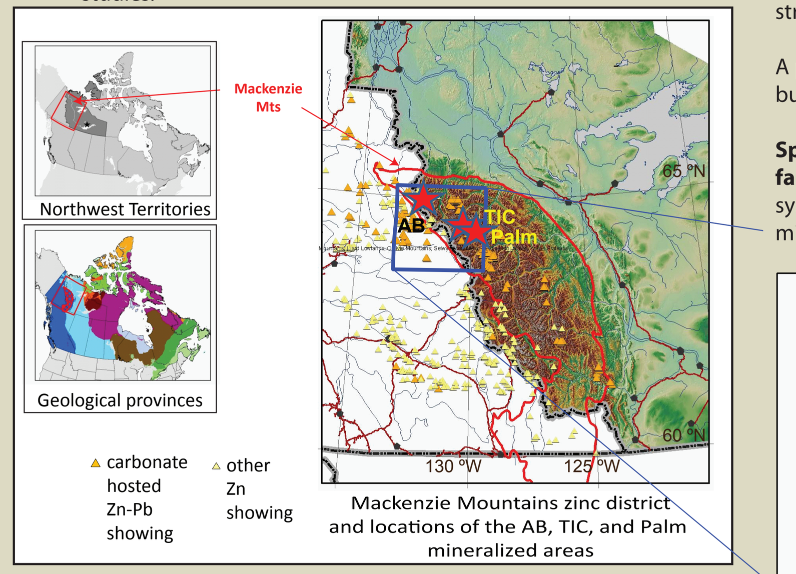
The Mackenzie Mountains zinc district is in the eastern fold and thrust belt of the northern Canadian Cordillera (Fig. 1). These mountains were formed when Neoproterozoic to Devonian sedimentary and minor volcanic rocks (Fig. 2) deposited on the western margin of Laurentia were uplifted and thrust northeastward (present-day directions) during Mesozoic orogenesis, resulting in an arcuate, northwest-trending belt of weakly to unmetamorphosed rocks in northeast-verging folds and thrust slices (Martel et al, 2011).

Over 200 carbonate-hosted Zn(-Pb) showings are known in this district. Explorationists in the 1970's noted the close association of these showings with faults related to Mesozoic orogeny, and preferential mineralization of the Lower Cambrian Sekwi Formation compared to other units. The aims of this study were to identify structural, stratigraphic, and lithologic controls on mineralization in the Sekwi Fm., and to provide deposit-model constraints that would help to focus exploration in the district.

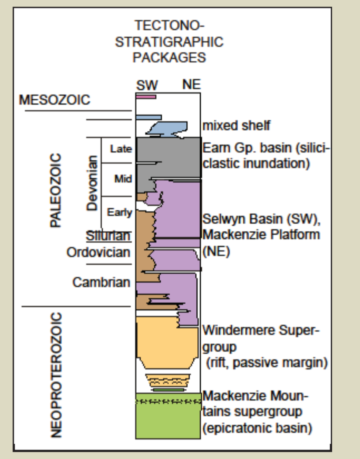
The Sekwi Fm. is one of the earliest depositional elements of the Mackenzie carbonate platform, which, together with the Selwyn basin to its west, endured on the western passive margin of ancestral North America from latest Proterozoic until Middle Devonian times. The lower part of the Sekwi Fm. was a mixed carbonate-siliciclastic ramp locally steepened by syn-depositional faulting, and its upper part was a low-relief carbonate-dominated ramp with intermittent ooid and oncoid shoals. The unit ranges from a few meters thick near the paleoshore, to almost 1400 m thick toward the basin (Fischer, 2012).

Methods

A compilation of available data (NORMIN, 2011) confirmed that mineralization is concentrated preferentially at three stratigraphic levels, one of which is the Lower Cambrian Sekwi Fm. Three areas, the AB, TIC, and Palm areas, were chosen that each have a number of Zn or Zn-Pb showings in Sekwi Fm. Composite stratigraphic sections of Sekwi Fm. were constructed from published data in the vicinity of the chosen areas, and stratigraphic sequences identified by Dilliard (2006) in southern sections of Sekwi Fm. were extended north to the composite sections. Mapping or measurement of sections in each of the three chosen areas were used to locate each area within this stratigraphic framework. Field work also established structural and lithological context, and samples of mineralization were taken for petrography, fluid-inclusion, and isotopic studies.



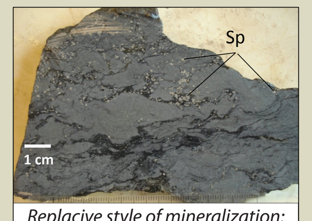
Mackenzie Mountains zinc district and locations of the AB, TIC, and Palm mineralized areas



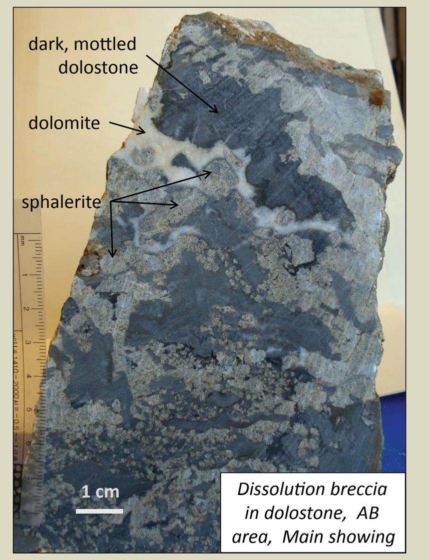
Results and their Implications

Description of Mineralization

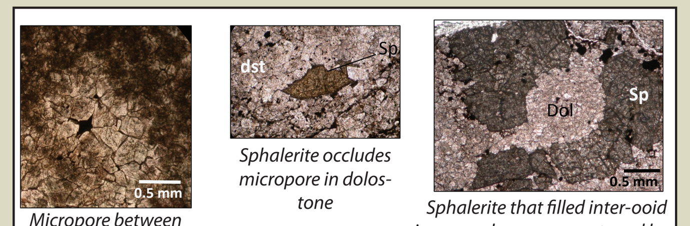
Mineralization is both replacive and void-filling (breccia style). Replacive mineralization (right) was initiated by sphalerite occluding micropores created by dolomitization. It proceeded to replacement of the dolomite by sphalerite (below).



Replacive style of mineralization: sphalerite in dark, silty, mottled dolostone (AB-C Lower showing)



Dissolution breccia in dolostone, AB area, Main showing



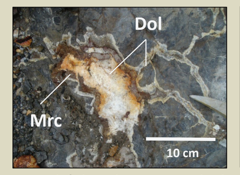
Micropore between secondary dolomite crystals

Sphalerite occludes micropore in dolostone

Sphalerite that filled inter-ooid micropores has grown outward by replacing inter-ooid dolomite.

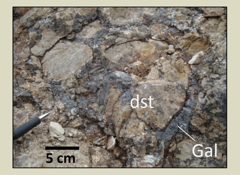
Photomicrographs of replacive style of mineralization from AB-C Lower showing. Unpolished thin sections in plane polarized light (PPL).

Breccia mineralization predominates volumetrically. Dissolution and fitted-fabric breccias are cemented by dolomite, sphalerite, pyrite, marcasite, ±galena, barite and minor pyrobitumen, quartz and calcite. Sphalerite is green, red, yellow, or bluish grey, fine to very coarse, and disseminated to massive. Mineral paragenesis varies from place to place but dolomite and pyrite are typically the earliest phases, followed by sphalerite; quartz and calcite are late. Dolomite pre-dates and post-dates the ore minerals.

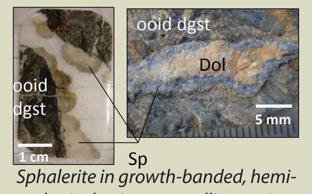


Fitted-fabric breccia in dark, mottled, silty dolostone, AB area.

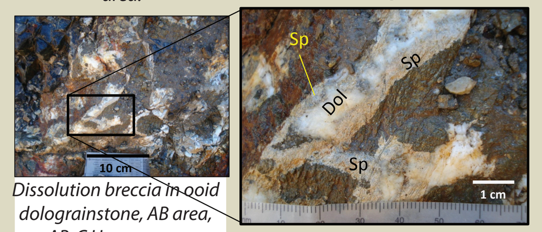
Fitted-fabric breccia in ooid dolograinstone, AB area, Link showing.



Rubble dissolution breccia in recrystallized dolostone, TIC area, C zone.



Sphalerite in growth-banded, hemispherical, micro-crystalline grains lining a breccia cavity; thin section left, outcrop right. AB-C Upper showing.



Dissolution breccia in ooid dolograinstone, AB area, AB-C Upper zone.

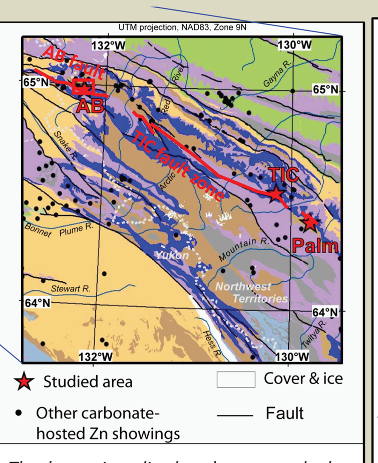
Controls on Mineralization

Evidence for a primary structural control

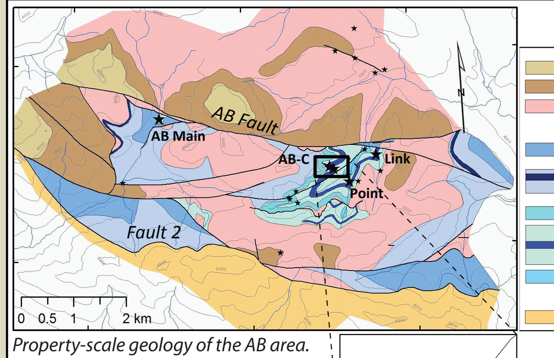
All three mineralized areas and other anomalies (eg. NORMIN, 2011) lie along a regional, NW-trending reverse fault (below left). Faults and fractures at multiple scales are spatially associated with mineralization at AB and Palm. Numerous showings in the AB area (below right) are in a fault-shattered zone between two regional reverse faults, where mineralization is localized along centimeter- to outcrop-scale fractures and faults, and concentrated at their mutual intersections (inset). A strong structural control is inferred.

A property-scale fault controlled mineralization in the Main zone of the Palm area (below, at bottom). The distribution of mineralized zones at TIC are best explained by an unidentified primary control which may be a fault.

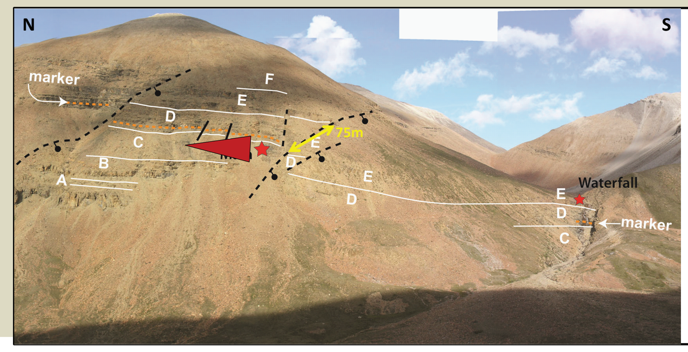
Spatial association at these various scales suggests a genetic relationship between mineralization and faulting. Furthermore, Sr-isotope evidence that a basement fluid reservoir contributed to the mineralizing system (see Isotope section) supports a genetic relationship, since faults or fractures were needed to conduct the mineralizing fluids to sites of precipitation in the overlying sedimentary pile.



The three mineralized study areas and other showings lie along a regional fault trend.



Property-scale geology of the AB area. Showings are concentrated in a faulted zone between two regional reverse faults. Inset shows faults & fractures at the AB-C Upper showing. Mineralization is outlined in red.



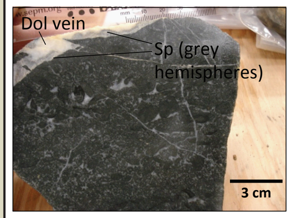
A property-scale fault in the Palm area divides unmineralized strata to its south from mineralized strata of the Main zone to its north. Red triangle points in the direction of decreasing grade. A fault control is inferred.

Controls on Mineralization (continued)

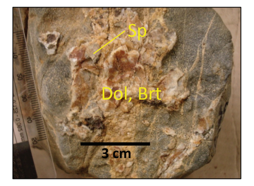
Evidence for a subordinate lithological control

Host lithologies in the AB, TIC, and Palm areas are ooid-intraclast grainstone and rudstone (photos below), skeletal wackestone, siliciclastic-silty, burrow-mottled dolostone (photos to left & below right), and minor fenestral dolostone, all of which have been dolomitized. **These rock types all have millimetre- to centimetre-scale variations in mineralogy and texture, and therefore in reactivity and dissolution potential, i.e. they are susceptible to being mineralized.** Rock types that are uniform and homogeneous are not mineralized.

However, susceptible rocks are not everywhere mineralized, and the controlling factor appears to be whether they are close to faults or fractures. Therefore, **although there is a lithological control, it is subordinate to the structural control.**



Dolomitized oncoid-intraclast rudstone with a matrix of ooid-intraclast grainstone. A dolomite-sphalerite vein occupies the top edge of the sample. This rock type hosts breccia style mineralization. (Cut surface, AB-C Upper showing)

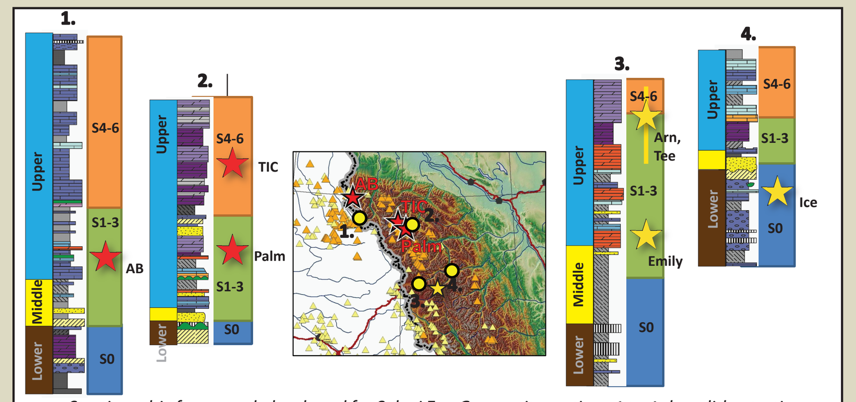


Ooid grainstone cut by dolomite-barite-sphalerite vein. In thin section, sphalerite replaces ooids in vein walls. (AB-C Upper showing)

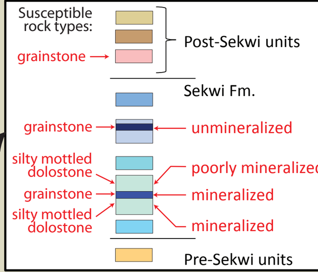
Thin beds of dark, mottled dolostone, host of dissolution-breccia style mineralization at Palm Main zone.

Evidence for and against stratigraphic control

The stratigraphic contexts of various mineralized areas were determined and are illustrated on thefigure below, which shows the **absence of a primary stratigraphic control.**



Stratigraphic framework developed for Sekwi Fm. Composite sections 1 to 4 show lithostratigraphic member-level units on left (based on Krause, 1979, Fritz 1976, 1978,1979, Dilliard et al, 2010 and second-order sequence-stratigraphic units on right (this study and Dilliard et al., 2010). Studied showing areas are marked by red stars, other showings by yellow stars. Showings are present in the Upper and Lower members and in each of the sequences.



Stratigraphy of the AB area. Susceptible horizons are indicated.

In the AB area, however, a secondary stratigraphic control over-rides the lithological control:

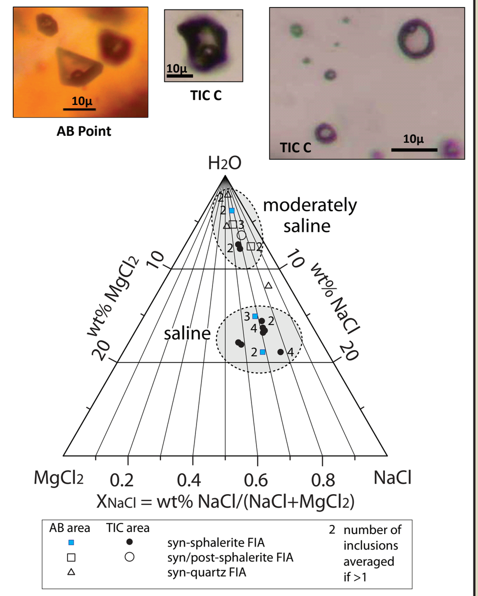
- The lower of two silty burrowed dolostone horizons is better mineralized.
- The lower ooid grainstone is mineralized, the upper is not.
- Sekwi Fm. is better mineralized than suitable rocks in the overlying formation.

Apparently, the rising fluid dumped its load in the first-encountered (structurally lowest) suitable horizon, and was depleted of minerals before it reached the upper horizon. Therefore, in the AB area, **suitable rock types cut by faults are mineralized only where they are the structurally lowest such rocks in the local succession.**

Results of the fluid inclusion study

Syn-sphalerite fluid inclusion assemblages (FIAs) are groups of inclusions that formed together from a homogeneous sample of fluid when the sphalerite crystal was precipitating (primary and pseudo-secondary FIAs). Syn-sphalerite FIAs containing three or more inclusions with a range of sizes were chosen for microthermometry. Some post-sphalerite (secondary) and syn-quartz FIAs were studied as well.

Most of these inclusions are dark, aqueous liquid-vapor inclusions with 5-10% vapor by volume. Most are ≤10 µm in diameter, ranging from ≤1 to 50 µm.



Fluid-inclusion salinity data in the H2O-NaCl-MgCl2 model system. Salinities clearly fall into two populations.

Freezing experiments

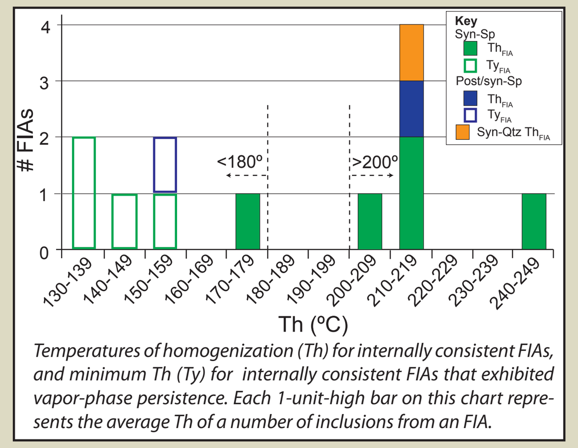
In most of the 49 inclusions large enough to freeze, the lowest-temperature melting events occurred between -55 and -40°C, suggesting the presence of $CaCl_2$ or $MgCl_2$ (Davis et al, 1990). Thirty-three inclusions from 18 FIAs provided both ice and hydrohalite melting temperatures, and therefore salinity. Salinities were calculated in two model systems, H_2O-NaCl-$CaCl_2$ (Oakes et al, 1990) and H_2O-NaCl-$MgCl_2$ (Dubois and Marignac, 1997). In all inclusions, hydrohalite melted before ice, indicating sub-eutectic salinities; and it melted within a narrow range of temperatures (-25.6 to -22.0°C), indicating a narrow range of concentrations for $CaCl_2$ or $MgCl_2$, irrespective of NaCl concentration (see figure, previous column).

The two populations of salinity indicate that two fluids participated in mineralization: a saline fluid (15-20 wt%$_{NaCl\ equiv}$) and a moderately saline fluid (2-8 wt%$_{NaCl}$).

Heating experiments

Temperature of homogenization (Th) is the minimum temperature of trapping. Heat-induced darkening and stretching prevented determination of Th for many inclusions.

Those that homogenized did so to the liquid phase, indicating that they were liquids when trapped. Some inclusions exhibited **vapor-phase persistence**, in which the vapor bubble became tiny on heating but failed to homogenize or change size with further heating. This behavior is atrributed to stretching induced by small amounts of dissolved volatiles. Ty, the temperature at which the bubble reaches its final tiny size, is consistent within each FIA and 5-50°C less than Th, based on bubble behavior in inclusions that did homogenize.



Temperatures of homogenization (Th) for internally consistent FIAs, and minimum Th (Ty) for internally consistent FIAs that exhibited vapor-phase persistence. Each 1-unit-high bar on this chart represents the average Th of a number of inclusions from an FIA.

The Th data define two groups, but given that Ty is 5-50°C less than Th, Ty must be corrected to plausible Th's. Two populations of Th exist if Ty is corrected by 5-25°C, but only one if Ty is corrected by 30-50°C.

Th of FIAs ranges from 174 to 241°C, and may define two populations although the data are equivocal. Ore-forming fluids were more than 174-241°C.

Applying Th consistency checks on each FIA

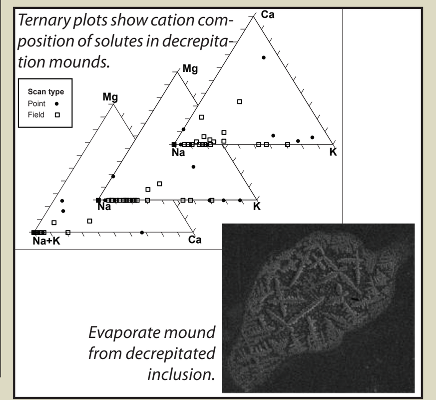
Post-entrapment modification of a fluid inclusion assemblage (FIA) is not always visually apparent, but will always be apparent as variability among the Th of component inclusions. It is therefore critical to check for such variability. If 90% of inclusions in an FIA have Th within 10°C of each other, the FIA is deemed unmodified (Goldstein and Reynolds, 1994).

That Th consistency check was applied to each FIA in this study. Most of them failed the test. For each of the five syn-sphalerite FIAs that passed, an average Th was calculated from its component inclusions. This ranged from 174 to 241°C with a mean of 211°C.

If the consistency check had not been applied and all 75 Th measurements from all 19 syn-sphalerite FIAs had been averaged, as per the standard approach, the mean Th would have appeared to be 19°C lower than it really was.

Fluid-inclusion solute cation compositions

Evaporate mounds formed by intentional decrepitation of fluid inclusions in sphalerite and galena from TIC were analyzed semi-quantitative by SEM-EDS. **The cation compositions of solutes form three populations: Na-rich, K>Na, and Na-, K-, Ca-, Mg-bearing with Na+K>Ca+Mg.**

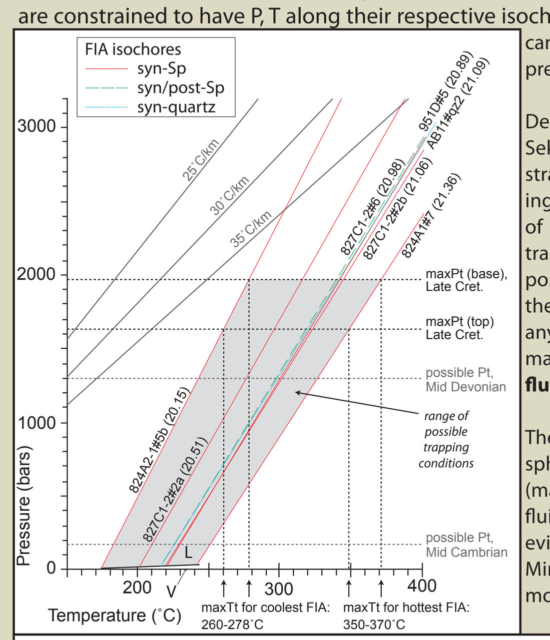


Ternary plots show cation composition of solutes in decrepitation mounds.

Evaporate mound from decrepitated inclusion.

Depth, pressure, and temperature of fluids at trapping

Fluid-inclusion densities can be calculated from Th and salinity (Bodnar, 2003). Densities can be used to construct isochores in P-T space (Bakker, 2003). Fluids trapped during mineralization are constrained to have P, T along their respective isochores. The temperature of trapping (Tt) can therefore be determined for any imagined pressure of trapping (Pt).



Isochores (lines of constant density in P-T space) for each internally consistent FIA in this study. Depths correspond to a pressure gradient of 303 bar/km. A geotherm of 25°C/km is typical of Phanerozoic orogens, whereas 35°C/km corresponds to modern measured heat flow under the northern Cordillera (Feinstein et al, 1996). Note that isochores do not intersect geotherms for any realistic pressure and temperature of trapping.

Depths of burial of the top and bottom of Sekwi Fm. over time were estimated from stratigraphic thicknesses (see figure in Building the model). The maximum possible depth of burial, 6.5 km, constrains the pressure at trapping (Pt) to have been <1970 bar. Three possible geothermal gradients are shown in the figure. None of the isochores intersect any of the geotherms at pressures below the maximum possible Pt, therefore **the trapped fluid must have been hydrothermal**.

The coolest fluid trapped in these syn-sphalerite FIAs was between 174°C and 268°C (maximum T at base of Sekwi Fm.). The hottest fluid was between 241°C and 370°C. Based on evidence for late mineralization (see Timing of Mineralization), the hotter temperatures are more likely.

Isotope studies and their implications in conjunction with other data

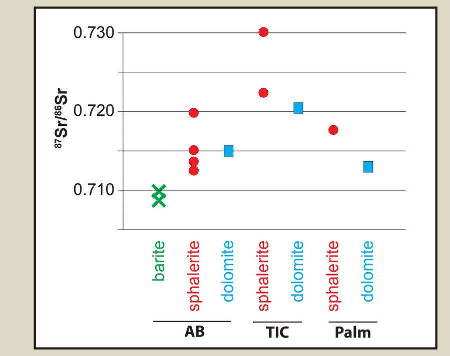
Evidence for interaction of fluids with basement

Strontium in sphalerite and dolomite at all showings is radiogenic to highly radiogenic ($^{87/86}$Sr of 0.713 to to 0.730).

→ **Implications:** Sr data indicate that the fluid that precipitated both sphalerite and dolomite resided in Precambrian basement beneath the Cordillera.

Fluid-inclusion cation compositions fall into three populations: Na-dominated, K>Na-dominated, and Na-K-Mg-Ca bearing dominated by Na-K (previous section).

→ The Na-dominated and K>Na fluid-inclusion populations formed among Na- and K-rich feldspars or clays, in this case probably felsic crystalline basement, and mixed partially with each other before rising to sites of precipitation. The Ca and Mg content of the third population suggests that during their rise, these fluids interacted with marine carbonate rocks in the overlying sedimentary pile.



Sr-isotope ratios for minerals from the AB, TIC, and Palm areas. Sphalerite ranges up to 0.730, the highest yet reported for the northern Canadian Cordillera. Highly radiogenic Sr is characteristic of tectonic provinces dominated by older graintes and gneisses (eg. Superior Province, 0.7295, Rae/Hearn 0.7248) whereas less-radiogenic Sr characterizes younger provinces (Gernville, 0.7151, Paleozoic 0.7117) (Faure and Mensing, 2005).

Evidence for two fluids

Two populations of salinity data, and possibly of Th data (previous section).

→ **Implications:** A moderately saline fluid and a saline fluid had partially mixed at the time of sphalerite precipitation.

Sr-isotope ratios of barite (0.7088-0.7100) are typical of a seawater or marine-carbonate source, and are much lower than those of sphalerite and dolomite (above), which are typical of a felsic crystalline or related clastic source.

$\delta^{18}O$ of the barite-precipitating fluid is calculated to be higher than $\delta^{18}O$ of the dolomite-sphalerite precipitating fluid at every temperature.

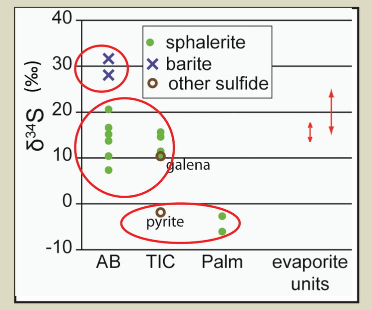
→ Sphalerite and dolomite were precipitated from a different fluid than barite, based on both Sr isotope ratios and $\delta^{18}O$.

$\delta^{34}S$ of sulfide minerals and of barite from AB (see Sources of sulfur, below) indirectly support the existence of two fluids that mixed without equilibrating before precipitation: one fluid containing SO_4 and TSR-derived H_2S, and another containing BSR-derived H_2S. TSR = thermochemical sulfate reduction. BSR = bacterial sulfate reduction.

Sources of sulfur and equilibration of oxygen isotopes

$\delta^{34}S$ isotope values for sulfide minerals range from mildly negative to moderately positive (-6 to +20 ‰). δ34S of barite in the AB area is +28.0 to 31.7 ‰. Potential sources of sulfate are Neoproterozoic evaporite units whose δ34S range from +14 to +25 ‰ (Turner, 2009; Straus, 1993), and seawater whose $\delta^{34}S$ has ranged from +12 to +30 ‰ since Sekwi time.

→ **The $\delta^{34}S$ data are best explained if the mineralizing fluid contained a mixture of H_2S** that had not attained isotopic equilibrium at the time of precipitation: **~20% H_2S from bacteriogenic sulfate reduction (BSR) in a closed system**, probably remobilized from diagenetic pyrite; and **~80% H_2S from incomplete, open-system thermochemical reduction (TSR) of SO_4** from Neoproterozoic evaporite rock or Cretaceous seawater. The mixing of sulfide into the SO_4-bearing fluid would permit fractionation of ^{34}S into heavier SO_4 in barite.



Measured $\delta^{18}O$ of a mineral can provide $\delta^{18}O$ of the fluid that precipitated it, if temperature and fractionation properties are known.

→ $\delta^{18}O$ data show that **both the dolomite- and barite-precipitating fluids had equilibrated with marine carbonate rock between 100 and 400°C**, but not with the same rocks, not the same fluid:rock ratio, not for the same amount of time, and/or not at the same temperature. Interaction of the dolomite-precipitating fluid with marine carbonate is supported by the presence of Mg and Ca in fluid-inclusion solutes in sphalerite.

Timing of mineralization - Evidence

Mineralization is associated with Cretaceous – Tertiary faulting at Palm and AB. In addition, a curvilinear zone of brecciation and mineralization in the AB area appears to cross-cut a Cretaceous/Tertiary fault.

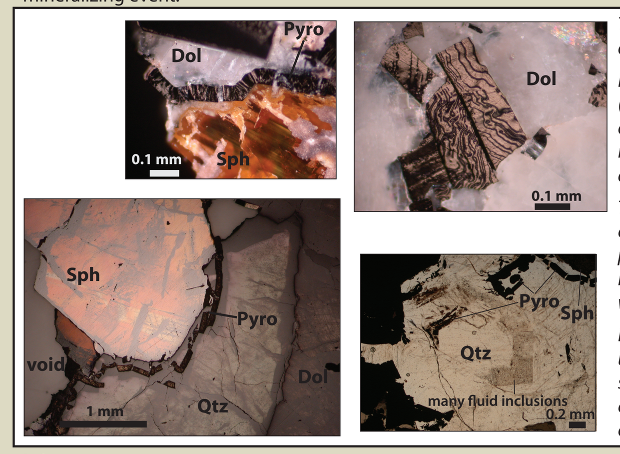
→ **Implications:** At least some mineralization was syn- or post-Cretaceous/Tertiary age at Palm, most AB showings, and possibly TIC.

One of the fluids involved was 135-217°C and geothermal (see Building the model, below). The maximum temperature comes from 6.5 km, the maximum depth of burial of the host unit under reasonable geothermal gradients of 25-35°C/km.

→ The depth at which the minimum temperature is achieved by burial under those gradients is 4-5 km. Stratigraphic thicknesses were used to determine that the host Sekwi Fm. was buried over 4 km deep between the Middle Devonian and the Late Cretaceous, therefore the age of mineralization falls within this time frame.

A pyrobitumen rind on sphalerite at the Point showing in the AB area spalled off and was captured between later dolomite crystals. Fragments retain their angular shapes, suggesting that no re-mobilization of pyrobitumen has occurred since spalling. At the same showing, pyrobitumen inclusions define a growth zone in quartz. Dolomite and quartz post-date the sphalerite but were part of the same mineralizing event.

→ Age of the Point mineralization is pre- or syn- hydrocarbon migration. The main migration in the Mackenzie Mountains was Late Devonian / Early Carboniferous (Morrow and Aulstead, 1995), which constrains the age of the Point showing if there was only the one migration.



Top left: Rind of pyrobitumen broken off sphalerite and trapped within a single quartz crystal.

Bottom left: Pyrobitumen rind on sphalerite (orange) has been disaggregated into straight-edged segments by intervening dolomite, and remains as stratight-edged segments within the dolomite (eg. top right).

Top right: Angular pieces of amorphous pleochroic pyrobitumen surrounded by dolomite. If pyrobitumen had invaded after dolomite formation, it would not have this angular shape, which is the shape of a piece of rind.

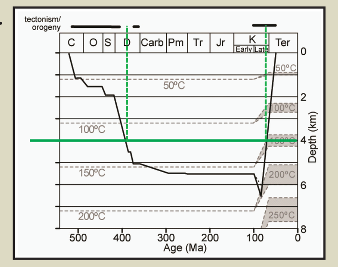
Bottom right: Growth zone in quartz is defined by pyrobitumen (black) and fluid inclusions, suggesting that quartz was syn- or post-hydrocarbon. Grain at top right is sphalerite with rim of pyrobitumen disrupted by quartz.

Building the model

One fluid was hydrothermal at time of trapping, 250-370°C (from Th, fluid densities, and burial history). This fluid must be the one that traversed basement and provided radiogenic Sr to sphalerite and dolomite. It will be called the deep fluid.

→ The other fluid must have been geothermal (by default) and therefore shallower. The maximum possible geothermal temperature at the base of the host Sekwi Fm., at its maximaum depth of burial of 6.5 km, was 217°C. The lowest possible temperature is the lowest inferred Th (Ty + 5°C), or 135°C, corresponding to a depth of about 4 km. The shallow fluid was therefore 135-217°C, and was trapped at depths of 4-6.5 km. The depth of trapping applies to both fluids, which mixed partially prior to trapping (see Evidence for two fluids).

By default the shallow fluid carried the marine-carbonate Sr that ended up in barite.



Depth of burial of base of Sekwi Fm. with time. Stratigraphic periods on top. Vertical green lines mark the time during which Sekwi was over 4 km deep.

The oxygen in dolomite and barite and therefore in the both the deep and shallow fluids had equilibrated isotopically with marine carbonate rocks.

Either fluid might have been the saline one. For the sake of argument, the shallow fluid was the saline one.

The deep fluid traversed the entire sedimentary/volcanic pile, therefore is the best candidate to have leached base metals.

Either fluid may have carried the required evaporitic or seawater sulfate; the requirement for the deep fluid to rise along faults and the presence of a potential source evaporite horizon along a major detachment surface makes it more likely that the deep fluid carried the sulfate.

→ Either fluid may have carried the required component of BSR-derived H_2S, but limited indirect evidence suggests this H_2S was not in the same fluid as SO_4.

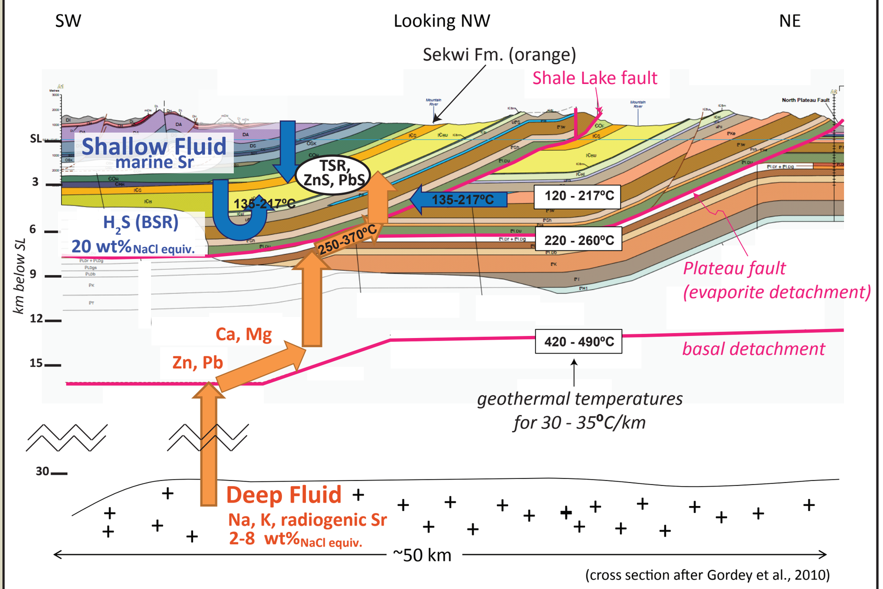
Deposit model

A saline connate geothermal fluid equilibrated with marine carbonate rock, possibly Sekwi Fm., at ~150°C and 4-6 km depth. It dissolved diagenetic pyrite produced by bacterial sulfate reduction (BSR) while traversing the sedimentary pile.

A deep fluid resided in the basement where it acquired Na, K, radiogenic Sr, and a high temperature. It began to move upward through a network of faults and fractures activated by deformation in the Late Cretaceous. As it rose, it lost heat and acquired metals from the overlying shales, Ca and Mg from carbonate rocks, and eventually sulfate from a Neoproterozoic evaporite horizon that accommodated the Plateau Fault detachment. The deep fluid was 250-370°C and hydrothermal when it was trapped in Sekwi Fm. at 4-6 km depth. The deep fluid was under pressure, and penetrated reactive carbonate horizons by hydraulic fracturing and dissolution.

Sulfate was reduced by thermochemical sulfate reduction (TSR), perhaps on encountering the shallow fluid, whose BSR-produced H_2S was able to jump-start the reaction. The presence of abundant sulfide in the metal-rich fluid triggered precipitation of metal sulfides. There is little evidence of what the reductant was; it may have been organic matter in the local strata or hydrocarbons that left no trace, however the measured organic carbon in host strata is low and there is no evidence of hydrocarbons in syn-sphalerite fluid inclusions.

This process creates Zn-Pb deposits that are concentrated in the lowest available horizons of differentially reactive rock types, near fractures that were fluid conduits.



Geological cross-section of the central Mackenzie Mountains. A basal detachment is inferred to lie within the sedimentary cover 14 km deep. The Plateau fault detachment follows a Neoproterozoic evaporite horizon (white) at 7 km depth. Numerous subordinate faults are not shown.

Temperature ranges at three depths are shown for gradients of 30 and 35°C/km. Blue arrows are alternative routes for the shallow fluid, assumed to be moderately saline and to have picked up diagenetic pyrite (BSR-derived sulfide). Orange arrows depict the deep fluid, assumed to be saline and to have dissolved sulfate while traversing the Neoproterozoic evaporite horizon. Blue and orange letters denote other fluid components.

Conclusions

- ★ **Proximity to faulting is a first-order structural control on carbonate-hosted Zn-Pb deposits in the Sekwi Fm.**
- ★ **Lithology is a second- and locally a third-order control: rock types that are preferentially mineralized have a high proportion of carbonate minerals, and mm- to cm-scale variations in mineralogy and texture (eg. grainstone, rudstone, silty dolostone).**
- ★ **A second-order stratigraphic control is locally evident: the structurally lowest potential host rocks in the local succession are better mineralized than similar rocks at structurally higher levels.**
- ★ **The age of most of the mineralization is Cretaceous-Tertiary, but one showing may have formed in the Late Devonian or Early Carboniferous. There is no reason to believe that all the carbonate-hosted Zn-Pb showings in the Sekwi Fm., or the Mackenzie Mountains, formed during a single event.**
- ★ **Mineralizing fluids were hotter than previously reported for these deposits, ranging up to 250-350ºC.**
- ★ **The deposit model: A saline geothermal connate fluid or modified Cretaceous seawater equilibrated isotopically at 150°C with marine carbonate rock, perhaps the host Sekwi Fm. A moderately saline fluid rose from its hot basement reservoir 30 km deep, along faults activated during Cretaceous orogeny, leaching metals from the overlying sedimentary pile. It dissolved sulfate while traversing a major detachment along a Neoproterozoic evaporite horizon 7 km deep, during which time it equilibrated thermally with its surroundings at 250-350ºC. Rising farther along faults, this fluid encountered the shallow fluid at about 4-6 km depth within Sekwi Fm, where TSR of evaporitic sulfate led to metal-sulfide precipitation in hydrothermally enhanced pores of susceptible host rock.**
- ★ **Carbonate-hosted Zn±Pb deposits throughout the Mackenzie Mountains should be sought near ramping thrusts or their splays, preferably in upper Sekwi Formation where it has been dolomitized and disrupted by multiple steep faults. The most prospective horizons are the structurally lowermost local occurrences of susceptible rock types.**
- ★ **Determinations of fluid temperature from microthermometry are suspect if fluid inclusion assemblages (FIAs) are assumed to be unmodified based on visual checks alone. The consistency of Th within each FIA must be verified, and data from inconsistent FIAs rejected so they do not skew the results.**

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