J.M. Magnall[1], S.A. Gleeson[1], S. Paradis[2], and N.J.F. Blamey[3]

MacMillan Pass SEDEX Mineralisation: The Geochemical Characterization of a Vent Complex

[1]Magnall, J.M., [1]Gleeson, S.A., [2]Paradis, S. and [3]Blamey, N.J.F.

[1]University of Alberta, Department of Earth and Atmospheric Sciences, 1-26 Earth Sciences Building, Edmonton, Alberta, T6G 2E3, Canada
[2]Geological Survey of Canada, Box 6000, 9860 West Saanich Road, Sidney, British Columbia, V8L 4B2, Canada
[3]New Mexico Tech, Department of Earth and Environmental Science, 801 Leroy Place, Socorro, NM 87801, USA

INTRODUCTION:

*Sedimentary exhalative (SEDEX) mineralisation in the Selwyn Basin occurs during 3 time intervals in the Cambrian, Silurian and Late Devonian (Goodfellow and Lydon, 2007). Rift-related magmatism is suggested to occur during each period (Goodfellow et al., 1995; Goodfellow, 2007), however its relationship with mineralisation is unconstrained. The Tom, Jason and Nidd deposits are located in the MacMillan Pass district, Yukon Territory (**Figure 1**). They are hosted within Late Devonian Selwyn Basin strata of the Lower Earn Group, Portrait Lake Formation (**Figure 2**). All 3 deposits display evidence of a vent complex, which represents the focused zone of hydrothermal upflow. The overlying stratabound mineralisation (not present at Nidd) forms the primary contribution to an inferred total resource (Pb+Zn) of 13.5 Mt and 11 Mt at Tom and Jason respectively (Scott Wilson RPA, 2007). Although only a relatively small resource compared to the world-class deposits of Red Dog (165Mt), Sullivan (162) and Howard's Pass (120Mt) (Goodfellow and Lydon, 2007), the MacMillan Pass deposits display the only vent complexes that are well preserved in the geological record. The results presented here are the first to record the geochemical signature of a vent complex, and provide valuable information on some of the processes that contribute to the formation of this deposit-type.*

Figure 1. Regional geological setting of the Selwyn Basin and location of MacMillan Pass. *Modified from Gordey and Anderson, 1993; Goodfellow, 2007; Nelson and Colpron, 2007.*

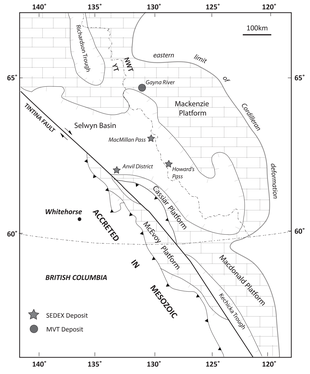
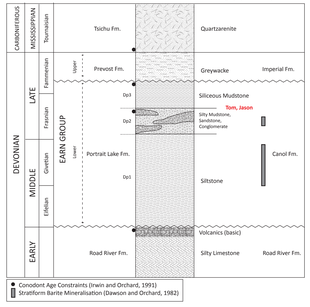


Figure 2. The stratigraphy of Earn Group strata at MacMillan Pass. Mineralisation is hosted within siliceous mudstones and siltstones with coarser grained sandstones and conglomerates immediately underlying.



Acknowledgements: this work is part of a PhD project funded by the Geological Survey of Canada, TGI-4 initiative. We would like to express appreciation to Teck Resources and Hudson Bay Mineral Company for respective access to Nidd and Tom drill core. Neil Fernandes, Bob Sharp and Sarah Gleeson are thanked for collecting samples from Nidd. Steve Taylor (Stable Isotope Laboratory, University of Calgary) performed the isotope analyses. Discussions with Jan Peter and Daniel Layton-Matthews provided valuable insight for the interpretation of the bulk geochemistry data.

SAMPLES:

Samples were obtained from 1 single drill-core (NB84-10; **Figure 3**) at Nidd and 6 (TYK001, TYK002, T91-14, TU-71, TU-70, TU-68; **Figure 4**) at Tom. At Tom, samples displaying stock work style veining, located beneath the stratabound sulphides were targeted. In contrast the mineralisation at Nidd displays no overlying sulphides (not preserved / ever formed), is more discrete, and host rocks (mudstones, conglomerates) are less intensely altered.

ANALYTICAL TECHNIQUES:

Ore and gangue minerals were identified following examination of polished thin sections under transmitted and reflected light. Cathodoluminescence (CL), backscatter electron (BSE) imaging and electron probe microanalysis (EPMA) were used to determine timing relationships. Stable isotopes (carbon and oxygen) were analysed at the University of Calgary, Stable Isotope Lab (1σ = 0.25‰; $\delta^{13}C$ + $\delta^{18}O$). Quantitative fluid inclusion gas analysis was performed using the incremental crush fast scan method (mass spectrometry) described by Blamey (2012). Samples were sent to Actlabs (Ancaster, Ontario) for bulk geochemistry analysis (method 4E research). SiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, TiO_2 and P_2O_5 were analysed by FUS-ICP. Trace elements were analysed by FUS-ICP / MS or INAA, and rare earth elements by FUS-MS.

Figure 3. *A and B (Nidd, 349m)* - hand sample of carbonate altered conglomerate cut by vuggy quartz, siderite and sphalerite vein. This is the vein from which fluid inclusions were sampled for. *C (Nidd, 287m)* - high grade stockwork style veining (stage 2 assemblage) hosted by mudstone.

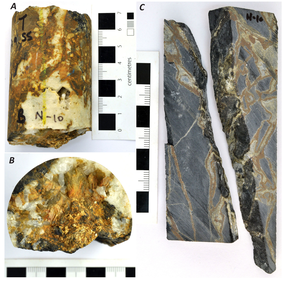
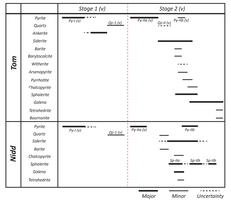


Figure 4. *A (TYK002; 45.8m) and B (TYK002; 48.55m)* - stockwork ankerite veining and alteration from the vent at Tom. Host mudstone is heavily pyritized and overprinted by later galena (see lower half of *A*).

Figure 5. Mineral paragenesis of vent complex mineralisation at Tom and Nidd.



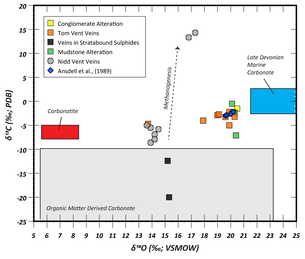
RESULTS - PETROGRAPHY:

there are 2 clear stages to mineralisation at Nidd and Tom (**Figure 5**). The first, characterized by ankerite alteration, is pervasive at Tom (much less so at Nidd), and associated with an early generation of quartz and pyrite. The main sulphide deposition occurs in stage 2, clearly overprinting stage 1. Importantly, the volumetric contribution of stage 1 within the vent is far greater than stage 2. It is possible that earlier fluid inclusion studies (Ansdell et al., 1985) analysed samples from the earlier stage, and so may not provide information on the temperature and salinity of the fluid responsible for mineralisation.

STABLE ISOTOPES:

carbon and oxygen isotopes (carbonate; n=24) from the vent and alteration at Tom and Nidd display greater variation (**Figure 6**) than previously documented (Ansdell et al., 1985). There are two groups of data; the first displays distinct ^{13}C signatures that record different stages in the diagenesis of organic matter. The negative values ($\delta^{13}C$ = -20‰ and -12.4‰) are typical of carbonate derived from CO_2 produced during sulphate reduction of organic matter, whereas the positive values ($\delta^{13}C$ = 13.3‰ and 14.3‰) are more typical of fermentation of organic matter (Irwin et al., 1977). This latter process occurs when sulphate reductions stops, and produces a large fractionation resulting in ^{13}C-rich CO_2.
The second group of data does not fall definitively into any particular reservoir. They display a narrower range of $\delta^{13}C$ (-0.5‰ to -8.6‰) and greater variability ^{18}O (VSMOW; 13.6‰ to 20.5‰). The trend towards lower $\delta^{18}O$ values could represent a change in the temperature of the hydrothermal fluid, or interaction of the fluid with lithologies of contrasting isotopic composition.

Figure 6. Oxygen vs carbon isotope plot for samples from the hydrothermal vent, carbonate alteration, and carbonate veins in overlying sulphides. Boxes are defined by Valley (1986) for carbonatite, Veizer et al., (1999) for Late Devonian marine carbonate, and Longstaffe (1989) for organic matter derived carbonate.



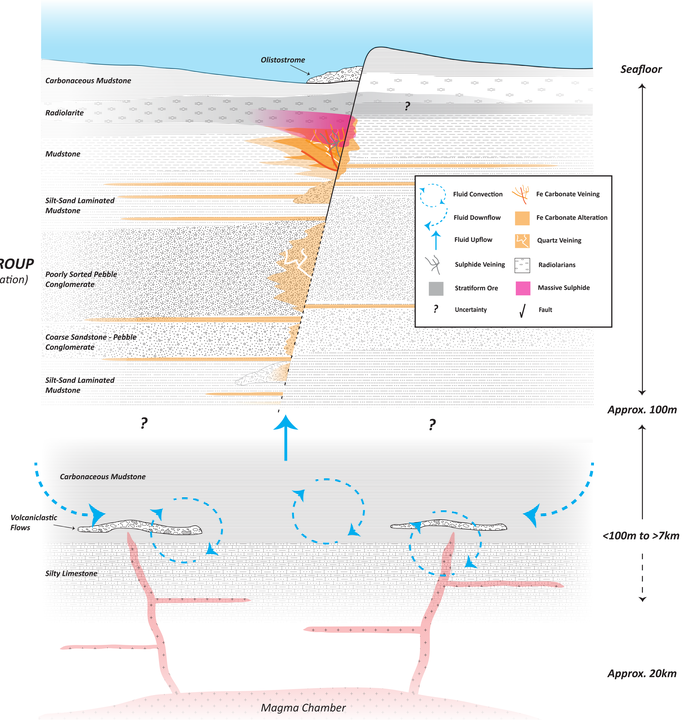


Figure 7. Schematic diagram of the vent complex at Tom, its position in the stratigraphy, and the associated alteration. In terms of lithology, alteration and vent morphology, the upper half (top 100m, approx.) is well constrained by drill-core. In the lower half, there is uncertainty relating to the lithology at depth, hydrothermal fluid circulation (as indicated by blue arrows) and the role of magmatic activity. This has been inferred according to the geochemistry of the vent (presented here) and the lithological position of volcaniclastic sediments and dykes; Goodfellow et al., 1984; Abbott and Turner, 1990). A 4°C / 100m geothermal gradient (back-arc setting; Morley, 2001) has been used to approximate depth of hydrothermal fluid circulation, based upon the magnitude of the Eu/Eu* anomaly (Sverjensky, 1984).

REFERENCES: ***Abbott, J.G., and Turner, R.J.W., 1990.*** Character and Paleotectonic Setting of Devonian Stratiform Sediment-Hosted Zn-Pb-Barite Deposits, Macmillan Fold Belt, Yukon: in Abbott, J.G., and Turner, R.J.W., eds., Mineral deposits of the northern Canadian Cordillera: Ottowa, International Association on the Genesis of Ore Deposits, Eighth Symposium, Field Trip 14 Guidebook, p. 99-136. ***Ansdell, K.M., Nesbitt, B.E., and Longstaffe, F.J., 1985.*** A fluid inclusion and stable isotope study of the Tom Ba-Pb-Zn deposit, Yukon Territory, Canada: Economic Geology, v. 84, p. 841-856. ***Beaudoin, G., and Molloy, P., 1992.*** Rare Earth Element Fractionation in Metamorphogenic Hydrothermal Calcite, Magnesite and Siderite: Mineralogy and Petrology, v. 45, p. 231-246. ***Blamey, N., and Norman, D., 2002.*** New Interpretations of Geothermal Fluid Inclusion Volatiles: Ar/He and N2/Ar Ratios — A Better Indicator of Magmatic Volatiles, and Equilibrium Gas Geothermometry. Proceedings, Twenty-seventh Workshop of Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 28-30, 2002, p. 188-197. ***Blamey, N.J.F., 2012.*** Composition and evolution of crustal, geothermal and hydrothermal fluids interpreted using quantitative fluid inclusion gas analysis: Journal of Geochemical Exploration, v. 116-117, p. 17-27. ***Carne, R.C., 1979.*** Geological setting and stratiform lead-zinc barite mineralisation, Tom Claims, Macmillan Pass, Yukon Territory: Canada, Department of Indian and Northern Affairs, Report EGS 1979-4, 30 p. ***Cook, N.J., Ciobanu, C.L., Pring, A., Skinner, W., Shimizu, M., Danyushevsky, L., Saini-Eidukat, B., Melcher, F., 2009.*** Trace and minor elements in sphalerite: A LA-ICPMS study: Geochimica et Cosmochimica Acta, v. 73, p. 4761-4791. ***Dawson, K.M., and Orchard, M.J., 1982.*** Regional metallogeny of the northern Cordillera: biostratigraphy, correlation and metallogenic significance of bedded barite occurrences in eastern Yukon and western District of Mackenzie: in Current Research, Part C, Geological Survey of Canada, Paper 82-1c, p. 31-38. ***German, C.R., Klinkhammer, G.P., Edmond, J.M., Mitra, A., and Elderfield, H., 1990.*** Hydrothermal scavenging of rare-earth elements in the ocean: Nature, v. 345, p. 516-518. ***Goodfellow, W.D., and Lydon, J.W., 2007.*** Sedimentary Exhalative (SEDEX) Deposits, in Goodfellow, W.D., ed., Mineral Deposits of Canada: A Synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 755-791. ***Gordey, S.P., and Anderson, R.G., 1993.*** Evolution of the northern Cordilleran miogeocline, Canada: Cordilleran Tectonics workshop, Lithoprobe Report 31, p. 49-51. ***Large, D.E., 1992.*** Geology and genesis of the Red Dog massive sulfide deposit, Brooks Range, Alaska: Economic Geology and the Bulletin of the Society for Economic Geologists, v. 87, p. 520-557. ***Longstaffe, F.J., 1989.*** Stable isotopes as tracers in clastic diagenesis: Short course in burial diagenesis: In: Hutcheon IE, (ed) Mineral Association of Canada Short Course, p. 201-284. ***McDonough, W.F., and Sun, S.-s., 1995.*** The composition of the Earth: Chemical Geology, v. 120, p. 223-253. ***McLennan, S.M., 2001.*** Relationships between the trace element composition of sedimentary rocks and upper crust: Geochemistry, Geophysics, Geosystems, v. 2. ***McLennan, S.M., 1989.*** Rare earth elements in sedimentary rocks; influence of provenance and sedimentary processes: Reviews in Mineralogy and Geochemistry, v. 21, p. 169-200. ***Morley, C.K., 2001.*** Combined escape tectonics and subduction rollback-back arc extension: a model for the evolution of Tertiary rift basins in Thailand, Malaysia and Laos: Journal of the Geological Society, London, v. 158, p. 461-474. ***Nelson, J., and Colpron, M., 2007.*** Tectonics and metallogeny of the British Columbia, Yukon and Alaskan Cordillera, 1.8Ga to the present, in Goodfellow, W.D., ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 755-791. ***Norman, D.I., and Musgrave, J.A., 1994.*** N2-Ar-He compositions in fluid inclusions: Indicators of fluid source: Geochimica et Cosmochimica Acta, v. 58, p. 1119-1131. ***Sverjensky, D. A., 1984.*** Europium redox equilibria in aqueous solution: Earth and Planetary Science Letters, v. 67, p. 70-78. ***Tornos, F., and Heinrich, C.A., 2008.*** Shale basins, sulfur-deficient ore brines and the formation of exhalative base metal deposits: Chemical Geology, v. 247, p. 195-207. ***Valley, J. W., 1986.*** Stable Isotope Geochemistry of Metamorphic Rocks: Stable Isotopes in High Temperature Geological Processes, Reviews in Mineralogy, v. 16, p. 445-486. ***Veizer, J., Ala, D., Azmy, K., Bruckschen, P., Buhl, D., Bruhn, F., Carden, G. A. F., Diener, A., Ebneth, S., Goddéris, Y., Jasper, T., Korte, C., Pawellek, F., Podlaha, O. G., and Strauss, H., 1999.*** 87Sr/86Sr, δ13C and δ18O evolution of Phanerozoic seawater: Chemical Geology, v. 161, p. 59-88. ***Yardley, B.W.D., 2005.*** Metal Concentrations in Crustal Fluids and Their Relationship to Ore Formation: Economic Geology, v. 100, p. 613-632.

RESULTS - FLUID INCLUSIONS:

Quartz (Figure 3A; Qz-I and II - **Figure 5**) within the vent at Nidd was targeted for bulk gas analysis. The dominant inclusion assemblage is primary in origin, contains a CO2-rich fluid, and inclusions that display variable phase proportions suggest fluid boiling probably occurred (**Figure 8A**, inset). N2-Ar-He compositions provide useful discriminators for the sources of gaseous phases in fluid compositions (Norman and Musgrave, 1994). Meteoric waters tend to display N_2/Ar ratios typical of equilibration with the atmosphere (approximately 38), whereas magmatic systems are orders of magnitude greater (100s to 1000s; Giggenbach, 1996). Although the breakdown of organic matter can produce enrichments of N_2 in amagmatic fluids, they can be discriminated against using the Ar/He ratio (Blamey and Norman, 2002). The Nidd samples (**Figure 8**) fall within the box defining calc alkaline magmatism (see Blamey and Norman, 2002; using data reported by Giggenbach, 1996).
This represents the first reported magmatic signature in a SEDEX system and raises the question over whether magmatism may have contributed volatile components (CO_2, SO_2, H_2S, HCl) to the hydrothermal fluid. At the very least, magmatic activity will have increased the geothermal gradient and promoted the circulation of hydrothermal fluids.

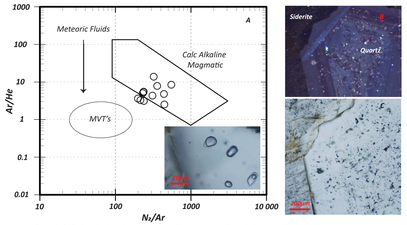
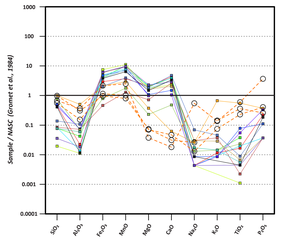


Figure 8. *A* - N_2/Ar vs Ar/He plot for samples from Nidd (see *figure 2A and B*). Figure inset is a typical fluid inclusion assemblage, with 2 and 3-phase CO_2-rich inclusions (plot adapted from Blamey, 2012). *B and C* - cathodoluminescence (CL) and transmitted light images of fluid inclusion wafer. Primary inclusions within this generation of quartz (Qz-II, see mineral paragenesis - *figure 2D*) are hosted within growth zones picked out in CL light (*B*).

Figure 9. Major elements normalised to the North American Shale Composite defined by Gromet et al., (1984). Solid coloured squares and lines represent samples from Tom; empty circles and dashed orange lines are samples from Nidd.



RESULTS - BULK ROCK GEOCHEMISTRY:

Major Elements: enrichments in Fe_2O_3, CaO, MgO and MnO (**Figure 9**) demonstrate the extensive carbonate alteration observed within the vent at Tom. This is not seen at Nidd. All vent samples display some degree of depletion in SiO_2, Al_2O_3, Na_2O, K_2O, TiO_2 and P_2O_5. This may represent the leaching of some major cations from the host rock during the buffering of an acidic fluid (Yardley, 2005).

Trace Elements: within vent samples, trace element enrichments (**Figure 10**) are largely controlled by minor mineralogical components. Ag and Sb are likely hosted by sulphosalts (tetrahedrite-tennanite), As and Cu by arsenopyrite and chalcopyrite, and Cd as a trace element within pyrite and galena. Hg and In can be partitioned into sphalerite (Cook et al., 2009), but along with Au, a mineral host remains unconstrained. The source of these trace elements remains a key question; rift clastics have been speculated as the source of base metals in these systems (Goodfellow, 2007). However black shales have also received attention both as a source and trap for metals (Tornos and Heinrich, 2008).

Figure 10. Trace elements within the vent normalised to upper crustal values defined by McLennan (2001). Coloured crosses are samples from Tom; solid grey line = mean. Orange squares are samples from Nidd; solid orange line = mean.

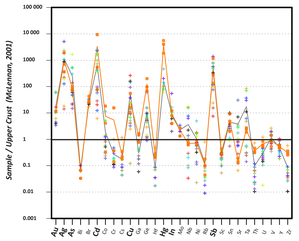
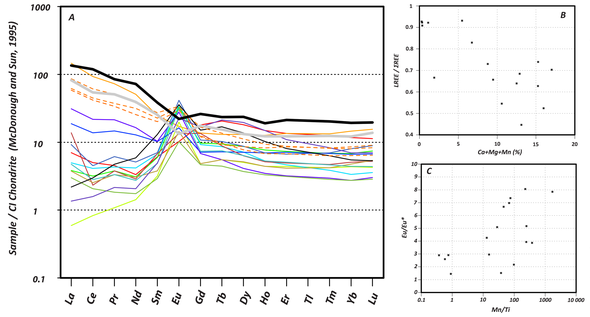


Figure 11. *A* - rare earth elements (REE) of vent samples normalised to chondrites (CI; McDonough and Sun, 1995). Solid coloured lines represent Tom samples; dashed orange lines are samples from Nidd. *B* - sum of light REE (LREE; La to Gd) / sum of total REE vs. total calcium, magnesium and manganese. This demonstrates control of carbonates in fractionating LREE. *C* - Europium anomaly vs. Mn / Ti. Higher Mn/Ti ratios correlate broadly with increasing Eu/Eu*. Europium anomaly defined as $Eu/Eu^* = Eu^* / (Sm^n \times Gd^n)^{0.5}$ by McLennan (1989)



CONCLUSIONS:

The chemistry of the hydrothermal fluid appears to be controlled by processes operating at both deep and shallow levels in the hydrothermal system:

DEEP: *positive Eu/Eu* anomaly suggests the hydrothermal fluid reached high temperatures (>250°C), perhaps infiltrating strata >7km depth.*

Fluid inclusion gas ratios may record the first real magmatic signature in a SEDEX system.

SHALLOW: *Carbon isotopes record organic matter decay within sediments undergoing early and late diagenesis.*

Negative Ce/Ce anomaly indicates the hot, deep fluid could have mixed with an oxidising fluid.*

[1]University of Alberta, Department of Earth and Atmospheric Sciences, 1-26 Earth Sciences Building, Edmonton, Alberta T6G 2E3
[2]Geological Survey of Canada, Box 6000, 9860 West Saanich Road, Sidney, British Columbia V8L 4B2
[3]New Mexico Tech, Department of Earth and Environmental Science, 801 Leroy Place, Socorro, New Mexico 87801

For more information, please contact S. Paradis (suzanne.paradis@canada.ca)

Publications in this series have not been edited; they are released as submitted by the author.
© Her Majesty the Queen in Right of Canada, as represented by the Minister of Natural Resources, 2017
For information regarding reproduction rights, contact Natural Resources Canada at nrcan.copyrightdroitdauteur.rncan@canada.ca.

doi:10.4095/300892
This publication is available for free download through GEOSCAN (http://geoscan.nrcan.gc.ca/).

Presented at Minister 2013: Geoscience for Discovery
Date presented: September 24-27, 2013

Recommended citation:
Magnall, J.M., Gleeson, S.A., Paradis, S. and Blamey, N.J.F., 2017. Macmillan Pass, Yukon SEDEX mineralization: The geochemical characterization of a vent complex: Geological Survey of Canada, Scientific Presentation 58, 1 poster. doi:10.4095/300892