# The Sullivan Deposit and its Geological Environment: The Sullivan Project

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The Sullivan Project is a collaborative effort between Cominco Ltd., the Geological Survey of Canada and the British Columbia Geological Survey Branch, to document the geological and geochemical details of the Sullivan deposit for the public record, and to provide a more detailed understanding of its geological environment by carrying out specialist studies. For the purpose of the project, Cominco Ltd. made available all its mining and exploration records since it acquired the Sullivan deposit in 1910 (summarized by Hamilton *et al.*, 1982, 1983), and this information provided a starting point for the specialist studies.

Some current thinking on the Sullivan deposit and its setting that may be of interest to the mineral deposits fraternity are summarized below. The full results of the Sullivan Project will be released as a GSC Bulletin during 1996.

## Tectonic Setting

Turbidites of the Aldridge Formation, which host the Sullivan deposit, represent the fill sequence of a north trending Middle Proterozoic rift (Höy). Up to 30% of the turbidite sequence consists of the tholeiitic Moyie sills (Fig. 1), which were emplaced before significant consolidation of the sediments (Höy) and are related to the rifting process. Basinal analysis of the Belt-Purcell Supergroup (Chandler) and petrochemistry of the Moyie Sills (Anderson) indicate that the rift was intracontinental and formed in response to crustal extension rather than in response to a thermal plume in the asthenosphere.

Stratigraphic analysis (Höy) shows that synsedimentary tectonism was expressed as northerly-trending border faults (Fig. 1) and easterly to northeasterly trending transfer faults, of which the Kimberley and St Mary Faults (Fig. 2) are examples, though they have been repeatedly reactivated since the Proterozoic.

## Environment

Several lines of evidence indicate that Aldridge sediments accumulated in a marine environment:

- i) Sedimentological evidence of tidal action in laterally equivalent and overlying strata (Chandler).
- ii) High sulphur contents and high S/C ratios of Aldridge sediments indicate high sulphate contents of sediment pore waters and, therefore, marine conditions (Goodfellow).
- iii) Boron isotopes of tourmalinite bodies in Aldridge rocks indicate the boron was leached from marine sediments (Palmer, Jiang).

Widespread lagoonal or lacustrine conditions did not develop until higher in the Purcell stratigraphy during the Creston through Dutch Creek formations, which represent the rift sag (rift cover) sequence (Chandler, Höy). Sabkha evaporites in units correlative with the Aldridge formation indicate a hot and relatively dry climate (Chandler).

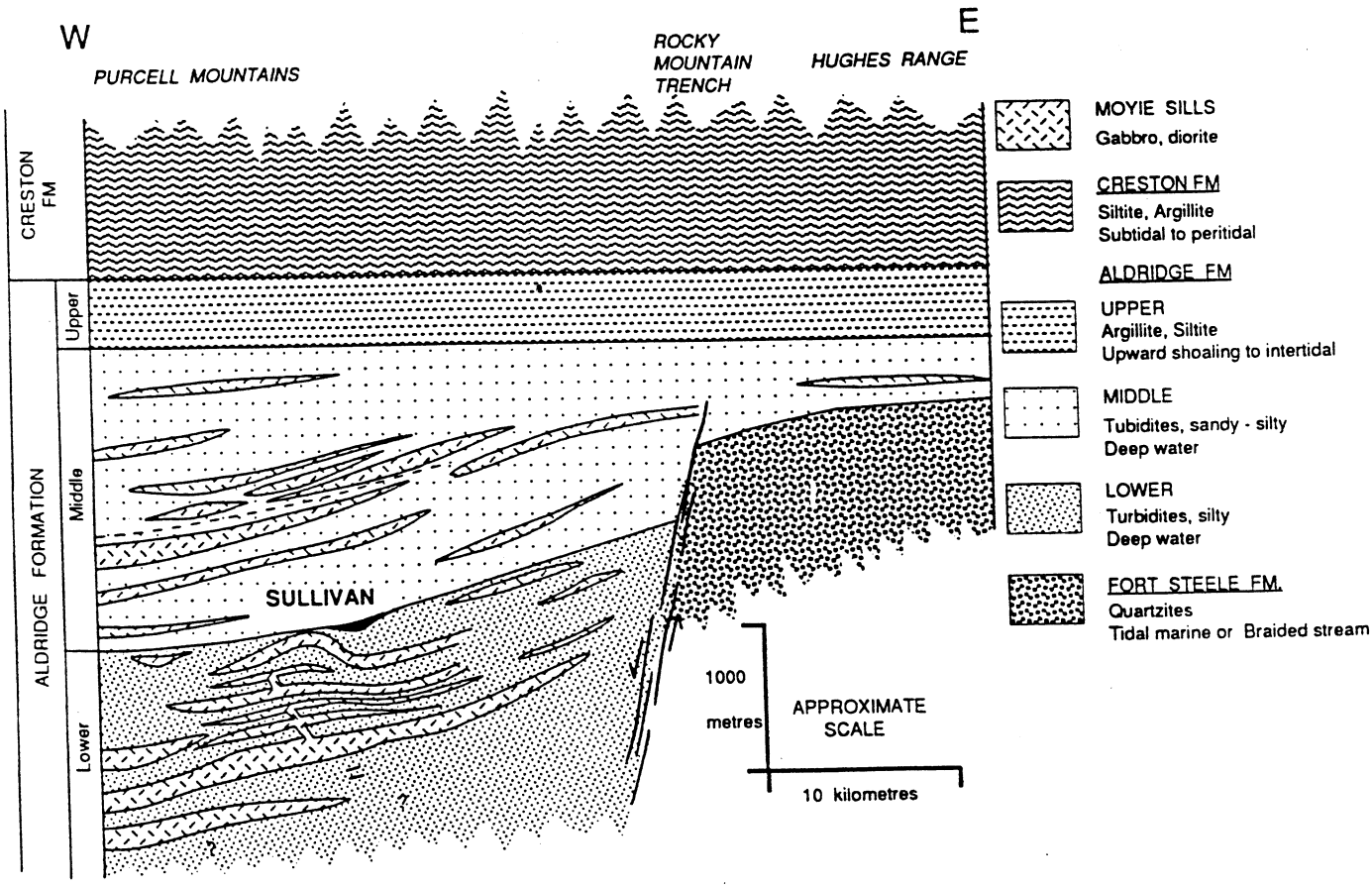


*Figure1. Semi-schematic restored section across the Purcell anticlinorium showing the setting of the Sullivan deposit in relation to major geological features of the Aldridge Formation and the stratigraphically equivalent (in part) Fort Steele Formation. The north trending border faults of the Aldridge rift coincide with the Rocky Mountain Trench. The Sullivan deposit is close to the axial zone of the rift where the cumulative thickness of Moyie Sills is at a maximum.*

## Siting Of Sullivan Deposit

The Sullivan deposit occurs at the intersection of the north trending axial(?) zone of the rift and a transfer fault (proto-Kimberley fault). The axial(?) zone was the locus of maximum heat flow and hydrothermal upflow as evidenced by:

- i) concentration of tourmalinite occurrences in Aldridge-Pritchard strata (Slack).
- ii) concentration of Aldridge Zn-Pb occurrences (Höy, Turner).
- iii) maximum cumulative thickness of Moyie sills (Höy, Turner).
- iv) a synsedimentary tectonic lineament and zone of hydraulically disrupted sediments - the Sullivan Corridor (Fig.2) (Turner, Höy)
- v) Proterozoic felsic intrusions.

## The Sullivan Deposit

The Sullivan deposit contained 170 mt of ore with a grade of 5.5% Zn, 5.8% Pb and 59 g/t Ag. About 70% of the ore was contained in a massive pyrrhotite-galena-sphalerite vent complex that overlies a heavily tourmalinized hydrothermal upflow zone. The remaining 30% of the ore occurred in concordant laminated pyrrhotite-sphalerite-galena "Ore Bands" that extends eastwards from the vent complex (Cominco).

Towards the south-east there is a progressive increase in the abundance of pyrite and magnetite and an increase in the relative proportion of sphalerite compared to galena (Cominco). "Waste Bands" of argillite that separate the Ore Bands are gravitationally settled slurried mudflows, and represent either mud volcano products, comparable to the extruded "Footwall Conglomerate" unit, or slumped seafloor muds (Ransom, Lydon).

Post-burial hydrothermal flow-through has caused replacement of pyrrhotite-galena-sphalerite by pyrite-carbonate-chlorite in the south-central part of the vent complex and along the Kimberley fault, and produced an overprinting of albite-chlorite that is most conspicuous in the hanging wall of the vent complex (Cominco). Early manganiferous sediments and bedded sulphide clasts in the Waste Bands indicate at least a component of seafloor metalliferous sedimentation (Ransom, Lydon).

Stable isotope support for a brine pool mode of genesis includes oxygen isotope data on dolomite and kutnohorite (Mn-dolomite) indicating formation from seawater at 150°C-225°C (Taylor) and distinctive stratigraphic sulphur isotope (Cominco, Taylor) and carbon isotope (Taylor) patterns that suggest a water column, rather than a diagenetic, reaction process. Post-burial modifications to the deposit complicate the evidence and arguments in the scientific debate on the subsurface replacement versus sedimentary sulphide genetic models for the ores.

Metamorphic recrystallization and tectonically-induced mechanical and chemical remobilization have obliterated primary textural features and blurred the original extent of the sulphide body (Del Bel Belluz, Lydon, Paakki). Metasomatic subsurface zone refinement during ore deposition and post-burial hydrothermal alteration has modified most geochemical signatures (Lydon, Paakki).

## Metamorphism

Silicate-carbonate fluid equilibria indicate a metamorphism at 450°C and 3.8 kbar (De Paoli and Pattison), and is textural/structurally consistent with a Proterozoic metamorphism. Sphalerite geobarometry/geothermometry is consistent with a Laramide metamorphism of 375°C and 4.5 kbar (Lydon, Reardon).

## Timing of Thermal & Hydrothermal Events

Sulphides of the vent complex are cut by gabbro apophyses of the Mine Sill, a Moyie Sill that cross-cuts the tourmalinite alteration pipe. U/Pb dating of zircons from Moyie sills from both the Lower and Middle Aldridge Formations give the same ages within the tange 1467±3 Ma (Anderson, Davis, Schandl), apparently indicating that the emplacement of all sills took place within a time span of 6 Ma, and before consolidation of turbidites of at least the Middle Aldridge (Höy).

U/Pb dating of titanite from Moyie Sills give ages in the 1050 Ma - 1100 Ma range (Anderson) , and presumably corresponds to a peak of Proterozoic metamorphism. Pb/Pb dating of titanite associated with chloritic alteration at Sullivan gives an age near 1330 Ma

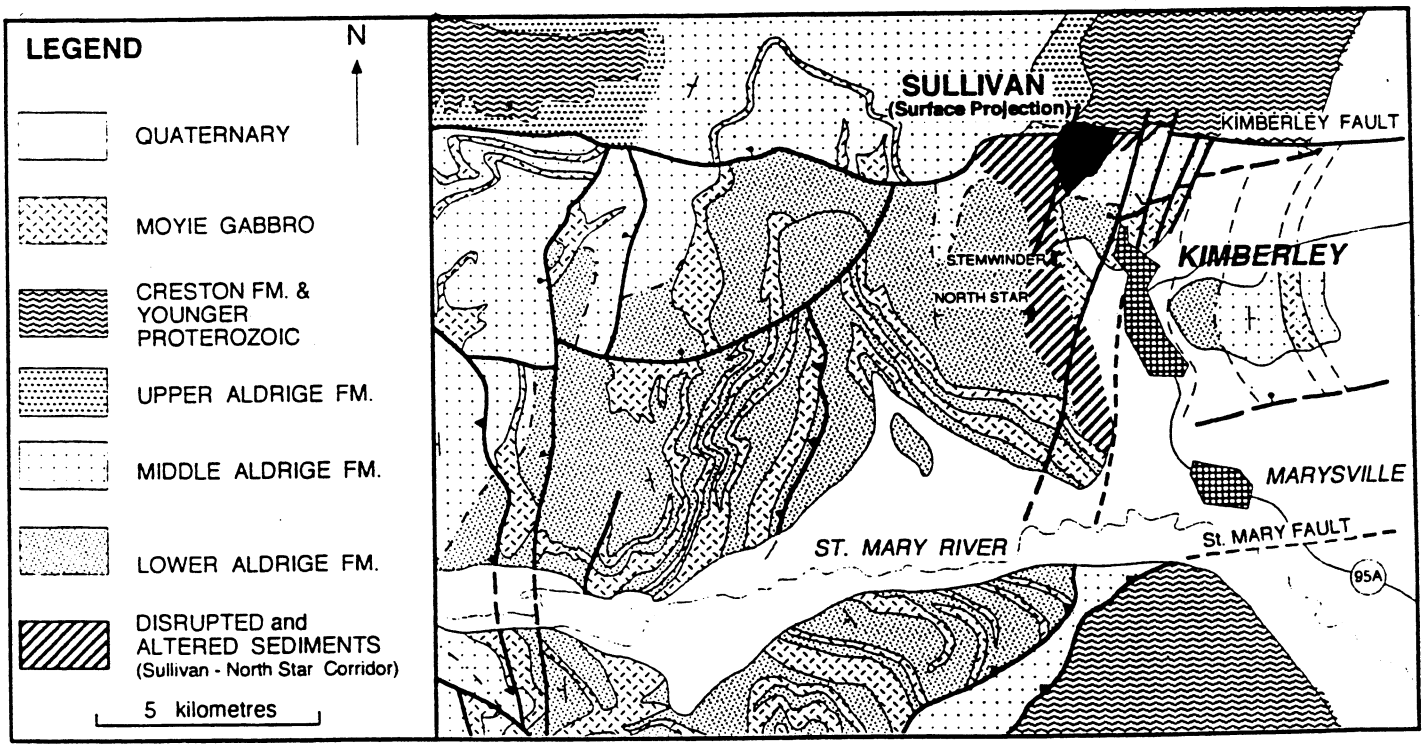


*Figure 2. Geological map of the Kimberley area showing the location of the Sullivan deposit at the intersection of the Kimberley Fault, a reactivated synsedimentary rift-related transfer fault, and the Sullivan Corridor, a rift-parallel fracture system that focussed fluid upflow and consequent disruption of sediments, mud volcano activity and hydrothermal alteration. The Sullivan Horizon is at the contact between Lower Aldridge and Middle Aldridge.*

(Davis, Schandl), which may represent a separate metamorphic peak or the chloritzation event. Pb isotope compositions of Sullivan sulphides form a linear array which is more radiogenic than sedex-type mineralization in the Middle Aldridge and more radiogenic than Proterozoic Pb-Zn-Ag veins that crosscut Belt-Purcell sediments.

Lead from pyrite-chlorite-carbonate alteration has $^{206}Pb/^{204}Pb$ values higher than that of the ore sulphides, and is a separate hydrothermal event up to 100 Ma later than the main ore-forming event (Beaudoin). If the introduction of mantle lead into the source region for base metals in Aldridge hydrothermal mineral deposits, presumed to be the lower part of the Belt-Purcell sequence, is represented by the emplacement of the Moyie Sills, then the sill emplacement post-dates the generation of Sullivan ore fluids but predates the generation of ore fluids for Middle Aldridge sedex-type mineralization and Belt-Purcell Pb-Zn-Ag veins (Beaudoin).

The Sullivan Horizon coincides with an excursion to increased del34S values in diagenetic sulphides, indicating a period of water column stratification and reducing bottom conditions during the time of Sullivan ore deposition (Goodfellow). The stratigraphic position of Sullivan in the rift fill sequence is anomalous when compared to most other sedex deposits, which typically occur in the rift sag sequence. In this connection, the Mineral King deposit in the Dutch Creek Formation, for example, which may be of the sedex type, occupies a more typical stratigraphic position (Lydon).

**Nature and source of hydrothermal fluids**

Boron isotopes of tourmalinites, whose formation brackets ore sulphide deposition at Sullivan but occur independently of sulphides elsewhere within the Belt-Purcell Supergroup, suggests the boron at least was derived by leaching of marine sediments or permissibly by the dissolution of continental evaporites, but precludes the hydrothermal fluids from being evaporated seawater or derived by the dissolution of marine evaporites (Jiang, Palmer, Slack).

Oxygen isotopes of footwall tourmalinite are consistent with alteration by a seawater-derived hydrothermal fluid above 270°C (Taylor). High salinity secondary fluid inclusions in quartz veins cutting tourmalinite in the footwall of the Sullivan deposit, and which elsewhere in the Aldridge are spatially associated with Pb-Zn mineralization, contain 15-27 wt.% $NaCl+CaCl_2$ ($MgCl_2$), and may represent the ore-forming fluids (Leitch).

Although there is no appreciable silica enrichment in hydrothermal products at Sullivan, silicon isotopes of various minerals allows a distinction to be made between silicon supplied by hydrothermal fluids and silicon of clastic grains (Jiang, Palmer).

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