The Bent Hill and ODP massive sulphide deposits, Middle Valley, Juan de Fuca Ridge: hydrothermal architecture, fluid evolution and sulphide formation in a sedimented rift environment

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Middle Valley is a hydrothermally active rift near the northern extremity of the Juan de Fuca Ridge, northeast Pacific Ocean. The rift is covered by hemipelagic and turbiditic sediments that thicken from nil at the margins to > 1000 m near the centre of the rift. At depths > 500 m, basaltic sills intrude hydrothermally altered sedimentary rocks and comprise 20–30% of the sequence. This sill-sediment complex represents a hydrothermal reaction zone that is composed of fractured,
brecciated, veined and lithified sediments containing quartz + wairakite + epidote + chlorite between 450 and 926 m below seafloor; current temperatures exceed 250 °C. Elements that are markedly depleted in this reaction zone include K, Ba, Na, CO$_2$, Rb, total organic carbon (TOC), Cu, Zn, As, Sb, Se, Be, and Co; elements added are Si, Ca, Al, and Sr.

Bent Hill and ODP are two long-lived (> 125,000 years), Zn-Cu massive sulphide deposits that are situated 9 km east of the rift axis along rift-parallel extensional faults. The Bent Hill deposit is 104 m thick and ?~200 m wide; the ODP deposit 350 m south of Bent Hill is of similar size. Combined tonnage for both deposits is ?~15–20 Mt. Metal grades are highly variable and range from high-grade Sp-rich sulphides (> 20% Zn) that are over 30 m thick in the ODP deposit to almost barren massive pyrite; average grades are 0.36% Cu and 4.66% Zn. The massive sulphide deposits was formed by the infilling and replacement of a clastic sulphide above a sulphide feeder zone. These sulphides are zone refined from a high-temperature core to the margins of the fluid upflow zone as follows: 1) Po + Is/Cp + Wz (Sp); 2) Sp + Po + Py; 3) Py + Ma. The sulphide feeder zone extends 100 m beneath the mounds and is comprised of veins and impregnations of Po (± Py) + Is + Cp that cut hydrothermally altered sediments.

Hydrothermal alteration consists of the following assemblages from the core to the margins of the feeder zone: 1) Qz + Fe-rich Ch + Ms + Po + Cp (> 300 °C); 2) Mg-rich Ch + Ab + Ms + Py; 3) Sm + An + Ba + Py; 4) Ca + Do + Il + Py (< 120 °C). The inner core has gained Si, Fe, Al, Mg, S, K, Mn, Cu, Ba, Zn, Se and Co, and lost Ca, Na, Sc, CO$_2$, TOC, and As. The enveloping zones have gained Mg and Fe at the expense of alkali elements bound in feldspar and micas. At the base of feeder zones is a laterally extensive (> 500 m) stratabound Deep Copper Zone (DCZ) up to 30 m thick composed of Cu-Fe-sulphides (average = 13% Cu) that infill and replace sandy turbidites that are pervasively altered to quartz and chlorite. The DCZ represents a stratal hydrothermal aquifer in sandy turbidites sealed by hemipelagic muds that has episodically fed hydrothermal vents along a north-south fault.

Mineral assemblages, fluid inclusions and isotopic data (Pb, Sr, S, C, and O) indicate that the Bent Hill-ODP deposits formed from > 350 °C fluids that reacted with basaltic crust. These deposits have been overprinted by 250–300 °C fluids generated in a hydrothermal reaction zone near the base of the sedimentary pile. The low permeability of sediments played an essential role in sulphide formation by reducing convective heat loss and by focusing fluid discharge at long-lived vent sites that have migrated off-axis. The focusing of thermal energy at discrete and long-lived vent sites may explain why the Bent Hill-ODP deposits are large compared to modern bare-ridge deposits (average = 0.2 Mt) and why ancient sediment-hosted VMS deposits are an order of magnitude larger, on average, than those hosted by volcanic rocks.