Characterization of footwall lithologies to the Greens Creek volcanic-hosted massive sulfide (VHMS) deposit, Alaska, USA

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any tertiary institution and, to the best of my knowledge and belief, contains no copy or paraphrase of material previously published or written by another person, except where due reference is made in the text of this thesis.

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Abstract

The Greens Creek volcanic-hosted massive sulfide (VHMS) deposit is located on northern Admiralty Island, southeastern Alaska, which is part of the Admiralty sub-terrane of the Alexander Terrane, a Late Proterozoic to Paleozoic island arc. The Alexander and Wrangellia Terranes are thought to have joined to become the Wrangellia Superterrane in the Late Carboniferous. The collision between the Wrangellia Superterrane and the North American craton probably occurred between the Early Jurassic and the Early Tertiary. The Late Triassic rifting of the eastern margin of the Alexander Terrane resulted in the most important metallogenic episode in southeast Alaska. Significant VHMS deposits, such as Windy Craggy and Greens Creek, are hosted in a Late Triassic rift sequence. The global resource of Greens Creek is approximately 24 million tonnes at an average grade of 14% Zn, 5% Pb, 600 g/t Ag and 5 g/t Au with insignificant Cu. There are three main ore bodies at Greens Creek: East, West (Northwest, 5250) and Southwest (200 South).

There are three basic divisions in the mine sequence at Greens Creek: hanging wall argillite with minor volcanic rocks (Tr3 and Tr4), mineralized horizon (Tr2), and the altered mafic footwall with minor sedimentary rocks (C1 to Tr1). Footwall rocks (C1 and C2) are dominantly subalkaline basaltic rocks of Early Carboniferous age, Tr1 is a Late Triassic polymict breccia. The Late Triassic hanging wall argillite is made up of organic rich pelagic muds and distal turbidites. The upper portion of the hanging wall sequence contains a minor igneous component consisting of gabbroic sills (I3), basalt, dacite and rhyolite. The regionally extensive Hyd basalts (Tr4) form the youngest Late Triassic stratigraphic element.

The structure of the Alexander Terrane is complex, reflecting its complex Cenozoic and Mesozoic history. There is a strong northwest-southeast structural fabric to the region which is formed by regional recumbent folds and thrusts. Metamorphic and plutonic belts are common. At Greens Creek, there have been at least four folding events, one major thrust event and one brittle strike-slip fault event.

The chemistry of Silurian to Devonian siliceous sedimentary rocks and Early Carboniferous mafic volcanic rocks indicates an island arc environment for the footwall and basement. The Late Triassic hanging wall basalts are slightly alkaline and are interpreted to have formed in a rift of the existing island arc. Late Triassic serpentinite rocks have both mafic and ultramafic chemical composition. The intensely altered refractory compositions are interpreted to have been peridotite. Ti versus Zr ratios for the Early Carboniferous fine-grained layered volcaniclastic footwall lithologies (C2) indicate at least two potential end member sources: (1) recycled footwall greenstones and (2) background marine sedimentation.

A new geochronology protocol, using small zircon grains, was developed in this project. Reliable U-Pb zircon dates on small in-situ zircon grains are possible if careful attention is paid to the quality of the analyses. Small zircon grains tend to have high U (and Th) content which can lead to Pb loss due to radiation damage. However, a precision of 1-2% relative error of the weighted mean age of the rock was achieved by analyzing small zircons where an adequate number of grains were present.

The oldest known rocks in the vicinity of Greens Creek are Late Proterozoic gneissic tonalitic to dioritic rocks from False Point Retreat (Karl et al., 2006). Schistose basement rocks at Greens Creek have a depositional age of Early Silurian to Middle Devonian and contain metamorphic zircon grains with a Late Permian age. The footwall is composed of massive coherent mafic volcanic rocks with a crystallisation age of 342

± 4 Ma (Early Carboniferous) and layered mafic volcaniclastic rocks with a possible crystallization age of 333 ± 6 Ma (Early Carboniferous). Permian metamorphic zircon grains from an amphibolite sample in Cliff Creek formed during the D1 metamorphic and deformational event that affects all Early Carboniferous footwall lithologies (units C1 and C2). The hanging wall argillite was deposited during the Carnian to Norian (Late Triassic). Volumetrically significant serpentinite bodies (I2 - undated) within the footwall show features associated with minor intrusion into the argillite and have anhydrous compositions that overlap with the Late Triassic microgabbros suggesting a Late Triassic emplacement age. Hanging wall microgabbro was emplaced at 221 ± 6 Ma and the overlying rhyolite crystallized at 226.9 ± 0.2 Ma. The Seymour Canal Formation is Late Jurassic to Early Cretaceous. An unfoliated set of mafic dikes offset by a northwest trending brittle fault were emplaced at 85 Ma, constraining the ductile deformation to older than 85 ± 4 Ma and brittle deformation to younger than 85 Ma.

Four alteration zones were recognized within the footwall to the Greens Creek deposit. From distal to proximal these are the chlorite alteration zone, the sericite alteration zone, the quartz-sericite alteration zone and the quartz-pyrite alteration zone. Infrared spectral data indicates a systematic change in white mica composition from phengite to muscovite with increasing proximity to mineralization. The wavelength position of the AlOH feature for background white micas is variable with values between 2190 and 2230 nm and is heavily dependent on bulk rock composition. Near mineralization the white mica composition is dominated by the hydrothermal fluid effects and the AlOH values are restricted to the 2200–2215 nm range. White mica alteration index (WMAI) values show an increase in the abundance of sericite, relative to chlorite, when near mineralization. Chlorite shows limited compositional variation and no recognizable systematic zoning. The wavelength position of the FeOH feature of chlorite is typically between 2246 and 2257 nm indicating Mg-chlorite to intermediate chlorite compositions.

Whole rock geochemical analyses show systematic trends in major oxides, trace elements and alteration indices as the ore position is approached. SiO_2 shows the greatest increase towards mineralization and Na_2O shows the greatest decrease. Trace elements Ba and Tl are elevated above background levels of 50 ppm and 0.1 ppm respectively, up to 500 feet (150 m) from mineralization. The Ishikawa alteration index is an effective monitor of the alteration intensity. The S/Na_2O ratio shows four orders of magnitude increase from background levels of <0.1 to approximately 20 at an unmineralized hanging wall – footwall contact with further increase up to >200 close to a mineralized contact.

Metal zoning within the footwall was investigated by concentrating on samples immediately below the ore position. The footwall to the Northwest West (NWW) ore body is Cu-rich throughout with Zn, Pb and Ag enrichment on the margins of the ore body. The footwall to the East ore body is Cu-poor throughout with moderate Zn and Pb contents, the entire footwall is enriched in Ag. High Cu ratios (>30) with coincident moderate Zn ratios (<83) within the footwall to the NWW ore body outline a feeder zone that is elongated north – south, along the restored western margin of the Maki Fault Zone. Moderate to high Cu ratios (>20) with coincident low Zn ratios (<70) in the footwall to the East ore body outline a feeder zone that is also elongate north – south. In the footwall to both ore bodies, Cu is largely associated with quartz-pyrite alteration and Zn, Pb and Ag with sericite alteration. Morphology and zone refining of the NWW ore body combined with alteration zonation and the Zn ratio and Cu ratio within the footwall feeder zones are all consistent with the NWW ore body forming at temperatures close to 200°C from a relatively prolonged and focused vent source. Zone refining of the East ore body, morphology of the East ore body and alteration zonation and the Zn ratio and Cu ratio within the footwall feeder zones are all consistent with the East ore body forming at temperatures <200°C from a diffuse vent source with a relatively short duration.

Two stages are envisaged for the formation of the Greens Creek deposit: Stage 1 is initiation and ground preparation. Rifting of the existing arc resulted in numerous sub-parallel, steeply dipping faults that initially provided sites for high crustal level intrusions. The heat from these mafic to ultramafic intrusions created an early stage hydrothermal system that locally altered the Early Carboniferous mafic footwall. The end of this stage is marked by the deposition of a polymict breccia with variably hydrothermally altered clasts. Stage 2 is ore deposition, burial and waning. Intense hydrothermal alteration along fluid conduits and proximal to fluid discharge sites signifies increased hydrothermal activity. Ore deposition occurred after the deposition of the polymict breccia and mineralization was immediately buried by fine-grained sediments. This hanging wall sequence is weakly altered which indicates that burial began while the hydrothermal system was still operating. No alteration of the basalts in the Hyd Formation was recognized.

In conclusion, the majority of the footwall to the Greens Creek deposit formed in the Early Carboniferous and was metamorphosed in the Permian. Therefore the deposit sits close to the base of the Late Triassic stratigraphy, above an approximately 100 Ma unconformity and the footwall was metamorphosed prior to ore formation. The apparently unusual base- and precious-metal endowment of the Greens Creek VHMS deposit can be partially explained by its stratigraphic position. The metal source must have included the underlying basement, not just the immediate mafic footwall. Furthermore, preciou- metal enrichment can be explained by low temperature boiling of the hydrothermal fluids, possibly as a result of shallow water depths.

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