Introduction and Overview of the U.S. Geological Survey–Kennecott Greens Creek Mining Company Cooperative Applied Research Project at the Greens Creek Mine

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Chapter 1 of
Geology, Geochemistry, and Genesis of the Greens Creek Massive Sulfide Deposit, Admiralty Island, Southeastern Alaska

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Background

In 1996, a memorandum of understanding was signed by representatives of the U.S. Geological Survey and Kennecott Greens Creek Mining Company to initiate a cooperative applied research project focused on the Greens Creek massive sulfide deposit in southeastern Alaska. The goals of the project were consistent with the mandate of the U.S. Geological Survey Mineral Resources Program to maintain a leading role in national mineral deposits research and with the need of Kennecott Greens Creek Mining Company to further development of the Greens Creek deposit and similar deposits in Alaska and elsewhere. The memorandum enumerated four main research priorities: (1) characterization of protoliths for the wall rocks, and elucidation of their alteration histories, (2) determination of the ore mineralogy and paragenesis, including metal residences and metal zonation within the deposit, (3) determination of the ages of events important to ore formation using both geochronology and paleontology, and (4) development of computer models that would allow the deposit and its host rocks to be examined in detail in three dimensions.

The work was carried out by numerous scientists of diverse expertise over a period of several years. The written results, which are contained in this Professional Paper, are presented by 21 authors: 13 from the U.S. Geological Survey, 4 from Kennecott Greens Creek Mining Company, 2 from academia, and 2 from consultants.

Geology and Geophysics

The first six papers in the Professional Paper summarize a large body of geologic and geophysical information starting at the regional scale and ending at the scale of the Greens Creek mine and immediate vicinity. The lead-off paper, by Taylor and others (chap. 2), describes the regional setting for Greens Creek on the eastern margin of the Alexander terrane in southeastern Alaska. The deposit lies in what Taylor and others (chap. 2) term the Alexander Triassic Metallogenic Belt (ATMB), a 200–800-m-thick sequence of conglomerates, limestones, marine clastic sediments, and tuffs with overlying and intercalated pyroclastic rocks and flows that can be traced some 600 km along strike. Fossil evidence suggests that the sequence spans Anisian to late Norian time (Middle Triassic to Late Triassic). In addition to Greens Creek, numerous other sulfide deposits are within the belt, most notably Windy Craggy, which is the largest volcanogenic massive sulfide deposit known in North America.

Within the ATMB, there are along-strike changes in the nature of the sulfide deposits and the depositional setting of the host rocks. From south to north, sulfide deposits change from structurally controlled Pb+Zn+Ag±Cu veins or pods or small stratiform lenses, to stratiform sulfosalt-bearing Zn-Pb-Ag deposits (Greens Creek), to stratiform copper-rich deposits (Windy Craggy). The host rocks also change from felsic volcanics with overlying oolitic limestones to mafic and ultramafic phyllites with overlying argillites or mafic volcanics. Taylor and others (chap. 2) suggest that the change in host rocks reflects a change in depositional environment from shallower waters on the flanks of the Alexander volcanic arc to deeper waters in a back-arc or intra-arc basin. A modern analog for the ATMB may be the southern projection of the Lau Basin, from Valu Fa Ridge to the Taupo Volcanic Zone on the North Island of New Zealand.

West (chap. 3) documents the exploration programs that focused attention on northern Admiralty Island and then defined and expanded the Greens Creek ore reserve. In 1973, Noranda Exploration, Marietta Resources, Exhalas Resources, and Texas Gas Exploration formed a partnership, Pan Sound Joint Venture, to explore for base and precious metals in the northern part of southeastern Alaska, in the Prince William Sound area, and on the Kenai Peninsula. That same year, extensive stream-sediment sampling across northern Admiralty Island revealed high concentrations of zinc and copper in the Cliff Creek drainage, just east of the present-day mine site, and near Hawk Inlet, northwest of the mine site. The following year, a large exposure of unvegetated ferricrete was discovered and dubbed the "Big Sore," and geophysics and soil geochemistry surveys of the area were carried out. The first drill hole, which was completed in 1975, recovered an 89-foot interval of massive pyrite and base metal sulfides.

The first production from the Greens Creek mine was in 1989, following a development stage that was greatly complicated by the Alaska National Interest Lands Conservation Act of 1980. Throughout the development of the mine, and in subsequent exploration programs, the understanding of the geology of the deposit and the preferred model for ore genesis have evolved considerably. The stratabound nature of the mineral deposits was recognized early on. Although the ores were first thought to be brine pool deposits and the host rocks to be volcanic tuffs and hydrothermal precipitates (exhalites) that had accumulated on the Devonian sea floor, subsequent interpretations favored sulfide precipitation in Triassic time in association with intense hydrothermal alteration of preexisting volcanic and plutonic rocks. It was suggested also that the heat source for the hydrothermal system was ultramafic magmas that were emplaced along faults, and that the ores formed epigenetically by replacement of Triassic sedimentary rocks. The understanding of post-ore deformation has also evolved. An accurate model of the structural geology is considered critical for mine planning and continuing exploration.

Duke and others (chap. 4) and Fueg (chap. 5) report on surface geologic mapping and results of an airborne geophysical survey, respectively, of the greater Greens Creek area. The geologic and geophysical coverages are nearly the same and can be conveniently compared. The data are displayed as maps that cover a 10–12-mile-long segment of the northwest-trending phyllite belt that hosts the Greens Creek deposit.

Greens Creek is in the low-grade metamorphic core of the Admiralty subterrane of Alexandria. The overall tectonostratigraphic setting is back-arc basement of late Paleozoic age overlain by flood basalts of Late Triassic age. The Admiralty back-arc basin is represented by Devonian greenstones of the Retreat Group, overlying Mississippian to Permian siliciclastics and dolomite-chert facies of the Cannery Formation, and the Lower Permian Pybus Formation. Amalgamation of the Alexander and Wrangellia terranes resulted in subaerial exposure of the region, and the formation of an unconformity. Rifting commenced in Late Triassic time leading to the accumulation of the Hyd Group, which is dominated by black argillite and flood basalts. Compressional tectonism in mid-Cretaceous time caused fold and thrust imbrication. Dextral transpression on the Denali transform system in the Tertiary caused strike-slip faulting.

The Greens Creek sulfide bodies are located at the unconformity between the Retreat and Hyd Groups. At the mine site, the Retreat Group contains serpentinite and metagabbro in addition to greenstone; hydrothermal alteration of this assemblage has given rise to phyllitic rocks (termed mine phyllite following common usage by Kennecott Greens Creek geologists; see also Proffett, chap. 7). The Hyd Group consists of a basal breccia/conglomerate, a medial argillite (termed mine argillite by Kennecott Greens Creek geologists; see also Proffett, chap. 7), and an upper basalt member.

The airborne geophysics has proven to be a valuable guide to stratigraphy and structure in the area. Ultramafic units appear as magnetic highs, and the argillite-phyllite contact, which is the mineralized horizon, is revealed as a sharp gradient in the electromagnetic data (contrast between low and high resistivities, respectively). The Greens Creek sulfide deposit is not apparent in the electromagnetic data mainly because the bulk of it is buried.

The geology of the mine site is described by Taylor and others (chap. 6), who focus on the ores and their immediate wall rocks, and Proffett (chap. 7), who focuses on the structural geology. The Greens Creek ore deposit is a series of massive sulfide bodies that lie along the contact between altered mafic-ultramafic phyllites and stratigraphically overlying Upper Triassic argillites. There are three main orebodies, East, West, and Southwest, that are themselves segmented by faults or attenuated zones. Within individual orebodies there is a common stratigraphic sequence in which white ores (less than 50 percent sulfides) give way upward to pyritic massive ores, and then to base-metal-rich massive ores (both greater than 50 percent sulfides). The global reserve, for a cutoff grade of zero percent metal, is estimated to be 21.9 million metric tonnes with grades of 13.9 weight percent zinc, 5.1 weight percent lead, 19.2 troy ounce per metric tonne silver, and 0.15 troy ounce per metric tonne gold.

Restoration of offsets along the Maki and Klaus faults, the two major ore-displacing faults, suggests that the mineral deposit was originally a single continuous horizon that was thickest in the Central West orebody and thinned to the north, east, and south. It appears that, in general, the ores change from Cu+Fe-rich against the footwall phyllites, to Zn-rich, to Zn+Pb-rich, to Ag-rich and polymetallic against the hanging-wall argillites. The absence of concentric metal zoning in plan view suggests that the sulfide-bearing mineral deposits may have formed above multiple centers of hydrothermal upwelling, or a broad zone of diffuse upwelling, rather than a single pipelike vent.

The host rocks show the effects of hydrothermal alteration, lower greenschist facies metamorphism, and multiple deformations. In the footwall, mafic rocks are higher in silica content and richer in sericite at the ore contact and become richer in chlorite and carbonate away from ore. Ultramafic rocks are either serpentinized or carbonate altered. In the hanging wall, the argillites are massive or slaty and can contain graphite, dolomite, or calcite. Carbonate rocks occur locally at or near the ore contact.

The complex distribution of ore at Greens Creek results mainly from the complex deformation history of the area. The earliest structures are schistosities (S1 and S1.5) that are apparent only in Paleozoic rocks. Three cleavage-forming folding events (F2–S2, F3–S3, F4–S4) affected both ores and wall rocks. Ductile shear zones are present above and below the ore zone; these formed between F2 and F3. Brittle faulting postdated the youngest folding event (F4).

Geochemistry

Next in the Professional Paper are five papers on geochemical topics. Johnson and others (chap. 8) report on the organic geochemistry, major and trace element geochemistry, and stable isotope geochemistry of sedimentary rocks in the hanging wall

of the Greens Creek deposit and of shales elsewhere on Admiralty Island. The sedimentary section immediately overlying the ores ranges from carbonate-poor shale to nearly pure dolomite. Some samples resemble normal marine shales in their base and precious metal contents, sulfur-to-organic carbon ratios, and degree-of-pyritization values. These sediments were laid down during periods when the overlying water column was oxic; the only suggestion of hydrothermal venting is a slight enrichment in barium. More commonly the hanging-wall samples are high in sulfur, metals, and degree of pyritization. This could reflect metal accumulation beneath an anoxic metalliferous brine pool but could also be explained by epigenetic emplacement of sulfur and metals during massive sulfide formation or during Cretaceous regional metamorphism as a consequence of mobilization from the neighboring sulfide bodies.

The carbon and oxygen isotopic compositions of hanging-wall carbonates are indistinguishable from the compositions of dolomite in the sulfide ores. The compositional ranges suggest precipitation from a single fluid over a temperature range of 200° to 350°C, which overlaps the range that has been inferred independently for formation of the adjacent massive sulfides (see Taylor and others, chap. 10). However, the compositions may also be consistent with dolomite formation from mixtures of hydrothermal and marine fluids. Whatever the dolomite precipitation mechanism, the isotopic similarity of hanging-wall and ore dolomites is strong evidence that the Greens Creek hydrothermal system persisted until after the hanging-wall sediments had been laid down.

Carbonate carbon isotopes show a negative correlation with the sulfur content of the rocks, which suggests that the oxidation of organic matter, or of methane produced therefrom, was linked to sulfate reduction to form hydrogen sulfide. During growth of the framboidal pyrite forms, sulfate reduction was probably microbially mediated, whereas during formation of base-metal sulfides, sulfate reduction could have been microbial or abiotic. Thus, at least some sulfate reduction took place during early diagenesis beneath the sediment/seawater interface. Limited isotopic data from Hyd Group shales elsewhere on Admiralty Island suggest that the same hydrothermal fluid that formed the Greens Creek massive sulfide deposit may also have interacted with basin-floor sediments several kilometers distant from Greens Creek.

The mineralogy, mineral chemistry, and textures of Greens Creek ores are described by Taylor and others (chap. 9). For mapping purposes, the ores have been divided into massive sulfide ores (greater than 50 percent sulfides), which can be either pyrite- or base-metal-rich, and white ores (less than 50 percent sulfides), which can contain carbonate, silica, or barite. Veining, brecciation, and faulting are also recognized giving rise to subdivisions of the main ore types. In the cores of individual orebodies, white ore gives way stratigraphically upward to massive pyritic ore, which gives way upward and laterally to massive base-metal-rich ore.

Ore with primary textures, which constitutes an estimated 30 percent of the deposit, contains pyrite with framboidal, colloform, dendritic, or "spongy" forms intergrown with sphalerite, galena, tetrahedrite, chalcopyrite, free gold, and various Pb-Sb-As(-Hg-Tl) sulfosalts. The textures exhibited by pyrite are consistent with formation during diagenesis from bacterial hydrogen sulfide and support a similar inference based on sulfur isotopic analyses (see Taylor and others, chap. 10). The remaining 70 percent of the ores show the effects of secondary processes including recrystallization and coarsening of sulfides, formation of atoll structures, and formation of secondary minerals in late fractures, veinlets, and matrix interstitial to euhedral pyrites. Common secondary minerals include chalcopyrite, low-iron sphalerite, galena, free gold, electrum, antimony-rich tetrahedrite, pyrargyrite, and numerous sulfosalts. Recrystallization also resulted in higher pyrite purity. A process akin to zone refining is inferred, causing recrystallization of large volumes of ore and the migration of lead, zinc, and precious metals outward toward the lower temperature margins of individual orebodies.

Sulfur and lead isotope analyses of Greens Creek sulfides and of hanging wall and footwall rocks provide information on the sources of these two ore constituents (Taylor and others, chap. 10). Ore pyrite ranged in $\delta^{34}S$ from –38 to 2 permil, and chalcopyrite, sphalerite, and galena were mostly between –16 and –11 permil. The lower values are strong evidence for sulfur acquisition from bacterial hydrogen sulfide, which was produced from seawater sulfate within the pore waters of argillaceous sediments. The higher values suggest that sulfur may have been derived also from mafic and ultramafic rocks beneath the sulfide deposit. Analyses of barite gave $\delta^{34}S$ values of 13 to 22 permil, which is consistent with sulfate derivation from Triassic seawater. The sulfur isotopic difference between coexisting sphalerite and galena suggests that the minerals equilibrated at temperatures of 276–313°C. It is uncertain whether this equilibration occurred during hydrothermal metal emplacement or during Cretaceous regional metamorphism.

Lead isotope analyses of Greens Creek samples and of sulfide minerals from elsewhere on Admiralty Island suggest that the lead represents mixtures from multiple sources. Ore sulfides display linear arrays on $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plots that are consistent with mixing of less radiogenic lead from a source resembling enriched midocean-ridge-type basalt (EMORB) and more radiogenic lead from an older crustal source. Analyses of host rocks suggest that the less radiogenic source could have been Upper Triassic basalts and gabbros, select phyllites, or Cannery Formation argillites. The more radiogenic source may have been the hanging-wall argillites, although the lack of obvious depletions in lead and other metals immediately above the Greens Creek deposit (Johnson and others, chap. 8) suggests that the source argillites would have been distal to the site of massive sulfide formation. For other sulfide localities on Admiralty Island, there appear to have been contributions from different sources. These include an older or less radiogenic source for the Kennecott Rand, Pyrola, Killer Creek, and Mt. Robert Barron localities that may correspond to Retreat Group sedimentary rocks, and a more highly radiogenic source for the Mammoth Claims, Cascade Creek, Portage, and Cub

Creek localities, as well as to a minor extent at Greens Creek, that may correspond to metasomatic additions of lead during the Cretaceous metamorphic event.

The last two geochemical papers cover age determinations from radiogenic isotopes and biostratigraphy and radiogenic isotope geochemistry of the Greens Creek wall rocks. Premo and others (chap. 11) report on conodonts from calcareous argillites that were obtained from mine workings and outcrops. The most age-restrictive index species is *Metapolygnathus primitius,* which lived during a narrow time interval at the Carnian-Norian boundary for which the estimated age is 220.7±4.4 Ma (Gradstein and others, 1995). The CAI (color alteration index) of most Greens Creek conodonts is 5 or 5–5.5, which implies that the samples experienced temperatures of 300° to 350°C. The general consistency of CAI values within individual samples, and from one sample to another, suggests that the values reflect a low-grade metamorphic event. Less common higher CAI values of 5.5–6 and 6.5–7 reflect higher temperatures or more prolonged heating locally, most likely due to contact metamorphism near basaltic flows or intrusions, or interaction with hydrothermal fluids. The conodont-bearing argillites were hemipelagic basinal deposits with additions of storm- or wave-generated siliciclastic and carbonate muds from shallow-water platforms or other near-surface submarine edifices that were transported and redeposited in deeper marine environments.

Measurements of whole-rock lead, neodymium, and strontium isotopic compositions gave scattered results for some sample suites implying post-depositional disturbance, but gave apparent isochrons for other suites. The U-Pb results for a suite of Hyd Group basalts gave an apparent isochron age of 218±16 Ma, which is consistent with their eruption after argillite sedimentation (220.7±4.4). A suite of altered gabbros that intruded both Hyd Group argillites and Hyd Group basalts gave ages of 206±35 Ma (U-Pb) and 200±27 Ma (Sm-Nd) consistent with the crosscutting relationships. Numerous sericite and fuchsite samples were dated by the $^{40}Ar/^{39}Ar$ technique, but most showed evidence for argon loss during Cretaceous time and thus were of limited value in dating hydrothermal mineral growth. However, fuchsite from an altered ultramafic rock at Gambier Bay yielded an undisturbed age of 210.3±0.3 Ma. Taken together, the geochronological data suggest that the lifetime of the Greens Creek hydrothermal system was between 0.4 and 15.1 million years. For some sample suites the U-Pb, Sm-Nd, Rb-Sr, and $^{40}Ar/^{39}Ar$ systematics appear to have been perturbed in the time period 110–85 Ma, which corresponds to the Cretaceous metamorphic event.

Premo and Taylor (chap. 12) present whole-rock U-Th-Pb, Rb-Sr, and Sm-Nd isotope data for metabasalts, metagabbros, serpentinites, phyllites, argillites, and crosscutting diabases from the vicinity of the Greens Creek deposit. The metabasalts and metagabbros yield Pb-Pb, Sm-Nd, and Rb-Sr systematics that are consistent with Triassic emplacement ages and with magma production in a depleted mantle source region within a volcanic arc setting. Phyllites show more compositional scatter, suggesting U-Pb fractionation during hydrothermal alteration and interaction with seawater or marine carbonate rocks. The hanging-wall argillites give Pb-Pb apparent ages consistent with sedimentation during Triassic time of detritus derived in part from an older, more radiogenic source region. The Rb-Sr isotope systematics of the argillites show evidence of disruption in Cretaceous time. Serpentinites also show disrupted isotope systematics. Values of epsilon-Nd increase through the stratigraphy from metabasalts to mafic volcanics and gabbroic plutons to Hyd Group basalts at the top of the Triassic section. The increase implies progressive depletion of magma source regions, which is consistent with the opening of preexisting crust in a rift setting.

The Greens Creek wall rocks span wider lead isotopic ranges than the ores. A comparison of ore and wall-rock compositions suggests that the ore lead was derived mainly from basaltic and gabbroic lithologies with a lesser contribution from the hanging-wall argillites. The isotopic uniformity of the orebody implies that the lead was homogenized prior to being deposited in sulfide minerals.

Models

The final three chapters in the Professional Paper (chaps. 13, 14, 15) describe models for the Greens Creek deposit. The first paper, by Freitag (chap. 13), presents a model for the geometry and structural development of the Lower Southwest orebody. The model is based on rib and plan maps that were prepared for the Lower Southwest orebody and for parts of the Upper Southwest, 244 West Bench, and 200 South orebodies. Similarities are apparent between the structures revealed in the deposit and the structures that have been observed regionally (see Proffett, chap. 7). Thus, the model may provide guidance for exploration away from the mine as well as for continued development within the mine.

Syndepositional normal faults were inferred from north-south-trending accumulations of sulfide and mineralized dolomite that appeared on isopach maps created from palispastic reconstructions. The accumulations are believed to represent thicker sulfide sections that developed above fault-controlled fluid conduits. Next in the structural history were ladder veins that developed perpendicular to bedding in argillaceous rocks; these were later offset by pressure solution seams. Compressional tectonics associated with terrane accretion in Late Jurassic to Cretaceous time caused small thrust faults, and then resulted in south-southwest- to southeast-plunging, open-to-isoclinal folds and southeast-plunging open folds. The effects of the folding events were more pronounced in less competent, thinner sulfide sections leading to greater fold frequencies and fold amplitudes, and more varied orientations of foliations and cleavages. The folding events were followed by a transition to a more brittle deformation style that produced gentle folds and thrust faults. Wrench tectonics in Eocene time led to high-angle faulting, in some cases along reactivated thrust faults.

Next, Lee and Taylor (chap. 14) present three-dimensional depictions of the orebodies, major workings, faults, shear

zones, and assay values for zinc, silver, gold, and antimony. The basis of the depictions is lithologic, structure, and assay data for 1,895 core holes that were drilled in the vicinity of the mine. The results are displayed relative to the mine grid, which is rotated 26.5651 degrees counterclockwise from due north. Mine coordinate elevations are 60 ft higher than above-sea-level elevations. The depictions allow readers to visualize and quickly appreciate a number of important aspects of the deposit and the mine, including the topography of the area, the complexity of the ore distribution, the influence of faults on the ore distribution, and the spatial relationship between zinc mineralization and precious metal mineralization.

In synthesizing the results of the entire cooperative research project, Taylor and others (chap. 15) point out that the Greens Creek deposit is not easily classified because it displays features characteristic of volcanogenic massive sulfide (VMS) deposits, features characteristic of sedimentary exhalative (SEDEX) sulfide deposits, and features characteristic of Mississippi Valley-type (MVT) sulfide deposits. Among the VMS characteristics are an association with abundant volcanic rocks (footwall phyllites), the existence of an alteration profile beneath the mineralized horizons, a metal endowment (Zn-Pb-Ag-Au-Cu) resembling Kuroko- or bimodal-felsic-type VMS deposits, and a mineral deposit type (white ores) that resembles the white smoker deposits found on the modern sea floor in areas of active volcanism. SEDEX characteristics include an association with carbonaceous sedimentary rocks (hanging-wall argillites), the presence of a broad chromium-barium-carbonate alteration halo, the lack of a hydrothermal root beneath the ores, and the diagenetic/bacterial origin of sulfide sulfur. The MVT characteristics are less compelling from a classification standpoint, but they include the local presence of epigenetic sulfide mineralization in carbonate rocks in the deposit footwall.

The tectonic setting for the Greens Creek deposit was a rift basin that developed in the Alexander terrane following a period of shale accumulation in open basins and carbonate platform development, and subsequent emergence and erosion of the Alexander landmass. Rifting commenced in Late Triassic time. Arc-contaminated tholeiites and minor alkaline basalts were extruded, probably subaqueously, in the Greens Creek area. Subsequently, a thin carbonate platform developed within the rift during a period of quiescence. Resumption of rifting caused the carbonate platform to founder, and it was at this time that the Greens Creek hydrothermal system was initiated. Shallowly emplaced mafic and ultramafic magmas supplied the requisite heat for the development of hydrothermal circulation. The first hydrothermal products to be formed were precious-metal-bearing silica-barite-carbonate deposits that formed at or just beneath the sea floor by mixing of metalliferous fluids with sulfate-bearing seawater. The accumulation of organic-rich sediments in the subsiding basin resulted in bacterial sulfate reduction within the sediment column, and possibly also within stagnant basin waters. Base-metal and iron sulfide minerals were formed where hydrothermal fluids encountered bacterial hydrogen sulfide, resulting in the replacement of both unlithified shale and preexisting silica-barite-carbonate

deposits. The deposit underwent a process akin to zone refining during prograde hydrothermal heating, causing precious metals, antimony, mercury, and other metals to migrate upward and outward within the deposit. Hydrothermal activity and shale accumulation were followed by the eruption of voluminous basalts. Heating and deformation during Cretaceous greenschist facies metamorphism recrystallized sulfide minerals and thickened the ore horizon locally.

Greens Creek is a hybrid deposit intermediate between more typical VMS and SEDEX deposits. Deposit characteristics suggest formation in a transitional environment within a rift that was propagating from dominantly oceanic crust toward the core of the Alexander terrane where the crust was increasingly continental. The change in crustal character along the strike of the propagating rift is thought to explain the change in metal endowments from copper-dominant at Windy Craggy to zinc-lead-silver-dominant at Greens Creek. Whereas the Windy Craggy hydrothermal system scavenged metals predominantly from copper-rich, lead- and zinc-poor ocean ridge basaltic rocks, the Greens Creek hydrothermal system scavenged metals from mafic and ultramafic rocks that were richer in zinc and lead because they had assimilated the evolved basement of the Alexander terrane.

Final Comment

As the reader proceeds through this Professional Paper, it will become clear that some research priorities set out in the original memorandum of understanding proved to be quite fruitful, whereas others proved to be less so. This is perhaps inevitable for a complex project with an ambitious work plan and a wide diversity of participants. In particular, attempts to characterize the protoliths and alteration histories of the footwall rocks were only partially successful because, as the data of Premo and Taylor (chap. 12) demonstrate, it is difficult to see backward through the multiple thermal and metasomatic overprints to determine original chemical and isotopic properties. On the other hand, the discovery of disturbed isotope systematics provides strong support for the conclusion that the Greens Creek footwall was intensely altered by throughgoing hydrothermal fluids. Overall, there is no question that the U.S. Geological Survey–Kennecott Greens Creek Mining Company cooperative research project was highly worthwhile; the final product—this Professional Paper—far exceeds what the individual organizations could have accomplished working in isolation.

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