Tectonic Setting and Metallogenesis of Volcanogenic Massive Sulfide Deposits in the Bonnifield Mining District, Northern Alaska Range

By Cynthia Dusel-Bacon, John N. Aleinikoff, Wayne R. Premo, Suzanne Paradis, and Ilana Lohr-Schmidt

Chapter B of

Recent U.S. Geological Survey Studies in the Tintina Gold Province, Alaska, United States, and Yukon, Canada—Results of a 5-Year Project

Edited by Larry P. Gough and Warren C. Day

Scientific Investigations Report 2007–5289–B

U.S. Department of the Interior
U.S. Geological Survey

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Abstract

This paper summarizes the results of field and laboratory investigations, including whole-rock geochemistry and radiogenic isotopes, of outcrop and drill core samples from volcanogenic massive sulfide (VMS) deposits and associated metaigneous rocks in the Wood River area of the Bonnifield mining district, northern Alaska Range (see fig. 1 of Editors' Preface and Overview). U-Pb zircon igneous crystallization ages from felsic rocks indicate a prolonged period of Late Devonian to Early Mississippian (373±3 to 357±4 million years before present, or Ma) magmatism. This magmatism occurred in a basinal setting along the ancient Pacific margin of North America. The siliceous and carbonaceous compositions of metasedimentary rocks, Precambrian model ages based on U-Pb dating of zircon and neodymium ages, and for some units, radiogenic neodymium isotopic compositions and whole-rock trace-element ratios similar to those of continental crust are evidence for this setting. Red Mountain (also known as Dry Creek) and WTF, two of the largest VMS deposits, are hosted in peralkaline metarhyolite of the Mystic Creek Member of the Totatlanika Schist. The Mystic Creek Member is distinctive in having high concentrations of high-field-strength elements (HFSE) and rare-earth elements (REE), indicative of formation in a within-plate (extensional) setting. Mystic Creek metarhyolite is associated with alkalic, within-plate basalt of the Chute Creek Member; neodymium isotopic data indicate an enriched mantle component for both members of this bimodal (rhyolite-basalt) suite. Anderson Mountain, the other significant VMS deposit, is hosted by the Wood River assemblage. Metaigneous rocks in the Wood River assemblage span a wide compositional range, including andesitic rocks, which are characteristic of arc volcanism. Our data suggest that the Mystic Creek Member likely formed in an extensional, back-arc basin that was associated with an outboard continental-margin volcanic arc that included rocks of the Wood River assemblage. We suggest that elevated HFSE and REE trace-element contents of metavolcanic rocks, whose major-element composition may have been altered, are an important prospecting tool for rocks of VMS deposit potential in east-central Alaska.

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Introduction

Devonian to Mississippian magmatism was widespread along the ancient Pacific margin of North America. Many of the volcano-plutonic complexes and associated sedimentary rocks contain volcanogenic massive sulfide (VMS) or sedimentary exhalative massive sulfide (SEDEX) syngenetic base-metal (zinc-lead-copper) mineral deposits, including several deposits in east-central Alaska (Newberry and others, 1997; Dusel-Bacon and others, 2006). (Syngenetic means that the deposit formed contemporaneously with the enclosing rocks.) The discovery in the mid-1990s of zinc-lead-silver massive sulfide deposits in the Finlayson Lake area of southeastern Yukon, Canada, prompted renewed interest in known and potential base-metal sulfide occurrences in similar rocks in Alaska. The potential for economic deposits provided the impetus for our investigations of the major known VMS deposits of the Bonnifield mining district and their host rocks. We summarize herein the results of our study to characterize the regional tectonic setting of the host rocks to the VMS deposits, the mineralogy and isotopic characteristics of the deposits, and the controls of mineralization in a submarine hydrothermal environment. The reader is referred to Dusel-Bacon and others (2004, 2005, 2006) for complete scientific referencing and more detailed results of our investigations.

Regional Geology

Greenschist-facies metavolcanic and metasedimentary rocks in the Bonnifield district form range-parallel, easttrending belts (Wahrhaftig, 1968; Gilbert and Bundtzen, 1979). Protoliths (premetamorphic rock types) consist of varying amounts of predominantly felsic and mafic volcanic and shallow intrusive rocks that are interlayered with carbonaceous and siliciclastic sedimentary rocks indicating deposition in a submarine, basinal setting. U-Pb zircon ages from felsic rocks indicate a prolonged period of Late Devonian to Early Mississippian (373±3 to 357±4 Ma) magmatism (Dusel-Bacon and others, 2004, 2005, 2006; C. Dusel-Bacon and J.N. Aleinikoff, unpub. data, 2007).

Quartz-rich schists and subordinate carbonaceous schist and marble of the informally named Healy schist form the core of a regional anticline (fig. B1). Carbonaceous metasedimentary rocks and minor conglomerate and rhyolite of the Keevy Peak Formation crop out north of, and stratigraphically above, the Healy schist (fig. B1). Bimodal — having both silica-poor (mafic) and silica-rich (felsic) compositions — metaigneous rocks, and carbonaceous and siliceous metasedimentary rocks of the Totatlanika Schist overlie the Keevy Peak Formation. Totatlanika Schist is subdivided into the following five members (Wahrhaftig 1968), from bottom to top: (1) Moose Creek (felsic and minor mafic schist); (2) California Creek (augen gneiss, grading to metarhyolite porphyry); (3) Chute Creek (metabasalt, which interfingers with both California Creek and Mystic Creek Members); (4) Mystic Creek (metarhyolite—mostly metamorphosed crystal tuff); and (5) Sheep Creek (quartzofeldspathic schist derived from near-source, reworked volcanic deposits; metasiltstone, metatuff, and marble). Carbonaceous phyllite, indistinguishable from that in the Keevy Peak Formation, is found within all members of the Totatlanika Schist. These rocks form a syncline, with the Sheep Creek Member occupying its core (fig. B1).

The Wood River assemblage comprises a package of metavolcanic and metasedimentary rocks on the south flank of the anticline cored by Healy schist (fig. B1). This assemblage has gross lithologic similarities to the metavolcanic and carbonaceous sedimentary assemblages in the Totatlanika Schist and was proposed by Gilbert and Bundtzen (1979) to be equivalent to it. One of the goals of our study was to evaluate this hypothesis, and our conclusions regarding this correlation are given below.

Deposits

Two of the largest VMS deposits in the Bonnifield district, the Red Mountain (Dry Creek) deposit and the WTF deposit, are located approximately 90 kilometers (km) south of Fairbanks in the northeastern part of the Wood River area (fig. B1). Both deposits are hosted by the Mystic Creek Member of the Totatlanika Schist and occur near the contact between phyllitic felsic metavolcanic and subordinate carbonaceous rocks of the Mystic Creek Member and the overlying, predominantly metasedimentary rocks of the Sheep Creek Member (Newberry and others, 1997; Smit, 1999). Drilling of one of the massive sulfide horizons just north of Red Mountain, named for its distinctive 1,800-meter (m)-thick zone of quartz-sericite-pyrite footwall alteration (fig. B2), identified an estimated resource of 3.2 million tons averaging 4.4 percent zinc, 1.9 percent lead, 0.2 percent copper, 3.01 ounces per ton (oz/t) silver, and 0.018 oz/t gold (Szumigala and Swainbank, 1998).

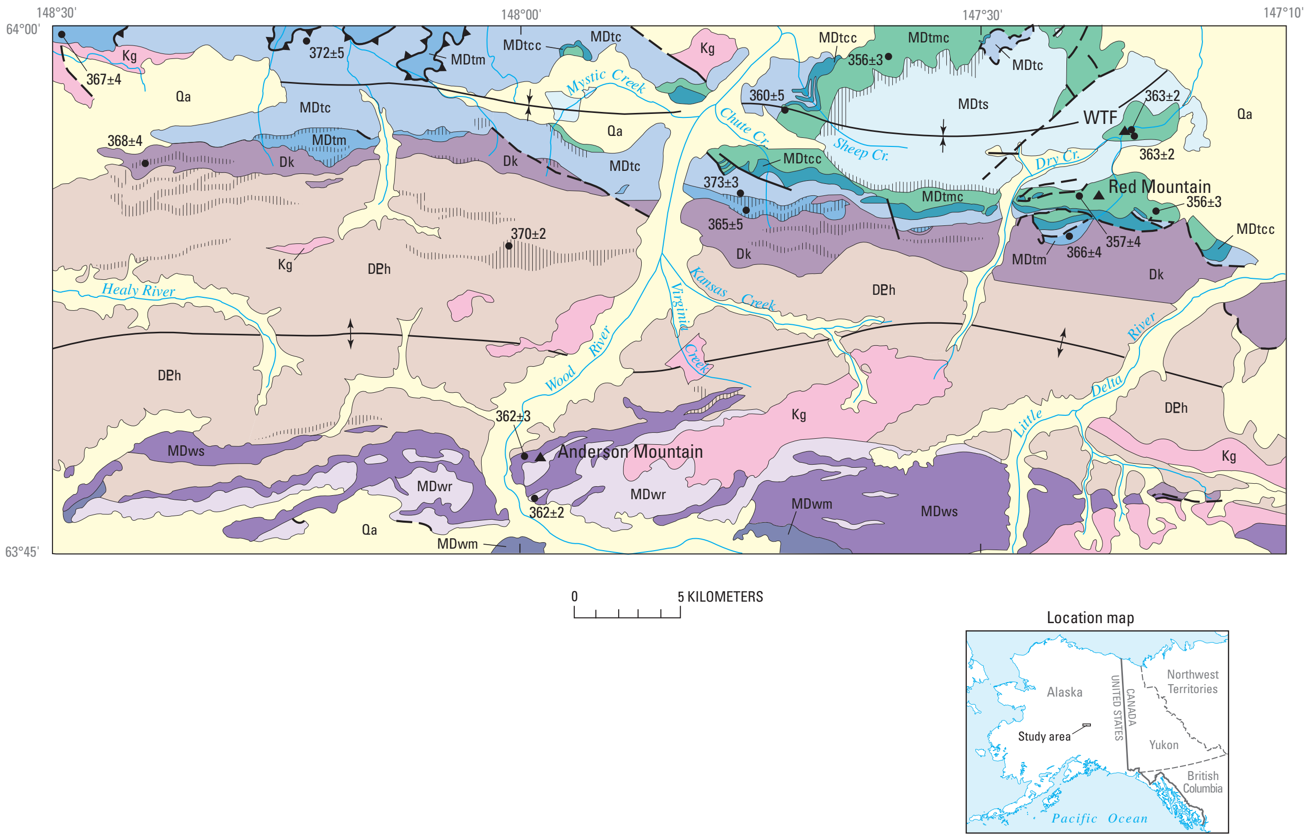
The WTF deposit (fig. B1) is located about 3 km northeast of Red Mountain. The structural and stratigraphic relationship between the WTF and Red Mountain deposits is disputed. Smit (1999) placed the shallowly dipping host rocks of the WTF deposit and the steeply north-dipping host rocks of the Red Mountain deposit on the northern and southern limbs, respectively, of an east-west-trending syncline (within the broader syncline cored by the Sheep Creek Member; fig. B1). Newberry and others (1997), on the other hand, placed the Red Mountain deposit in a separate and lower stratigraphic interval. As discussed below, our geochemical and U-Pb zircon sampling addressed these two possibilities. WTF has an estimated resource of 3.09 million tons averaging 6 percent zinc, 2.5 percent lead, 0.1 percent copper, 5.73 oz/t silver, and 0.029 oz/t gold (Szumigala and Swainbank, 1998).

The Anderson Mountain VMS prospect, located 32 km southwest of the Mystic Creek deposits, is exposed on the south limb of the antiform cored by the Healy schist. This prospect occurs within felsic to mafic metavolcanic rocks and associated carbonaceous metasedimentary rocks of the Wood River assemblage (fig. B1).

Methods

We collected outcrop and drill core samples of sulfide-bearing and unmineralized rocks from the Wood River area (figs. B1, B3) of the Bonnifield district. We utilized sensitive high-resolution ion microprobe (SHRIMP) U-Pb dating of zircon crystals separated from felsic igneous rocks to determine the crystallization ages of volcanic and plutonic units in the Wood River area (fig. B1). This dating technique has the advantage of being able to analyze minute (about 30-micrometer-diameter) areas, allowing age determination and analysis of both inherited zircon cores (from incorporated crustal material) and magmatic rims of zircons. Whole-rock neodymium isotopic compositions helped us identify the relative abundance of mantle versus continental crust components in the parent magmas of the metaigneous rocks.

A major part of our study employed whole-rock trace-element geochemistry of metaigneous rocks to determine their origin and tectonic setting, particularly of those that are associated with the VMS deposits. Considerable care was taken to sample only the freshest, least altered material. Our conclusions are based on trace elements that have been shown to be immobile, except during high-temperature metamorphism or because of pronounced hydrothermal alteration, neither of which has affected the rocks of the Wood River area. Because



EXPLANATION

- **Qa** Alluvium (Quaternary)
- **Kg** Granite (Cretaceous)

Totatlanika Schist (Early Mississippian to Late Devonian)— Individual members are mapped separately and listed below from youngest to oldest. Ages of individual members are based on SHRIMP U-Pb zircon ages and limited fossil age control. With the exception of the California Creek Member that yielded two Late Devonian ages, U-Pb zircon ages for all other dated members span the Late Devonian-Early Mississippian boundary (360±2 Ma; Okulitch, 2002); therefore, all members are assigned the map unit symbol of MD

- **MDts** Sheep Creek Member—Epiclastic quartz-feldspar-sericite schist and tuffaceous slate
- **MDtmc** Mystic Creek Member—Felsic metavolcanic schist
- **MDtcc** Chute Creek Member—Mafic metavolcanic schist
- **MDtc** California Creek Member—Quartz-potassium feldspar-sericite schist and augen gneiss
- **MDtm** Moose Creek Member—Quartz-potassium-feldspar gneiss, felsic schist, and mafic schist

Wood River assemblage (Early Mississippian to Late Devonian)

- **MDwm** Metasedimentary rock—Includes marble, quartzite, and calcarenite
- **MDws** Green metavolcanic schist and carbonaceous schist
- **MDwr** Rhyolite schist
- **Dk** Keevy Peak Formation (Devonian)—Quartz-sericite schist, carbonaceous quartz schist, slate, and stretched-pebble conglomerate
- **DЄh** Healy schist (informal) (Devonian and older)—Quartz-sericite schist, quartzite, chlorite schist, marble, and metagabbro
- Carbonaceous schist—Pattern superimposed on various units
- Contact
- Anticline
- Syncline
- Thrust fault—Sawteeth on upper plate
- Fault—Unclassified
- 362±3 Location of sample and SHRIMP zircon age (in Ma)
- ▲ Major volcanogenic massive sulfide (VMS) deposit

Figure B1. Generalized geologic map of the Wood River area, northeastern Healy quadrangle, showing the location of the three main volcanogenic massive sulfide targets and U-Pb zircon ages. Abbreviations are as follows: SHRIMP, sensitive high-resolution ion microprobe; Ma, millions of years. Geology modified from Wahrhaftig (1968) and Gilbert and Bundtzen (1979); SHRIMP U-Pb zircon crystallization ages from Dusel-Bacon and others (2004, 2005) and C. Dusel-Bacon and J.N. Aleinikoff (unpub. data, 2007).

Figure B2. View of Red Mountain, looking west, showing quartz-sericite-pyrite alteration and north-dipping metarhyolite of the Mystic Creek Member. Cynthia Dusel-Bacon and Melanie Hopkins (U.S. Geological Survey (USGS)) in foreground. Photograph by Charlie Bacon (USGS).

Figure B3. Sampling drill core from the Dry Creek VMS deposit, stored at the Ester core facility, Alaska. Geologists from left to right: Rainer Newberry (University of Alaska), Curt Freeman (Avalon Development Corp.), Cameron Rombach (U.S. Geological Survey (USGS)), and Melanie Hopkins (USGS). Photograph by Charlie Bacon (USGS).

of major-element mobility, especially of alkalis and silica, magma compositions are identified utilizing a Zr/TiO_2 versus Nb/Y diagram (fig. B4).

Results

U-Pb zircon crystallization ages indicate a prolonged period of felsic magmatism from 373±3 to 357±4 Ma (fig. B1). Ages determined on felsic samples from the various map units overlap one another. Crystallization ages from throughout the Mystic Creek Member of the Totatlanika Schist overlap within the range of 363±3 to 357±4 Ma. Metarhyolites hosting both the WTF and Anderson Mountain deposits include SHRIMP U-Pb zircon ages of about 363 Ma, but their whole-rock compositions, trace-element signatures, and neodymium isotope compositions differ, as discussed below. U-Pb analyses of zircon cores from Totatlanika Schist and Healy schist felsic rocks yield Archean and Proterozoic ages (ranging from 2,681±16 to 981±31 Ma; Dusel-Bacon and others, 2004).

Epsilon neodymium isotope values (εNd_t; time-corrected to 360 Ma) are relatively elevated for the Mystic Creek Member metarhyolites (-1.0, -1.5, -1.6) and Chute Creek metabasalts (+1.7 and +5.3), indicating an enriched mantle component for both members of the bimodal suite. In contrast, metarhyolite from the Wood River assemblage and the Healy schist have lower εNd_t values (-4.5 and -13.5, respectively), reflecting a large continental crustal component. Proterozoic neodymium model ages of 1,030 to 2,010 Ma for metarhyolites (including samples from the Mystic Creek Member, Wood River assemblage, and Healy schist) and 570 to 910 Ma for Chute Creek Member metabasalt are consistent with a continental margin setting.

Trace-element analyses indicate that the metarhyolites of the Mystic Creek Member and the metabasalts of the Chute Creek, Sheep Creek, and Mystic Creek Members have high concentrations of high-field-strength and rare-earth elements, and yttrium and gadolinium, relative to average continental crust (for the metarhyolites) and primitive mantle (for the metabasalts). High-field-strength elements (HFSE) are those elements with a high charge to ionic radius ratio and include Zr, Hf, Nb, Ta, and Ti; rare-earth elements (REE) include La, Ce, Nd, Sm, Eu, Gd, Yb, and Lu. Rare-earth elements, not surprisingly, also are anomalously high in surface and water samples collected in the vicinity of Red Mountain, which is underlain by Mystic Creek metarhyolite (Eppinger and others, this volume, chap. I). The Zr/TiO_2–Nb/Y diagram (fig. B4) reveals the distinctive, highly alkaline (“peralkaline”) composition of the Mystic Creek metarhyolites, which plot as comendites. In contrast, felsic rocks from the California and Moose Creek Members of the Totatlanika Schist have lower Nb/Y and Zr/TiO_2 ratios and plot as rhyodacite and dacite. Metabasalt from the Mystic Creek, Sheep Creek, and Chute Creek Members of the Totatlanika Schist also have high Nb/Y ratios and plot as alkali basalt. Compositions of the Wood River assemblage metavolcanic rocks differ from those of the Totatlanika Schist in that the former do not have alkaline compositions (that is, they do not fall within the alkali basalt, trachyandesite, trachyte, or comendite-pantellerite fields), with the exception of one sample that plots as a trachyte, and their compositions span a broad range that includes intermediate-composition andesite.

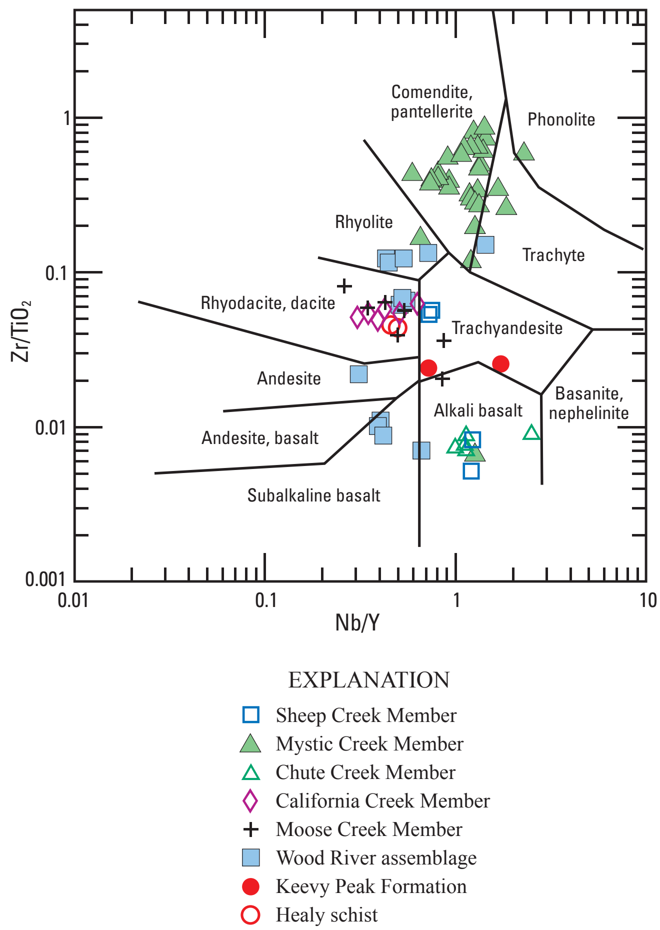


Figure B4. Metaigneous samples from the Wood River area plotted on the Zr/ TiO_2 versus Nb/Y discrimination diagram of Winchester and Floyd (1977).

Information about the tectonic setting in which magmas were generated can be attained from discrimination diagrams that utilize the immobile trace elements. The tantalum-ytterbium diagram (fig. B5) shows such information for our felsic igneous rocks (SiO_2 is 68–86 weight percent). The high tantalum and ytterbium contents of Mystic Creek peralkaline metarhyolites cause them to plot in the within-plate-granite field on the tantalum-ytterbium discrimination diagram (fig. B5). Within-plate rhyolites commonly are associated with rifting, an example being within-plate rhyolites from the Yellowstone Plateau volcanic field. Metarhyolites from the other members of the Totatlanika Schist and the Keevy Peak Formation plot in the field for volcanic-arc granites; however, the fact that their tantalum and ytterbium values are similar to the values for average upper continental crust (UCC, fig. B5) allows the possibility that the their chemical signatures could reflect involvement of continental crust during magma generation and ascent rather than being an indication of an arc (as opposed to a within-plate) setting. Wood River assemblage metarhyolites form a linear cluster that extends from the volcanic arc field into the transitional field between within-plate and anomalous ocean-ridge granites, in addition to having two samples that plot just inside the within-plate granite field.

The hafnium-thorium-tantalum diagram (fig. B6) shows the empirically determined magma types applicable to Bonnifield metabasalts (SiO_2 is 47–53 weight percent). Metabasalts from the Sheep Creek and Chute Creek Members of the Totatlanika Schist plot as ocean-island basalt (OIB), a magma type that is commonly associated with rifting and also is referred to as “within-plate basalt.” Metabasalts from the Wood River assemblage plot in the calc-alkalic arc basalt and the enriched mid-ocean-ridge fields.

Conclusions

A continental margin setting and original proximity to the North American craton for the Late Devonian and Early Mississippian VMS host rocks of the Bonnifield district is indicated by (1) the quartz-rich compositions of many metasedimentary rocks; (2) the presence of Archean and Proterozoic inherited zircon cores and detrital zircons; (3) radiogenic neodymium isotopic compositions for the Healy schist and, to a lesser degree, the Wood River assemblage; (4) Proterozoic neodymium model ages for the Totatlanika Schist, Healy schist, and Wood River assemblage; and (5) the similarity in trace-element ratios between some of the felsic metaigneous samples and average upper continental crust.

Evidence for an extensional setting for the submarine eruption of the Mystic Creek Member metarhyolite consists of (1) its peralkaline composition and inferred within-plate tectonic setting; (2) its association with Chute Creek Member basalt, which also has alkalic, within-plate trace-element characteristics; and (3) elevated εNd_t values for Mystic Creek metarhyolite and Chute Creek metabasalts that indicate an enriched mantle component for both members of the bimodal suite. Dusel-Bacon and others (2004) speculated that the distinctly peralkaline, within-plate metarhyolites of the Mystic Creek Member may have been partial melts of underplated, deep crustal alkalic gabbros that also were the source of the alkalic, within-plate metabasite of the Chute Creek Member. Dark-gray shales interstratified with metarhyolite and massive sulfide horizons at WTF and Red Mountain show HFSE and light-REE enrichment similar to that in Mystic Creek metarhyolite, suggesting a significant peralkaline rhyolitic tuff component in the seafloor sediments that is consistent with their deposition in a synvolcanic, extensional basin. Similar U-Pb ages and geochemical characteristics for the WTF and Red Mountain deposits suggest that they occur in the same host-rock stratigraphic interval and support the syncline model of Smit (1999).

Mid-Paleozoic bimodal magmatic rocks, including mafic rocks that have within-plate geochemical characteristics, occur throughout much of the Yukon-Tanana Upland and northern Alaska Range. Dusel-Bacon and others (2004, 2006) proposed that this magmatism resulted from attenuation of the continen-

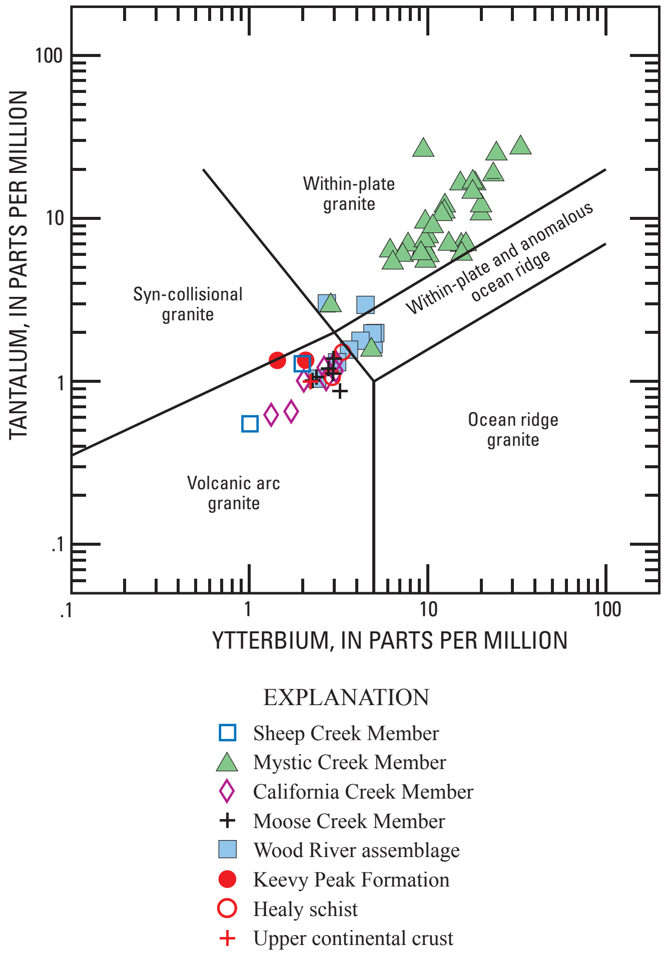


Figure B5. Felsic metaigneous samples from the Wood River area and the composition of average upper continental crust (values are those of McLennan, 2001) plotted on the tantalum-ytterbium (Ta-Yb) diagram of Pearce and others (1984).

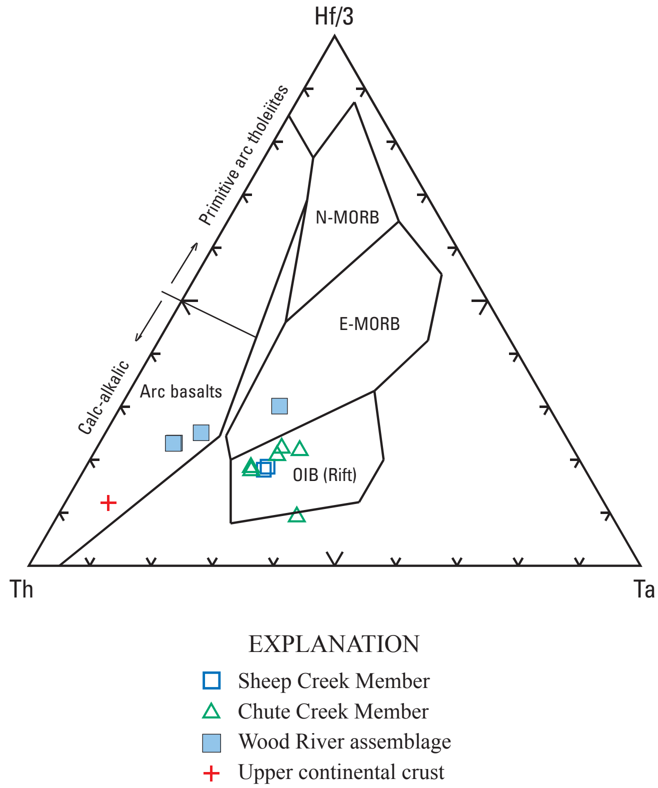


Figure B6. Mafic metavolcanic samples from the Wood River area plotted on the hafnium-thorium-tantalum (Hf-Th-Ta) diagram of Wood (1980). Abbreviations are as follows: E-MORB, enriched mid-ocean ridge basalt; N-MORB, normal mid-ocean ridge basalt; OIB, ocean-island basalt.

tal margin behind an east-dipping subduction zone. Evidence suggesting that the Wood River assemblage originated as an arc developed within continental crust above this subduction zone includes (1) metaigneous rocks that span a wide range of compositions, including andesitic rocks that are characteristic of arc magmatism; (2) some basalts that have trace-element arc signatures; and (3) an εNd_t value of -4.5 indicating a crustal component in the melt. This interpretation implies that the coeval Mystic Creek Member of the Totatlanika Schist formed an extensional (back-arc) basin that was associated with an outboard volcanic arc that included rocks of the Wood River assemblage (Dusel-Bacon and others, 2005).

Peralkaline metarhyolites of the Mystic Creek Member of the Totatlanika Schist that exhibit extreme within-plate geochemical characteristics host, or are associated with, the largest VMS deposits in the Bonnifield mining district. This association suggests that the presence of highly elevated HFSE and REE trace-element contents in metarhyolites, whose major-element compositions may have been altered, is an important prospecting tool for VMS deposits that formed in an extensional setting. Our trace-element data for Wood River assemblage metarhyolites that host the Anderson Mountain deposit further indicate that even slightly elevated HFSE and REE contents (for example, tantalum and ytterbium; fig. B5) can be prospective for VMS deposits formed in an arc setting.

Acknowledgments

We are indebted to Tom Bundtzen for introducing the senior author to the geology of the Wood River area. We also thank Pacific Alaska Resources Company geologists Barry Hoffmann, Jo Drechsler, Rob McLeod, Gary Andersen, and Ted Erdman; and Grayd Resource Corporation Vice President Hans Smit for providing access to drill core and company reports for the Bonnifield VMS deposits. Rainer Newberry, Sam Dashevsky, and Sean Bemis helped with drill core sampling. Curt Freeman, Cameron Rombach, Melanie Hopkins, and Charlie Bacon assisted during fieldwork, as well as drill core sampling. We thank Joe Wooden for re-analyzing one of the U-Pb zircon samples. This paper benefited from reviews by Marti Miller and Dave John.

References Cited

Dusel-Bacon, Cynthia, Hopkins, M.J., Mortensen, J.K., Dashevsky, S.S., Bressler, J.R., and Day, W.C., 2006, Paleozoic tectonic and metallogenic evolution of the pericratonic rocks of east-central Alaska and adjacent Yukon, *in* Colpron, Maurice, and Nelson, J.L., eds., Paleozoic evolution and metallogeny of pericratonic terranes at the ancient Pacific margin of North America, Canadian and Alaskan Cordillera: Geological Association of Canada, Special Paper 45, p. 25–74.

Dusel-Bacon, Cynthia, Premo, W.R., and Aleinikoff, J.N., 2005, Geochemical and Nd isotopic evidence for an extending continental-margin arc/back arc setting for peralkaline rhyolite-hosted massive sulfide deposits of the Bonnifield district, east-central Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 97.

Dusel-Bacon, Cynthia, Wooden, J.L., and Hopkins, M.J., 2004, U-Pb zircon and geochemical evidence for bimodal mid-Paleozoic magmatism and syngenetic base-metal mineralization in the Yukon-Tanana terrane, Alaska: Geological Society of America Bulletin, v. 116, no. 7–8, p. 989–1015.

Eppinger, R.G., Briggs, P.H., Dusel-Bacon, Cynthia, Giles, S.A., Gough, L.P., Hammarstrom, J.M., and Hubbard, B.E., 2007, Environmental geochemistry at Red Mountain, an unmined volcanogenic massive sulphide deposit in the Bonnifield district, Alaska Range, east-central Alaska: Geochemistry: Exploration, Environment, Analysis, v. 7, no. 3, p. 207–223.

Gilbert, W.G., and Bundtzen, T.K., 1979, Mid-Paleozoic tectonics, volcanism, and mineralization in north-central Alaska Range, *in* Sisson, Alexander, ed., The relationship of plate tectonics to Alaskan geology and resources, Proceedings, Alaska Geological Society Symposium 6, Anchorage, Alaska, April 4–6, 1977: Anchorage, Alaska, Alaska Geological Society, p. F1–F22.

McLennan, S.M., 2001, Relationships between the trace element composition of sedimentary rocks and upper continental crust: Geochemistry, Geophysics, Geosystems, v. 2, no. 4, 24 p., available only online at *http://www.agu.org/journals/gc/gc0104/2000GC000109*. (Subscription may be required.) (*doi: 10.1029/2000GC000109*)

Newberry, R.J., Crafford, T.C., Newkirk, S.R., Young, L.E., Nelson, S.W., and Duke, N.A., 1997, Volcanogenic massive sulfide deposits of Alaska: Economic Geology Monograph 9, p. 120–150.

Okulitch, A.V., 2002, Geological time chart, 2002: Geological Survey of Canada, Open File 3040, 1 sheet.

Pearce, J.A., Harris, N.B.W., and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 25, no. 4, p. 956–983.

Smit, H., 1999, The Dry Creek VMS project, Bonnifield district, central Alaska, *in* Pathways '99, Extended Abstracts Volume: Vancouver, British Columbia, Canada, British Columbia and Yukon Chamber of Mines, p. 17–18.

Szumigala, D.J., and Swainbank, R.C., 1998, Alaska's mineral industry 1998: Alaska Division of Geological and Geophysical Surveys Special Report 53, 71 p.

Wahrhaftig, Clyde, 1968, Schists of the central Alaska Range: U.S. Geological Survey Bulletin 1254–E, p. E1–E22.

Winchester, J.A., and Floyd, P.A., 1977, Geochemical discrimination of different magma series and their differentiation products using immoble elements: Chemical Geology, v. 20, no. 4, p. 325–343.

Wood, D.A., 1980, The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province: Earth and Planetary Science Letters, v. 50, no. 1, p. 11–30.