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The Southwestern Alaska Mercury Belt and Its Relationship to the circum-Pacific Metallogenic Mercury Province

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THEME 10: Metallogenetic Provinces in the Circum-Arctic Region

Summary: A belt of small but numerous mercury deposits extends for about 500 km in the Kuskokwim River region of southwestern Alaska. The southwestern Alaska mercury belt is part of widespread mercury deposits of the circum-Pacific region that are similar to other mercury deposits throughout the world because they are epithermal with formation temperatures of about 200 °C, the ore is dominantly cinnabar with Hg-Sb-As±Au geochemistry, and mineralized forms include vein, vein breccias, stockworks, replacements, and disseminations. The southwestern Alaska mercury belt has produced about 1,400 t of mercury, which is small on an international scale. However, additional mercury deposits are likely to be discovered because the terrain is topographically low with significant vegetation cover. Anomalous concentrations of gold in cinnabar ore suggest that gold deposits are possible in higher temperature environments below some of the Alaska mercury deposits. We correlate mineralization of the southwestern Alaska mercury deposits with Late Cretaceous and early Tertiary igneous activity. Our $^{40}Ar/^{39}Ar$ ages of 70 ±3 Ma from hydrothermal sericites in the mercury deposits indicate a temporal association of igneous activity and mineralization. Furthermore, we suggest that our geological and geochemical data from the mercury deposits indicate that ore fluids were generated primarily in surrounding sedimentary wall rocks when they were cut by Late Cretaceous and early Tertiary intrusions. In our ore genesis model, igneous activity provided the heat to initiate dehydration reactions and expel fluids from hydrous minerals and formational waters in the surrounding sedimentary wall rocks, causing thermal convection and hydrothermal fluid flow through permeable rocks and along fractures and faults. Our isotopic data from sulfide and alteration minerals of the mercury deposits indicate that ore fluids were derived from multiple sources, with most ore fluids originating from the sedimentary wall rocks.

INTRODUCTION

Mercury deposits found throughout the world are generally epithermal (<250 °C) and formed in hydrothermal systems at shallow depths. The largest mercury deposits in the world are concentrated primarily in two large subduction related volcanic-orogenic belts along present or past plate boundaries (Fig. 1), the Variscan belt extending through Europe and Asia and the circum-Pacific belt (BAILEY et al. 1973). The Europe-Asia belt extends from Spain, Algeria, Italy, Slovenia, Turkey, through the Himalayas, China, Mongolia, Russia, and into northeastern Siberia; this belt includes three of the largest mercury mines in the world, Almaden, Spain (260,000 t), Idria, Slovenia (103,000 t), and Monte Amiata, Italy (69,000 t) (Fig. 2). The circum-Pacific belt follows the western margin of South, Central, and North America, extends through California and southern Alaskan, southward to Japan, through the Philippines to New Zealand (BAILEY et al. 1973), and includes large mercury mines in the California Coast Ranges (121,000 t), and Huancavelica, Peru (52,000 t) (BAILEY et al. 1973, PEABODY 1993). The southwestern Alaska mercury belt is part of the circum-Pacific belt, and although the Alaska belt is small on an international scale, mercury production from the Alaska mercury belt has been important for the local economy.

Cinnabar was discovered in southwestern Alaska by Russian traders as early as 1838 along a bank of the Kuskokwim River near the site of the old Russian Fort at Kolmakof (Fig. 3), but they did not develop the deposit (CADY et al. 1955). Since that time, dozens of cinnabar- and stibnite-rich deposits were found scattered over several tens of thousands of square kilometers in the Kuskokwim River region (Fig. 3) (CADY et al. 1955, SAINSBURY & MACKEVETT 1965). Generally, the terrain throughout the region consists of low-rolling hills with abundant vegetation cover, and thus, most of the known mercury deposits are located proximal to large rivers and streams, many along the Kuskokwim River, the largest waterway in the region. Many of the mercury deposits were discovered by tracing cinnabar float and detrital material (usually in stream beds) back to their source (WEBBER et al. 1947). About 1,400 t of mercury were produced from the region from the early 1900's until the 1970's, which represents over 99 % of the mercury produced in Alaska (Fig. 2). Mercury mines in southwestern Alaska were generally small and retorted on-site with most mines producing less than one metric ton of mercury. For example, about 0.52 t of mercury was produced from the Barometer mine, near Sleetmute (CADY et al. 1955). The exception is the Red Devil mine (Fig. 3), the largest mercury mine in Alaska, where about 1,240 t of mercury were recovered (MILLER et al. 1989). Moderate-sized mines in the region were Decourcy Mountain and Cinnabar Creek that produced about 42 t and 18 t, respectively. The mercury mines of southwestern Alaska are presently closed, as are many mercury mines worldwide, due to low demand, low mercury prices, and significant recycling of mercury containing products.

Numerous metallic mineral resources are known from southwestern Alaska including gold, silver, tungsten, tin, copper, lead, and zinc (BUNDTZEN & MILLER 1997), but until recently, the mercury deposits were probably the most poorly understood (GRAY 1996). Using geologic, age, fluid inclusion, and stable

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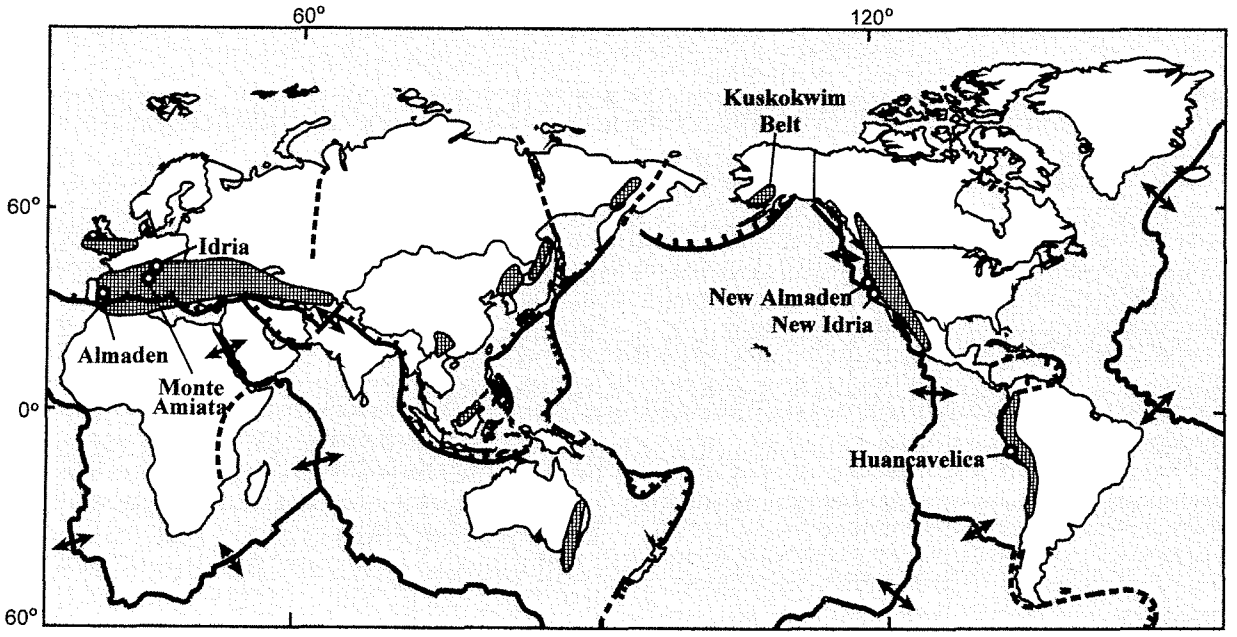


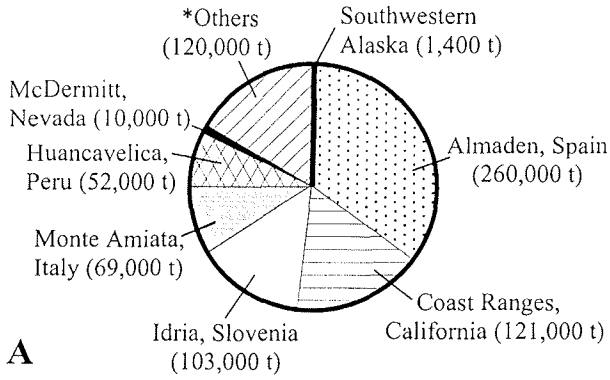
Fig. 1: Location of significant mercury mines (O) and mercury belts (cross-hatched areas) found worldwide (modified from BAILEY et al. 1973). Spreading centers are shown as solid lines with arrows and tectonic plate boundaries are shown as solid lines with hatch marks on upper plates. Inferred plate margins are dashed. The location of some of the largest mercury mines in the world are shown including: Almaden, Spain; Idria, Slovenia; Monte Amiata, Italy; Huancavelica, Peru; New Almaden and New Idria, California (part of the Coast Ranges mercury belt); and McDermitt, Nevada.

and radiogenic isotope data, GRAY (1996) suggested that there was a close association between the formation of the cinnabar- and stibnite-bearing deposits and the intrusions of Late Cretaceous and early Tertiary age found in the region, and that these deposits formed in shallow epithermal environments at temperatures generally less than 210 °C. These mercury deposits are probably related to deeper level precious- and base-metal vein deposits found in the region (GRAY 1996, BUNDTZEN & MILLER 1997). This paper briefly summarizes the geology, mineralogy, geochemistry, and genesis of the mercury deposits of southwestern Alaska, and their similarity to mercury deposits of the circum-Pacific region. For additional details of the epithermal mercury-antimony deposits of southwestern Alaska refer to GRAY (1996) and GRAY et al. (1997).

GEOLOGY, MINERALOGY, AND GECHEMISTRY OF THE ALASKA MERCURY BELT

The mercury deposits show a close spatial association with Late Cretaceous and early Tertiary intrusions that cut surrounding sedimentary wall rocks, and many of the deposits are hosted in these igneous rocks, or in contacts between the igneous and sedimentary rocks (CADY et al. 1955, SAINSBURY & MACKEVETT 1965, GRAY 1996). Postaccretionary Cretaceous clastic sedimentary rocks of the Kuskokwim Group are the most common sedimentary wall rocks, but mercury deposits also cut Paleozoic carbonate rocks of the Holitna Group of the Farewell terrane, and Late Triassic to Early Cretaceous sedimentary rocks of the Gemuk Group of the Togiak terrane (Fig. 3). Extensive geochronologic, petrologic, major- and trace-element geochemical, and isotopic studies of the Late Cretaceous and early Tertiary igneous rocks in the region indicate that these southwestern Alaska igneous complexes formed in a subduction-arc environment (WALLACE & ENGEBRETSON 1984, SZUMIGALA 1993, MOLL-STALCUP 1994). This Late Cretaceous and early Tertiary magmatism is interpreted to be part of a broad belt of volcanic and intrusive rocks (extending from the Alaska Range to beyond the Kuskokwim Mountains) that formed in response to northward, gently-dipping, rapid subduction of the Kula plate under southern Alaska (ENGEBRETSON et al. 1982, WALLACE & ENGEBRETSON 1984, WALLACE et al. 1989, MOLL-STALCUP 1994). Paleomagnetic data for the Late Cretaceous and early Tertiary rocks do not indicate significant northward translation of these rocks relative to North America, suggesting that they formed near their present locations; paleomagnetic results also indicate 30-55° of counterclockwise rotation of these rocks since the Paleocene (HILLHOUSE et al. 1985, THRUPP & COE 1986). MOLL-STALCUP (1994) indicates that the Late Cretaceous and early Tertiary rocks (about 75 to 56 Ma) are subduction related, calc-alkaline to shoshonitic in composition, and constitute an unusually wide magmatic arc. This arc initially consisted of the Alaska Range, Talkeetna Mountains, and the Kuskokwim Mountains from 75 to 66 Ma, broadening to include the Yukon-Kanuti belt from 65 to 56 Ma (Fig. 4) (MOLL-STALCUP 1994).

The mercury deposits commonly consist of mineralized veins and vein breccias, but stockworks, replacements, and disseminations are also found. Cinnabar and stibnite are the dominant minerals, whereas realgar, orpiment, pyrite, native mercury, gold, and hematite are less abundant (MACKEVETT & BERG 1963, SAINSBURY & MACKEVETT 1965, GRAY 1996). Cinnabar and stibnite are commonly found in open-space fillings in quartz-rich veins that also contain carbonate, limonite, dickite, and



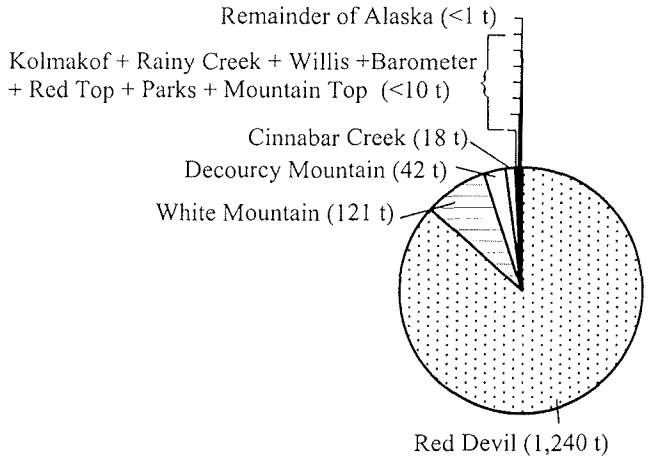


Fig. 2: Diagrams showing estimated mercury production in metric tons (t). (A) Mercury production from the mines in southwestern Alaska is compared to some of the largest mercury mines in the world. *Others includes several countries with the most significant mercury production in the past 30 years including Algeria, Canada, China, Czechoslovakia, Finland, West Germany, Mexico, Turkey, the former USSR (mostly Kyrgyzstan, Russia, Tajikistan, and Ukraine) and is estimated to be at least 120,000 t from 1996-1967. This estimate includes mining related by-product mercury such as that from base-metal mines in Czechoslovakia, Germany, and Finland.
(B) Mercury production from mines in southwestern Alaska (data from CADY et al. 1955, SAINSBURY & MACKEVETT 1965).

kaolinite gangue minerals; minor solid and liquid hydrocarbons and sericite are present locally. The mercury deposits generally consist of small, discontinuous mineralized veins that are typically less than 2.5 cm wide, but veins of 1 m in width and several tens of meters in length have been reported from a few deposits such as Red Devil (SAINSBURY & MACKEVETT 1965). Although most of the deposits are small, mercury grades can exceed 50 %, but generally ores contain about 1-5 % Hg and less that 1 % Sb and As (WEBBER et al. 1947, MACKEVETT & BERG 1963, SAINSBURY & MACKEVETT 1965). Mercury ore is generally base-metal poor (Tab. 1) (GRAY et al. 1991).

Ore samples collected from some of the southwestern Alaska mercury deposits contain anomalous concentrations of gold (Tab. 1) (HAWLEY et al. 1969, GRAY 1996). Gold has also been identified in detrital cinnabar nuggets collected downstream from cinnabar deposits (CADY et al. 1955) and in crushed heavy-mineral concentrates of ore samples collected from a few localities (GRAY 1996). These results are not particularly unusual because other epithermal mercury deposits are known to contain gold; for example, deposits in California such as the McLaughlin mine (LEHRMAN 1986) and the Wilbur Springs district (DONNELLY-NOLAN et al. 1993). Gold deposits may be present below some of the southwestern Alaska mercury deposits because the mercury deposits are scattered throughout a broad region where precious-metal and base-metal deposits are spatially related to Late Cretaceous and early Tertiary igneous complexes; furthermore, some of the precious-metal deposits contain cinnabar (BUNDTZEN & MILLER 1997), also indicating a possible association with the shallower mercury deposits. We have not thoroughly investigated the relationship of gold to the mercury deposits, but the association of epithermal deposits to deeper gold deposits in the area is supported by drilling of the Donlin Creek deposit were about 210,000 kg (6,700,000 oz) of gold reserves have been delineated (FREEMAN 1998) below the epithermal, stibnite-rich Snow Gulch prospect (Fig. 3).

AGE OF MINERALIZATION AND TEMPERATURE OF FORMATION

Hydrothermal sericite was separated from altered rocks collected adjacent to mineralized veins from the Fairview prospect, Rhyolite prospect, and Snow Gulch deposit. At these localities, mineralized veins are located in altered granite-porphyry dikes or adjacent sedimentary rocks of the Kuskokwim Group; sericite and kaolinite replace potassium feldspar in the altered dikes. Our field and petrographic observations of intergrown cinnabar, stibnite, and hydrothermal sericite indicate that sericite formation and ore-mineral precipitation were coeval. $^{40}Ar/^{39}Ar$ ages we have determined are: (1) 72.6 ±0.8 Ma (plateau age) for the Fairview prospect, (2) 69.5 ±1.1 Ma (isochron age) for the Snow Gulch prospect, and (3) 70.9 Ma (minimum age) for the Rhyolite prospect (GRAY 1996). These hydrothermal-sericite ages are similar to 75 to 56 Ma intrusions that are spatially associated with the deposits indicating a temporal relationship between mercury mineralization and Late Cretaceous and early Tertiary magmatism in southwestern Alaska.

We conducted fluid-inclusion studies on vein samples from several mercury deposits in southwestern Alaska to help determine the nature of the ore-forming fluids and the environment of deposition. We made microthermometry measurements and mass spectrometry analyses on fluid inclusions in hydrothermal quartz crystals containing cinnabar, and on quartz crystals intergrown with cinnabar. The fluid inclusions we studied were a two-phase, liquid + vapor type and daughter salt minerals were not observed in the inclusions. Such liquid-vapor inclusions are common in many epithermal deposits (BODNAR et al. 1985). For the Red Devil, Decourcy Mountain, Kagati Lake, and Fairview deposits studied, fluid inclusion homogenization temperatures ranged from about 131 to 211 °C. Ice-melting temperatures that

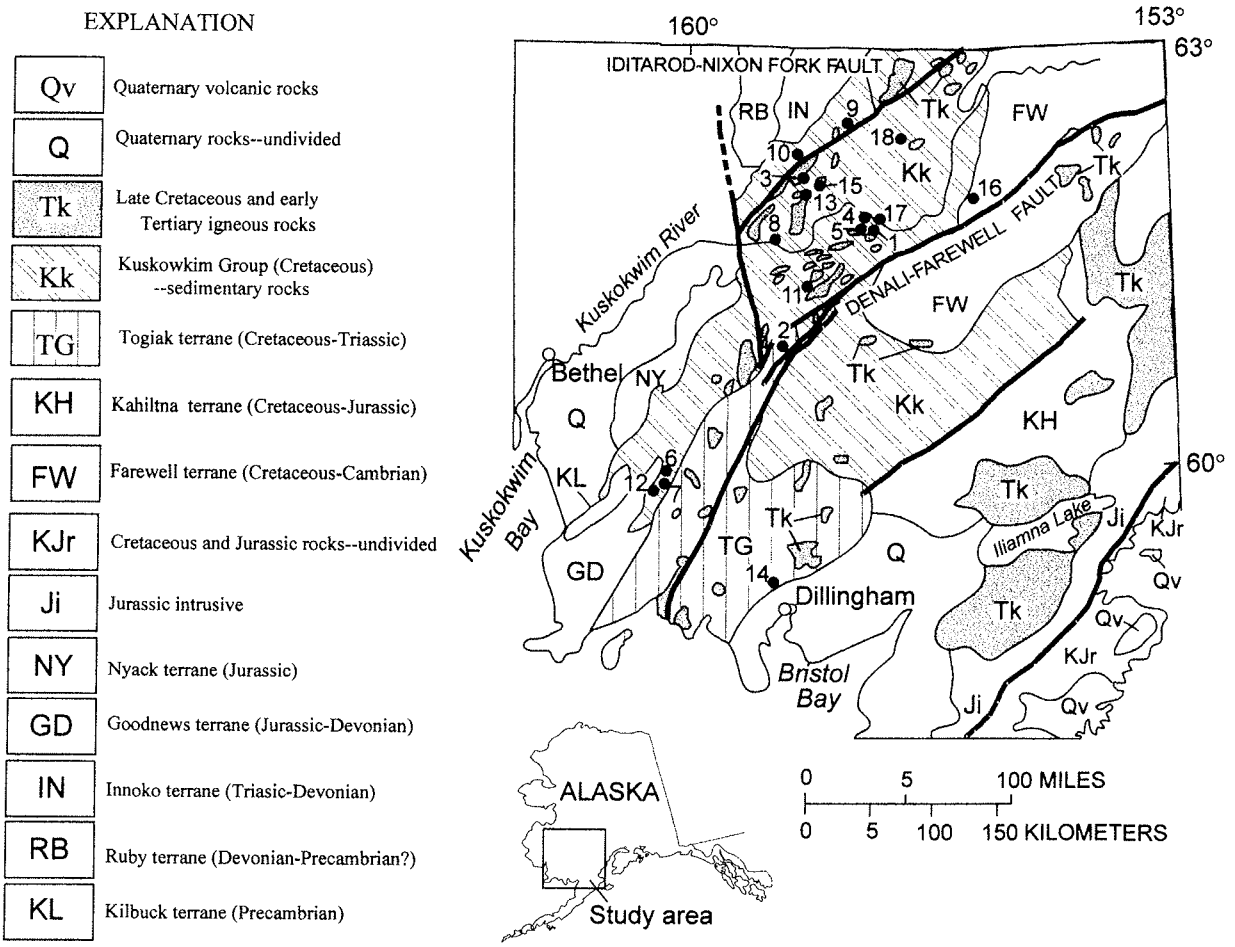


Fig. 3: Simplified geologic map showing location of mercury mines and mercury-antimony deposits in southwestern Alaska. The mercury mines and deposits numbered are: (1) Red Devil mine, (2) Cinnabar Creek mine, (3) Decourcy Mountain mine, (4) Barometer mine, (5) Fairview prospect, (6) Fisher Dome prospect (7) Kagati Lake prospect, (8) Kolmakof mine, (9) McGimsey prospect, (10) Millers prospect, (11) Mountain Top mine, (12) Rainy Creek mine, (13) Rhyolite prospect, (14) Red Top mine, (15) Snow Gulch prospect, (16) White Mountain mine, (17) Willis mine, and (18) Granite Creek prospect. Geology generalized from CADY et al. (1955), DECKER et al. (1994), BUNDTZEN & MILLER (1997).

we measured indicate that fluid salinities vary from 1.5-4.6 wt.% NaCl equivalent; such low salinities are similar to those observed in other epithermal deposits (BODNAR et al. 1985). Using our trapping temperatures (131-211 °C) and assuming that confining pressure was hydrostatic, resultant pressure-volume-temperature relationships indicate trapping pressures of about 150 to 200 bars, or a depth of formation for the deposits of about 1,500 m. If the confining pressure was partially lithostatic (which is more realistic), then the depth of formation for would be less than 1500 m.

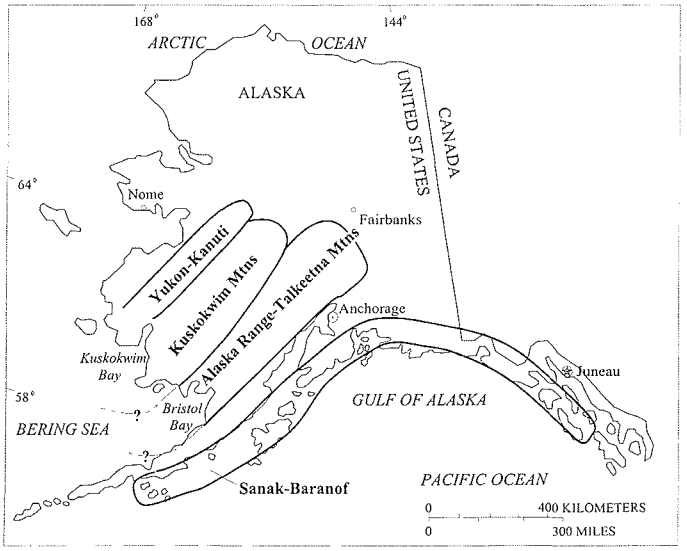


Fig. 4: Location of Late Cretaceous and early Tertiary igneous belts in southern and southwestern Alaska (modified from MOLL-STALCUP 1994).

Microthermometry data and quadrupole mass spectrometric analysis of fluid-inclusion volatiles provide a quantitative estimate of the composition of the inclusions. Volatile compositions of fluid inclusions were determined for hydrothermal quartz crystals from Red Devil and Decourcy Mountain. Microthermometry data indicate that the fluid inclusions generally contain more than 95 % H_2O; gas analyses indicate that inclusions contain as much as about 4 % CO_2, with traces of N_2 and CH_4 (GRAY 1996). These results confirm the presence of hydrocarbons in some fluid inclusions and indicate that organic matter was probably added to ore fluids during the formation of the mercury deposits.

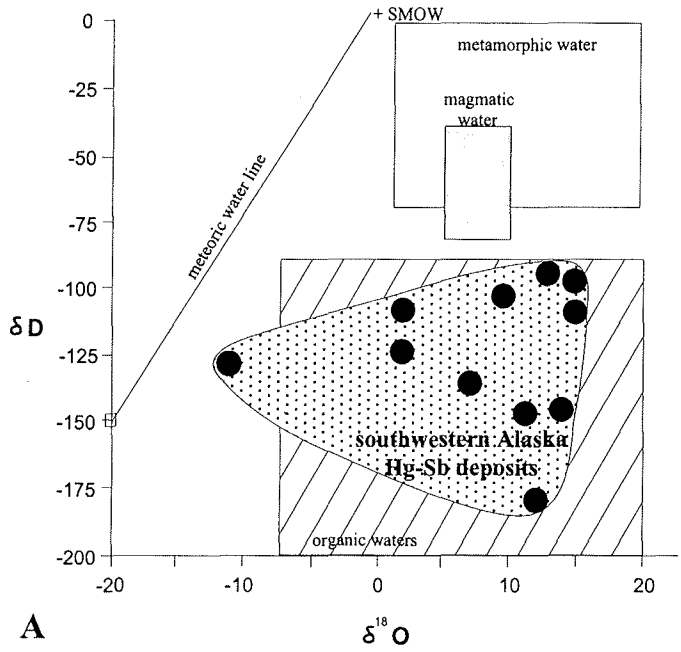
Sample	Hg (%)	Sb (ppm)	As (ppm)	Ag (ppm)	Au (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)
Red Devil-1	>1 %	2,200	73	<0.07	0.66	<0.03	<0.7	<0.02
Red Devil-1C	—	>8,000	>3,000	.26	4.4	12	9.2	<.03
Red Devil-1D	—	>8,000	390	.45	1.1	8.8	11	<.03
Red Devil-4	>1 %	>9,300	230	<.07	.2	<.02	<.7	<.02
Cinnabar Creek-1B	>1 %	13	94	<.07	<.002	2.7	1.2	<.03
Cinnabar Creek-50	>1 %	>10,000	7,000	—	.40	—	—	—
Mountain Top-1C	—	4	7.3	.12	.32	<.03	1.5	<.03
Kolmakof-1	>1 %	12	<.7	.15	.064	7.9	3.3	<.02
Kolmakof-3	>1 %	130	17	13	87	53	11	<.02
Kolmakof-4	>1 %	200	54	38	150	66	18	3.4
Barometer-3	>1 %	>9,300	410	<.07	1.1	52	<.7	<.02
Barometer-4	>1 %	>9,300	780	<.07	1.6	13	1.8	<.02
Fairview-1	>1 %	>9,300	480	<.07	.012	<.02	<.7	<.02
Fairview-2	>1 %	>9,300	170	<.07	.009	<.02	<.7	<.02
Rhyolite-1	>1 %	120	90	.79	.005	23	4.4	<.02
Rhyolite-2	>1 %	1,800	150	.41	.15	18	6.0	5.2
Rhyolite-3	>1 %	480	200	.31	.76	24	5.6	31
White Mountain 1A	>1 %	18	20	.09	.37	<.03	1.5	<.03

Tab. 1: Trace-element concentrations in ore samples collected from mercury mines and deposits in southwestern Alaska (see Figure 3 for locations). Analysis of Hg by cold-vapor atomic absorption spectrophotometry; Sb, As, Ag, Cu, Pb, and Zn by inductively coupled plasma spectrometry; Au by atomic absorption spectrophotometry; —, not determined]

ISOTOPIC STUDIES OF THE SOUTHWESTERN ALASKA MERCURY DEPOSITS

We measured oxygen and hydrogen isotope ratios in pure mineral separates, primarily in hydrothermal quartz associated with ore minerals for oxygen, and dickite for hydrogen. Hydrogen ratios were normalized to Vienna-Standard Mean Ocean Water (V-SMOW) and Standard Light Antarctic Precipitation (SLAP). Analytical reproducibility is ±0.2 ‰ for oxygen and ±3 ‰ for hydrogen. Isotope values are expressed relative to V-SMOW in standard $d^{18}O$ notation for oxygen and dD for hydrogen. The $d^{18}O$ values determined for twenty-six samples of vein quartz from the southwestern Alaska mercury deposits are highly variable from +0.3 to +29.4 ‰ (GRAY 1996). Using an average homogenization temperature (180 °C) from our fluid inclusion studies and the equilibrium fractionation equation for quartz-water (CLAYTON et al. 1972), the compositions of ore fluids calculated to be in equilibrium with hydrothermal quartz range from about -12 to +16 ‰ $d^{18}O$ (Fig. 5A). However, most of the ore fluids are isotopically heavy and ranged from about +7 to +15 ‰ $d^{18}O$. Such heavy oxygen isotope compositions indicate that the ore fluids that formed these deposits were derived largely from a heavy oxygen-isotope source and if meteoric water was involved, it was not the dominant fluid source. Sedimentary host rocks are the most likely heavy oxygen-isotope source involved during the formation of the mercury deposits (Fig. 5A). The $d^{18}O$ values of whole-rock shale and graywacke samples of the Kuskokwim Group analyzed range from +17.0 to +19.9 ‰, averaging about +18.2 ‰, and are evidence of the presence of high $d^{18}O$ source rocks in the study area. Hydrothermal fluids with isotopically heavy oxygen were probably generated when igneous intrusions heated local formation waters and dehydrated minerals in the surrounding sedimentary wall rocks. In such contact metamorphic zones, liberated hydrothermal fluids moved along fractures and, in some instances, mixed with local meteoric water. This interpretation is consistent with the close proximity of intrusions, sedimentary rocks, and the mercury deposits. Some contribution of magmatic water, commonly $d^{18}O$ = +5 to +10 ‰ (TAYLOR 1979), may have also been added the hydrothermal fluids, and is even likely, considering the close temporal and spatial relationship of the intrusions to the deposits. However, magmatic water cannot be the only heavy oxygen-isotope reservoir because it probably was not isotopically heavy enough to explain the high $d^{18}O$ fluid values for the mercury deposits.

We determined hydrogen isotopic compositions for twelve hydrothermal mineral samples collected from various mercury deposits which also suggest a sedimentary rock source. Hydrogen isotopic compositions (dD) of hydrothermal minerals (pri-



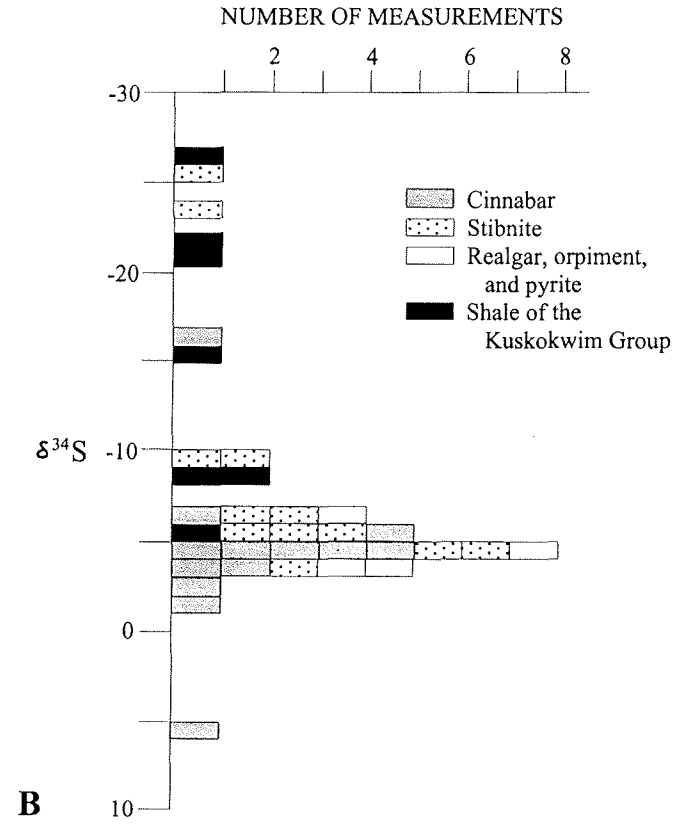


Fig. 5: (A) Isotopic compositions of oxygen and hydrogen for ore fluids for the Hg-Sb lodes (solid circles), calculated at 180 °C using the fractionation equation from CLAYTON et al. (1972). Fields shown for reference are metamorphic and magmatic waters (TAYLOR 1979), and organic waters derived primarily from sedimentary rocks (SHEPPARD 1986). SMOW-Standard mean ocean water. (B) Sulfur isotope compositions of ore minerals from mercury deposits in southwestern Alaska and surrounding sedimentary rocks.

marily dickite) from the mercury deposits are low, ranging from -92 to -181 ‰. These highly negative hydrogen-isotope compositions are similar to those derived during dehydration, devolatilization, oxidation, or exchange reactions in sedimentary rocks forming organic-rich fluids that are depleted in deuterium (SHEPPARD 1986). Fluid inclusions containing CO_2, CH_4, and N_2 gases also suggest that they were added to ore fluids when sedimentary rock organic matter was broken down during the formation of the mercury deposits. The range of the dD values in dickite indicates that some portion of the hydrogen was inherited from sedimentary rocks during breakdown of organic matter (Fig. 5A). Dehydration and devolatilization is the most likely mechanism for breaking down organic matter when the sedimentary rocks were heated during local intrusion of magmas.

Sulfur isotope ratios determined for twenty-eight mineral separates from ore samples and seven whole-rock samples of Kuskowkim Group rocks were used to identify sources of sulfur involved in the formation of the mercury deposits (GRAY 1996). Sulfur isotope ratios are expressed relative to Canyon Diablo Troilite and have a precision of ±0.2 ‰. The $d^{34}S$ data for samples of sulfide minerals indicate derivation of sulfur from multiple sources such as local sedimentary rocks (-26.5 to -5.2 ‰ $d^{34}S$) and magmatic sulfur (0 ±3 ‰; OHMOTO & RYE 1979). The $d^{34}S$ values for ore sulfides are generally between -25.0 to -1.7 ‰ and are within the $d^{34}S$ endpoint values defined by local sedimentary rocks and magmatic sulfur (Fig. 5B). The negative $d^{34}S$ values determined for most of the sulfide minerals are similar to those for sedimentary wall rocks of the Kuskokwim Group and indicate a significant proportion of sulfur was probably derived from these local sedimentary rocks, probably sedimentary pyrite and organic sulfur, during the formation of the mercury deposits (GRAY 1996). The close spatial association of intrusions and the mercury deposits suggests that magmatic sulfur would be a probable component in the ore forming fluids. A magmatic sulfur source could be derived from magmatic fluids or dissolution of sulfide minerals in the igneous rocks during hydrothermal alteration.

Lead isotope compositions were measured in nine ore mineral separates from vein samples to identify sources of lead involved during the formation of the mercury deposits. All lead isotope determinations were made by solid-source mass spectrometry. Values were corrected for thermal fractionation using the NBS SRM-981 common lead standard, and are accurate within 0.1 percent at the 95 % confidence level. The lead isotope compositions of ores collected from the mercury deposits range from $^{206}Pb/^{204}Pb$ = 18.75 to 19.03, $^{207}Pb/^{204}Pb$ = 15.54 to 15.65, and $^{208}Pb/^{204}Pb$ = 38.14 to 38.65 (GRAY 1996). The lead isotope compositions of the mercury deposits are similar to those of Late Cretaceous and early Tertiary igneous rocks in southwestern Alaska (SZUMIGALA 1993, MOLL-STALCUP written commun. 1995). Similar to the oxygen, hydrogen, and sulfur isotope data, the lead isotope compositions of the mercury deposits suggest derivation of lead from multiple sources, such as proximal sedi-

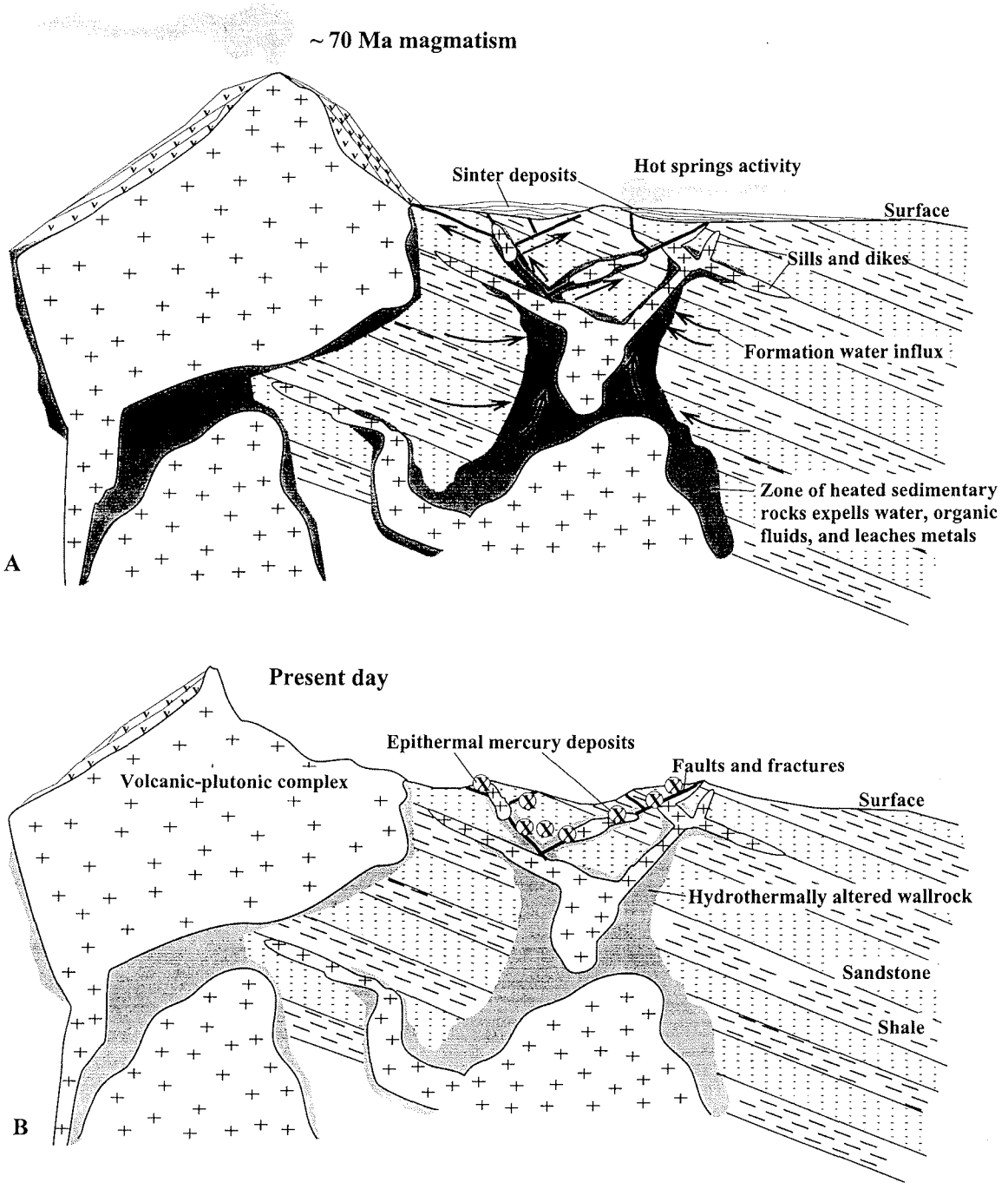


Fig. 6: Schematic formation model for the southwestern Alaska mercury deposits. (A) Hydrothermal activity is closely related to emplacement of magmas primarily into intercalated shales and graywackes. Fluids are expelled from the heated sedimentary rocks and flow along faults and fractures forming vein deposits near the surface. Arrows indicate direction of hydrothermal fluid flow. (B) Shows the present day location of epithermal mercury deposits after erosion since Late Cretaceous-early Tertiary time. The deposits are found in faults, fractures, and permeable rocks, as well as in and near geologic contacts between sedimentary and igneous rocks.

mentary and igneous rocks. The radiogenic character of lead isotope values of the mercury deposits indicates that if lead from a mantle source was involved it was probably minor; for example, local intrusions spatially associated with the mercury deposits may provide a source of mantle lead because they were formed in a magmatic arc. The lead isotope data for the mercury deposits indicates little or no lead from a lower crust (cratonized crust) source.

GENESIS MODEL FOR MINERALIZATION

Our geologic, fluid inclusion, and isotopic data for the southwestern Alaska mercury deposits indicate that ore fluids were derived from multiple sources. Most of the ore fluids probably originated from sedimentary wall rocks, but evolved meteoric water and magmatic water were important local fluid sources for some deposits. The majority of the deposits studied have

heavy oxygen isotope ore fluid compositions ($d^{18}O$) of about +6 to +15 ‰ that indicate a sedimentary rock source. Light sulfur and hydrogen isotope compositions of the mercury deposits also indicate derivation from sedimentary rocks. Hydrous minerals and formation waters were the primary ore-fluid sources in the sedimentary rocks. The sedimentary rocks have undergone little or no regional metamorphism (MILLER et al. 1989) and as a result there has been only minor dewatering of the rocks, and clay minerals have not undergone conversion to metamorphic minerals. Hydrous minerals, formational waters, and sedimentary rocks would have similar $d^{18}O$ compositions because the trapped waters isotopically equilibrate gradually with the rocks over time. Some of the mercury deposits have $d^{18}O$ fluid compositions as light as -11 ‰ that we interpret to represent evolved meteoric water. Thus, the dominant fluid sources were from sedimentary rocks and meteoric waters, but some component of magmatic water of about $d^{18}O$ +5 to +10 ‰ is also possible and consistent with the geology of the deposits. In addition, $d^{34}S$ values of ore sulfide minerals indicate that sulfur was derived from sedimentary rock and magmatic sources during the formation of the mercury deposits.

The close spatial association and similar ages of the mercury deposits and Late Cretaceous and early Tertiary intrusions indicates a relationship between mineralization and magmatism (Fig. 6). High heat flow related to igneous activity probably induced reaction with surrounding sedimentary wall rocks. The igneous activity initiated thermal convection, expelled formation waters, and dehydrated minerals from contact metamorphic aureoles (Fig. 6). These expelled hydrothermal fluids flowed through permeable rocks and fractures, reacted with wall rocks, and in some cases mixed with meteoric water. Isotopic data for oxygen, hydrogen, sulfur, and lead indicates that a significant part of the ore fluids originated from sedimentary rocks. In addition, the occurrence of solid and liquid hydrocarbons in some of the mercury deposits, as well as fluid inclusions containing constituents such as CO_2, N_2, and CH_4, probably indicates that organic matter in the sedimentary rocks was also broken down during contact metamorphism and released into ore fluids. Mercury, and perhaps other metals, were probably derived from sedimentary wall rocks (GRAY 1996). Surrounding sedimentary rocks are the most likely source of mercury because crustal abundances of Hg are generally higher in shale (0.4 ppm), than in granitic (0.04 ppm), mafic (0.01 ppm), and ultramafic (0.004 ppm) igneous rocks (ROSE et al. 1979). In addition, the average Hg concentration in shale of the Kuskokwim Group is about 0.6 ppm (24 samples) and about 0.36 ppm in sandstone (43 samples)(GRAY 1996), which are higher than worldwide averages of 0.4 ppm Hg for shale and 0.03 ppm Hg in sandstone (ROSE et al. 1979). These data suggest that sedimentary wall rocks were probably an important local source of Hg.

SIMILARITY OF THE ALASKA DEPOSITS TO THE CIRCUM-PACIFIC MERCURY BELT

Deposits in the southwestern Alaska mercury belt are epithermal, hydrothermal deposits using the classification of LINDGREN (1933). Diagnostic characteristics of these deposits include their Hg-Sb-As±Au geochemistry, formation temperatures of about 200 °C, mineralized forms including vein, vein breccias, stockworks, replacements, and disseminations, open-space ore textures, quartz and carbonate gangue, and argillic alteration. Many of these characteristics are similar to those of hot-spring mercury deposits (WHITE & ROBERSON 1962, RYTUBA 1986). Perhaps the best example of an epithermal, hot-spring system is McLaughlin, California, where cinnabar in siliceous sinter (the Manhattan mine) was located above a gold-rich deposit (the McLaughlin mine) (LEHRMAN 1986). Siliceous sinter representing surface deposition of silica that is common in hot-spring deposits, has not been observed in any of the southwestern Alaska mercury deposits, but erosion could have removed any sinter deposits.

We consider the southwestern Alaska mercury deposits analogous to the mercury deposits of the California Coast Ranges (DONNELLY-NOLAN et al. 1993) and New Zealand (DAVEY & VAN MOORT 1986) of the circum-Pacific mercury belt. Mercury deposits in California have been extensively studied; examples include, Sulphur Bank (WHITE & ROBERSON 1962, DONNELLY-NOLAN et al. 1993), New Idria (BOCTOR et al. 1987), McLaughlin and Manhattan (LEHRMAN 1986), Culver-Baer (PEABODY & EINAUDI 1992), and the Wilbur Springs district (DONNELLY-NOLAN et al. 1993). For most of these deposits, geologic, isotopic, and age data indicate that there is a relationship between mercury mineralization and heating of sedimentary rocks in response to magmatism (WHITE & ROBERSON 1962, WHITE et al. 1973, PEABODY & EINAUDI 1992, DONNELLY-NOLAN et al. 1993). Isotopic and fluid chemistry characteristics of several of the northern California deposits indicate that ore fluids were primarily derived from mixed evolved connate and meteoric waters (WHITE et al. 1973, DONNELLY-NOLAN et al. 1993). DONNELLY-NOLAN et al. (1993) related hydrothermal activity to shallow, 0.5-0.8 Ma magmatism that heated sedimentary and metasedimentary rocks of the Franciscan Complex and Great Valley sequence and initiated thermal convection and hydrothermal fluid flow along fractures and faults, primarily the San Andreas transform fault system. Similarly, present-day hot-springs deposition of mercury at Ngawha Springs, New Zealand has been related to shallow magmatic intrusions heating basement sediments (DAVEY & VAN MOORT 1986).

Mercury deposits worldwide are found in nearly all rock types, but studies of large mercury deposits such as Almaden, Spain (SAUPÉ & ARNOLD 1992), Huancavelica, Peru (MCKEE et al. 1986), and those in California (DONNELLY-NOLAN et al. 1993, PEABODY 1993) generally indicate that mercury deposit formation was related to interaction of igneous activity with surrounding rocks. Similarly, our data strongly favor a connection between mercury mineralization and subduction-related igneous activity indicating that ore fluids were derived primarily from surrounding sedimentary rocks as they were heated by local intrusions.

7. CONCLUSIONS

• The southwestern Alaska epithermal mercury deposits contain relatively simple mineralogy. Ore is dominantly cinnabar with subordinate stibnite, native mercury, realgar, orpiment, pyrite, and gold. Although the southwestern Alaska mercury belt is small (about 1400 t) compared to large deposits found in the circum-Pacific (about 121000 t from the California Coast Ranges) and throughout the world, their mineralogy is similar (cinnabar dominant).

• Anomalous gold concentrations in ore from several of the southwestern Alaska deposits suggest that the mercury deposits may be the epithermal part of deeper gold and base-metal systems.

• Our ages for the mercury deposits in southwestern Alaska are about 70 ±3 Ma, similar to nearby intrusions indicating that hydrothermal mineralization was closely related to Late Cretaceous-early Tertiary magmatism (about 75-56 Ma) that was generated during subduction of the Kula plate under southern Alaska.

• Our geologic and isotopic data for the mercury deposits indicate that Late Cretaceous and early Tertiary igneous activity provided the heat source to initiate hydrothermal convection and fluid flow. Ore fluids were derived from multiple sources, but primarily from surrounding sedimentary wall rocks heated by the local igneous activity. The intrusions initiated dehydration reactions and expelled formation waters and organic fluids from the sedimentary rocks. Isotopically light oxygen ore-fluid values indicate the involvement of exchanged meteoric water during the formation of some mercury deposits. Minor contributions of magmatic water to ore fluids are also possible and consistent with local geology. Mercury was probably derived from surrounding sedimentary wall rocks.

References

Bailey, E.H., Clark, A.L., & Smith, R.M. (1973): Mercury.- In: D.A. BROBST & W.P. PRATT (eds.), United States Mineral Resources. U.S. Geol. Surv. Prof. Paper 820: 401-414.

Bocton, N.Z., Shieh, Y.N., & Kullerud, G. (1987): Mercury ores from the New Idria district, California: Geochemical and stable isotope studies.- Geochim. Cosmochim. Acta 51: 1705-1715.

Bodnar, R.J., Reynolds, T.J., & Kuehn, C.A. (1985): Fluid inclusion systematics in epithermal systems.- In: B.R. BERGER & P.M. BETHKE (eds.), Geology and Geochemistry of Epithermal Systems. Soc. Econ. Geol., Rev. Econ. Geol. 2: 73-97.

Bundtzen, T.K., & Miller, M.L. (1997): Precious metals associated with Late Cretaceous-early Tertiary igneous rocks of southwestern Alaska.- In: R.J. GOLDFARB & L.D. MILLER (eds.), Mineral Deposits of Alaska. Econ. Geol. Monogr. 9: 242-286.

Cady, W.M., Wallace, R.E., Hoare, J.M., & Webber, E.J. (1955): The central Kuskokwim region, Alaska.- U.S. Geol. Surv. Prof. Paper 268: 132 pp.

Clayton, R.N., O'Neil, J.R., & Mayeda, T.K. (1972): Oxygen isotope exchange between quartz and water.- J. Geophy. Res. 77: 3057-3067.

Davey, H.A., & van Moort, J.C. (1986): Current mercury deposition at Ngawha Springs, New Zealand.- Appl. Geochem. 1: 75-93.

Decker, John, Bergman, S.C., Blodgett, R.B., Box, S.E., Bundtzen, T.K., Clough, J.G., Coonrad, W.L., Gilbert, W.G., Miller, M.L., Murphy, J.M., Robinson, M.S., & Wallace, W.K. (1994): Geology of southwestern Alaska.- In: G. PLAFKER & H.C. BERG (eds.), The Geology of Alaska. Geol. Soc. Am. G-1: 285-310.

Donnelly-Nolan, J.M., Burns, M.G., Goff, F.E., Peters, E.K., & Thompson, J.M. (1993): The Geysers-Clear Lake area, California: Thermal waters, mineralization, volcanism, and geothermal potential.- Econ. Geol. 88: 301-316.

Engebretson, D.C., Cox, A., & Gordon, R.G. (1982): Relative motions between oceanic and continental plates in the Pacific Basin.- Geol. Soc. Am. Spec. Paper 206: 59 pp.

Freeman, C.J. (1998): Exploration Review.- Soc. Econ. Geol. Newsletter 34: 28.

Gray, J.E. (1996): Exploration, genesis, and environmental geochemistry of mined and unmined mercury-antimony vein lodes in southwestern Alaska.- Boulder, Univ. Colorado, Ph.D. Thesis: 297 pp.

Gray, J.E., Gent, C.A., Snee, L.W., & Wilson, F.H. (1997): Epithermal mercury-antimony and gold-bearing vein lodes of southwestern Alaska.- In: R.J. GOLDFARB & L.D. MILLER (eds.), Econ. Geol. Monogr. 9: 287-305.

Gray, J.E., Goldfarb, R.J., Detra, D.E., & Slaughter, K.E. (1991): Geochemistry and exploration criteria for cinnabar-stibnite epithermal vein systems in the Kuskokwim River region, southwest Alaska.- J. Geochem. Expl. 41: 363-386.

Hawley, C.C., Martinez, E.E., & Marinenko, J.W. (1969): Geochemical data on the south ore zone, White Mountain mine and on the gold content of other mercury ores, southwestern Alaska.- U.S. Geol. Surv. Circ. 615: 16-20.

Hillhouse, J.W., Grommé, C.S., & Csejtey, Béla, Jr. (1985): Tectonic implications of paleomagnetic poles from early Tertiary volcanic rocks, south-central Alaska.- J. Geophy. Res. 90: 12,523-12,535.

Lehrman, N.J. (1986): The McLaughlin mine, Napa and Yolo counties, California.- In: J.V. TINGLEY & H.F. BONHAM (eds.), Precious-metal mineralization in hot springs systems, Nevada-California. Nevada Bureau Mines Geol. Rep. 41: 85-89.

Lindgren, W. (1933): Mineral deposits.- 4th ed., McGraw-Hill Book Co., Inc., New York: 930 pp.

MacKevett, E.M., Jr., & Berg, H.C. (1963): Geology of the Red Devil quicksilver mine, Alaska.- U.S. Geol. Surv. Bull. 1142-G: G1-G16.

McKee, E.H., Noble, D.C., & Vidal, C. (1986): Timing of volcanic and hydrothermal activity, Huancavelica mercury district, Peru.- Econ. Geol. 81: 489-492.

Miller, M.L., Belkin, H.E., Blodgett, R.B., Bundtzen, T.K., Cady, J.W., Goldfarb, R.J., Gray, J.E., McGimsey, R.G., & Simpson, S.L. (1989): Pre-field study and mineral resource assessment of the Sleetmute quadrangle, southwestern Alaska.- U.S. Geol. Surv. Open-File Rep. 89-363: 115 pp.

Moll-Stalcup, E.J. (1994): Latest Cretaceous and Cenozoic magmatism in mainland Alaska.- In: G. PLAFKER & H.C. BERG (eds.), The Geology of Alaska. Geol. Soc. Am. G-1: 589-619.

Ohmoto, H., & Rye, R.O. (1979): Isotopes of sulfur and carbon.- In: H.L. BARNES (ed.), Geochemistry of Hydrothermal Ore Deposits.- 2nd ed., John Wiley & Sons, New York: 509-567.

Peabody, C.E. (1993): The association of cinnabar and bitumen in mercury deposits of the California Coast Ranges.- In: J. PARNELL, H. KUCHA, & P. LANDAIS (eds.), Bitumens in Ore Deposits. Society for Geology Applied to Mineral Deposits. Spec. Publ. 9, Springer-Verlag, New York: 178-209.

Peabody, C.E., & Einaudi, M.T. (1992): Origin of petroleum and mercury in the Culver-Baer cinnabar deposit, Mayacmas district, California.- Econ. Geol. 87: 1078-1103.

Rose, A.W., Hawkes, H.E., & Webb, J.S., (1979): Geochemistry in mineral exploration.- 2nd ed., Academic Press, New York, 657 p.

Rytuba, J.J. (1986): Descriptive model of hot-spring Hg.- In: D.P. COX & D.A. SINGER (eds.), Mineral Deposit Models. U.S. Geol. Surv. Bull. 1693: 178-179.

Sainsbury, C.L., & MacKevett, E.M., Jr. (1965): Quicksilver deposits of southwestern Alaska.- U.S. Geol. Surv. Bull. 1187, 89 pp.

Saupé, F., & Arnold, M. (1992): Sulphur isotope geochemistry of the ores and country rocks at the Almaden mercury deposit, Ciudad Real, Spain.- Geochim. Cosmochim. Acta 56: 3675-3780.

Sheppard, S.M.F. (1986): Characterization and isotopic variations in natural waters.- In: J.W. VALLEY, H.P. TAYLOR, & J.R. O'NEIL (eds.), Stable isotopes in high temperature geological processes. Mineral. Soc. Am., Rev. Min. 16: 165-183.

Szumigala, D.J. (1993): Gold mineralization related to Cretaceous-Tertiary magmatism in the Kuskokwim Mountains of west-central and southwestern Alaska.- Ph.D. Thesis, Univ. California, Los Angeles, 301 pp.

Taylor, H.P., Jr. (1979): Oxygen and hydrogen isotope relationships in hydrothermal mineral deposits.- In: H.L. BARNES (ed.), Geochemistry of Hydrothermal Ore Deposits, 2nd ed., John Wiley & Sons, New York: 236-277.

Thrupp, G.A., & Coe, R.S. (1986): Early Tertiary paleomagnetic evidence and the displacement of southern Alaska.- Geology 14: 213-217.

Wallace, W.K., & Engebretson, D.C. (1984): Relationship between plate motions and Late Cretaceous to Paleogene magmatism in southwestern Alaska.- Tectonics 3: 295-315.

Wallace, W.K., Hanks, C.L., & Rogers, J.F. (1989): The southern Kahiltna terrane: Implication for the tectonic evolution of southwestern Alaska.- Geol. Soc. Am. Bull. 101: 1389-1407.

Webber, B.S., Bjorklund, S.C., Rutledge, F.A., Thomas, B.I., & Wright, W.S. (1947): Mercury deposits of southwestern Alaska.- U.S. Bureau Mines Rep. Inv. 4065, 57 pp.

White, D.E., Barnes, I., & O'Neil, J.R. (1973): Thermal and mineral waters of non-meteoric origin, California Coast Ranges.- Geol. Soc. Am. Bull. 84: 547-560.

White, D.E., & Roberson, C.E. (1962): Sulphur Bank, California, a major hot spring quicksilver deposit.- Geol. Soc. Am. Bull., Vol. to Honor A.F. Buddington: 397-428.