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# Applications of Gravity Data to Studies of Framework Geology, Evaluation of Mineral Deposits, and Mineral Prospecting in Northwestern Alaska

*By* David F. Barnes *and* John S. Kelley

More than 5,000 gravity measurements in the western Brooks Range, Alaska, aid in the interpretation of thrust-belt structures, estimation of the mass of two known mineral deposits, and possible identification of other undiscovered mineral deposits. The data set includes reconnaissance measurements that use river gradients and altimetry for elevation control and have an accuracy of about 15 m, very detailed traverses over two ore deposits, where surveyed elevations are accurate to about 0.3 m, and 3,500 measurements with similar surveyed elevation control along seismic lines in the National Petroleum Reserve in Alaska (NPRA).

Geologic structures are reflected in an arcuate band of strongly positive isostatic anomalies that strike northeastward approximately parallel to geologic grain across the western end of the Brooks Range. These anomalies are

Figure 1 (Barnes and Kelley). Oblique aerial photograph of the Nimiuktuk barite deposit, which forms a small hill (10 m high, 50 m wide, and 80 m long) of almost pure barite in the western Brooks Range, Alaska. Nimiuktuk and the giant Red Dog massive sulfide deposit were used to define the gravitational signature searched for among the 3,500 gravity measurements of the National Petroleum Reserve in Alaska. The photograph was taken from the west-northwest by I.L. Tailleur in 1978.

coincident with a belt of mafic volcanic and plutonic rocks, which many workers believe to be klippen of an extensive thrust sheet rooted in the Angayucham terrane along the south flank of the Brooks Range. Magnitudes of the isostatic anomalies are, however, much larger than those associated with rocks of the Angayucham terrane. The sources of positive gravity anomalies are better modeled as inclined stocks or, possibly, stacked slabs of igneous rocks rather than as simple klippen. The postulated stocks are probably still close to their emplacement sites.

Detailed gravity surveys of the Nimiuktuk (fig. 1) and Red Dog mineral deposits are part of the western Brooks Range data set. Two gravity profiles across the Nimiuktuk barite body indicated a 2-mgal anomaly having horizontal dimensions of more than 100 m. The model that best fits the Nimiuktuk deposit is a cylinder having a density contrast of 1.70 $g/cm^3$; this model implies that the deposit is almost pure barite and has a radius and depth of about 50 m and a total mass of about 1.5 Mt. The Red Dog massive sulfide deposit, nearing production in 1990, causes a gravity anomaly of about 2 mgal with horizontal dimensions of about 200×500 m; an associated barite-rich body has an anomaly of about 4 mgal with horizontal dimensions of about 500×700 m. Preliminary estimates of ore quantities based on densities from surface sampling and possible mathematical models are comparable to those provided by early developmental drilling. The agreement among the estimates probably is partly due to the shallowness of the deposit.

The NPRA investigation within the mountainous part of northwestern Alaska included more than 3,500 gravity measurements with surveyed elevation control and station separations of about 400 m. Anomalies similar to those at Nimiuktuk and Red Dog appear in this data set as single-station spikes having amplitudes of 2–4 mgal; initially, such spikes were deleted from the data set because they were considered either errors or anomalies too narrow to represent deep structures. However, in 1981, the entire data set was reviewed, and 12 single-station anomalies in areas geologically favorable for mineralization and having associated geochemical anomalies were selected for possible verification and reexamination. In the ensuing 9 yr, only one anomaly has been reinvestigated. Here the gravity and elevation data were verified, but an adjacent bedrock outcrop indicated that basement topography beneath Quaternary sediments might explain the anomaly. The remaining promising gravity anomalies are yet to be field checked.

## Assessment of Undiscovered Mineral Resources, Tongass National Forest, Southeastern Alaska

*By* David A. Brew, Lawrence J. Drew, Jeanine M. Schmidt, David H. Root, *and* Donald F. Huber

The Tongass National Forest is the Nation's largest national forest; it covers about 70,000 km$^2$, which is more than 80 percent of southeastern Alaska (fig. 1). The U.S. Forest Service, which is revising the Tongass Land Management Plan, has requested resource information from many sources, has analyzed and interpreted the information, and has prepared a Draft Environmental Impact Statement. It is now reviewing the comments thereon and revising the alternatives prior to releasing the Final Environmental Impact Statement. The Forest Service is attempting to include mineral-resource data in the plan.

The U.S. Geological Survey (USGS) has been continuously active in southeastern Alaska since 1956 and is currently conducting a probabilistic assessment of the undiscovered mineral resources of the region. This regional assessment is based largely on previously completed assessments of individual Wilderness Areas, Wilderness Study Areas, and quadrangles that make up almost all of southeastern Alaska and that have been mapped at the scale of 1:250,000 as part of the Alaska Mineral Resources Assessment Project. These previously completed assessments were based on USGS reconnaissance geologic, geochemical, and geophysical mapping that has been reported in USGS publications. A few assessments were joint USGS-U.S. Bureau of Mines (USBM) efforts, and one is primarily a joint effort by the USBM and the State of Alaska Division of Geological and Geophysical Surveys. Only 4 of the 15 quadrangles in southeastern Alaska are not included in a preexisting assessment; however, 2 of the 4 are already studied.

The available data on regional geology, economic geology, stream-sediment and panned-concentrate geochemistry, bedrock geochemistry, and mineral resources were reviewed at the 1:250,000 scale along with aeromagnetic, gravity, aeroradiometric, and telegeologic information. One hundred twenty-seven mineral-resource tracts, ranging in area from 16 to 2,920 km$^2$, were identified as likely to contain undiscovered metallic mineral resources in 34 different types of deposits. Each tract was judged to contain one or more different types of mineral deposits. The number of as-yet-undiscovered deposits of each type discoverable by conventional mineral exploration methods was estimated for each tract at the 0.95, 0.90, 0.50, 0.10, and 0.05 probability levels. Many small tracts were combined to allow probabilistic assessment, but, because such assessments were not made of the smallest tracts or of tracts judged to be already well explored, we made final probabilistic assessments of 96 tracts containing 21 different types of deposits. Areas not assigned to tracts are interpreted to lack undiscovered mineral deposits of the types specified.

Estimates of the number of deposits in each tract were used in combination with the worldwide tonnage and grade distributions for each deposit type to calculate a probabilistic undiscovered mineral-resource endowment for each tract by means of the USGS MARK3 mineral-resource-endowment simulator (Root and Scott, 1988). By Monte Carlo simulation, this computer program produces a distribution of tonnages for each metal contained in each deposit type in a given tract. When aggregated over all deposit types, these distributions yield a probabilistic estimate of the undiscovered mineral resources in each tract. The estimates of mineral-resource endowment for all the individual tracts are combined to provide an aggregated estimate of the undiscovered mineral-resource endowment of the Tongass National Forest and adjacent lands in southeastern Alaska.

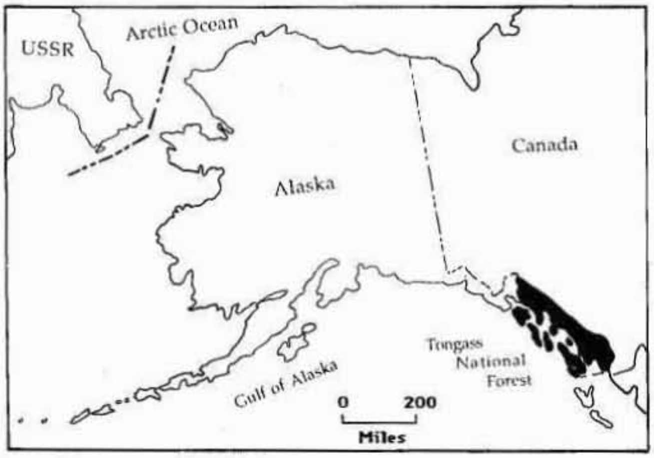


**Figure 1** (Brew and others). Location of the Tongass National Forest in southeastern Alaska.

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## Laser-Microprobe Studies of Sulfur Isotopes in Stockwork and Massive Sulfide Ores, Rua Cove Mine, South-Central Alaska

*By* Douglas E. Crowe, Wayne C. Shanks III, *and* John W. Valley

Many of the massive sulfide deposits in the Prince William Sound district of south-central Alaska (fig. 1), which historically were interpreted as epigenetic vein and replacement deposits, recently have been reinterpreted as volcanogenic massive sulfide (VMS) deposits formed syngenetically on or near the sea floor (Wiltse, 1973; Koski and others, 1985; Crowe and others, 1988). Understanding the origin of the deposits is critical for defining this region as a potential exploration target for VMS deposits. The morphologies and geologic settings of the deposits are consistent with Cyprus- and Besshi-type VMS models. The host rocks are predominantly flysch and dismembered ophiolite of the Chugach (Late Cretaceous) and Prince William (early Tertiary) terranes, which constitute the bulk of the rocks exposed in southern Alaska. Conventional analyses of stable sulfur isotopes show $\delta^{34}S$ ranging from +3.5 to +4.5 per mil; these values are consistent with a VMS model for the deposits but are not definitive. The major limitation to obtaining meaningful isotope data is the fine-grained, intergrown nature of the sulfide ores that typify the deposits.

A new laser-microprobe technique for performing micro-scale stable-isotope analyses (Crowe and others, 1990) allows us to measure sulfur-isotope ratios of individual minerals in fine-grained slabbed samples. Sulfur-isotope data were collected at the University of Wisconsin, Madison, by using a Nd-YAG (yttrium-aluminum-garnet) laser connected to an isotope-ratio mass spectrometer. A similar system (which uses a $CO_2$ laser) at the U.S. Geological Survey in Reston, Va., is shown in figure 2. Laser-microprobe sulfur-isotope data for samples from the Rua Cove mine, Prince William Sound, provide new evidence that many of these deposits are syngenetic.

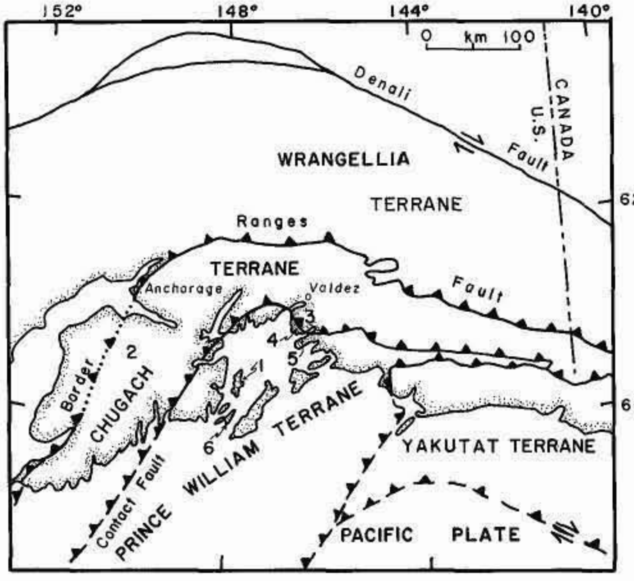


**Figure 1** (Crowe and others). Tectonostratigraphic terranes and locations of mines in selected historically significant massive sulfide deposits in south-central Alaska. 1, Rua Cove mine; 2, Lynx Creek mine; 3, Standard Copper mine; 4, Ellamar mine; 5, Port Fidalgo mine; 6, Beatson mine.

Conventional combustion-extraction measurements of $\delta^{34}S$ from hand-picked coexisting chalcopyrite-pyrrhotite (cp-po) pairs (fig. 3) from both the massive sulfide blanket and the underlying stockwork feeder zone indicate isotopic disequilibrium; pyrrhotite is slightly depleted in $^{34}S$, in contrast to the expected equilibrium enrichment with respect to chalcopyrite. The conventional data are inconsistent with ore formation by epigenetic replacement and vein mineralization or by syngenetic precipitation in the stockwork zone of a VMS deposit. Physical separation of the cp-po pairs is difficult because the samples are fine grained; thus, the results obtained conventionally are suspect.

Laser-microprobe analyses of the same samples (fig. 3) reveal that the stockwork sulfide pairs *are* in isotopic equilibrium if $\Delta_{cp-po}$ = 1.4 per mil at the 300 °C temperature indicated by fluid-inclusion homogenization data. However, the massive sulfide sample analyzed by laser microprobe shows an average $\Delta_{cp-po}$ = 2.1 per mil; this value suggests either lower temperature precipitation or rapid quenching. These data are inconsistent with epige-

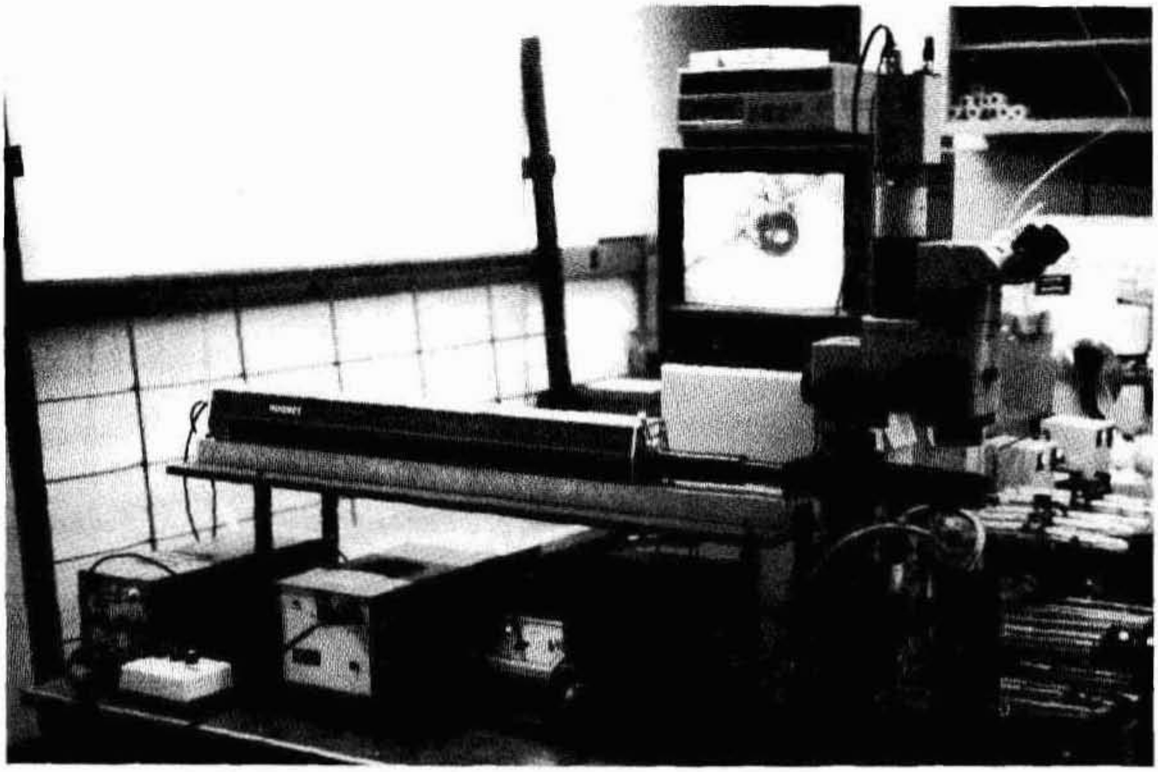

Figure 2 (Crowe and others). $CO_2$ laser microprobe connected to an isotope-ratio mass spectrometer at the U.S. Geological Survey in Reston, Va. The equipment is used to determine sulfur-isotope ratios for individual minerals in fine-grained slabbed rocks. Photograph by W.C. Shanks III in 1990.

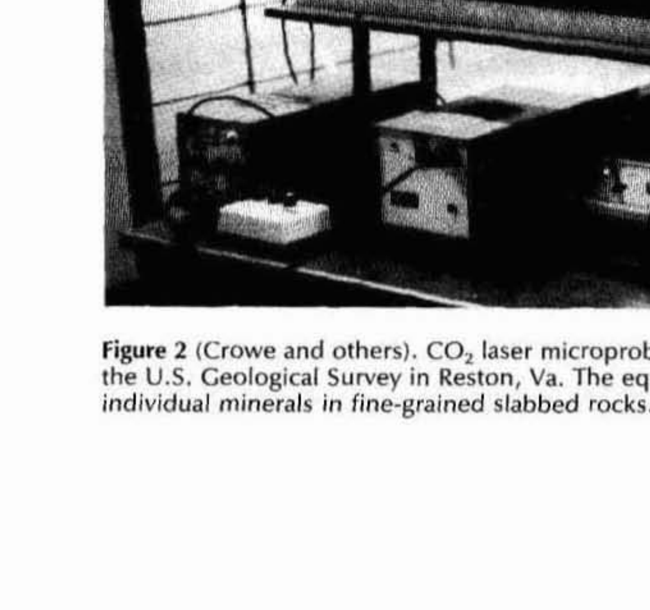


**Figure 3** (Crowe and others). Conventional and laser-microprobe data for sulfur isotopes from the Rua Cove mine. The fine-grained, intergrown nature of the chalcopyrite-pyrrhotite (cp-po) pairs made conventional mineral separation difficult; this difficulty is reflected in the nearly identical $\delta^{34}S$ values for these sulfides. The laser-microprobe data indicate equilibrium $\delta^{34}S$ values for the stockwork pairs and lower temperature or disequilibrium $\delta^{34}S$ values for the massive sulfide pairs.

netic vein or replacement formation under equilibrium conditions at similar temperatures, where spatial variations in temperature required to produce $\Delta_{co-po}$ variations of this magnitude are uncommon. The laser-microprobe data are consistent with the predicted isotopic values for sulfide mineral pairs from the physicochemically distinct stockwork and massive sulfide environments.

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# Lithologic and Tectonic Controls on Mercury Mineralization in the Bethel 1° × 3° Quadrangle, Southwestern Alaska

*By* Thomas P. Frost *and* Stephen E. Box

As part of the Alaska Mineral Resources Assessment Project (AMRAP), 1,486 stream-sediment and 1,104 heavy-mineral-concentrate samples were collected from first- and second-order streams from 1987 to 1989 in the Bethel 1° × 3° quadrangle and in the southern part of the Russian Mission quadrangle in southwestern Alaska. In addition, 1,375 bedrock samples were analyzed. Mercury and, to a lesser extent, arsenic contents are closely linked to locally subtle variations in bedrock lithology and to major structural elements in the area.

The region is underlain by at least five pre-mid-Cretaceous tectonostratigraphic terranes (fig. 1). Proterozoic orthogneisses and granitic rocks make up the Kilbuck terrane; Paleozoic and Mesozoic arc- and oceanic-affinity metabasalts, metacherts, clastic rocks, and minor marble are present in the Goodnews, Togiak, and Tikchik terranes; and Mesozoic arc volcanic rocks make up the Nyac terrane. Unconformably overlying all but the Nyac terrane is the Lower and Upper Cretaceous Kuskokwim Group, which consists predominantly of marine turbidites. Shallow-marine to deep-marine conglomerates and sandstones are present above a basal unconformity in the central part of the Kuskokwim basin.

The Kuskokwim Group can be divided into three belts, each having a distinct provenance. The western belt consists of an eastward-prograding deltaic sequence derived from an enigmatic chert-rich source area not presently exposed in the Bethel region. The basement on which the westernmost chert-rich facies was deposited is also not exposed. The eastern belt rests unconformably on the Togiak terrane and consists of turbiditic base-of-slope deposits derived from an eroded volcanic source. The central belt was deposited in a northeastward-flowing submarine fan system, which received sediment from both flanks and from a southern high-grade metamorphic source. The Kuskokwim Group was complexly deformed prior to the Late Cretaceous to early Tertiary magmatic episode.

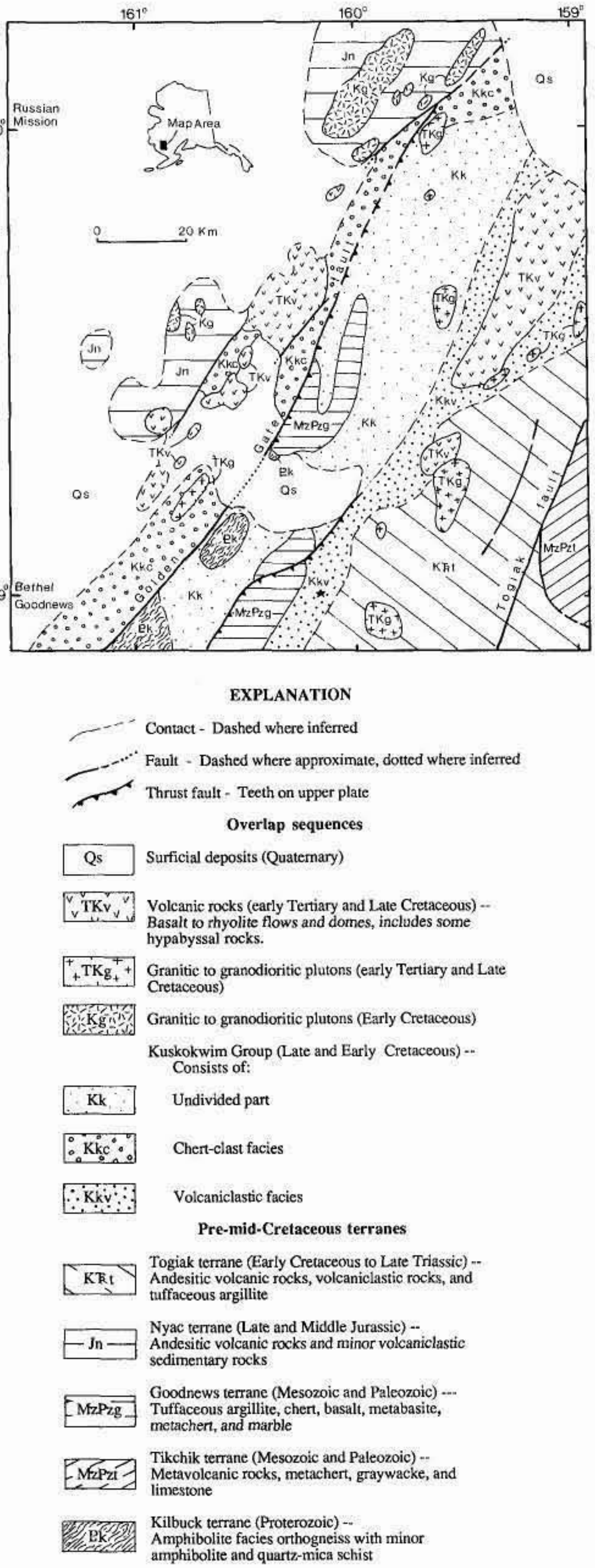


**Figure 1** (Frost and Box). Regional geology of the Bethel quadrangle and parts of the Russian Mission and Goodnews quadrangles, southwestern Alaska. The Rainy Creek locality is indicated by a star.

Granitic to granodioritic rocks of Early Cretaceous age were emplaced only in the Nyac terrane. Similar plutons (73–55 Ma) were emplaced in the older terranes to the east and in the overlying Kuskokwim Group. Wall rocks generally are metamorphosed to biotite and cordierite hornfels within a kilometer of the intrusive contacts.

Latest Cretaceous and early Tertiary intermediate to silicic volcanic fields and hypabyssal intrusions were erupted through both the eastern volcaniclastic and western chert-rich facies of the Kuskokwim Group. Rhyolite domes and ash-flow tuffs, which may be part of the western volcanic field, also were erupted through the andesitic volcanic rocks of the Nyac terrane, the westernmost of the exposed basement terranes. Dikes of andesitic to dacitic composition are common throughout the Kuskokwim Group and older rocks, although their relationship to the volcanic fields is uncertain.

Anomalous mercury contents are present in sedimentary rocks of the Kuskokwim Group (0.5–1.1 ppm Hg), in overlying volcanic rocks (0.5–11 ppm Hg), and in stream sediments (1–>36 ppm Hg) wherever the eastern volcaniclastic facies of the Kuskokwim Group is exposed in the region. The epithermal Rainy Creek mercury prospect (Sainsbury and MacKevett, 1965) at the southern edge of the Bethel quadrangle is hosted by the eastern volcaniclastic facies of the Kuskokwim Group. Anomalous mercury concentrations (1–10 ppm) also are present in stream-sediment samples from just west of the eastern volcaniclastic facies of the Kuskokwim Group, where it is strongly deformed by east-dipping thrust faults in the southern part of the map area.

Despite similarities in age, lithology, and bulk chemistry, the western and eastern Late Cretaceous to early Tertiary volcanic fields have significant differences in their potential for mercury mineralization. The volcanic rocks emplaced through the eastern volcaniclastic facies of the Kuskokwim contain anomalous mercury, whereas those emplaced through the western chert-rich facies contain significantly less mercury. In addition to many stream-sediment samples that have anomalous mercury concentrations and to heavy-mineral concentrates that contain cinnabar, some rhyolite samples from the eastern field contain more than 36 ppm mercury. The western volcanic field has few mercury anomalies in any sample media that are clearly related to the volcanic rocks or to underlying Kuskokwim sedimentary rocks. Arsenic anomalies show some overlap with the mercury anomalies but are more heavily concentrated in the Togiak terrane beneath the eastern edge of the Kuskokwim Group. The difference in mercury content between the eastern and western volcanic fields appears to reflect variations in the composition of the underlying Kuskokwim Group and its basement.

Mercury anomalies also are present in sediments from streams that drain serpentinite having silica-carbonate alteration along the Golden Gate and related faults that form the western boundary between the Kuskokwim Group and the Jurassic volcanic rocks of the Nyac terrane. Samples collected near the active Togiak fault in the southeastern corner of the area also contain anomalous mercury. Sediment samples from streams draining several of the Cretaceous granitic plutons also have anomalous mercury concentrations, which suggest that the plutons may have mobilized mercury from the Kuskokwim Group or the underlying basement.

Rocks having the greatest potential for undiscovered mercury deposits in the Bethel region are the eastern volcaniclastic facies of the Kuskokwim Group and volcanic rocks that were emplaced through the eastern volcaniclastic facies. Additional mercury deposits may be found in rocks associated with the major fault zones that form terrane boundaries.

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## Synorogenic Auriferous Fluids of the Juneau Gold Belt, Southeast Alaska—Stable-Isotope Evidence for a Deep Crustal Origin

*By* R.J. Goldfarb *and* W.J. Pickthorn

Mesothermal gold deposits of the Juneau gold belt extend for 200 km along both sides of the Coast Range megalineament, a major steeply dipping shear zone about 125 km inland of the continental margin. Gold-bearing fissure veins, stockworks, and stringers were deposited in a variety of igneous and metasedimentary host rocks at 55 Ma; deposition took place at depths of at least 5–8 km during the late stages of activity in the mid-Cretaceous to Eocene southeast Alaska-British Columbia orogen. Fluid migration and vein emplacement were coeval with rapid uplift of host rocks along the western edge of the orogen. The source of the fluids responsible for mesothermal gold veins throughout the accreted terranes of the northern part of the cordillera is controversial. New stable-isotope data for minerals from auriferous veins and country rocks along the Juneau gold belt provide new information on the source of these ore fluids.

The $\delta^{18}O$ values of gold-bearing quartz from mines of the gold belt range from +15.2 to +20.8 per mil and thus indicate ore fluid values of +10.0±2.8 per mil at about 300 °C, as determined from fluid-inclusion studies. Similar $\delta^{18}O$ values for quartz veins hosted by igneous and metasedimentary rocks indicate little local wall-rock control on oxygen-isotope compositions. The $\delta^{18}O$ values are best interpreted as representative of a fluid in isotopic equilibrium with pelitic metasedimentary rocks. The narrow range in oxygen-isotope compositions precludes the use of any fluid-mixing model for gold deposition along the gold belt. Calculated $\Delta^{18}O_{qtz\text{-}kspar}$ values of −0.2 to + 1.1 per mil for igneous rocks in the vicinity of the gold belt are suggestive of postcrystallization exchange between an isotopically heavy metamorphic fluid and the igneous rocks.

Hydrothermal micas from many of the gold deposits are characterized by δD values of −75 to −53 per mil. Ore fluids calculated to be in equilibrium with the micas have values of −35 to −15 per mil. These data, as well as the gas geochemistry of the fluids determined by fluid-inclusion investigations, are most consistent with a metamorphically derived ore fluid (fig. 1). Extracted fluid-inclusion waters from gold-bearing quartz have a broader range of δD, from −48 per mil in relatively undeformed veins to about −110 per mil for more deformed veins. This range of greater than 60 per mil reflects various mixtures of fluids from inclusions containing isotopically heavy primary ore solutions

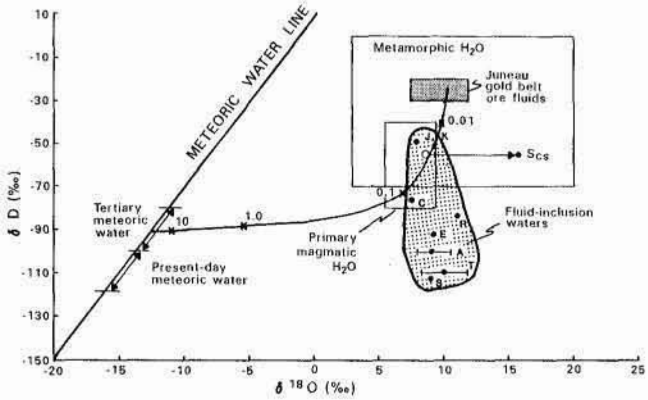


**Figure 1** (Goldfarb and Pickthorn). Plot of $\delta^{18}O$ versus δD showing the composition for the ore fluids calculated on the basis of isotopic measurements of quartz and micas. The field for δD values determined from fluid-inclusion waters in quartz is significantly lighter. Specific deposits: J, Jualin; K, Kensington; $S_{cs}$, glassy quartz in calc-silicates at Sumdum Chief—figure shows a shift to an anomalously heavy oxygen value because of low water:rock ratios in calc-silicates; C, Crystal; R, Reagan; E, EPU; A, Alaska-Juneau; T, Treadwell; S, Sumdum Chief. A meteoric water evolution path, calculated for Tertiary waters at 300 °C, indicates water:rock ratios required to reach various isotopic compositions. In the calculations for the path, metasedimentary rocks are assumed to have an average $\delta^{18}O$ value of +16 per mil and δD of −60 per mil.

and those containing isotopically light meteoric waters trapped during uplift of the veins to shallow crustal levels.

The large isotopic shifts from the meteoric water line required to attain the $\delta^{18}O$ and $\delta D$ values of the ore fluids preclude significant contributions from meteoric sources in the ore-forming process. Required oxygen shifts of about 20 per mil would necessitate water:rock ratios of less than 0.1; required hydrogen shifts demand ratios of even less than 0.01 (fig. 1). Such rock-dominated conditions are unlikely for any type of channelized, downward flow of meteoric waters into the deep crust. Rather, isotopically heavy fluids produced through prograde metamorphic reactions are more likely to have migrated upward during periods of failure along the Coast Range megalineament.

## Geochemical Exploration Criteria for Epithermal Cinnabar and Stibnite Deposits, Southwestern Alaska

*By* J.E. Gray, D.E. Detra, R.J. Goldfarb, *and* K.E. Slaughter

Epithermal cinnabar- and stibnite-bearing vein systems are scattered over several thousand square kilometers in southwestern Alaska. More than 40,000 flasks of mercury have been produced in the region, mostly from the Red Devil mine. Mineralized quartz-carbonate veins and stockworks are found within Cretaceous basin-fill sedimentary rocks of the Kuskokwim Group and adjacent accretionary terranes. Many of the deposits are in or adjacent to brittle rocks, largely mafic dikes, rhyolite dikes and sills, and intermediate to felsic stocks, that intrude sedimentary rock. Mineralized veins are commonly localized where bedding-plane faults in surrounding sedimentary rocks intersect these more competent units. Cinnabar is the dominant ore mineral; it typically is accompanied by stibnite. Realgar, orpiment, pyrite, limonite, hematite, and native mercury are less common. Dickite is a typical alteration mineral at many of these occurrences.

In 1989, a geochemical orientation survey was conducted around several cinnabar and stibnite vein deposits. Stream-sediment, heavy-mineral-concentrate, stream-water and vegetation samples were collected in drainages surrounding the Red Devil, Cinnabar Creek, White Mountain, Rhyolite, and Mountain Top deposits. Three size fractions of the stream-sediment samples were selected for analysis. The heavy-mineral-concentrate samples were split into nonmagnetic, paramagnetic, and magnetic fractions. These samples and the stream-water and vegetation samples were analyzed for multielement suites by different chemical procedures. Nonmagnetic heavy-mineral concentrates were also examined microscopically to identify their mineralogy.

Results confirm that Hg, Sb, and As in minus-80-mesh stream sediments are effective pathfinder elements in exploration for epithermal cinnabar and stibnite occurrences. Concentrations greater than 3 ppm Hg, 1 ppm Sb, and 15 ppm As in the minus-80-mesh stream sediments, regardless of the host lithology, are indicative of upstream cinnabar and stibnite occurrences in the Kuskokwim River region. Stream sediments coarser grained than minus-80-mesh are less useful in the exploration for these mineral occurrences. Base metals in stream sediments and heavy-mineral concentrates are ineffective pathfinders for this epithermal type of occurrence.

Heavy-mineral concentrates provide little additional advantage in the exploration for these mineral systems. Sb and As dispersion patterns downstream from mineralized areas are generally more restricted in heavy-mineral concentrates than they are in the stream sediments. Distribution patterns of placer cinnabar observed in heavy-mineral concentrates are similar to those of anomalous Hg and Sb in corresponding stream sediments. Stream waters are a less effective geochemical sample medium than stream sediments or heavy-mineral concentrates, and vegetation samples are ineffective geochemical sample media in exploration for this type of mineral occurrence.

Several of the epithermal cinnabar and stibnite vein deposits in the Kuskokwim River region contain anomalous gold concentrations. Gold contents in vein samples containing cinnabar and stibnite range from 0.05 to 6.9 ppm. These concentrations indicate that gold may be a byproduct of some of these epithermal systems, which were previously recognized only for their Hg and Sb contents. The gold anomalies suggest the potential for significant gold concentrations deeper in some of these cinnabar- and stibnite-bearing deposits.

## Comparative Metallogeny of the Soviet Far East and Alaska

*By* Donald J. Grybeck, Warren J. Nokleberg, *and* Thomas K. Bundtzen

For the last year and a half, we have been engaged in a systematic study with Soviet geologists from the Academy of Science and the Ministry of Geology of the metallogeny of the Soviet Far East and Alaska. In 1989, we spent more than a month visiting mineral deposits throughout the Soviet Far East and participated in extended discussions with Soviet geologists at numerous mines and research institutes. In return, last summer, two groups of Soviet geologists visited Alaska to examine important mineral deposits and to participate in workshops with American geologists.

The work to date has been productive. Numerous maps, publications, and data have already been exchanged and are in the process of being integrated into a consistent description of the geology and metallogeny of the Soviet Far East and Alaska. Differences remain, partly because of our different approaches to geology, but more often because both sides of the exchange have been introduced to new facets of the geology of the northern Pacific and to new types of mineral deposits. For instance, we visited the "Bor" deposit at Dalnegorsk in Primorye, which is a unique skarn deposit that is the major source of boron in the Soviet Union. It was certainly unknown to us and apparently was unmentioned in the Western literature. As the work has progressed, we feel that there has been marked convergence in our thinking. We are confident that the result will be a joint publication (in English and Russian versions) describing the mineral deposits of Alaska and the Soviet Far East in mutually agreeable terms and relating them to the geologic history of the two areas. Plans are underway to extend the work to the Canadian Cordillera.

This study is useful to both Soviet and American geologists because new knowledge and ideas are being exchanged across the northern Pacific. In addition, it is particularly germane at this time because of the opportunities that seem to be opening up for foreign investment in Soviet mineral deposits.

## Low-Level Gold Determinations by Use of Flow Injection Analysis-Atomic Absorption Spectrophotometry—An Application to Precious-Metal-Resource Assessment in the Iditarod 1° × 3° Quadrangle, Southwestern Alaska

*By* D.M. Hopkins, J.E. Gray, *and* K.E. Slaughter

Low-level gold determinations were performed by the U.S. Geological Survey (USGS) to assess the precious-metal resources in the Iditarod 1° × 3° quadrangle, Alaska, as part of the ongoing Alaska Mineral Resources Assessment Project. Flow injection analysis-atomic absorption spectrophotometry (FIA-AAS) was used to determine gold concentrations in stream-sediment samples collected during a reconnaissance geochemical survey of the quadrangle.

The most common method for gold determination is separation from hydrochloric or hydrobromic acid solution with methyl isobutyl ketone (MIBK) and detection by means of flame atomic-absorption spectrophotometry (FAAS) or graphite-furnace atomic-absorption spectrophotometry (GFAAS). Although FAAS is less sensitive than GFAAS, some advantages of FAAS are (1) fewer problems with interference, (2) continuous monitoring of the analyte in a liquid stream, (3) suitability for online automated analysis, and (4) more rapid determinations. Furthermore, FAAS procedures can be transformed conveniently into a FIA-AAS technique that uses solvent extraction and a 10-fold analyte preconcentration to produce a lower limit of determination, one that approaches the crustal abundance of gold (3–5 ppb). Thus, the analysis of gold at concentrations that formerly required GFAAS is accomplished more effectively with the FIA-AAS technique.

The FIA-AAS technique uses a sample weight of 10 g for digestion with a hydrobromic acid-bromine solution. Gold is extracted from the acid mixture with 1 mL of MIBK; a 10-fold preconcentration and a detection limit of 5 ppb can be achieved. The flow injection device introduces 0.1 mL of MIBK extractant per determination into the spectrometer; more than 50 determinations per hour can be completed by this technique. Precision of the technique at the 100-ppb level is 14.3 percent relative standard deviation based on a 5-g aliquot of USGS reference GXR–2 in 1 mL MIBK. Results for reference standards by this FIA-AAS technique agree well with values reported in the literature.

Approximately 12 percent of the stream-sediment samples from the Iditarod quadrangle contain greater than 5 ppb gold. Most of these samples cluster into 13 distinct areas. Five of these areas are associated spatially with Cretaceous-Tertiary volcano-plutonic complexes that intrude sedimentary rocks of the Cretaceous Kuskokwim Group. Six other anomalous areas are near Cretaceous-Tertiary dikes or small stocks that intrude rocks of the Kuskokwim Group. One gold anomaly is found in an area underlain by Cretaceous-Tertiary volcanic rocks of the Yetna field; another occurs in an area underlain by rocks of the Kuskokwim Group.

Samples that contain anomalous gold cluster in areas of known placer districts such as Flat, Moore Creek, and Donlin Creek. Gold anomalies are observed also in areas in which little or no gold had been reported previously, such as the Beaver Mountains, Mount Joaquin, and Granite Mountain. These anomalies probably are related to (1) vein deposits containing quartz, carbonate, fluorite, stibnite, cinnabar, gold, scheelite, and arsenopyrite similar to those near Flat or (2) veins containing chalcopyrite, galena, sphalerite, cassiterite, tourmaline, and fluorite such as those in the Beaver Mountains. These gold anomalies correlate well with anomalous concentrations of Ag, Sb, As, Cu, Pb, Zn, Sn, or W in stream-sediment or heavy-mineral-concentrate samples. However, the low-level gold concentrations in the stream-sediment samples most effectively define areas of precious-metal favorability in the Iditarod quadrangle.

# Mineral-Resource Potential of the Sitka 1° × 3° Quadrangle, Southeastern Alaska

*By* S.M. Karl, R.J. Goldfarb, K.D. Kelley, D.M. Sutphin, C.A. Finn, A.B. Ford, *and* D.A. Brew

The Sitka 1° × 3° quadrangle encompasses roughly 11,000 $km^2$ in southeastern Alaska and contains sedimentary, volcanic, and plutonic rocks derived from Paleozoic and Mesozoic arc settings. Paleozoic rocks are assigned to the Alexander and Wrangellia terranes; three different Mesozoic arc assemblages are assigned to the Wrangellia, Alexander, and Chugach terranes, respectively.

In the Sitka quadrangle, the Chichagof mining district, which has a history of activity that dates to the 1800's, was a leading producer of gold in Alaska until 1945. The opening of the Greens Creek mine, only a few kilometers north of the quadrangle, has renewed interest in the base- and precious-metal potential of the region.

Nine tracts have been identified as having potential for certain types of mineral deposits because of the presence of known deposits, specific lithologic types, and geochemical and geophysical anomalies:

(1) mafic-ultramafic synorogenic-synvolcanic Ni-Cu deposits in Tertiary norites on western Chichagof Island and eastern Yakobi Island;

(2) polymetallic veins and porphyry Mo-Cu deposits in Jurassic to Tertiary intermediate to felsic plutons on Chichagof and Baranof Islands;

(3) low-sulfide gold-quartz veins within major fault zones on western Chichagof Island and Baranof Island and along Lisianski Inlet-Hoonah Sound;

(4) U, Th, and rare-earth elements in Paleozoic alkalic plutons on eastern Chichagof Island;

(5) marine evaporite gypsum and hydrothermal gypsum in Mississippian limestone on eastern Chichagof Island;

(6) volcanogenic massive sulfide deposits in Permian and Triassic volcanic and sedimentary rocks on central and eastern Admiralty Island;

(7) epithermal vein and hot-spring Au and Ag deposits in Tertiary volcanic rocks on southern Admiralty Island;

(8) skarn, replacement, and polymetallic vein deposits in Paleozoic carbonate rocks intruded by late orogenic plutons on eastern Chichagof Island and Admiralty Island; and

(9) coal and sandstone U deposits in Tertiary nonmarine clastic rocks on southern Admiralty Island.

In addition, scattered low-temperature geothermal systems are active on Baranof and Chichagof Islands.

The greatest resource potential for the area lies in tracts 3 (gold-quartz veins) and 6 (volcanogenic massive sulfide deposits). The gold-quartz veins, identified in 59 deposits in the western Chichagof gold belt, have yielded 800,000 oz of gold, mostly from the Chichagof and Hirst-Chichagof deposits. These deposits consist of ribbon quartz filling northwest-trending shears. Gold is accompanied by minor amounts of pyrite, arsenopyrite, galena, sphalerite, pyrrhotite, and chalcopyrite. Fluid-inclusion analyses indicate that ore-forming fluids were low-salinity, aqueous-dominant solutions having trapping temperatures between 190 and 238 °C and trapping pressures in excess of 500 bars; these characteristics suggest a metamorphic origin. The $\delta^{18}O$ values of quartz are 15.7–16.0 per mil, which are typical of mesothermal hydrothermal systems. The $\delta D$ values of fluid inclusions are equivocal; they range from −55 to −110 per mil.

The main volcanogenic massive sulfide (VMS) deposits are Pyrola and several deposits near Pybus and Gambier Bays. They occur within the Retreat Group in a setting similar to that of the Greens Creek and other Triassic VMS deposits in a 350-km-long belt in southeastern Alaska. At Pyrola, massive basalt with chlorite-carbonate alteration overprinted by sericite-quartz-pyrite alteration is in contact with fine-grained clastic and chemical sedimentary rocks. At this contact, pods of massive pyrite, sphalerite, and Ag-rich barite contain minor associated galena, chalcopyrite, jamesonite, and boulangerite. The deposit is underlain by a siliceous stockwork containing auriferous pyrite, and remobilized mineralization is present in later quartz veins.

## Mineral-Resource Assessment of the Goodnews 1° × 3° Quadrangle and Parts of the Hagemeister Island and Nushagak Bay Quadrangles, Southwestern Alaska

*By* J.E. Kilburn, S.E. Box, R.J. Goldfarb, J.E. Gray, *and* J.L. Jones

Mineral resources were assessed in the Goodnews 1° × 3° quadrangle and in parts of the Hagemeister Island and Nushagak Bay quadrangles, which are north of Bristol Bay in southwestern Alaska. The region is underlain largely by volcanic and sedimentary rocks of the northeast-trending Togiak and Goodnews tectonostratigraphic terranes. Jurassic ultramafic rocks and associated gabbros are most common in the west near Goodnews Bay and Island Mountain. Late Cretaceous to early Tertiary granitic stocks are widespread, though they are more prevalent in the central and eastern parts of the study area. The ultramafic rocks south of Goodnews Bay have yielded high-grade platinum placers in the Salmon River and its tributaries. A few minor gold placers, an isolated sphalerite-rich vein, and an epithermal cinnabar lode are the only other documented mineral occurrences in the study area.

During the mineral assessment of the region in 1975–77, stream-sediment and heavy-mineral-concentrate samples were collected and analyzed. Geochemical data from these media delineate areas characterized by large elemental anomalies. The samples are enriched in Ag, As, Au, Bi, Cr, Cu, Mo, Pb, Sn, W, or Zn (Cieutat and others, 1988).

During the summer of 1990, additional rock samples were collected from several of the areas having geochemical anomalies. In all the revisited drainage basins, strongly oxidized Cretaceous-Tertiary stocks of intermediate composition and associated hornfels zones were observed. During the followup study, geochemical anomalies were identified in the following areas:

(1) the Mt. Waskey-Rainbow basin region—samples of quartz-arsenopyrite-pyrite veins and stockworks in granite and silicified argillite collectively contain maximum concentrations of 1.5 ppm Ag, >10,000 ppm As, 1.4 ppm Au, 1,000 ppm Bi, 2,000 ppm Cu, 15 percent Fe, 50 ppm Mo, 200 ppm Sb, 20 ppm Sn, and 500 ppm Zn;

(2) a drainage basin south of Atshichlut Mountain—samples of silicified, bleached, and Fe-stained argillite with minor pyrite veinlets collectively contain maximum concentrations of 100 ppm Ag, 0.40 ppm Au, >5,000 ppm Ba, 200 ppm Cu, 10 percent Fe, 1.8 ppm Hg, 50 ppm Mo, 300 ppm Pb, and 1,000 ppm Zn;

(3) the Trail Creek-Mt. Oratia area—samples of silicified quartz vein breccia, Fe-stained hornfels containing quartz-tourmaline stockworks, and silicified graywacke with minor quartz veins contain maximum concentrations of 0.7 ppm Ag, 2,000 ppm As, 0.15 ppm Au, >2,000 ppm B, >5,000 ppm Mn, and 150 ppm Sb; and

(4) the west bank of the Togiak River—samples from an oxidized sphalerite-rich vein hosted in pillow basalt contain maximum concentrations of 5 ppm Ag, 0.35 ppm Au, 500 ppm Cd, 700 ppm Cu, 5 percent Fe, 10.4 ppm Hg, >5,000 ppm Mn, and >10,000 ppm Zn.

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## Areas of Mineral-Resource Favorability (with Emphasis on Gold and Chromite) in the Anchorage 1° x 3° Quadrangle, Southern Alaska

*By* D.J. Madden-McGuire *and* G.R. Winkler

The U.S. Geological Survey conducted geologic, geochemical, and geophysical investigations to determine areas of mineral-resource favorability in the Anchorage 1°×3° quadrangle. The quadrangle contains three major fault-bounded terranes that were accreted between mid-Cretaceous and early Tertiary time. The Peninsular terrane, bounded on the south by the Border Ranges fault system, comprises intrusive and extrusive phases of an early Mesozoic intraoceanic magmatic arc and late Mesozoic marine sedimentary rocks deposited in forearc basins. The Peninsular terrane is intruded by voluminous composite plutons of Late Cretaceous and Paleocene age. Paleocene and younger nonmarine volcanic and coal-bearing sedimentary rocks overlap both the Peninsular terrane and the Chugach terrane to the south. The Chugach terrane consists of Mesozoic polygenetic melange and accreted wedges of Upper Cretaceous flysch and minor metatuff. South of the Contact fault, the Prince William terrane consists of an accreted Paleogene deep-sea fan complex interbedded with minor tholeiitic basalt.

Gold, which is currently the commodity of greatest economic interest, has been produced from gold-quartz veins and related placer deposits in the Peninsular and Chugach terranes, primarily in the Willow Creek and Girdwood mining districts (fig. 1). The two areas that include the historic mining districts are assigned the highest and most certain levels of potential for gold-quartz veins and gold-placer deposits in the quadrangle.

In the Willow Creek district, high-sulfide gold-quartz-carbonate veins cut a pluton dated at 79–72 Ma (recording multiple stages of alteration) and adjacent pelitic schist. A fault contact between these host rocks might have served as a conduit for mineralizing fluids (mineralization occurred at 66 Ma and at 57–55 Ma). The extent of the high-potential area is defined by mineral deposits, geologic contacts, and panned concentrates that contain gold and are enriched in As, Ag, Sb, and Pb; stream sediments have anomalous As contents.

In the Girdwood district, Au and Ag are concentrated in quartz-carbonate veins within joints and shears in greenschist-facies metasedimentary rocks of Cretaceous age and Eocene quartz diorite (53 Ma). Mineralization is younger than 53 Ma. Elsewhere in the Valdez Group (in adjacent quadrangles), gold-quartz veins are younger than 34 Ma. Panned concentrates from Crow Creek and surrounding drainages contain gold and locally are enriched in Ag, As, and Sb.

In Prince William Sound, areas around Harriman Fiord and the Coghill River have been assigned a moderate resource potential because gold-quartz veins are exposed in a mine, in prospects, and in outcrop. Additional areas of moderate potential for gold-quartz veins in the Chugach terrane have been identified on the basis of the presence of gold in panned concentrates and, locally, in mineralized outcrops. A particularly large area of moderate potential for gold-quartz veins is between Mount Marcus Baker and the Border Ranges fault.

Podiform chromite occurs in the Peninsular terrane within two fault-bounded ultramafic complexes near Eklutna and in the upper part of Wolverine Creek on the north side of the Border Ranges fault (fig. 1). Cumulate chromitite, having a moderate potential for $Cr_2O_3$, occurs within deformed cumulate dunite and wehrlite. Adjacent outcrops of ultramafic rocks have a moderate potential for $Cr_2O_3$ but a lower level of certainty. Chromitite has not been observed in the serpentinized ultramafic rocks that

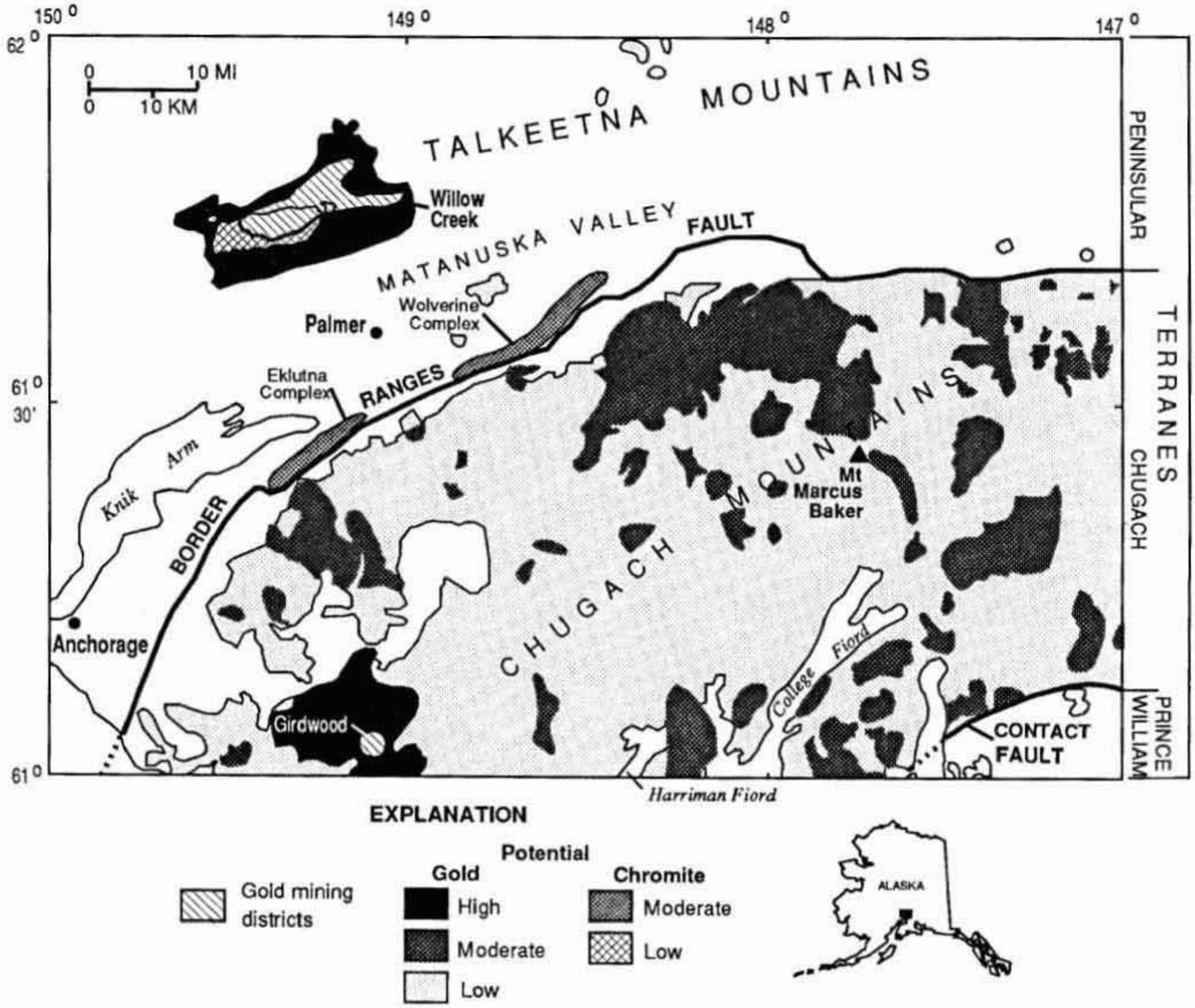


**Figure 1** (Madden-McGuire and Winkler). Areas of favorability for gold-quartz veins and podiform chromite in the Anchorage 1° x 3° quadrangle, southern Alaska. Wolverine and Eklutna Complexes of Burns (1985).

occur within pelitic schist in the Willow Creek district, and nearby stream sediments are not enriched in chromium; the area of exposed serpentinite is therefore assigned a low potential for $Cr_2O_3$.

The Peninsular terrane includes areas that have low potential for porphyry-copper deposits, copper-silver skarns, volcanic-rock-hosted stratiform and stratabound mineralization, and uranium mineralization associated with granitic rocks. Coal has been mined from the Chickaloon and Tyonek Formations north of the Border Ranges fault. The Chugach and Prince William terranes include areas of moderate and low potential for base-metal veins, massive sulfide deposits, and uranium mineralization. A moderate potential for base metals has been assigned to a prospected area in the southeastern corner of the quadrangle between Kadin and Miners Lakes, where veins and massive sulfide occurrences in the Prince William terrane are locally enriched in Zn, Cu, Pb, and Ag, and panned concentrates contain chalcopyrite and sphalerite.

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## Resource Assessment of the Mount Katmai 1° × 2° Quadrangle and Adjacent Parts of the Naknek and Afognak Quadrangles, Alaska Peninsula

*By* J.R. Riehle, S.E. Church, *and* L.B. Magoon

Geologic and geochemical field studies have been completed in 15,000 km$^2$ of the Mount Katmai 1° × 2° quadrangle and adjoining parts of the Naknek and Afognak quadrangles on the Alaska Peninsula as part of the Alaska Mineral Resources Assessment Project (AMRAP). Nearly the entire study area is within either the Katmai National Park and Preserve or the Becharof National Wildlife Refuge. The area is, in some ways, a geologic frontier: gravity data comprise only a few profiles or isolated measurements, aeromagnetic data are restricted to the Naknek quadrangle, and there are neither drill-hole data nor published reports on the several unpatented lode and placer claims.

The study area is within the Peninsular terrane. The Bruin Bay reverse fault (fig. 1) separates Middle Jurassic plutonic rocks and roof pendants in the northwest part of the area from Upper Jurassic sandstones and siltstones of the Naknek Formation to the southeast. Upper Cretaceous flysch occurs near Cape Douglas. Early to middle Tertiary volcanic rocks of the Aleutian arc are exposed northwest of the Bruin Bay fault, and middle Tertiary plutonic rocks are intruded along and adjacent to the fault in the north-central part of the study area. Late Tertiary volcanic and hypabyssal rocks occur in the central and eastern parts of the area. Quaternary volcanoes (fig. 2) of the active part of the Aleutian arc are constructed on some of the late Tertiary hypabyssal and volcanic rocks along the crest of the Aleutian Range.

Contributions of the Katmai AMRAP study to a fuller understanding of the geology and mineral potential of the Alaska Peninsula are (1) a better definition of the age and distribution of volcanic and plutonic rocks in the western, north-central, and northeastern parts of the area, (2) subdivision of the Naknek Formation, (3) discovery of a 50-km-long belt of hypabyssal rocks adjacent to the Valley of Ten Thousand Smokes (fig. 1), (4) systematic reconnaissance geochemical coverage throughout the area, and (5) a mineral-resource assessment.

Bedrock and stream-sediment geochemical data outline areas of anomalous concentrations of base and precious metals. The most important are (1) around Tertiary plutons in the north-central part of the study area; (2) within late Tertiary plutonic rocks and Tertiary sedimentary wall rocks near Cape Douglas; (3) in late Tertiary volcanic and hypabyssal intrusive rocks in the eastern part of the study

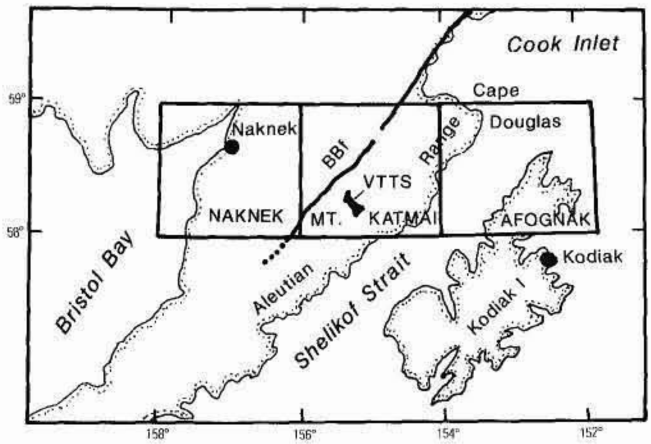


**Figure 1** (Riehle and others). The Katmai AMRAP (Alaska Mineral Resources Assessment Project) study area on the Alaska Peninsula. The study area consists of the Mount Katmai 1° × 2° quadrangle and adjacent parts of the Naknek 1° × 2° and Afognak 1° × 2.5° quadrangles. The trace of the Bruin Bay fault (BBf), the major structural feature of the Alaska Peninsula, is interrupted by middle Tertiary plutons. VTTS, the Valley of Ten Thousand Smokes.

**Figure 2** (Riehle and others). View to the north of Griggs Volcano, a Quaternary stratovolcano of the Aleutian arc. Griggs Volcano is built on Upper Jurassic sandstones and siltstones of the Naknek Formation that have been intruded by Tertiary sills, dikes, and shallow porphyritic plutons. The head of the Valley of Ten Thousand Smokes, site of the 1912 eruption of Novarupta dome (the "Katmai eruption"), is in the middle foreground. Two glaciers are visible in the lower right, and thick fallout deposits of the 1912 eruption can be seen mantling the lower slopes of Griggs Volcano. Griggs Volcano is about 8 km across at its base. Photograph by J.R. Riehle in July 1983.

area; (4) in Mesozoic sedimentary wall rocks and Tertiary hypabyssal rocks in the central part of the study area; and (5) in volcanic rocks of the Aleutian arc and underlying Naknek Formation near the southern margin of the area. On the basis of element suites, followup studies of selected areas, and permissive geologic attributes, we infer, at the 10 percent level of confidence, the existence of one or more porphyry Cu systems. Geochemical and geologic data suggest that polymetallic vein and epithermal gold systems are also present; however, the lack of subsurface data and the low density of our surface data preclude our making a quantitative estimate of the number of such deposits present where these deposits occur within an area of $<1$ km$^2$. These inferred deposit types are similar to porphyry deposits or occurrences and to vein occurrences south of the Katmai area and to vein occurrences associated with Tertiary plutonic rocks in the Iliamna quadrangle to the north. Other deposit types known elsewhere in southern Alaska (for example, tin-bearing granites, skarn deposits, syngenetic sea-floor gold in Jurassic volcanic rocks) are unlikely to be present in the Katmai area, where the geology is unfavorable for their occurrence.

The potential for producible hydrocarbons in the study area is small, primarily because the most favorable reservoir rocks have been uplifted and dissected by erosion. Thermal springs near Quaternary volcanoes in the eastern part of the area indicate some low-temperature geothermal potential. Surficial sand and gravel deposits are abundant in the western half of the study area.