UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GENESIS OF GOLD VEIN MINERALIZATION IN AN UPPER CRETACEOUS TURBIDITE SEQUENCE, HOPE-SUNRISE DISTRICT, SOUTHERN ALASKA

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U.S. Geological Survey
OPEN-FILE REPORT
81-103

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

1981

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A Preliminary Report

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INTRODUCTION

The Hope-Sunrise mining district is situated in the Kenai Mountains of southern Alaska, approximately 45 km southeast of Anchorage (fig. 1). The district is

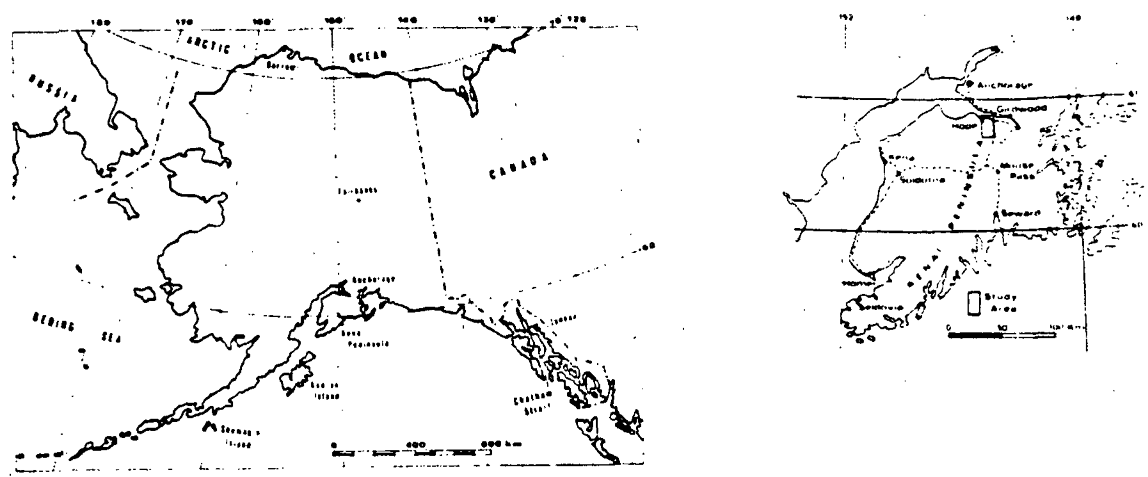


Figure 1.--Map of Alaska and adjacent areas, with inset map of the Kenai Peninsula showing the Hope-Sunrise district (study area) and the major towns and roads.

located within the western most portion of the Valdez Group sedimentary sequence, which is comprised predominantly of turbidite deposits formed during Late Cretaceous subduction.

The mineral deposits of the Hope-Sunrise mining district are low-tonage,high-grade occurrences. Mining within the district was most intense between 1910 and

1930. During these years several small properties were active, however, only one mine, the Lucky Strike, had significant production. The Lucky Strike mine produced more than 50,000 troy ounces of gold.

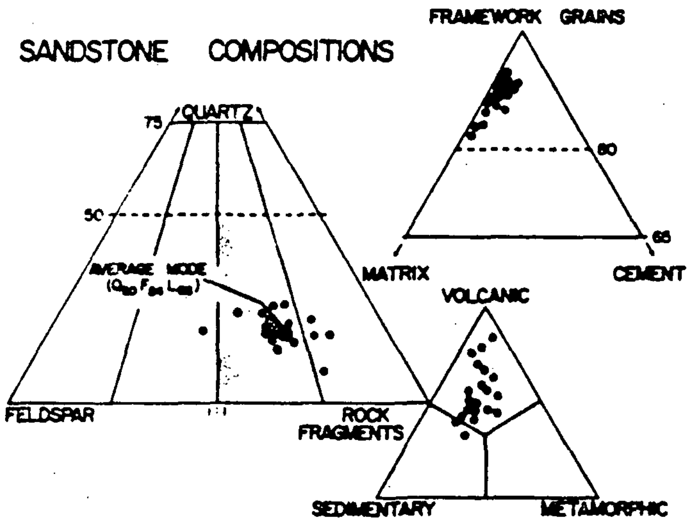
GEOLOGIC SETTING

Regionally, the Valdez Group sedimentary sequence is dominated by quartzo-feldspathic to feldspatholithic sandstone and siltstone, with minor conglomerate, claystone, limestone and calcareous sedimentary rocks, tuff and bedded chert. These units have been metamorphosed to the chlorite zone, and locally to the biotite zone, of the greenschist facies or defined by Miyashiro (1973) (Tysdal and Case, 1979).

Sandstone Petrography

The sandstones of the Hope-Sunrise district are subquartzose to nonquartzose (detrital quartz <50 percent of all detrital constituents) rocks rich in volcanic lithic fragments. They are compositional graywackes (unstable rock fragments $>$ feldspar grains), but in general are not textural graywackes (primary matrix >15 percent). The average mode of the sandstones studied, $Q_{20}F_{24}L_{56}$, plots within the feldspatholithic field, which is denoted by the shaded area of figure 2.

The Valdez sandstones of the Hope-Sunrise district are compositionally unstable and immature. Texturally, the mean sandstone is comprised of 88 percent framework grains, 10 percent primary matrix, and 2 percent authigenic phyllosilicate and rare carbonate cement (fig. 2). No zeolite minerals were identified either by optical or X-ray diffraction techniques.



	% QUARTZ (Q)	% FELDSPAR (F)	% LITHIC (L)
MEAN	20.4	24.2	55.4
RANGE	8-27	11-43	36-72
STANDARD DEVIATION	4.2	4.1	8.5

C = TOTAL POLYCRYSTALLINE QUARTZOSE GRAINS, V = TOTAL VOLCANIC LITHIC GRAINS, P = TOTAL PLAGIOCLASE FELDSPAR GRAINS

	C/Q	P/F	V/L
MEAN	0.34	0.82	0.56
RANGE	0.19-0.59	0.50-0.97	0.35-0.80
STANDARD DEVIATION	0.09	0.13	0.14

MODAL ANALYSES OF 19 VALDEZ SANDSTONES

Figure 2.--Composition diagram and salient statistics for 19 Valdez Group sandstones.

A petrographic analysis of these 19 sandstone samples indicates that the sedimentary rocks were derived from a volcanic arc provenance (Mitchell, 1979). The dominance of felsite and hypabyssal rock fragments suggest a supracrustal volcanic or volcaniclastic source terrane that was comprised chiefly of rhyolite to dacite lithologies, but included minor basalt and andesite. A relative major contribution of sedimentary and metasedimentary detritus implies that the volcanic arc was being actively eroded. Plutonic rock fragments are a minor phase, but suggest the incipient unroofing of subjacent plutons.

Intrusive Rocks

In coastal southern Alaska, major intrusive events occurred during the Paleocene to Late Eocene time (60 to 43 m.y., Hudson and others, 1979) and again in early Oligocene time (37 to 35 m.y., Lanphere, 1966). The composition of the central mass of these intrusive bodies ranges from granodiorite to granite. The only intrusive rocks exposed within the Hope-Sunrise area are narrow (∿3 m), fine-grained dikes, that were intruded by ∿53 m.y. B.P. Compositionally the dikes are either tonalite, granodiorite, or alkali granite.

Structure

A detailed structural analysis of the Hope-Sunrise district (Mitchell, 1979) suggests that folding began shortly after sediment deposition, producing two broad, arcuate, open folds and a weak axial plane cleavage. As deformation continued, the limbs of these early folds were deformed additionally by the development of small, closely spaced isoclinal folds that were accompanied by pervasive axial plane slaty cleavage oriented ∿N20°E. Folding accounted for over 40 percent horizontal shortening, increasing the overall thickness of the sedimentary prism to greater than 10 km. Shearing and faulting began late during isoclinal folding and minor movement has continued to the present, but without major displacement on any known fault. Post-folding stress release produced a penetrative joint system oriented west-northwest and north.

Mineralization

Gold mineralization hosted by the sedimentary rocks of the Valdez Group has a pronounced spatial distribution concentrated along a north south belt that may be related to deep-seated structures, variations in lithology, and regional geothermal gradients (fig. 3). The deposits are primarily fissure fillings in which native gold is hosted by a quartz calcite gangue (Tuck, 1933). Gold veins within the

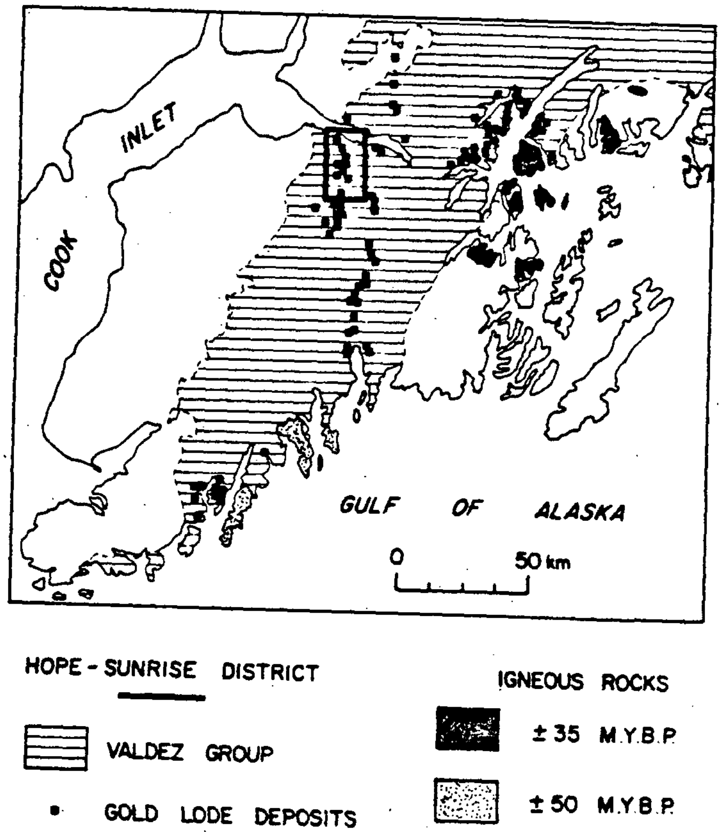


Figure 3.--Distribution of gold lode deposits and occurrences within the Valdez Group sedimentary sequence that is exposed on the Kenai Peninsula, Alaska.

Hope-Sunrise district are narrow, that is, generally less than 10 cm, and persist for only a few meters along strike, though the larger veins may exceed 1 m in width and may be laterally continuous for more than 100 m along strike and dip.

Quartz Veins

The oldest veins identified within the Hope-Sunrise district are thin, irregular quartz veins that in general parallel the regional cleavage. These barren veins are common throughout the district and are believed to be related to the metamorphism that followed the main stages of regional deformation. Metamorphic segregation quartz is milky, fine-grained and massive, and typically is free of sulfide and iron oxide minerals.

A second type of vein is comprised of milky to blue-gray mineralized quartz usually accompanied by calcite. These veins are coarse-grained and commonly vuggy, contain prominent sulfide and iron oxide minerals, and are typically sheared or brecciated. Joints, faults and mineralized quartz veins cross-cut the regional cleavage and metamorphic segregation quartz veins.

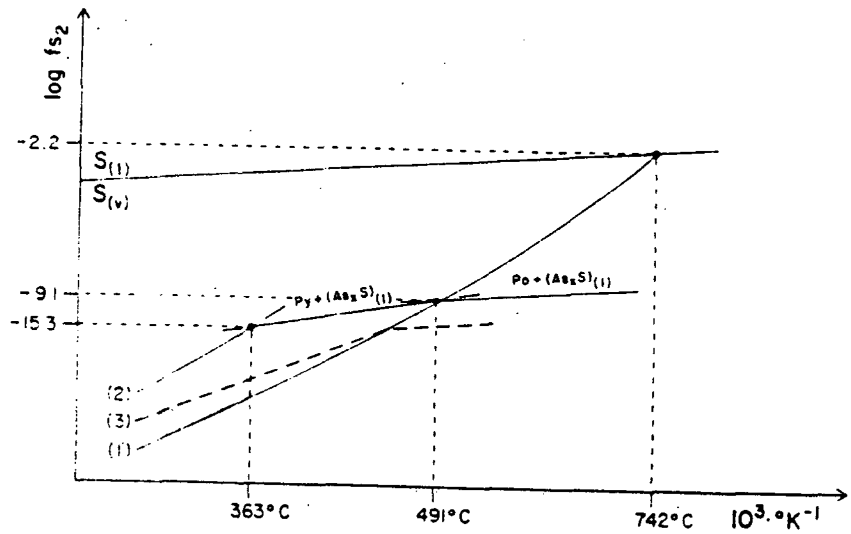
Vein mineralogy

The principal gangue minerals, quartz and calcite, are locally accompanied by alkali feldspar (albite + orthoclase). Zoning of the gangue minerals is common in many of the larger veins, however, quartz is always the earlier mineral and is generally more abundant. Locally base metal sulfides are spatially associated with the calcite, or are found along the quartz-calcite interface. Minor amounts of arsenopyrite, pyrite, sphalerite, hemimorphite(?), galena, gold, silver, and locally pyrrhotite occur in all of the major veins, but disseminated wall-rock mineralization is rare. Arsenopyrite is the most abundant sulfide phase present in the veins, and gold is the most common precious metal.

GEOCHEMISTRY

The presence of arsenopyrite and pyrite in all of the mineral assemblages restricts the sulfur fugacity to a relatively narrow range. The lower limit of sulfur fugacity is established by the coexistence of pyrite and pyrrhotite (fig. 4). Pyrrhotite is a minor phase and is not always present, thus in general the fugacity of sulfur remained at or above the reaction:

$$\text{Pyrrhotite} + \text{Sulfur}_{(g)} \rightleftharpoons \text{Pyrite}. \quad (1)$$



$Po + S_{2(g)} \rightleftharpoons Py$ (1)

$Asp + S_{2(g)} \rightleftharpoons Py + As$ (2)

$Cp + Asp + S_{2(g)} \rightleftharpoons Tn + Py$ (3)

Figure 4.--Temperature (T)-sulfur fugacity (F_{S_2}) diagram showing the possible range in T-f_{S_2} suggested by equations 1-3. The thermodynamic data was taken from Clark (1960), and Barton and Skinner (1979). The Sulfur condensation curve is represented by the line $S_{(v)}$-$S_{(1)}$.

The upper limit of sulfur fugacity is set by the reaction

$$\text{Arsenopyrite + Sulfur}_{(g)} \rightleftharpoons \text{Pyrite + Arsenic.} \qquad (2)$$

The assemblage pyrite + arsenic is not known within the district, and consequently the fugacity of sulfur must be below the upper limit established by equation (2).

The possible variations in sulfur fugacity are further restricted by the presence of copper as chalcopyrite, although these restrictions are speculative, since copper is present only locally. Nonetheless it is important to note that chalcopyrite is the only copper species that was identified. Since tennantite is not present, the upper limit of sulfur fugacity must be less than that needed to cause the reaction

$$\text{Chalcopyrite} + \text{Arsenopyrite} + \text{Sulfur}_{(g)} \rightleftharpoons \text{Tennantite} + \text{Pyrite}. \qquad (3)$$

Further, reaction (3) must lie at a sulfur fugacity intermediate to reactions (1) and (2) (fig. 4).

Mineral Assemblages and Metamorphic Grade

The mineral assemblages of the veins provides an upper temperature limit for mineralization. The presence of pyrite with arsenopyrite establishes an upper temperature limit of 491°C (Clark, 1960), from the invarient point pyrrhotite + pyrite + arsenopyrite + a member of the orpiment-realgar solid solution series [$As_xS_{(1)}$], (fig. 4).

Additional, although uncertain, constraints on the temperature of hydrothermal vein formation are suggested by the regional metamorphic grade of the sedimentary sequence. Although metamorphic grade in the Valdez Group varies somewhat, the rocks exposed within the Hope-Sunrise district have been metamorphosed to very low-grade greenschist facies. Their metamorphic grade is established by the pervasive presence of tri-octahedral septachlorite (Deer and others, 1971). Low-grade greenschist facies metamorphism occurs between 300° and 425°C (Winkler, 1976; Miyashiro, 1973). We believe that the early metamorphic segregation quartz veins were probably deposited at these temperatures. However, preliminary fluid inclusion filling temperatures suggest that the mineralized quartz veins were deposited at significantly lower temperatures.

Fluid Inclusion Temperatures

Fluid inclusion filling temperatures are available from only two samples, one from a mineralized quartz vein, and one from a calcite vein occurring within a mineralized dike (table 1).

Table 1.--Preliminary fluid inclusion filling temperatures for mineralized quartz and calcite veins of the Hope-Sunrise district

VEIN TYPE	FILLING TEMPERATURE (MEAN °C)	STANDARD DEVIATION
QUARTZ	191	16.7
CALCITE	137	12.4
GROUP A	153	2.3
GROUP B	129	7.5

The quartz contains very small, liquid-rich inclusions with variably sized gas bubbles. Homogenization took place in the liquid phase, and filling temperatures vary from 168 to 219°C, averaging 191°C. No daughter minerals were observed, suggesting at most moderate salinity. In general, salinities of fluid inclusions in epithermal ore deposits similar to those at Hope are less than 2 weight percent (Nash, 1972). Vugs, open spaces, and common drusy quartz crystals lining cavities in mineralized veins attest to their shallow depth of emplacement, hence no pressure corrections for the fluid inclusion filling temperatures were made.

The fluid inclusions in the calcite sample are also small. Filling temperatures range from 100° to 155°C, and appear to fall into two groups, one from 100° to 136°C, and another from 150° to 155°C. These limited data suggest that late-stage calcite may have precipitated during two stages, at somewhat different temperatures. The gas bubbles are small, occupying one eighth to one tenth of the inclusion volume. No daughter minerals were observed in the calcite fluid inclusions.

STABLE ISOTOPE RESULTS

Four quartz vein samples were chosen for a preliminary stable isotope evaluation. These samples include three mineralized veins (including the sample upon which the fluid inclusion filling temperatures were determined) and one metamorphic segregation vein (table 2). The δD of fluid inclusion waters of the three mineralized quartz veins averages -106±6 per mil, which is about the same value as modern meteoric water in this area (-110 per mil; Taylor, 1974). These data strongly suggest that the source of the hydrothermal fluid was dominantly meteoric water. Assuming that meteoric water was the source of the ore fluid, and using the meteoric water equation, $\delta D = 8\delta^{18}O + 10$ (Craig, 1961), the original $\delta^{18}O$ of the water is calculated to be -14.5 per mil.

Table 2.--Stable isotope data for hydrothermal and metamorphic segregation quartz from the Hope-Sunrise district

STABLE ISOTOPE DATA
(VEIN QUARTZ)

SAMPLE	ORIGIN	$\delta^{18}O$ ‰ (QUARTZ)	δD ‰ (FLUID INCLUSION)
1	HYDROTHERMAL	+16.2	-100
2*	HYDROTHERMAL	+17.1	-101
3	HYDROTHERMAL	+16.6	-117
4	METAMORPHIC SEGREGATION	+19.9	–

The average $\delta^{18}O$ of the three mineralized quartz samples is +16.6±0.3 per mil (standard error). Utilizing the quartz-water fractionation relationship of Bottinga and Javoy (1973) and the average fluid inclusion filling temperature of 191°C, we calculate that main stage quartz was in equilibrium with an aqueous fluid whose $\delta^{18}O$ was +1.3 per mil. Water with an original $\delta^{18}O$ of -14.5 per mil could attain a $\delta^{18}O$

* FLUID INCLUSION TEMPERATURE SAMPLE

of +1.3 per mil by isotopic exchange with the silicate minerals of the sedimentary and metamorphic host rocks at elevated temperatures.

Thermal waters of meteoric origin usually undergo an oxygen shift of a few per mil toward higher $\delta^{18}O$ from exchange with "heavier" oxygen in their host rocks (Taylor, 1974; White, 1974). Shifts of as large as +16.8 per mil have been documented for such fluids in epithermal vein deposits hosted by sedimentary and low-grade metamorphic rocks in central Nevada (O'Neil and Silberman, 1974). The shift in $\delta^{18}O$ in our samples is about +16 per mil, and is within the range of the shift identified in the Nevada deposits hosted by wall rocks similar to those at Hope. No isotopic data presently exists for the host rocks in the Hope-Sunrise district, but low-grade metamorphic rocks of this composition are usually in the range of +8 to +18 per mil (Taylor, 1974; O'Neil, 1979). In order to undergo an oxygen shift of approximately 16 per mil from exchange with the wall rocks, the water to rock ratio must have been very small (O'Neil and Silberman, 1974). The fact that so much isotopic exchange is inferred to have taken place between the water and the host rocks implies that other components of the mineralized veins, such as the metals, sulfur and carbon, may have originated in the wall rocks. Additional geochemical and isotopic analyses are necessary to confirm this suggestion.

No δD analyses from fluid inclusions are available for the metamorphic segregation quartz. The $\delta^{18}O$ of the metamorphic segregation quartz has a slightly heavier value than the mineralized quartz (table 2). Based on an assumed lower greenschist facies metamorphic temperature of 350°C and the quartz-water fractionation relationship of Bottinga and Javoy (1973), we calculate that the metamorphic segregation quartz was in isotopic equilibrium with water of $\delta^{18}O$ of +11 per mil. This fluid appears to be richer in ^{18}O than the ore fluid, and is within the oxygen isotopic composition range identified with water of metamorphic origin, +5 to +25, per mil (Taylor, 1974). The fluids in equilibrium with metamorphic quartz thus appear to be of different oxygen isotopic composition from those in equilibrium with the mineralized quartz. However, additional data, principally δD analyses of inclusions waters of the metamorphic quartz have to be obtained to confirm origin of these fluids suggested by our interpretation.

Sulfur Isotope Results

The preliminary results of sulfur isotope analyses were obtained from two samples (table 3). The arsenopyrite of sample 1 occurs in a mineralized quartz

Table 3.--Sulfur isotope data for two sulfide minerals from the Hope-Sunrise district

SULFUR ISOTOPE DATA			
Sample	Mineral	Origin	$\delta^{34}S$ per mil
1	Arsenopyrite	Hydrothermal quartz vein	-0.14
2	Pyrite	Disseminated in meta-siltstone	+7.69

vein, whereas the pyrite of sample 2 occurs in siltstone adjacent to metamorphic segregation quartz sample no. 4 (table 2). Since the available sulfur isotope data is so restricted and only individual mineral rather than total sulfur data are available (Rye and Ohmoto, 1974). Conclusions concerning the genesis of the mineralization are obviously very speculative. However, we believe some discussion is warrented.

The pyrite sample has a $\delta^{34}S$ similar to that derived from ocean water sulfates, (Rye and Ohmoto, 1974) perhaps by diagenetic or metamorphic reduction. The arsenopyrite sample has a $\delta^{34}S$ value of close to zero, which would normally be interpreted as igneous sulfur. However, we suggest that kinetic effects on sulfur isotope fractionation may better explain the difference in $\delta^{34}S$ between metamorphic and mineralized vein sulfides. If the sulfur was diffusing out of the wall rocks, along with other components of the ore, as we suggest on the basis of our interpretation of the oxygen and deuterium data, then preferential enrichment of the light sulfur isotope, ^{32}S, may have occurred in the mineralized sample. Our data suggest than an enrichment of 8 per mil between the wall rock and vein sulfide must have occurred. Although fractionation of ^{32}S between pyrite and arsenopyrite is not known, it is unlikely that it is this large at 200°C (Friedman and O'Neil, 1977, fig. 46). Enrichment of 14 per mil in ^{32}S was documented in the East Tintic district, Utah, where diffusion controlled the distribution of sulfides adjacent to lode deposits (Jensen, 1967) during mineralization.

POTASSIUM-ARGON AGES

Potassium-argon ages were obtained from two hydrothermally altered and mineralized dikes. Muscovite, separated from an alkali granite dike cut by thin mineralized quartz veins gave a K-Ar age of 53.2±1.6 m.y. (sample 1, table 4). A whole rock sample of an intensely altered dike recrystallized to an assemblage of muscovite, quartz, carbonate, chlorite and albite gave an age of 52.7±1.6 m.y. (sample 2, table 4). The latter dike is strongly brecciated, cut by mineralized quartz-carbonate veins and contains disseminated arsenopyrite (Mitchell, 1979). From these data we infer that hydrothermal alteration and mineralization occurred during earliest Eocene time.

Table 4.--Potassium-argon ages for two hydrothermally altered and mineralized dikes of the Hope-Sunrise district

SAMPLE	LITHOLOGY	MINERAL	ORIGIN	AGE (m.y.)
1	ALKALI GRANITE DIKE	MUSCOVITE	HYDROTHERMAL ALTERATION	53.2 ± 1.6
2	ALKALI GRANITE DIKE (?)	WHOLE ROCK	HYDROTHERMAL ALTERATION	52.7 ± 1.6

DISCUSSION

Gold lode mineralization occurred, at least locally, in the Valdez Group sedimentary rocks during early Eocene time. The auriferous veins formed from fluids of dominantly meteoric origin, and were localized by steeply dipping west-northwest and north trending joint and fault systems. These structures generally cross-cut the regional cleavage that developed during penetrative deformation of the sedimentary prism as it was accreted to the North American continent. Accretion probably was accomplished during Late Cretaceous to Early Tertiary time (MacKevett and Plafker, 1974; Byrne, 1978). Small plutons intruded the sedimentary prism between 60 and 43 m.y. ago (Hudson and others, 1979). These intrusions are part of the Sanak-Baranoff belt of plutonic rocks, and are believed to be of anatectic origin (Hudson and others, 1979). The plutons are undeformed, and must have been intruded after accretion. In the Kenai Peninsula, potassium-argon ages of these plutonic rocks range from 59 to 55 m.y. B.P. (Tysdal and Case, 1979). Granitic dikes, similar to the ones that were hydrothermally altered in the Hope-Sunrise district occur throughout the Kenai Peninsula, and are probably the same age and origin as the plutons. Thermal effects of the accretion process probably led to high-grade metamorphism and partial melting of the lower parts of the accretionary prism after it was joined to the continent (Hudson and others, 1979). We suggest that lower grade metamorphism occurred in the upper parts of the prism generating the greenschist facies mineral assemblage and the cleavage localized metamorphic segregation quartz. During late stages of the thermal evolution of the area, temperatures waned, and the structures that cut regional cleavage opened after stress, caused by accretionary vergence of the terrane was released, perhaps during regional uplift. This allowed access of meteoric water, which formed small hydrothermal circulation cells. The meteoric-water-dominated fluid dissolved silica, carbon, sulfur, and metals from the unstable volcanic component in the sedimentary prism and deposited them as auriferous lodes in the open structures. Thus, hydrothermal mineralization occurred late in the accretionary history of the Valdez Group sedimentary sequence, as a result of metamorphic-hydrothermal processes whose later stages were dominated by the influx of meteoric water.

An unanswered question in this proposed model is why the fluids generated by prograde metamorphism shortly after accretion did not result in solution of ore components from the volcanic material deeper in the prism and their deposition in quartz veins localized along regional cleavage in the shallower, lower grade zones of the greenschist facies meta-sediments - a process which Henley and others (1976) propose for lode deposits in the Otago area of New Zealand. The cleavage localized quartz in the Kenai peninsula is notably barren. It may be that a declining temperature regime was necessary, and that open structures were required, and these may not have been present to the required extent until post-accretionary uplift was taking place.

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