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Geochronology, geochemistry, and tectonic environment of porphyry mineralization in the central Alaska Peninsula

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Abstract

Porphyry type sulfide systems on the central Alaska Peninsula occupy a transition zone between the Aleutian island magmatic arc and the continental magmatic arc of southern Alaska. Mineralization occurs associated with early and late Tertiary magmatic centers emplaced through a thick section of Mesozoic continental margin clastic sedimentary rocks. The systems are of the molybdenum-rich as opposed to gold-rich type and have anomalous tungsten, bismuth, and tin, attributes of continental-margin deposits, yet gravity data suggest that at least part of the study area is underlain by oceanic or transitional crust.

Potassium-argon age determinations indicate a variable time span of up to 2 million years between emplacement and mineralization in a sulfide system with mineralization usually followed by postmineral intrusive events. Finally, mineralization in the study area occurred at many times during the time span of igneous activity and should be an expected stage in the history of a subduction related magmatic center.

Introduction

This report describes the environment and timing of porphyry-type mineralization in the volcanic arc of the Alaska Peninsula. The data presented were collected as part of the Geological Survey's Alaska Mineral Resource Assessment Program (AMRAP) which includes geologic mapping, geochemical sampling, and magnetic and gravity studies in the Chignik and Sutwik Island quadrangles. A complex history of igneous activity from early Tertiary to Quaternary time in a distinctive tectonic setting resulted in the formation of porphyry deposits with peripherally related metallic mineral occurrences and a characteristic geochemical expression.

The term sulfide system has been adopted from Fields (1977) and is used to describe combinations of igneous and hydrothermal effects that result in clusters of geochemical anomalies. These effects include hydrothermal alteration; concentration of copper and molybdenum in vein and disseminated forms; and concentration of lead, zinc, arsenic, and precious metals in dispersed veinlets. Each system described does not show all of the above effects, but all share a common feature, the introduction of sulfur and deposition of pyrite in large volumes of rock. Weathering and oxidation of this pyrite produces color anomalies that are a common feature of sulfide systems in the Alaska Peninsula.

A brief investigation by Armstrong and others (1976) of the Dry Creek (Bee Creek in this report) and Pyramid prospects on the Alaska Peninsula and a description of the Pyramid prospect by Hollister (1978) are the previously published studies of porphyry-type mineralization in the Alaska Peninsula. Bear Creek Mining Co., on contract with the Bristol Bay Native Corp., examined a number of prospects in the Chignik area. Their work included extensive geochemical sampling, geologic mapping, and core drilling at the Bee Creek prospect. Their reports to the Bristol Bay Native Corp. (Robinson, 1975; Fields, 1977) served as a data base for some of the age studies reported here. The geologic framework for the Alaska Peninsula on which this report is based is from reconnaissance mapping by Burk (1965) and Detterman and others (1981). Work by Silberman and others (1977), Morton and others (1977), Ashley and Silberman (1976), and Whalen and McDougall (1980) has shown the potential value of dating hydrothermal minerals to define the timing of hydrothermal events, and M. L. Silberman has given many helpful suggestions to aid in this study.

Regional Environment of Porphyry Mineralization

Tectonically, the Alaska Peninsula forms a transition zone between the Aleutian Island magmatic arc and the continental magmatic arc of southern Alaska. Volcanic rocks of generally andesitic composition, but range from leuco-basalt to dacite (these and subsequent volcanic petrologic names follow Streckeisen (1979)) and are of Permian(?), Tertiary and Quaternary age. Jurassic to Quaternary intrusive rocks are also known. The Chignik and Sutwik Island area straddles the central Alaska Peninsula in an east-west direction (fig. 1). The Alaska-Aleutian Range batholith (Reed and Lanphere, 1969, 1973) forms the geologic backbone of the peninsula north of 57 degrees and includes plutonic rocks of Jurassic, Late Cretaceous to early Tertiary, and middle Tertiary age. The remainder of the peninsula, including the Chignik region, is composed of clastic sedimentary rocks of Paleozoic, Mesozoic, and Miocene age; and Paleocene to Pliocene volcaniclastic sedimentary rocks (Burk, 1965; Detterman and others, 1981; Wilson, 1980). Coal deposits interbedded with shallow marine sedimentary rocks are common in strata ranging in age from Late Cretaceous to Miocene. The sedimentary rock section aggregates 12 km in thickness and contains unconformities representing major hiatuses during Cretaceous (Hauterivian to Santonian), Paleocene and Miocene time. Structural complications include gentle folding, major thrust and reverse faulting, and less important normal faulting.

The stratigraphic section suggests that Mesozoic deposition occurred on a rapidly subsiding continental shelf and coastal plain and magmatic arc. Mancini and others (1978) interpreted contrasting facies in sedimentary rocks of Late Cretaceous age as evidence of deposition in an arc-trench gap environment; however, little definitive evidence exists for a Late Cretaceous magmatic arc in the Chignik region. The central Alaska Peninsula was the site of increasing andesitic volcanism, beginning in the Paleogene and reaching a climax in the deposition of the Meshik Formation, a thick pile of lava and tuff of Eocene, Oligocene, and early Miocene age. An aeromagnetic interpretation by Case and others (1981) suggested that this volcanism occurred at well defined centers. Volcanism was reinitiated in late Miocene time and continues to the present. These episodes of magmatism resulted in the development of the porphyry-type sulfide systems described in this paper.

Sulfide Systems and Porphyry Deposits of the Aleutian Volcanic Arc

Sulfide systems comprising hydrothermal alteration and sulfide mineralization are irregularily distributed from the Lake Clark quadrangle, in the northern Alaska Peninsula, (Eakins and others, 1978) to the Komandorskey Islands (Vlasov, 1964) in the far western Aleutian Archipelago. Hollister (1978) listed 16 areas of intense alteration between Umnak Island and the

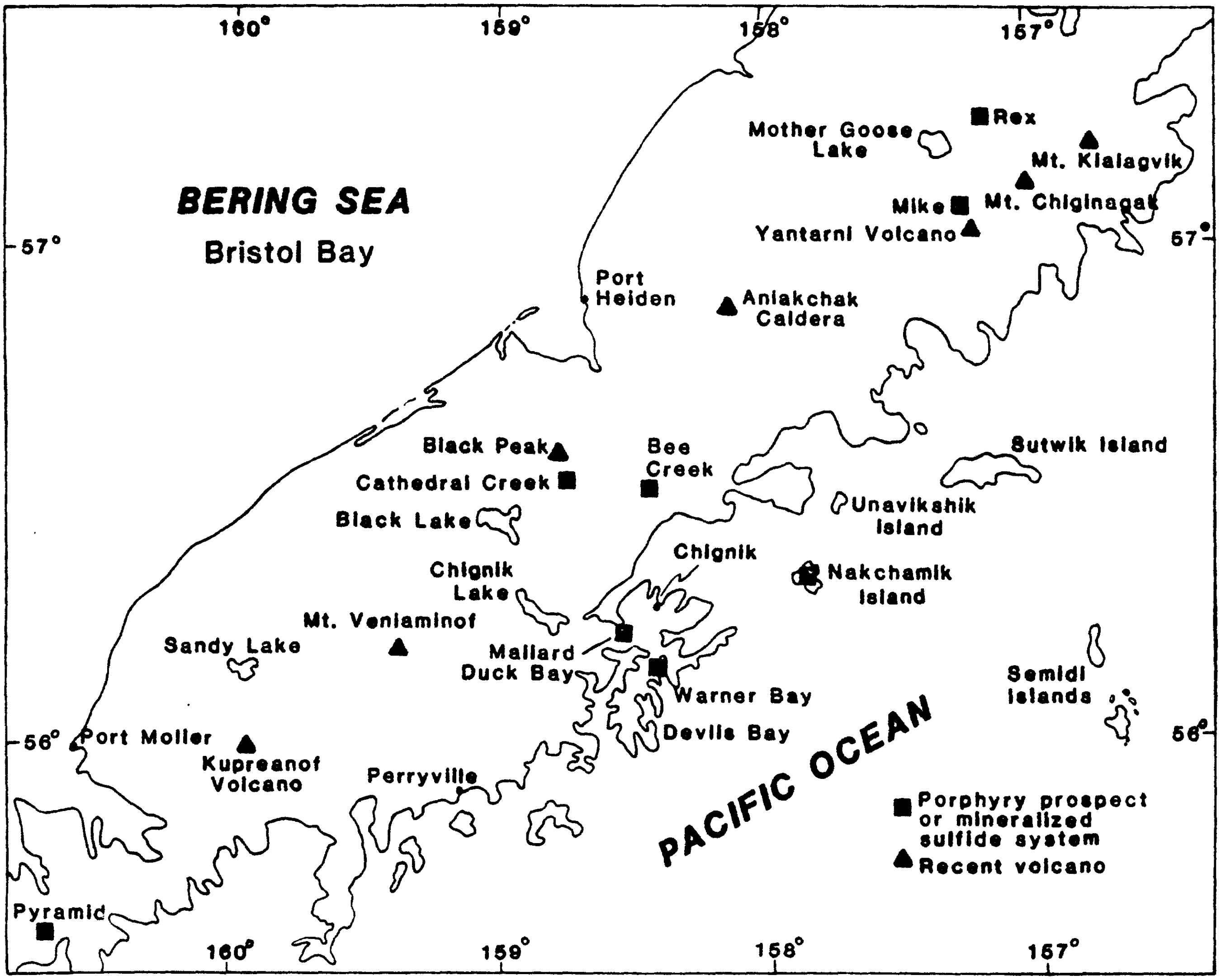

Figure 1. Map showing location of major sulfide systems on the central Alaska Peninsula.

Chignik area; descriptions of mineralization on the central Alaska Peninsula include Armstrong and others (1976), MacKevett (1977), Wilson (1980), and Cox and others (1981). Of the known areas of alteration and mineralization, only the Pyramid deposit has been estimated to have sufficient tonnage and metal concentrations to be of economic interest (V. F. Hollister, oral commun., 1980).

In general, copper mineralization is found in contact zones in sandstone surrounding hypabyssal porphyritic dacitic rocks on the central Alaska Peninsula. The Bee Creek Prospect is the best known example of this type. However, molybdenum and subordinate copper mineralization is represented in tonalite and granodiorite at Warner Bay by fine-grained coatings on thin, partly open fractures.

Geochemical Characterization

The only data available on the geochemistry of porphyry copper mineralization in the Chignik area is from analyses of drill core from the Bee Creek deposit generously provided by Bear Creek Mining Company. These data, plotted in figure 2 according the convention introduced by Kesler (1973), show that Bee Creek is a copper-molybdenum system as contrasted with copper-gold systems common to arc environments of the southwest Pacific and Greater Antilles.

Stream sediment sample data (Detra and others, 1978) has also been useful in characterizing the geochemistry of the sulfide systems. Cox and others (1981), showed that drainage basins containing anomalous concentrations of metals occur in clusters 15 to 20 km in maximum dimension on the basis of analyses of the nonmagnetic heavy-mineral fraction of stream sediments. The Bee Creek and other sulfide systems occur in drainage basins with anomalous copper, molybdenum, and, locally, tungsten. These basins are in the center of the anomalous clusters and are surrounded by drainage basins containing anomalous concentrations of lead, zinc, silver, gold, and arsenic, as well as copper (fig. 3). Drainage basins on the outer fringes of the clusters contain anomalous tin and bismuth. The association of the lithophile elements tin and tungsten with copper-molybdenum mineralization suggests similarities to deposits formed in continental crust rather than to oceanic environments. Mineralogic study of the Chignik and Sutwik Island heavy mineral concentrates (Tripp and Detra, 1980) indicate that tungsten occurs as scheelite and arsenic as arsenopyrite. No tin or bismuth minerals were identified. Scheelite has been noted in porphyry ore mineral suites in Sonora (Sillitoe, 1976); Gaspe, Quebec and the Northern Cascades, Washington (Hollister, 1978). Tungsten was not detected in studies of Puerto Rico porphyry ores (D. P. Cox, unpublished data).

This zonal pattern of anomalous metal concentrations is thought to be the result of erosion of small veinlets emplaced around volatile-rich intrusions. The zoning is caused by the relative stability of various sulfide minerals in hydrothermal fluids at decreasing temperatures related to increasing distance from a heat source(s) within the sulfide system. The distribution of peripheral gold anomalies suggests expulsion of gold from the central parts of the sulfide systems indicated by the low gold content of the Bee Creek deposit. Incomplete data from the Chignik area shows that there are significant geochemical differences between Alaska Peninsula sulfide systems and those of the southwest Pacific and Greater Antilles.

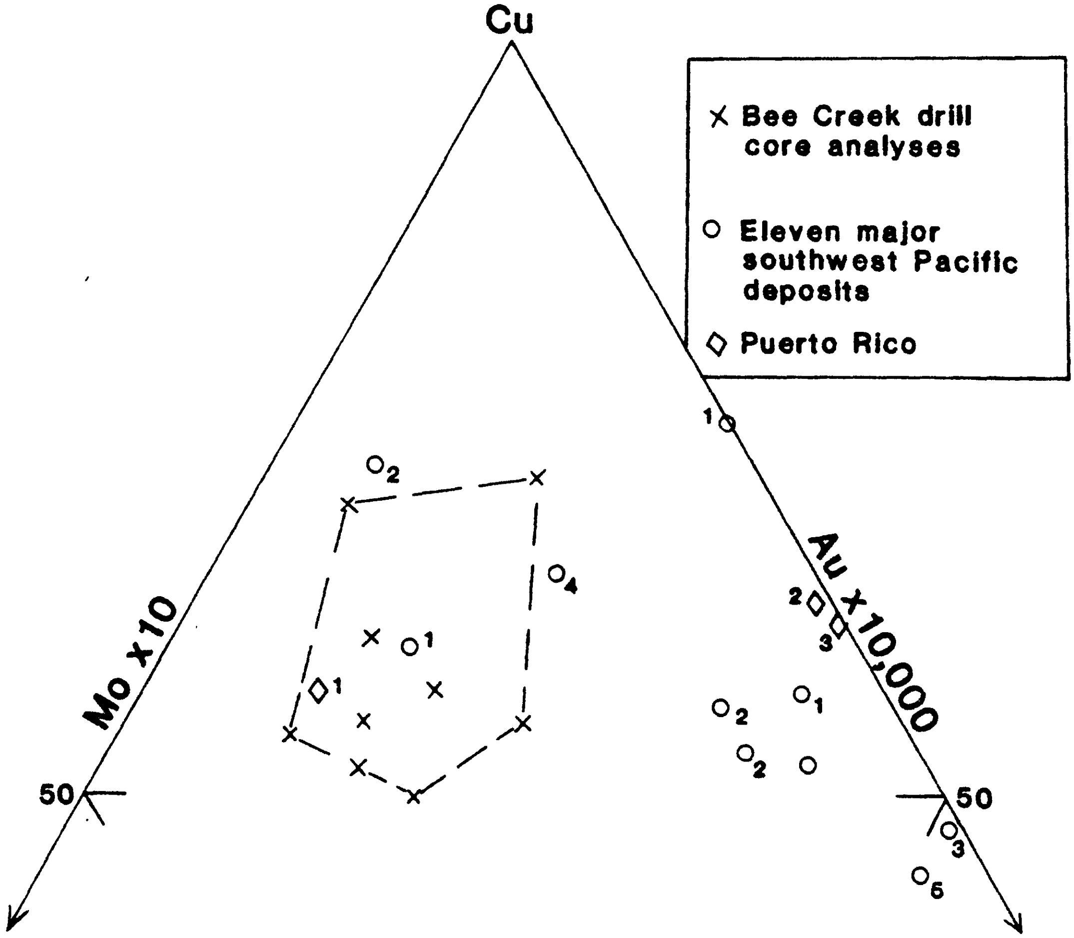

Figure 2. Copper, molybdenum, gold ratios in the Bee Creek deposit compared with other deposits in island arc environments. Values in ppm. Molybdenum values x10 gold values x10000. Bee Creek analyses are from 50-foot intervals in drill hole B-2 provided by Bear Creek Mining Company. Southwest Pacific data are from Titley (1978). Deposits are located in New Guinea-Irian Jaya (1), Phillipines (2), Borneo (3), Manus Island (4), and Bougainville Island (5). Puerto Rico deposits are Sapo Alegre (1) (Cox and others, 1975), Tanama (2), and Helecho (3) (D. P. Cox, unpublished data).

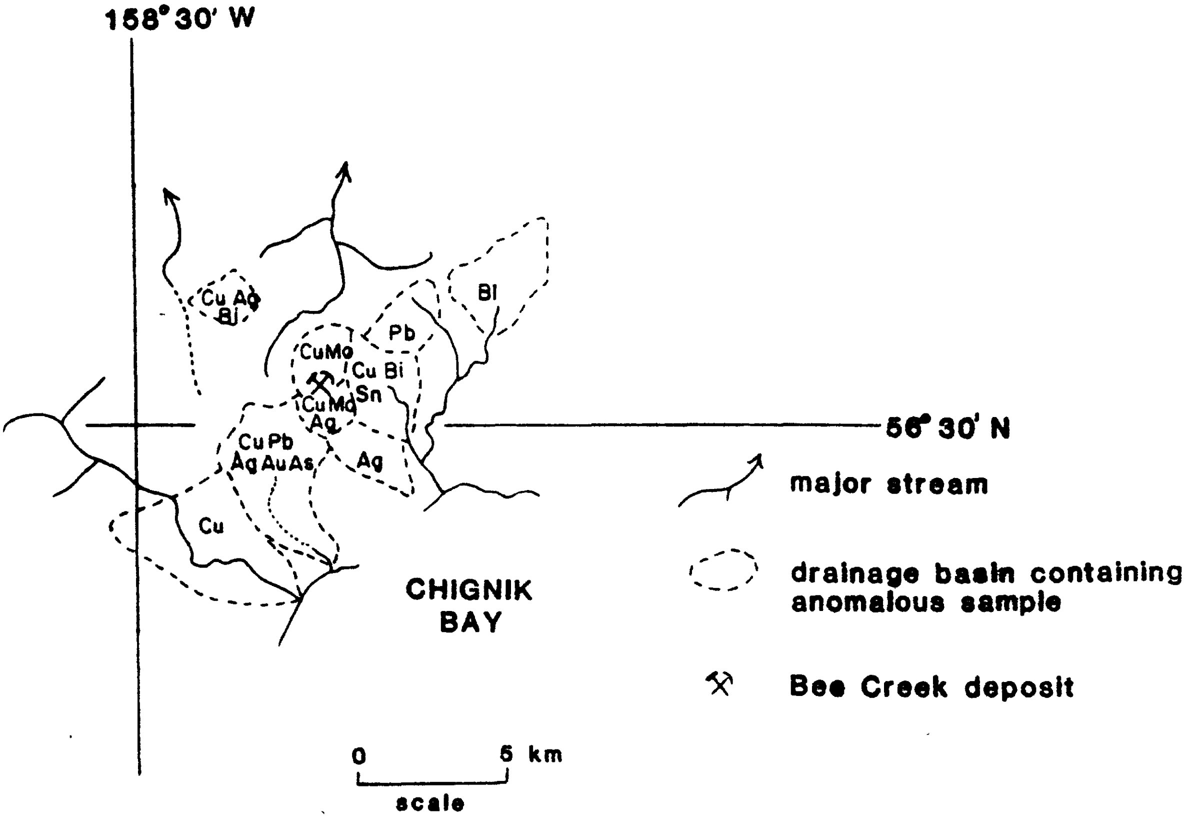

Figure 3. Associations and zoning of anomalous metals in nonmagnetic heavy mineral concentrates from stream sediments near the Bee Creek deposit. Anomalous values in ppm for each element are as follows: Ag >2, As >500, Au >20, Bi >20, Cu >700, Mo >10, Pb >150, Sn >20, Zn >500. W, >500, was not anomalous in this system.

Kesler (1973) related geochemistry of porphyry copper deposits to tectonic environment and showed that gold-rich porphyry copper deposits tend to occur most commonly in island arc environments whereas molybdenum-rich deposits are most common in regions of thick continental crust. However, Cox and others (1975) and Titley (1978) described molybdenum-rich deposits in the same tectonic environment as gold-rich deposits in the Caribbean and southwest Pacific. Sillitoe (1979) then showed that high gold content is related to high magnetite content in the ore mineral assemblage and may not depend on tectonic environment. The significance of magnetite content on Alaska Peninsula sulfide systems remains to be evaluated.

Description and Potassium-Argon Determinations of Individual Sulfide Systems

The sensitivity of many datable minerals to argon and potassium loss in response to thermal events is an asset in the dating of mineralization events as distinguished from emplacement or crystallization events. Biotite, chlorite, sericite, and potassium feldspar have proven useful in dating porphyry mineralization (Damon and Mauger, 1987; Silberman and others, 1977). In the present study, hydrothermal chlorite and/or biotite separates have been analyzed from rocks exhibiting propylitic and potassic alteration. The very fine grain-size of sericite in the porphyry systems studied has precluded separation of pure sericite from the rock; however, it was possible to concentrate sericite from many samples. In rocks that were completely altered to quartz, sericite, and sulfides, the sulfides and some quartz were removed using magnetic and gravity techniques. This resulted in concentrates with up to 2.5 percent K2O. Quartz remaining was assumed to have negligible potassium and argon; therefore, the potassium-argon age determination should reflect simply the sericite age. Previous age studies using whole rock or modified whole rock potassium silicate and propylitic alteration assemblages indicate that these quartz-sericite concentrates yield reliable ages (Morton and others, 1977; Ashley and Silberman, 1976).

Argon extraction and mass spectrometry were carried out in the U.S. Geological Survey isotope laboratories in Menlo Park, California. Procedures of isotope dilution argon extraction generally follow the methods of Dalrymple and Lanphere (1969) with some modifications due to changes in equipment. Most samples had replicate extractions. Mass spectrometry was done on a mass spectrometer of Nier design. Data reduction of the spectrometer data was by a Fortran-language computer program. Estimated analytical errors (precision) were assigned using a modification of the method of Cox and Dalrymple (1967).

Bee Creek System

The Bee Creek prospect is located about 22 km north of Chignik, approximately 5 km inland of Chignik Bay (fig. 1). Elevation ranges from 150 to 600 m. Vegetation is sparse, but talus and alluvium cover much of the prospect. The Bee Creek intrusive rocks are part of a linear east-west trend of intrusive rocks extending 65 km from Weasel Mountain though the 1-2 my old Cathedral Creek prospect, to Black Peak, a late Tertiary to Recent volcanic center (fig. 1). Scattered K-Ar ages suggest westward decreasing ages. The sulfide system has an areal extent of 2.5 by 3 km and is truncated on the north by a northward dipping low angle thrust (Detterman and others, 1981). The system is centered on a small intrusive complex emplaced into the Upper Jurassic Naknek Formation and is marked by a distinct zone of iron-staining containing areas of copper stained float. Bear Creek Mining Co. drilled five holes at this prospect in 1976 and made the drill core and results of their study available to the U.S. Geological Survey.

At Bee Creek, chalcopyrite is most abundant in arkose of the Naknek Formation near its contact with dacitic intrusive rocks. The matrix of the arkose is largely replaced by hydrothermal and contact metamorphic biotite and sulfides accompanied by abundant rutile. Quartz, feldspar, and chert clasts in the arkose are unaltered. The contact zone is locally a complex mixture of altered igneous and sedimentary rocks in which distinction between intrusive and country rocks is difficult. The intrusive rocks are abundantly veined with quartz but chalcopyrite is rare.

Fluid inclusions up to 30 micrometers in diameter are abundant in the quartz phenocrysts and veinlets in the intrusions. Many inclusions are packed with cubes of halite and crystals of other minerals, and are closely associated with vapor-rich inclusions, indicating that hydrothermal fluids were highly saline and boiling at the time of trapping. Outward from the intrusive contact, fluid inclusions become smaller, less abundant, and of lower salinity as copper mineralization becomes more intense. It appears that highly saline, boiling fluids carried copper outward from the intrusion into the arkosic rocks. There, chalcopyrite was deposited in favorable sites for replacement, namely carbonate and iron oxide minerals in the arkose matrix.

A cluster of copper, lead, zinc, arsenic, gold and silver anomalies in stream sediments surrounds the Bee Creek deposit and a bismuth anomaly was detected 6 km to the northwest. These are believed to represent the peripheral effects of the hydrothermal solutions related the Bee Creek sulfide system (fig. 3).

Alteration is roughly centered around the intrusions, and includes a potassic core and a propylitic periphery. Irregular zones of sericitic alteration are superimposed on the potassic and propylitic zones. Local argillic alteration occurs in portions of the interior of the prospect. Alteration assemblages are similar to those described by Lowell and Guilbert (1970), except for a quartz-magnetite assemblage in one small area near the center of the potassic zone, and local presence of a carbonate-actinolite assemblage in arkose within the potassic zone.

The larger of the intrusions (fig. 4) is a tonalite porphyry containing phenocrysts of plagioclase (An 35 - 50). The groundmass contains plagioclase, quartz, and hornblende and has a medium to fine-grained texture. The biotite in all samples is apparently hydrothermal and is commonly in clots partially or fully replacing hornblende or along grain boundaries. Some samples have minor potassium feldspar of probable hydrothermal origin. Chlorite is also a common hydrothermal mineral. Unfortunately, no datable primary mineral phases were found in this intrusion.

Subsequent to tonalite intrusion, possibly during cooling, alteration and mineralization occurred. Alteration ages have been determined on hydrothermal biotite from two samples (fig. 5, Table 1, no. 1,8), on sericitic alteration from two samples (fig. 5, Table 1, no. 2,5), and two dates on chlorite fig. 5, Table 1, no. 4,6). Armstrong and others (1976) determined a 3.2 $\pm$ .4 my age on a sericite-chlorite separate. These ages average 3.6 $\pm$ 0.38 my and are analytically indistinguishable though the samples have potassium contents ranging over an order of magnitude.

A dacite intrusion is similar to the tonalite except it is finer-grained and that the hornblende is unaltered. The hornblende has an apparent

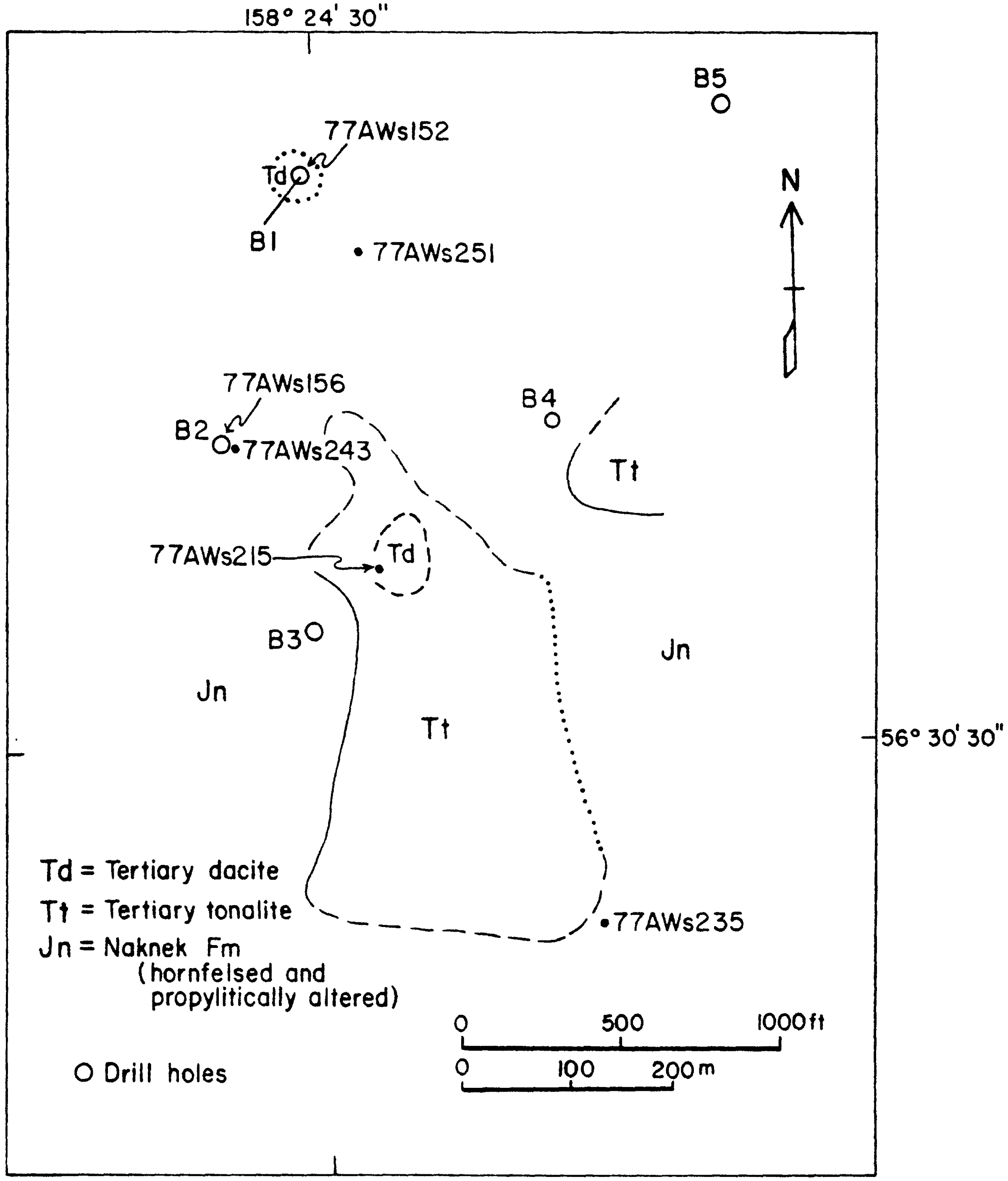

Figure 4. Sketch geologic map of the Bee Creek prospect, showing location of drillholes and dated samples.

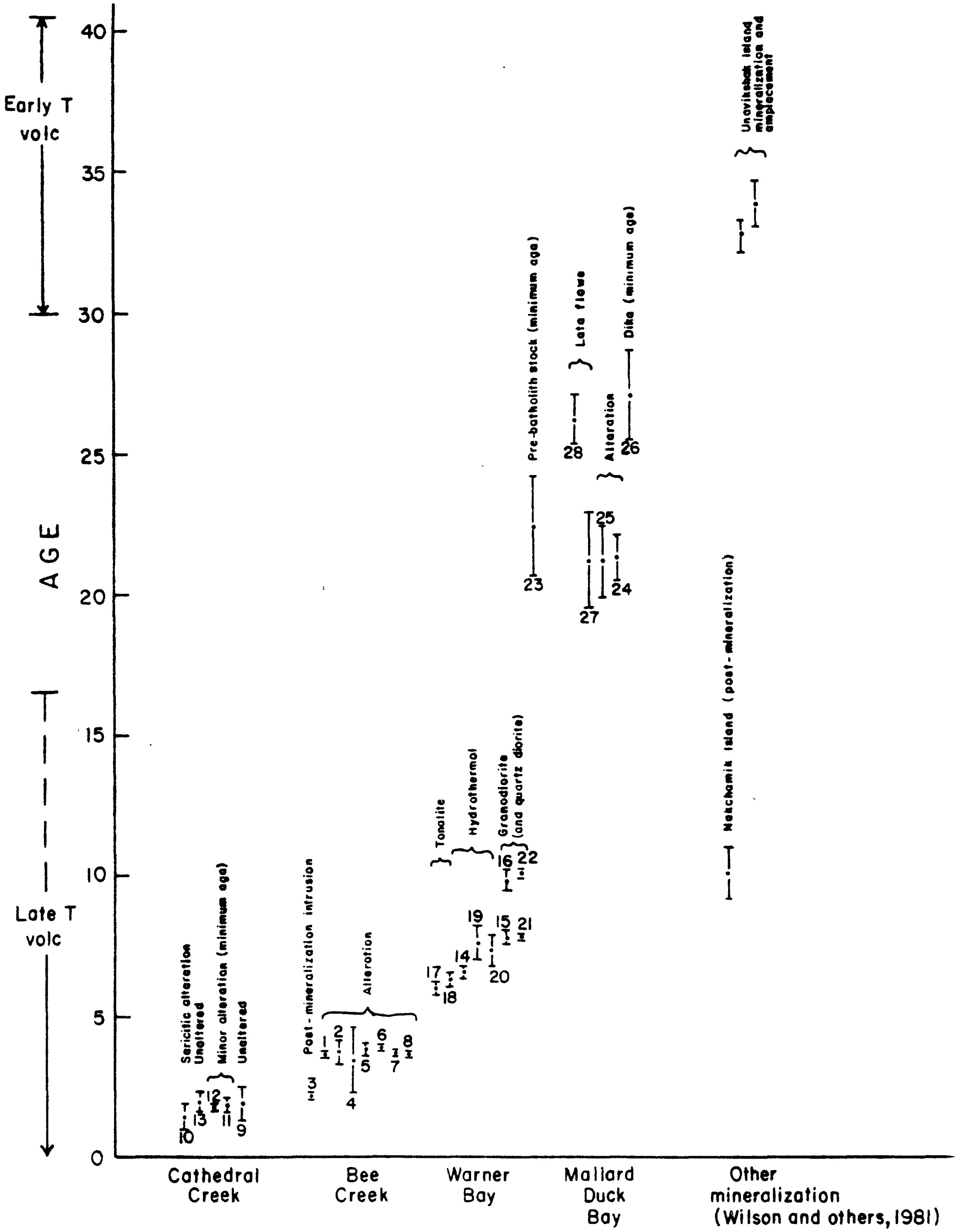

Figure 5. Diagram showing ages from mineral prospects relative to volcanic activity on the central Alaska Peninsula.

TABLE 1. Potassium-argon age determinations, central Alaska Peninsula porphyry systems.

Sample number	Field number	Rock type	Mineral†	Percent†† K_2O	$^{40}Ar_{rad}$ moles/gm	Percent of $^{40}Ar_{rad}$	Age††† (m.y.)	Error (m.y.)	Comments
				BEE CREEK SULFIDE SYSTEM					
1	77AWs 152	Potassically altered tonalite	Bio	8.53	4.499×10^{-11}	11.88	3.67	.09	
				8.46	4.43×10^{-11}	34.8	3.62	.07	
						Mean------	3.65	.11	
2	77AWs 156	Quartz sericite altered rock	WR	.947 .948	5.572×10^{-12}	21.03	4.08	.06	
				.951	4.721×10^{-12}	23.74	3.45	.03	
						Mean------	3.77	.45	
3	77AWs 215	Dacite	Hbl	.424 .430	1.572×10^{-13}	1.75	2.12	.12	
				.433 .429	2.072×10^{-13}	2.92	2.17	.09	
						Mean------	2.15	.15	
4	77AWs 235	Propylitically altered arkose	Chl	.762	2.926×10^{-12}	3.41	2.65	.20	
				.770	4.765×10^{-12}	7.00	4.32	.26	
						Mean------	3.49	1.23	
5	77AWs 243	Quartz sericite altered rock	Ser	5.44 5.45	3.111×10^{-11}	31.5	3.96	.02	
				5.47	2.090×10^{-11}	38.1	3.70	.02	
						Mean------	3.83	.19	
6			Chl	.634 .620	3.541×10^{-12}	9.35	3.92	.048	
				.625 .627					
7			WR	.930 .922	4.919×10^{-12}	7.81	3.72	.09	
				.912 .903					
8	77AWs 251	Potassically altered hybrid rock	Bio	8.15	4.378×10^{-11}	24.11	3.73	.07	
				8.16	4.229×10^{-11}	18.25	3.60	.08	
						Mean------	3.67	.10	
				CATHEDRAL CREEK SULFIDE SYSTEM					
9	78AWs 125	Dacite	Hbl	.297 .294	9.179×10^{-13}	2.83	2.16	.38	
				.295	6.761×10^{-13}	1.82	1.59	.20	
						Mean------	1.88	.59	
10	77ACx 4	Quartz sericite altered rock	WR*	1.856 1.857	3.351×10^{-12}	3.17	1.25	.04	
				1.874 1.866	4.060×10^{-12}	5.56	1.51	.05	
						Mean------	1.38	.20	
11	78AYb 57	Dacite	Plag	1.701 1.715	4.810×10^{-12}	22.6	1.96	.02	
				1.685 1.712	4.000×10^{-12}	15.5	1.63	.05	
						Mean------	1.80	.24	
12	78AYb 58	Andesite	Plag	2.097 1.098	5.272×10^{-12}	23.2	1.75	.01	
				2.096	5.119×10^{-12}	12.7	1.70	.02	
						Mean------	1.72	.05	
13	78ADt 187	Dacite	WR	1.454 1.411	3.535×10^{-12}	20.4	1.68	.05	
				1.497 1.494	4.628×10^{-12}	8.71	2.20	.11	
						Mean------	1.94	.39	

TABLE 1. Potassium-argon age determinations, central Alaska Peninsula porphyry systems (continued)

Sample number	Field number	Rock type	Mineral†	Percent†† K_2O	$^{40}Ar_{rad}$ moles/gm	Percent of $^{40}Ar_{rad}$	Age††† (m.y.)	Error (m.y.)	Comments
				DEVILS BATHOLITH AND WARNER BAY SULFIDE SYSTEM					
14	77AWs 96b	Pegmatite	Kfd	14.07 14.06	1.337×10^{-10} 1.309×10^{-10}	44.1 51.6 Mean------	6.59 6.46 6.53	.11 .10 .17	
15	77AWs 100	Granodiorite	Bio	9.10 9.11 9.11 9.15	1.037×10^{-10} $1.009 \times 10^{-1-}$	37.9 43.1 Mean------	7.88 7.67 7.78	.13 .12 .23	
16			Hbl	.531 .531 .530 .532	7.702×10^{-12} 7.406×10^{-12}	21.3 27.2 Mean------	10.05 9.66 9.86	.18 .15 .36	
17	77AWs 125	Tonalite	Bio	8.97 8.97	7.95×10^{-11} 7.63×10^{-11}	62.3 48.7 Mean------	6.15 5.90 6.03	.09 .09 .22	
18			Hbl	.533 .533 .536	4.786×10^{-12} 4.938×10^{-12}	16.0 12.4 Mean------	6.25 6.41 6.33	.14 .15 .23	
19	77AWs 179	Altered tonalite	Bio	9.00 9.01 9.01	1.020×10^{-10} 9.674×10^{-11}	4.55 31.31 Mean------	7.85 7.45 7.65	.53 .27 .66	
20	77AWs 180	Pegmatite	Bio	9.00 9.16 9.07 9.04	9.220×10^{-11} 1.008×10^{-10}	20.8 17.1 Mean------	7.04 7.71 7.38	.17 .23 .55	
21	78AWs 95	Quartz diorite	Bio	7.94 7.91	8.970×10^{-11}	38.8	7.85	.04	
22			Hbl	.526 .533 .530	7.664×10^{-11}	21.1	10.08	.14	
23	77AWs 122	Dacite	Hbl	.338 .332 .324 .323	1.125×10^{-11} 1.009×10^{-11}	24.1 17.5 Mean------	23.57 21.17 22.4	.59 .47 1.86	Minimum age possibly reset due to near proximity to Devils Batholith. Impure hornblende concentrate with inclusion of plagioclase
				MALLARD DUCK BAY SULFIDE SYSTEM					
24	77AWs 137	Tonalite	Bio/Chl	5.54 5.56 5.55 5.57	1.684×10^{-10} 1.742×10^{-10}	20.0 42.4 Mean------	20.93 21.65 21.3	.39 .38 .79	
25	77AWs 183	Quartz sericite altered rock	WR*	2.498 2.607 2.467 2.462	7.938×10^{-11} 7.475×10^{-11}	56.3 75.9 Mean------	21.81 20.54 21.2	.68 .63 1.31	
26	77AMs 1	Andesite	Hbl	.344 .342	1.301×10^{-11} 1.389×10^{-11}	29.6 15.3 Mean------	26.2 27.9 27.1	.57 .86 1.58	
27	78AWs 98	Leuco-basalt	WR	.201 .199 .200 .203	6.486×10^{-12} 5.826×10^{-12}	20.4 25.8 Mean------	22.31 20.05 21.2	.33 .38 1.68	
28	78AWs 134	Dacite	WR	1.093 1.132 1.134 1.106	4.296×10^{-11} 4.195×10^{-11}	57.3 66.6 Mean------	26.54 25.92 26.2	.55 .51 .87	

† Bio = biotite; WR = whole rock; Hbl = hornblende; Chl = chlorite; Ser = sericite(?); Plag = plagioclase; Kfd = potassium feldspar; WR* treated to remove sulfides and some quartz.

†† Potassium analyses by Paul Klock using flame photometry with a lithium metaborate flux and lithium internal standard (Engels and Ingamells, 1970).

††† = 5.72×10^{-11} yr^{-1}, = 8.78×10^{-13} yr^{-1}, = 4.963×10^{-10} yr^{-1}, $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol.

age of 2.15 ± .15 my, (fig. 5, Table 1, no. 3) indicating this hypabyssal intrusion postdates mineralization.

The dates from this prospect indicate the magmatic center was active for at least 1.5 my, that the sulfide system developed before the final intrusion and mineralization postdates the tonalite intrusion by an undetermined interval.

Warner Bay System

The Warner Bay prospect is near sea level 15 km south of Chignik (fig. 6), within the northeastern portion of the Devils batholith. The prospect was discovered in the early part of this century and has two adits driven into it (Atwood, 1911, p. 124). Relief is approximately 300 m and exposure is almost entirely within a vertical cliff extending from sea-level on Warner Bay.

Copper-molybdenum mineralization occurs on joint surfaces in the closely jointed plutonic rock, copper and zinc minerals occur in veins parallel to the jointing. Lead and zinc minerals are also disseminated in a small breccia zone on the north edge of the exposure. Chalcopyrite and molybdenite form the bulk of the mineralization and occur on joint surfaces throughout the prospect area (Robinson, 1975; Yount and others, 1978). Hematite-rich veins with minor pyrite, chalcopyrite, and sphalerite are also present in the Warner Bay prospect. The relationship between the joint-controlled copper-molybdenum and the breccia zone lead-zinc mineralization is obscure. The small breccia zone or diatreme on the north edge of the prospect contains rounded pebbles of propylitically altered granodiorite. In addition, large crystals of quartz, calcite, zeolite, pyrite, galena, and sphalerite occur in the interstices of the breccia zone. Except for the breccia zone, alteration in the batholith is restricted to incomplete alteration of amphibole to biotite, and minor chloritization of the biotite. In particular, sericitic or argillic alteration is rare and feldspar is generally fresh.

The Devils batholith is a multiphase medium-grained granodiorite to quartz diorite body approximately centered on Devils Bay (fig. 6) and is nearly 500 square kilometers in area. Hornblende and biotite are in approximately equal proportions in the rock and average about 5 to 10 percent. Many thin sections show a discontinuous reaction series from clinopyroxene to hornblende to biotite. Plagioclase has a composition of An 40-45, and commonly occurs as phenocrysts. Potassium feldspar (orthoclase) may constitute as much as 15 percent of the rock and quartz as much as 30 percent. Small areas of pegmatite, commonly parallel to jointing are found in the prospect. These pegmatites are simple mineralogically, consisting of orthoclase and biotite. Hornblende-bearing felsic and intermediate intrusive rocks in the contact zone have been thermally metamorphosed by intrusion of the batholith. An age determination on an impure hornblende separate from one of these intrusions yielded 22.4 ± 1.86 my (fig. 5, Table 1, no. 23) is a minimum age of emplacement because of contact metamorphism by the Devils batholith.

Potassium-argon age determinations on the southern portion of the batholith yield Late Miocene discordant ages (fig. 5, Table 1, no. 15, 16, 21, 22). The northeastern part of the Devils batholith represents a younger phase based on concordant ages of 6 my (fig. 5, Table 1, no. 17, 18). The thermal event associated with the intrusion of the younger phase may be responsible for the discordant ages in the rest of the batholith by partially

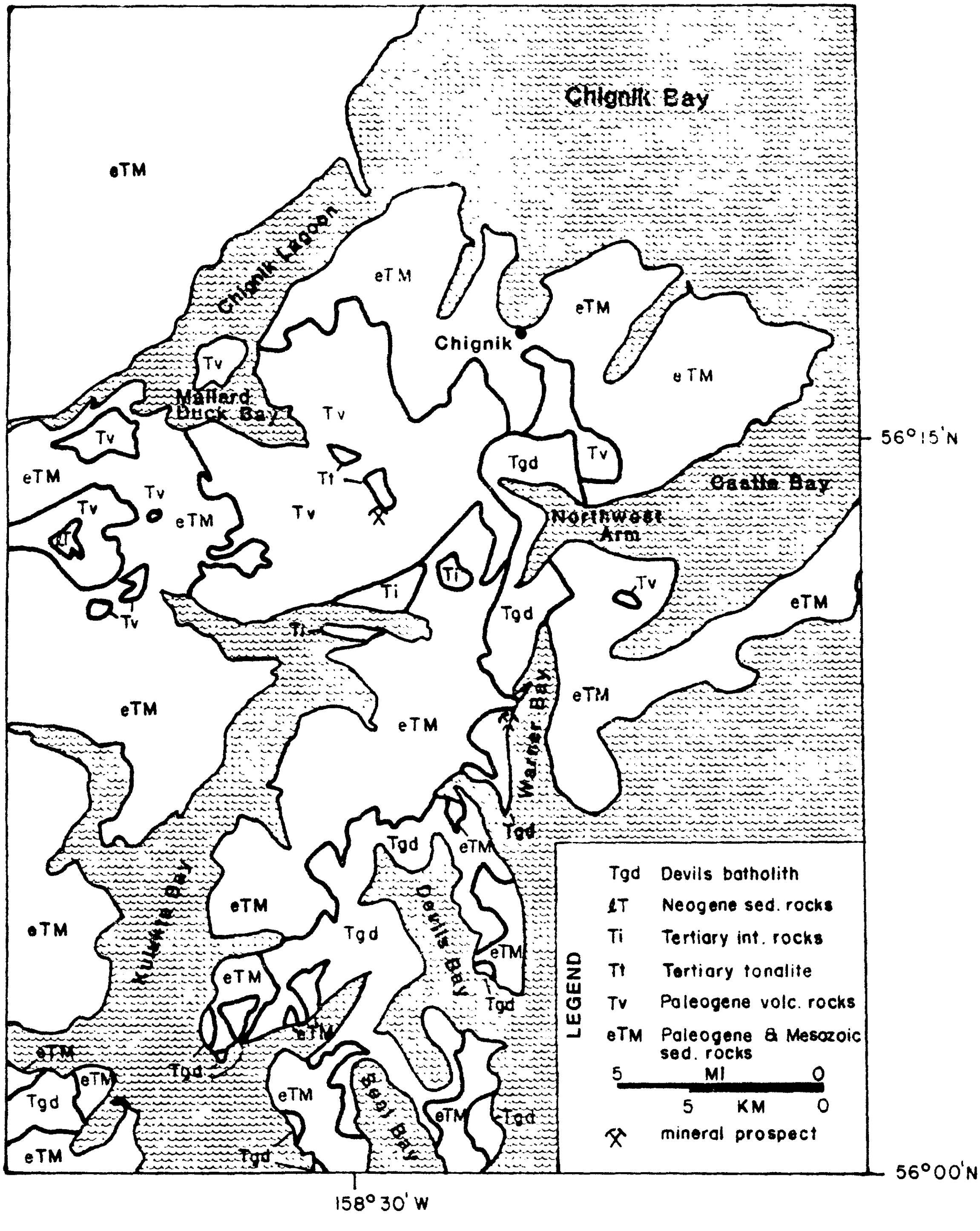

Figure 6. Sketch geologic map of the Devils batholith and surrounding area, Chignik quadrangle. Simplified from Detterman and others (1981).

resetting pre-existing minerals. Age determination on biotite and orthoclase from pegmatite and mixed primary and secondary biotite from granodiorite at Warner Bay (fig. 5, Table 1, no. 14,19,20) yield ages between that of the main (southern) phase of the batholith and the 6 my age from the younger phase.

Geologic mapping together with age determinations on rocks associated with the Warner Bay prospect and the surrounding Devils batholith, suggest that sometime in the period between the end of the Eocene and the start of the late Miocene a number of small hypabyssal stocks and dikes intruded rocks of the Late Cretaceous Chignik and Hoodoo Formations, and the Paleocene and Eocene Tolstoi Formation. One of these stocks is closely associated with a mineralized area as indicated by color and geochemical anomalies (Yount and others, 1978); this suggests that some mineralization may predate emplacement of the Devils batholith.

The main phase of the batholith, a medium-grained biotite-hornblende granodiorite, was emplaced at about 10 my (late Miocene) on the basis of hornblende ages (fig. 5, Table 1, no. 16,22). This pluton may account for most of the Devils batholith. Injection of the small pegmatites in the batholith at Warner Bay occurred as cooling progressed, followed by the development of closely spaced jointing at Warner Bay. Cu-Mo mineralization on joint surfaces developed while temperatures remained relatively high. Later, a more feldspar-rich biotite-hornblende tonalite represented by the 6 my old younger phase (fig. 5, Table 1, no. 17,18) was emplaced. This last intrusive phase does not appear to be mineralized. The diatreme or breccia pipe, at the north end of the Warner Bay exposure was emplaced after cooling of the main phase of the batholith.

Harrison and others (1979) study of thermal histories of plutons in the Coast Plutonic Complex of British Columbia is useful as an aid in interpreting the ages in the Devils batholith. On the basis of Rb-Sr, K-Ar, and fission-track dating, and estimated isotopic closure temperatures (the temperature the system retains daughter products or evidence of decay) for various mineral phases, they were able to construct temperature versus time plots and, therefore, cooling histories for each pluton studied. Although Rb-Sr and fission-track data are not available for the Devils batholith, a temperature versus time plot of the K-Ar data yields a plot (fig. 7) similar to their plot for the Ecstall pluton in British Columbia. Closure temperatures used were the argon retention (blocking) temperatures they derived for individual mineral phases; the potassium-argon age is plotted on the time axis. Three possible cooling curves are shown on the diagram; each assumes that cooling occurs at an exponential rate. The first, a dashed line projected through the hornblende, biotite, and orthoclase data points from the main phase of the batholith assumes a slow cooling history. The second, a combination dot and dash line, is the apparent rapid cooling trend of the younger phase of the batholith. The third curve is a dotted line parallel to that drawn for the younger phase, drawn from the hornblende point for the main phases, and is drawn to suggest the timing of rapid event affecting Warner Bay. If the thermal event occurred at the time of intrusion of the younger phase, then partial resetting of the biotite and increased degassing of the pre-existing orthoclase at Warner Bay occurred. This would indicate that mineralization predated the intrusion of the younger phase of the batholith by at least the difference between the hydrothermal mineral ages and the primary mineral ages in the younger phase. This could be 1 my or more.

The approach used by Harrison and others (1979) yields equivocal results in the Devils batholith based on the limited data available.

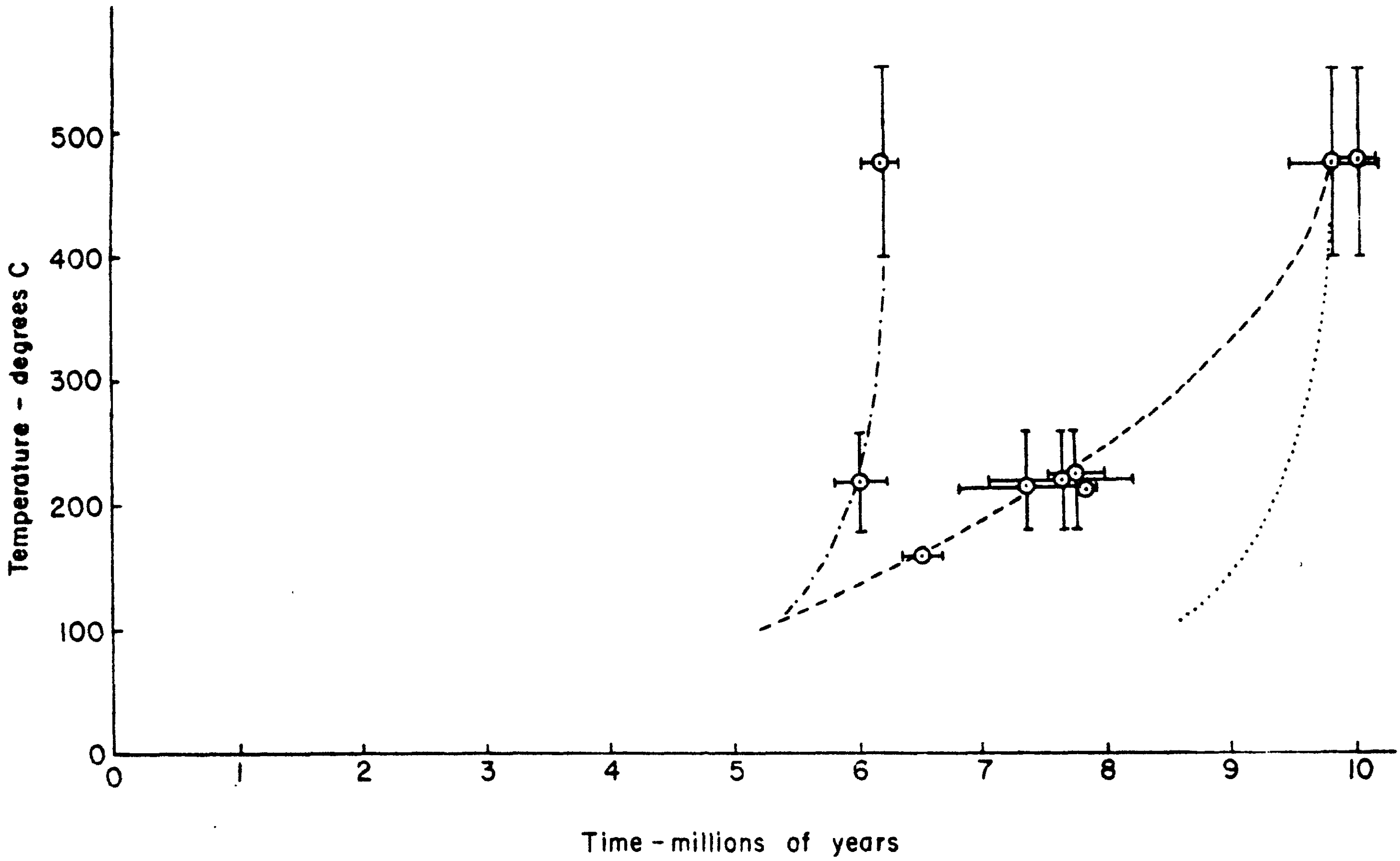

Figure 7. Temperature versus time plot for data from the Devils batholith, using blocking temperatures of Harrison and others (1979) and ages determined in Wilson and others (1981). Dashed line indicates possible slow cooling history of main phases of batholith; dot and dash line indicates rapid cooling of younger phase; dotted line shows parallel rapid cooling extrapolated for main phase.

However, in conjunction with other geological data, a post-cooling thermal event associated with the intrusion of the younger pluton is the explanation preferred by the writers to explain the potassium-argon age pattern in the main phases of the Devils batholith. This thermal event must have been of sufficient intensity and duration to partially reset mica and potassium feldspar ages. The effect of this event on older hornblende ages is unknown.

Mallard Duck Bay System

The Mallard Duck Bay sulfide system is a 4 by 10 km altered zone exposed in the headwaters of Mallard Duck Bay, approximately 10 km southwest of Chignik (fig. 6). The altered zone ranges from near sea level to approximately 600 meters in elevation. Exposure is poor on the well-vegetated slopes and most outcrops are on steep cirque walls or along fresh meander cuts in the braided streams draining the prospect.

The altered rocks belong to a thick Tertiary (Oligocene) andesitic volcanic and volcaniclastic rock sequence intruded by swarms of andesite dikes and a small tonalite stock. Propylitic alteration is characteristic, pervasive sericitic alteration is irregularily distributed, and potassic alteration concentrated in a small area of the tonalite pluton (Fields, 1977).

Geochemical sampling shows the Mallard Duck Bay system to be low in Cu, Mo, Zn, Pb, Ag, and, Au; however, relative to the other prospects in the area (except possibly Warner Bay), Mallard Duck Bay is proportionately higher in lead and zinc. Mineralization tends to be fracture-controlled, with intense shattering throughout the area (Fields, 1977).

A sample of porphyritic tonalite from one of the stocks contains large phenocrysts of quartz, plagioclase (about An 45), and fine biotite and chlorite pseudomorphs after hornblende. The groundmass is composed of fine-grained plagioclase, quartz, and hydrothermal biotite. Both phenocryst and groundmass plagioclase is generally fresh; sericitization is not common. Hydrothermal alteration is centered on this tonalite exposure and Fields (1977) reported that the tonalite is pre-mineralization and noted that mineralization decreases towards the core of the pluton. A 21.3 ± .79 my age (fig. 5, Table 1, no. 24) has been determined on chloritized biotite from this sample. A 21.2 ± 1.31 my age has also been determined on a sericitically-altered sample from this prospect (fig. 5, Table 1, no. 25).

The andesitic dike swarm was considered post-mineralization by the Bear Creek Mining Company, yet thin sections reveal pervasive propylitic alteration. A dike sample collected by M. L. Silberman is a fine-grained hornblende andesite porphyry with abundant hornblende and plagioclase phenocrysts up to 1 cm in size. The rock contains abundant epidote and chlorite. A potassium-argon age of 27.1 ± 1.58 my has been determined on hornblende (fig. 5, Table 1, no. 26) from this sample. Other samples of the dikes are also hornblende andesite or dacite porphyries; however, pervasive sericitic and propylitic alteration has largely destroyed the amphibole and plagioclase. The dikes trend northwest and are up to a kilometer in length and up to 100 meters wide. Whole-rock dates on unaltered volcanic rocks on the periphery of the prospect area range from 21 to 26 my (fig. 5, Table 1, no. 27,28) and probably represent late flows from the volcanic center. Also, other stocks and dikes in the vicinity of the Devils batholith to the south are possibly of similar age.

Mineralization at Mallard Duck Bay occurred after the emplacement of the tonalite, because the tonalite is hydrothermally altered. The available age determinations indicate the Mallard Duck Bay system was active for at least 6 my and that mineralization occurred near the end of this period.

Cathedral Creek System

This sulfide system, marked by a large color anomaly in the drainages of Cathedral, Milk, and Braided Creeks, lies north-northwest of Chignik (Fig. 1). Pan American Oil Company (now Amoco) drilled 9 to 10 core holes in the area from 1965 to 1967, and Bear Creek Mining Company (Robinson, 1975) evaluated the prospect in 1975. Robinson (1975) concluded that if any significant copper mineralization exists, it is at depth.

Base and precious metal veins cropping out in the headwaters of Braided Creek contain quartz, arsenopyrite, sphalerite, chalcopyrite and galena. The veins range in thickness from a few centimeters to a few tens of centimeters, and cut dacite porphyry intrusions as well as rocks of the Chignik Formation. They are thought to represent a peripheral manifestation of the Cathedral Creek sulfide system.

The Cathedral Creek system lies within the largest cluster of stream sediment geochemical anomalies in the study area (Cox and others, 1981). The center of the cluster is marked by molybdenum and copper anomalies in the Cathedral and Milk Creek drainage basins. The veins at Braided Creek lie within a drainage basin containing anomalous copper, silver, and bismuth, and represent one of the few examples where the mineralization responsible for the stream sediment anomalies has been seen in outcrop.

At Cathedral Creek, hypabyssal stocks intrude sedimentary rocks of the Chignik, Hoodoo, Tolstoi, and Meshik Formations. These stocks lie near the northwest end of the intrusive rocks extending from Weasel Mountain to Black Peak, mentioned in relation to the Bee Creek prospect. The stocks range in composition from two-pyroxene andesite and hornblende andesite porphyry to biotite dacite. Plagioclase compositions are quite calcic and range from An 50 to An 70 in the andesites. Biotite is rare in the thin sections examined. Dacitic and andesitic flows, pyroclastics, and agglomerates from Black Peak, a Quaternary to Recent volcano, overlie the northwest portion of the area. Robinson (1975) reports chloritization is common in the intrusive rocks within the altered zone. Textures and the geologic setting indicate that these stocks were emplaced at very shallow depths and may in part be extrusive. Sericitic alteration is extensive in the sedimentary rocks surrounding the stocks but, potassic alteration is not apparent. A potassium-argon date of 1.38 $\pm$ .19 my has been determined on a sample of sericitically altered sedimemtary rock (fig. 5, Table 1, no. 10). The stocks range from unaltered to strongly sericitically altered. An unaltered hornblende andesite stock on the periphery of the prospect has yielded a hornblende age of 1.88 my, and an unaltered dacite gave a whole-rock age of 1.94 my (fig. 5, Table 1, no. 9,13). Two samples from within the prospect area of dacite and weakly propylitically altered andesite have yielded 1.80 and 1.72 my (fig. 5, Table 1, no. 11,12) ages on plagioclase respectively. These ages are analytically indistinguishable from the above-mentioned unaltered rocks. The sericite alteration age is not significantly different analytically, yet a 0.4 my difference is suggested. Black Peak and its associated Pleistocene and Quaternary volcanic rocks are a part of the magmatic activity related to the Cathedral Creek prospect. A span of nearly 2 my is suggested for this system, with hydrothermal alteration and mineraliztion occurring early in this period.

Crustal Environment

The Alaska-Aleutian Range batholith (Reed and Lanphere, 1973) has served as basement of the northern part of the Alaska Peninsula terrane, since middle and late Mesozoic time. Case and others (1981) suggest that basement from Chignik southwestward, consist of pre-Jurassic oceanic or transitional crust which produces large positive Bouguer anomalies. In an attempt to further characterize the environment into which porphyry-type mineralization has been introduced, a sample of galena from within the Warner Bay sulfide system was isotopically analyzed. It came from a breccia pipe or diatreme that intruded the Devils batholith (10-6 my) which in turn intruded a thick section of Mesozoic and early Cenozoic clastic sedimentary rocks in the southwest part of the Chignik quadrangle. B. R. Doe and Ann Lehuray reported the results of analysis by surface emission ionization technique as follows:

206Pb/204Pb	207Pb/204Pb	208Pb/204Pb
18.894	15.544	38.398

These ratios, according to Doe (written commun., June, 1980), are characteristic of mantle-derived volcanic rocks, tending to support the argument (Case and others, 1981) that oceanic crust is at shallow depth beneath the southwest part of the Chignik area.

At present, the active volcanos of the Alaska Peninsula and Aleutian Islands are the subareal expression of a magmatic arc associated with the convergent margin at the Aleutian Trench between the North American and Pacific plates. Recent work (Wilson, 1980; Detterman and others, 1981) has shown the Peninsula to be the locus of possibly four igneous arcs since Jurassic time. Paleomagnetic work (Stone and Packer, 1977) has suggested a mobile tectonic history for the Peninsula; therefore, the specific tectonic setting and location of the Peninsula at any time is unclear. Wilson (1980) suggested translation along the western margin of the North American plate in compliance with the constraints set by Stone and Packer (1977) and Hillhouse (1977). Episodic subduction, implied by Byrne (1979), is probably also part of the history.

Conclusions and Discussion

Sulfide systems, some of which contain porphyry copper and porphyry molybdenum prospects, are associated with hypabyssal andesitic, dacitic and tonalitic intrusions in the central Alaska Peninsula.

With regard to timing of magmatic and hydrothermal phases of sulfide systems and porphyry deposits:

1. Potassium-argon age determinations indicate the time between hydrothermal alteration and mineralization, and emplacement is variable where it can be determined and may be as much as two million years. This timing, largely defined by the Warner Bay ages is similar to that demonstrated by Page (1975) for porphyry copper prospects in Papua, New Guinea. Chivas and McDougall's (1978), study of the Koloula prospect on Guadalcanal Island, documented a lifetime of 0.8 to 0.9 my for a hydrothermal system related to copper mineralization active in the area. They interpret voluminous K-Ar data on igneous and hydrothermal stages to indicate that cooling occurred slowly due to continued fluid circulation. They suggest that in some porphyry systems, where there is a resolvable difference in age between intrusion and subsequent hydrothermal mineralization, that this interval

can be interpreted as a near maximum estimate of hydrothermal system circulation, rather than indicating that a distinct interval between intrusion and mineralization occurred. In deposits where the apparent interval is greater than several million years, and probably too long for the lifetime of a continuous hydrothermal system, Chivas and McDougall (1978) suggest it is more likely that a complex series of igneous and hydrothermal events occurred, and that the intrusive phase temporally associated with mineralization remains to be dated. We suggest, based on Warner Bay, that such an intrusive phase may not necessarily exist. The Warner Bay data presented here suggests an interval of approximately 2 my between intrusion of the main phase of the batholith and mineralization. The equivocal nature of the data, however, precludes a definite statement about the exact time of the mineralization as opposed to intrusion or the duration of the hydrothermal system except that it had a life of less than 4 my. The longest period of hydrothermal activity clearly documented by adequate data is that of Warnaars and others (1978) at Bingham, where hydrothermal activity apparently occurred, perhaps episodically, for at least 2.2 my, although its exact onset is conjectural. Hydrothermal activity in epithermal precious metal deposits lasting as long as 1 my, at Goldfield (Ashley and Silberman, 1976), and 1.5 my at Bodie, California (Silberman and others, 1972) has been documented. The Steamboat Springs, Nevada geothermal system has been active, probably intermittantly, for at least the last 2.5 my (Silberman and others, 1979). These examples suggest that hydrothermal activity can be a long-lived episode lasting far beyond the period of time necessary for the cooling of any particular igneous phase.

2. In most sulfide systems examined, the development of a sulfide system was not the final stage in the igneous and hydrothermal history of these prospects; a magmatic event followed the mineralization or alteration, indicating continued life of the magmatic system.

3. Potassium-argon age determinations in the Chignik region show that porphyry-copper type mineralization occurred during all periods of igneous activity since late Eocene time, demonstrating that hydrothermal alteration and mineralization occurred throughout subduction related magmatic history, which is still continuing, rather than being restricted to some particular stage of that history.

In most of these examples, the presently measured life of the magmatic system within which a particular prospect occurs is on the order of several million years. It has not been possible to relate mineralization to any particular igneous phase or stage, and at this level of reconnaissance mapping would be difficult at best and virtually impossible in some cases. Where careful, detailed mapping and alteration studies have been made such as at El Salvador, Chile (Gustafson and Hunt, 1975), and Koloula, Guadalcanal (Chivas and McDougall, 1978) a relationship between hydrothermal and intrusive stages can be clearly documented. Development of a sulfide system is a phase in the evolution of some magmatic systems, and any center may evolve to this point, possibly more than once, as indicated at El Salvador (Gustafson and Hunt, 1975) and Koloula (Chivas and McDougall, 1978). The presence of post-mineralization igneous phases at nearly all of the prospects suggests that the magmatic system continues to be viable after operation of the hydrothermal system. This supports the contention that continued life of a magmatic system and the heat associated with it drives the hydrothermal system and not the intrusion of any particular igneous phase.

The following conclusions concerning the environment of emplacement of these systems can be made:

1. The sulfide systems and associated intrusions are emplaced in a thick sequence of Mesozoic clastic rocks having characteristics of both continental coastal plain and a magmatic arc environment, or in volcanic piles that overlie Mesozoic clastic rocks.
2. Most of the systems contain molybdenum and the known deposits are all molybdenum-rich. Systems in which gold is retained in the innermost zones were not found.
3. Analysis of heavy mineral concentrates from stream sediments derived from these systems indicates that anomalous W, Bi and Sn are commonly associated. In this way these systems more closely resemble those of continental margins.
4. Gravity data suggests that the southwestern part of the study area is underlain by oceanic or transitional crust.
5. Lead isotope ratios from galena in a small breccia pipe at Warner Bay are more similar to those of ore minerals derived directly from oceanic crust than to ores emplaced in continental margins.

Analysis of sedimentary rocks and interpretation of the depositional environments that have characterized the Alaska Peninsula since Mesozoic time indicate that island arc, continental arc and continental margin environments are juxtaposed. The Tertiary magmatic arcs are emplaced through this Mesozoic pile. The intermixed depositional environments result in a variety of characteristics in the sulfide systems that suggest both island arc and continental prophyry systems.

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