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Late Mesozoic and Cenozoic Tectonics
and the Age of Porphyry Copper Prospects;
Chignik and Sutwik Island quadrangles, Alaska Peninsula

by
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Abstract

During Tertiary time, two major episodes of igneous activity occurred in the Chignik and Sutwik Island quadrangles of Alaska. Leuco-basaltic to dacitic volcanism and granodioritic plutonism occurred during Eocene to Early Oligocene time, whereas leuco-basaltic to dacitic volcanism and quartz dioritic to granodioritic plutonism occurred from Late Miocene to Holocene time.

The Eocene to Oligocene volcanic arc, the Tolstoi-Meshik arc, was apparently oriented east-northeast to west-southwest; this is related to a more northerly directed convergence direction than present and to subduction of the Kula Plate. Following the model of DeLong and others, subduction of the Kula-Pacific Ridge in Late Oligocene time caused cessation of volcanism. After ridge subduction, volcanism resumed to form the present Aleutian arc, which is oriented in a northeast to southwest direction. This is essentially perpendicular to the present convergence direction at the Aleutian trench near the Chignik region. Isotopic dating results indicate a rapid migration (<10 m.y.) of the locus of volcanism across the Alaska Peninsula from southeast to northwest since Late Miocene time. Less conclusive is evidence suggesting migration of the locus of volcanism in the Tolstoi-Meshik arc from north to south in Eocene to Early Oligocene time.

Hydrothermal alteration and copper porphyry-type mineralization has been related to both periods of igneous activity. Potassium-argon dating of hydrothermal mineral phases and geologic relations indicate a distinct time period between emplacement of an igneous phase and mineralization of that phase.

Three porphyry prospects were examined in detail. Bee Creek is a copper porphyry prospect associated with a dacite intrusion in the Upper Jurassic Naknek Formation. No primary minerals from the dacite were datable; therefore no emplacement age was determined. A hornblende date on post-mineralization dacite was 2.15 m.y., whereas potassium-argon ages on hydrothermal biotite, sericite, and chlorite suggest a 3.7 m.y. age for mineralization.

Warner Bay is a plutonic porphyry deposit in the multiphase Late Miocene Devils batholith. Mineralization occurs in the Sweater Bay phase of the batholith; potassium-argon dating of primary and hydrothermal(?) mineral phases indicates a time span of at least 2.5 m.y. between emplacement and mineralization. Intrusion of the Northwest Arm phase of the batholith may have thermally overprinted these dates or may be contemporaneous with mineralization. Another interpretation can explain the isotopic results through slow cooling of the Sweater Bay phase followed by rapid cooling of the later Northwest Arm phase.

Mallard Duck Bay is a volcanic porphyry prospect in volcanic and volcanoclastic rocks of the Meshik Formation. Potassium-argon dates on the volcanic rocks range from 27 m.y. on a dike intruding the volcanic rocks to 21 m.y. on fresh leuco-basalt peripheral to the prospect. Hydrothermal biotite and chlorite mixtures and sericite also yield a 21 m.y. ages, suggesting mineralization occurred very late in the more than 7 m.y. history of the volcanic center.

Geologic mapping and potassium-argon dating has indicated at least three and possibly four episodes of volcano-plutonic arc activity in the study area. These episodes took place in Early to Middle Jurassic, early

Late Cretaceous(?), Eocene to Early Oligocene, and Late Miocene to Holocene times. A geologic history of the Chignik region has been derived from this work; this history has been used to help construct a speculative southern Alaska model. The model describes the motion of the Baja Alaska terrane from Early Jurassic to Holocene time and relates this motion to other major terranes in Alaska and to cratonal North America. Large scale northward translation and rotation of portions of southern Alaska, suggested by paleomagnetic data, are reconciled with the known geologic history. The proposed model involves accretion of these terranes to North America and strike-slip translation along the western margin of North America.

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Table of Contents

Abstract	ii
Acknowledgements	iv
Table of Contents	v
List of Tables	vii
List of Illustrations	viii
Introduction and Purpose	1
Location and Geography	2
Methods and Techniques	
Field Work	3
Laboratory Work	3
Potassium-argon Age Determinations	3
Previous Work	6
General Geologic Setting	7
Stratigraphic Review	9
Igneous Rocks	
Introduction	13
Alaska-Aleutian Range Batholith	17
Kodiak-Shumagin Plutonic Series	17
Devils Batholith	18
Chiginagak Bay Batholith	20
Meshik Volcanic Rocks	22
Eocene to Oligocene Intrusive Rocks	22
Late Tertiary Igneous Rocks	24
Economic Geology and Age of Mineralization	
Porphyry Models	28
Potassium-argon Ages in Porphyry Copper Deposits	33
Bee Creek Prospect	35
Warner Bay Prospect	37
Mallard Duck Bay Prospect	41
Cathedral Creek Prospect	42
Nakchamik Island	44
Unavikshak Island	44
Conclusions Regarding the Genesis of Porphyry Systems	44
Chignik Region Tectonic Synthesis	
Paleomagnetic Studies	47
Other Geophysical Studies	49
Geochronologic Studies	51
Conclusions	53
Speculations - Southern Alaska Tectonics	
Introduction	61
Speculative Model	61
Explanation	65
References Cited	68
Appendix 1 Hydrofluoric Acid Leaching Procedure	75
Appendix 2 Argon Extraction Procedure	76
Appendix 3 Stratigraphy	
Shelikof Formation	79~
Naknek Formation	80
Staniukovich Formation	81
Herendeen Limestone	82
Shumagin Formation	82

Chignik Formation	84
Hoodoo Formation	86
Tolstoi Formation	87
Stepovak Formation	88
Meshik Formation	89
Bear Lake Formation	89
Milky River Formation	90
Appendix 4 Chemical and Normative data, and Rock Descriptions for analyzed rocks	91 and Plate 2

List of Tables

Table 1	Table showing percent of silica and normative color index for analyzed volcanic and nypabyssal rocks	16
Table 2	Potassium-argon ages - Kodiak-Shumagin Plutonic Series	19
Table 3	Potassium-argon ages - Devils Batholith and Warner Bay Prospect	21
Table 4	Potassium-argon ages - Meshik Formation	23
Table 5	Potassium-argon ages - Cape Kumlik and Cape Kunmik	25
Table 6	Potassium-argon ages - Miscellaneous Intrusive and Volcanic Rocks	26
Table 7	Potassium-argon ages - Bee Creek Prospect	38
Table 8	Potassium-argon ages - Mallard Duck Bay Prospect	43
Table 9	Potassium-argon ages - Miscellaneous Prospects	45

List of Illustrations

Figure 1	Location map showing the Alaska Peninsula and the Chignik and Sutwik Island region	8
Figure 2	Stratigraphic section, Chignik region	10
Figure 3	Normative Q:Or:Pl ternary diagram for analyzed rocks	14
Figure 4	A:F:M ternary diagram for analyzed rocks	15
Figure 5	Porphyry copper deposit model, after Sillitoe (1973)	29
Figure 6	Type I or phallic porphyry model, after Sutherland-Brown (1976)	31
Figure 7	Type II or volcanic porphyry model, after Sutherland-Brown (1976)	32
Figure 8	Type III or plutonic porphyry model, after Sutherland-Brown (1976)	34
Figure 9	Temperature versus time plot for the Devils batholith	40
Figure 10	Map showing location of the Wrangellia and Baja Alaska terranes in southern Alaska	48
Figure 11	Map showing correlation between aeromagnetic anomalies and geochronologically dated igneous rocks, Chignik and Sutwik Island quadrangles	50
Figure 12	Histogram of dates from the Chignik and Sutwik Island quadrangles	52
Figure 13	Schematic cross-section - Tectonic development of the Chignik region Part I	55
Figure 14	Schematic cross-section - Tectonic development of the Chignik region Part II	56
Figure 15	Schematic cross-section - Tectonic development of the Chignik region Part III	58
Figure 16	Tectonostratigraphic terranes of Alaska exclusive of southeastern Alaska and Seward Peninsula, modified after Jones and Siblingling (1979)	62
Figure 17	Schematic diagram - Generalized Southern Alaska model	63
Figure A1	Schematic diagram - Argon extraction line	77
Plate 1	Generalized geologic map of the Chignik and Sutwik Island quadrangles, Alaska (Detterman and others, 1979)	in pocket
Plate 2	Map showing potassium-argon age sample locations and named features, Chignik and Sutwik Island quadrangles, Alaska	in pocket
Plate 3	Geologic map of the Bee Creek Prospect, after Fields (1977)	in pocket
Plate 4	Alteration map of the Bee Creek Prospect, after Fields (1977)	in pocket
Plate 5	Geologic map of the Mallard Duck Bay Prospect, after Fields (1977)	in pocket

Introduction and Purpose

This dissertation is a partial result of studies carried out as part of the Chignik and Sutwik Island quadrangles AMRAP (Alaska Mineral Resource Assessment Program) of the U.S. Geological Survey, Branch of Alaskan Geology. Parts of the study area were being considered for inclusion into Aniakchak National Monument and into the National Wildlife Refuge System. In addition, areas are claimed by the Bristol Bay Native Corporation under the Alaska Native Claims Settlement Act of 1971. As a result of these considerations, an evaluation of geologically related resources, coupled with a general reconnaissance geological evaluation was begun. The purpose of this dissertation is to report on a study of the timing of plutonism and mineralization in the Chignik and Sutwik Island quadrangles of Alaska. This dissertation attempts to place intrusive events within a time framework established using potassium-argon dating and to present a coherent tectonic synthesis of intrusive activity within this framework. Within the constraints of this work and other geologic data, a regional tectonic synthesis is attempted. In addition, the timing of mineralization is studied by potassium-argon dating of the alteration assemblages formed concurrently with mineralization.

Location and Geography

The study area is composed of the Sutwik Island and Chignik quadrangles spanning the Alaska Peninsula in an east-west direction just southwest of Kodiak Island (Figure 1). The extent of the area is approximately 18,000 sq km (7,000 sq mi) and it encompasses parts of two physiographic regions (Wahrhaftig, 1965), the Aleutian Range Province and the Nushagak-Bristol Bay Lowland Province.

The Aleutian Range Province is characterized by jagged glaciated peaks with elevations averaging 1000m, with some peaks extending to over 2000m. The valleys are U-shaped and often fjord-like though many are filled with recent ash from the active volcanos of Mt. Veniaminof, Aniakchak and Black Peak. The northwestern edge of this province in the study area is bounded by these three volcanos.

The Nushagak-Bristol Bay Lowland is characterized by extreme low relief (<100m). In general, the terrain has been built by Quaternary processes, the material usually glacial drift or ash-flow and ash-fall debris. Near the Bristol Bay coast, there are marine terraces at an elevation near 30m, evidencing a higher sea level stand (oral communication, R.L. Detterman, 1978), or relative post-glacial uplift of the Alaska Peninsula.

Human habitation is concentrated around Chignik Bay in the villages of Chignik, Chignik Flats, Chignik Lake, and Chignik Lagoon and at Port Heiden in the village of Meshik with a total year-round population near 300. The area can be reached by air with scheduled service by Reeve Aleutian Airways to Port Heiden and connecting service by Peninsula Airways to other points. There are no roads maintained in the area except within villages. Much of the area lies within the territorial boundaries of the Bristol Bay Native Corporation and Koniag Inc., the Kodiak Native corporation.

Methods and Techniques

Field Work

Field work in association with this project was done in the early summers of 1977 and 1978 by this writer and associates of the Branch of Alaskan Geology of the U.S. Geological Survey. The field party included R.L. Detterman (Team leader), D.H. Richter, T.P. Miller, M.E. Yount, myself and guest scientists. Each year, in late May and during the month of June, a mobile field camp was established on board the Alaska Branch's ship, the R.V. Don J. Miller II. This ship is equipped with four skiffs for shore work, a helicopter landing deck for helicopter support, rock saws and associated equipment for slabbing and staining of rocks, and a work room with map cabinets and drafting tables for compilation and map work. The ship will support up to an 11 person geologic field party. Each year during the first two weeks of July the field party moved to a land-based camp at Columbia Ward Fisheries in Chignik Lagoon. Helicopter support was contracted to ERA Helicopters in 1977 and a Bell 206B was flown by Robert McDonald. In 1978, Air Logistics of Alaska received the contract and Gordon Hine was our pilot, also in a Bell 206B. While ship-board, logistic support was provided by the ship's crew; on land, food and lodging were contracted to Columbia Ward Fisheries.

Frequent storms originating in the Aleutian Low passed through the area during the field season, often forcing us to remain in camp or curtail work in progress. Winds often exceeded 50 knots and reached 95 knots (109 mph) in one storm. Calmer weather was often accompanied by thick fog. The result was that we were able to work about half the time, generally under marginal conditions. When good days occurred they were truly spectacular, and made the rest of the stay worthwhile.

During 1977, traverses were often made alone but a number of unfortunate bear encounters in our and other field parties caused us to change our working procedures in 1978, and as a result we usually worked in pairs. Each pair carried two-way radios, allowing communication with the helicopter, other working pairs and the ship. Mapping was done on a reconnaissance basis, using 1:63,360 scale topographic sheets as field maps except at the Bee Creek prospect where a steel tape and compass survey was made by M.L. Silberman and myself. The final compilation map is being made at 1:250,000 scale.

Laboratory Work

After the finish of the first field season, hand sample and thin section study of the available rocks was begun. Samples collected for age determination were evaluated in thin section, and those judged suitable for further work were selected. Fossils collected by the field party were submitted to the U.S. Geological Survey Branch of Paleontology and Stratigraphy for study and identification.

Potassium-argon Age Determinations

A large part of this dissertation is based on potassium-argon dating work by this author; therefore some discussion of the procedures used is warranted. Two strategies were used in dating; 1. dating of primary minerals or whole rocks to determine crystallization ages and 2. dating of secondary or hydrothermal minerals to determine the time of alteration and mineralization.

Whole-rock samples, other than quartz sericite samples, were crushed to 60-100 or 100-200 mesh, dependent on mineral grain size, followed by a hydrofluoric acid leaching (Appendix 1). The leaching process removes secondary minerals and glass and etches the remainder. Experimentally, this procedure has been shown to dramatically increase the relative percent radiogenic argon in the sample while apparently not affecting the determined age, thus measurably decreasing the analytical error in the age determination. Using a microsplitter, aliquots of the sample were separated and submitted to the U.S. Geological Survey Branch of Analytical Laboratories for potassium analysis. Other aliquots were retained for argon analysis.

Rocks that were to yield mineral separates were crushed, washed, and separated using methylene iodide for density separation, a Franz Isodynamic Separator for magnetic separation, and a vibrating inclined table for separation of platy minerals. Purities of the mineral separates in most cases exceeded 99 percent. Splits of these separates were then made for potassium analysis and argon extraction.

Argon extraction and mass spectrometry were carried out in the U.S. Geological Survey Branch of Isotope Geology laboratories in Menlo Park, California, generally following the methods of Dalrymple and Lanphere (1969). Procedures and equipment have been modified somewhat since 1969 and the argon extraction procedure is described in an appendix (Appendix 2). Potassium analyses were by Paul Klock and were made by flame photometry using a lithium metaborate flux and lithium internal standard (Engels and Ingamells, 1970). All potassium analyses were in duplicate and most were in quadruplicate.

The extracted argon sample was loaded on one of two mass spectrometers, one of so-called Nier design and the other of similar, though multi-collector, design. Argon measurement is based on isotope dilution techniques, using the argon-38 introduced into the sample during extraction as a tracer of known amount. The Nier mass spectrometer works essentially as described in Dalrymple and Lanphere (1969); however, there have been numerous improvements in the control electronics since 1969, which have improved the precision of the data.

Data reduction from the spectrometer charts was made using a Fortran-language computer program written by myself. Linear and exponential line fits were made of each set of peak data (i.e. argon-40, argon-38, and argon-36) and the best fit was chosen between the linear and exponential fits on the basis of the correlation coefficients calculated in the program. From the line fit chosen for each peak, the line intercept or the peak height at "T-zero" (the time of sample introduction into the spectrometer) is determined; this yields the argon isotope ratios of the gas introduced to the spectrometer. Corrections are then made for spectrometer mass discrimination, background, and tracer composition to yield the "true" argon isotope ratios (Ar-40/Ar-38 and Ar-38/Ar-36). The standard potassium-argon age equation;

$$t \text{ (yrs)} = 1.804 \times 10^9 \ln(9.541(^{40}\text{Ar}/^{40}\text{K}) + 1.0)$$

was used to calculate the age and then the program calculated an estimated analytical error based on the line fit chosen, measured tracer error, the percent radiogenic argon, and the estimated error in the potassium analysis. The procedure used to calculate the analytical error is modified

from Cox and Dalrymple (1967).

A number of different indices are calculated to provide information in order to assist in the interpretation of the quality of the analysis. These include the percent radiogenic argon yield, spectrometer mass discrimination and spectrometer sensitivity. Most samples dated were extracted at least in duplicate; often the results were unacceptable analytically, so a number of tests and modifications were introduced to minimize the analytical difficulties. The procedure described in Appendix 2 was found to be the most successful means of argon extraction.

As of July, 1976, all potassium-argon age determinations from the U.S. Geological Survey are reported using new isotope abundance and decay constants. These constants are:

$$\begin{aligned}\lambda_e &= 5.72 \times 10^{-11} \text{ year}^{-1} \\ \lambda_{e'} &= 8.78 \times 10^{-13} \text{ year}^{-1} \\ \lambda_{\beta} &= 4.963 \times 10^{-10} \text{ year}^{-1} \\ {}^{40}\text{K}/\text{K}_{\text{total}} &= 1.167 \times 10^{-4} \text{ mol/mol} \\ &\quad \text{(Beckinsale and Gale, 1969;} \\ &\quad \text{Garner and others, 1975).}\end{aligned}$$

For ages between 1 and 100 million years, this change adds approximately two percent to ages calculated using the previous constants. All ages reported in this thesis have been calculated using the 1976 constants, including previously published ages, which have been recalculated.

Previous Work

Prior work in the area has not been extensive and most of it is discussed and amplified in Burk's (1965) study of the geology of the Alaska Peninsula. This work laid the framework for most of the present study, which is the beginning of a major effort by the U.S. Geological Survey, Branch of Alaskan Geology in Alaska Peninsula geology. Some of the earliest geologic work here was done by Spurr (1900) on a hurried traverse across the northern part of the peninsula, near Naknek Lake (Figure 1). Atwood (1911), Capps (1923) and Knappen (1929) all contributed early reconnaissance geologic studies to the literature of the region. With respect to dating work, Imlay and Detterman (1973; 1977; Imlay, 1953; 1975) and Wolfe (1972) have reported on paleontologic and paleobotanic studies. Prior to the present study only two radiometric dates have been published on rocks in the study area: one by Armstrong and others (1976) and one by Kienle and Turner (1976).

The geologic literature contains abundant reports concerning porphyry-type mineralization, though few have attempted major radiometric studies in association with work on the mineralization. Most important have been those by Moore and Lanphere (1971), Page and McDougall (1972a, 1972b), Page (1975), Theodore and others (1973) and Chivas and McDougall (1978).

General Geologic Setting

The Alaska Peninsula is a terrane primarily composed of clastic sedimentary rocks ranging from Triassic to Quarternary in age. The abundant volcanic rocks are generally of andesitic composition, ranging from leuco-basalt to dacite, and are of Permian, Tertiary, and Quarternary age. Intrusive rocks of Jurassic to Quarternary age are also known. Major geologic features include the Quarternary to Recent volcanos: Iliamna, Augustine Island, Katmai, Chiginagak, Aniakchak, Veniaminof, Pavlof and other less spectacular volcanos (Figure 1). The Alaska-Aleutian Range batholith forms the geologic backbone of the Alaska Peninsula in its northern half. Aeromagnetic (U.S. Geological Survey, 1978) and drill hole data (Brockway and others, 1975) indicate that this batholith may extend at least as far south as Port Heiden in the subsurface. The batholith is formed of quartz-bearing intrusive rocks of granitic to dioritic composition (Reed and Lanphere, 1969). Potassium-argon work by Reed and Lanphere (1974) has shown that these batholithic rocks fall into three age clusters; 180 to 158 m.y., 85 to 59 m.y., and 39 to 26 m.y..

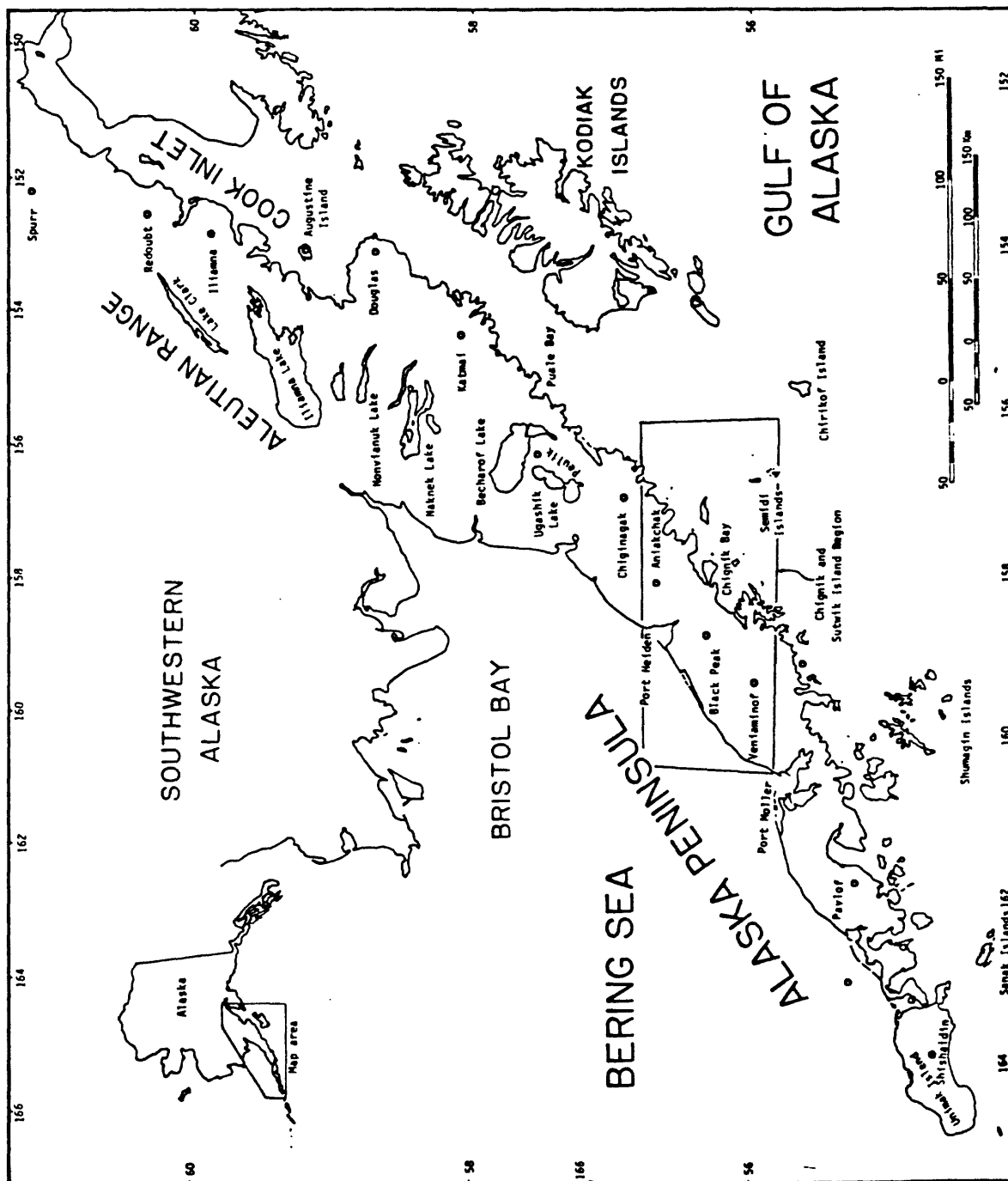
Along a northeast to southwest trend parallel to the Alaska Peninsula in the Kodiak, Semidi and Shumagin Islands (Figure 1) is a belt of plutons generally of intermediate composition, all of approximately 60 m.y. age. Kienle and Turner (1976) called this the Shumagin-Kodiak batholith, and suggested it represents a Paleocene magmatic arc, although no evidence is presented demonstrating any continuity of the rocks in the subsurface.

The remainder of the Alaska Peninsula is composed of sedimentary and volcanic rocks, primarily of Middle Jurassic to late Tertiary age, Pleistocene to Recent volcanic rocks, and the Kodiak and Shumagin Formations, a slate and metagraywacke sequence apparently of Upper Cretaceous age. The older sediments tend to be arkosic, whereas the younger are more volcanoclastic and tend to contain more shale. There does not appear to be an overall fining upward trend, though individual sediment packages may show this. The volcanic rocks are primarily of Tertiary age, are generally andesitic in composition, and are represented in part by many geomorphic features that are apparently volcanic necks. There are Permian to Jurassic volcanic and volcanoclastic rocks on the west side of Kodiak Island and at Puale Bay on the Alaska Peninsula (Moore and Connelly, 1977; Burk, 1965).

The Alaska Peninsula, at present, is the subareal expression of a volcanic arc associated with the convergent margin between the North American and Pacific plates. The presently active volcanos of the Alaska Peninsula and Aleutian archipelago can all be related to subduction along the Aleutian Trench.

Potassium-argon dating undertaken as part of this study has shown that a northwestward dipping thrust fault truncating the Bee Creek prospect (Plate 2) has been active during the past 3.6 m.y., this movement may continue to the present day.

The Chignik and Sutwik Island region straddles the Alaska Peninsula (Figure 1) just south of its midpoint and probably contains the most complete stratigraphic section to be seen on the Peninsula. Structurally the study area is dominated by the Chignik anticline, an overthrust anticline trending subparallel to the Alaska Peninsula. Hypabyssal, volcanic and plutonic rocks of Tertiary age outcrop in the area, though the Alaska-Aleutian Range batholith of Jurassic, Cretaceous, and Tertiary age does not. Within the study area, our work has indicated numerous changes



must be made on Burk's (1965) geologic map (see Plate 1).

Stratigraphic Review

The sedimentary and volcanic formations of the Chignik and Sutwik Island area indicate a number of different geologic environments and therefore place important constraints on the geologic history of the Chignik and Sutwik Island region. Each lithologic package defines a particular environment and, through time, each different environment must follow the other in a logical sequence. Each formation is more fully described in Appendix 3; what follows is a summary of these descriptions.

Briefly reviewing the stratigraphic column of the area (Figure 2), from oldest to youngest, there is the following sequence of lithologic packages and presumed environments:

1. The Shelikof Formation is composed of fine- to medium-grained sandstone and siltstone of Middle Jurassic age that is up to 2000m thick. There are three members, 1. a lower siltstone containing volcanic ash deposits, 2. a massive gray-green sandstone with interbedded siltstone and plutonic pebble conglomerate and, 3. an upper massive black shale with minor limestone lenses and nodules. The Shelikof was deposited in a rapidly subsiding basin and from a terrane yielding an abundant supply of volcanic detritus. The source terrane was to the present north and northwest of the depositional basin. The lower siltstone was deposited below wavebase and thin interbedded ashes indicate active volcanism at the time. The middle sandstone was deposited near shore, and apparently minor volcanism continued. Imlay (1963, p. 57) suggested deposition in a major ocean basin.

2. The Naknek Formation is a sandstone and conglomerate unit unconformably overlying the Shelikof and equivalents. The lower Naknek is a pale green, fine-grained, arkosic sandstone with some coarse plutonic cobble conglomerate. The upper Naknek is a dark olive green siltstone with abundant fossils and thin calcareous layers of large lateral extent. The environment of deposition for the Naknek was a nearshore, moderate to high-energy braided stream or beach environment with rapid sediment influx, short sediment transport distances and gradual subsidence with time to a farther offshore environment.

3. The Staniukovich Formation is lithologically continuous with the Naknek and indicates that a very similar depositional environment extended into the Lower Cretaceous. The source terrane for both formations was plutonic. Lithologically, the Staniukovich is identical to the Naknek and can only be reliably separated from it on paleontologic criteria. This is further discussed in Appendix 3.

4. In limited areas, the Herendeen Limestone (Burk, 1965, p.45) is exposed in the study area. The Herendeen Limestone may be indicative of subsidence of the Naknek and Staniukovich Formations source area. The Herendeen Limestone is a fossiliferous calcarenite. Inoceramus prisms are extremely common, in some areas constituting three fourths of the rock. The noncalcareous portions of the formation are similar lithologically to the Staniukovich.

5. The Shumagin Formation is a poorly dated Late Cretaceous (Maestrichtian?) flysch derived from a volcanic terrane to the northwest, except in the Sanak Islands where the source terrane was apparently to the east or southeast. No stratigraphic top to this formation is known. This formation is found in the Outer Shumagin and Sanak Islands at the present

AGE		FORMATION	THICKNESS meters	LITHOLOGY	
TERTIARY	Neogene	Holocene and Pleistocene	10 - 1,000	Sand, gravel, and silt	Dacite, andesite, tuff, pumice
		Pliocene	300 - 1,500	Volcaniclastic sandstone and conglomerate	Basaltic flows, tuffs, lahars
	Paleogene	Miocene	1,000 - 2,400	Sandstone, siltstone, conglomerate, shale, coal	Quartz diorite, dacite, andesite gabbro
		Oligocene	500 - 1,500	Sandstone, siltstone, conglomerate, shale, coal.	Basaltic flows, breccia, lahars, and diorite
		Eocene			
		Paleocene	1,000-1,500	Sandstone, siltstone, conglomerate, shale, coal	Basaltic to dacitic flows, breccia, lahars.
					Granodiorite
CRETACEOUS	Upper	Maestrichtian	0 - 500	Dark siltstone, shale, minor sandstone	
		Campanian	300 - 500.	Sandstone, conglomerate, siltstone, shale, coal	
		Santonian			
	Lower	Coniacian			
		Turonian			
		Cenomanian			
		Albian			
		Aptian			
		Barremian			
		Hauterivian			
		Valanginian	0 - 30	Calcarenite	
		Berriasian	0 - 300	Feldspathic to arkosic sandstone	
		Staniukovich			
JURASSIC	Upper	Tithonian			
		Kimmeridgian	1,500 - 1,800	Upper part - dark siltstone Lower part - arkosic sandstone, conglomerate, siltstone	
		Oxfordian			
	Middle	Callovian	150 - 300	Dark siltstone	

Figure 2 Stratigraphic section of the Chignik region.

edge of the continental shelf. Maestrichtian(?) fossils have been reported from the Shumagin Formation (Jones and Clark, 1973, p. 134). The Shumagin may be as old as Albian; it is probably no younger than Late Maestrichtian in age. It was probably deposited in a fore-arc basin by turbidity currents. It is apparently correlative with the similar Kodiak Formation, from which Maestrichtian fossils have been reported. The Shumagin is complexly folded and faulted and has undergone zeolite facies metamorphism. Fold axes parallel the existing continental shelf edge and deformation may have been caused by underthrusting at a convergent plate margin (Moore, 1973b). Moore thought deposition occurred at abyssal or near-abyssal depths.

6. The Chignik Formation is an Upper Cretaceous argillaceous and arkosic sandstone and conglomerate unit. The Coal Valley Member includes much of the conglomerate, in addition to siltstone and coal horizons. The Coal Valley is a nonmarine deposit, the conglomerates are alluvial fan deposits, and the siltstones and coals represent deltaic or lagoonal facies. The remainder of the Chignik Formation is made up of well-bedded argillaceous sandstones and siltstones. The volcanic component of this formation is somewhat greater than that of the Naknek and Staniukovich Formations which the Chignik overlies unconformably. Bentonitic shales may indicate active volcanism at the time of deposition. The source area for the Chignik was to the north or northwest and yielded mixed plutonic and volcanic rocks.

7. The Hoodoo Formation conformably overlies(?) the Chignik and is a black, well-bedded siltstone. It was deposited in fairly deep water, possibly offshore of the nearly contemporaneous Chignik Formation and has characteristics of turbidity current deposition. Depth of deposition is not thought to be great, though the Hoodoo might represent a distal turbidite. At present, the direction of sediment inflow is unknown. The Hoodoo has been subjected to a very low grade of metamorphism.

8. The Tolstoi Formation is an Eocene-Oligocene(?) volcaniclastic unit unconformably overlying the older formations. A number of hypabyssal intrusions into the Tolstoi have yielded late Eocene to Oligocene ages. The extremely coarse grain size of some of the conglomerates and the nonmarine floral assemblages found in the Tolstoi indicate short transport distances; the interbedded flows and agglomerates (possibly including volcanic breccias and lahars) indicate nearness to a volcanic source area. Occurrences of pyrite in the siltstones may indicate euxinic basins or lagoonal deposition of the siltstones.

9. Conformably overlying the Tolstoi is the Meshik Formation, a leuco-basalt to dacite volcanic unit. This unit is composed of flows, agglomerates and breccias, with minor interbedded volcaniclastic sediments. The Meshik is thought to represent a Late Eocene to Oligocene volcanic arc deposit, related to a convergent plate margin.

10. Unconformably overlying the earlier units, the Bear Lake Formation reflects a hiatus in volcanic activity and possibly a change in the subduction regime of the proto-Aleutian Trench. The Bear Lake is composed of sandstones, conglomerates, and minor siltstone containing abundant nonvolcanic clasts. The Formation is considered to be Middle to Late Miocene in age based on pelecypods, gastropods and echinoids (Detterman and others, 1980b). The Bear Lake is essentially derived from reworking of earlier sediments in a non-marine to inner neritic environment. It probably reflects a marine regression, followed by a minor transgression.

11. The Milky River Formation reflects the reinitiation of volcanism along the Alaska Peninsula. The unit unconformably overlies the Bear Lake Formation. The coarse volcanoclastic rocks, porphyritic flows and lahars indicate short transport distances and nearness to source. The sedimentary structures and textures indicate nonmarine deposition. This unit probably represents a regime very similiar to that of the Tolstoi-Meshik package.

The sediment source terrane for the study area has always (except possibly for the Hoodoo) apparently been to the north or northwest. Volcanism has been an important contributor to the Tertiary units, except for the Bear Lake Formation. The Late Jurassic through Early Cretaceous Formations and the Bear Lake Formation reflect the erosion of a plutonic source terrane, or reworking of pre-existing sediments. The Middle Jurassic Shelikof and possibly the Late Cretaceous Chignik Formation in part may reflect erosion of a quiescent volcanic arc. Except for the Shumagin and Hoodoo, sedimentation has always been relatively nearshore or nonmarine. The Shumagin was probably deposited in a fore-arc basin and lithologically may be indicative of the erosion of a volcanic arc.

Igneous Rocks

Introduction

Intrusive rocks in the Chignik and Sutwik Island area range in age from Paleocene to Quarternary. In this thesis, the igneous terminology will follow that of Streckeisen (1976, 1979). Many hypabyssal rocks are intrusive in form and texturally intermediate between fine- and medium-grained; to avoid confusion, hypabyssal rocks will be named using volcanic rock names because they are often indistinguishable from their extrusive equivalents. Compositionally they range from leuco-basalt to dacite, though the bulk of the intrusions are near andesite in composition. Most intrusive rocks are hypabyssal; relatively deep seated plutons are represented by three major occurrences, which are: 1. the large late Miocene quartz diorite(?) body extending along the coast to the northeast from Chiginagak Bay (Plate 1) in the Sutwik Island and Ugashik quadrangles; 2. the Devils batholith, a late Miocene granodiorite to tonalite multiphase intrusive south of Chignik at Devils Bay (Plate 1) in the Chignik quadrangle; and 3. the Paleocene biotite granodiorite (Kienle and Turner, 1976) in the Semidi Islands in the Sutwik Island quadrangle. Minor occurrences of plutonic rocks include a number of small tonalite bodies at Mallard Duck Bay. A major feature of the Alaska Peninsula is the Alaska-Aleutian Range batholith described by Reed and Lanphere (1969, 1973). Though this batholith is not exposed in the study area, aeromagnetic data (U.S. Geological Survey, 1978) implies its southwesterly continuation in the subsurface of the Nushagak-Bristol Bay Lowland near Port Heiden. Eroded debris from it is common in the Naknek, Chignik and possibly Bear Lake Formations.

Figure 3 and Table 1 contain the data used to classify and name the volcanic and hypabyssal rocks in this thesis. Figure 3 is a Q:Or:Pl ternary diagram upon which normative quartz, orthoclase, and plagioclase have been plotted. Samples that fall within the andesite, basalt field are named after being plotted on the small normative color index versus %silica diagram in Figure 3. Complete listings of chemical analyses and normative minerals are in Appendix 4. An A:F:M diagram of the igneous rocks of the study area is shown in Figure 4. Also shown in Figure 4 is an outline of the calc-alkaline trend (Ringwood, 1977) to provide a reference frame for comparison with the rocks of this thesis.

The exposed intrusive rocks of the study area can be considered the roots of now eroded volcanos and as such these rocks tend to be silica oversaturated and alkali-poor. The intrusive rocks are often closely associated with sills, dikes, and volcanic rocks in the immediate area of outcrop. The major mafic mineral is hornblende, though pyroxenes and biotite are also present. No rocks, other than eroded plutonic debris of the Alaska-Aleutian Range batholith, contain primary muscovite, though Burk (1965, p. 110) reported some muscovite along the margin of the batholith in the Shumagin Islands (Figure 1). Primary biotite and potassium feldspar are rare in all but the large batholithic plutons of the Kodiak-Shumagin Plutonic Series, and the Devils batholith.

Alaska-Aleutian Range Batholith

The Alaska-Aleutian Range batholith was described by Reed and Lanphere (1969, 1973) and the name reflects a physiographic grouping of granitic rocks rather than a genetic unit. This unit does not crop out in the study

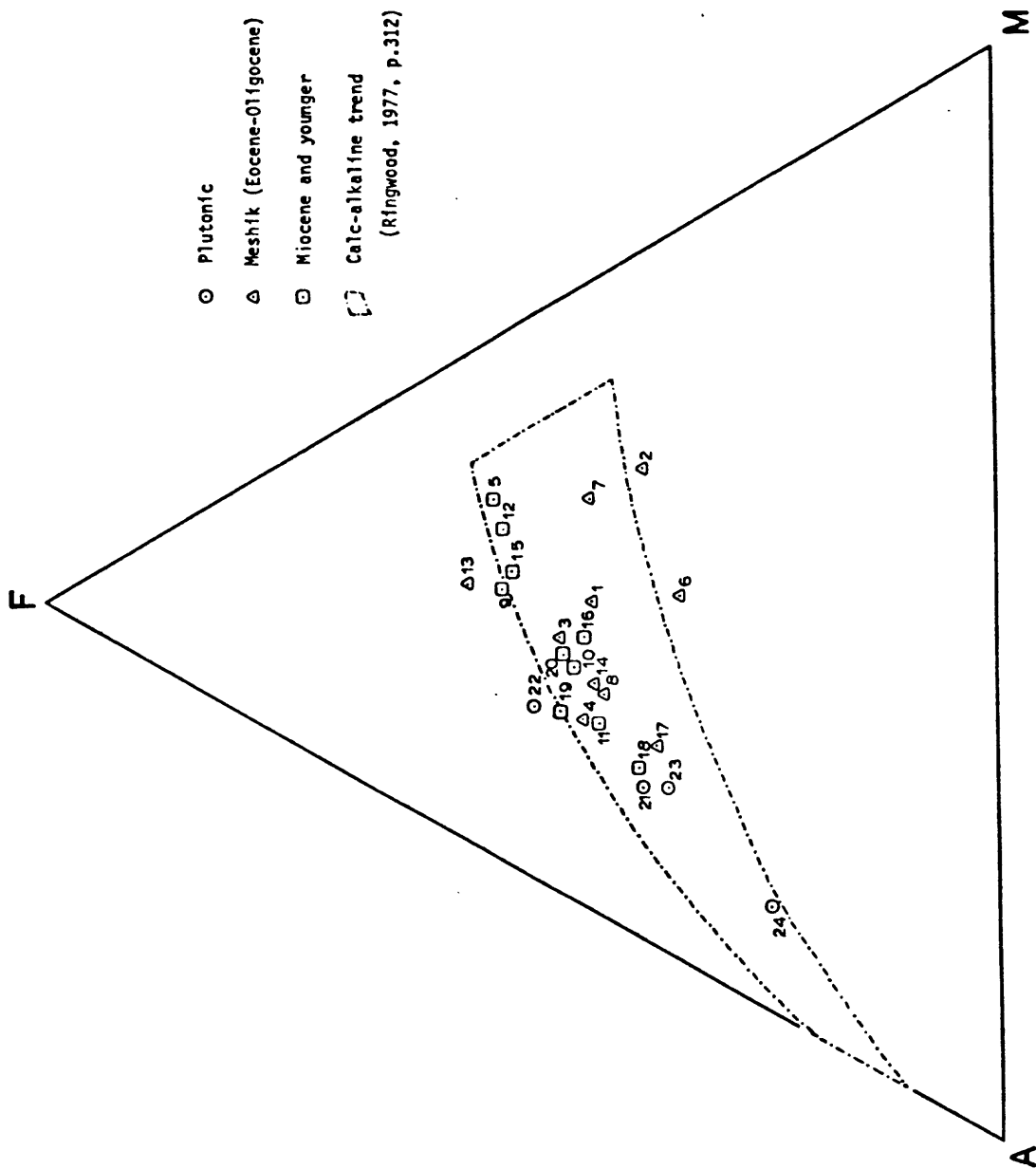


Figure 4 A-F:M ternary diagram for analyzed rocks (see Appendix 4 for complete chemical data).

Table 1.--Percent of SiO₂ and normative color index for analyzed samples from the Chignik and Sutwik Island area
Refer to Appendix 4 for complete chemical data

Point number (on figures 3 and 4)	Sample number	SiO ₂	Color index	Rock type
1	78AWs 31	55.54	21.8	Andesite
2	78AWs 32	54.00*	36.3	Andesite
3	78AWs 58	59.37*	18.1	Dacite
4	78AWs 61	63.81*	11.5	Dacite
5	78AWs 98	51.69*	36.1	Leuco-basalt
6	78AWs 24	55.58*	27.4	Andesite
7	78AWs 17	50.07*	34.6	Leuco-basalt
8	78AWs 42	59.70*	16.1	Andesite
9	77AWs 1	55.54	24.8	Andesite
10	77AWs 190b	58.54*	19.7	Andesite
11	77AWs 134	62.77	12.6	Dacite
12	77AWs 112b	49.28	36.3	Leuco-basalt
13	77AWs 40	51.49*	29.1	Leuco-basalt
14	77AWs 30	60.53*	15.1	Andesite
15	77AWs 12	51.89*	33.5	Leuco-basalt
16	77AWs 9	56.89	23.3	Andesite
17	77AWs 74	64.14	12.3	Dacite
18	77AWs 122	66.25*	10.28	Dacite
19	77AWs 215	62.2	13.82	Dacite
20	77AWs 152	60.39*	17.51	Dacite
21	77AWs 100	67.54	11.10	Granodiorite
22	77AWs 125	57.62	17.35	Tonalite
23	77AWs 137	66.6	10.39	Tonalite
24	77AWs 186	68.93	5.65	Granite

*Normalized; analysis recomputed to 100 percent water and CO₂-free.

area of this thesis, yet its apparent presence in the subsurface and the contribution of it to sediments of the Naknek and Staniukovich Formations in the Chignik and Sutwik Island region warrant some discussion of it here. Intrusive rocks mapped within the unit range in age from 180 m.y. to 26 m.y. (Reed and Lanphere, 1973). A Jurassic intrusive event starting near 180 m.y. and continuing for some 20 to 25 m.y. contributed most of the rocks to the batholith in the area between Becharof Lake and Chakachamma Lake (see Figure 3, Reed and Lanphere, 1973, p. 2588-2589). These Jurassic plutonic rocks range from gabbro to rarely granite; tonalite and granodiorite are most common (Reed and Lanphere, 1973, p.2596). The presence of granite clasts in sedimentary debris from the batholith suggests that felsic rocks are more common in the now-buried plutons of the batholith than would be inferred from present surface exposures. There is some evidence to suggest that parts of the Jurassic batholith were rapidly cooled and unroofed, contributing to sediments of the Middle Jurassic (Bajocian) Tuxedini Group and Kialagvik Formation within a few million years of emplacement (Reed and Lanphere, 1973, p. 2596; Burk, 1965, p. 73; Detterman and Hartsock, 1966). Large intrusions tend to be elongate and structurally concordant, and to induce the development of a foliation in the country rock parallel to the contact. Reed and Lanphere (1973, p.2595) note that where intrusive relations and potassium-argon age determinations have been made within an intrusive sequence, the mafic intrusions are oldest, and younger intrusions become successively more felsic. Closely associated areally with the Jurassic plutonic rocks is a thick Lower Jurassic volcanic and volcanoclastic sequence (Talkeetna Formation, see Detterman and Hartsock, 1966); volcanic rock types range at least from andesite to dacite. Reed and Lanphere (1973) suggested the Talkeetna Formation implies an Early Jurassic volcano-plutonic arc following the trend of the Alaska-Aleutian Range batholith.

Reed and Lanphere (1973) also distinguish a Late Cretaceous to Early Tertiary intrusive event in the batholith; potassium-argon age determinations on these rocks range from 85 to 59 m.y.. Rocks from this episode have only been found on the northwest side of the batholith north of Iliamna Lake (see Figure 1). It was not possible to distinguish a contact between these Cretaceous to Early Tertiary and the Jurassic plutonic rocks. The Cretaceous to Early Tertiary plutonic rocks range in composition from tonalite to rarely granite; the bulk are tonalite (Reed and Lanphere, 1973, p.2597). No associated volcanic rocks are known for the Cretaceous to Early Tertiary plutons.

The third group of plutonic rocks described by Reed and Lanphere (1973) in the Alaska-Aleutian Range batholith are middle Tertiary intrusive rocks. These do not demonstrate the relatively homogeneous chemistry of the older suites; compositions range from tonalite to alkali-feldspar granite. However, those near Nonvianuk Lake (Figure 1) cluster in the tonalite and granodiorite fields and have similar modal and chemical compositions. The ages of these rocks range from 37.0 to 25.7 m.y., with a cluster at 29.1 to 25.7 m.y. and one pluton at 37.0 m.y. (hornblende) and 35.6 m.y. (biotite)(Reed and Lanphere, 1973).

Kodiak-Shumagin Plutonic Series

The Kodiak-Shumagin Plutonic Series is the name used here for the Shumagin-Kodiak batholith of Kienle and Turner (1976). They hypothesized a batholith based on the occurrence of granitic rocks of similar age and composition in the Kodiak, Semidi, and Shumagin Islands and on Sanak Island

in southwestern Alaska (see Figure 1).

Burk (1965, p.110) discussed a portion of the Kodiak-Shumagin Plutonic Series, the Shumagin batholith, of the Shumagin Islands. This pluton is a medium-grained, partly porphyritic biotite granodiorite (Grantz, 1963, p. B108) and intrudes meta-sediments of the Shumagin Formation. It is of hypidiomorphic granular texture, with late potassium feldspar crystals up to 4 mm in diameter (Grantz, 1963, p. B108; Burk, 1965, p.110). Muscovite occurs locally along the margins of the body; otherwise the character of the pluton is quite uniform (Burk, 1965, p.110). Potassium-argon ages range between 65.6 and 57.4 m.y. (Paleocene, Table 2, Burk, 1965, p.111; Moore, 1974a). In the Semidi Islands and on Sanak Island a biotite granodiorite of similar appearance and age was reported by Burk (1965, p. 110) and Moore (1974b)(see Table 2). Kienle and Turner (1976) obtained samples of these rocks and reported new potassium-argon age determinations (Table 2) which are generally concordant (62.0 to 59.3 m.y.) with previous determinations and with ages on similar rocks on Kodiak Island (Burk, 1965, p.111; Moore, 1974a; 1974b; and Kalstrom and Ball, 1969, p.28). However, it is doubtful that these plutons represent a continuous batholith; more likely they are a series of anatectic plutons intruding the Kodiak and Shumagin Formations (Hudson and others, 1979). On the Kodiak Islands, the Kodiak batholith, a part of the Kodiak-Shumagin Plutonic Series, intrudes the Kodiak Formation. Here the continuity of the Shumagin-Kodiak batholith of Kienle and Turner (1976) is not demonstrated by outcrop patterns from island to island. Therefore in this thesis the name Kodiak-Shumagin Plutonic Series is used to refer to this series of plutons.

Devils Batholith

The Devils batholith is a multiphase granodiorite to tonalite batholith approximately centered on Devils Bay in the southeastern part of the Chignik quadrangle (Plate 1) and covering some 500 square kilometers (200 square miles). The rocks are medium-grained hypidiomorphic granular-textured. Hornblende and biotite are in approximately equal proportions in the rock and average about 5 to 10 percent each. A number of thin sections show a discontinuous reaction series from clinopyroxene to hornblende to biotite. Plagioclase has a composition of An 40-45, and is often in phenocrysts. Potassium feldspar (orthoclase) may constitute as much as 15 percent of the rock and quartz as much as 30 percent. A particularly mafic-rich phase corresponds to an aeromagnetic high (U.S. Geological Survey, 1978) at Seal Bay. The mafic phase contains clino- and orthopyroxene, hornblende, and biotite. The plagioclase is sieve-textured and of composition An 40-45. A sample of this mafic phase has yielded a potassium-argon age of $7.84 \pm .04$ m.y. on biotite and $10.08 \pm .04$ m.y. on hornblende (sample 78AWs 95, Table 3). In contact with this mafic phase is a slightly foliated fine-grained granodiorite with biotite veinlets oriented sub-parallel to the foliation.

In a number of localities along the periphery of the batholith are earlier hornblende-bearing felsic intrusive rocks that have been contact metamorphosed by intrusion of the batholith. These intrusive rocks were noted at Fishhook Bay, two bodies located near northeastern Kuiukta Bay, one northeast of VABM "Goat" (56 01'N, 158 26'W), and others at Ship Mountain, Castle Bay, and Castle Cape. These rocks range from a hypabyssal hornblende dacite to coarser-grained rocks of similar composition and to dikes of uncertain, but possibly original andesitic composition. Feldspars

Table 2.--Potassium-argon ages - Kodiak-Shumagin plutonic series

Location	Rock type	Phase	Age* (m.y) and error**	Reference
Kodiak Islands				
Kodiak Island-----	Granodiorite	Bio	59.5 \pm 2.6	Kalstrom and Ball, 1969.
Semidi Islands				
Chowiet Island-----	Granodiorite	Bio	59.3 \pm 1.8	Kienle and Turner, 1976.
Shumagin Islands				
Nagai Island-----	Granodiorite	Bio	60.7 \pm 1.8	Kienle and Turner, 1976.
	Granite	Mus	57.4	Burk, 1965.
		Bio	58.4	Burk, 1965.
	Granite	Mus	65.6	Burk, 1965.
Simeonof Island-----	Granodiorite	Bio	59.9 \pm 3.0	Moore, 1974a.
Big Koniujii Island--	Granodiorite	Bio	60.2 \pm 1.8	Kienle and Turner, 1976.
Sanak Islands				
Sanak Island-----	Granodiorite	Bio	62.0 \pm 1.8	Kienle and Turner, 1976.
	Granodiorite	Bio	61.4 \pm 1.8	Moore, 1974b.

*All ages recalculated using new constants (see text).

**Reported estimated analytical error.

in these older rocks tend to be less calcic (An 25-30) than in the batholith, and mafics are generally altered to chlorite, epidote and calcite. One of these bodies, located in the vicinity of northeastern Kuiukta Bay, was originally rich in biotite, all of which, except for traces, is now altered to chlorite. Plagioclase feldspars in these older bodies are strongly sericitized in contrast to those of the batholith which are characteristically fresh-appearing. An age determination on hornblende from the Castle Bay body yielded 22.4 ± 1.86 m.y. which is considered a minimum age of emplacement because it has been contact metamorphosed by the Devils batholith. The batholith also intrudes and contact metamorphoses rocks of the Chignik, Hoodoo and Tolstoi Formations. Often the parent rock is readily recognizable; however in some areas (Ship Mountain and Necessity Cove (Plate 2)) the country rock resembles the Shumagin or Kodiak Formation, both of which are not expected to be present in this area on structural grounds.

Potassium-argon age determinations on the batholith yield a late Miocene age (10 m.y.); however, these ages are discordant. At Sweater Bay, an age determination on biotite ($7.78 \pm .23$ m.y.) is two million years younger than one on hornblende ($9.86 \pm .36$ m.y.) at the same locality (Table 3, sample 77AWs 100). This discordancy is similar to that of the mafic phase at Seal Bay. There is evidence that the northeastern part of the Devils batholith may represent a younger phase (6 m.y., Table 6, sample 77AWs 125). The thermal event associated with the intrusion of this younger phase may have partially reset the pre-existing biotite of the Sweater and Warner Bay portions of the batholith. These ages will be discussed more fully in the section on the Warner Bay Prospect.

Chiginagak Bay batholith

Extending along the Pacific coast to the northeast from Chiginagak Bay in the northeastern part of the Sutwik Island quadrangle for some 25 to 30 km (17 to 20 mi) is a large diorite to quartz diorite(?) batholith. Most of this body lies outside of the study area and therefore our examination of this was quite brief. It apparently intrudes volcanic and volcanoclastic rocks that may be co-genetic along its southern margin, the only point where the contact has been examined by this writer. Burk (1965, p.108) described this batholith as being very similar to the Devils batholith (his Kuiukta Bay batholith) and considered it to be of mid-Tertiary age. Based on very limited sampling, the Chiginagak Bay body is apparently somewhat more mafic than the Devils batholith. At Chiginagak Bay, a volcanic neck thought to be continuous with the larger batholith has been examined in detail and dated. The rock is gabbroic or basaltic in appearance and thin-section examination reveals phenocrysts of plagioclase (An 55 to An 60), augite and hypersthene in a glassy groundmass. A potassium-argon age of $9.25 \pm .25$ m.y. has been determined on a whole-rock sample of this neck (Table 6, sample 77AWs 09). Chemically, this sample is virtually identical to the Northwest Arm phase of the Devils batholith, a medium-grained biotite hornblende tonalite (Appendix 3, samples 77AWs 09 and 125); andesite is possibly the best name that can be applied to this rock. A dating sample from the Chiginagak Bay batholith collected by Lee Smirnov of Amoco is a pyroxene diorite and may be more representative of the batholith. Further examination of this batholith in the future is planned.

Table 3.--Potassium-argon ages for Devils Batholith and Warner Bay Prospect

Location	Sample number	Rock type	Phase	K ₂ O (percent)	⁴⁰ Ar (rad) (percent)	Age (m.y.) and error*
Sweater Bay-----	77AWs 100	Granodiorite	Bto	9.12	37.9	7.88 ± 0.13
					43.1	7.67 ± .12
	Mean-----					7.78 ± .23
Northwest Arm, Castle Bay.	77AWs 125	Tonalite	Bto	8.97	62.28	6.15 ± .09
					48.67	5.90 ± .09
	Mean-----					6.03 ± .22
Warner Bay Prospect.	77AWs 96b	Pegmatite	Hbd	.534	15.96	6.22 ± .15
	77AWs 179	Pegmatite	Ksp	14.07	44.10	6.59 ± .11
					51.59	6.46 ± .10
	Mean-----					6.53 ± .17
	77AWs 179	Altered granodiorite	Bto	9.01	4.55	7.85 ± .11
					31.31	7.45 ± .27
Castle Bay-----	77AWs 180	Pegmatite				7.65 ± .41
	Mean-----					7.04 ± .17
						7.71 ± .23
Castle Bay-----	77AWs 122	Dacite	Bto	9.07	20.81	7.38 ± .55
					17.14	
	Mean-----					
Seal Bay-----	77AWs 122	Dacite	Hbd**	.329	24.10	23.57 ± .59
					17.53	21.17 ± .47
	Mean-----					22.37 ± 1.86
Seal Bay-----	78AWs 95	Qtz diorite	Bto	7.93	38.8	7.86 ± .04
	Mean-----					10.08 ± .14

*See footnote ** on table 2.

**Impure separate, inclusions of plagioclase.

Meshik Volcanic Rocks

The volcanic rocks mapped as the Meshik Formation are dacitic to leuco-basaltic flows, agglomerates, and breccias. These are usually hydrothermally altered, though in a number of areas, fresh, columnar-jointed andesite and dacite plugs are included in the formation. A number of these plugs have been dated and therefore provide a probable upper limiting date on the formation. The ages range from 35 to 30 m.y. (Table 4, samples 78AWs 31, 32, 58, and 61).

The samples dated (Table 4) range from hornblende dacites to two-pyroxene andesites. The hornblende often appears to be resorbed and is commonly rimmed in opaque oxides. The andesites often have two populations of plagioclase, An 35 and An 60, or a single plagioclase at about An 45-55. Textures range from glomeroporphyritic to subophitic and some rocks have glassy groundmasses. A few of the thin sections examined contain olivine; these rocks in general are more mafic and may include leuco-basalt or basalts.

In a number of areas, hypabyssal hornblende leuco-basalt and andesite porphyry plutons intrude sediments of the Tolstoi Formation, particularly on Cape Kumlik and Kumlik Island (Plate 2). Potassium argon ages of these intrusions all cluster about 35 m.y. or Oligocene (Tables 5 and 6, samples 77AWs 30, 40, 46, 74, 78AWs 17, and 24). This indicates that these intrusions may be the roots of volcanos that were sources for some of the Meshik volcanic rocks. The previously mentioned dacite and andesite plugs may also be necks of volcanos that were sources for some of the Meshik.

Eocene to Oligocene Intrusive Rocks

On Cape Kumlik and Kumlik Island, a number of hypabyssal hornblende andesite and leuco-basalt porphyry intrusive rocks are found. Each of these rocks is associated with areas of extensive alteration and possible mineralization. Phenocrystic amphibole is the dominant mafic mineral in all of these rocks; however a few samples (samples 77AWs 30, 78AWs 17) contain relicts or pseudomorphs of pyroxene. The amphibole commonly shows resorbed edges and sieve texture. The plagioclases, also phenocrystic in part, are usually strongly zoned, Carlsbad- and albite- twinned and sometimes show glomeroporphyritic texture. A number of these rocks have two distinct populations of plagioclase phenocrysts having compositional ranges of An 15-30 and An 50-60. Partial alteration of the feldspars to sericite, and/or clays is ubiquitous. Calcite and epidote are quite common and in some rocks the groundmass is chloritized. Apatite is an important and sometimes abundant accessory. The groundmasses of these rocks are fine grained and are composed of plagioclase feldspars and opaque minerals. Quartz phenocrysts have been seen in a few of the thin sections; these usually have resorbed edges. The disequilibrium mineral assemblages of these rocks strongly suggest mixed magmas; particularly the two feldspar compositions and the resorbed edges on the quartz phenocrysts. Potassium-argon age determinations on the amphiboles range from 39.1 ± 2.54 to 34.2 ± 2.07 m.y. (Eocene-Oligocene) (Table 5, samples 77AWs 30, 40, 46, and 78AWs 17) and are approximately co-eval with the Meshik Formation.

Similar to the above rocks are the intrusive rocks found on Cape Kunmik. At Cape Kunmik, autolithic aggregates of pyroxene and amphibole are common, and from a distance give the rock a porphyritic appearance. Mineralization and alteration of the surrounding country rocks is not as extensive as at Cape Kumlik. The erosion level does not appear to be as

Table 4.--Potassium-argon ages of the Meshik Formation

Location	Sample number	Rock type	Phase	K ₂ O (percent)	⁴⁰ Ar (rad) (percent)	Age (m.y.) and error*
Chignik quadrangle						
Mallard Duck Bay	---78AWs 98	Leuco-basalt	WR	0.201	20.36	22.31 ± 0.33
				Mean-----	25.80	20.05 ± .38
						21.18 ± 1.68
Chignik Island	-----78AWs 134	Dacite	WR	1.116	57.33	26.54 ± .55
				Mean-----	66.56	25.92 ± .51
						26.23 ± .87
**Gulf #1 Port Heiden.	Core 1 ?					42 ± 4
						36 ± 8
Sutwik Island quadrangle						
Foggy Cape	-----78AWs 31	Andesite***	WR	1.260	90.48	30.35 ± .47
				Mean-----	84.85	30.10 ± .14
						30.33 ± .52
Sutwik Island	-----78AWs 32	Andesite***	WR	.983	67.05	31.05 ± .48
"Easy"	-----78AWs 58	Dacite***	WR	1.543	90.56	34.21 ± .61
				Mean-----	89.76	34.56 ± .36
						34.44 ± .73
"Julik"	-----78AWs 61	Dacite***	WR	1.210	94.84	34.74 ± .16
Ugashik quadrangle						
**Great Basins #1 Ugashik.	Core 1					33 ± 1.5
	Core 2					39 ± 7

*See footnote ** on table 2.
 **Reference, Brockway and others, 1975.
 ***Associated with Tolstoi Formation.

great as at Cape Kumlik and some samples were apparently emplaced at very shallow depths. The rocks on Cape Kunmik exhibit some abnormal alteration features; in one sample the plagioclase appears to be fresh, yet the amphibole is completely altered to a yellow mineral, possibly another amphibole. In other samples, amphiboles are fresh-appearing but plagioclase phenocrysts are thoroughly sericitized. A potassium-argon age of 33.5 ± 2.33 m.y. (Oligocene) has been determined on a green pleochroic amphibole from a hornblende andesite in which the plagioclase is so altered as to be virtually unrecognizable (Table 5, sample 78AWs 24).

A very strongly altered rock that was apparently a biotite-hornblende dacite dome was found on the northwest side of Sutwik Island (Plate 2). This one of the few rocks in the study area with primary biotite. Alteration of the plagioclase is such that the composition is indeterminate; hornblende has been resorbed or altered to calcite and opaques. A whole-rock chemical analysis of this rock indicated 3.5 percent CO₂ (Appendix 3). Quartz is common and apatite is extremely abundant. The biotite appears quite fresh and has yielded a potassium-argon age of 34.5 ± 1.66 m.y. (Oligocene) (Table 6, sample 77AWs 74).

Pinnacle Mountain, 7 miles southeast of Aniakchak Crater (Plate 2), is a hornblende dacite porphyry pluton intruding rocks of the Tolstoi and Meshik Formations. This intrusive has abundant green pleochroic hornblende phenocrysts, plagioclase of composition An 60, and quartz phenocrysts with resorbed edges. The texture is porphyritic, with the fine-grained groundmass comprising about 50 percent of the rock. A potassium-argon age of $34.5 \pm .85$ m.y. was determined on hornblende from this rock (Table 6, sample 78AWs 35).

A two pyroxene andesite from near Nakalilok Bay in the Sutwik Island quadrangle has been collected, and a plagioclase dated at $48.1 \pm .89$ m.y. The pyroxenes, both clino and orthopyroxene are slightly altered along cleavage planes and grain boundaries. The feldspar is fresh, Carlsbad- and albite-twinning, zoned, and approximately An 45 composition. The texture is porphyritic, with plagioclase comprising the bulk of the phenocrysts and pyroxene primarily in the groundmass.

Late Tertiary Igneous Rocks

Throughout the study area are many intrusive and volcanic rocks of Late Tertiary age, particularly in the vicinity of the presently active volcanos. These include numerous volcanic rocks around Mt. Veniaminof, most of the small intrusive rocks that are associated with alteration zones, and other scattered intrusive rocks in the northeastern portion of the Sutwik Island quadrangle.

Most of the small intrusive rocks are petrographically similar and a general description is as follows. Either phenocrystic hornblende or hypersthene and/or augite is the mafic mineral; it has resorbed edges and is probably partially chloritized. The plagioclase, where it can be determined is of An 45 to An 55 composition. The plagioclase is usually altered, often to the point that individual phenocrysts are difficult to distinguish. Quartz may or may not be present in the groundmass or as phenocrysts. The texture is porphyritic, with a fine-grained to aphanitic groundmass and medium-grained phenocrysts of plagioclase and the mafic mineral.

Two of these rocks have been dated, but unfortunately no chemical analyses are available. A hornblende separate from a sample collected at

Table 5.---Potassium-argon ages of Cape Kumlik and Cape Kunmik, Sutwik Island quadrangle

Location	Sample number	Rock type	Phase	K20 (percent)	⁴⁰ Ar (rad) (percent)	Age (m.y.) and error*
W Cape Kumlik----	77AWs 30	Hornblende andesite porphyry.**	Hbd	0.319	29.09	35.9 + 1.03
				Mean-----	35.16	36.7 ± .79
						36.3 ± 1.42
Cape Kumlik-----	77AWs 40	Leuco-basalt porphyry.**	Hbd	.467	24.23	33.7 + .60
				Mean-----	36.73	36.2 ± .56
						35.0 ± 1.95
E Cape Kumlik----	77AWs 46	Andesite.**	Hbd	.311	19.81	37.8 + 1.58
				Mean-----	27.81	40.3 ± .91
						39.1 ± 2.54
Kumlik Island----	78AWs 17	Leuco-basalt.	Hbd	.401	33.30	32.7 + .34
				Mean-----	36.22	35.5 ± .51
						34.2 ± 2.07
SE Cape Kúnmik--	78AWs 24	Andesite. Intrudes Hoodoo Formation.	Hbd	.430	30.94	34.6 + .55
				Mean-----	35.19	32.4 ± 1.65
						33.5 ± 2.33

*See footnote ** on table 2.

**Associated with Tolstoi Formation.

Table 6.--Potassium-argon ages of miscellaneous intrusive and volcanic rocks

Location	Sample number	Rock type	Phase	K ₂ O (percent)	⁴⁰ Ar(rad) (percent)	Age (m.y.) and error*
Chignik quadrangle						
Kametolook River---	77AWs 112b	Leuco-basalt.	WR	0.645	9.56 7.57 3.87	0.60 + 0.013 .48 + .015 .35 + .016
				Mean-----		.48 + .12
Chignik Lagoon-----	77AWs 186	Granite cobble. Chignik Formation.	Bio	6.98	70.5 78.2	91.8 + .56 87.7 + 1.38
				Mean-----		89.8 + 3.3
Anchorage Bay-----	77AWs 176	Andesite sill. Intrudes Tolstoi Formation.	Hbd	.277	12.37 14.87	15.6 + .25 17.4 + .71
				Mean-----		16.5 + 1.48
Sutwik Island quadrangle						
Sutwik Island-----	77AWs 74	Dacite. Associated with Tolstoi Formation.	Bio	8.48	43.65 73.95	35.5 + .64 33.5 + .59
				Mean-----		34.5 + 1.66
North quadrangle edge.	78AWs 11	Dacite. Intrudes Tolstoi Formation.	Hbd	.491	30.53 30.96	19.4 + .16 19.08 + .16
				Mean-----		19.25 + .33
Nakalilok Bay-----	78AWs 5	Andesite(?). Intrudes Chignik and Hoodoo Formations.	Plag	.483	45.45 40.38	48.55 + .55 47.64 + .29
				Mean-----		48.10 + .89
Pinnacle Mountain--	78AWs 35	Dacite. Associated with Tolstoi Formation.	Hbd	.365	36.02 18.86	33.93 + .16 35.01 + .33
				Mean-----		34.47 + .85
Ugashik quadrangle						
Chiginagak Bay-----	77AWs 9	Andesite. Intrudes Meshik(?) Formation.	WR	1.78	60.97 52.24	9.39 + .14 9.11 + .04
				Mean-----		9.25 + .25

*See footnote ** on table 2.

Anchorage Bay (Plate 2) near Chignik from an andesite sill has yielded a 16.5 ± 1.48 m.y. age (Table 6, sample 77AWs 176). This sill is quite similar to other sills intruding sediments of the Chignik Formation in the area of Anchorage Bay. Such sills often intrude along coal horizons, thermally upgrading the coal from lignite to bituminous. The dated sample is partially hydrothermally altered, the feldspars, both in phenocrysts and groundmass, are strongly sericitized and kaolinized, and there is clinozoisite in the groundmass. The amphibole is pleochroic in deep browns and has resorbed edges, whereas the clinopyroxene is very pale green and has sharp subhedral grain boundaries. This is one of the very few rocks that has been dated that yields an age between 10 and 20 m.y. The age is considered a minimum age. A similar sill, from across Anchorage Bay has proved to be difficult to date, though the apparent age may be near 10 to 6 m.y.

A dating sample collected from the north edge of the Sutwik Island quadrangle (Plate 2) is a hornblende dacite that is virtually a perfect match for the general description of the Late Tertiary rocks given earlier in this section. The amphibole is in good condition and has yielded an age of $19.4 \pm .16$ m.y. (Table 6, sample 78AWs 11). The feldspar is nearly completely altered to sericite; what remains is strongly zoned, and Carlsbad-twinned, with minor albite-twinning. The rock texture is cataclastic-porphyrific, with phenocrysts shattered and dislocated. The phenocrysts range up to 7 mm in diameter.

Economic Geology and Age of Mineralization

Porphyry Models

It is generally accepted that porphyry copper deposits form in converging plate margin environments (Sillitoe, 1972, 1976), but agreement on a genetic model or models of how they form has not been reached. Several models are currently in use. Sillitoe (1973) has described a volcanic-plutonic model for copper porphyries as an extension of his plate tectonic model (Sillitoe, 1972). This volcanic-plutonic model proposes that the metals of porphyry copper systems are derived from the mantle at divergent plate margins and transported in the oceanic crust to a convergent plate margin. Through partial melting of metal-enriched oceanic crust in subduction zones, calc-alkaline magmatism is thought to occur, and porphyry copper systems are believed to constitute a normal facet of this magmatism. Therefore the time and space distribution of porphyry copper deposits is dependent on the subduction of metal-enriched oceanic crust and on calc-alkaline magma generation. Oyarzun and Frutos (1974) have shown that the requirement for enriched oceanic crust is unnecessary and point out that according to Krauskopf (1967), the average abundance of metals in sediments and magmas is sufficient to supply the metals in a porphyry system; therefore the important problem is the definition of the segregation and transport mechanisms. As an example, of Oyarzun and Frutos' (1974) model, a calculation using data from Krauskopf (1967) on crustal abundances of copper was made. In order to produce the amount of metallic copper in the El Salvador porphyry copper deposit of Chile (Gustafson and Hunt, 1975), it would only require the subduction of a slab of oceanic crust 10 km wide and 2 to 10 km long, assuming a 25% segregation efficiency. Assuming a subduction rate of 5 cm/yr, this is on the order of 40,000 to 200,000 years of subduction.

Sillitoe (1973) has refined his 1972 model (Figure 5), proposing that porphyry copper deposits typically occur sub-volcanically in the "cupola" region of phaneritic intrusive rocks comagmatic with a calc-alkaline volcanic pile. Grading downward from the typical porphyry copper deposit is a transitional zone of stockwork mineralization and potassium-silicate alteration succeeded further down by an essentially unaltered pluton of large dimensions relative to the porphyry stock. Sillitoe (1973) feels that the evidence favors the interpretation that the tops of porphyry systems are emplaced at depths of 1.5 to 3.0 km beneath the summits of the related stratovolcano, and that the porphyry system (essentially the cupola) may have a vertical extent of 8 km.

In detail, a porphyry copper deposit consists of concentrically arranged shells of hydrothermal alteration and mineralization approximately centered about a high level calc-alkaline stock. Lowell and Guilbert (1970) have described the arrangement of the alteration halos in porphyry deposits and Sillitoe (1973) attempts to characterize the nature of these halos vertically throughout the porphyry system. Figure 5 is a drawing showing the typical simple porphyry copper model as envisioned by Sillitoe (1973). Important points to notice are: 1. the limited vertical extent of sericitic alteration; 2. that epithermal copper, lead, zinc and precious metal veins are an integral part of the porphyry system, accompanying propylitic alteration; and 3. the advanced argillic alteration, silicification and/or propylitic alteration which occurs in the overlying comagmatic volcanic pile. The ore body typically occurs in the

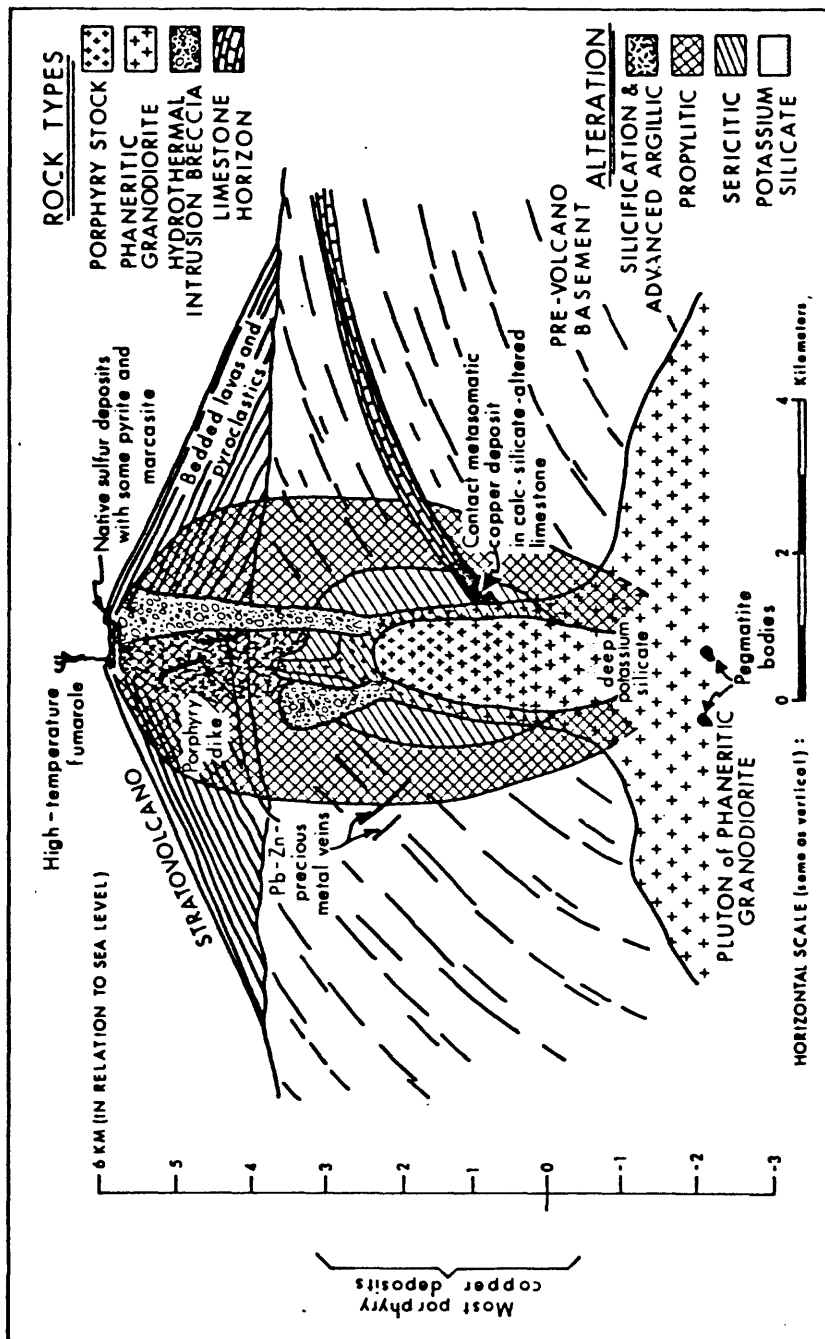


Figure 5 Porphyry copper deposit model, after Sillitoe (1973).

pre-existing older and genetically unrelated country rock below the volcanic pile. Regarding the volcanic pile, this "..... need not be a simple cone, but may be multiple in character and include the development of domes and collapse calderas, perhaps resurgent" (Sillitoe, 1973, p. 802).

Rather than attempt to model porphyry systems within the restrictions of one model, Sutherland-Brown (1976) uses three distinct models based on his observations in the Canadian Cordillera. Sutherland-Brown's (1976) three models are based in part on morphology, magma pressure and volatile content, degree and isotropy of the external stress field and the type and condition of the host rocks. He does not really discuss most of these factors directly and his classification is heavily based on the first and last, i.e. morphology and the condition of the host rocks. His models are particularly applicable to Canadian porphyries though he feels many porphyries worldwide are "...recognizable within the proposed framework" (Sutherland-Brown, 1976).

Type 1 or phallic porphyry deposits are ideally centered on a small single or multiphase cylindrical pluton (Figure 6). Breccias are a distinctive feature, as pipes, dikes or shells and are an indication that the body was formed high in the crust. The pluton is usually late or post-orogenic, commonly has vented to the surface, as evidenced by the breccias, yet had not built up an extensive volcanic pile and intruded it. "Radiating or concentric dikes are normal and may form a swarm" (Sutherland-Brown, 1976, p.46). The alteration shells are essentially as described by Lowell and Guilbert (1970) and as in Sillitoe's (1973) model. An important factor Sutherland-Brown (1976) mentions is the thermal metamorphic aureole in the country rock around the pluton and the possible confusion of the potassium-silicate alteration zone with this aureole. A characteristic mineral of the thermal aureole is a very fine felted biotite, easy to confuse with the secondary or hydrothermal biotite of the alteration system. The ore zone is generally synonymous with the sericitic zone, though it can also lie partly within the potassium-silicate zone. Examples of a phallic type porphyry copper deposit are the Casino deposit (Godwin, 1976) in the Yukon Territory or the deposit at El Salvador, Chile (Gustafson and Hunt, 1975).

Type 2, volcanic porphyry deposits "...ideally are formed adjacent to variably shaped porphyry intrusions...to intrude a coeval and partly consanguineous volcanic pile in an orogenic setting that is commonly marine" (Sutherland-Brown, 1976, p.46). These deposits typically have large ore zones in relation to the size of the porphyry body, which is in essence a dike swarm. Breccias are of several types within a particular deposit and are an important aspect of the system. Breccias are pre- and post-ore, and the post-ore breccias often contain fragments of the porphyries that decrease in size and abundance away from the porphyry contacts (Sutherland-Brown, 1976)(Figure 7). Alteration is not as regular as in the phallic porphyries though the types of alteration, including the thermal aureole are generally similar. Often the contact metamorphic biotite is destroyed by later alteration; therefore it is not always readily apparent. Potassium-silicate alteration is slight, sericitic alteration is relatively widespread but weak, and propylitic alteration is distributed over a broad peripheral zone and is pervasive. Alteration in quartz-poor alkalic systems is mineralogically quite different and can lead to alteration of the volcanic host rocks to "pseudo-syenites or fenites" (Sutherland-Brown,

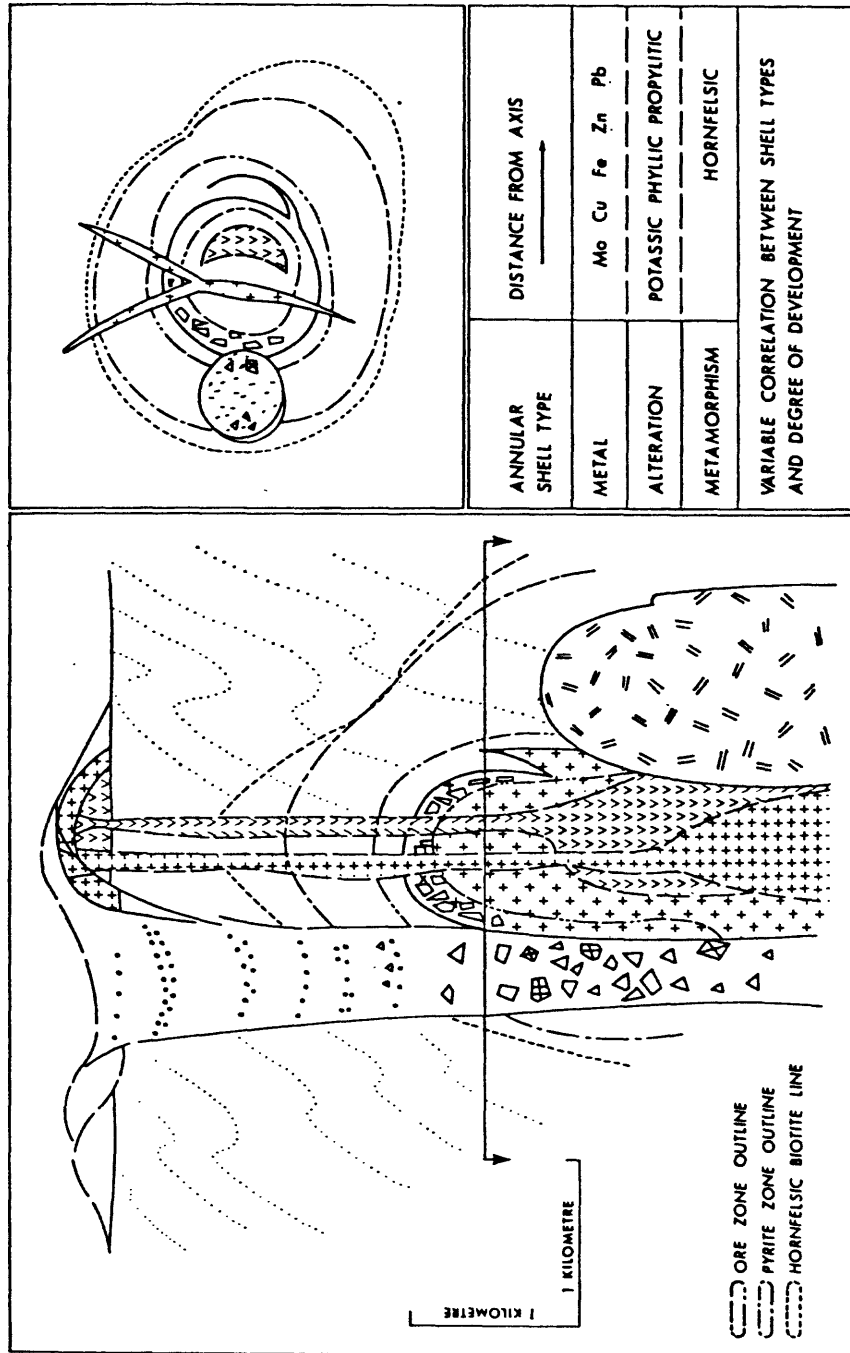


Figure 6 Type I or phallic porphyry model, after Sutherland-Brown (1976).

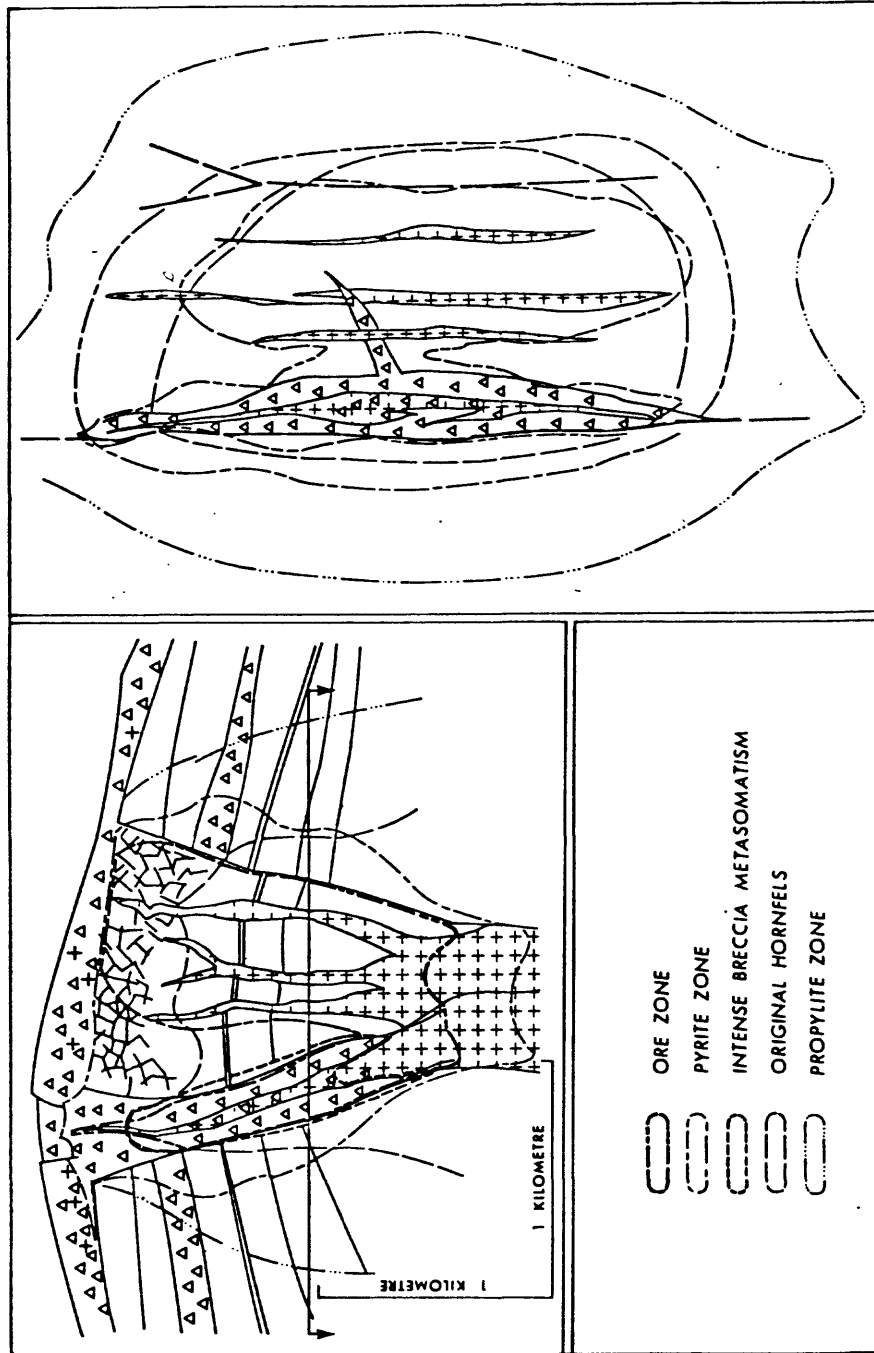


Figure 7 Type II or volcanic porphyry model, after Sutherland-Brown (1976).

1976).

The pattern of mineralization in a volcanic porphyry is analogous to the alteration pattern, and often forms the core of the altered zone. However pre-ore faults, dikes and/or breccia bodies in the system can localize the mineralization. Along with a distinct type of alteration, alkalic volcanic porphyries tend to be molybdenum-poor and are solely copper deposits. There are no molybdenum volcanic porphyries, regardless of intrusion chemistry (Sutherland-Brown, 1976). An example of a volcanic type copper porphyry deposit is the Island Copper deposit (Cargill and others, 1976) on northern Vancouver Island.

The third model proposed by Sutherland-Brown (1976) is the plutonic porphyry model (Figure 8). These form in petrologically zoned medium-sized plutons which may intrude a coeval volcanic pile or lie within unrelated host rock. These plutons are intruded at the end of the early stage or at the middle stage of orogenesis and dynamothermally metamorphose the enclosing host rocks to amphibolite facies. A schistosity in the country rock is formed parallel to the contact, and parts of the pluton itself may show foliation. Typically the pluton does not display a porphyritic texture. Taken as a whole, the evidence seems to indicate that this type "porphyry" is emplaced at a greater depth than the previous two models. In contrast to the other two types, breccias are rare in these systems and therefore unimportant. However, fracturing of high density is always seen, and veining is common. The veining is commonly of four to five ages though, Sutherland-Brown (1976, p.50) states that isotopic dating work has shown these to be analytically indistinguishable.

Alteration in plutonic porphyry copper deposits is typically weak and quite unlike the model of Lowell and Guilbert (1970). Contact metamorphism is described by Sutherland-Brown as not being part of the alteration array; however from the previous discussion the metamorphism associated with the intrusion is quite obvious. Sutherland-Brown (1976) relates the ore deposit to a late felsic core (see Figure 8); contact metamorphism is not directly associated with this core. Apparently, the core of the felsic zone is usually barren of mineralization but it may show a form of sericitic alteration, and the alteration undergoes a transition outward to a propylitic-kaolinitic alteration or a quartz-chlorite + sericite alteration. As ore deposits, the plutonic porphyries are usually copper-molybdenum or molybdenum deposits. Veining can be quite important economically with veins up to a meter wide and hundreds of meters long. Copper mineralization is typically related to early veins, whereas molybdenum mineralization seems to come later in the vein sequence. Plutonic porphyry copper deposits in the Guichon Creek batholith of British Columbia include Valley Copper (Ostenko and Jones, 1976) and J.A. (McMillan, 1976).

Potassium-argon Ages in Porphyry Copper Deposits

One of the major constraints on the use of potassium-argon dating is the sensitivity of many datable minerals to argon loss in response to thermal events. This sensitivity may be reflected by recrystallization in response to changing temperature and pressure conditions, as for example the exsolution of potassium feldspars or the replacement of biotite by chlorite. Another common effect is the outward diffusion of argon caused during a weakening of lattice bonds during heating. In the dating of mineralization events as distinguished from emplacement or crystallization

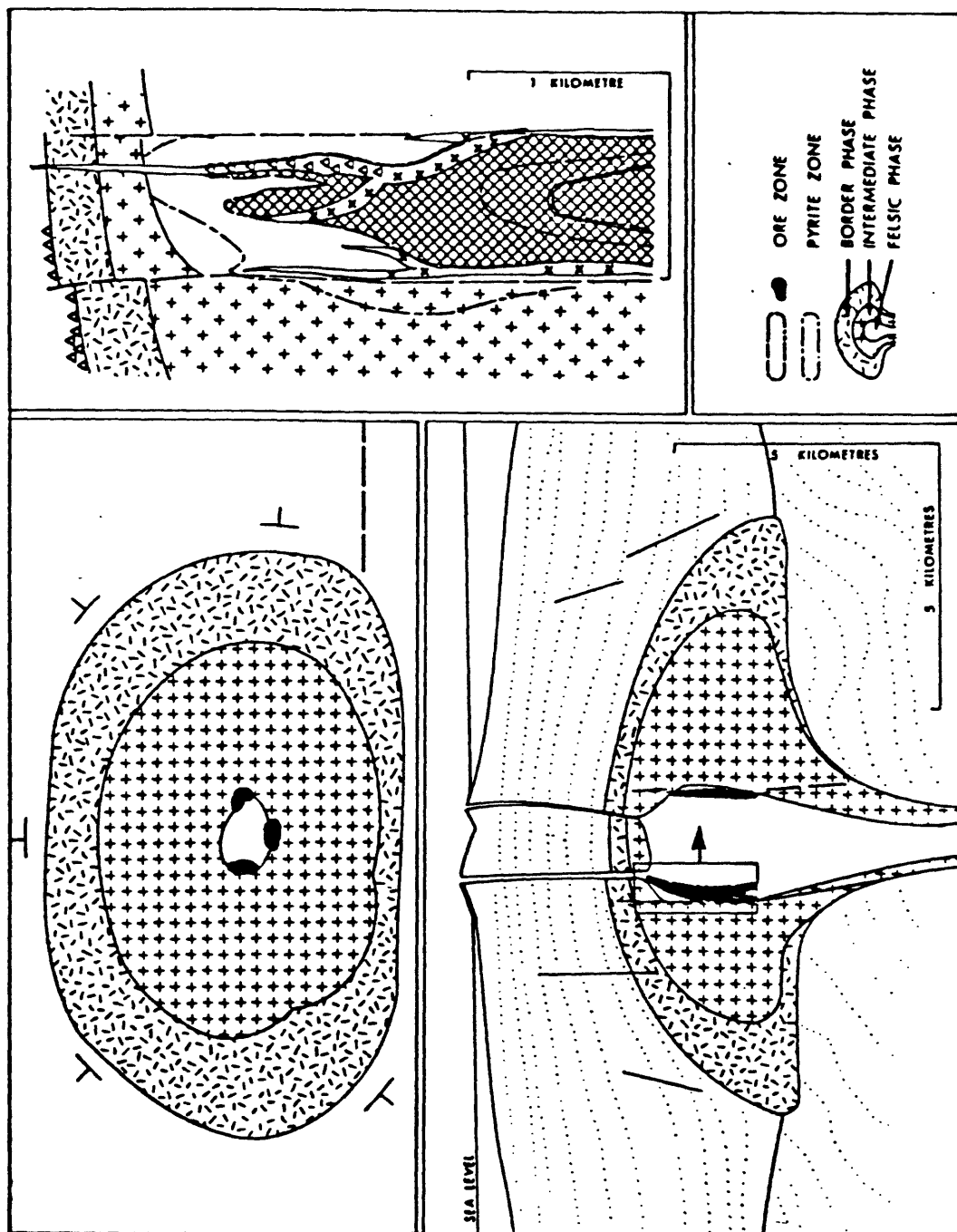


Figure 8 Type III or plutonic porphyry model, after Sutherland-Brown (1976).

events, both of these types of thermal responses become assets. The basic assumption in applying potassium-argon dating to porphyry ores is that during recrystallization minerals will degas argon and reset the radiometric clock. Therefore if separates or concentrates can be made of the replacement or hydrothermal minerals which form during the mineralization process, the resulting age determinations will reflect the mineralization events. Regarding simple thermal diffusion of argon, complete resetting of the radiometric clock is arguable; however discordant dates will generally indicate a thermal event since different minerals, for example biotite and hornblende, have different argon diffusion characteristics, resulting in differing degrees of argon retention at a given temperature (Hart, 1964).

In porphyry systems, a number of minerals are characteristic of hydrothermal alteration and mineralization (Lowell and Gilbert, 1970). In particular, biotite, sericite, and potassium feldspar have proven useful in dating porphyry mineralization (Silberman and others, 1977, Damon and Mauger, 1966). Chlorite, another characteristic alteration mineral of some zones of alteration in porphyry coppers has also been successfully used to date alteration and mineralization in a group of porphyry copper deposits in south-central Alaska (Silberman and others, 1977). In the present study, hydrothermal chlorite and biotite separates have been dated 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 the sericite in many samples. In rocks that thin section study showed to have been completely altered to quartz, sericite, and sulfides, the sulfides and some quartz were removed using magnetic and gravity techniques. In some cases, this resulted in concentrates exceeding 2% K₂O. The quartz is assumed to have no potassium and no argon; therefore the potassium-argon date 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).

To date, very little information has been published on Alaska Peninsula porphyry copper occurrences. Armstrong and others (1976) reported potassium-argon age determinations on two prospects, Dry Creek and Pyramid. Their Dry Creek prospect is the Bee Creek prospect discussed in detail in a later section of this thesis. Berg and Cobb (1967, p. 5-7) gave general information on lode deposits in the Alaska Peninsula. Bear Creek Mining Co. (Fields, 1977) on contract with 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 report to the Bristol Bay Native Corp. served as a data base for some of the age studies reported here.

Bee Creek Prospect

The Bee Creek prospect is located about 22 km north of Chignik, approximately 5 km inland of Chignik Bay on Dry Creek (Plate 1). Elevation ranges from 150 to 600 m. Vegetation is sparse, though talus and alluvium cover much of the prospect (Plate 3). 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, 1980). The country rock is the Upper Jurassic Naknek Formation. The main dacite intrusion is of

porphyritic texture, with abundant phenocrysts of plagioclase ranging in composition from approximately An 35 to An 50. Interstitial to the phenocrysts is a fine to very fine grained groundmass of plagioclase, quartz, and hornblende. The hornblende is partially or completely altered to biotite; therefore this phase probably predates mineralization. The biotite in all samples is apparently hydrothermal and is often found in clots replacing hornblende or along grain boundaries. Unfortunately, no datable primary mineral phases were found for this intrusion. Chlorite is also a common hydrothermal mineral. A number of samples have very minor potassium feldspar; the bulk of this is hydrothermal in origin. A second dacite intrusion is very similar except that the hornblende is unaltered. The hornblende has been dated at $2.15 \pm .15$ m.y. (Table 7, sample 77AWs 215). This date indicates that this hypabyssal intrusion may postdate mineralization. Studies are underway to attempt to confirm this by other isotopic dates. Regionally, this intrusion and the associated alteration halo are part of a linear east-west intrusion trend extending 65 km from Weasel Mountain to Black Peak, a late Tertiary to Recent volcanic center (Plate 1).

The intrusion of the main pluton at Bee Creek resulted in the development of contact metamorphic biotite in the arkoses of the Naknek Formation and possibly more intense hornfelsing nearer the intrusion. In portions of the "inner" zones of the prospect, a composite rock is mapped. This composite rock has both sedimentary and igneous features and may be strongly contact-metamorphosed Naknek Formation obscured by later alteration and mineralization.

Subsequent to the time of intrusion of the pluton, alteration and mineralization occurred. An apparent alteration age of $3.66 \pm .18$ m.y. has been determined on hydrothermal biotite from a number of samples (Table 7, sample 77AWs 152, 251). A potassium-argon age determination on sericitic alteration yields an age of $3.86 \pm .22$ m.y. (Table 7, sample 77AWs 243) whereas dates on chlorite have yielded an age of 3.58 ± 1.01 m.y. (Table 7, samples 77AWs 235, 243). Armstrong and others (1976) determined a $3.2 \pm .4$ m.y. age on a sericite-chlorite separate (Table 7, sample Dry Ck.). These numbers are somewhat older than the age determined on hornblende from one dacite intrusion, and studies are underway to examine the hypothesis of excess argon in the hydrothermal minerals. Isochron plots do not indicate excess argon in the hydrothermal minerals.

This is one of the better known prospects in the region as five drill holes were bored hereby Bear Creek Mining Co. in 1976. Alteration is roughly centered on the intrusions (Plate 4), with a potassium-silicate core, sericitic outer halo and a propylitic periphery. There is also the possible existence of advanced argillic alteration (Lowell and Guilbert, 1970) in portions of the inner zones of the prospect. Alteration assemblages are essentially as described by Lowell and Guilbert (1970), except for a quartz-magnetite assemblage seen in one small area near the center of the mapped potassium-silicate zone, and the presence of a carbonate-actinolite assemblage in some arkoses also found within the potassium-silicate zone.

Mineralization decreases toward the core of what was mapped as the diorite intrusion by Fields; this is true both on the surface and at depth (Fields, 1977). The bulk of the mineralization is in the composite rocks external to the intrusions, though sulfides replace some mafic minerals within the diorite. Copper in chalcopyrite is the major economic metal.

However, there is also molybdenum and associated silver and gold. Lead and zinc are found peripheral to the prospect at sub-economic grades based on rock sample geochemistry (Fields, 1977; Yount and others, 1978).

Warner Bay Prospect

The Warner Bay prospect is located at tidewater 15 km south of Chignik, within the northeastern portion of the Devils Batholith, a large granodiorite to tonalite pluton intruding sediments of the Chignik, Hoodoo, Shumagin(?), and Tolstoi Formations (Plate 1). The prospect was apparently discovered in the early part of this century and has two adits driven into it (Atwood, 1911, p.124). Relief is approximately 300m and the exposure is almost entirely within a vertical cliff extending from sea level on Warner Bay. The mineralization occurs on joint surfaces in the closely jointed (N 45 W) plutonic rock, in veins parallel to the jointing, and also disseminated in the small breccia zone on the north edge of the exposure. Molybdenite is quite common, though it is subordinate to chalcopyrite (Robinson, 1975; Yount and others, 1978). A small breccia zone or diatrema on the north edge of the exposure contains rounded pebbles of the granodiorite with pervasive propylitic alteration. In the interstices are found large crystals of galena, sphalerite, and abundant pyrite. Except for the breccia zone, alteration in the rock seems to be restricted to incomplete alteration of amphiboles to biotite, and minor chloritization of the biotite. In particular, there is no sericitic alteration and feldspars are fresh in thin section.

A number of age determinations have been made or are in progress on rocks associated with the Warner Bay prospect and the surrounding Devils batholith. The presently available results are in accord with the following suggested history; sometime in the period between the end of the Eocene and the start of the late Miocene a number of small hypabyssal hornblende andesite and biotite dacite plutons and dikes intruded a sedimentary sequence consisting of Chignik, Hoodoo and Tolstoi formation rocks. These bodies were described in the previous section of this thesis that discusses the Devils batholith. An age determination on hornblende from one of the intrusions at Castle Bay (22.4 ± 1.86 m.y., Table 3, sample 77AWs 122) suggests that this group of small intrusions may be related to igneous activity at Mallard Duck Bay (see next section). Following the emplacement of the andesites and dacites, the medium-grained biotite-hornblende granodiorite batholith at Seal, Sweater, and Warner Bays, was emplaced during the Late Miocene at about 10 m.y. based on the hornblende ages (Table 3, samples 77AWs 100, 78AWs 95). This pluton may account for the bulk of the intrusions of the Devil's batholith. Jointing occurred at Warner Bay as this large pluton cooled. At approximately the same time as the jointing, the diatrema or breccia pipe now seen at the north end of the Warner Bay exposure was formed. Injection of the small pegmatites at Warner Bay occurred after the jointing. At a still later time, Cu-Mo mineralization at Warner Bay developed, possibly concurrently with, but probably prior to emplacement of a more feldspar-rich biotite-hornblende tonalite represented by the 6 m.y. old sample from Northwest Arm, Castle Bay (Table 3, sample 77AWs 125). This last intrusive phase has very minor mineralization associated with it. In some areas the intrusion is so rich in autoliths(?) that it appears conglomeratic from a distance. Age determinations on biotite ($7.38 \pm .55$ m.y.) and orthoclase ($6.53 \pm .17$ m.y.) from the pegmatites and mixed primary and secondary

Table 7.---Potassium-argon ages of Bee Creek Prospect, Chignik quadrangle

System component	Sample number	Rock type	Phase	K ₂ O (percent)	⁴⁰ Ar (rad) (percent)	Age (m.y.) and error*
Potassically altered intrusive rock.	77AWs 152	Altered Dacite.	Bio	8.50	11.88	3.67 ± 0.09
					34.84	3.62 ± .07
				Mean-----		3.65 ± .12
Intrusive rock-----	77AWs 215-2	Dacite.	Hbd	.430	1.75	2.12 ± .12
					2.92	2.17 ± .09
				Mean-----		2.15 ± .15
Propylitically altered Naknek Fm.	77AWs 235	Arkose.	Chl	.766	3.41	2.65 ± .20
					7.00	4.32 ± .26
				Mean-----		3.5 ± 1.0
Quartz-sericite altered Naknek Fm.	77AWs 243	---	WR Chl Ser	.917	7.81	3.72 ± .09
				.626	9.35	3.92 ± .05
				5.45	31.62	4.00 ± .03
Potassically altered composite rock.	77AWs 251	Composite rock.	Bio	8.16	24.11	3.73 ± .07
					18.25	3.60 ± .08
				Mean-----		3.67 ± .14
**Quartz-sericite altered rock.	Dry Creek.	---	Ser/Chl	1.45	8	3.2 ± .4

*See footnote ** on table 2.

**Reference, Armstrong and others, 1976.

biotite ($7.65 \pm .41$ m.y.) from granodiorite at Warner Bay (Table 3, samples 77AWs 96b, 179, 180) and biotite ($7.78 \pm .23$ m.y.) at Sweater Bay (Table 2, sample 77AWs 100) yield ages between that of the hornblende at Sweater Bay ($9.86 \pm .36$ m.y., Table 3, sample 77AWs 100) and at Seal Bay ($10.08 \pm .04$ m.y., Table 3, sample 78AWs 95) and the apparent 6 m.y. age at Northwest Arm.

Though we were not able to reach the outcrops, extensive alteration of the country rock around the margins of the Northwest Arm pluton was visible. The Castle Bay pluton is closely associated with a mineralized area; this mineralization probably predates emplacement of the Devils batholith.

Harrison and others (1979) studied thermal histories of a number of plutons in the Coast Plutonic Complex of British Columbia. Based on Rb-Sr, K-Ar, and fission-track dating and estimated isotopic closure temperatures for various mineral phases, they were able to construct temperature versus time plots for each pluton that they studied. Though Rb-Sr and fission-track data are not available, a temperature versus time plot for the data from the Devils batholith yields a plot (Figure 9) similar in form to their plot for the Ecstall pluton. Temperatures used were the blocking temperatures they derived for individual mineral phases; the potassium-argon age of each phase 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 Sweater Bay phase of the batholith assumes a slow cooling history. The second is the apparent cooling trend of the Northwest Arm phase of the batholith shown by the combination dotted and dashed line. The third curve is a dotted line very similar to that drawn for the Northwest Arm phase, drawn from the hornblende point for the Sweater Bay phase.

This diagram (Figure 9) can be interpreted in a number of ways and the available data do not allow selection of a best case based on the information in the diagram. One possible interpretation would explain the thermal history by slow cooling of the initial Sweater Bay phase of the batholith, with the hydrothermal alteration and mineralization taking place during this period. This slow cooling could be due to near proximity to the still-active magma chamber. The intrusion and rapid cooling of the Northwest Arm portion of the batholith followed hydrothermal alteration. Slow cooling of the Sweater Bay phase would explain the discordance of the older ages, whereas later rapid cooling and uplift would account for concordant ages in the later phase. However, with this sort of thermal history, one would expect a greater thermal aureole around the batholith than exists; i.e. like that described by Sutherland-Brown (1976) for plutonic porphyry deposits. The shales of the Hoodoo Formation maintain original structure and texture with the development of contact metamorphic biotite near the pluton; no dynamothermal effects have been described.

The data shown in Figure 9 do not rule out the possibility that cooling of the initial Sweater Bay phase of the Devils batholith may have occurred along a path similar to that suggested for the Northwest Arm phase. This rapid cooling may have then been followed by a thermal event of sufficient intensity and duration to partially reset the biotite ages of the pluton. The presence of hydrothermal biotite in the mineralized phases at Warner Bay, along with primary biotite in the same rocks suggests that this post-crystallation thermal event may have been associated with

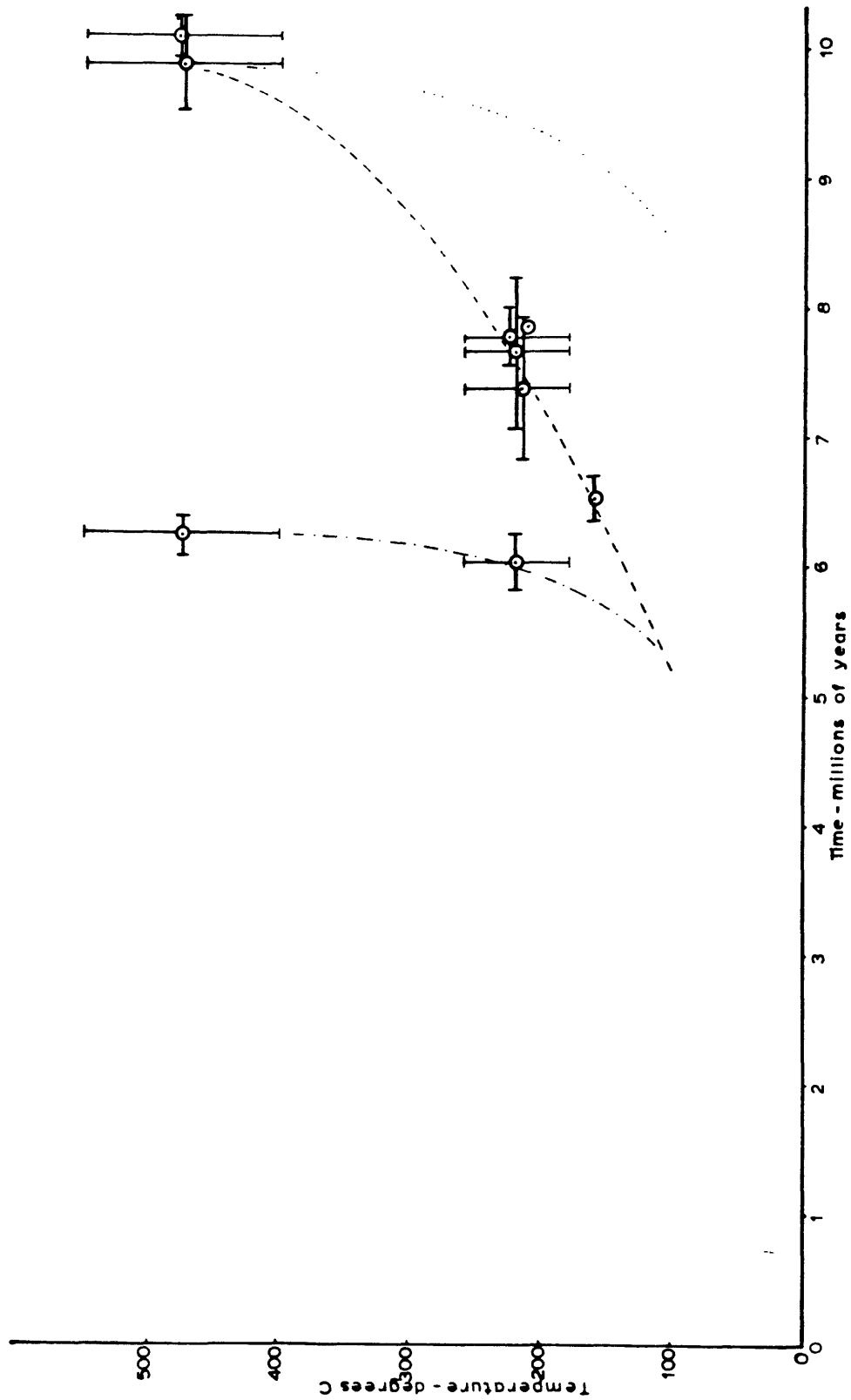


Figure 9 Temperature versus time plot for data from the Devils batholith, using blocking temperatures of Harrison and others (1979) and ages determined in this thesis (see Table 3). Dashed line indicates possible slow cooling history of Sweater Bay phase; dotted and dashed line indicates rapid cooling of Northwest Arm phase; dotted line shows parallel rapid cooling extrapolated for Sweater Bay phase.

mineralization but it may also reflect the emplacement of the Northwest Arm pluton. The hydrothermal mineral and pegmatite potassium-argon ages would also reflect this thermal event; formation of the hydrothermal minerals may be related to the thermal event. In this postulated history, the intrusion and rapid cooling of the Northwest Arm phase was the last event; this may have occurred simultaneously with the thermal event. If the thermal event occurred at the time of intrusion of the Northwest Arm phase, then almost complete resetting of the orthoclase at Warner Bay and less complete resetting of the biotite occurred.

The approach used by Harrison and others (1979) yields equivocal results in the Devils batholith based on the limited data available. However, in conjunction with other geological data, a post-crystallization thermal event associated with the intrusion of the Northwest Arm pluton is the explanation preferred by the writer to explain the potassium-argon age pattern in 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 Prospect

The Mallard Duck Bay prospect is a 4 by 10 km altered zone exposed in the headwaters of Mallard Duck Bay, approximately 10 km southwest of Chignik. Elevation ranges from near sea level to approximately 600 meters. Outcrop 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 rocks of the prospect area are a thick Tertiary (Oligocene?) andesitic volcanic sequence (Meshik?) intruded by swarms of andesite dikes and small tonalite stocks (Plate 5). (Note: Fields (1977) called the volcanic rocks andesites, but they probably include leuco-basalts and dacites also. He also called the tonalites granodiorite, undoubtedly both are present.) Bear Creek Mining Company (Fields, 1977) found the volcanic rocks to be composed of subhorizontal andesite flows, volcaniclastic sediments and tuffaceous units with a total thickness of at least 3000 feet (900m). Intruding the volcanic rocks is a pre-mineralization tonalite complex of small plutons and large dikes. A sample collected from one of the stocks is a porphyritic hornblende tonalite with large phenocrysts of quartz, plagioclase of approximately An 45 composition, and hornblende. The hornblende phenocrysts are entirely replaced by fine biotite and chlorite. The groundmass is composed of finer-grained plagioclase, quartz, and hydrothermal(?) biotite. The plagioclase is generally fresh; sericitization is not common. The dikes trend northwest and are up to a kilometer in length and up to 100 meters wide. Apparently, hydrothermal alteration is centered on one small tonalite exposure on the southwest edge of the alluvial valley. Fields (1977) reported that all the tonalites are of pre-mineralization age, although he notes that mineralization decreases towards the core of the plutons. A $21.3 \pm .79$ m.y. age has been determined on chloritized biotite from one of the tonalite stocks and a 21.2 ± 1.31 m.y. age has been determined on a quartz-sericite whole rock sample from this prospect (Table 8, samples 77AWs 137 and 183). The andesitic dike swarm was considered post-mineralization by Fields (1977), yet thin sections reveal pervasive propylitic alteration. A dike sample collected in 1977 by M.L. Silberman is a fine-grained hornblende andesite porphyry

with large hornblende phenocrysts and abundant plagioclase phenocrysts up to 1 cm in size. The rock contains abundant epidote and chlorite. A potassium-argon age of 27.1 ± 1.58 m.y. has been determined on hornblende (Table 8, sample 77AMs 1) from this sample. Other samples of these dikes were also hornblende andesite porphyries; however, pervasive sericitic and propylitic alteration has affected these, and the amphibole and plagioclase are largely destroyed. Whole-rock dates on unaltered volcanic rocks associated with the Mallard Duck Bay volcanic pile range from 22 to 26 m.y. (Table 4, samples 78AWs 98, 134) and probably represent late stage flows from the volcanic center.

The geology of the Mallard Duck Bay prospect has a close correspondence to the volcanic model of Sutherland-Brown (1976) or possibly the upper reaches of the volcanic-plutonic model of Sillitoe (1973). Geochemical sampling shows the Mallard Duck Bay prospect to be low in the metals that were of economic interest (Cu, Mo, Zn, Pb, Ag, Au); however, relative to the other prospects in the area (except possibly Warner Bay), Mallard Duck Bay is proportionately higher in lead and zinc. Molybdenum concentrations are particularly low. Mineralization tends to be fracture-controlled, with intense shattering throughout the area (Fields, 1977).

Alteration is characterized by widespread propylitic alteration, irregular pervasive sericitic alteration and potassium-silicate alteration concentrated in a small area of the granodiorite pluton (Fields, 1977).

Cathedral Creek Prospect

This prospect is a large color anomaly in the drainages of Cathedral, Milk, and Braided Creeks, and lies north-northwest of Chignik. Pan American (now Amoco) drilled 9 to 10 core holes on the prospect in 1965 to 1967 and Bear Creek Mining Co. evaluated the prospect in 1975 (Fields, 1977). Pan American's drilling was to evaluate the potential of a number of sphalerite, galena, chalcopyrite, silver, and gold veins cropping out in the headwaters of Braided Creek; Fields (1977) reported that their records were lost, and Bear Creek Mining Co. was only able to locate 4 of the drill sites. Bear Creek Mining Co. spent 3 days examining and sampling the prospect in 1975 and concluded that if any significant copper mineralization exists, it is at depth.

At this prospect, a large andesite pluton intrudes sediments of the Chignik, Hoodoo, Tolstoi, and Meshik Formations. This pluton lies near the northwest end of the belt of intrusive rocks extending from Weasel Mountain to Black Peak, previously mentioned in relation to the Bee Creek prospect. Samples collected from the Cathedral Creek area indicate that the pluton is a hypabyssal body ranging in composition from a two-pyroxene andesite to a hornblende andesite porphyry. Plagioclase compositions are quite calcic and range from An 50 to An 70. Biotite is rare in the thin sections examined, though chlorite has replaced the mafic phase in one sample. Fields (1977) reports chloritization is common in the intrusive rocks within the altered zone. The textures in these rocks and the geologic setting indicate that they were intruded at very shallow depths and may in part be extrusive. The sediments intruded by these igneous rocks lie on the north flank of the Chignik anticline and according to Fields (1977), dip some 35 to 70 degrees to the north-northeast. Dacitic and andesitic flows, pyroclastics, and agglomerates from Black Peak, a Quarternary to Recent volcano overlie the northwest portion of the area. Sericitic

Table 8.--Potassium-argon ages of Mallard Duck Bay Prospect, Chignik quadrangle

System component	Sample number	Rock type	Phase	K ₂ O (percent)	⁴⁰ Ar (rad) (percent)	Age (m.y.) error*
Altered intrusive rock.	77AWs 137	Tonalite	Bio/chl	5.56	19.98	20.9 ± 0.39
					42.36	21.7 ± .38
				Mean-----		21.3 ± .79
Quartz sericite altered volcanic.	77AWs 183	---	WR	2.51	56.32	21.8 ± .68
					75.93	20.5 ± .63
				Mean-----		21.2 ± 1.31
Pre-mineralization dike.	77AWs 1	Andesite	Hbd	0.343	29.56	26.2 ± .57
					15.31	27.9 ± .86
				Mean-----		27.1 ± 1.58

*See footnote ** on table 2.

alteration is extensive in the sedimentary rocks surrounding the andesite and chloritization is common in the pluton. Potassic alteration is not apparent. Dennis Cox collected samples of sericitically altered sediments; a potassium-argon date of $1.38 \pm .19$ m.y. has been determined on one of these (Table 9, sample 77ACx 4). A potassium-argon age of $3.08 \pm .14$ m.y. has been determined on hornblende from andesite thought to be part of the main intrusion (Table 9, sample 78AWs 125).

Nakchamik Island

Nakchamik Island is highly mineralized offshore island lying south of Cape Kumlium in Chignik Bay (Plate 1). We spent one day there in the summer of 1977 and a single dating sample was collected. This sample was porphyritic hornblende dacite (Streckisen, 1979) with phenocrysts of hornblende, plagioclase, and possibly potassium feldspar. The hornblende phenocrysts are large subhedral crystals with partially resorbed edges and inclusions of plagioclase. There is minor secondary chlorite associated with the hornblende. The zoned plagioclase phenocrysts are generally shattered, are apparently partially sericitically altered and are of An 45 to An 55 composition. The more sericitically altered plagioclase phenocrysts may be of a different composition. The groundmass is fine-grained and composed of plagioclase, quartz and hornblende. An age of $10.1 \pm .92$ m.y. (Table 9, sample 77AWs 134) was determined on hornblende from this sample. The sample was unmineralized and little altered; therefore the sample and its age probably represent a post-mineralization event. The rock dated was a cataclastic hypabyssal porphyritic tonalite and it intrudes propylitically and sericitically altered intrusive rocks and volcanic rocks making up the island.

Unavikshak Island

Unavikshak Island is also a small island in Chignik Bay lying east of Cape Kumlium (Plate 1). Hornblende from a hornblende andesite sill that has been dated at $36.4 \pm .15$ m.y. (Table 9, sample 78AWs 42) intrudes volcanic rocks and coal bearing sediments of unknown age. This hornblende andesite is similar petrographically to the hornblende dacite on Nakchamik Island, though not as fresh. The feldspar phenocrysts are of An 50 composition and are strongly sericitized. Subhedral quartz phenocrysts are present in small amounts ($\pm 10\%$). The groundmass is composed of plagioclase, quartz, hornblende and accessory apatite. A small zone of sericitic alteration lies near the northern end of the island and this alteration has been dated at $29.9 \pm .65$ m.y. (Table 9, sample 78AWs 43). The two dates reported here are single determinations, unlike most others in this thesis, therefore the reliability of the age determination is unknown. It can be assumed that the analytical error is somewhat larger than that indicated. The mineralization system at Unavikshak Island is best classified as a volcanic porphyry deposit, similar to Mallard Duck Bay on a much smaller scale. The 6.5 million year gap between emplacement of the sill and mineralization is significant and of the same order of magnitude as that at Mallard Duck Bay.

Conclusions Regarding the Genesis of Porphyry Systems

In a number of studies, Page and McDougall (1972a, 1972b, Page, 1975), have distinguished a difference of 1 or more million years between the age

Table 9.--Potassium-argon ages of miscellaneous prospects

Location	Sample number	Rock type	Phase	K ₂ O (percent)	⁴⁰ Ar (rad) (percent)	Age (m.y.) and error*
Sutwik Island quadrangle						
Nakchamik Island---	77AwS 134	Dacite.	Hbd	0.389	4.08	9.94 ± 0.87
					12.91	10.26 ± .21
				Mean-----		10.10 ± .92
Unavikshak Island--	78AwS 42	Andesite.	Hbd	.662	52.98	36.38 ± .15
	78AwS 43	Quartz-sericite altered volcanic.	WR	.547	21.6	29.9 ± .65
Chignik quadrangle						
Cathedral Creek----	77ACx 4	Quartz-sericite altered volcanic.	WR	1.863	3.17	1.25 ± .04
					5.56	1.51 ± .05
				Mean-----		1.38 ± .19
	78AwS 125	Andesite(?).	Hbd	.295	5.05	3.08 ± .14

*See footnote ** on table 2.

of emplacement of an intrusive rock and the age of hydrothermal minerals related to the mineralization of the intrusion. As would be expected and hoped, the hydrothermal mineral ages are consistently younger than emplacement ages of the host rocks. Moore and Lanphere (1971) reported a similar result at Bingham. One of the initial goals of this dissertation was to determine if a similar time span could be measured by dating of concentrates and separates of hydrothermal and primary mineral phases from mineralized zones in the Chignik and Sutwik Island region.

The results obtained on the Warner Bay, Unavikshak Island, and Mallard Duck Bay prospects provide additional evidence towards the existence of this time span between emplacement and alteration-mineralization. These results also indicate the complexity of the intrusion/alteration systems. At the Warner Bay and Mallard Duck Bay prospects, mineralization developed after the initial intrusive events and just before or during the latest magmatism.

The Bee Creek prospect should have provided a clear cut case for study. However, problems arose when it became clear that in only one sample would it be possible to separate primary hornblende for dating. An initial separate was made, and after repeated argon extractions it was apparent that no date was going to be obtained. Each split yielded an age older than any hydrothermal phase, yet no two splits were concordant. At about the same time, difficulty with a number of hornblende separates of similar age was encountered and no cause or solution for this problem was ever determined. A second hornblende separate was made of the sample from Bee Creek (77AWs 215-2) and after three attempts a duplicate analysis was obtained. However, the 2 m.y. old result suggests that the intrusion is younger than mineralization, which was unexpected, and the low yield of radiogenic argon makes the results analytically suspicious. The good agreement between the two extractions could be mere coincidence. Further studies will have to be undertaken to resolve the problem and to arrive at a solution.

The results of the study of porphyry systems in the Alaska Peninsula, coupled with the earlier studies cited, indicate that porphyry mineralization and the associated hydrothermal alteration systems are probably not related to the emplacement and cooling of a particular igneous body. Most descriptions of porphyry deposits indicate that mineralization occurred after igneous emplacement, and often after jointing or brecciation of the pluton. This may indicate that the hydrothermal alteration system is more related to the overall magmatic center rather than any particular igneous phase. This is particularly apparent with respect to volcanic porphyry systems. In these, the time span between the emplacement and alteration events is particularly large. The plutonic system at Warner Bay may have been thermally altered, yet it is clear that the time span between emplacement of the igneous phase that is now mineralized and the activation of the hydrothermal system was much shorter than that in the volcanic systems. The data are not conclusive but may suggest an inverse relationship between depth of mineralization and the time span between emplacement and mineralization.

Chignik Region Tectonic Synthesis

Paleomagnetic Studies

Stone and Packer (1977) reported on a paleomagnetic investigation of rocks from the Alaska Peninsula. They collected samples from a number of localities, including rocks of the Naknek, Chignik, Hoodoo, and Tolstoi Formations. Some of their sample localities were within the study area of this thesis. Though their paleopole error limits were large, their best fit reconstruction requires a large northward migration and clockwise rotation of a block they named "Baja Alaska", relative to the North American Plate since Jurassic and prior to Eocene time. On the basis of early data, Packer and Stone (1974) had proposed the Baja Alaska model for the Alaska Peninsula; later work (Stone, 1979) supports and extends the proposed model. This model describes the motion of the Baja Alaska block in the time range from Jurassic to Eocene. The Jurassic paleopoles for the Baja Alaska block indicate that it lay in the southern hemisphere. Cretaceous paleopoles indicate a rapid migration northward until, by Eocene time, the block was in approximately its present position relative to cratonal North America. Stone's (1979; Stone and Packer, 1977) definition of Baja Alaska was based entirely on the area from which their samples were collected, and not on any geologic or tectonic boundaries. In essence, their Baja Alaska is the Alaska Peninsula; geologically the rock units on the Alaska Peninsula are not limited to its geographic boundaries, but extend into southern Alaska in the Cook Inlet region.

Jones and others (1977) have defined a large allochthonous terrane in southern Alaska, western Canada, and Idaho as Wrangellia, which is distinguished by a characteristic stratigraphic sequence, structure, fossil fauna, and overall geologic history (Figure 10). The principal parts of the stratigraphic sequence include a thick Middle and Upper Triassic unit of tholeiitic basalt disconformably overlain by calcareous sediments deposited during late Karnian or earliest Norian (Late Triassic) time (Jones and others, 1977, p.2565). Older parts of the terrane where exposed, "are dominantly of sedimentary and arc-related (?) volcanic rocks that nowhere may be older than Pennsylvanian and, from indirect evidence, may have been in part, deposited on oceanic crust" (Jones and others, 1977, p.2656).

This terrane, according to Jones and others (1977, p.2571-2572) is distinct from the Triassic and older rocks exposed at Puale Bay (Cape Kekurnoi, Figure 1) and other places to the northwest on the Alaska Peninsula. D.L. Jones (oral communication, 1979) believes that these two Triassic terranes were separate during Triassic and Early Jurassic times, as is indicated by the distinctly different Triassic faunas, and their apparently different Early Jurassic histories. In the Talkeetna Mountains the Alaska-Aleutian Range batholith is continuous across both terranes, indicating they were joined by Middle Jurassic time. The Puale Bay Triassic rocks are part of the Baja Alaska block of Stone and Packer (1977). Jones and others (1977), citing earlier work by Jones (1963), point out that the two Triassic terranes were contiguous by Cretaceous time because the faunas and stratigraphy across the two terranes since that time are similar. Hillhouse (1977) presented paleomagnetic data for the Nikolai greenstone from the Wrangellia terrane in south-central Alaska. His interpretation was that this terrane had undergone 27 degrees of northward migration and 90 degrees of counter-clockwise rotation, or 57 degrees of northward migration and 90 degrees of clockwise rotation relative to the

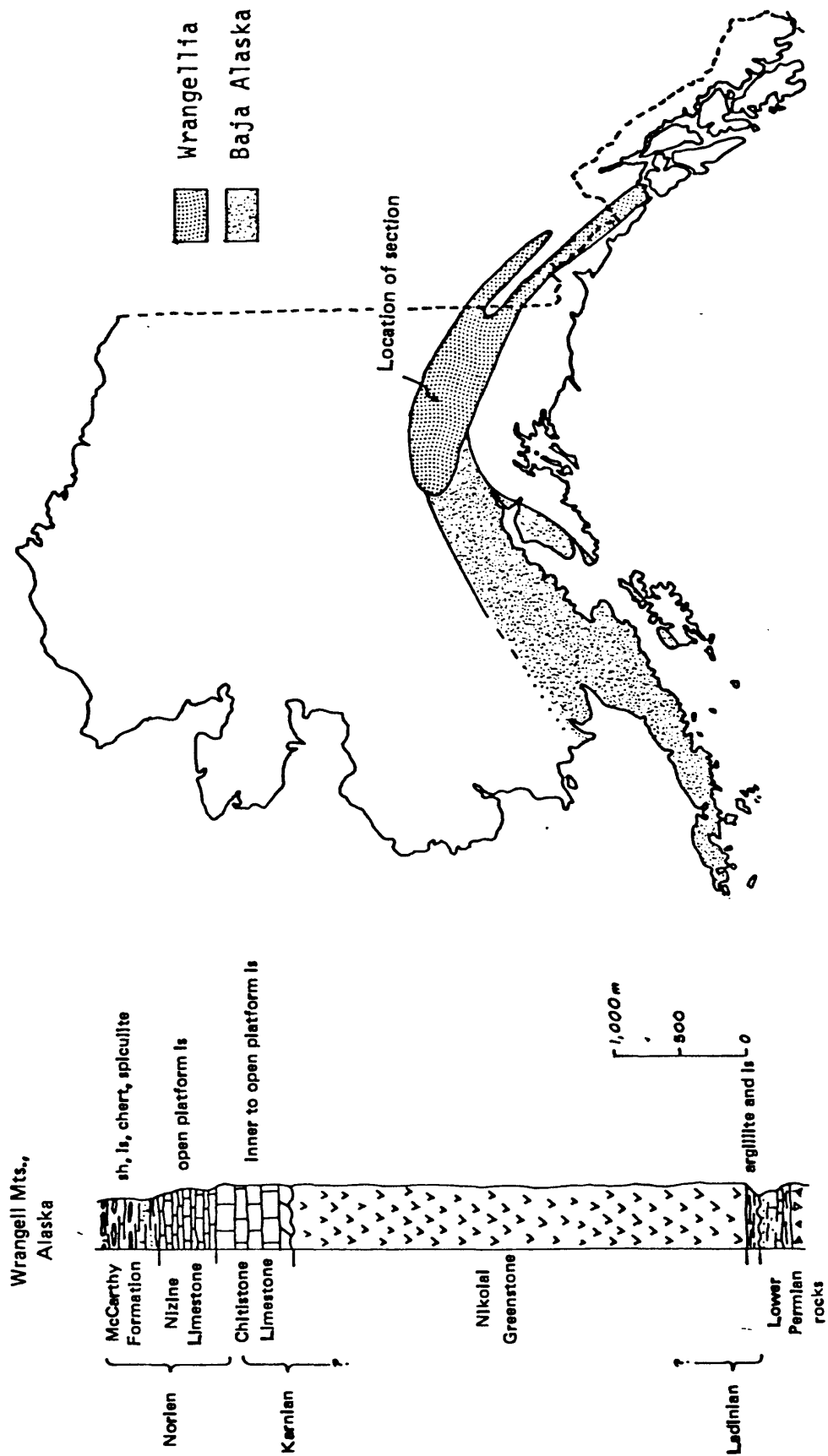


Figure 10 Map showing location of the Wrangellia and Baja Alaska terranes in southern Alaska, modified from Jones and others (1977) and Jones and Silberling (1979).

North American Plate since Triassic time. To this writer, the fairly close agreement between Stone and Packer's (1977) interpretation and Hillhouse's (1977) interpretation lends credence to the Baja Alaska model. Stone and Packer's (1977) data restricts the timing of the northward migration and rotation of the combined terranes to the late Mesozoic or early Tertiary.

Other Geophysical Studies

As part of the geologic investigation of the Chignik and Sutwik Island quadrangles, the U.S. Geological Survey contracted to have an aeromagnetic survey (U.S. Geological Survey, 1978) flown of the area by LKB Resources, Inc. Interpretation of the data is underway by J.E. Case (oral communication, 1979); some of the preliminary results can be discussed here. As mentioned earlier, the data show the continuation of a trend thought to be the Alaska-Aleutian Range batholith in the subsurface as far south as the vicinity of Port Heiden. Pratt and other's (1972) shipborne magnetic data indicate a possible continuation of this trend offshore in the Bering Sea (Bristol Bay).

Case interprets a number of the other magnetic highs to be the roots of older volcanic centers. Case (oral communication, 1979) has interpreted the line of aeromagnetic highs following the trend of the Chignik antiform just west of Chignik Bay as buried plutons. Figure 11 is a map showing the outline of aeromagnetic anomaly highs based on the aeromagnetic map of the Chignik and Sutwik Island quadrangles (U.S. Geological Survey, 1978). Also shown is an interpretation of the age of each anomaly based on ages determined on rocks from each anomalous area. From this map, the following trend is apparent. The Eocene to Oligocene volcanic centers (Tolstoi-Meshik arc) cluster in the center of the Chignik and Sutwik Island area; however this may be an artifact of the dating, which is quite sparse on the perimeter of the area. Assuming the apparent distribution is meaningful, there is a northeast-southwest elongation in the cluster of magnetic highs with a bend to the east to encompass Sutwik Island. In general this trend is markedly more east-west than other magnetic anomaly trends in the Chignik and Sutwik Island area (Figure 11). Another trend of magnetic highs is aligned parallel to the trend of the Alaska Peninsula and corresponds to the belt of late Miocene (5-10 m.y.) intrusive rocks, including the Devils batholith, the Chiginagak Bay pluton, and the pluton dated on Nakchamik Island. These plutons form the Pacific coast of the Alaska Peninsula. A third trend of 0-5 m.y. anomalies also parallels the Alaska Peninsula and corresponds to the Holocene volcanos on the Bering Sea side of the peninsula.

No compilation gravity anomaly map is yet available for the study area; Case's (oral communication, 1979) suggest the following interpretation: simple Bouguer anomaly gravity data indicate a +50 mgal anomaly along the axis of the Alaska Peninsula in the Chignik area. This anomaly occurs throughout the southern Alaska Peninsula and Aleutian arc, and suggests crust with a gravity signature transitional between oceanic and continental crust beneath the arc. There is a major change to a negative anomaly in the region of Becharof Lake, (Figure 1) approximately 100 km northeast of the Chignik and Sutwik Island region, suggesting continental crust there. In the study area, the positive anomaly has two minima, one paralleling the Meshik River and the other just south of Mt. Veniaminof (Plate 1). J.E. Case believes these may be "splay" basins off the Bristol Bay basin. They also may be major crustal breaks. In

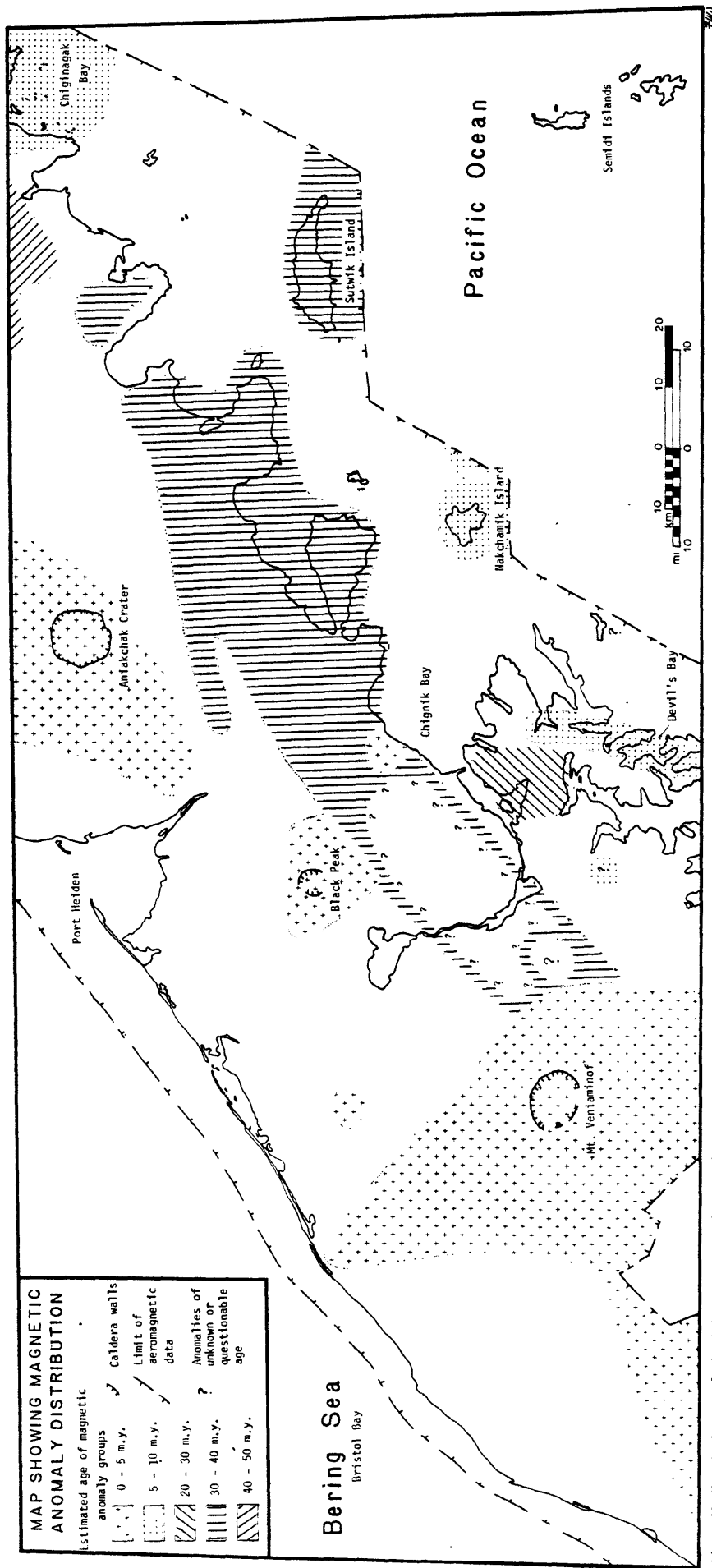


Figure 11 Map showing correlation between aeromagnetic anomalies and related potassium-argon dated rocks in the Chignik and Sotvik Island quadrangles.

particular, the gravity anomaly trend of the Peninsula is offset in a right lateral sense across the Meshik River. The surface geology is permissive for either case; however, the major structure of the Chignik and Sutwik Island region, the antiform west of Chignik Bay (Plate 1), is also offset at the Meshik River. To the north of the river a similar feature is mapped as the Wide Bay Anticline (see Burk, 1965, Part 3). The presently active volcanos, Mt. Veniaminof and Aniakchak do not lie on the gravity anomaly trend.

Geochronologic Studies

The geochronologic work undertaken here has indicated two important Tertiary magmatic episodes in the Chignik and Sutwik Island region area. These magmatic episodes may correspond to similar events in the Aleutians reported by Delong and others (1978); however, the ages reported in the Aleutians are metamorphic ages. The magmatic episodes in the Chignik and Sutwik Island region occur 5 to 10 million years later than in the Aleutians, possibly indicating the propagation rate of magmatic activity related to subduction along the Aleutian Trench. Figure 12 is a histogram of potassium-argon dates from the Chignik and Sutwik Island region. Each date plotted represents a single discrete event, i.e. only a single date was used for the alteration age at Bee Creek even though a number of different age determinations were run. Also shown on this graph by a long and short dashed line is a schematic estimate of the "true" distribution of ages in the region, based both on the age determinations and on the known and inferred geologic distribution of the igneous rocks. The large peak, centered about 34 m.y., represents the Tolstoi-Meshik Arc. The large volume and wide distribution of Tolstoi Formation volcanoclastic rocks and Meshik Formation volcanic rocks would tend to confirm the importance of this event. A smaller peak on the flank of the 34 m.y. old peak, centered about 22 m.y. is based primarily on the distribution of age determinations. Most of the dates in this range come from the vicinity of the Mallard Duck Bay prospect; it is unclear that this event is discrete from the Tolstoi-Meshik Arc and therefore the dotted line may be a more accurate representation. The second peak is incompletely shown, because it may be centered about presently active volcanism related to plate convergence at the Aleutian Trench. Radiometric work has shown that there is little evidence for Paleocene igneous activity except for the plutons of the Kodiak-Shumagin Plutonic Series. In particular, my work to date suggests that the previous Paleocene (Burk, 1965) age assignment for the Tolstoi Formation is incorrect. Some stratigraphic evidence (discussed later) is suggestive of a late Cretaceous volcanic arc, there is still no evidence of a source terrane, nor have any samples from the study area yielded Late Cretaceous ages. A single mid-Cretaceous age (Table 6, sample 77AWs 186) on a plutonic cobble from the Chignik Formation is thought to represent a minimum age on a weathered sample of the Jurassic portion of the Alaska-Aleutian Range batholith by this writer.

The potassium-argon studies reported here have been used primarily to interpret the Tertiary history of the Chignik and Sutwik Island area. They have not been of use to interpret of older events, except to indicate that no older igneous rocks outcrop in the Chignik region. The only pre-Tertiary igneous rocks known are found as sedimentary debris in Mesozoic formations.

The studies on mineralized areas have been of some use in defining the

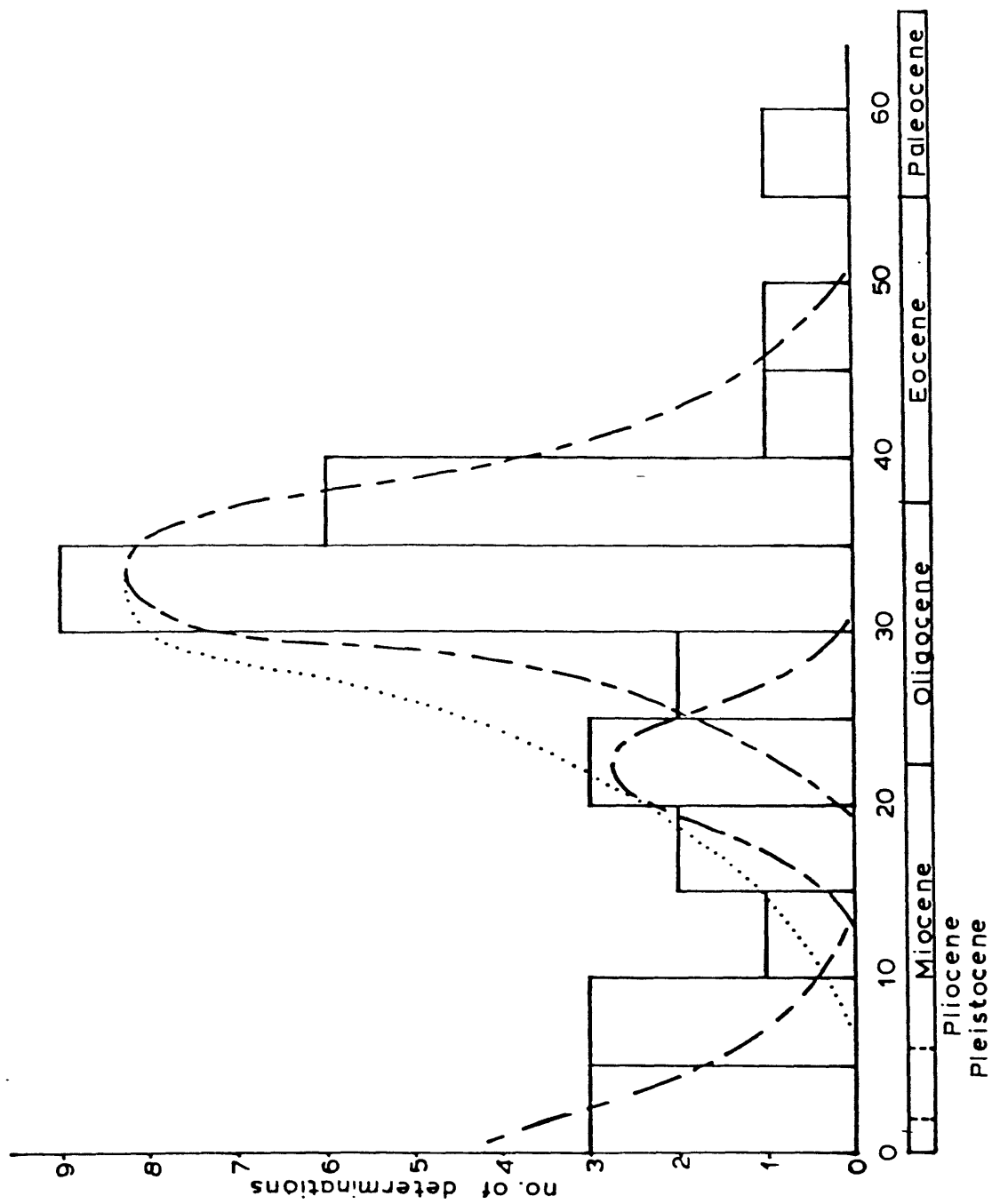


Figure 12 Histogram of dates from the Chignik and Sutwik Island quadrangles. Dashed lines indicate estimated "true" distribution of ages. Dotted line indicates suggestion that 22 and 34 m.y. old peaks are not distinct.

timing and sequence of events in these areas. At Warner Bay, dating of hydrothermal minerals has indicated that mineralization occurred between the time of emplacement of two phases of the Devils batholith. Because of the paucity of hydrothermal phases at Warner Bay, further refinement of the timing of the alteration event is not possible. Dating at Mallard Duck Bay indicates mineralization occurred during the late stages of the life of the volcanic center, was active for at least 7 m.y. A similar result was obtained at Unavikshak Island. At Bee Creek, the prospect I studied most intensively, the dating has not been as successful, nor the results as clear cut. The hydrothermal or secondary minerals all yield similar ages and isochron plots indicate no important loss or gain of radiogenic argon. Unfortunately, primary minerals have been difficult to collect and the one hornblende separate yields an age somewhat younger than the other minerals. I view hornblende age with some suspicion; however no good case can be made for rejecting the date, except for the low yield of radiogenic argon. The geological relations at the Bee Creek prospect suggest that the hornblende should be at least as old as the hydrothermal minerals; however, it may represent a late intrusive phase.

A problem with dating in this sort of terrane is the almost ubiquitous alteration of igneous rocks, and therefore the very limited population of fresh igneous rocks from which samples can be collected. In addition, the generally low potassium content of the rocks limited dating to whole rocks, plagioclase, and hornblende. Since it was rarely possible to date mineral pairs, a good knowledge of the geological relations between rocks units is required in order to determine the consistency of the analytical work. Unfortunately, our knowledge of the geology of the Alaska Peninsula is often inadequate in this respect.

Another problem is due to the very young age of many of the units. Low potassium content and young ages require large samples to generate sufficient argon for accurate and precise measurement. There is however, a practical limit to the size sample that can be loaded in the argon extraction lines and often the desired sample size exceeded this limit.

In dealing with the geological and analytical problems encountered as part of this study, a number of avenues of research are being pursued or considered. These include:

1. Continued dating of igneous rocks from the area in an effort to determine if the early Miocene hiatus in igneous activity is real.
2. Further dating of phases from the Bee Creek prospect to attempt to resolve the apparent inconsistencies; this will also involve the dating of hydrothermal quartz to examine the likelihood of excess argon.
3. Fission-track dating of suitable phases from mineralized or altered zones, to provide more information for deciphering the thermal histories of these areas.
4. Laboratory work to determine if the HF acid leaching technique can be applied to amphiboles to improve the analytical results. Amphiboles, particularly the younger ones, exhibit poor reproducibility, in part because of the low yield of radiogenic argon. The small amount of radiogenic argon evolved during extraction is easily obscured by the large atmospheric component. Any means that can reduce the amount of atmospheric argon without significantly affecting the radiogenic argon component will improve the precision of the age determination. Other authors (Dalrymple and Lanphere, 1969, p.189) have stated that the HF leaching technique should not be used on mafic minerals; yet apparently no tests of the

technique have actually been carried out. The use of the technique on basalts and andesites has not been theoretically justified, yet empirical data (M.L. Silberman and E.H. McKee, oral communication, 1979; Morton and others, 1977) clearly indicate that it works.

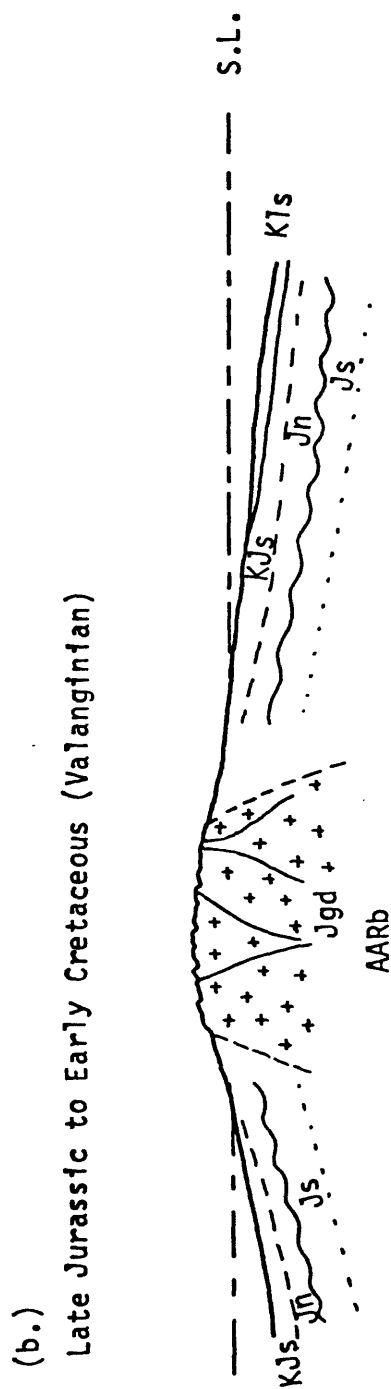
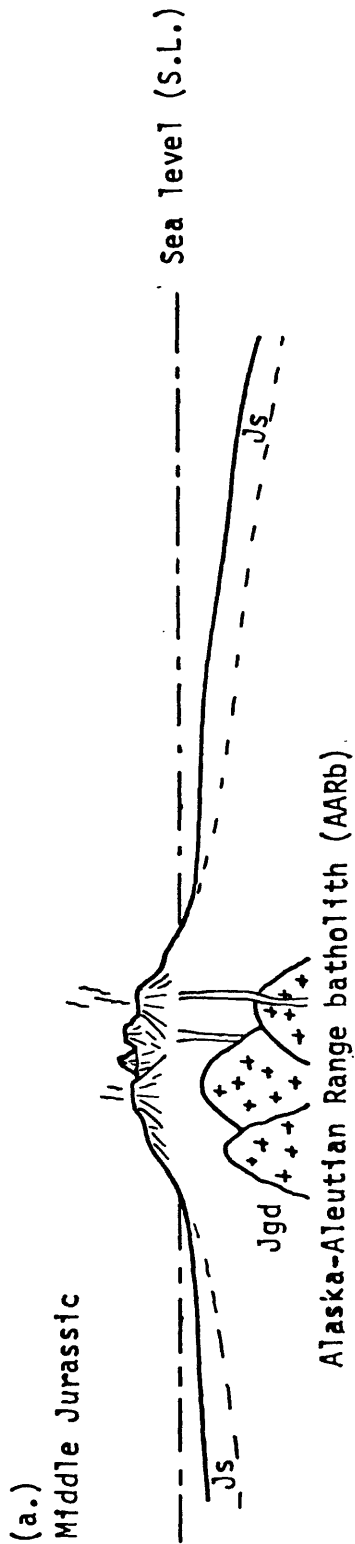
Conclusions

A series of schematic cross sections are shown in Figures 13-15. The discussion that follows is generally related to these cross sections, which give a visual representation of the geologic history of the study area through time.

Jurassic sedimentation in the Chignik and Sutwik Island region commenced after volcanism in a proto-Aleutian arc (Talkeetna Arc?) waned. The earliest rocks exposed in the Chignik and Sutwik Island area are parts of the Shelikof Formation, deposited as the last phases of volcanism ended (Figure 13a). The volcanoclastic rocks associated with this arc are exposed much further north as the Talkeetna Formation (Detterman and Hartsock, 1966) which belongs stratigraphically to the Lower Jurassic. Blueschist included in melange on Kodiak Island (Carden and others, 1977), the Jurassic parts of the Alaska-Aleutian Range Batholith, and the Talkeetna Formation are all evidence of this arc. The spatial arrangement of these components suggests that the arc formed over what in the present would be a northwest-dipping subduction zone. The Shelikof Formation was deposited in an open ocean basin, and indicates an important change in the tectonic regime of the Baja Alaska Block. Its deposition records the ending of a phase of convergent plate margin activity, and the beginning of a passive plate margin phase, lasting through middle Cretaceous time. After deposition of the Shelikof, the Shelikof underwent partial erosion and its volcanic-plutonic source terrane was eroded further.

Approximately 150 m.y. ago (earliest Oxfordian, Late Jurassic time) deposition of the Naknek began (Figure 13b). I believe it had the same northerly source terrane as the Shelikof, except that the terrane was being eroded at a deeper level and therefore the percentage of plutonic rocks is significantly greater. Deposition continued uninterrupted, along with gradual subsidence, until Valanginian (Early Cretaceous, 125 m.y.) time. The source of sediment supply decreased progressively, ultimately allowing deposition of the Herendeen Limestone. The Herendeen Limestone is a calcarenite and may indicate starved basin conditions. A similar unit of this age is common in many parts of southern Alaska.

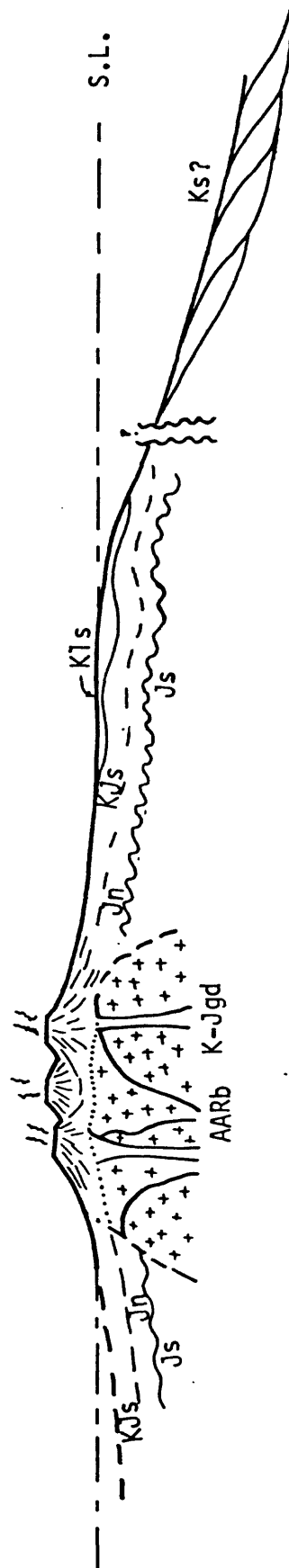
During the Late Cretaceous the existence of another volcanic arc (Shumagin Arc), in approximately the same position as the Jurassic arc, may be inferred (Figure 14a). This inference is based on evidence showing that the source terrane for the Shumagin Formation was a volcanically active region to the north and northwest of the depositional basin (Moore, 1973a). In addition, the 85-59 m.y. plutonic event in the Alaska-Aleutian Range batholith may indicate the sub-volcanic plutonic phase of this arc. The deposits of the Shumagin Arc were apparently carried across the shelf and dumped into a forearc basin as flysch of the Kodiak, Shumagin, and, possibly, the Hoodoo Formations. Correlative sequences also include parts of the Valdez and Yakutat groups in southern Alaska, and the Sitka Graywacke in southeastern Alaska (Plafker and others, 1977). There is some disagreement among geologists working in southern Alaska on the existence of this arc; Arthur Grantz (oral communication, 1979) believes the source for the extensive flysch terrane was erosion of the Lower Jurassic



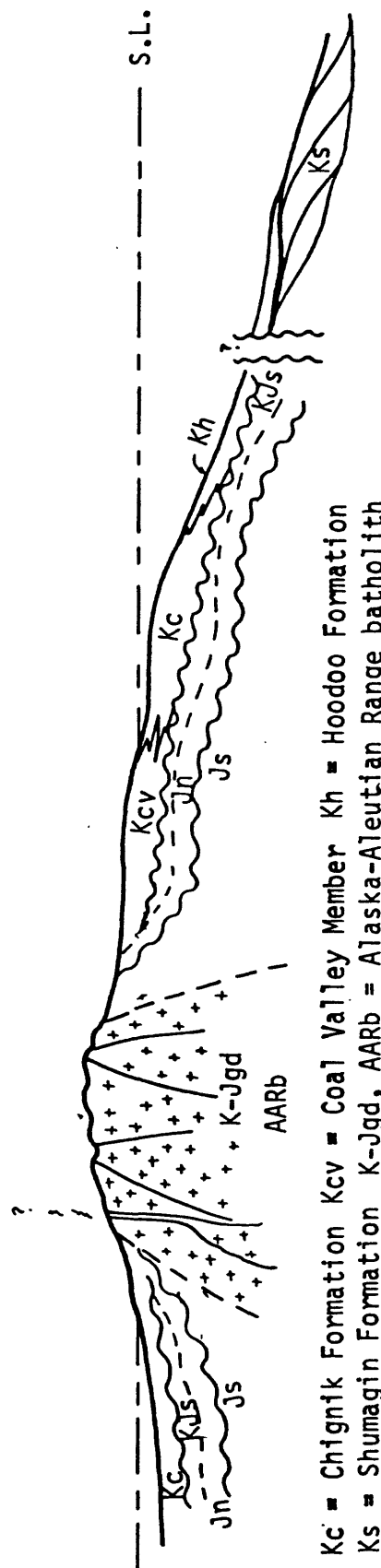
Js = Shelikof Formation Jn = Naknek Formation KJs = Stanlukovich Formation Kls = Herendeen Limestone
Jgd = Alaska-Aleutian Range batholith S.L. = Sea level

Figure 13. Schematic Cross-section - Tectonic development of the Chignik Region Part 1

(a.)
Late Cretaceous (pre-Campanian)



(b.)
Late Cretaceous (Campanian - Maestrichtian)



Kc = Chignik Formation Kcv = Coal Valley Member Kh = Hoodoo Formation
Ks = Shumagin Formation K-Jgd, AARB = Alaska-Aleutian Range batholith

Figure 14 Schematic Cross-section - Tectonic development of the Chignik region - Part 2

Talkeetna Formation. However, this does not account for the evidence for active volcanism at the time of deposition of the flysch, nor does it seem geologically possible that the Talkeetna Formation could act as a source for the flysch in the Shumagin or Sanak Islands. No reasonable case can be made for erosion of the Talkeetna Formation on the southern Alaska Peninsula at any time during the Cretaceous because, among other things, there is no evidence that the formation extends that far southwest. There remains the possibility that the turbidity currents responsible for deposition of the flysch flowed long distances along the axis of the ancestral Aleutian trench. The volcanic and volcanoclastic rocks that formed the actual arc are now missing, and the time-equivalent shallow-water sediments of the Alaska Peninsula do not reflect an active volcanic arc. There is, however, evidence of minor volcanic activity based on the bentonitic shales in the Chignik Formation. In the Chignik and Sutwik Island region, minor folding prior to the deposition of the Chignik Formation may be related to a renewal of subduction related to the postulated Shumagin Arc (Figure 14b). The geologic record of the Alaska Peninsula contains a depositional hiatus that may range from the Valanginian to the Campanian (Cretaceous, see Figure 2). The source terrane for the Chignik Formation probably was, in part, the Upper Jurassic Naknek Formation, and in part volcanic detritus incorporated from what might have been the Shumagin Arc. According to Stone and Packer (1977), most of the migration of Baja Alaska took place after the deposition of these Cretaceous rocks and before or during the initiation of the early Tertiary volcanic arc. At nearly the same time as the deposition of the Chignik and Shumagin Formations, the Hoodoo Formation was also being deposited. The Hoodoo Formation, apparently a distal turbidite, represents a major transgression. It may be a shelf facies lying inboard of the Shumagin and generally outboard of the Chignik. The location and type of source terrane for the Hoodoo is uncertain, as is the direction of flow of the turbidity currents. A provenance study, similar to Moore's (1973a) on the Shumagin, would be of great value for the Hoodoo. Intrusion of the Kodiak-Shumagin Plutonic Series granodiorite in the Semidi Islands during Early Paleocene time may be related to anatexis in the thick Shumagin flysch (Hudson and others, 1977, p.170).

During Eocene time, a new volcanic arc was initiated, the Tolstoi-Meshik Arc (Figure 15a). Paleomagnetic data of Stone and Packer (1977) indicate that the Tolstoi was deposited essentially at its present latitude. Initiation of this arc probably was coeval with the end of subduction to the north in the Bering Sea basin (Hopkins and Silberman, 1978) and the complete transfer of subduction to the south to a proto-Aleutian trench, located in probably the same relative position as the present Aleutian Trench. Baja Alaska-Wrangellia was no longer being rafted with the Kula or Pacific plates, and other than readjustments along various faults, this block was in position on the North American Plate. Volcanism was probably initiated in the far western Aleutian Arc (Early Series, Marlow and others, 1973); this is discussed more fully later. Volcanism in the far western Aleutian Arc during Eocene time may indicate that the arc was straighter or the convergence direction between the North American Plate and the Kula plate was more northerly or northeasterly than the present convergence between the North American and the Pacific plates. This part of the Aleutian Arc is not presently active, possibly due to a large transform component to the subduction of the Pacific Plate in the

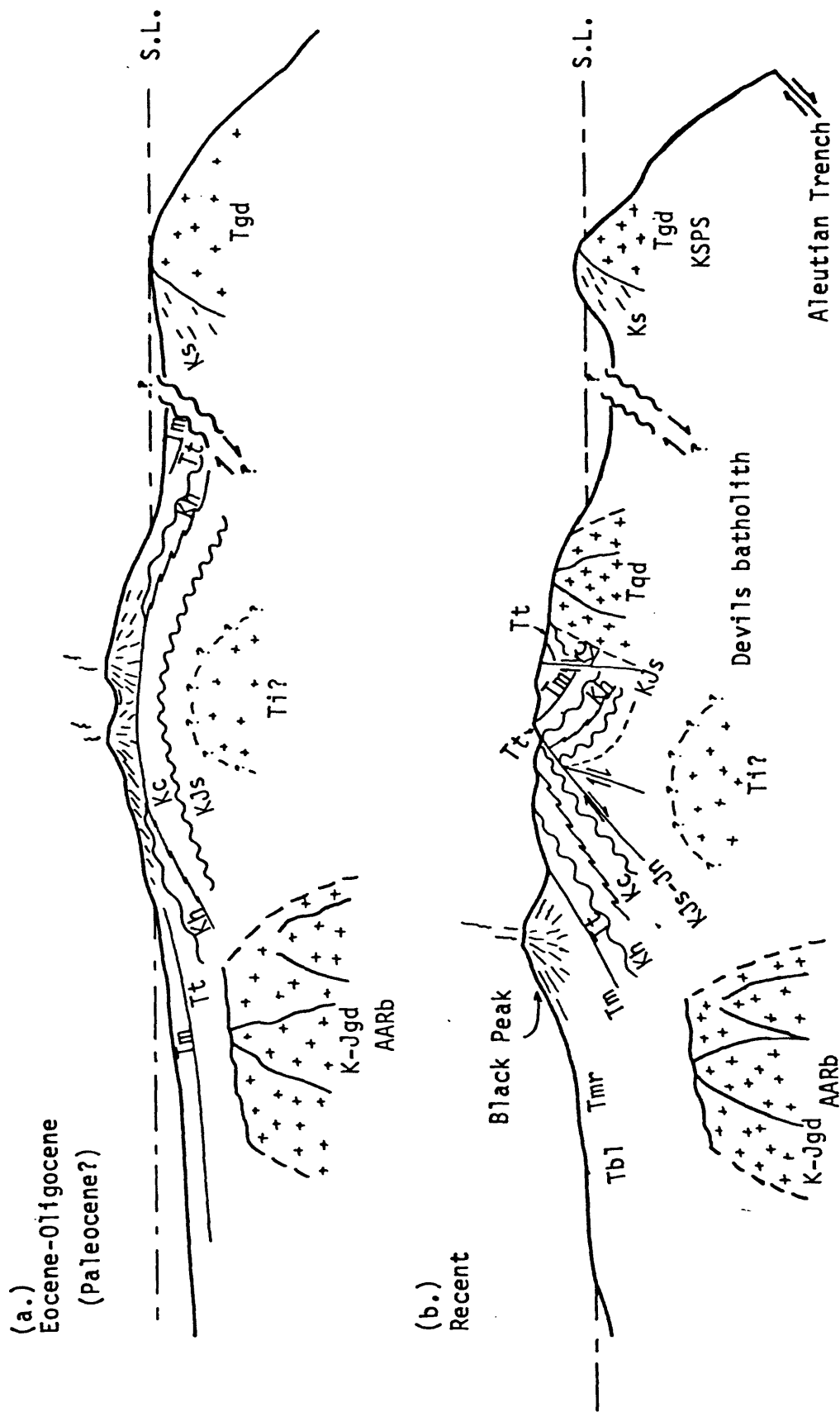


Figure 15 Schematic Cross-section - Tectonic development of the Chignik region - Part 3.

western part of the Aleutian Arc. The apparently more east-west elongation of the Tolstoi-Meshik Arc (Figure 11) compared to later structural features agrees with this interpretation of a more northerly convergence direction during Eocene time. The presence of plutons of this age (45-25 m.y.) in many places in southern Alaska may indicate other extensions of this arc from the Chignik and Sutwik Island region (Turner and others, 1975; Wilson and others, 1979; Dadisman, 1980). As yet, there are no Paleocene age determinations on rocks associated with the Tolstoi-Meshik arc in the Chignik and Sutwik Island area. The 85-59 m.y. event distinguished by Reed and Lanphere (1973) in the Alaska-Aleutian Range Batholith is not associated with the Tolstoi-Meshik arc; the younger 37 to 26 m.y. Middle Tertiary event is. The Tolstoi Formation was deposited on an uplifted terrane, relative to the Hoodoo, and it is channeled into the Hoodoo in some areas (R.L. Detterman, oral communication, 1978). There is no stratigraphic continuity between the Late Cretaceous Chignik and Hoodoo Formations and the younger Tolstoi Formation. No plutons or volcanic rocks in the Chignik and Sutwik Island region or on the entire Alaska Peninsula are known to have ages in the range between 59 and 48 m.y.

Radiometric ages indicate that the Tolstoi-Meshik arc essentially ceased activity in the Oligocene; this may correspond to the beginning of subduction of the Kula-Pacific Ridge in this area (DeLong and others, 1978) as it migrated northward. DeLong and others (1978) proposed a model for subduction of the Kula-Pacific Ridge that would require a temporary cessation of volcanism at the time of actual ridge subduction. Assuming the model is correct, the predicted cessation of volcanism should occur sometime near the end of the Oligocene in the Chignik and Sutwik Island region. The timing is somewhat dependent on the orientation of the ridge and its rate of migration along the trench. Also, segmentation of the ridge will exert another control on the timing of ridge subduction.

In Middle to Late Miocene time, deposition of the Bear Lake Formation began, probably by reworking of pre-existing sediments (R.L. Detterman, oral communication, 1979). Its lithology indicates a quiescence of volcanism and a marine transgression in the region. The present outcrop distribution of the Bear Lake Formation is primarily in the southwest portions of the Chignik quadrangle. The formation is encountered in drill holes as far north as Becharof Lake (Figure 1); therefore this transgression must have covered a large portion of the Alaska Peninsula. At the end of the Miocene, major volcanism and plutonism began again in the study area, along the trend of the Devils Batholith, Nakchamik Island and Chiginagak Bay. This volcanism has apparently migrated quickly inland to its present position along a line from Mt. Veniaminof to Aniakchak, as subduction has continued along the Aleutian Trench. Migration inland of the locus of volcanism could be due to acceleration in the rate of subduction and an associated shallowing in the angle of subduction. However, according to G.B. Dalrymple (oral communication, 1979), work in the Hawaiian Islands indicates a relatively constant rate of movement (or of volcanic propagation of the Hawaiian Islands) of the Pacific Plate over the last 60 m.y., with possibility of a slight change in the 28 to 20 m.y. age range. Therefore it is unlikely that the Miocene to Recent migration of volcanism in the Chignik and Sutwik Island region could be due to a change in the rate of subduction. Another possibility is an increase in the depth of partial melting with time. Mapping and geochemical data are as yet insufficient to apply petrogenetic models to rocks of the area to

test this hypothesis.

In Pliocene time, uplift, thrusting to the southwest, and minor intrusion occurred along the eastern side of the Peninsula, while deposition of the Milky River Formation occurred on the western side (Figure 15b). Thrusting from the northwest occurred along the core of the Chignik anticline and continued until later than 3.6 m.y., as dated by the northwest dipping thrust at the Bee Creek prospect.

Speculations - Southern Alaska Tectonics

Introduction

Speculating on a model for the tectonic development of southern Alaska, by extrapolation of the synthesis from the Chignik and Sutwik Island region, one is struck by the sheer number and diversity of small tectonic blocks or terranes involved. Jones and Silberling (1979) on stratigraphic grounds have divided southern Alaska, exclusive of southeastern Alaska, into at least nineteen different tectonostratigraphic terranes. Figure 16 is modified from Jones and Silberling (1979) and in a general sense shows some of the terranes they have defined for Alaska, exclusive of southeastern Alaska and the Seward Peninsula. Many of these terranes are not yet described in the literature; however, the Peninsular terrane as defined by Jones and Silberling is essentially the same as Baja Alaska. Southeastern Alaska has been divided into six distinct terranes alone (Berg and others, 1978) and as mapping proceeds in other parts of southern Alaska, other terranes are sure to be recognized. The first terrane in southern Alaska to be described in detail was Wrangellia (Jones and others, 1977). (Baja Alaska predates this in the literature (Packer and Stone, 1974) but has not been geologically described or delimited.) Some models for the tectonic development of southern Alaska assume that these terranes are "microplates" rafted in and welded to the Alaska margin (i.e. Jones and others, 1977). Other models suggest that these are "slivers" of continental material carried along the western margin of north (and south?) America (Stone, 1977). None of the published models is fully satisfactory for one or more significant reasons.

Speculative Model

The above geologic history of the Chignik region places a number of constraints on the tectonic history of southern Alaska. Additionally, the apparent island arc nature of some of the Triassic rocks involved in Wrangellia and Baja Alaska; the southern hemisphere paleopoles suggested by Stone (1979) and Hillhouse (1977) for Baja Alaska and the Triassic Nikolai Greenstone respectively; and the lack of any obvious continental collision zones, except possibly the volcanic and sedimentary unit (KJvs) of Hoare and Coonrad (1978a), suggest to this author that a model involving both accreted tectonic blocks and a shifting plate edge (Stone, 1977, p.30) is supported by available data and best accomodates these constraints.

Reflected in this model is that no collision boundary with mainland Alaska has been mapped north of the Baja Alaska-Wrangellia block, yet paleomagnetic evidence clearly indicates large scale transport. However, the dismembered Jurassic ophiolite of southwestern Alaska (Goodnews terrane) may be a small block of oceanic crust caught in a fault slice or sliver as other blocks rotated and translated northward. The lack of a major collision boundary would seem to constrain motion to translation along the North American continental margin unless the KJvs unit (Hoare and Coonrad, 1978a) of southwestern Alaska is the remnant of a collision terrane. A modern example of such translation is Baja California (source of the name, Baja Alaska) which has at times been on the Pacific and the North American plates and is translating northward along the San Andreas and other faults. Figure 17 is a schematic sketch of a crude, very generalized model along these lines, as envisaged by this writer. It indicates the general positions of the Yukon Crystalline Terrane,

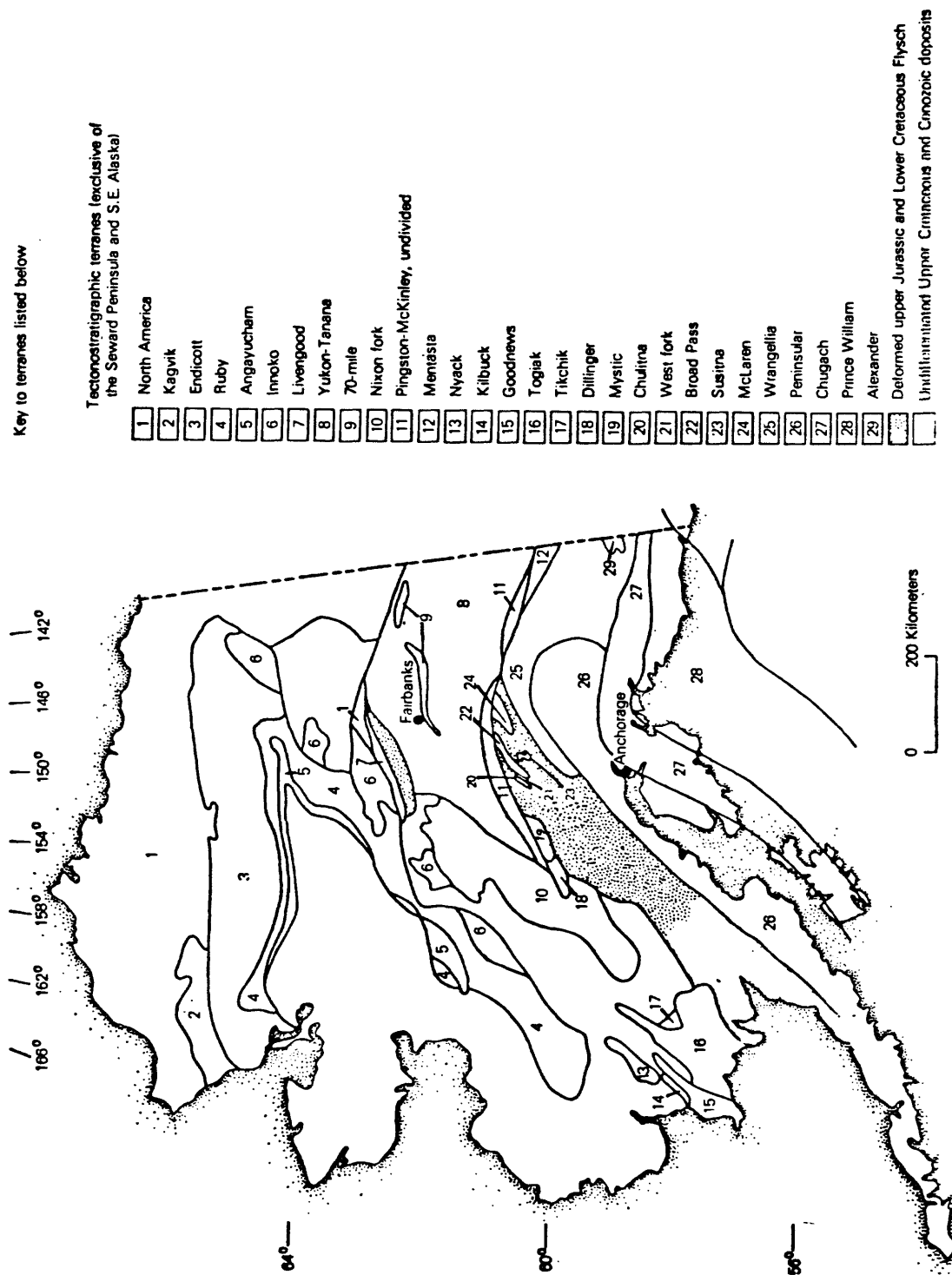


Figure 16 Tectonostratigraphic terranes of Alaska, exclusive of southeastern Alaska and the Seward Peninsula, modified after Jones and Silberling (1979).

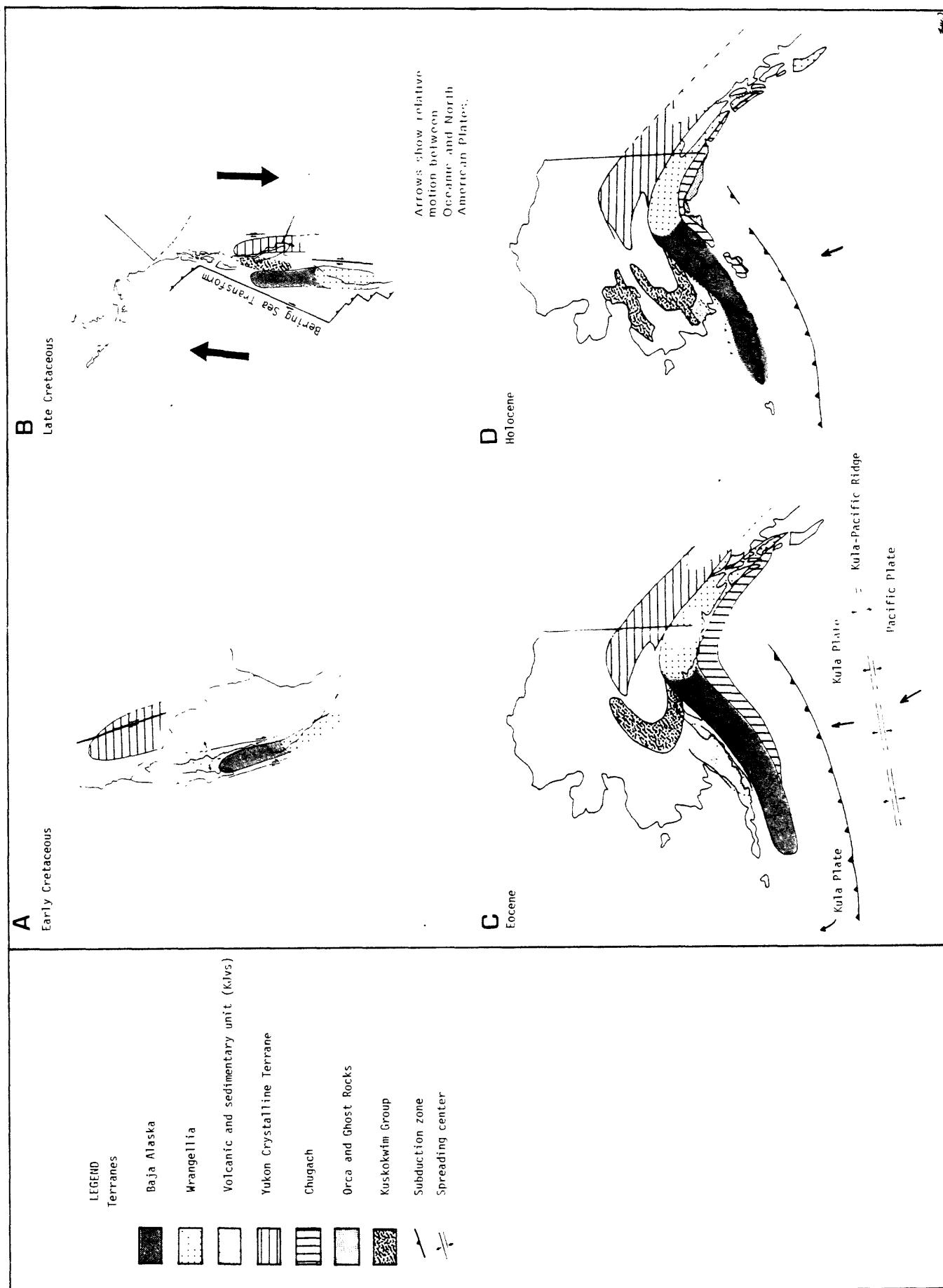


Figure 17 Schematic diagram - Generalized Southern Alaska model

Wrangellia, Baja Alaska and other terranes from Early Cretaceous to Holocene time. In the following paragraphs my speculative model for the tectonic development of southern Alaska, consistent with the history of the Chignik region, is briefly described. A key assumption of my model, based on discussions with Bela Csejtey, and on the continuity of the Alaska-Aleutian Range batholith across the two terranes, is that Baja Alaska and Wrangellia were adjacent in Middle Jurassic time, this larger terrane is herein called the Southern Alaska block. Numerous other terranes of southern Alaska (Jones and Silberling, 1979) were accreted to this block at various times. Not all will be discussed here, as they are beyond the scope of this thesis, and in any case the information is often not available.

(1) Middle Jurassic

The Baja Alaska and Wrangellia terranes were joined at a latitude near the paleoequator. This joining was due to subduction, possibly from the west or south, under the Southern Alaska block and the formation of the Jurassic portion of the Alaska-Aleutian Range batholith. The block may have undergone some northward migration during Middle Jurassic time.

(2) Late Jurassic-Middle Cretaceous

The Southern Alaska block underwent major northward migration along the North American plate edge (Figure 17a) in a manner similar to Baja California. Apparently, no subduction was involved; like Baja California, the Southern Alaska block was part of an oceanic (Kula?) plate.

(3) Middle Cretaceous

The deposition of the Chugach terrane flysch and the 85-59 m.y. plutonic event in the Alaska-Aleutian Range batholith may indicate that some convergence occurred between the oceanic plate and the Southern Alaska block. The melange facies of the Chugach terrane was accreted to the Southern Alaska block during this time, as part of this subduction event.

(4) Late Cretaceous

The Southern Alaska block continued northward with rotation (Figure 17b). Some underthrusting of the Southern Alaska block (including other accreted terranes) under the North American plate probably occurred on the northeastern (now northern and northwestern) or leading edge. Apparently, little or no subduction took place under the northern part (Baja Alaska) of the Southern Alaska block. Subduction occurred to the far north along the eastern ancestral Bering Sea continental margin and north-south(?) transform motion occurred along the southeastern ancestral Bering Sea margin.

(5) Early Tertiary (Paleocene-Eocene)

The Southern Alaska block overrode the Bering Sea transform fault (Figure 17c) causing the step-out of subduction from the northern Bering Sea margin to an "ancestral" Aleutian trench. This step-out of subduction caused entrapment of a portion of the Kula plate behind the newly forming Aleutian Arc.

The Paleogene subduction complex (Orca Group and Ghost Rocks) of southern Alaska began to form during Paleocene time. In addition, the volcanism of the Tolstoi-Meshik Arc was initiated during Eocene time.

(6) Middle Tertiary to Recent (Oligocene-Holocene)

The Paleogene subduction complex was accreted to the Southern Alaska block during subduction of the Kula-Pacific Ridge at the proto-Aleutian trench. After subduction of the Kula-Pacific Ridge, the convergence direction at the Aleutian Trench had a more westerly component (Figure

17d). Volcanism along the Aleutian Arc began again, starting the present cycle of activity.

Explanation

A brief explanation of some aspects of the speculative model follows. Each explanation is numbered to correlate with the same time interval described in the foregoing section.

(1) Pre-Jurassic rocks in the Baja Alaska terrane include Triassic carbonates and volcanic rocks and Permian carbonates at Puale bay (Burk, 1965, p.19) and similar rocks further north along Cook Inlet (Detterman and Reed, 1980). In the Naknek quadrangle north of Becharof Lake (Figure 1) limestone of probable Silurian or Devonian age have been reported by Detterman and others (1980a).

Stone's (1979) and Hillhouse's (1977) Triassic southern hemisphere paleopoles for Baja Alaska and Wrangellia may require a migration of these terranes from the South American plate across to the North American plate. Since the two American plates may not have been connected until after the Triassic, this would require Baja Alaska and Wrangellia to be rafted on the Kula (or Pacific or Farallon) plate during this period, until they encountered the North American plate. Recent mapping in Alaska and western Canada has indicated other slivers or blocks that possibly have been included in northward translation along the western North American continental margin. These other terranes (not shown on Figure 16 or 17) include the Alexander Terrane of southeastern Alaska, the Taku, Tracy Arm (or Coast Plutonic Complex), Stikine, and Cache Creek terranes (Berg and others, 1978). Further inland is the Yukon Crystalline Terrane (Templeman-Kluit, 1976) which includes the Yukon-Tanana terrane of Jones and Silberling (1979). In southwestern Alaska, the Kanektok terrane (Hoare and Coonrad, 1978a; Kilbuck terrane of Jones and Silberling, 1979) and the dismembered ophiolite of the Cape Newenham area (Hoare and Coonrad, 1978b; Goodnews terrane of Jones and Silberling, 1979) are two of possibly many originally(?) distinct terranes.

(2) The paleomagnetic data for the Alaska Peninsula suggests large displacement of the Baja Alaska block from the south and rotation, yet the Mesozoic stratigraphy requires a continental source terrane during much of this migration, in the opinion of this writer. Possibly the Baja Alaska-Wrangellia block was large enough to act as its own source since the Jurassic, but one can alternatively assume that this block maintained contact with the North American plate through much its migration northward.

Two units that help to define the motion of the Southern Alaska block are the volcanic and sedimentary unit (KJvs) and the Kuskokwim Group of Hoare and Coonrad (1978a) shown on Figure 16. These are briefly described below.

The KJvs unit of southwestern Alaska described by Hoare and Coonrad (1978a) is a thick and widespread marine volcanic and sedimentary rock unit ranging in age from Middle Jurassic to Early Cretaceous. According to them, it includes volcanic rocks ranging "in composition from mafic pillow basalts to more abundant andesitic and trachytic flows, tuffs, and breccias. Interbedded with the volcanic rocks are thick sections of tuffaceous siltstone, tuffaceous cherts, and massive or thin-bedded argillite."

The Kuskokwim Group (Hoare and Coonrad, 1978a, Cady and others, 1955, p. 35-47) is a thick sedimentary unit of inferred Early Cretaceous (Albian)

and early Late Cretaceous age. The lithology of the unit includes a basal conglomerate up to 1500m thick overlain by micaceous shales and siltstones. Overlying this is a thick section of interbedded graywacke, siltstone, and shale. In one area, Hoare and Coonrad (1978a) report abundant plant material, thin coal beds, and impure limestones which they suggested may be nonmarine; otherwise, the Kuskokwim is considered marine. The Kuskokwim Group is extensive in southwestern Alaska; unfortunately, other than the reconnaissance work of Cady and others (1955) and Hoare and Coonrad (1978a), little has been published.

(3) Very prominent on any would-be tectonic map of Alaska would have to be the extensive accretionary flysch terrane of southern Alaska. Extending continuously from Baranof Island in southeastern Alaska to the Sanak Islands off the southwestern Alaska Peninsula, it is possibly the largest such terrane in the world. This terrane, Late Cretaceous in age, and including the Shumagin and Kodiak Formations, the Valdez Group, part of the Yakutat Group and the Sitka Graywacke (Plafker and others, 1977) corresponds to the younger Chugach terrane of Berg and others (1972, 1978)(see Figure 16). The Chugach terrane is separated by the Border Ranges Fault (MacKevett and Plafker, 1974) on its inboard margin from an associated melange. The Border Ranges fault is mapped in the Cook Inlet region and on Kodiak Island; it is approximately the boundary between the Chugach and Peninsular terranes shown on Figure 16. Jones and Silberling (1979) include the melange in the Peninsular terrane, though Berg and others (1972) considered it part of the Chugach. As of yet, no source terrain for the largely volcanoclastic accretionary flysch of the Chugach terrane is definitely known. In discussing the Late Cretaceous history of the Chignik region (p. 86), I suggested that the volcanic debris was derived from an inferred Shumagin Arc. Paleocurrent analysis (Moore, 1973a) agrees with this hypothesis; however, as mentioned above, a source terrane is still difficult to pinpoint.

The melange associated with the Chugach Terrane includes blocks of late Paleozoic to Early Cretaceous age in a matrix of middle to upper Cretaceous pelite or tuffaceous pelite (Plafker and others, 1977). This writer suggests that a possible equivalent of the melange is found in southwestern Alaska as the volcanic and sedimentary unit (KJvs) of Hoare and Coonrad (1978a).

(4) Recent work by McLean (1979) shows that the extension of the Chugach terrane along the Bering Sea shelf margin as proposed by other authors (Patton and others, 1976; Hopkins and Silberman, 1978) did not occur; he suggested that the shelf margin was probably a Cretaceous transform fault.

(5) Rather weak evidence for a late Cretaceous age of parts of the Aleutian Ridge is reported in Scholl and others (1970, p.3589). Marlow and others (1973) postulated a middle to late Eocene age for the origin of the Aleutian Ridge. In light of the translational and rotational movement of the numerous blocks of southern Alaska, I believe there was a gradual rotation of the present eastern Bering Sea continental margin until late Cretaceous or early Tertiary time. This may have led to an instability in the existing subduction regime and the postulated Bering Sea transform boundary (Figure 17b), which caused the plate margin to jump to the then-forming Aleutian trench and island arc from the northern Bering Sea edge. This step-out of the plate margin would result in entrapment of a portion of oceanic crust (Figure 17c). This entrapment has occurred and

has been interpreted as a portion of the Kula Plate (Cooper and others, 1976, Scholl and others, 1975, Patton and others, 1976).

Subduction or "leaky" transform motion may have continued to occur along the eastern Bering Sea margin until early Tertiary time but by Eocene time, motion was taken up at the Aleutian trench. Eocene initiation of volcanism in the Aleutian Islands therefore corresponds with Eocene initiation of volcanism in the Tolstoi-Meshik arc in the Chignik and Sutwik Island region. A Paleogene subduction complex has been described (Plafker and others, 1977, p.842) along the northernmost southern Alaska coast (Prince William Sound) and along the eastern shore of Kodiak Island. The complex is represented by the Orca Group in Prince William Sound and by the Ghost Rocks Formation on Kodiak Island (Moore, 1969); these have been accreted outboard of the Cretaceous melange and flysch. Tysdal and Case (1979) reported that portions of the Orca Group are similar to those to be expected for a "fossil" spreading center of Paleocene to early Eocene(?) age. They mapped a pillow basalt and sheeted dike complex in the Seward and Blyling Sound quadrangles of Prince William Sound, and interpreted it as forming near the junction of the continental margin with a "leaky" transform fault (Tysdal and others, 1977). They also suggested the possibility that these rocks may represent remnants of the Kula-Pacific Ridge; however, they point out a number of difficulties with such an interpretation. Their interpretation suggests that the Kula-Pacific Ridge was probably still active and not near the continental margin during Paleocene time, as was suggested by Byrne (1979).

Byrne (1979) reconstructed the history of the Kula-Pacific Ridge using sea-floor magnetic anomaly patterns and speculated that the Kula-Pacific Ridge had ceased activity during Paleocene time. He also suggested that the near proximity of the Kula-Farallon Ridge to the Aleutian Trench at that time is responsible for the anomalous near-trench plutonism of the Kodiak-Shumagin Plutonic Series. Byrne's reconstruction would allow little or no subduction of oceanic crust at the Aleutian Trench since Paleocene time. This is because his reconstruction produces virtually the present sea-floor magnetic anomaly pattern in Paleocene time. This is in serious disagreement with the presently known geologic history. Assuming the present subduction rate is 6 cm./y., over the last 10 m.y., the amount of crust subducted is greater than Byrne's reconstruction would allow. Addition of the amount of crust subducted during the life of the Tolstoi-Meshik Arc only makes the fit of the presently known facts to Byrne's model worse.

Byrne's (1979) suggestion that the turbidites of the Aleutian Abyssal Plain were derived from Alaska across the defunct Kula-Pacific Ridge is apparently based on a misinterpretation of a paper by Stewart (1976) who suggested southeastern Alaska and western British Columbia as a source for the sediments of the Aleutian Abyssal Plain; this would require transport across the Pacific-Farallon Ridge; not the Kula-Pacific Ridge.

(6) Subduction of the Kula-Pacific Ridge in Oligocene to Miocene time (Delong and others, 1978) was the final major tectonic episode, leading to the present tectonic setting. The reinitiation of volcanism in late Miocene time that continues to the present suggests that the current configuration of underthrusting of the Pacific Plate at the Aleutian Trench and the general distribution and placement of tectonic blocks in southern Alaska was established by the end of Miocene time.

References Cited

- Armstrong, R.L., Harakal, J.E., and Hollister, V.F., 1976, Age determination of late Caenozoic porphyry copper deposits of the North American Cordillera: Institute of Mining and Metallurgy Transactions, Section B, v. 85, p. 239-244.
- Ashley, R.P., and Silberman, M.L., 1976, Direct dating of mineralization at Golfield, Nevada, by potassium-argon and fission-track methods: Economic Geology, v.71, p.904-924.
- Atwood, W. W., 1911, Geology and mineral resources of parts of the Alaska Peninsula: U. S. Geological Survey Bulletin 467, 137p.
- Beckinsale, R.D. and Gale, N.N., 1969, A reappraisal of the decay constants and branching ratio of K : Earth and Planetary Science Letters, v.6, p.239-294.
- Berg, H.C., and Cobb, E.H., 1967, Metalliferous lode deposits of Alaska: U.S. Geological Survey Bulletin 1246, 254p.
- Berg, H.C., Jones, D.L., and Richter, D.H., 1972, Gravina-Nutzotin belt - tectonic significance of an upper Mesozoic sedimentary and volcanic sequence in southern and southeastern Alaska, in Geological Survey Research 1972: U.S. Geological Survey Professional Paper 800-D, p.D1-D24.
- Berg, H.C., Jones, D.L., and Coney, P.J., 1978, Map showing pre-Cenozoic tectonostratigraphic terranes of southeastern Alaska and adjacent areas: U.S. Geological Survey Open-file Report 78-1085, scale 1:1,000,000, 2 sheets.
- Blatt, Harvey, Middleton, Gerard, and Murray, Raymond, 1972, Origin of sedimentary rocks: Prentice - Hall, Inc., Englewood Cliffs, New Jersey, 634p.
- Bouma, A.H., 1962, Sedimentology of some flysch deposits: Elsevier Publishing Co., Amsterdam, 186p.
- Bouma, A.H., and Hollister, C.D., 1973, Deep ocean basin sedimentation in Turbidites and Deep Water Sedimentation, Society of Economic Paleontologists and Mineralogists, Pacific Section Short Course, Anaheim, California, p.79-118.
- Brockway, R., Alexander, B., Day, P., Lyle, W., Hiles, R., Decker, W., Polski, W., and Reed, B., 1975, Bristol Bay Region, Stratigraphic correlation section, southwest Alaska: The Alaska Geological Society., 1 sheet.
- Burk, C.A., 1965, Geology of the Alaska Peninsula - island arc and continental margin: Geological Society of America Memoir 99, 250p., 2 maps, scales 1:250,000 and 1:500,000.
- Byrne, Tim, 1979, Late Paleocene demise of the Kula-Pacific spreading center: Geology, v.7, p.341-344.
- Cady, W.M., Wallace, R.E., Hoare, J.M., and Webber, E.J., 1955, The central Kuskokwim region, Alaska: U.S. Geological Survey Professional Paper 268, 132p.
- Capps, S. R., 1923, The Cold Bay District in Brooks, A. H., and others, 1923, Mineral resources of Alaska, Report on progress of investigations in 1921, U. S. Geological Survey Bulletin 739, p.77-116.
- Carden, J.R., Connelly, W., Forbes, R.B., and Turner, D.L., 1977, Blueschists of the Kodiak Islands, Alaska: An extension of the Seldovia schist terrane: Geology, v.5, p.529-533.
- Cargill, D.G., Lamb, J., Young, M.J., and Rugg, E.S., 1976, Island Copper,

- in Sutherland Brown, A., ed., Porphyry deposits of the Canadian Cordillera: Canadian Institute Mining and Metallurgy, Special Volume 15, p.206-218.
- Chivas, A.R., and McDougall, Ian, 1978, Geochronology of the Koloula porphyry copper prospect, Guadalcanal, Solomon Islands: Economic Geology, v. 73, n. 5, p. 678-689.
- Cooper, A.K., Scholl, D.W., and Marlow, M.S., 1976, A plate tectonic model for the evolution of the eastern Bering Sea basin: Geological Society of America Bulletin, v.87, p.1119-1126.
- Cox, Allan and Dalrymple, G.B., 1967, Statistical analysis of geomagnetic reversal data and the precision of potassium-argon dating: Jour. of Geophysical Research, v.72, p.2603-2614.
- Dadisman, S.V., 1980, Map and table showing radiometric ages of rocks in southcentral Alaska: U.S. Geological Survey Open-file Report, in press.
- Dalrymple, G.B., and Lanphere, M.A., 1969, Potassium-argon dating, principles, techniques, and applications to geochronology: W.H. Freeman and Co., San Francisco, California, 258p.
- Damon, P.E. and Mauger, R.L., 1966, Epeirogeny-orogeny viewed from the Basin and Range province: Trans. AIME, v.235, p.99-112.
- DeLong, S.E., Fox, P.J., and McDowell, F.W., 1978, Subduction of the Kula Ridge at the Aleutian Trench: Geological Society of America Bulletin, v.89, p.83-95.
- Detterman, R.L., 1978, Interpretation of depositional environments in the Chignik Formation, Alaska Peninsula: in Johnson, K.M., The United States Geological Survey in Alaska: Accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B62-B63.
- Detterman, R.L., and Hartsock, J.K., 1966, Geology of the Iniskin-Tuxedni region, Alaska: U.S. Geological Survey Professional Paper 512, 78p.
- Detterman, R.L., Miller, T.P., Yount, M.E., and Wilson, F.H., 1979, Generalized geologic map of the Chignik and Sutwik Island quadrangles, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1053A, scale 1:250,000.
- Detterman, R.L., and Reed, B.L., 1980, Stratigraphy, structure, and economic geology of the Iliamna quadrangle, Alaska: U.S. Geological Survey Bulletin 1358-B, 86p.
- Detterman, R.L., Case, J.E., and Wilson, F.H., 1980a, Paleozoic rocks on the Alaska Peninsula: in Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska -- Accomplishments during 1978, U.S. Geological Survey Circular 804-B, p. B85-B86.
- Detterman, R.L., Miller, T.P., Yount, M.E., and Wilson, F.H., 1980b, Geologic map of the Chignik and Sutwik Island quadrangles, Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-1229, scale 1:250,000, in press.
- Engels, J.C., and Ingamells, C.O., 1970, Effect of sample inhomogeneity in K-Ar dating: Geochimica et Cosmochimica Acta, v. 34, p. 1007-1017.
- Fields, E.D., 1977, 1976 Annual report, Alaska Search, Chignik area - Bristol Bay region: written report by Bear Creek Mining Co. to Bristol Bay Native Corp. cited by permission, 44p.
- Garner, E.L., Murphy, T.J., Gramlich, J.W., Paulsen, P.J., and Barnes, I.L., 1975, Absolute isotopic abundance ratios and the atomic weight of a reference sample of potassium: Jour. Research National Bureau of Standards - A. Physics and Chemistry, v. 79A, p.713-725.

- Godwin, C.I., 1976, Casino in Sutherland Brown, A., ed., Porphyry deposits of the Canadian Cordillera, Canadian Institute Mining and Metallurgy, Special Volume 15, p.344-354.
- Grantz, Arthur, 1963, Aerial reconnaissance of the Outer Shumagin Islands, Alaska: U.S. Geological Survey Professional Paper 475-B, p. B106-B109.
- Gustafson, L.B., and Hunt, J.P., 1975, The porphyry copper deposit at El Salvador, Chile: Economic Geology, v. 70, p. 857-912.
- Harrison, T.M., Armstrong, R.L., Naeser, C.W., and Harakal, J.W., 1979, Geochronology and thermal history of the Coast Plutonic Complex, near Prince Rupert, British Columbia: Canadian Journal of Earth Sciences, v. 16, p.400-410.
- Hart, S.R., 1964, The petrology and isotopic-mineral age relations of a contact zone in the Front Range, Colorado: Jour. of Geology, v.72, p.493-525.
- Hillhouse, J.W., 1977, Paleomagnetism of the Triassic Nikolai Greenstone, McCarthy quadrangle, Alaska: Canadian Jour. of Earth Sciences, v. 14, p.2578-2592.
- Hoare, J.M. and Coonrad, W.L., 1978a, Geologic map of the Goodnews and Hagemester Islands quadrangles region southwestern Alaska: U.S. Geological Survey Open-file Report 78-9-B, scale 1:250,000, 2 sheets.
- Hoare, J.M. and Coonrad, W.L., 1978b, Lawsonsite in southwestern Alaska: in Johnson, K.M., ed., The United States Geological Survey in Alaska: Accomplishments during 1977: U.S. Geological Survey Circular 772-B, p.B105.
- Hollick, Arthur, 1930, The Upper Cretaceous floras of Alaska, with a description of the plant-bearing beds by George C. Martin: U.S. Geological Survey Professional Paper 159, 123p.
- Hopkins, D.M. and Silberman, M.L., 1978, Potassium-argon ages of basement rocks from Saint George Island, Alaska: U.S. Geological Survey Journal of Research, v.6, p.435-483.
- Hudson, Travis, Plafker, George, and Lanphere, M.A., 1977, Intrusive rocks of the Yakutat - St. Elias area, south-central Alaska: U.S. Geological Survey Jour. of Research, v.5, p.155-172.
- Hudson, Travis, Plafker, George, and Peterman, Z.E., 1979, Paleogene anatexis along the Gulf of Alaska margin: Geology, v.7, p.573-577.
- Imlay, R.W., 1953, Callovian (Jurassic) ammonites from the United States and Alaska, part 2. Alaska Peninsula and Cook Inlet regions: U. S. Geological Survey Professional Paper 249-B, p.41-108.
- Imlay, R.W., 1975, Stratigraphic distribution and zonation of Jurassic (Callovian) ammonites in southern Alaska: U. S. Geological Survey Professional Paper 836, 28p.
- Imlay, R.W., and Detterman, R. L., 1973, Jurassic paleobiogeography of Alaska: U. S. Geological Survey Professional Paper 801, 34p.
- Imlay, R.W., and Detterman, R.L., 1977, Some Lower and Middle Jurassic beds in Puale Bay - Alinchak Bay area, Alaska Peninsula: American Association of Petroleum Geologists Bulletin, v. 61, p. 607-611.
- Jones, D.L., 1963, Upper Cretaceous (Campanian and Maestrichtian) ammonites from southern Alaska: U.S. Geological Survey Professional Paper 432, 53p.
- Jones, D.L., and Clark, S.H.B., 1973, Upper Cretaceous (Maestrichtian) fossils from the Kenai-Chugach mountains, Kodiak and Shumagin Islands, southern Alaska: U.S. Geological Survey Jour. of Research, v.1, n.2, p.125-136.

- Jones, D.L., and Miller, J.W., 1976, Geologic map of the Alaska Peninsula showing post-Callovian fossil localities: U.S. Geological Survey Open-file Report 76-76, scale 1:500,000.
- Jones, D.L., Silberling, N.J., and Hillhouse, J.W., 1977, Wrangellia - A displaced terrane in northwestern North America: Canadian Journal of Earth Sciences, v. 14, p.2565-2577.
- Jones, D.L. and Silberling, N.J., 1979, Mesozoic stratigraphy -- the key to tectonic analysis of southern and central Alaska: U.S. Geological Survey Open-file Report 79-1200, 37p.
- Kalstrom, Thor N.V. and Ball, G.E., eds., 1969, The Kodiak Island refugium: Its geology, flora, fauna and history: Ryerson Press, Toronto, 262p.
- Kienle, Juergen, and Turner, D.L., 1976, The Shumagin-Kodiak batholith - a Paleocene magmatic arc? in Short notes on Alaskan geology - 1976, Alaska Division of Geological and Geophysical Surveys, Geologic Report 51, p. 9-11.
- Knappen, R. S., 1929, Geology and mineral resources of the Aniakchak District (Alaska): in Smith, P. S. and others, 1929, Mineral Resources of Alaska, Report on progress of investigations in 1926: U. S. Geological Survey Bulletin 797, p. 161-227.
- Krauskopf, K.B., 1967, Introduction to Geochemistry: McGraw-Hill Book Company, New York, 721p.
- Lowell, J.D. and Guilbert, J.M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: Economic Geology, v. 65, p.373-408.
- MacKevett, E.M., Jr., and Plafker, George, 1974, The Border Ranges Fault in south-central Alaska: U.S. Geological Survey Jour. of Research, v.2, p.323-329.
- Mancini, E.A., Deeter, T.M., and Wingate, F.H., 1978, Upper Cretaceous arc-trench gap sedimentation on the Alaska Peninsula: Geology, v. 6, p. 437-439.
- Marlow, M.S., Scholl, D.W., Buffington, E.C., and Alpha, T.R., 1973, Tectonic history of the central Aleutian Arc: Geological Society of America Bulletin, v.84, p.1555-1574.
- Martin, G. C., 1926, The Mesozoic stratigraphy of Alaska: U. S. Geological Survey Bulletin 776, 493p.
- McLean, Hugh, 1979, Pribilof segment of the Bering Sea continental margin: A reinterpretation of Upper Cretaceous dredge samples: Geology, v.7, p.307-310.
- McMillan, W.J., 1976, J.A., in Sutherland Brown, A., ed., Porphyry deposits of the Canadian Cordillera: Canadian Institute Mining and Metallurgy, Special Volume 15, p.144-162.
- Miller, T.P., and Smith, R.L., 1977, Spectacular mobility of ash flows around Aniakchak and Fisher Calderas, Alaska: Geology, v.5, p.173-176.
- Moore, G.W., 1969, New formations on Kodiak and adjacent islands, Alaska: U.S. Geological Survey Bulletin 1274A, p. A27-A35.
- Moore, J.C., 1973a, Cretaceous continental margin sedimentation, southwestern Alaska: Geological Society of America Bulletin, v. 84, p.595-614.
- Moore, J.C., 1973b, Complex deformation of Cretaceous trench deposits, southwestern Alaska: Geological Society of America Bulletin, v. 84, p. 2005-2020.
- Moore, J.C., 1974a, Geologic and structural map of part of the Outer Shumagin Islands, southwestern Alaska: U.S. Geological Survey

- Miscellaneous Investigations Series Map I-815, scale 1:63,360.
- Moore, J.C., 1974b, Geologic and structural map of the Sanak Islands, southwestern Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-817, scale 1:63,360.
- Moore, J.C. and Connelly, William, 1977, Mesozoic tectonics of the southern Alaska margin: in Talwani, Manik and Pitman, W.C. III, eds., Island Arcs, Deep Sea Trenches and Back-Arc Basins, American Geophysical Union, Maurice Ewing Series, v.1, p.71-82.
- Moore, W.J. and Lanphere, M.A., 1971, The age of porphyry type copper mineralization in the Bingham mining district, Utah - a refined estimate: *Economic Geology*, v.66, p.331-334.
- Morton, J.L., Silberman, M.L., Bonham, H.F., Jr., Garside, L.J., and Noble, D.C., 1977, K-Ar ages of volcanic rocks, plutonic rocks, and ore deposits in Nevada and eastern California - Determinations run under the U.S.G.S. - N.B.M.G. cooperative program: *Isochron/West*, no.20, p.19-29.
- Ostenko, M.J. and Jones, M.B., 1976, Valley Copper, in Sutherland Brown, A., ed., *Porphyry deposits of the Canadian Cordillera: Canadian Institute Mining and Metallurgy, Special Volume 15*, p.130-143.
- Oyarzun, J., and Frutos, J., 1974, Porphyry copper and tin-bearing porphyries - a discussion of genetic models: *Physics of the Earth and Planetary Interior*, v. 9, n.3, p. 254-263.
- Packer, D.R. and Stone, D.B., 1974, Paleomagnetism of Jurassic rocks from southwestern Alaska and their tectonic implication: *Canadian Journal of Earth Sciences*, v.11, p.976-997.
- Page, R.W., 1975, Geochronology of late Tertiary and Quarternary mineralized intrusive porphyries in the Star Mountains of Papua New Guinea and Irian Jaya: *Economic Geology*, v. 70, p. 928-936.
- Page, R.W., and McDougall, Ian, 1972a, Ages of mineralization of gold and porphyry deposits in the New Guinea Highlands: *Economic Geology*, v. 67, p. 1034-1048.
- Page, R.W., and McDougall, Ian, 1972b, Geochronology of the Panguna porphyry copper deposit, Bougainville Island, New Guinea: *Economic Geology*, v. 67, p. 1065-1074.
- Palache, Charles, 1904(1910), *Geology about Chichagof Cove* in Emerson, B.K., and others, eds., *Smithsonian Institution Harriman Alaska Series, Geology and Paleontology*, Publication 1993, v. 4, p. 60-90.
- Patton, W.W., Jr., Lanphere, M.A., Miller, T.P., and Scott, R.A., 1976, Age and tectonic significance of volcanic rocks on St. Matthew Island, Bering Sea, Alaska: *U.S. Geological Survey Journal of Research*, v.4, p.67-73.
- Plafker, George, Jones, D.L., and Pessagno, E.A.Jr., 1977, A Cretaceous accretionary flysch and melange terrane along the Gulf of Alaska margin: *U.S. Geological Survey Circular 751B*, p.841-843.
- Pratt, R.M., Rutstein, M.S., Walton, F.W., and Buschur, J.A., 1972, Extension of Alaskan structural trends beneath Bristol Bay, Bering Shelf, Alaska: *Jour. Geophys. Research*, v. 77, p. 4994-4999.
- Reed, B.L., and Lanphere, M.A., 1969, Age and chemistry of Mesozoic and Tertiary plutonic rocks in south-central Alaska: *Geological Society of America Bulletin*, v. 80, p. 23-44.
- Reed, B.L., and Lanphere, M.A., 1973, Alaska-Aleutian Range batholith: geochronology, chemistry, and relation to circum-Pacific plutonism: *Geological Society of America Bulletin*, v. 84, p. 2583-2610.

- Reed, B.L., and Lanphere, M.A., 1974, Chemical variations across the Alaska-Aleutian Range batholith: U.S. Geological Survey Journal of Research, v. 2, p. 343-352.
- Ringwood, A.E., 1977, Petrogenesis in island arc systems in Talwani, Manik and Pitman, W.C., III, eds., Island Arcs, Deep Sea Trenches and Back-Arc Basins, American Geophysical Union, Maurice Ewing Series, v. 1, p.311-324.
- Robinson, R.F., 1975, Reconnaissance mineral survey of the Bristol Bay region, Chignik area, Alaska: written report by Bear Creek Mining Co. to Bristol Bay Native Corp., cited by permission, 13p.
- Scholl, D.W., Greene, H.G., and Marlow, M.S., 1970, Eocene age of the Adak 'Paleozoic (?)' rocks, Aleutian Islands, Alaska: Geological Society of America Bulletin, v.81, p.3583-3592.
- Scholl, D.W., Buffington, E.C., and Marlow, M.S., 1975, Plate tectonics and the structural evolution of the Aleutian-Bering Sea region: in Forbes, R.B., ed., The geophysics and geology of the Bering Sea region: Geological Society of America Special Paper 151, p.1-32.
- Silberman, M.L., Morton, J.L., Cox, D.C., and Richter, D.H., 1977, Potassium-argon ages of disseminated copper and molybdenum mineralization in the Klein Creek and Nabesna plutons, eastern Alaska Range: U.S. Geological Survey Circular 751B, p.B54-B56.
- Sillitoe, R.H., 1972, A plate tectonic model for the origin of porphyry copper deposits: Economic Geology, v. 67, p. 184-197.
- Sillitoe, R.H., 1973, The tops and bottoms of porphyry copper deposits: Economic Geology, v.67, p.799-815.
- Sillitoe, R.H., 1976, Andean mineralization: a model for the metallogeny of convergent plate margins: in Strong, D.F., ed., Metallogeny and Plate Tectonics: Geological Association of Canada, Special Paper 14, p.59-100.
- Spurr, J. E., 1900, A reconnaissance in southwestern Alaska in 1898: U. S. Geological Survey Twentieth Annual Report, pt.7, p. 169-171.
- Stewart, R.J., 1976, Turbidites of the Aleutian abyssal plain: Mineralogy, provenance, and constraints for Cenozoic motion of the Pacific plate: Geological Society of America Bulletin, v.87, p.793-808.
- Stone, D.B., 1977, Plate tectonics, paleomagnetism and the tectonic history of the N.E. Pacific: Geophysical Surveys, v.3, p.3-37.
- Stone, D.B., 1979, Paleomagnetism and paleogeographic reconstruction of southern Alaska, in Sisson, Alexander, ed., 1979, The relationship of plate tectonics to Alaskan geology and resources; Proceedings, Sixth Alaska Geological Society Symposium, Anchorage, 1977, p.K1-K17.
- Stone, D.B. and Packer, D.R., 1977, Tectonic implications of Alaska Peninsula paleomagnetic data: Tectonophysics, v.37, p.183-201.
- Streckeisen, Albert, 1976, To each plutonic rock its proper name: Earth-Science Reviews, v.12, p.1-33.
- Streckisen, Albert, 1979, Classification and nomenclature of volcanic rocks, lamprophyres, carbonatites, and melilitic rocks: Recommendations and suggestions of the IUGS Subcommittee on the Systematics of Igneous Rocks: Geology, v.7, p.331-335.
- Sutherland-Brown, A., 1976, Morphology and classification: in Sutherland-Brown, A., ed., Porphyry deposits of the Canadian Cordillera, Canadian Institute Mining and Metallurgy, Special Volume 15, p. 44-51.
- Templeman-Kluit, D.J., 1976, The Yukon Crystalline Terrain: Enigma in the

- Canadian Cordillera: Geological Society of America Bulletin, v.87, p.1343-1357.
- Theodore, T.G., Silberman, M.L., and Blake, D.W., 1973, Geochemistry and potassium-argon ages of plutonic rocks in the Battle Mountain Mining District, Lander County, Nevada: U.S. Geological Survey Professional Paper 798-A, 24p.
- Turner, D.L., Grybeck, Donald, and Wilson, F.H., 1975, Radiometric dates from Alaska -- A 1975 compilation: Alaska Division of Geological and Geoph. Surveys Special Report 10, 64p.
- Tysdal, R.G., Case, J.E., Winkler, G.R., and Clark, S.H.B., 1977, Sheeted dikes, gabbro, and pillow basalt in flysch of coastal southern Alaska: Geology, v.5, p.377-383.
- Tysdal, R.G. and Case, J.E., 1979, Geologic map of the Seward and Blying Sound quadrangles, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1150, scale 1:250,000.
- U.S. Geological Survey, 1978, Aeromagnetic map of Chignik and Sutwik Island quadrangles, Alaska: U.S. Geological Survey Open-file Map 78-262, scale 1:250,000.
- Wahraftig, Clyde, 1965, Physiographic divisions of Alaska: U.S. Geological Survey Professional Paper 482, 52p.
- Wilson, F.H., Dadisman, S.V., and Herzon, P.L., 1979, Map showing radiometric ages of rocks in southeastern Alaska: U.S. Geological Survey Open-file Report 79-594, 33p., 1 map, scale 1:1,000,000.
- Wolfe, J.A., 1972, An interpretation of Alaskan Tertiary floras: in Graham, A., ed., Floristics and Paleofloristics of Asia and Eastern North America, Elsevier Publishing Company, Amsterdam, p. 202-233.
- Yount, M.E., Cooley, E.F., and O'Leary, R.M., 1978, Sample location map, analytical data, and statistical summary of analyses of rock samples, Chignik and Sutwik Island quadrangles, Alaska: U.S. Geological Survey Open-file Report 78-557, 1 sheet.

Appendix 1 - Hydrofluoric Acid

Leaching Procedure

Whole rock samples were prepared for argon extraction by first treating them with a hydrofluoric acid leaching procedure to remove secondary phases and glass. The procedure is as follows:

1. Place 50-100 gms of crushed 50-100 or 100-200 mesh sample in a plastic beaker and wet with distilled water. Excess water should be decanted off.
2. Add 200-300 ml of 5 to 6% hydrofluoric acid to the sample and allow it to react for 1 to 1.5 minutes with constant stirring. At the end of the allotted time the acid is decanted off.
3. Wash the sample about 5 times, decanting off water and light suspended material with each washing.
4. Transfer the sample to a glass beaker by washing it in with distilled water and decant excess water.
5. Add 200-300 ml of 14% nitric acid and allow to react 30 minutes with occasional stirring.
6. Decant acid and wash with water until fines are removed.
7. Suspend beaker with the sample in water in the bath of an ultrasonic vibrator. Vibrate sample no more than 2 minutes and wash to remove fines.
8. Dry sample and split for potassium and argon analysis.

Appendix 2 - Argon Extraction Procedure

In preparation for argon extraction, a split of the sample is weighed and loaded into a 0.01 mm molybdenum inner crucible. This is then loaded into a degassed (used) outer crucible of 0.05 mm molybdenum and placed in the sample holder on the argon extraction line (Figure A-1). This line is essentially that described by Dalrymple and Lanphere (1969), though with some modifications. A sample take-off and ^{38}Ar tracer are blown on to the line, the sample bottle sealed (copper gasket metal to metal seal) and the line evacuated with the roughing pump. After leak testing, the mercury diffusion pump is started, the associated liquid nitrogen (LN₂) cold trap filled and the bake-out oven started. The bake-out takes overnight, at 300°C, and is done in order to drive off atmospheric argon and other gases adsorbed on the sample and the extraction line and therefore minimize atmospheric contamination in the gas to be collected. With older samples and good conditions, yields of 90% radiogenic argon are common. The samples in this study generally yielded 1 to 40% radiogenic argon; less than 5% is normally considered analytically unacceptable.

The next morning the line pressure is checked with the ion gauge. If the initial pressure reading is 5.0×10^{-5} torr or less the extraction is continued. At this point the ion gauge is degassed using the internal filament and then a final or outgas pressure is obtained. This must be less than 5.0×10^{-7} torr and frequently is less than 1.0×10^{-7} torr. If an acceptable pressure is obtained, the Cu-CuO furnace is outgassed by pumping on it while it heats to 525 to 600°C. This furnace contains pellets of metallic copper and copper oxide and its purpose is to oxidize the gases that are evolved during the extraction, particularly hydrogen. At the end of this period, the bottle valve is closed (Cu-CuO furnace still on) and a LN₂ trap is placed on the charcoal finger, a glass tube containing activated charcoal. The radio frequency (RF) generator and coil are energized and while the bottle is fan cooled on the outside, the molybdenum crucibles and sample are heated by induction. Heating is carried out in stages and generally takes between one half hour and one and one half hours to come to fusion temperature, which is as high as an estimated 1600°C based on optical pyrometry. Quartz-sericite whole rock and volcanic whole rock samples are prone to "puffing" if heated too fast and therefore these take the longest time to bring to temperature. "Puffing" is the result of the sample exploding out of the crucible due to rapid release of adsorbed or absorbed water. Once out of the crucible the sample can't be fused and therefore the extraction is a failure. While the sample is being brought to fusion temperature, the ^{38}Ar tracer is introduced to the line through the break-seal. This break-seal is a thin loop of glass that can be broken with a steel weight manipulated with an external magnet. Once fusion temperature is reached, the sample is equilibrated 10 to 15 minutes and then over a period of about five minutes the RF is turned down and off. During the entire fusion process, the LN₂ trap is maintained full to minimize pressure in the line, which increases the efficiency of the induction heating and prevents readsorption of the released gases on the cooling sample. After the RF is off and the sample has cooled, the LN₂ trap is removed, the charcoal warms and the gases are released. These gases react with Cu-CuO furnace, and the zeolite trap absorbs water and some carbon dioxide. To test for completeness of this "cleanup" a tesla coil is used. Initially a blue glow due to water vapor and carbon dioxide is apparent; upon completion of the reactions a red to pink glow (primarily

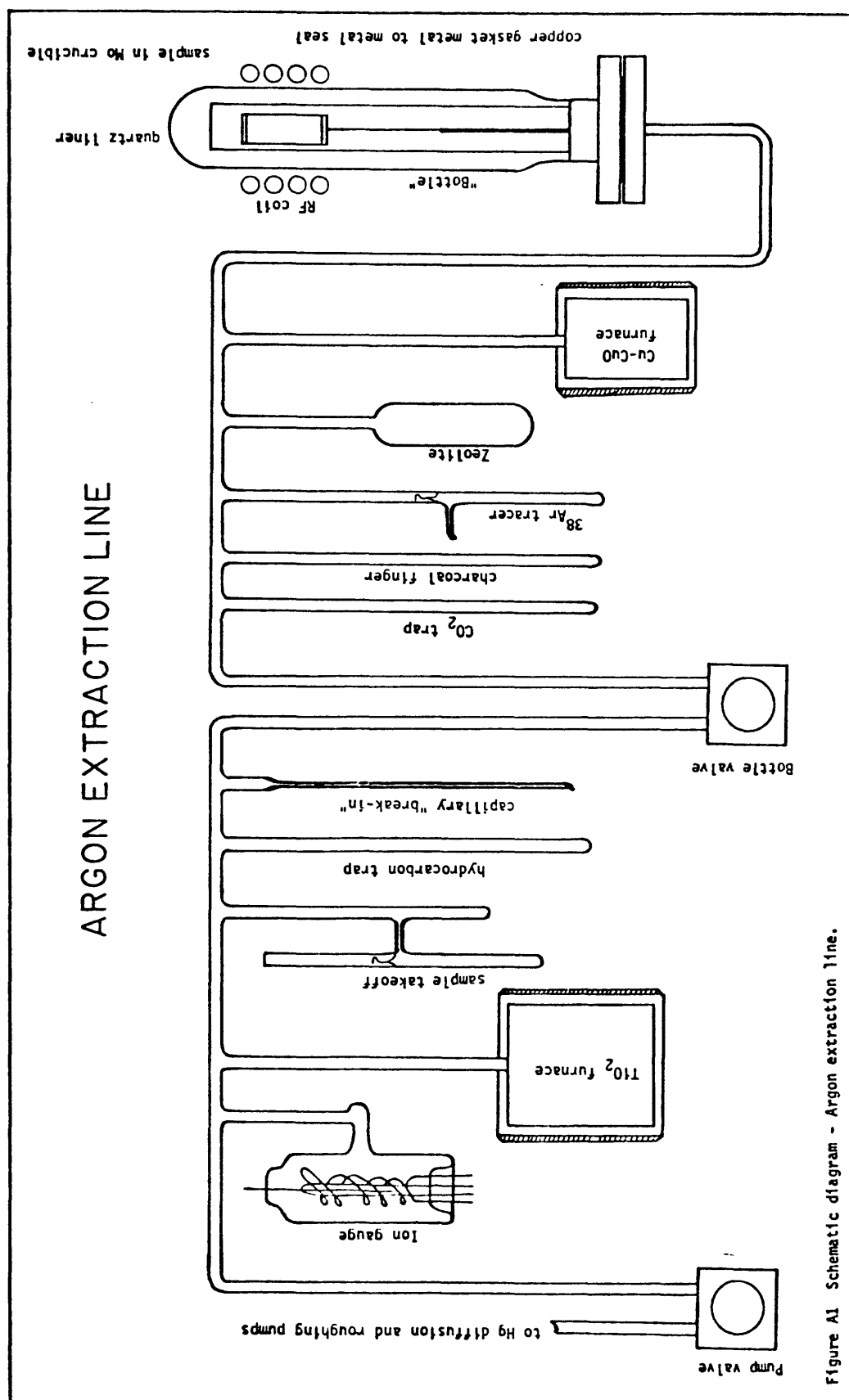


Figure A1 Schematic diagram - Argon extraction line.

from nitrogen) is obtained. In many of the samples used in this study, so much carbon dioxide was generated in the fusion that the zeolite trap was unable to remove it all. If a sample doesn't show evidence of cleaning up after about one half hour, LNG is placed on the carbon dioxide trap to freeze out this gas and water vapor. This trap is an empty tube of glass, unlike the charcoal finger. Therefore the argon doesn't freeze out along with the other gases since the LNG is not of low enough temperature to freeze argon. While the cleanup takes place, the TiO_2 furnace is brought to temperature and degassed at 825 to 900°C.

When the sample cleanup is complete, the pump valve is closed, LNG is placed on the sample takeoff and the bottle valve is opened to cryogenically transfer the sample to the "pump side" of the extraction line. Once the transfer begins, the mercury diffusion pump can be turned off. If the CO_2 trap had to be used, the LNG is maintained on it during the transfer to prevent the simultaneous transfer of the frozen-out carbon dioxide and water. The transfer procedure takes one half hour; upon completion the bottle valve is closed and the LNG trap can be removed from the sample takeoff. The Cu-CuO furnace can also be turned off and the LNG removed from the carbon dioxide trap. The remaining gases on the pump side of the line are allowed to react with the TiO_2 furnace and after about 20 minutes the furnace is turned off and allowed to cool slowly. Most of the "gettering" action of the furnace takes place as it cools; when the cooling furnace reaches 100°C a fan can be used to complete the cooling to room temperature. Fifteen minutes before sample freeze-out LNG may be placed on the hydrocarbon trap, a glass tube identical to the CO_2 trap; otherwise LNG is immediately placed on the sample takeoff and the sample is frozen out. After a half hour, the capillary tube joining the sample takeoff to the extraction line is collapsed with a torch and the sample takeoff removed. LNG is maintained on the sample takeoff and the hydrocarbon trap, if used, during the cutoff procedure. The entire argon sample is now in the sample takeoff and is ready to load on the mass spectrometer. The extraction line is opened and the crucible checked to be certain the sample has been fused; usually only a glass remains, though micas often vaporize leaving only a coating on the crucible.

Appendix 3 - Stratigraphy Shelikof Formation

The Shelikof Formation is only exposed in one small fault slice in the Chignik and Sutwik Island area; it is best seen along Shelikof Strait west of Kodiak Island (particularly Puale Bay) where it was originally described by Capps (1923, p. 97-101). It is of Callovian (Middle Jurassic) age and was considered by Capps (1923, p.101) to be generally correlative with the Chinitna Formation of lower Cook Inlet. The formation is usually divided into three lithologic members; a lower siltstone ranging from 250 to 500 m (800 to 1800 ft) thick; a middle sandstone ranging from near 300 to over 1000m (1000 to 3500 ft) thick and an upper siltstone ranging from 275 to 450m (900 to 1500 ft) thick (Imlay, 1953, p. 49). The lowermost contact of the Shelikof is probably conformable with the Kialagvik Formation, a Middle (Bajocian) Jurassic unit (Imlay and Detterman, 1977, p.609). The upper contact is an unconformity with the Naknek Formation (Imlay, 1975, p. 2).

The lower siltstone member is a gray sandy siltstone that becomes harder and darker upsection. Sandy interbeds from a few centimeters to 70m thick are common, and thin beds of white to yellowish brown material, interpreted as volcanic ash are fairly abundant and distinguish this unit from the siltstones in the underlying Kialagvik Formation (Imlay, 1953, p. 49). Limestone concretions are abundant in many places as are ammonite fossils (Imlay, 1953, p. 49).

The middle member of the Shelikof is dominantly a massive gray-green sandstone with interbeds of siltstone and lenses of plutonic pebble conglomerate (Imlay, 1953, p. 49). It is concretionary in many places (Capps, 1923, p. 98). Imlay (1953, p. 57) mentions the occurrence of some volcanic cobbles in some conglomerates.

The upper Shelikof is a massive black shale containing some limestone lenses and nodules. It is poorly fossiliferous and may be sandy or calcareous in places (Capps, 1923, p. 97).

Fossils generally occur throughout the Formation in calcareous concretions and are generally ammonites though belemnites, pelecypods, brachipods, crustaceans and plant fragments have been reported (Imlay, 1953, p. 58-59).

The fault slice exposing the Shelikof Formation in the Chignik area occurs north of Chignik Bay at the head of Through Creek (Figure 2). The lower and upper members are exposed here, and consist chiefly of black shales with calcareous concretions and layers, and abundant ammonites.

The 800 to 2000m thickness of the Callovian (Shelikof and equivalents) rocks implies rapid subsidence of the sea floor and an abundant supply of sediment (Imlay, 1953, p.57). This sediment supply Imlay (1953, p. 57) believes came from a mountainous source to the north and northwest of the present outcrop area, based on the southward thinning of massive sandstones and a general decrease in grain size southward. The nearshore environment of the sediments he believes is shown by the pebbly character of some beds and the local occurrence of granitic boulders 0.7m (2 ft) in diameter. In the lower siltstone member, thin seams of apparent volcanic ash imply deposition below wave base and indicate active volcanism at the time; Imlay (1953, p. 57) also implied that ash may be the source of the greenish color in some of the sandstones. He believes that the deposition of the Shelikof took place along a steep slope in a major ocean basin, rather than in a shallow arm of the sea such as Cook Inlet.

The faunal assemblages described by Imlay (1953) led him to interpret the depositional environment of the Shelikof Formation as rather deep water, yet quite nearshore based on the lithologic assemblage. The sediments also show intraformational unconformities, as evidenced by scouring seen in the lower siltstone and some unconformable boundaries between the lower siltstone and the middle sandstone members (Imlay, 1953, p. 57).

Naknek Formation

The Naknek Formation is well exposed in the study area, and in general along the Alaska Peninsula. The Naknek Formation (Series) was named in 1898 by Spurr (1900) after type occurrences on Naknek Lake and in the Katmai area. The formation is Upper Jurassic (earliest Oxfordian to early Tithonian) in age and in general consists of arkosic sandstone, siltstone, conglomerate and claystone (Imlay and Detterman, 1973, p. 10). The formation is known to extend from the Talkeetna Mountains in south-central Alaska to the Port Moller area in the southwestern Alaska Peninsula. According to Imlay and Detterman (1973, p. 15), the Naknek Formation always unconformably overlies older units with rocks of late Callovian to early Oxfordian age (150-165 m.y.) missing below it.

Within the study area, the Naknek Formation has a number of different lithologies. The lower Naknek is usually a pale green fine-grained sandstone with thin laminae of magnetite, some arkosic sandstone, and some coarse cobble conglomerate. The conglomerate is composed primarily of granitic clasts with minor metamorphics in an arkosic matrix, and is lithologically similar to many of the conglomerates in the younger Chignik Formation. The arkosic sandstones are composed primarily of quartz and feldspar; hornblende may make up 5 percent of the rock with biotite slightly less common (Burk, 1965, p. 36). Burk (1965, p. 36) reported that feldspar is dominant in the coarser-grained rocks, whereas quartz is dominant in the finer-grained (siltstone) rocks.

The upper Naknek formation tends to be a dark olive green siltstone, mudstone and sandstone with abundant *Buchia* pelecypods, belemnites and other mollusks (see Atwood, 1911, p. 33-38; Martin, 1926, p. 203-218; Imlay and Detterman, 1973, p. 25). Plant fragments have also been reported (Spurr, 1900; Martin, 1926, p. 211; Burk, 1965, p. 30) though no major studies or collections have been made of these. Thin calcareous layers are often found in the upper Naknek; these layers often have large lateral extent relative to their thickness. In addition, horizons with abundant calcareous concretions are also present in the Naknek as well as in the Chignik Formation.

The lithology of the Naknek Formation in general indicates a nearshore environment of moderate to high energy. The conglomerates probably are indicative of braided stream or high-energy beach environments, based on the large size and well-rounded nature of the cobbles. This, plus the presence of fresh angular hornblende and biotite in the arkosic sands is probably indicative of short transport and rapid deposition (see Detterman and Hartsock, 1966, p. 54). R.L. Detterman (written communication, Jan., 1979) interprets the lower sand-rich part of the Naknek as representing a nearshore high-energy environment, whereas the upper silt-rich part probably represents slightly deeper water deposits. Burk (1965, p. 39) reported that in general the Naknek is finer grained to the southwest; possibly due to greater distance from the apparent source in the present

day Alaska-Aleutian Range batholith. Knappen (1929, p. 184) and Burk (1965, p. 39) note that the sedimentary structures seem to indicate a south-to-southeast transport direction for the sediments of the Naknek.

Staniukovich Formation

The Staniukovich Formation is found generally in the northern portions of the Chignik and Sutwik Island map area, and to the southwest of the map area at the type locality, Staniukovich Mountain. Atwood (1911, p. 38) first described the Staniukovich as a series of shales that were lithologically distinct from the underlying Naknek Formation. Atwood considered the formation to be of Early Cretaceous age and possibly conformable with the Naknek. Atwood's (1911) age determination was based on fossil collections of Buchia crassicollis and B. piochii. B. crassicollis and B. piochii have not been found in the Naknek Formation. Burk (1965, p. 39-42) recognized a much wider extent of the Staniukovich based, in part on its lithologic character and in part on the contained fossils. Burk (1965, p. 39-40) in re-examining the type section described it as "fine to medium grained feldspathic sandstones and arkoses which weather to a characteristic tan or yellowish brown and contain very abundant large Buchia." Burk (1965, p. 43) discusses the fossil data from the Staniukovich Formation and concludes that the age range of the formation is from Kimmeridgian (155 m.y., Late Jurassic) to Valanginian (125 m.y., Early Cretaceous). This age range, at its oldest, overlaps that of the Naknek Formation and implies that the basal Staniukovich is equivalent to the younger parts of the Naknek. Fossils other than Buchias found in the Staniukovich include limited belemnites, rare Inoceramus and carbonaceous plant debris (Burk, 1965, p. 42).

Lithologically, the Staniukovich consists of about 600m (2000 ft) of

"sandstones and siltstones (that) are composed almost exclusively of subangular grains of feldspar and quartz. Hornblende and biotite are by far the most dominant accessory minerals, each commonly constituting about 5 per cent of the rock and together as much as 15 per cent. (Burk, 1965, p. 42)."

Rock fragments are rare, although Burk (1965, p. 42) reported rare felted volcanic fragments and possible chert in coarser-grained rocks. In addition he reported that the biotite is commonly chloritized and that traces of epidote and garnet (?) have been recognized (Burk, 1965, p. 42).

Environmentally, the Staniukovich and the Naknek appear to have been deposited under similar conditions from a probably identical source terrane. Because of this and because parts of the Naknek weather the same characteristic buff to yellowish color as the Staniukovich, and because parts of the Staniukovich weather gray-green as does the Naknek, it often proved impossible to distinguish the two formations in the field. The different lithologies reported by Atwood (1911, p. 38) and by Burk (1965, p. 39-42) in the type locality of the Staniukovich only further confuse the identification of the formation. In the author's personal experience, it was found that only with expertise in the identification of the various Buchia species could the Staniukovich Formation be reliably identified; therefore it should not be considered a separate formation, but possibly an upper member of the Naknek.

Herendeen Limestone

The Herendeen Limestone has been recognized in limited areas of the Chignik region. The formation was originally described by Atwood (1911) in the Port Moller-Herendeen Bay area south of the Chignik and Sutwik Island quadrangles (Figure 1). Burk (1965, p.45) re-examined the type exposures and expanded Atwood's description. The description that follows is from Burk (1965, p.45-48); this writer was not able to examine exposures of the Herendeen Limestone in the field.

Lithologically, the Herendeen Limestone is a light gray to gray, dense arenaceous limestone and calcareous sandstone. Maximum thickness is 150m (500 feet); in the Chignik region it is only 30m thick (Detterman and others, 1980b). Clasts are well-sorted, angular to subrounded quartz and feldspar; quartz is about twice as abundant as feldspar. Hornblende and biotite are the most common accessory minerals. The noncalcareous material constitutes from one quarter to three quarters of the rock at any particular locality. Except for the large component of calcareous material, the Herendeen Limestone is very similar to the Staniukovich Formation.

The calcareous portion of the formation is composed of fragments and prisms of Inoceramus shells. Burk (1965, p.47) mentions that in the past B. crassicollis was reported from the Herendeen Limestone; he believed that these were actually from the Staniukovich Formation. Therefore, Inoceramus is the only fossil known from the Herendeen Limestone. Burk assigned a latest Valanginian age to the Herendeen Limestone based on its conformity with the Staniukovich and its distinct lithologic difference from the overlying Chignik and Hoodoo Formations.

Stratigraphically, the Herendeen Limestone conformably overlies the Staniukovich Formation. The contact is gradational over a short vertical distance. Burk suggested that the Herendeen Limestone might be considered a member of the Staniukovich due to their very great lithologic similarity; apparently, the only important difference is the presence of abundant Inoceramus in the Herendeen Limestone. In view of this author's suggestion that the Staniukovich might be considered a member of the Naknek, might the Herendeen Limestone be a facies of the Naknek?

The Herendeen Limestone is unconformably overlain by the Upper Cretaceous Chignik Formation. The Chignik also unconformably overlies the Naknek and Staniukovich Formations, therefore the areal distribution is presently limited due to cutout and no accurate estimate of its original thickness and distribution can be made.

Shumagin Formation

The Shumagin Formation is an Upper Cretaceous (Maestrichtian?) flysch sequence found on the Outer Shumagin Islands and on the Sanak Islands. Equivalent units are found on Kodiak Island (Kodiak Formation) and throughout southern Alaska in the "slate and graywacke belt" (Plafker and others, 1977). It was first described and named by Burk (1965, p.63-72) from exposures in the Shumagin and Sanak Islands. Inoceramus kusiroensis is probably of Maestrichtian age and is known from the Kodiak Formation; an apparently similar related species(?) has been collected from the Shumagin Formation in the Shumagin Islands (Jones and Clark, 1973, p. 134) and this formation has also been assigned a Maestrichtian age. An upper age limit of earliest Tertiary is provided by the radiometric ages on the plutonic rocks of the Kodiak-Shumagin plutonic series that intrude the

Shumagin Formation (Table 2). Stratigraphic control on the Shumagin Formation is lacking; the base is exposed in a small area on Long Island in the Sanak Islands (Moore, 1973a, p. 597). Here an unnamed, undated pillow lava, bedded chert and graded-bed sequence conformably underlies the Shumagin. The top of the Shumagin has not been recognized and may not be exposed. The Shumagin Formation is not known to crop out in the study area, yet a description of it is important in establishing the tectonic framework of the Alaska Peninsula, and in particular the study area.

Interbedded dark-gray sandstones and mudstones that have undergone zeolite facies metamorphism characterize the lithology of the Shumagin Formation. Moore (1973a, p. 598-603) describes the formation in some detail, and a brief summary of his work follows.

Two end member lithologies and a continuous spectrum of intermediate rock types are found. Massive, evenly bedded, medium-grained sandstone beds, ranging from less than 1m to greater than 20m in thickness, but usually 1 to 5m thick comprise one end member. Moore (1973a, p.598) reported these have high sandstone/shale ratios, very poor to nonexistent grading and no internal structure. Basal contacts are sharp whereas the contact with overlying mudstones is generally "distinct." Mudstone breccia is often seen at the base of or within the massive beds and is composed of clasts ranging from about 3 to 30cm in diameter. The massive sandstones are well indurated, are medium-light to medium-dark gray in color, and weather to lighter gray, green or brown hues.

The second end member lithology is characterized by thin graded beds, usually to 20cm thick and evenly bedded. The grading is from fine sand or silt upwards to clay-size particles. Moore (1973a, p. 599) reported sharp upper and lower contacts. Sandstone/shale ratios are always less than one, usually 1:3 or 1:4. These units are medium to dark gray or grayish-black on fresh surfaces; weathering to lighter grays and buffs.

These two end member lithologies account for 70 percent of the variation of the Shumagin Formation. An intermediate type accounts for almost all the rest of the formation. This intermediate type, by definition, includes all mixtures of the two end members.

"All variations exist, making the description of an average bed difficult. However, a typical intermediate bed may be 20 to 60cm thick with basal sandstone of medium-fine grain size, and a sandstone/shale ratio of 1:1 to 6:1. Generally the beds show well-developed internal and external structures (Moore, 1973a, p. 599)."

Rare conglomerates, with pebbles of calcareous siltstone and sandstone, chert, and volcanic and plutonic rocks in variable proportions, and greenish-gray volcanic ash beds make up the remainder of the Shumagin Formation; these constitute less than 0.5 percent of the rocks. Moore (1973a, p. 603) considers the massive sandstones to represent Bouma "A" intervals and the thin graded beds represent Bouma "C-D-E" or "D-E" intervals (See Bouma, 1962).

Sandstone of the massive and intermediate lithologies is primarily composed of volcanic lithic fragments, plagioclase and quartz. Volcanic lithic fragments comprise 51 percent of the framework grains and Moore (1973a, p. 601) estimates 44 percent of the total rock volume. These volcanic fragments are pilotaxitic-textured andesites. Considering the contributions of feldspar, heavy minerals and clays of volcanic origin, and

the volcanic lithic fragments, Moore (1973a, p.602) estimates, that probably 60 percent of the rock is of volcanic origin. The remainder is made up of half plutonic lithic fragments and half sedimentary lithic fragments with very minor metamorphic lithic fragments. The thin graded beds are compositionally quite similar to the massive sandstone.

Moore (1973a, p. 610) suggests that the Shumagin Formation was derived from an active, predominantly andesitic, volcanic terrane from which some plutonic and sedimentary rocks were also being eroded. There is no agglomerate or volcanic breccia in the Shumagin, therefore a volcanic source within the depositional basin is unlikely. Because the formation apparently contains no calcareous micro- or nanofossils, Moore (1973a, p. 608) suggested that this indicates deposition below the calcium carbonate compensation depth. The lack of shallow-water features and the evidence for turbidity current deposition led him to propose that the depth of deposition was greater than 1000m, or at abyssal depths. Paleocurrent analysis in the Shumagin indicates that the predominant direction of sediment transport in the Shumagin Islands was southwestward, whereas in the Sanak Islands the direction of transport was west-northward (Moore, 1973a, p.605-607).

Moore (1973a, p. 610) suggested that if the age assignment of the Shumagin is correct, then it is an age equivalent of the Chignik and Hoodoo Formations. This implies that all are facies of one another. Difficulties with this interpretation include: 1. the less abundant volcanic lithic fragments in the Chignik, which should have been deposited close to the presumed volcanic source area, though the amount of volcanic debris does increase upward in the Chignik Formation; 2. the apparently non-volcaniclastic nature of the Hoodoo which is also close to the supposed volcanic source region; and 3. the lack of a known suitable source terrane for the overwhelmingly volcanic composition of the Shumagin. As yet, no volcanic rocks of sufficiently old age to be a source for the Chignik, Hoodoo or Shumagin Formations have been found on the Alaska Peninsula. Burk (1965, p. 59) and Moore (1973a, p. 610) suggested that the missing volcanic source terrane may be unrecognized among the later Cenozoic volcanic rocks or, that the source terrane is buried under the Nushagak-Bristol Bay Lowland northwest of the present volcanic arc. Reed and Lanphere's (1974) 85-59 m.y. plutonic event represents igneous activity within the expected time interval. Burk (1965, p.69-71) recognized the difficulty of correlating the Shumagin and the other Upper Cretaceous Formations of the Peninsula and suggested that the Shumagin may be somewhat older than the other formations. This still leaves the question of its volcanic source region an unanswered enigma.

Chignik Formation

The Chignik Formation is a major Upper Cretaceous unit seen throughout the Chignik and Sutwik Island area. Recently, Mancini and others (1978) have attempted to demonstrate that it may be equivalent in age to the Hoodoo Formation, which is also widespread in the study area. However, R.L. Detterman and D.L. Jones (written communication, Jan. 1979) state that megafossil data indicate that the Hoodoo in general is younger than the Chignik.

The Chignik Formation was first described by Atwood (1911, p. 41) from a type section exposed in Whalers Creek near Chignik Lagoon, and from other exposures on the shores of Chignik Lagoon and Chignik Bay. The Chignik

Formation consists of approximately 250m (800 ft) of sandstones, shales, conglomerate and coal. Fossil assemblages include Inoceramus and other pelecypods, ammonites and an excellent floral assemblage.

Burk (1965, p. 50) studied the Chignik Formation and determined that the basal portion of the formation was usually non-marine. He separated this unit as the Coal Valley Member based on type exposures at Herendeen Bay. The Coal Valley Member consists of carbonaceous to lignitic shales, siltstones, sandstones, and conglomerate, locally bentonitic and weathering to typical orange and reddish-brown colors. The conglomerate contains largely volcanic, granitic, and chert clasts (Burk, 1965, p. 52). Mancini and others (1978, p. 438) describe the conglomerates as alluvial fan deposits; they interpret the Coal Valley Member as a facies of the Chignik, not necessarily basal. Detterman (1978, p. B-62) shows in a measured section on the shore of Chignik Lagoon that the Chignik is depositionally cyclic and he documents four cycles in the measured section. Fossils found in the Coal Valley member include pollen and spores (Mancini and others, 1978, p. 438) and abundant carbonaceous plant fossils (Hollick, 1930; J.A. Wolfe, oral communication, 1978).

The main portion of the Chignik Formation consists of upwards of 500m of well-bedded, fairly homogeneous argillaceous sandstones and siltstones. The sandstones are composed of subangular to subrounded grains consisting of feldspar, quartz and lithic fragments. Lithic fragments consist predominantly of fine-grained sediments and a lesser amount of volcanic rocks. Unlike the older sedimentary units in the region, hornblende is a scarce accessory, but chloritized biotite may represent 5 percent of the rock. Calcite is common as cement or replacing feldspar grains; this is most abundant in rocks rich in plant remains (Burk, 1965, p. 52). "Trough crossbedding, ripple lamination and bioturbation are common" and these sedimentary structures, along with the pollen spores, occasional phytoplankton and open marine ammonites and bivalves indicate the Chignik was deposited in an inner-neritic, continental shelf environment (Mancini and others, 1978, p.439)."

Difficulty in distinguishing the Chignik Formation from the underlying formations has been mentioned in the literature (Knappen, 1929; Burk, 1965) and occurred often in the field in the Chignik and Sutwik Island area. The conglomerates are very similar to those in the Naknek; the abundant volcanic clasts in the conglomerates, and the volcanic lithic fragments in the sandstones can also be quite similar to those in overlying Tertiary formations. In many ways, the main body of the Chignik is lithologically transitional between the earlier and later units. In the field, the Chignik usually can be distinguished from the Naknek by the greater volcanic component in the Chignik. Granitic and some metamorphic clasts are still common in Chignik conglomerates though, and this criterion can be used to distinguish the Chignik from the Tertiary formations.

The Upper Cretaceous Chignik Formation unconformably overlies the Upper Jurassic to Lower Cretaceous Naknek, Staniukovich, and Herendeen Limestone Formations, often cutting out the Staniukovich, Herendeen Limestone, and parts of the Naknek. Where the Chignik Formation, including the Coal Valley Member, is best developed, the underlying section is most complete; this may indicate

"that the Chignik Formation was deposited on an erosion surface cut into broad folds rather than on a regionally tilted crust,

and that the initial nonmarine Chignik deposits filled the synclinal depressions while the adjacent anticlinal arches were being eroded (Burk, 1965, p. 57)."

Burk (1965, p. 56) assigned a Campanian (Late Cretaceous) age to the Chignik based on the Inoceramus fossils present. Recently, Mancini and others (1978, p. 438) have shown the Chignik to range upward into the early Maestrichtian, based on pollen recovered from both the Coal Valley Member and the main body of the Chignik. A granitic cobble from a Chignik exposure across Chignik Lagoon from Detterman's measured section has yielded a 89.8 ± 1.60 m.y. potassium-argon date on chloritized biotite (Table 4, sample 77AWs 186). This is taken as a minimum age.

Hoodoo Formation

The Hoodoo Formation is an Upper Cretaceous Formation distributed in general, throughout the study area. The unit was originally named and described by Burk (1965, p. 59-63) from exposures southeast of Mt. Hoodoo in the Port Moller quadrangle (Figure 1, southwest of Chignik. The formation consists of more than 600m (2000 ft) of "black to dark-gray, well-bedded siltstone and silty shale, with some claystone, clay shale and small amounts of very fine-grained sandstone" in the type section (Burk, 1965, p.60). The type section is incomplete and disturbed, and no complete section has been described in the literature. Mancini and others (1978) consider the Hoodoo to be a distal facies of the Chignik and therefore age-equivalent whereas Burk (1965, p. 62) considers it to be the upper, younger part of an Upper Cretaceous transgressive sequence including the Chignik and Hoodoo Formations. According to R.L. Detterman and D.L. Jones (written communication, Jan. 1979) fossil data from ammonites and pelecypods support Burk's interpretation.

In general the Hoodoo Formation is composed of a black to dark-gray poorly fossiliferous well-bedded siltstone and shale. Outcrop exposures are generally poor, as these rocks tend to weather easily. However, where exposures are good, for example along the southwestern shore of Chignik Bay and along the margins of the Devils batholith, graded bedding is visible in thin layers of large lateral extent. On the west shore of Chignik Bay, between Lumber and Lake Bays, the Hoodoo exposures are of gray-green sandstone layers generally about 0.5m thick but up to 1.5m thick, interbedded with and grading into green-gray siltstone layers 20 cm thick, but ranging up to 1 m in thickness. This outcrop also has some intervals of the more typical, rhythmically-layered shale and siltstone characteristic of the Hoodoo. Just south of Jack Bay, the Hoodoo exposures are thin-bedded shales and siltstones rhythmically interlayered and having large lateral extent. Normal faulting is common along this exposure.

In many places, dark-gray to black shales and siltstones are seen and mapped as Hoodoo; often these are interbedded with Chignik-appearing rocks (Plate 2, Black Creek and Bluff Creek areas) and some confusion results. Often the rhythmic layering and graded bedding which characterize the Hoodoo are not seen, because of poor exposure. In addition, the overlying Tertiary units contain dark shales that can be confused with the Hoodoo; therefore field identification often has a degree of uncertainty.

Fossil occurrences in the Hoodoo are quite rare and most collections have Inoceramus schmidtii as the prime species. Mancini and others (1978, p. 439) report a Campanian outer-neritic to bathyal foraminiferal assemblage collected from the Hoodoo and Jones and Miller (1976) report two species of

Amminoids. Burk (1965, p.62) and Mancini and others (1978) consider the Hoodoo to be of Campanian to early Maestrichtian age.

In general the Hoodoo has the appearance of a distal turbidite (Bouma and Hollister, 1973, p. 89). Both "A" and "B" divisions of the Bouma turbidite facies model are missing and the "C" division is often poorly developed. (see Blatt and others, 1972, p.122-124) If it can be assumed the Upper Cretaceous coastal margin was at all similar to that of the present southeast side of the Alaska Peninsula, turbidite deposition could possibly occur very near-shore and the present pattern of close juxtaposition of the Chignik and Hoodoo Formations represents minor, if any, telescoping of the section by faulting. X-ray diffraction analysis of the clay minerals from silts of the Hoodoo indicate a low grade metamorphism as there are no mixed-layer clays (P.D. Nadeau and R.C. Reynolds, oral communication, 1979). This may be due to burial in an active volcanic terrane.

Tolstoi Formation

The Tolstoi Formation is an Eocene(?) volcanoclastic unit widespread on the Alaska Peninsula. Burk (1965, p. 83-84) originally defined it from type exposures "along the east shore of Pavlof Bay, north of Cape Tolstoi and Tolstoi Peak" (Figure 1). He considered it to be Paleocene to Eocene in part based on floral assemblages collected from it.

The formation consists of 1000 to 1500m (3000 to 5000 ft) of black siltstones with interbedded volcanoclastic sandstones and conglomerates, flows, sills and agglomerate. A rich fossil floral assemblage has been collected from these rocks and Eocene marine invertebrates have also been recovered (Burk, 1965, p. 83). Burk (1965, p.83-101) mentioned that often the Tolstoi is difficult to distinguish from the overlying Stepovak Formation and that the black to dark-gray siltstones from the underlying Hoodoo have at times been erroneously included in the Tolstoi. R.L. Detterman (oral communication, Nov., 1978) has recommended abolishing the Stepovak Formation and mapping all the Eocene (Oligocene(?)) sediments on the Alaska Peninsula as Tolstoi Formation.

The black siltstones in the Tolstoi are generally nonmarine rocks as distinguished from those of the Hoodoo. Burk (1965, p.84) describes them as commonly very sandy and carbonaceous, sometimes containing pyrite crystals. The sandstones and conglomerates of the Tolstoi consist essentially of mafic volcanic fragments, though chert pebbles are seen in some conglomerates. Rounding varies from angular to subrounded, and sorting is almost universally poor. The rocks of the Tolstoi tend to have a strong green to black cast, though Burk (1965, p. 84) reported the presence of "a characteristic, pale pebble to granule conglomerate.... of pastel (usually greenish) volcanic clasts, with a large part of the finer constituents eroded away." This pale conglomerate crops out on the ridge west of Sleepy Creek (Plate 2), interbedded with black siltstones of the Hoodoo (?) and Tolstoi Formations. Apparently, at this locality it forms the base of the Tolstoi.

The Tolstoi exhibits a general reverse grading, and angular volcanic breccia is much more common in the upper half of the formation (Burk, 1965, p. 98).

During the summers of 1977 and 1978 extensive collections of floral assemblages of the Upper Cretaceous and Tertiary units in the study area were made by J.A. Wolfe and R.L. Spicer. Work is underway on these fossil

determinations. Prior work by Wolfe (1972, p.205-206) indicates an early Paleocene flora in the Tolstoi of probable subtropic provenance. Eocene floras of southern Alaska are indicative of a tropical or near-tropical climate reflecting a warmer climate than in the late Paleocene. However, according to R.W. Allison (oral communication, 1979) no evidence exists among known mega- or microfossil assemblages for a Paleocene or even early Eocene age assignment to the Tolstoi. This assertion and the radiometric dates on apparently interbedded volcanic rocks (presently considered Meshik Formation, see Tables 4,5, and 6) bring into question Wolfe's assignment of the fossil floras to the Paleocene. If the floras of the Tolstoi are Eocene, rather than Paleocene as Wolfe (1972) suggests, a much simpler tectonic interpretation is possible. Paleomagnetic (Stone and Packer, 1977) and other geologic interpretations indicate that there probably had been a northward movement of the rocks of the Alaska Peninsula between Paleocene and Eocene time, rather than southward as Wolfe (1972, p.206) suggested.

Channeling into the Hoodoo by the Tolstoi was seen in the area of Cape Kunmik (oral communication, R.L. Detterman, 1978) and the Tolstoi unconformably overlies the Naknek in the area south of Chignik Lake (Plate 2). The upper boundary of the Tolstoi is difficult to place; where present, the Stepovak Formation is conformable and Burk (1965, p. 85) mapped these two formations together as the Beaver Bay Group. The Meshik Formation overlies the Tolstoi in the Chignik Bay area and northward. The Meshik has been mapped by our field party as a predominantly volcanic unit. In any case, the top of the Tolstoi is difficult to distinguish in the field. Isotopic work reported herein indicates a number of late Eocene to Oligocene volcanic centers within the Tolstoi.

Stepovak Formation

The Stepovak Formation is a Late Eocene to Oligocene, andesitic (?) volcanic and volcanoclastic unit conformably overlying the Tolstoi Formation. Lithologically it is a continuation of the Tolstoi, though Burk (1965, p.88) reported that the amount of coarse volcanic debris (conglomerates, agglomerates and breccia) is less than that in the Tolstoi and bedding is more even. Stratigraphically, the Stepovak is thought to be equivalent to the Meshik Formation and in field mapping it is often easy to confuse the Tertiary units. Palache (1904), while on the 1899 Harriman hunting expedition was first to examine and name rocks of the Stepovak in the area of Chichagof Bay (Port Moller quadrangle and Figure 1). R.L. Detterman (oral communication, Nov., 1978) has recommended abolishing this formation name.

The type Stepovak section consists of more than 2100m (7000 ft) of interbedded volcanic sandstones and conglomerates with nearly 300m (1000 ft) of interbedded black siltstone containing abundant calcareous concretions (Burk, 1965, p.86). Burk (1965, p.86) reported that "thick conglomerates are rare and angular, poorly bedded volcanic debris is uncommon except in the lower 2000 ft" (600m). The exposure examined by the author with J.A. Wolfe and R.L. Spicer on Boulder and Fox Bays in the Stepovak Bay quadrangle consisted almost entirely of volcanic flows, rubble flows and volcanic breccia with rare siltstone and rarer sandstone; this lithology seems at some variance with the measured section described by Burk (1965, p.205-208) at the same locality. Experience during the summers of 1977 and 1978 indicates that at least in the study area, the Stepovak is

generally a volcanic unit, consisting of andesitic rubble flows, waterlaid tuffs, volcanic breccias, and lahars. It is virtually indistinguishable from the Meshik Formation and R.L. Detterman (oral communication, Nov., 1978) has proposed that the volcanic portions of the Stepovak formation be included in the Meshik as one unit and that the sedimentary portions of the Stepovak be mapped as the Tolstoi Formation.

Meshik Formation

The Meshik Formation was named by Knappen (1929, p.198) from exposures along the Meshik River and around Meshik Lake (Figure 2). He described a reverse-graded andesitic volcanic section including interbedded clay, fine sand, volcanic ash, and coarse agglomerate (Knappen, 1929, p.198-199). The clays are bentonitic and the lower part of the formation contains many paleosols. Knappen (1929, p.200) noted abundant silicified and carbonized plant fragments in the lower sediments, including silicified stumps and tree trunks up to 15 inches (0.4m) in diameter. The upper part of the formation was composed entirely of coarse volcanic materials including numerous flows (Knappen, 1929, p.198). Based on lithologic correlation with the Tolstoi and Stepovak Formations, Knappen (1929, p.201) believed the Meshik was of Oligocene to early Miocene age. According to Burk (1965, p.99), the Meshik rests conformably on the Paleocene to Eocene Tolstoi Formation and is overlain unconformably by Pliocene and younger volcanic rocks or alluvial and glacial debris. Burk (1965, p.99) estimated the formation to be 5000 ft (1500m) thick. It was distinguished by Burk (1965, p.99) from the underlying Tolstoi by the brighter colors, brown and yellow "with local pastel tints of green, red, and purple." The Meshik is thought to be equivalent in age to the Stepovak Formation though no fossils have been collected from the Meshik. As a result of our work in the Chignik area, R.L. Detterman (oral communication, Nov., 1978) has proposed mapping the Meshik Formation as an entirely volcanic unit and including the sediments in the Tolstoi Formation. Potassium-argon work to date has indicated that some of the volcanic rocks included in the Meshik are of late Eocene to Oligocene age.

Bear Lake Formation

Burk (1965, p. 89) named the Bear Lake Formation after a sequence of Middle to Late Miocene sandstones, conglomerates, and minor siltstone exposed along the eastern shore of Port Moller and in the mountains around Bear Lake. Burk (1965, p.89) considered the unit to be at least 5000 ft (1500m) thick. This unit is distinctive with respect to the other Tertiary units in the study area owing to the "abundance of nonvolcanic clasts, in the greater rounding and better sorting of the grains, and in the poor consolidation of much of the rock" (Burk, 1965, p.91). R.L. Detterman (oral communication, 1979) suggests these sedimentologic features are probably due to the reworking of older units, as does Burk (1965, p.91). The author has seen few exposures of the Bear Lake Formation; the bulk of this description is based on Burk (1965) and Detterman and others (1980b).

The type section, designated by Detterman and others (1980b), consists of 1525m of inner neritic and nonmarine sandstone, conglomerate, siltstone, shale, and thin coal beds. A thickness of 2400m has been encountered in drilling (Brockway and others, 1975). The Formation is locally abundantly fossiliferous, containing pelecypods, gastropods, and echinoids of late Miocene age (Detterman and others, 1980b). Burk (1965, p.91) reported the

fossiliferous beds were most common in the upper parts of the formation. The type section is rhythmically bedded in units 1 to 10m thick with individual beds ranging from 6cm to 1m thick (Detterman and others, 1980b). The interbeds are composed of conglomerate and sandstones interbedded with dark-gray siltstones and carbonaceous shale (Burk, 1965, p.91). In the conglomerates, the clasts are about one third quartz and chert, one third volcanic fragments and one third sedimentary lithic clasts (Detterman and others, 1980b). The rock is generally dark-brown to pale yellowish-brown in color.

The Bear Lake Formation unconformably overlies the Tolstoi and Meshik Formations and is disconformably overlain by the Milky River Formation (Detterman and others, 1980b).

Milky River Formation

The type section for the Milky River Formation was designated by Detterman and others (1980b) as 1525m of volcanigenic non-marine sedimentary rock with interlayered andesite flows and sills. Though this Formation is not often encountered on the surface, it is seen in drill holes bored on the Nushagak-Bristol Bay Lowland. The type section is located just east of Bear Lake in the Chignik quadrangle. The description that follows is taken from Detterman and others (1980b).

This formation unconformably overlies the Bear Lake Formation and is the youngest Tertiary unit mapped in the study area. It is unconformably overlain and preserved by volcanic flows of apparent Quaternary age. The lower 1000m is almost entirely of coarse, fluvial, highly cross-bedded and channeled volcanic sandstones and cobble to boulder conglomerates. The upper parts of the unit contain numerous porphyritic andesite flows, lahars, and tuffaceous units interlayered with volcanoclastic rocks. The proportion of volcanic rocks increases upward in the unit. The rocks are poorly indurated and are dark brown to gray in color.

Appendix 4 Rock Descriptions

- 77AWs 9 Andesite Chiginagak Bay Lat. 57 00.3'N Long. 156 40.4'W Very dark gray andesite with clino- and orthopyroxene phenocrysts and plagioclase phenocrysts (An 55). Much of groundmass is composed of fine grained opaque oxides and glass(?). Plagioclase phenocrysts are glomeroporphyritic.
- 77AWs 30 Andesite Cape Kumlik Lat. 56 38.2'N Long. 156 35.3'W Light greenish gray porphyritic andesite with hornblende phenocrysts and strongly zoned glomeroporphyritic plagioclase phenocrysts (about An 40 though some phenocrysts are An 15-20). Calcite with chlorite or talc, possibly pseudomorphing pyroxene. Abundant accessory Mn-bearing purple apatite. Groundmass with abundant opaque oxides and possibly devitrified glass. Thoroughly fractured, probably proclastic texture.
- 77AWs 40 Leuco-basalt Cape Kumlik Lat. 56 38.2'N Long. 157 28.9'W Dark green porphyritic leuco-basalt with hornblende phenocrysts up to 10 mm in size. Altered plagioclase phenocrysts (Anorthite greater than 50). Abundant calcite, chlorite and epidote. Hornblende phenocrysts partially altered to chlorite. Phenocrysts and groundmass fractured, may be cataclastic rather than proclastic. Dike in mineralized area.
- 77AWs 46 Andesite(?) Cape Kumlik Lat. 56 38.2'N Long. 157 27.7'W Dark green porphyritic andesite(?) with chloritized amphibole phenocrysts and altered zoned plagioclase phenocrysts (An 35(?) and An 55). Minor quartz. Rock is deuterically altered, calcite is common. In mineralized area.
- 77AWs 74 Dacite Sutwik Island Lat. 56 32.5'N Long. 157 20'W Tan dacite. Fresh biotite phenocrysts(?) in a thoroughly altered rock. Hornblende phenocrysts altered to opaque oxides and calcite, sericitized plagioclase of indeterminate composition, quartz and abundant accessory apatite and sphene.
- 77AWs 96b Pegmatite Warner Bay Lat. 56 09.7'N Long. 158 24'W Small pegmatite of feldspar and biotite formed in granodiorite of Devils batholith.
- 77AWs 100 Granodiorite Sweater Bay Lat. 56 05.0'N Long. 158 30.0'W Light gray medium-grained granodiorite. Major minerals are plagioclase (An 25-30), potassium feldspar, biotite, hornblende and quartz. Minors include pyroxene(?), chlorite, and opaque oxides. Accessory apatite. Very fresh rock, plagioclase zoned An 30 core, An 25 rim. Hypidiomorphic-granular texture.
- 77AWs 112b Leuco-basalt Kametolook River Lat. 56 01.7'N Long. 159 11.2'W Dark gray-black porphyritic leuco-basalt. Plagioclase in phenocrysts and groundmass (An 60-70), clinopyroxene and olivine(?). Flow structure, nearly opaque groundmass of devitrified glass(?).
- 77AWs 122 Dacite Castle Bay Lat. 56 17.7'N Long. 158 19.0'W Light gray iron-stained dacite with hornblende and plagioclase phenocrysts (An 30(?)) in a fine-grained groundmass. Some quartz, hydrothermal(?) biotite, and sericite. Hornblende is sparsely distributed and is in long laths. Hyalo-ophitic texture.
- 77AWs 125 Tonalite Northwest Arm, Castle Bay Lat. 56 13.2'N Long. 158 23.3'W Light gray medium-grained tonalite with biotite and hornblende. Minor pyroxene, some chlorite and epidote from hornblende. Minor sericitization of plagioclase (An 45). Accessory zircon. Hypidiomorphic-granular texture.

- 77AWs 134 Dacite Nakchamik Island Lat. 56 19.8'N Long. 157 19.6'W Light gray dacite with hornblende and plagioclase phenocrysts. Large phenocrysts of hornblende floating in a groundmass of fine-grained plagioclase (An 40-60, possibly two populations). Rock is slightly altered and strongly brecciated.
- 77AWs 137 Tonalite Mallard Duck Bay Lat. 56 13.6'N Long. 158 28.9'W Gray tonalite with highly altered phenocrysts of hornblende in a fine-grained groundmass of plagioclase (An 46) and quartz. Chlorite and biotite alteration products from hornblende abundant, some sericitization of plagioclase.
- 77AWs 152 Dacite Bee Creek Drill Hole B-1 Lat. 56 31.0'N Long 158 23.5'W Light gray dacite with amphibole phenocrysts altered to biotite and chlorite. Plagioclase phenocrysts (An 45) show minor sericitization. Abundant quartz and very minor potassium feldspar. Hypidiomorphic-granular texture.
- 77AWs 176 Andesite(?) Lat. 56 18.0'N Long. 158 22.8'W Dark gray-green andesite(?) with coarse-grained brown pleochroic partially resorbed amphibole and some clinopyroxene. Amphibole fairly fresh, fine-grained groundmass strongly altered to epidote, kaolinite, and sericite. Hyalo-ophitic porphyritic texture.
- 77AWs 179 Granodiorite Warner Bay Lat. 56 09.7'N Long. 158 24.0'W Light gray hornblende biotite granodiorite. Hornblende partially altered to biotite, primary and hydrothermal(?) biotite, fresh zoned plagioclase (An 48), quartz and potassium feldspar. Trace chlorite. Epidote in fractures. Hypidiomorphic-granular texture.
- 77AWs 180 Pegmatite in Devils batholith Warner Bay Lat. 56 09.7'N Long. 158 24.0'W Biotite, feldspar pegmatite in Devils batholith.
- 77AWs 183 Quartz-sericite altered rock Bee Creek Lat. 56 13.8'N Long. 158 29.0'W Strongly ironed altered sediment(?) of Naknek Formation. Rock is completely altered to quartz, sericite, and pyrite. Apparent relict bedding(?). Possibly some argillic alteration.
- 77AWs 186 Granite Chignik Lagoon Lat. 56 20.0'N Long. 158 30.0'W Coarse- to medium-grained biotite granite cobble from Chignik Formation. Biotite partially altered to chlorite, some sericitization of plagioclase. Abundant quartz and potassium feldspar. Hypidiomorphic-granular texture.
- 77AWs 190b Andesite Anchorage Bay Lat. 56 18.5'N Long. 158 24.5'W Dark gray-green porphyritic hornblende andesite. Large phenocrysts of hornblende in a very fine groundmass of altered feldspar and devitrified glass(?). Hornblende phenocrysts are poikilitic textured with resorbed edges.
- 77AWs 215 Dacite Bee Creek Lat. 56 30.6'N Long. 158 24.0'W Light gray porphyritic dacite with phenocrysts of hornblende and plagioclase. Hornblende shows minor alteration to chlorite, plagioclase (An 43) slightly sericitized. Fine-grained groundmass of plagioclase, quartz, and biotite. Plagioclase phenocrysts are glomeroporphyritic. Small late quartz- and chlorite-filled fractures.
- 77AWs 235 Propylitically altered sandstone Bee Creek Lat. 56 30.4'N Long. 158 23.5'W Green propylitically altered sandstone of Naknek Formation. Arkose with sedimentary plagioclase, quartz, quartzite, and potassium feldspar(?). Hydrothermal calcite, chlorite, sericite and kaolinite(?) are found interstitial to grains and disseminated through grains.
- 77AWs 243 Sericitically and propylitically altered sandstone Bee Creek Lat.

- 56 30.5'N Long. 158 24.1'W Green sericitically and propylitically altered sandstone of Naknek Formation. Slightly iron-stained, with relict bedding. Primary quartz, hydrothermal chlorite, sericite, and pyrite. Chlorite is fracture filling, sericite is disseminated.
- 77AWs 251 Potassically altered dacite(?) Bee Creek Lat. 56 31.0'N Long. 158 24.0'W Light gray, slightly iron-stained medium-grained composite or hybrid rock. Appears to have been hornblende dacite or arkose. Biotite and chlorite pseudomorph amphibole. Plagioclase and quartz abundant, some hint of hypidiomorphic-granular texture.
- 78AWs 5 Andesite Nakalilok Bay Lat. 56 56.5'N Long. 156 57'W Gray fine- to medium-grained andesite. Ortho- and clinopyroxene with unaltered plagioclase phenocrysts (An 45). Minor groundmass of opaque oxides, fine-grained plagioclase, and iddingsite(?). Some calcite. Intersertal porphyritic texture.
- 78AWs 11 Dacite North edge, Sutwik Island quadrangle Lat. 56 59.0'N Long. 157 07.5'W Gray porphyritic dacite with phenocrysts of green hornblende and plagioclase. Strongly zoned and carlsbad twinned plagioclase phenocrysts are of indeterminate composition due to sericitic alteration. Cataclastic porphyritic texture, phenocrysts are shattered and dislocated. Mirolitic(?) cavities filled with rusty quartz crystals.
- 78AWs 17 Leuco-basalt Kumlik Island Lat. 56 38.0'N Long. 157 25.0'W Green porphyritic leuco-basalt. Large phenocrysts of hornblende (.1 cm) and augite. Unevenly distributed autolithic aggregates or xenoliths of amphibolite, rich in hornblende and plagioclase. Minor plagioclase phenocrysts (An 60) are sericitically altered. Abundant calcite, chlorite and sericite in fine-grained groundmass.
- 78AWs 24 Andesite Cape Kunmik Lat. 56 47.3'N Long. 157 11.8'W Light gray porphyritic hornblende andesite. Green pleochroic hornblende phenocrysts in a groundmass of hornblende and sericitically altered plagioclase. Sphene and actinolite alteration products from pyroxene. Weakly developed flow structure. Sample was collected from rubble mixed with hornfels, apparently upper contact of intrusion.
- 78AWs 31 Andesite Foggy Cape Lat. 56 33.0'N Long. 156 59.6'W Dark gray porphyritic andesite with plagioclase phenocrysts (An 55) and phenocrysts of ortho- and clinopyroxene. Groundmass of very fine-grained plagioclase and pyroxene. Weak development of flow structure. Very minor alteration of plagioclase.
- 78AWs 32 Andesite Sutwik Island Lat. 56 31.6'N Long. 157 11.7'W Dark gray andesite with phenocrysts of plagioclase (An 55-60) and minor clinopyroxene. Complete gradation from medium to very fine-grained crystal sizes. Apparently, orthopyroxene phenocrysts are altered to bastite. Weak development of flow structure. Feldspar is unaltered.
- 78AWs 35 Dacite Pinnacle Mountain Lat. 56 49.1'N Long. 157 56.3'W Light gray dacite with phenocrysts of green pleochroic hornblende and plagioclase (An 60). Rare quartz phenocrysts(?), partially resorbed. Very fine-grained groundmass, primarily of feldspar. Most plagioclase phenocrysts are broken and dislocated, hornblende phenocrysts are generally aligned indicating a weak development of flow structure.
- 78AWs 42 Andesite Unavikshak Island Lat. 56 30.4'N Long. 157 43.1'W Gray porphyritic andesite with phenocrysts of plagioclase (An 55) hornblende and opaque oxides. Phenocrysts are variable in size from 4 mm to groundmass and all show resorption. Plagioclase zoned,

- alteration varies with zoning. Hyalo-ophitic porphyritic texture.
- 78AWs 43 Quartz-sericite altered andesite Unavikshak Island Lat. 56 30.4'N Long. 157 43.2'W Iron-stained quartz-sericite altered andesite. Rock is completely altered to quartz, sericite, sulfides, oxides, and clays. Pseudomorphs of plagioclase and hornblende phenocrysts. Accessory apatite.
- 78AWs 58 Dacite VABM "Easy" Lat. 56 30.4'N Long. 157 49.4'W Gray-brown porphyritic dacite with hornblende and plagioclase (An 55) phenocrysts. Groundmass of fine-grained plagioclase, glass, and opaque oxides. Pilotaxitic texture.
- 78AWs 61 Dacite VABM "Julik" Lat. 56 36.1'N Long. 157 58.9'W Gray-green porphyritic dacite. Phenocrysts of hornblende and plagioclase (An 55?) in an extremely fine-grained groundmass of plagioclase(?) and glass. Hornblende phenocrysts outlined in opaque oxides. Interiors of some plagioclase phenocrysts altered; most are fresh. Hand sample appears coarse-grained due to abundance of phenocrysts and the nature of the groundmass.
- 78AWs 95 Quartz diorite Seal Bay Lat. 56 01.1'N Long. 158 30.3'W Gray medium-grained quartz diorite phase of Devils batholith. Major minerals are plagioclase (An 40-45), biotite and chlorite, hornblende, augite, and quartz. Minor potassium feldspar. Accessory sphene, apatite, and ilmenite. Augite shows reaction relationship to hornblende, which goes to biotite, and finally to chlorite plus epidote. Plagioclase is sieve-textured with inclusions of pyroxene; it also shows minor sericitic alteration. Hypidiomorphic-granular texture.
- 78AWs 98 Leuco-basalt Mallard Duck Bay Lat. 56 12.7'N Long. 158 19.9'W Dark gray fine-grained leuco-basalt. Glomeroporphyritic phenocrysts of plagioclase (An 65?) and orthopyroxene in a groundmass of plagioclase, clinopyroxene, orthopyroxene, devitrified glass, and opaque oxides. Plagioclase fresh and unaltered. Pilotaxitic texture.
- 78AWs 125 Andesite(?) Milk Creek Lat. 56 29.5'N Long. 158 48.4'W Light gray porphyritic andesite(?). Phenocrysts of hornblende and plagioclase (An 55) in a groundmass of fine-grained plagioclase and opaque oxides (magnetite?). Plagioclase phenocrysts and glomeroporphyritic.
- 78AWs 134 Dacite Chignik Island Lat. 56 17.1'N Long. 158 35.2'W Dark gray medium-to fine-grained porphyritic dacite. Medium-grained phenocrysts of plagioclase (An 40-45) in a fine-grained groundmass of plagioclase, ortho-, and clinopyroxene. Late quartz. Some plagioclase crystals show fractures and dislocations. Fractures are filled with devitrified glass, indicating a proclastic subophitic texture.