Geologic Studies of the Lower Cook Inlet COST No. 1 Well, Alaska Outer Continental Shelf

U.S. GEOLOGICAL SURVEY BULLETIN 1596

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GEOLOGIC STUDIES OF THE LOWER COOK INLET COST NO. 1 WELL, ALASKA OUTER CONTINENTAL SHELF

The ODECO *Ocean Ranger,* a semisubmersible drilling vessel, on location in lower Cook Inlet drilling the COST No. 1 well. The view is southwest with Augustine Volcano, an active andesitic volcano, on the horizon. In the summer of 1977 Atlantic Richfield, the operator, with 18 other participants from the petroleum industry drilled the well in Block No. 489 to a total depth of 3,775.6 m. The well penetrated rocks that ranged in age from Late Jurassic to early Cenozoic. This well, drilled just before the opening of OCS Lease Sale No. CI, confirmed among other things that Lower and Upper Cretaceous rocks are present under lower Cook Inlet and, as an additional bonus, penetrated several Upper Cretaceous sandstone bodies with petroleum reservoir potential.

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Leslie B. Magoon, *Editor*

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DEPARTMENT OF THE INTERIOR

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Geologic Studies of the Lower Cook Inlet COST No. 1 Well, Alaska Outer Continental Shelf

Leslie B. Magoon, *Editor*

Abstract

1. The COST No. 1 well was drilled in 65 m (214 ft) of water and penetrated 3,776 m (12,387 ft) of sedimentary rocks in the Alaska Outer Continental Shelf (OCS) block 489 about midway between the Iniskin Peninsula on the northwest and the Kenai Peninsula on the southeast. The ages of the sedimentary units were determined by wireline logs and the analysis of foraminifers, radiolarians, calcareous nannoplankton, and marine and terrestrial palynomorphs. The section from 413 m (1,356 ft) to 797 m (2,615 ft) is Cenozoic. The underlying section, from 797 m (2,615 ft) to 2,112 m (6,930 ft), is Cretaceous; at 1,541 m (5,055 ft) the section is divided into Upper and Lower Cretaceous rocks. The bottom section, from 2,112 m (6,930 ft), to 3,775.6 m (12,387 ft), is Upper Jurassic (Oxfordian through Tithonian). The base of this section probably was not penetrated so the 1,663 m (5,455 ft) thickness is probably a minimum. The top of this unit is controversial. Drill cutting samples indicate that the top is at 2,109 m (6,918 ft), 2,112 m (6,928 ft), or 2,135 m (7003 ft). Paleontologic evidence indicates that the top is at 2,109 m (6,918 ft) or 2,417 m (7,930 ft). I place the top at 2,112 m (6,930 ft), just below the abundant *Inoceramus* fragments and just above the first occurrence of laumontite.

The West Foreland Formation, of early Cenozoic age, extends down to 797 m (2,615 ft). The sediments are sandstone, siltstone, coal, and some conglomerate. Modal analyses of the sandstone indicate that it is feldspatholithic with an average composition of $Q_{23}F_{30}L_{47}$. The Kaguyak Formation (Upper Cretaceous), from 797 m (2,615 ft) to 1,541 m (5,055 ft) contains marine and nonmarine sediments. The feldspathic sandstone has an average composition of $Q_{23}F_{61}L_{16}$. The Herendeen Limestone (Lower Cretaceous) contains sandstone, siltstone, shale and abundant *Inoceramus* fragments from 1,541 m (5,055 ft) to 2,112 m (6,930 ft). The lithofeldspathic sandstone has an average composition of $Q_{36}F_{44}L_{20}$. The bottom section, the Naknek Formation (Upper Jurassic), down to 3,776 m (12,387 ft), is dominantly siltstone, shale, and sandstone. The average composition of the lithofeldspathic sandstone is $Q_{24}F_{55}L_{21}$.

The West Foreland Formation, the shallowest unit sampled, has a minimum thickness of 384 m (1,259 ft). Paleontologic data indicate Mesozoic rocks were reworked in a nonmarine environment. The organic carbon content of the unit is low and the section is thermally immature. No hydrocarbon shows were indicated. The Kaguyak Formation is 744 m (2,440 ft) thick and includes three sandstone bodies that are potential hydrocarbon reservoirs. Paleontologic and lithologic evidence indicate two prograding sedimentary sequences that prograde seaward from an upper bathyal environment to nonmarine. Although the organic carbon content is as much as 1.07 weight percent, the kerogen is low in oil-prone material and lacks an adequate thermal history to generate oil. Two different hydrocarbon shows were reported in this unit. The Herendeen Limestone is 572 m (1,875 ft) thick. Foraminiferal data indicate that it formed in middle bathyal to inner neritic marine environments. The organic carbon content is low, and the thermal history is insufficient to generate hydrocarbons. Only a few hydrocarbon indications were reported. Reservoir properties of the sandstones are poor. The deepest rock unit penetrated, Naknek Formation, is at least 1,663 m (5,457 ft) thick. Even though the rock is thoroughly cemented with laumontite, it contained most of the hydrocarbon shows. Since the strata, mostly sandstone and siltstone, is low in organic content, and the organic matter is not the type to generate oil, the oil must have migrated into the area of the well bore from another part of the basin where mature oil-prone source rocks were present.

2. Information about the environmental geology of the lower Cook Inlet basin is limited; and no quantitative information has been collected from the upper Cook Inlet basin.

A number of geologic features and processes have been identified that may pose problems to engineering installations in the lower Cook Inlet and along the adjacent coastline. Strong earthquakes have caused major damage to the area by ground failure, surface warping, and tsunamis. Four active volcanoes on the west side of lower Cook Inlet are andesitic, so they can have violent eruptions. Very little is known about the swift bottom currents and sandwaves that have broken pipelines in the upper Cook Inlet.

3. The seismic horizons were determined by comparing the measured seismic reflections with the calculated reflections from the COST No. 1 well. Horizon A, at 900 m (2,950 ft) depth in the well, is near the top of the Upper Cretaceous rocks. Horizon B is at the depth of 2,005 m (6,575 ft) in the well. That depth represents the Cretaceous-Jurassic contact where the rocks no longer have intergranular porosity but are cemented with calcite and laumontite. The third horizon, C, is 1,400 m (4,600 ft) below the bottom of the well and about 3,100 m (10,200 ft)

below the top of the Upper Jurassic rocks. It represents the contact between the top of the Middle Jurassic rocks and the base of the Upper Jurassic.

4. The paleontology and biostratigraphy are based on detailed analysis of foraminifers, marine and terrestial palynomorphs, calcareous nannoplankton, and radiolarians. Eocene fossils from 413 to 552 m (1,356 to 1,810 ft) represent a predominantly nonmarine depositional environment in a warm temperate climate. Paleocene, from 552 to 799 m (1,810 to 2,620 ft) is characterized by a palynomorph assemblage containing *Paraalnipollenites confusus*. Well developed Late Cretaceous (Maestrichtian) microfossil assemblages, from 799 to 1,539 m (2,620 to 5,050 ft), indicate nonmarine and marine intervals. Sparse but diagnostic assemblages of Early Cretaceous (Hauterivian to Valanginian?) microfossils, from 1,539 m (5,050), indicate a marine depositional environment whose paleobathymetry fluctuated twice from upper slope to middle-shelf water depths. Late Jurassic (Tithonian to Oxfordian) microfossils, from 2,417 m (7,930), indicate an intertidal to inner neritic marine depositional environment.

5. The COST No. 1 well does not contain prospective petroleum source rocks. The organic carbon content, which ranges from 0.08 to 0.65 weight percent, is more abundant in the upper part of the well than in the lower. The thermal maturity, however, increases with increasing depth. The transition from immature to mature hydrocarbon generation seems to be from 2,100-2,700 m (6,900-8,900 ft) in the well.

The Mesozoic sediments in the COST No. 1 well contain much less organic matter than the Mesozoic sediments in the upper Cook Inlet and the North Slope in Alaska. Although the thermochemical transformation of the organic matter in the Mesozoic rocks is marginally mature to mature, the organic matter is dominantly of the type that has a poor oil-generating capacity. However, because the COST No. 1 well did not penetrate the source rocks for petroleum in the upper Cook Inlet—the shales of the Middle Jurassic—the prospect for petroleum in the lower Cook Inlet should not be judged only on the data obtained from the COST No. 1 well. The oil-generating system in the Cook Inlet basin is probably made up of migrating paths from the Middle Jurassic rocks.

6. The present-day geothermal gradient for the COST No. 1 well is 2.28°C/100 m. Even though this gradient is close to that of the Swanson River oil field gradient of 2.37°C/100 m, the gradient is too low when compared to the geothermal trends in the upper Cook Inlet. The evidence from the stratigraphy of the rocks, the first occurrence of laumontite, and the TAI values indicate that the rocks in the well were subjected to high temperature gradients before uplift and erosion. The low vitrinite reflectance values do not substantiate this inference.

7. The compositions of the sandstones in the COST No. 1 well indicated that they were derived from an igneous source terrane which had outcrops of both volcanic and plutonic rock types. The shallowest samples are volcanic lithic sandstone. The West Foreland Formation of early Cenozoic age contains feldspatholithic sandstone with an average composition of $Q_{23}F_{30}L_{47}$. The Kaguyak Formation (Upper Cretaceous) contains feldspathic sandstone with an average composition of $Q_{23}F_{61}L_{16}$. Both the Herendeen Limestone (Lower Cretaceous) and Naknek Formation (Upper Jurassic) contain lithofeldspathic sandstone with average modal compositions of $Q_{36}F_{44}L_{20}$ and $Q_{24}F_{55}L_{21}$, respectively.

8. The diagenetic changes most affected the volcanic rock fragments and plagioclase feldspar that are abundant in the sandstone samples. Sandstone diagenesis increases with increasing depth in the COST No. 1 well. Pseudomatrix is more common in the deeper sandstones than in the higher sandstones. Authigenic clay, montmorillonite and chlorite, increases with depth, and some of it formed before laumontite crystallization. Laumontite is present in most sandstone samples from depths greater than 2,134 m (7,000 ft) where most plagioclase is partly to completely albitized and intergranular porosity is destroyed.

The major cause for the reduction of porosity and permeability in the COST No. 1 well is due to the formation of authigenic clay matrix and pseudomatrix. The minor cause is that of compaction and diagenesis.

The sandstones of the West Foreland Formation (lower Cenozoic) have a porosity of nearly 20 percent. The porosity and permeability of the sandstone of the Herendeen Limestone (Lower Cretaceous) has been reduced by compaction and pore fillings of clay and calcite. The original porosity of the sandstone of the Naknek Formation (Upper Jurassic) was probably high but is now substantially reduced by compaction and by precipitation of authigenic minerals, predominantly laumontite.

9. The Middle Jurassic sandstones of the Tuxedni Group and the lower part of the Chinitna Formation were derived largely from a volcanic terrane. Important differences in composition occur between the Tonnie Siltstone Member of the Chinitna Formation and its overlying Paveloff Siltstone Member; the lower member is volcanic-lithic rich, is virtually devoid of hornblende, and is cemented dominantly with chlorite; and the upper member is less lithic-rich (more feldspathic fragments from a dissected pluton), contains an average of 7 percent hornblende, and is cemented with laumontite as well as chlorite.

The cementation and compaction of the sandstones in the Tuxedni Bay area in the western Cook Inlet should be considered when evaluating the hydrocarbon-reservoir potential of the Middle and Upper Jurassic sandstone in Cook Inlet.

The new data about the composition of the sandstones from the Tuxedni Group and Chinitna and Naknek Formations provide evidence that the Alaska-Aleutian Range batholith was unroofed during the deposition of the Paveloff Siltstone Member of the Chinitna Formation.

10. Eight separate episodes of plutonism in southern Alaska may have affected or have affected the provenance history of the forearc

basin that includes Cook Inlet. The petrologic variations of the plutons representing these eight episodes reveal a general trend to higher felsic composition from the older to the younger plutonic groups. Generally, Jurassic plutonism produced mafic to intermediate compositions, Cretaceous plutonism produced mostly intermediate compositions, and Tertiary plutonism produced felsic compositions.

Both short-term and long-term plate-convergent episodes have affected the provenance of the Cook Inlet forearc basin. Four relatively short-term episodes that affected the Cook Inlet basin occurred during the Late Triassic(?) and Early Jurassic, Middle and Late Jurassic, Late Cretaceous and early Tertiary, and middle Tertiary. Widespread late Cenozoic volcanic rocks and the presence of many calc-alkaline volcanoes in the region are evidence that a fifth episode is taking place now.

Over the long term, the provenance evolved from simple magmatic arc sequences in the early Mesozoic to a composite of regional sedimentary, metamorphic, and magmatic arc sequences in the late Mesozoic and Cenozoic. In effect, each succeeding magmatic arc increased the proportion of crystalline rocks in the provenance. The simple magmatic arc provenance of the Late Triassic, Jurassic, and Early Cretaceous produced sandstones changing from lithic to feldspathic compositions. The sandstones in the Late Cretaceous should reflect a composite provenance that includes magmatic arc and recycled orogen types, and, after a new magmatic arc cycle began in the Late Cretaceous, local development of volcanolithic sandstones.

Late Cenozoic sandstones should reflect a complex composite provenance that includes magmatic arc, recycled orogen, and continental block provenance types. The diverse sandstones should range from lithic to quartzose types.

The development of three major provenance types in southern Alaska should produce a complete range of sandstone framework modes. However, the younger sandstones of the Cook Inlet basin tend to have quartzose framework modes. This may be explained by the increasing proportion of metamorphic and plutonic rocks to volcanic rocks during provenance evolution and the more felsic compositions of the younger dissected plutons.

11. Only the sandstones from the Lower Jurassic through the Lower Cretaceous changed compositions in the way Dickinson and Suczek (1979) predicted for magmatic arc provenances. In the forearc basin, the Upper Cretaceous sandstones change composition from a feldspathic to a feldspatholithic sandstone with very little change in quartz content; this change is the reverse of the kind of change expected in a magmatic arc provenance and more like the dissection of the previous magmatic arc provenance. The composition of the Cenozoic sandstones in the forearc basin and in the adjacent accreted terranes are again derived from a magmatic arc; the sandstones were all feldspatholithic but they increased in quartz content very rapidly as they decreased in age, undoubtedly reflecting the more felsic provenance and a drainage system that reached into interior Alaska.

Only in the Cenozoic sandstones was the quartz content high enough to provide adequate petroleum reservoirs consistently. The Upper Jurassic sandstone would have been a good petroleum reservoir before the laumontite filled all the pores in the rocks.

12. Considering all the data, only three sandstone beds of Upper Cretaceous age are potential hydrocarbon reservoirs in the COST No. 1 well. These rocks, however, are not the source rocks for the petroleum in the upper Cook Inlet. COST No. 1 well did not penetrate the shales of the middle Jurassic, so the question of whether potential prospective petroleum rocks are present in the lower Cook Inlet basin still remains unanswered.

Introduction

By Leslie B. Magoon

The lower Cook Inlet COST (Continental Offshore Stratigraphic Test) No. 1 well is 65 km southwest of Homer, Alaska in the Alaska Outer Continental Shelf block 489 (fig. 1). The well was drilled in 65.2 m (214 ft) of water to a total depth of 3,775.6 m (12,387 ft) from the rig Kelly bushing (KB). The well was spudded June 10, 1977, and it reached total depth on September 9, 1977. Other specific information is given in tables 1 through 4.

COST No. 1 well was drilled in Cook Inlet Outer Continental Shelf waters to obtain stratigraphic information before the oil and gas Lease Sale No. CI was held October 27, 1977. Atlantic Richfield Company, acting as operator, solicited support from industry to form a COST group to drill a stratigraphic test well; 18 petroleum companies responded. The proposed location of the well was about midway between the Iniskin Peninsula on the northwest and the Kenai Peninsula on the southeast. The granting of Federal leases within 92.6 km (50 nautical miles) of the drill site on December 1, 1979 has made possible the publication of detailed information about the geologic findings from the COST No. 1 well, in accordance with Title 30, Code of Federal Regulations, Chapter II, paragraph 251.15, which provides for public disclosure by the U.S. Geological Survey (USGS) of all geologic information on the well 60 days after such leasing. Open-File Report 78-145, entitled "Geological and operational summary, Atlantic Richfield lower Cook Inlet, Alaska, COST well No. 1" (Wills and others, 1978), was published at the time the detailed well information was released by the USGS in 1978. The present report discusses the detailed geologic information derived from the well and provides information on the framework geology and hydrocarbon potential of the Cook Inlet basin.

This volume is divided into separate reports on geologic, geophysical, and geochemical topics. Some operational details from Wills and others (1978) are included. No information on the nine industry wells drilled offshore since Lease Sale No. CI is included (table 5). Special reports are included on the older rock units near Tuxedni Bay that were not penetrated by the COST No. 1 well; on the plutonic terranes of southern Alaska for sandstone provenance; and a compilation of the sandstone composition for most units present in the Cook Inlet forearc basin. Specific information about the COST No. 1 well is discussed first, and then special reports on framework geology with emphasis on sandstone composition follow.

Acknowledgments—As editor, I wish to thank all the authors who contributed chapters to this report on the COST No. 1 well. Without their total support and cooperation, this report could not have been published. Special thanks go to David M. Hite of Atlantic Richfield Company who reviewed and checked the information in several chapters for accuracy and to the geologists of Chevron USA who reviewed the chapter on "Stratigraphic units of the COST No. 1 well". Petroleum Information Corporation, using a Calma plotter, displayed the wireline log curves and lithology column used in figure 4. I gratefully acknowledge T. A. Coit, S. B. Griscom, M. A. McCall, P. A. Swenson, and L. M. Wood whose considerable efforts were crucial to getting this bulletin to the printer.

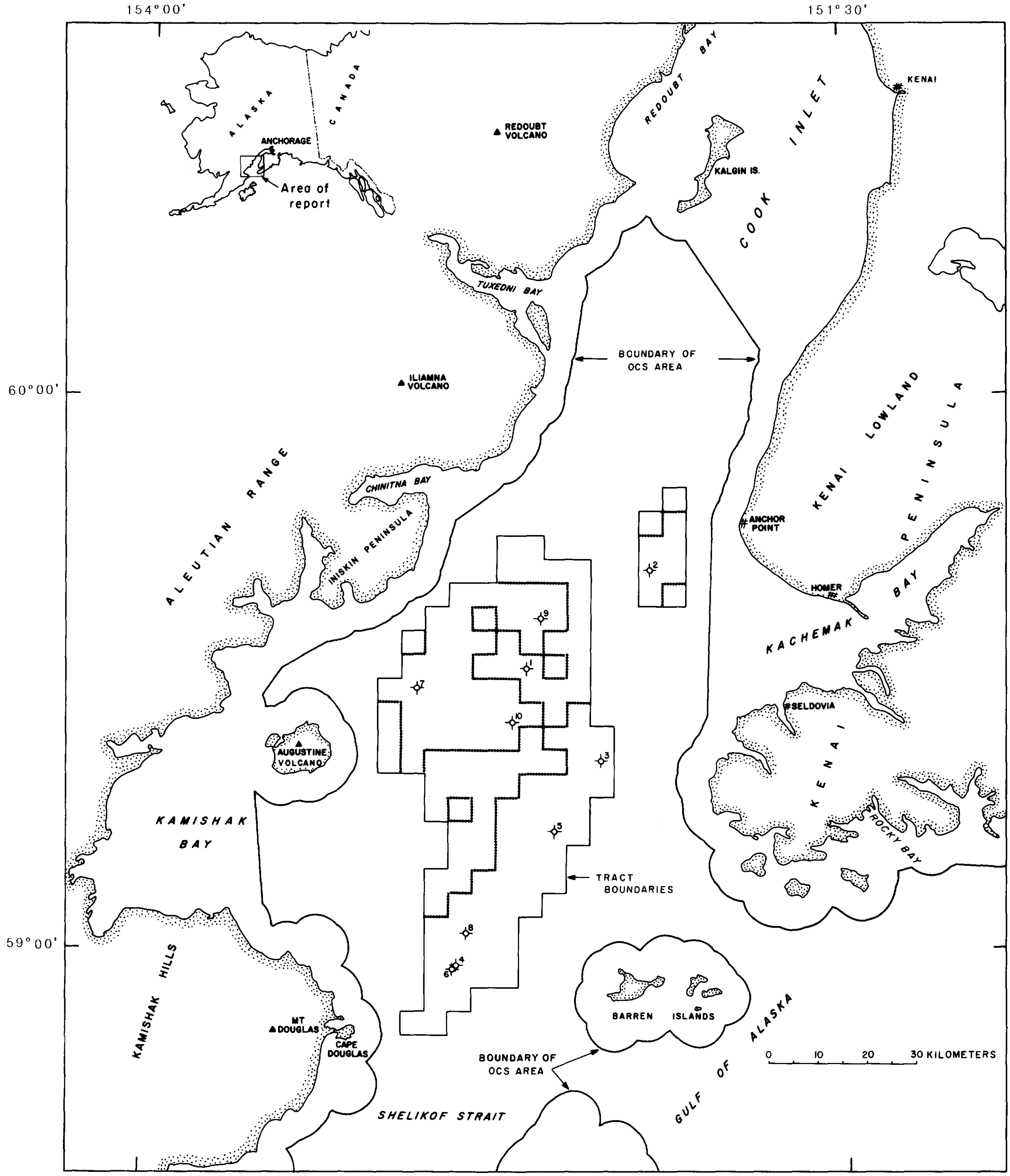


Figure 1. Geographic features, leased OCS tracts, and wells drilled to date (1980) in the lower Cook Inlet OCS. Well numbers refer to table 5.

Table 1. Selected information for "Well Completion and Recompletion Report and Log"

[Information from U.S. Geological Survey Form 9-330]

Operator:	Atlantic Richfield Company
Well No.:	Lower Cook Inlet, COST[1] No. 1
Category:	Geologic test
Location:	OCS[2] block 1375 N., 105 E. Block No. 489 Surface: 2,371.8 m FNL (from north line) and 973.7 m FWL (from west line) Total depth: same location
Permit:	OCS-77-5 issued June 3, 1977
Spud date:	June 10, 1977
Total depth date:	September 9, 1977
Elevation Kelly bushing[3]:	30.8 m (101 ft) MLLW (above mean lower low water) 96.0 m (315 ft) RKB-ML (rig Kelly bushing above mud line or sea floor)
Total depth:	3,775.6 m (12,387 ft) RKB
Casing record:	Size / Depth (RKB) 11.8 cm (30 in.) — 127.1 m (417 ft) 7.9 cm (20 in.) — 403.9 m (1,325 ft) 5.3 cm (13 3/8 in.) — 1,475.2 m (4,840 ft)
Well logs:	See table 2
Cores:	See table 3
Status:	Plugged and abandoned

[1] COST — Continental Offshore Stratigraphic Test

[2] OCS — Outer Continental Shelf

[3] MLLW and RKB-ML corrected by D. M. Hite, Atlantic Richfield Company.

Table 2. Type and depth of well logs run in COST No. 1 well

Type	Acronym	Depth interval m	Depth interval ft
Dual induction laterolog[1]	DIL	91.4-3,775.9	300-12,388
Borehole compensated sonic log	BHC[1]	403.9-3,776.8	1,325-12,391
Sonic log-sequential long spaced 8-10 feet	LSS[1]	403.9-3,764.3	1,325-12,350
Sonic log-sequential long spaced 10-12 feet	LSS[1]	403.9-3,764.3	1,325-12,350
Formation density log	FDC[1]	129.5-3,777.1	425-12,392
Compensated neutron-formation density log	CNL[1]/FDC[1]	403.9-3,777.1	1,325-12,392
Proximity log/microlog survey	PL/ML	1,475.2-3,120.5	4,840-10,238
	PL/ML	2,987.0-3,775.6	9,800-12,387
High resolution dipmeter[2]	HDT[1]	403.9-1,490.2	1,325- 4,889
	HDT[1]	1,475.2-3,120.0	4,840-10,236
	HDT[1]	3,048.0-3,775.6	10,000-12,387
Temperature log		0 -3,775.9	0-12,388
Well-site geologist's lithologic log		411.8-3,775.6	1,351-12,387
Mud log[3]		411.8-3,775.6	1,351-12,387
Instantaneous drilling evaluation log[4]		411.5-3,775.6	1,350-12,387
Delta chloride log[4]		426.7-3,775.6	1,400-12,387
Shale density log[4]		2,026.9-3,764.3	6,650-12,350

[1] Mark of Schlumberger.
[2] Dipmeter arrow plot available.
[3] Borst and Giddens Logging Service, Inc.
[4] The Analysts, Inc.

Table 3. Conventional cores acquired from COST No. 1 well

Core No.	Age	Interval cored				Core recovered		Description	Dip (degree)
		Top		Bottom					
		m	ft	m	ft	m	ft		
1	Early Cretaceous	1,642.9	5,390	1,649.6	5,412	5.5	18	Interbedded sandstone and shale	0-3,
2	Late Jurassic	2,165.3	7,104	2,173.5	7,131	7.6	25	Sandstone	0,
3	Late Jurassic	2,844.4	9,332	2,850.5	9,352	5.3	17.5	Interbedded sandstone and siltstone	0-2,
4	Late Jurassic	3,766.4	12,357	3,775.6	12,387	9.1	30	Sandstone grading to siltsone	0,

Table 4. Petroleum industry participants and contractors in COST No. 1 well

Petroleum industry participants

Aminoil USA, Inc.
Amoco Production Company
Atlantic Richfield Company
BP Alaska Exploration
Champlin Petroleum Company
Chevron USA
Cities Service Oil Company
Depco, Inc.
Exxon Company, USA
Freeport Oil Company
Getty Oil Company
Gulf Energy & Minerals
Hunt Oil Company
Mobil Oil Corporation
Murphy Oil Corporation
Phillips Petroleum Company
Shell Oil Company
Texaco Incorporated
Union Oil Company of California

Petroleum industry contractors

Principal contractor: ODECO International, Inc.
Ocean Ranger—semisubmersible drilling vessel

Support contractors and services:
Adolf Curry—support boats
Alaska Aeronautical, Inc.—air transportation
Big T Oilfield Services—expediting services
Christensen Diamond—bits
Eastman Whipstock—directional survey
Evergreen Helicopters of Alaska, Inc.—helicopters
GBR Equipment Rental—tool rental
Halliburton Services—cement
Hughes Tool Company—bits
International Technology Ltd.—position survey
IMCO Services, Inc.—mud
Land and Marine Rental Company—casing services and rentals
Manley Terminals—warehouse, office space, and logging
Oceaneering International, Inc.—diving
ODECO International Corporation—rig
Offshore Logistics, Inc.—boats
Regan Offshore International, Inc.—wellheads
Smith Tool Company—bits
Tri-State Oil Tools—tool rentals

Geoscience contractors and services:
The Analysts, Inc.—mud logging
BBN Geomarine Services Company—hazard survey
Borst and Giddens Logging Service, Inc.
Core Laboratories—core cutting and analysis
Dames and Moore—meteorological services and bio-assay
Geochem Laboratories, Inc.—geochemical analyses
Schlumberger Ltd.—logging
Seismic References Service—velocity survey
Anderson, Warren and Associates—micropaleontology

Table 5. Wells drilled in lower Cook Inlet outer continental shelf to 1980

Well No. on fig. 1	Operator	Name	API No.	OCS block	Hydrocarbon shows
1	Atlantic Richfield Company	COST No. 1	55-220-00001	489	Trace oil
2	Marathon Oil Company	OCS Y-0086 No. 1	55-220-00003	318	Some oil
3	Phillips Petroleum Company	OCS Y-0124 No. 1	55-220-00004	668	None reported
4	Marathon Oil Company	OCS Y-0168 No. 1	55-219-00003	2	None reported
5	Phillips Petroleum Company	OCS Y-0136 No. 1	55-220-00005	798	None reported
6	Marathon Oil Company	OCS Y-0168 No. 2	55-219-00005	2	None reported
7	Atlantic Richfield Company	OCS Y-0161 No. 1	55-250-00001	572	None reported
8	Phillips Petroleum Company	OCS Y-0152 No. 1	55-220-00006	970	None reported
9	Atlantic Richfield Company	OCS Y-0097 No. 1	55-220-00002	401	None reported
10	Atlantic Richfield Company	OCS Y-0113 No. 1	55-220-00008	576	None reported

Well No. on fig. 1	Date		Depth					
	Spud	Abandoned	Kelly bushing		Water		Total	
			m	ft	m	ft	m	ft
1	10 June 1977	26 September 1977	30.8	101	65.2	214	3,775.6	12,387
2	21 July 1978	22 December 1978	15.9	52	32.9	108	4,058.4	13,315
3	9 October 1978	19 July 1979	15.2	50			3,448.5	11,314
4	11 January 1979	27 April 1979	15.9	52	167.6	550	852.5	2,797
5	23 April 1979	21 September 1979	23.8	78			3,146.8	10,324
6	28 April 1979	21 August 1979	15.2	50	165.2	542	2,714.9	8,907
7	15 July 1979	28 January 1980	31.4	103	39.9	131	4,564.4	14,975
8	24 September 1979	22 April 1980	23.8	78			4,001.4	13,128
9	6 April 1980	29 May 1980			65.5	215	2,283.3	7,491
10	9 May 1980	28 June 1980	23.8	78	62.5	205	2,141.5	7,026

Environmental Geology

By Arnold H. Bouma[1] *and* Monty A. Hampton

INTRODUCTION

Information about the environmental geology of the lower Cook Inlet is limited. Oceanographic studies and a monitoring program were conducted while the COST No. 1 well was being drilled (Miller and others, 1978). The semi-submersible, *Ocean Ranger*, was moored at lat 59° 31' 06.3445" N. and long 152 38' 36.6037" W. in lease block No. 489 in a water depth of 65.2 m (214 ft). Also the U.S. Geological Survey made cruises to the lower Cook Inlet in 1976-79. Data on sand waves and other bedforms were obtained from high-resolution seismic-reflection profiling, side-scan sonar surveying, bottom television and camera observations, bottom sampling, a limited number of vertical current profiles, and a few longer term current measurements. From these data and other published information, a number of geologic features and processes have been identified that may pose problems to engineering installations in lower Cook Inlet and along the adjacent coastline. Strong earthquakes (14 have occurred since 1920) have caused major damage to the area by ground failure, surface warping, and tsunamis. The four active volcanoes on the west side of lower Cook Inlet are andesitic; therefore they can have relatively violent eruptions. The most recent eruption was in 1979. Swift bottom currents and sand waves are known to break pipelines. Very little is known about their characteristics.

Oil and gas have been produced for several years in the upper Cook Inlet, but little quantitative information has been accumulated that can be applied to the lower Cook Inlet.

BATHYMETRY AND MORPHOLOGY

The bathymetry of lower Cook Inlet is complex (Bouma and others, 1978b). A boomerang-shaped ramp at about lat 59° 20' N. divides the area into a northern part that generally is shallower than 70 m (230 ft) and a southern part that is deeper than 120 m (394 ft) (fig. 2). In the northern part, a central axial depression (Cook Trough) is flanked by shallow shelflike areas. A relatively deep trough parallels the northeast shore of the Kenai Peninsula and ends in Kachemak Bay. The southern part is marked by local closed depressions. Water depth increases from south of the ramp into Shelikof Strait. Under Kennedy and Stevenson Entrances on either side of the Barren Islands, the sea floor has a complex morphology of ridges and troughs.

[1]Gulf Corporation.

HAZARDS

Water Currents

The circulation of water in the lower Cook Inlet is affected by several factors. Water entering the inlet from the Gulf of Alaska is pushed by the counterclockwise Alaskan gyre through the Kennedy and Stevenson Entrances. Strong tidal effects are superimposed on the currents (Muench and others, 1978). Most of the water flows along the ramp and down into Shelikof Strait; the rest of the water flows up the inlet along the east side into Kachemak Bay. Cross currents move part of this water westward. The west side of the inlet is dominated by ebb tides (Burbank, 1977).

Sand waves and other bedforms cover the sea floor off the coast of the Kenai Lowland and Kenai Peninsula. The area is roughly 50 km (80 mi) in diameter (fig. 3) and the bedforms range in height from 0.2 to 12 m (0.7–40 ft). Swift bottom currents formed these bedforms in the past; how active the bottom currents are at present is unknown.

Seismic Activity

Since 1920, 14 earthquakes of magnitude 6 or greater have occurred within the lower Cook Inlet area. Earthquakes of this size typically can produce major damage to manmade structures, either directly by ground shaking, surface faulting, and surface warping, or indirectly by ground failure, sediment consolidation, and tsunamis (seismic sea waves).

Tsunamis can be considered hazardous in the lower Cook Inlet area. They caused more loss of life than any other effect of the 1964 earthquake. They also caused damage along the east coast of the inlet, at Rocky Bay and Seldovia, but not along the west coast of the inlet.

Tsunamis are generated when large volumes of water are suddenly displaced, either by tectonic displacement of the sea floor or by large rockfalls or landslides. The narrow, elongate geometry of Cook Inlet and its narrow entrances reduce the chance that a tsunami generated outside the inlet will propagate significant destructive energy into it. Nevertheless, local tsunamis can be exceptionally large; for example, a surge of water ran 530 m (1,750 ft) up the wooded slopes of Lituya Bay in the Gulf of Alaska during the southeastern Alaska earthquake in 1958.

Sediment consolidation and its resulting subsidence can be another hazard in the lower Cook Inlet. This seismic-related hazard causes flooding along coastlines and con-

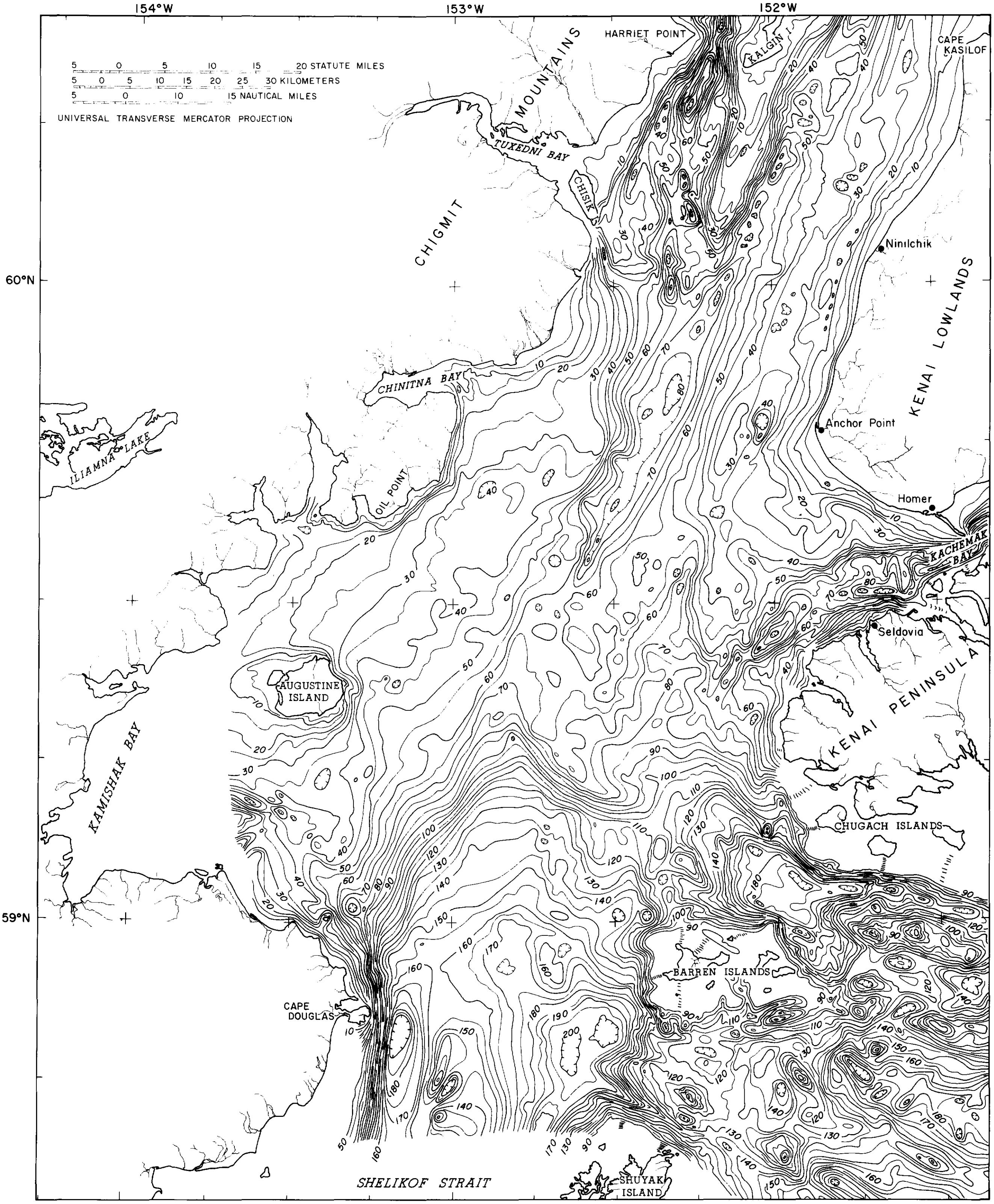


Figure 2. Bathymetric map of lower Cook Inlet, Alaska. Water depth in meters.

sequent damage to onshore installations. Consolidation of sediment was a significant cause of subsidence along Homer Spit during the 1964 earthquake (Waller, 1966).

Surface warping caused by earthquakes can raise the level of the coastline, putting docks and facilities out of reach of water, as occurred at Cordova in the Gulf of Alaska area during the 1964 earthquake. Downwarping can cause flooding of structures and dry land. Any change in the level of a coastline can be destructive, and at present no system of forewarning is known.

Faulting is not considered a serious problem in the Cook Inlet area. A few small faults have been observed on seismic-reflection profiles obtained north of the Augustine-Seldovia arch, but these could not be found on adjacent tracklines 5 km (3 mi) away. South of the arch, a few surface faults are in the lease area. There are many normal faults with accompanying horst and graben structures near Augustine Island and near the Barren Islands (fig. 3; Bouma and Hampton, 1976). Faulting may create some minor problems with pipelines near landfalls.

Usually ground failure caused by severe shaking, both on land and under water, is a major cause of destruction associated with large earthquakes, especially in areas containing thick sections of unconsolidated, fine-grained sediment. Deltas are especially susceptible to earthquake-induced liquefaction and sliding. Underwater movement of slide sediment can cause physical damage to structures and exposed pipelines. Potential problems along coastlines are rock falls from steep cliffs, translatory block sliding, and ground fissuring with associated sand extrusions.

Surprisingly, little ground failure of any kind took place along the coastline of the lower Cook Inlet during the 1964 earthquake. Little effect from ground failure can be expected within the open-water area of lower Cook Inlet because the sediment on the nearly horizontal sea-floor slopes is typically coarse grained.

Volcanic Activity

Four volcanoes, Redoubt, Iliamna, Augustine, and Mount Douglas, are located along the west side of lower Cook Inlet (fig. 1). All the volcanoes are andesitic, so they can have relatively violent eruptions. Except for Mount Douglas, all the volcanoes have erupted in historic time. In fact, Augustine Volcano, the most active, erupted in 1964, 1976, and 1979. Although its ejecta are not considered a serious problem more than 500 m (1,600 ft) away from the volcanic throat, its fine ash, which can be physically and chemically destructive, can travel for thousands of kilometers. Augustine Volcano also produces nuée ardentes, but little is known about the distance such hot ash clouds can travel over water.

With an adequate warning system, most volcanic eruptions can be detected in time to shut machinery down and evacuate offshore structures. However, it is not safe to construct installations at the base of a volcano because nuée ardentes and lahars can cause significant damage and loss of life.

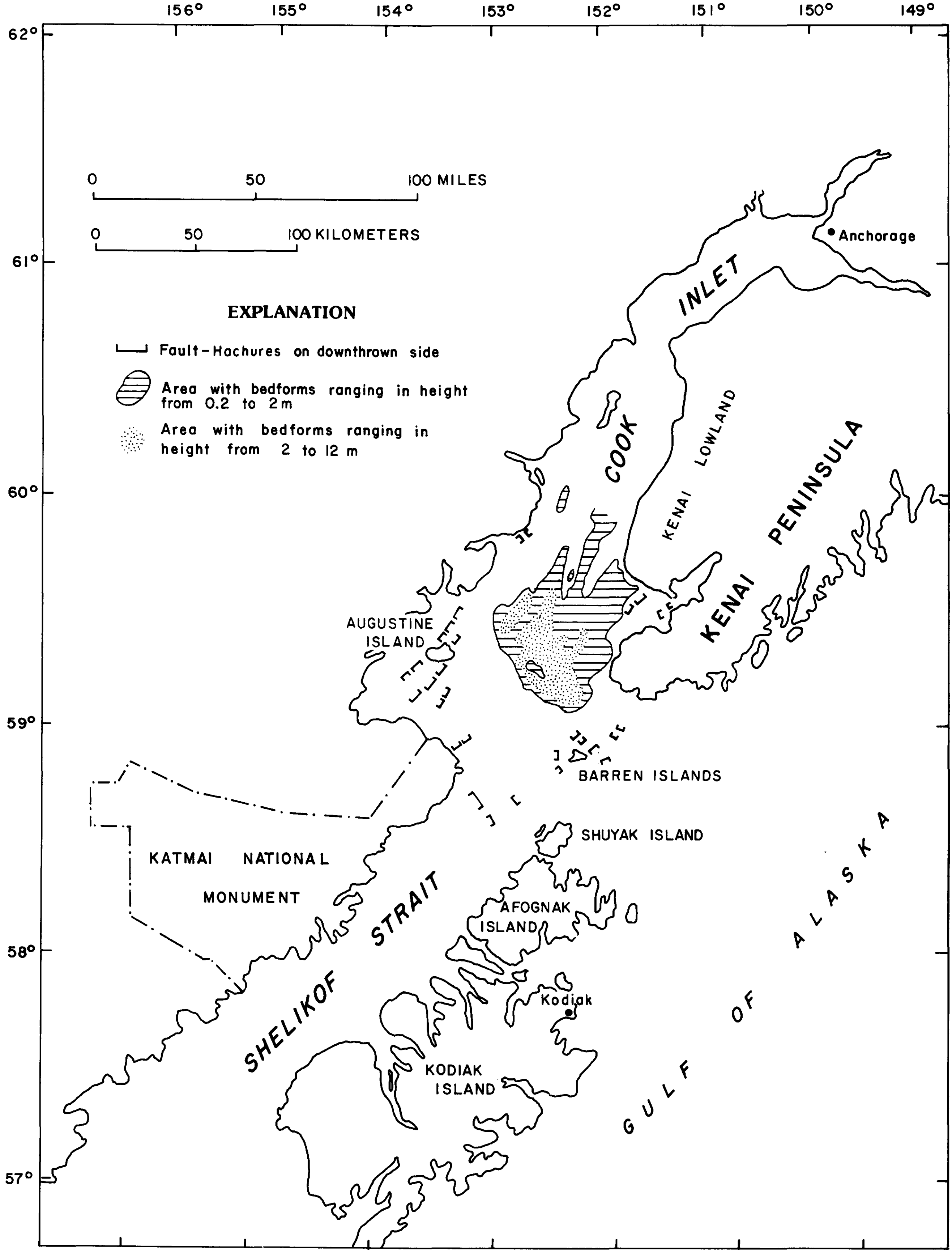
Sand Waves and Other Bedforms

A blanket of sand overlying a pebbly mud of glacial origin (Bouma and others, 1977, 1978a) covers the central part of lower Cook Inlet (fig. 3). This sand blanket, which ranges from a few centimeters to more than 12 m (40 ft) in thickness, makes up several different kinds of bedforms such as sand waves, sand ridges, dunes, sand ribbons, and comet marks (Bouma and others, 1977, 1978a,b, 1979; Whitney and others, 1979).

An attempt was made to study the migration of the largest sand waves, which have heights from 6 to 8 m (20 to 25 ft) and lengths from 400 to 800 m (1,300 to 2,600 ft). Within the accuracy of navigation, we could not detect migration of the larger sand waves when comparing 1973 industrial survey lines with our 1977 and 1978 resurveys (Whitney and others, 1979). Possibly the period of observation of sand, or perhaps its significant movement, may take place only during abnormal conditions such as severe storms, which did not happen during the 4-5 years of observation.

We did observe changes in small sand waves superposed on larger sand waves. Time-lapse photography revealed significant ripple movement during a small storm as well as reversal of the ripple asymmetry during ebb and flood cycles. Moreover, by comparing 1977 and 1978 side-scan sonographs run along coincident tracklines, changes in the distribution and characteristics of small sand waves was discerned (Bouma and others, 1979; Whitney and others, 1979). Local bottom television, current measurements, and long-term observations during summer months revealed movement of sand grains only during spring tides for about one hour of each ebb and flood cycle.

Comparable results were obtained from the semisubmersible *Ocean Ranger*, which was moored near the west side of a sand-wave field made up of bedforms ranging in height from 2 to 5 m (7 to 16 ft). Several short cores collected around the semisubmersible contained drill cuttings from two horizons; the first from at 4.5 to 6.5 cm (11 to 17 in.) depth and the second from 11.5 to 13.0 cm (29 to 33 in.) depth. These buried drill cuttings are evidence that a certain amount of sand transport occurred, and also that the depth of the trough of the smallest bedforms was 6.5 cm (Bouma and others, 1978a).


156°
155°
154°
153°
152°
151°
150°
149°
62°
61°
60°
59°
58°
57°
0
50
100 MILES
0
50
100 KILOMETERS
EXPLANATION
Fault-Hachures on downthrown side
Area with bedforms ranging in height from 0.2 to 2 m
Area with bedforms ranging in height from 2 to 12 m
Anchorage
COOK INLET
KENAI LOWLAND
KENAI PENINSULA
AUGUSTINE ISLAND
BARREN ISLANDS
SHUYAK ISLAND
KATMAI NATIONAL MONUMENT
SHELIKOF STRAIT
AFOGNAK ISLAND
Kodiak
KODIAK ISLAND
GULF OF ALASKA

Movement of sand waves and other bedforms can cause severe problems to offshore installations by undermining or burying fixed structures, anchors, semisubmersibles (when pontoons are close to the bottom), and pipelines. This kind of damage commonly occurs to the pipelines in the upper Cook Inlet (Visser, 1969). There, pipelines rupture repeatedly over several years; however others may remain intact for a long time (F. Duthweiler, oral commun., 1978). Environmental data has not been collected continuously in the upper Cook Inlet so there is no quantitative information that can be applied to the problems in the lower Cook Inlet.

Figure 3. Geomorphology of lower Cook Inlet. Surface faults that may be active are shown in two areas (1) Augustine Island and (2) around the Barren Islands.

Stratigraphic Units of the COST No. 1 Well

By Leslie B. Magoon

INTRODUCTION

The COST NO. 1 well, drilled by the Atlantic Richfield Company, penetrated sandstone, siltstone, shale, conglomerate, and coal. The stratigraphic units represented are the Naknek Formation (Upper Jurassic), Herendeen Limestone and Kaguyak Formation (Lower and Upper Cretaceous, respectively), and West Foreland Formation (lower Cenozoic). These units are shown in relation to the wireline well-log curves in figure 4.

Minor oil shows were found in the well but significant amounts of gas (C_1-C_5 hydrocarbons) were not. The well also lacked organic matter capable of generating significant amounts of oil or gas. However, the sandstones of the West Foreland Formation and Kaguyak Formation, and possibly the Herendeen Limestone, were of potential reservoir quality.

The interpretation of the COST No. 1 well in this report is based on the data of many workers. Data was submitted by industry, (Wills and others, 1978), as required by the U.S. government. Descriptions of conventional cores and sidewall cores were supplied by Ariey and McCoy (1977) and Ariey and Rathbun (1977). Petrographic analyses of sandstone were provided by Babcock (1977), Christensen (1977), Kuryvial (1977), Schluger (1977), and Swiderski (1977). Porosity and permeability data were supplied by Core Laboratories (1977a,b). Paleontologic reports were supplied by Boettcher (1977), Haga (1977), and Newell (1977a,b). Simpson (1977) and Van Delinder (1977) submitted the organic geochemical data.

UPPER JURASSIC ROCKS

This unit, dominantly siltstone, shale, and sandstone, extends from the bottom of COST No. 1 well at 3,775.6 m (12,387 ft) to 2,112 m (6,930 ft) for a minimum thickness of 1,663 m (5,457 ft). Cass Ariey (written commun., 1980) places the top of the unit at 2,135 m (7,005 ft) at the "abrupt change in character of (drill) cuttings, from a dirty-looking, but quartz-rich glauconitic sandstone above, to a light grey, or salt-and-pepper feldspathic sandstone below". According to the foraminiferal report, the top of the unit is at 2,109 m (6,970 ft) where the "hard gray sandstone becomes the dominant lithology". Turner (this volume), basing his decision on paleontological evidence, places the top of this unit at 2,417 m (7,930 ft). Wills and others (1978) place the top of the lowermost sandstone of the Lower Cretaceous at the large increase in interval velocity (decrease in interval transit time) that occurs at 2,088 m (6,850 ft). This calcite-cemented sandstone is diagenetically altered (Bolm and McCulloh, this volume) but does not contain zeolite (laumontite). The zeolite boundary in the well is 24 m (80 ft) below this altered sandstone. I place the top of this unit at 2,112 m (6,930 ft) just below the abundant *Inoceramus* fragments from the sidewall core at 2,109 m (6,920 ft) and just above the first extensive presence of zeolite (laumontite) at 2,146 m (7,040 ft). Here the resistivity, interval transit time, bulk density, and differential caliper curves do not change significantly because of the cements, laumontite below and calcite above. The high resolution dipmeter indicates a consistent dip of 2° to 8° to the northwest.

Paleontological evidence in this unit is sparse. Haga (1977) assigns a Middle to Late Jurassic age (Callovian to Tithonian) to the palynological evidence; Turner (this volume; fig. 5) assigns a Late Jurassic age (Oxfordian to Tithonian) to the foraminifers. The fossils suggest a marginal to shallow marine environment, possibly ranging as deep as middle neritic.

The dominant rock types found in the sidewall cores (fig. 6) are siltstone, shale, and sandstone. Modal analyses of 28 thin sections indicate that the sandstone is lithofeldspathic (Crook, 1960) with an average composition of $Q_{24}F_{55}L_{21}$, an average porosity of 17.9 percent, and an average permeability of 39 millidarcies (table 6).

The lower part of this unit (1,200-1,600 m; 3,900-5,200 ft) correlates with the Naknek Formation exposed in the Iniskin-Tuxedni region (Detterman and Hartsock, 1966); the upper part (450-600 m; 1,500-2,000 ft) correlates with the rocks exposed along the southwest coast of the Kamishak Bay.

Only 12 of the 172 recorded sidewall cores had favorable reservoir lithology. The organic carbon content from the core and drill cuttings ranges from 0.15 to 0.49 weight percent (fig. 7 and table 7). Traces of hydrocarbons were reported at many depths (table 8).

LOWER CRETACEOUS ROCKS

The COST No. 1 well penetrates 572 m (1,875 ft) of sandstone, siltstone, and shale from 1,540 m (5,055 ft) to 2,112 m (6,930 ft). The top of this unit is placed at the large, abrupt excursion of the gamma ray and resistivity curves and the slight excursions of the interval transit and bulk density curves (fig. 4). The dipmeter indicates consistent dips from 5

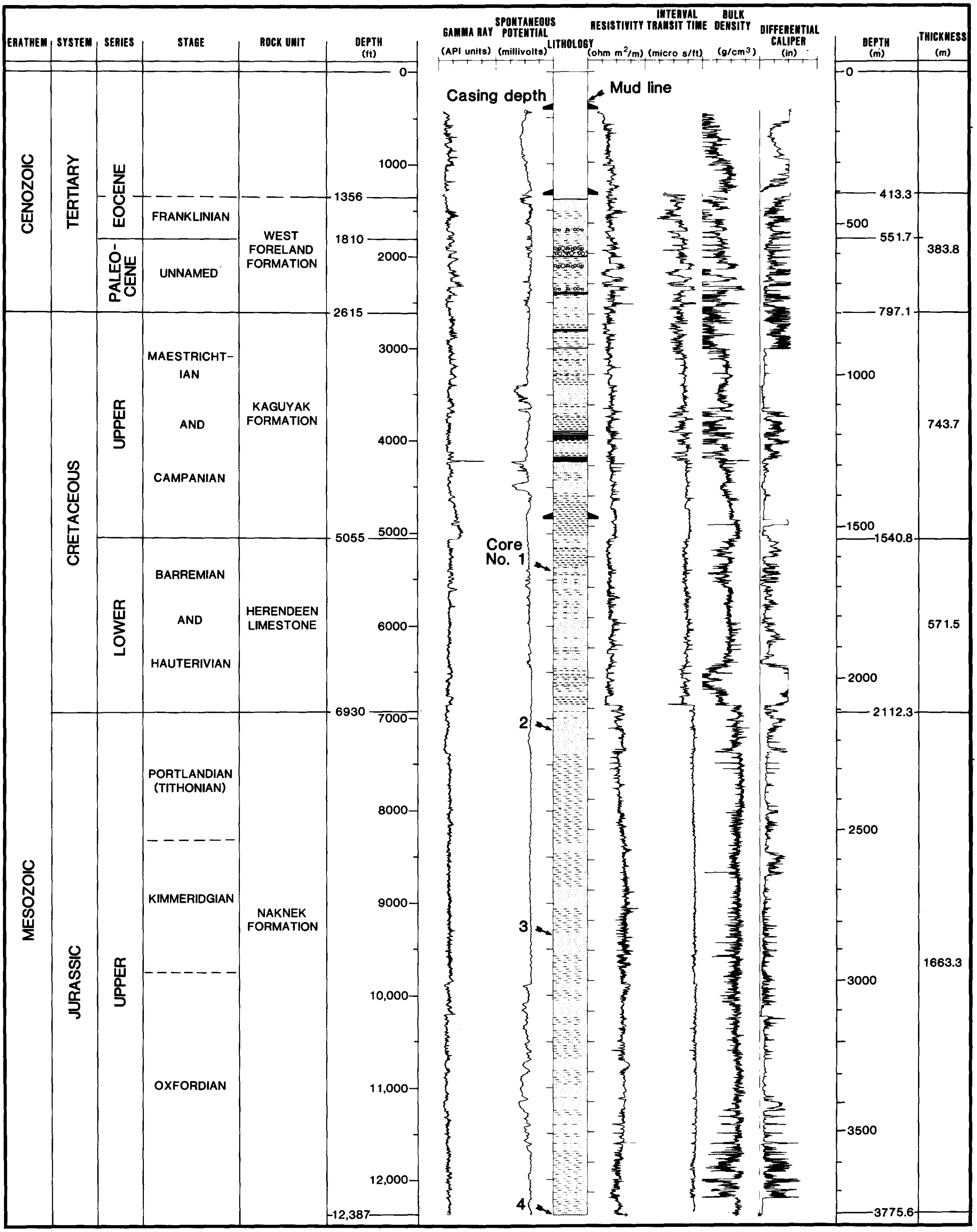


Figure 4. Wireline well-log curves, lithology, and rock units penetrated in the COST No. 1 well. The lithology symbols are: (1) solid lines are coal; (2) thin dashes are shale; (3) thin dashes and dots are siltstone; (4) dots are sandstone; and (5) circles are conglomerate. The arrows on the left of the lithology are the depths for core Nos. 1-4.

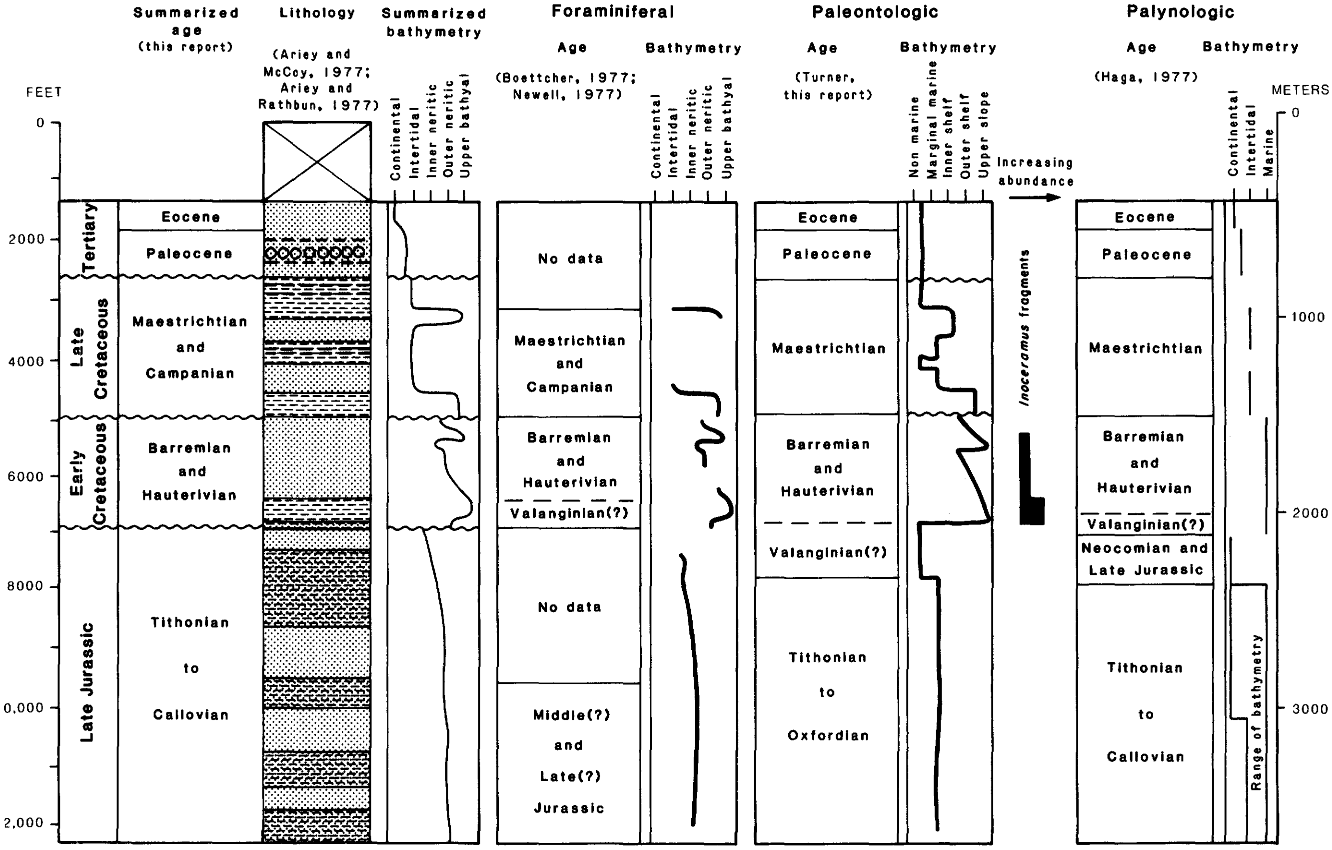


Figure 5. Age and depositional environment of the sediments from the cores of COST No. 1 well, determined from bathymetry as interpreted from foraminiferal and palynological data and *Inoceramus* fragments. See figure 4 for explanation of lithologic symbols.

to 10 to the east-northeast. Samples from the sidewall cores consist of sandstone, siltstone, shale, and fragments of *Inoceramus*. The *Inoceramus* fragments found below this unit were sloughed or caved.

Modal analyses of 37 thin sections made from the sidewall cores revealed that the lithofeldspathic sandstone has an average composition of $Q_{36}F_{44}L_{22}$, an average porosity of 21.5 percent, and an average permeability of 80 millidarcies (table 6). The average porosity and permeability of the sandstone from the conventional cores are significantly lower than the averages from the sidewall cores; the samples from depths of 1,643 m (5,390 ft) to 1,650 m (5,410 ft) have an average porosity of 13.9 percent and an average permeability of 0.3 millidarcies. The large differences are attributed to the difference in sampling methods; sidewall cores are fractured by a core gun.

A diverse assemblage of marine microplankton and calcareous nannofossils was found throughout this unit. These fossils indicate a Hauterivian to Barremian age except at the base; there the fossils may be as old as Valanginian. Foraminifers found between 1,594 m (5,230 ft) and 2,109 m (6,920 ft) substantiate the Hauterivian to Barremian age; they indicate middle bathyal to inner neritic marine environments.

This unit correlates with the Herendeen Limestone in the Kamishak Hills (Jones and Detterman, 1966). The rocks there are 215 m (705 ft) thick and are Lower Cretaceous in age (Magoon and others, 1978).

The organic carbon content from core and drill cuttings ranges from 0.07 to 0.55 weight percent. Hydrocarbons were reported at 1,646 m (5,400 ft) on the mud log (table 8).

UPPER CRETACEOUS ROCKS

The marine and nonmarine sediments that make up this unit in the COST No. 1 well are 744 m (2,440 ft) thick. The unit extends from 1,541 m (5,055 ft) to 797 m (2,615 ft); the top is placed at the small, abrupt excursion of the resistivity, interval transit time, and bulk density curves (fig. 4). The dipmeter indicates fairly consistent 5° dips to the north-northwest.

Modal analyses of 21 thin sections taken from sidewall cores reveal that the feldspathic sandstone has an average composition of $Q_{23}F_{61}L_{16}$, an average porosity of 22.8 percent, and an average permeability of 43 millidarcies (table 6).

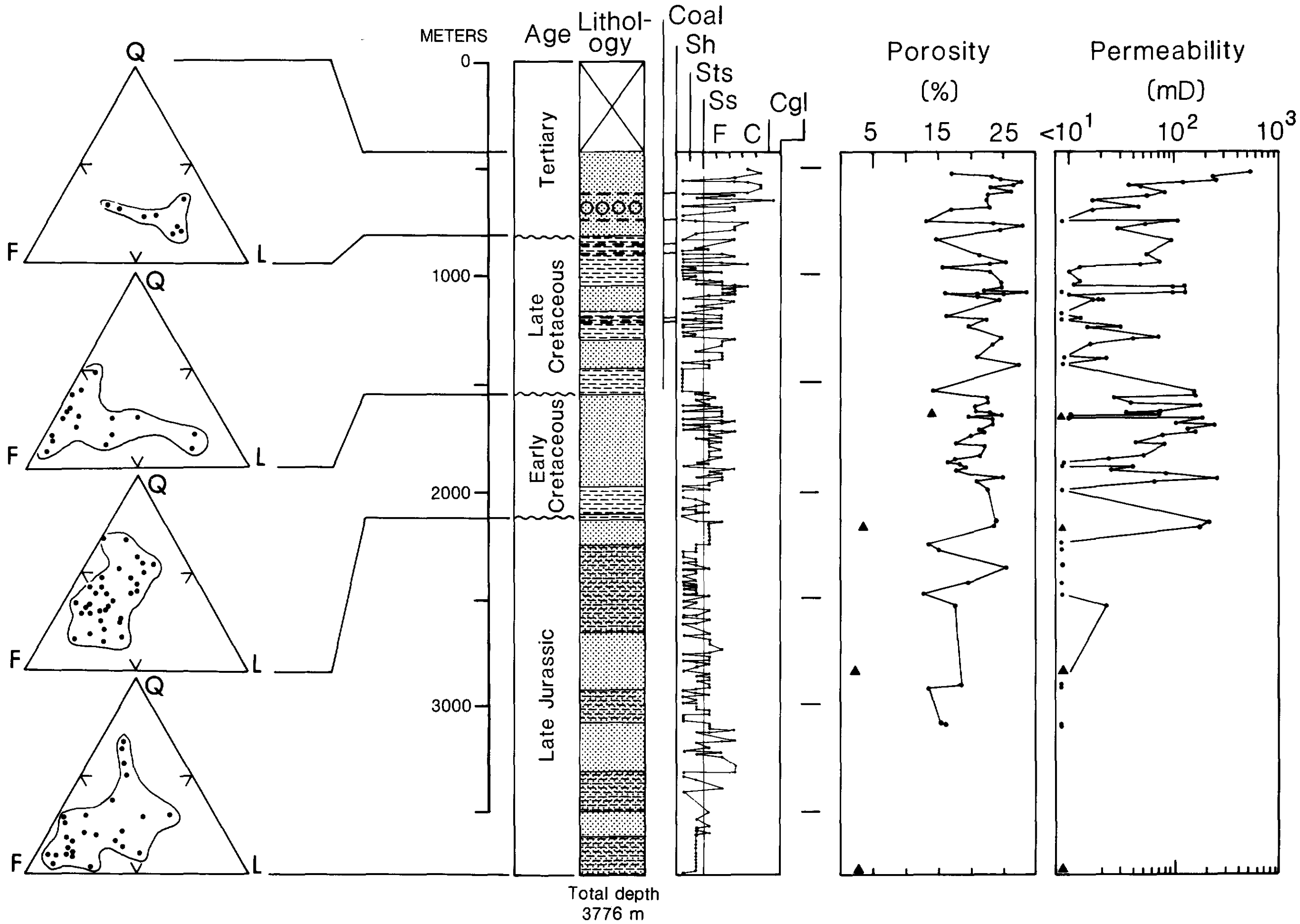


Figure 6. Sandstone composition, grain size, porosity, and permeability of stratigraphic units penetrated in the COST No. 1 well. Modal analyses done by oil company petrographers (Babcock, 1977; Christensen, 1977; Kuryvial, 1977; Schluger, 1977; Swiderski, 1977) and reported on by McLean (this volume), grain sizes from sidewall sample descriptions (Ariey and McCoy, 1977), and petrophysical properties from Core Laboratories (1977a,b). Abbreviations used are: Sh, shale; Sts, siltstone; Ss, sandstone; F, fine-grained sandstone; C, coarse-grained sandstone; and Cgl, conglomerate. See figure 4 for explanation of lithologic symbols. Triangles represent porosity or permeability values from cores.

The palynomorphs in this unit are Maestrichtian; the foraminifers are Campanian and Maestrichtian in age. Throughout two intervals, at 797-1,036 m (2,615-3,400 ft) and 1,036-1,541 m (3,400-5,055 ft), the palynomorphs and foraminifers indicate that the sediments were deposited in shallowing depths. The sediments change from upper bathyal marine to nonmarine, therefore two prograding sedimentary sequences make up this unit (fig. 5).

The Kaguyak Formation correlates with the Maestrichtian part of the Matanuska Formation north of Anchorage in the Matanuska Valley (Magoon and others, 1976a,b, 1980; Fisher and Magoon, 1978).

The organic carbon content from core and drill cuttings range from 0.22 to 1.07 weight percent (table 7). Three sandstones penetrated from 1,036 to 1,088 m (3,400-3,570 ft); from 1,286 to 1,294 m (4,220-4,245 ft); and from 1,353 to 1,381 m (4,440-4,530 ft) show log characteristics of potential hydrocarbon reservoirs. Hydrocarbons were reported at two depths, at 3,551-3,560 m (11,650-11,680 ft) and at 2,847 m (9,340 ft) (table 8).

LOWER CENOZOIC ROCKS

The first indication (minimum depth) of a lithologic break is 413 m (1,355 ft) and the next lower break is at 797 m (2,615 ft); so this unit is at least 384 m (1,260 ft) thick (fig. 4). Though the dips are inconsistent, the dip 5° in either a northwest or southeast direction is approximately right.

Samples from the sidewall cores are of sandstone, siltstone, coal, and some conglomerate (fig. 6). Modal analyses of eight thin sections of the sandstone indicate that it is feldspatholithic with an average composition of $Q_{23}F_{30}L_{47}$, an average porosity of 22.7 percent, and an average permeability of 108 millidarcies (table 6).

Table 6. Petrophysical properties of sandstone, COST No. 1 well

Rock unit	Thick-ness (m)	Measure-ments	Porosity (percent) Low	High	Average	Permeability (millidarcy) Low	High	Average
			Sidewall cores					
West Foreland Formation	419	17	13.2	28.1	22.7	2.2	565	108
Kaguyak Formation	709	35	15.6	28.9	22.8	1.8	153	43
Herendeen Limestone	571	28	17.7	25.2	21.5	1.7	265	80
Naknek Formation	1,664	12	12.6	25.5	17.9	.7	228	39
			Conventional cores					
Herendeen Limestone	6.7	12	8.5	19.5	13.9	0	0.8	0.3
Naknek Formation	7.6	27	1.8	6.7	3.5	0	7.8	0.6
Naknek Formation	4.9	17	0.3	3.3	2.2	0	0	0
Naknek Formation	9.2	31	1.1	4.1	2.9	0	0	0

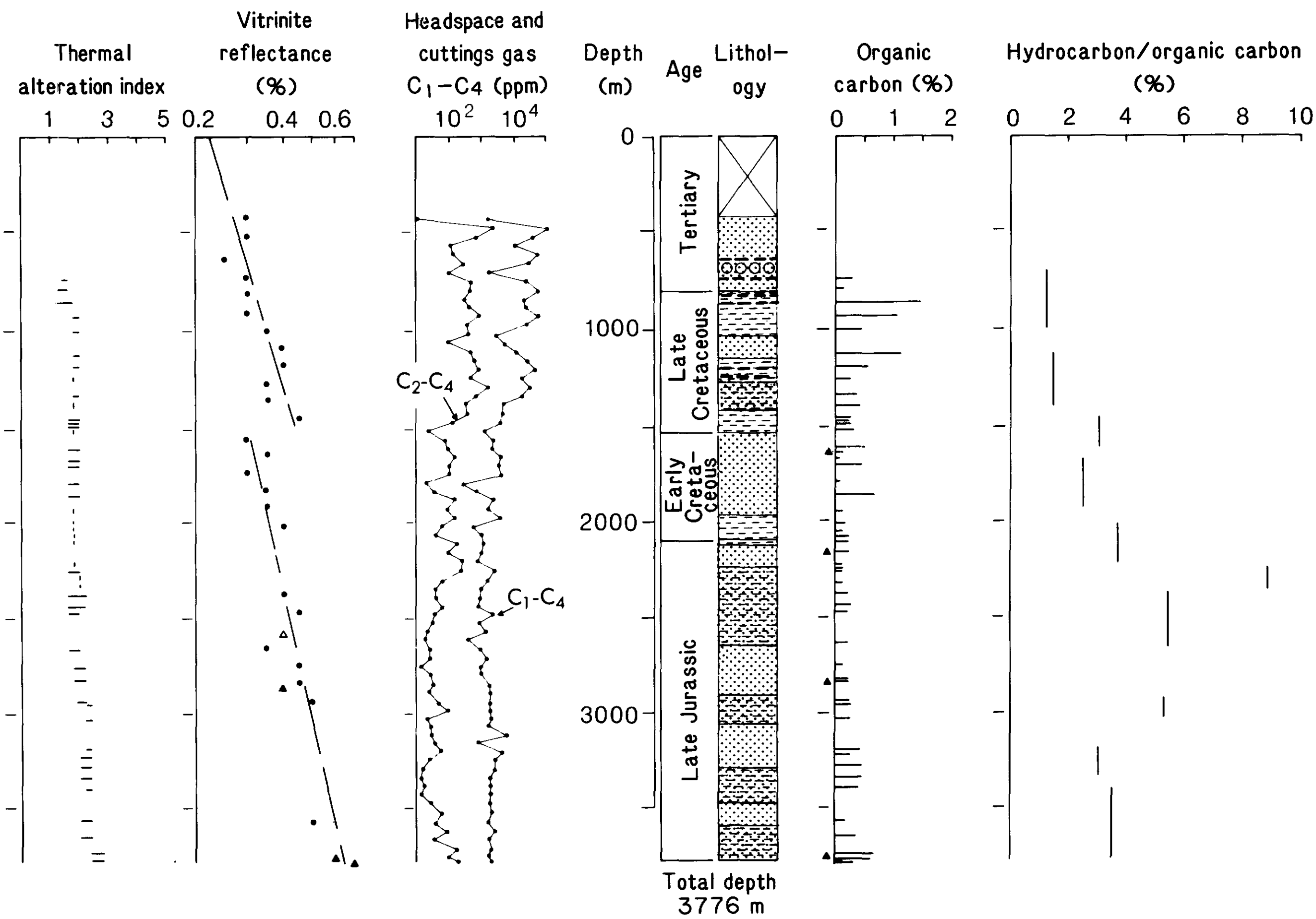


Figure 7. Organic geochemistry of stratigraphic units penetrated in the COST No. 1 well, from data provided by Geochem Laboratories (Van Delinder, 1977) and ARCO (Simpson, 1977). See figure 4 for explanation of lithologic symbols. In vitrinite reflectance, ▲, core; △, sidewall core; and •, drill cutting. In organic carbon, ▲, organic carbon in core.

Table 7. Organic carbon content of rock units penetrated in COST No. 1 well

[Number of samples from each core is in parentheses, content in weight percent]

Rock unit	Drill cuttings		Core	
	Composite	Picked	Sidewall	Conventional
West Foreland Formation	0.93(5)	0.55(4)	0.20(2)	--
Kaguyak Formation	1.07(8)	.22(8)	.56(12)	--
Herendeen Limestone	.55(6)	.07(8)	.26(10)	0.11(1)
Naknek Formation	.15(18)	.49(13)	.26(29)	.22(3)

The specimens of foraminifers, calcareous nannofossils, and radiolarians are nondiagnostic. The marine section, from 413 m (1,355 ft) to 552 m (1,810 ft), contains palynological evidence of Eocene age; and the nonmarine section, from 552 m (1,810 ft) to 797 m (2,615 ft), contains palynological evidence of Paleocene age. The nonmarine section also contains Mesozoic fossils.

This unit is assumed to be the West Foreland Formation which crops out on the west side of the Cook Inlet basin (Magoon and others, 1976b; Fisher and Magoon, 1978).

The content of organic carbon from the core and drill cuttings range from 0.20 to 0.93 weight percent (table 7).

Table 8. Hydrocarbon indications reported in the COST No. 1 well

[Oil in laumontite-lined fractures at 2,847 m, figure 18 this volume. NR, none reported]

Rock unit	Depth		Mud log	Geologist's log
	m	ft		
Kaguyak Formation	1,250	4,100	Cut fluorescence	NR
Kaguyak Formation	1,326	4,350	NR	Cut fluorescence
Herendeen Limestone	1,646	5,400	Cut fluorescence	NR
Naknek Formation	2,204-2,326	7,230-7,360	Cut fluorescence	Cut fluorescence
Naknek Formation	2,347-2,356	7,700-7,360	Cut fluorescence	Cut fluorescence
Naknek Formation	2,416-2,423	7,925-7,950	Cut fluorescence	Cut fluorescence
Naknek Formation	2,707-2,716	8,880-8,910	Cut fluorescence	NR
Naknek Formation	3,252-3,258	10,670-10,785	Cut fluorescence	NR
Naknek Formation	3,283-3,287	10,770-10,785	Cut fluorescence	NR
Naknek Formation	3,551-3,560	11,650-11,680	Cut fluorescence	Trace oil
Naknek Formation	3,598-3,621	11,805-11,880	Cut fluorescence	NR
Naknek Formation	3,766-3,776	12,357-12,387	NR	Cut fluorescence

Correlation of the COST No. 1 Well Data and the Marine Seismic Data

By Michael A. Fisher

INTRODUCTION

The purpose of this report is to compare the velocity information from COST No. 1 well with the velocity information from multichannel seismic data and to determine the ages of prominent seismic horizons by correlating the measured seismic reflections with the reflections calculated from the well data.

The COST No. 1 well is 7 km (4.3 mi) southwest of seismic line 752 and about midway between seismic lines 756 and 757 (fig. 8). The well location, when projected perpendicularly onto seismic line 752, is closest to shot point 830. The direction of the projection is parallel to the regional structural fabric of the basin which strikes northeast.

Sonic velocity data are derived from the interval-transit time of the sonic logs (fig. 9). By integrating sonic velocity data, converting depth to two-way time, RMS (root-mean-square) velocities can be computed from the equation:

$$V_{rms} = \left(\frac{1}{t}\int V_{son}^{2}\,dt\right)^{1/2}$$

where

V_{rms} = RMS velocity,
V_{son} = sonic velocity, and
t = two-way time.

Stacking velocities are computed during the stacking of multichannel reflection data. From the stacking velocities, interval velocities are calculated by using the equation:

$$V_{int} = \frac{V^2_{stk2}\,t_2 - V^2_{stk1}\,t_1{}^{1/2}}{t_2 - t_1}$$

where

V_{int} = interval velocity,
V_{stk} = stacking velocity, and
t = two-way time.

Sonic velocities can be compared to interval velocities, and RMS velocities can be compared to stacking velocities.

These velocities may compare poorly for several reasons. Dip of strata causes stacking velocities to vary whereas RMS velocities are unaffected. Different frequencies of sound waves are used to measure the velocities. Sonic velocities are measured with a 20 kHz wavelet over a distance of 2.4 m (8 ft) to 3.7 m (12 ft), whereas interval velocities are measured with frequencies between 5 and 50 Hz over a distance typically as large as 100 m (300 ft). Sonic logs may record higher velocities than those recorded by the seismic method because of frequency-dependent velocity dispersion.

Fisher and Magoon (1978) computed interval-velocity curves at 22 locations in the lower Cook Inlet basin and grouped the curves having similar values. Four sets of interval-velocity curves resulted, and the geographic area that contained one set of curves was called a velocity domain (fig. 8). An average of all interval-velocity curves in each set was used to convert reflection time to depth in each of the velocity domains. The COST No. 1 well is in domain 2.

Although the interval-velocity curve of domain 1 is close to the average of its sonic velocity curve, the interval velocity curve of domain 2 has lower values, about 15 percent, than the sonic velocity curve of COST No. 1 well (fig. 9*A*). This 15 percent difference between the interval velocity curve of domain 2 and the sonic velocity curve of the well means that the structure contour map of horizon C (Fisher and Magoon, 1978) gives depths in domain 2 that are too shallow by at most 15 percent. This difference can be expected because sonic logs give inherently higher velocities than interval velocities.

The abrupt increase in sonic velocity from 3,500 m/s to 4,500 m/s at just below the 2,000-m (6,560-ft) depth (fig. 9*A*) was evident in the sonic velocity curve but not in the interval velocity curve before averaging. The reason for the discrepancy is shown on the RMS velocity curve in figure 9*B*—the abrupt increase in sonic velocities causes only a slight inflection in the RMS velocity curve. The resolution of the stacking velocity data apparently is too poor to discriminate between such subtle features; hence, the interval velocities do not show the same abrupt increase as the sonic velocities.

RELATION BETWEEN WELL LOG AND SEISMIC DATA

Reflection coefficients were calculated from the sonic and density logs (fig. 10*C*). Some of the largest reflection coefficients result from erroneous velocity and density data

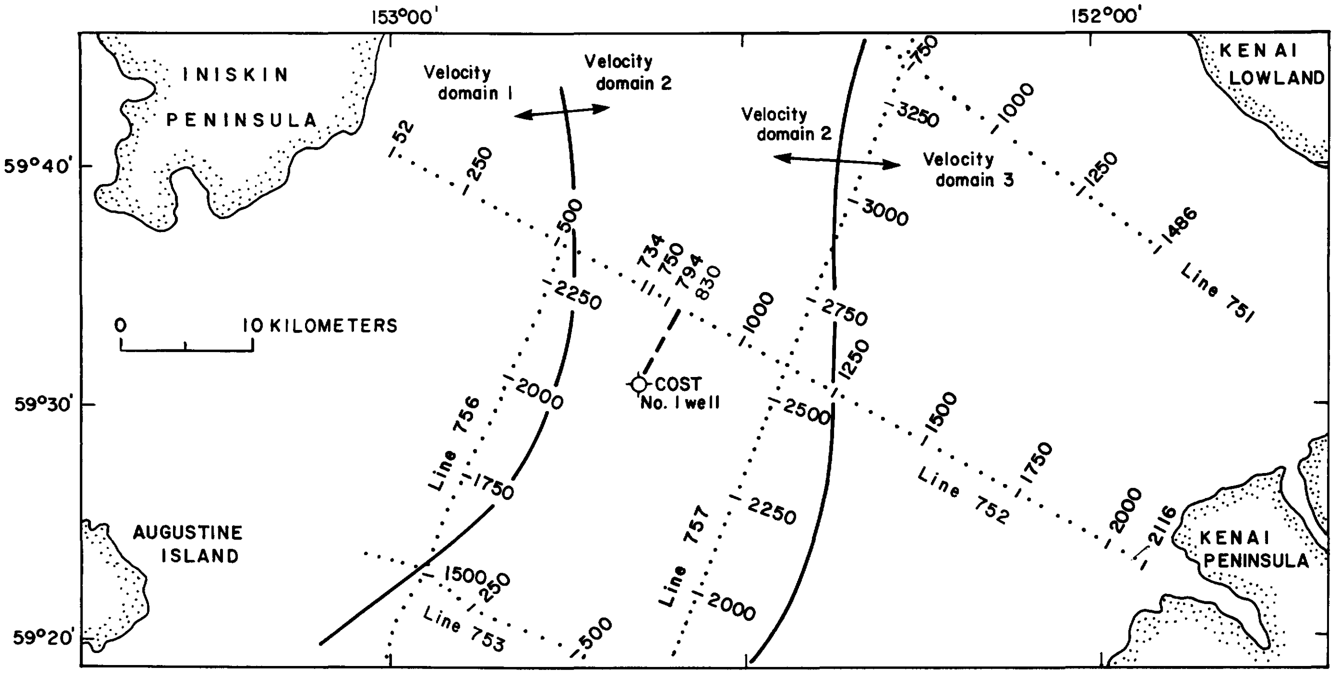


Figure 8. Location of COST No. 1 well and multifold seismic-reflection lines (dotted) in lower Cook Inlet. Numbers along seismic-reflection lines show the locations of shot points. Velocity domains (solid lines) are from Fisher and Magoon (1978).

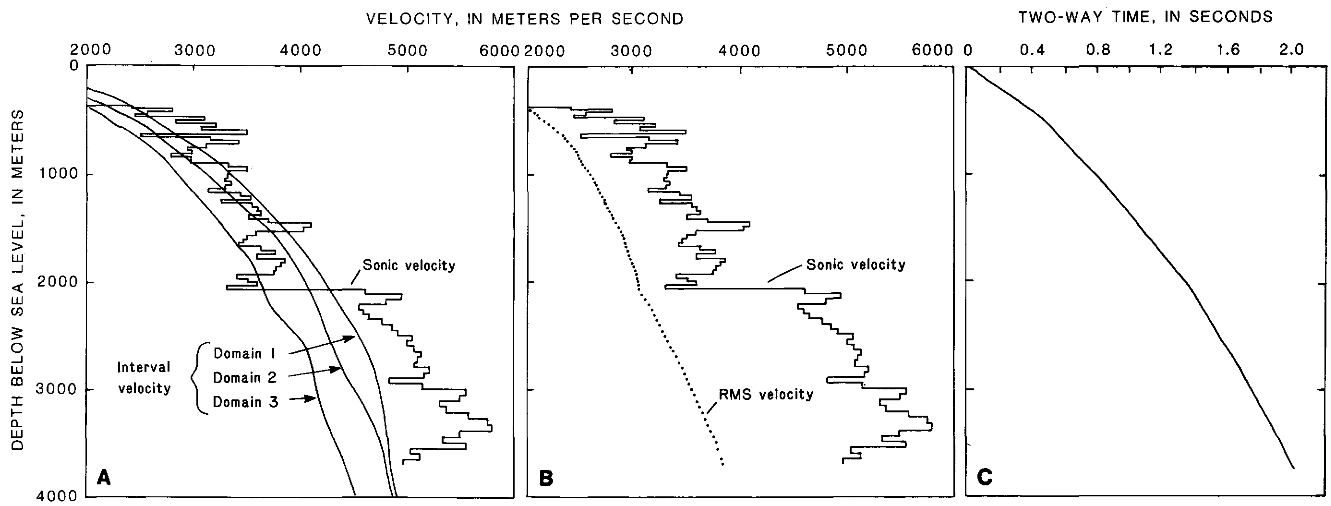


Figure 9. Velocity information from sonic logs and seismic data are compared. *A*, Comparison of interval-velocity curves of velocity domains 1 through 3 with the sonic velocity curve from the COST No. 1 well. *B*, Effect of large increase in sonic velocities or RMS velocities that are calculated from the sonic velocities. *C*, Time-depth curve from COST No. 1 well data. Datum is sea level.

that were obtained from zones where the borehole is washed out. In these washed out zones, both the sonic and density logs mimic the caliper log (fig. 4). This effect is most pronounced in the upper 900 m (2,950 ft) of the well but occurs also with lesser effect at depths of 1,200 m (3,935 ft), 2,000 m (6,560 ft), and 3,600 m (11,810 ft). These erroneous reflection coefficients that result from the rough borehole would produce spurious reflections on a synthetic seismogram; consequently, a synthetic seismogram is not included here.

The relation between well data and seismic data consists of a comparison of depths calculated from sonic logs to

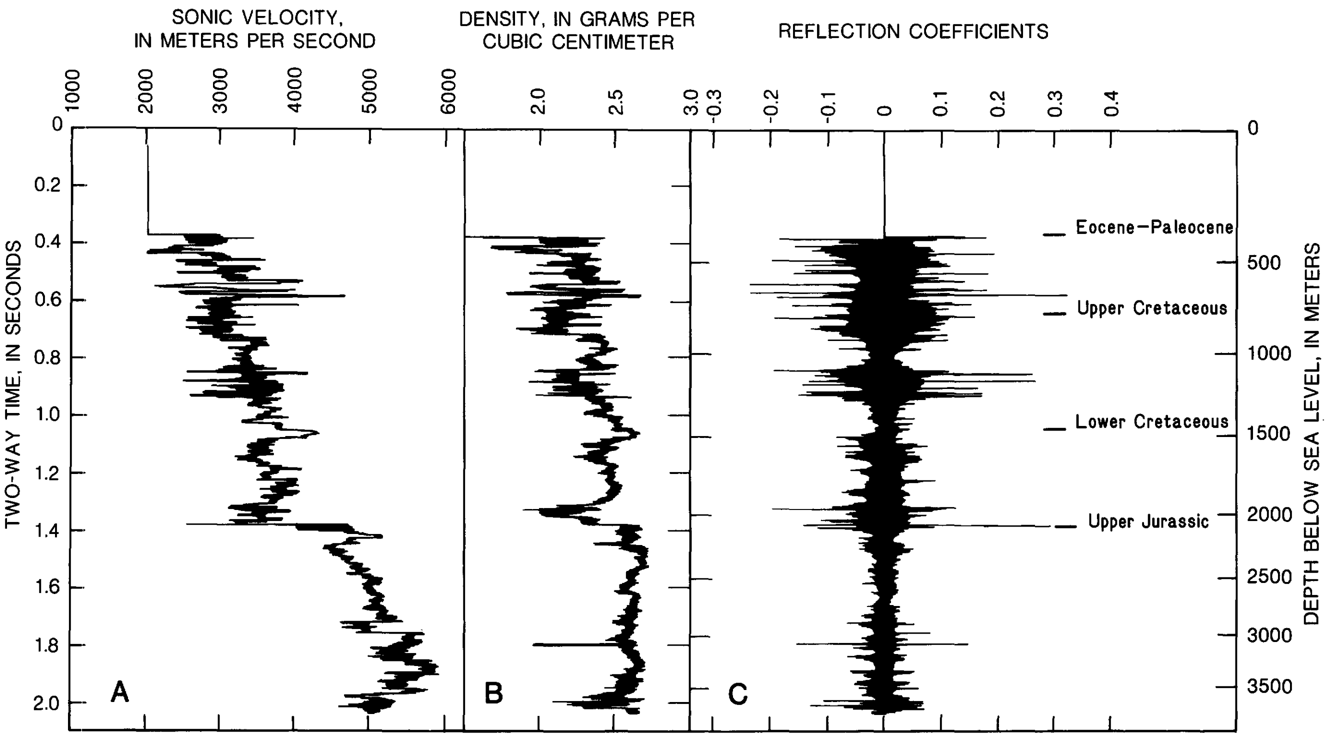


Figure 10. Relation between well-log and seismic data. *A*, Sonic velocity from the COST No. 1 well. *B*, Density from the COST No. 1 well. *C*, Reflection coefficients computed from the well data and formation tops. Datum is sea level.

certain horizons on an interpreted seismic line with depths to geologic interfaces in the well. These depths compare favorably despite the 7-km (4.4-mi) distance between the well and the line.

Three seismic horizons are shown on a segment of line 752 (fig. 11). Horizon A was thought to be at the base of Paleocene rocks by Fisher and Magoon (1978). However, the velocity data from the sonic log indicate that horizon A is at a depth of 900 m (2,950 ft), near the top of the Upper Cretaceous, at the projected well location. Although the washed out borehole invalidates much of the velocity and density data near this interface, the reflection coefficient at the base of the Paleocene rocks is near 0.06. In comparison, some of the reflection coefficients that result from the washed-out borehole are as large as 0.30. A reflection coefficient of 0.06 would produce a reflection of moderate strength. Line 752 near the projected well location shows that horizon A is strong in the northeast, weakens toward the southeast, and is of moderate to low strength near the projected well location.

The biostratigraphic evidence places the base of the Paleocene rocks in the well at a depth of 767 m (2,515 ft) (798 m [2,615 ft] from KB). Thus, the qualitative reflection strength and the depth to the horizon on the line and in the well are similar.

Horizon B is at a depth of 2,005 m (6,575 ft) at the projected well location on line 752. On seismic data, horizon B is a strong reflection that can be followed throughout the basin. Estimates of velocity and density across the Jurassic-Cretaceous contact suggest that the reflection coefficient is as large as 0.25.

The reflection may be caused by the Jurassic-Cretaceous contact. Or regionally, the reflection may depict the boundary between the rocks cemented by calcite and laumontite and the porous rocks. If so, then the reflection level may not always coincide with the Jurassic-Cretaceous contact. The contact between the Jurassic and Cretaceous rocks is at a depth of 2,082 m (6,830 ft) (2,112 m [6,930 ft] from KB) in the well. At that depth, the 20-m thick basal Cretaceous sandstone is cemented with calcite, and the Jurassic rocks are cemented with laumontite (Bolm and McCulloh, this volume). In the area of the well, then, horizon B is probably caused by the abrupt change in the physical properties of the rocks at the top of the thin Lower Cretaceous sandstone and the altered Jurassic rocks. Fisher and Magoon (1978) thought horizon B was at the base of the Lower Cretaceous, or more likely, at the base of the Upper Cretaceous.

The reflection coefficient at the unconformity between the Lower and Upper Cretaceous rocks is estimated to be about -0.06. This value should produce a moderate reflection. The unconformity between Lower and Upper Cretaceous rocks spans nearly 40 m.y.; this amount of geologic time does not produce a strong reflection in seismic data. Although the sonic and density logs both decrease at 1,511 m (4,955 ft) (1,541 m [5,055 ft] from KB), the depth of the unconformity

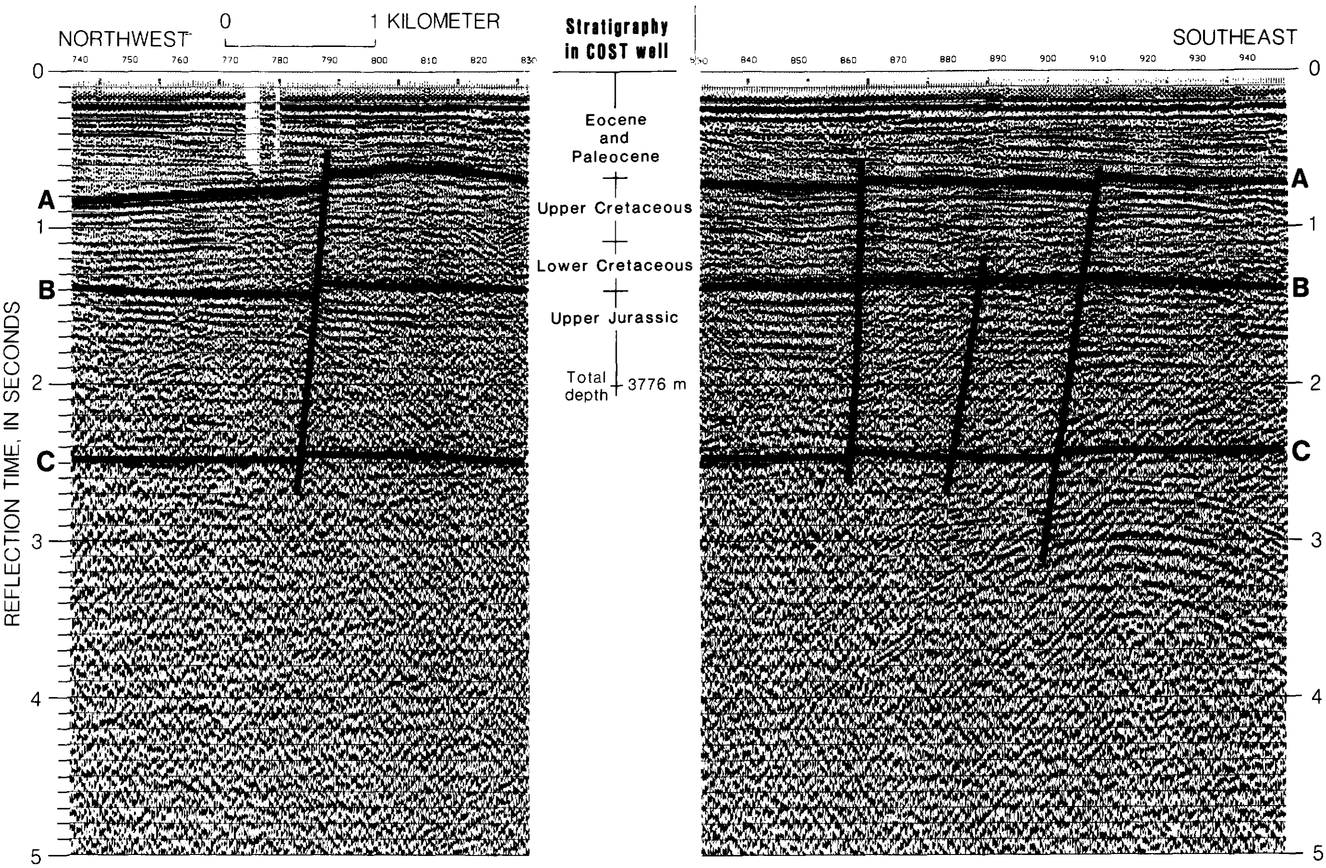


Figure 11. A part of seismic line 752 is split at shot point 830 into which the COST No. 1 well is projected. Horizon A is strong in northeast, weak toward southeast, and of moderate to low strength near projected well location. Horizon B is near the depth of the contact of the Jurassic and Cretaceous rocks. The stratigraphic position of C is extrapolated from the time-depth curve (fig. 10C). Horizon C, 1,400 m below the bottom of the well, is believed to be in upper part of Middle Jurassic rocks.

in the well, the caliper log shows that the hole is washed out in this area. If so, then this unconformity is not being delineated by a real seismic reflection.

Horizon C is 1,400 m (4,600 ft) below the bottom of COST No. 1 well and about 3,100 m (10,200 ft) below the top of the Upper Jurassic rocks. This top is based on an extrapolation of the time-depth curve that was derived from well data (fig. 10*C*) to the seismic time of horizon C. Along the Alaska Peninsula a composite stratigraphic section of Upper Jurassic rocks may be as much as 3,050 m (10,000 ft) thick (Burk, 1965), but at the Iniskin Peninsula the rocks are 1,435 m (4,700 ft) thick (Detterman and Hartsock, 1966) and at the Kamishak Hills they are 750 m (2,460 ft) thick (Magoon and others, 1976a). The COST No. 1 well penetrated only 1,663 m (5,455 ft) of Upper Jurassic rocks, therefore, horizon C may be the top of the Middle Jurassic Chinitna Formation or the top of the Tuxedni Group.

This estimate of the stratigraphic position of horizon C is approximate because the Chinitna Formation may thin southeastward from the Iniskin Peninsula across Cook Inlet (Fisher and Magoon, 1978) so the thickness of the formation measured onshore, even though the section may be incomplete, may be greater than the thickness of the formation at the location of the COST No. 1 well.

A cross section B-B′, constructed from seismic line 752 (Fisher and Magoon, 1978), shows the relations of the seismic horizons to the formations and COST No. 1 well (fig. 12). Horizons A, B, and C on the cross section can be compared to seismic line 752 in figure 11. The three seismic horizons that extend throughout the Cook Inlet basin appear to be caused by contacts at the base of the Paleocene rocks, near the base of the Lower Cretaceous rocks, and near the base of the Upper Jurassic rocks and the top of the Middle Jurassic rocks.

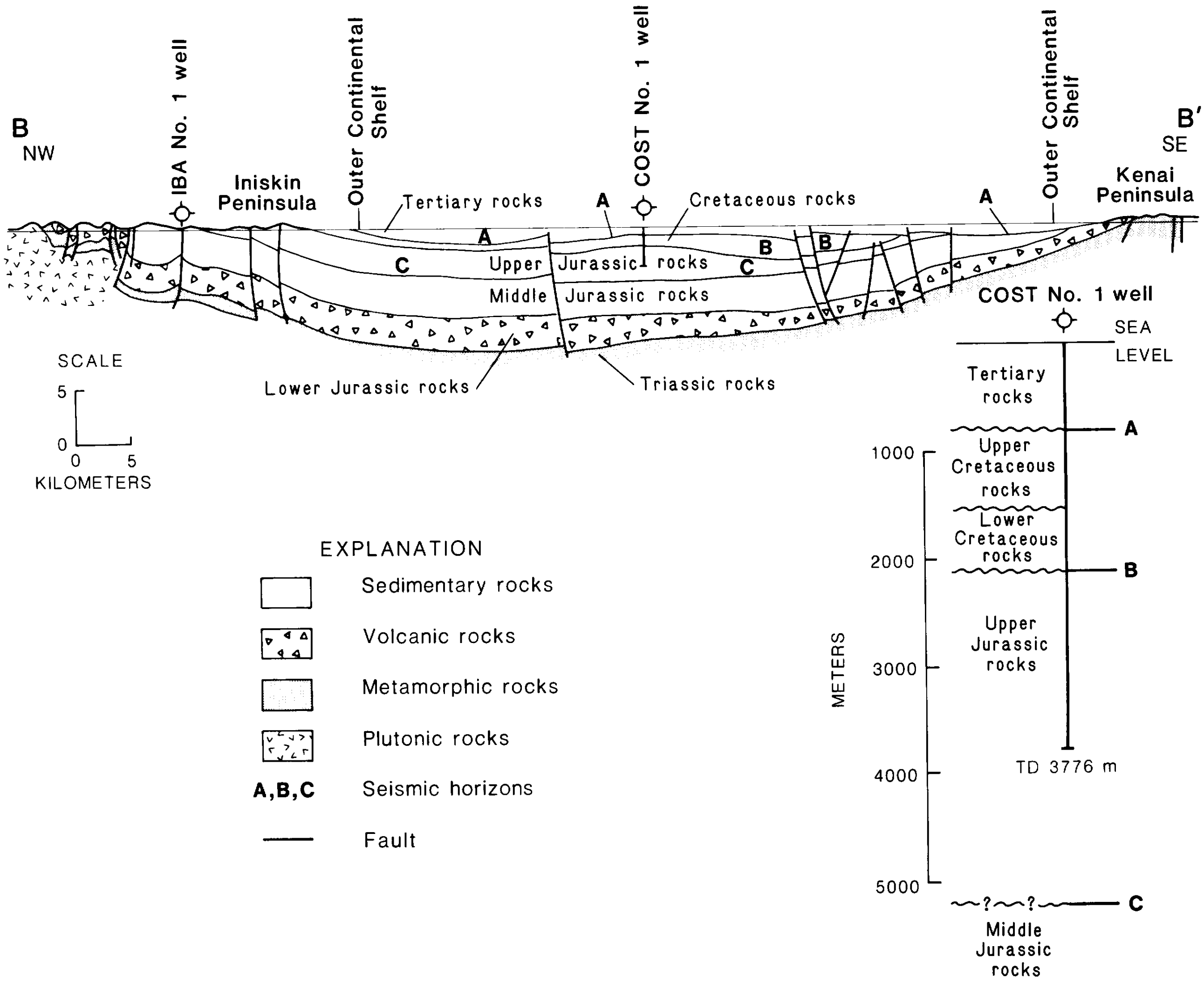


Figure 12. Lower Cook Inlet COST No. 1 well, placed on cross section B-B', is constructed from seismic line 752 (Fisher and Magoon, 1978). Major reflectors A, B, and C, are indicated on the cross section and in the enlarged inset at right. The location of this cross section is shown on figure 34 in this volume.

Paleontology and Biostratigraphy of the COST No. 1 Well

By Ronald F. Turner[2]

INTRODUCTION

Biostratigraphic and paleoenvironmental interpretations of the COST No. 1 well are based on the detailed analysis of assemblages of foraminifers, marine and terrestrial palynomorphs, calcareous nannoplankton, and radiolarians. Well cuttings from 413 m (1,356 ft) to 3,776 m (12,837 ft) collected at 30 ft intervals were disaggregated by treatment with mineral spirits or by boiling in Quaternary-O industrial detergent and washed over a 200 mesh (75 micron) screen. Conventional cores and material taken from sidewall cores were prepared and examined in the same manner.

Palynological slides, calcareous nannoplankton slides, and biostratigraphic reports prepared for the industry participants by Anderson, Warren and Associates (Boettcher, 1977; Haga, 1977; Newell, 1977a,b) were analyzed, interpreted, and integrated with the foraminiferal analysis. Radiolarian identifications were based on the work of Pessagno (1977) and Mickey (oral commun., 1978). Palynological identifications and interpretations generally follow Haga (1977), although the dinoflagellate taxonomy has been updated to conform with the systematics proposed by Stover and Evit (1978). Calcareous nannoplankton interpretations are based on Newell (1977a). Foraminiferal identifications and interpretations are based on the work of Bandy (1951), Bartenstein and Bettenstaedt (1962), Boettcher (1977), Church (1968), Dailey (1973), Martin (1964), Maync (1973), McGugan (1964), Scott (1974), Sliter (1968, 1973), Sliter and Baker (1972), and Trujillo (1960). Ostracode identifications are from Holden (1964) and Swain (1973).

Examination of paleontologic samples from wells is usually from top to bottom, so the biostratigraphic units are discussed from youngest to oldest. A summary of my interpretation is on figure 5.

BIOSTRATIGRAPHY

Eocene

The interval from 413 m (1,356 ft, first sample) to 552 m (1,810 ft) represents a predominately nonmarine depositional environment. A warm temperate paleoclimate is indicated by a microfloral assemblage characterized by species of *Alnus, Carya, Ulmus, Tilia, Nyssa, Fagas,* and *Ilex*. Coal is present in most samples. No foraminifers are present. Calcareous nannoplankton are quite rare and poorly preserved in this interval, although specimens with affinities to *Markalius* sp. and *Cyclococcolithina* sp. support a Paleogene age. Rare reworked *Inoceramus* prisms were present in the first sample.

Paleocene

The nonmarine interval from 552 m (1,810 ft) to 799 m (2,620 ft) is characterized by a palynomorph assemblage containing *Paraalnipollenites confusus* associated with *Alnus, Carya,* and *Tilia*. Reworked specimens of Cretaceous and Jurassic palynomorphs occur sporadically throughout this interval. No foraminifers, calcareous nannoplankton, or siliceous microfossils were observed.

Late Cretaceous

The interval between 799 m (2,620 ft) and 1,539 (5,050 ft) is Maestrichtian in age. A well developed microflora containing specimens of *Aquilapollenites striatus, Aquilapollenites bertillonites, Cranwellia striata, Kurtzipites tripissatus, Sympolcacites sibiricus,* and *Wodehouseia spinata* is present in a nonmarine coal-bearing sandstone section from 799 m (2,620 ft) to 963 m (3,160 ft).

A Late Cretaceous marine microfossil assemblage of foraminifers, ostracodes, dinoflagellates, coccoliths, and molluscan fragments is present from 963 m (3,160 ft) to 1,036 m (3,400 ft). Rare specimens of the dinoflagellate *Palaeocystodinium* cf. *P. golzowense* and the calcareous nannoplanktons *Arkhangelskiella cymbiformis* and *Chiastozygus initialis* at 963 m (3,160 ft) presage the appearance of the relatively diverse Maestrichtian assemblage. The foraminiferal fauna is characterized by *Gavelinella whitei, G.* cf. G. *stephensoni, Cribrostomoides cretaceus, C. trifolium, Haplophragmoides kirki, H. excavatus, Trochammina* cf. *T. texana, Bathysiphon vitta, Gyroidinoides* cf. *G. nitidus, Praebulimina* sp., and *P. kickapooensis*. Rare trachylebrid ostracodes are present. Deposition probably occurred in an outer shelf to upper slope environment (100 to 600 m water depth). A dinoflagellate assemblage containing relatively rare specimens of *Isabelidinium cooksoniae, Palaeocystodinium* cf. *P. golzowense,*

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Spiniferites spp., and *Isabelidinium* cf. *I. cretaceum* is also present. This marine component of the palynomorph assemblage persists to a depth of 1,197 m (3,926 ft) (sidewall core data) and reappears with new, less diagnostic elements at 1,292 m (4,240 ft).

The predominantly sandstone section between 1,036 m (3,400 ft) and 1,402 m (4,600 ft) represents intertidal to nonmarine deposition. The interval from 1,036 m (3,400 ft) to 1,197 m (3,926 ft) is considered to be intertidal on the basis of the sparse, low diversity dinocyst assemblage noted above. The interval from 1,197 m (3,926 ft) to 1,265 m (4,150 ft) is nonmarine based on the presence of an entirely terrestrial microflora. Rare specimens of the calcareous nannoplankton *Micula* cf. *M. decussata, Watznaueria* sp., and *W. barnesae,* associated with a marine palynomorph assemblage characterized by *Ceratiopsis diebeli, Isabelidinium* cf. *I. cretaceum, I. belfastensis, Spiniferites* spp., *Palaeocystodinium* cf. *P. golzowense,* and *Baltisphaeridium* sp., indicate an inner neritic environment from 1,265 m (4,150 ft) to 1,402 m (4,600 ft). This dinocyst assemblage is present in samples down to the major unconformity between the Late and Early Cretaceous at 1,539 m (5,050 ft).

An abundant and diverse Late Cretaceous (Maestrichtian) forminiferal fauna indicative of an upper slope paleoenvironment is present between 1,402 m (4,600 ft) and 1,539 m (5,050 ft). Forty-one genera containing ninety species were identified. The most significant are listed in table 9.

The only planktonic foraminifer observed was a single crushed specimen tentatively assigned to *Hedbergella*. Rare fragments and crushed specimens of ostracodes with possible affinities to *Cytheresis* sp., *Cletocytheresis* sp., and *Paracypris* sp. are present.

Early Cretaceous

A major unconformity exists between the Late Cretaceous (Maestrichtian) and the Early Cretaceous (Neocomian). The Neocomian (Hauterivian to Valanginian) section from 1,539 m (5,050 ft) to 2,417 m (7,930 ft) contains a relatively diagnostic assemblage of foraminifers, calcareous nannoplankton, and marine and terrestrial palynomorphs, but the presence of reworked material, downhole contamination, poor preservation, and sparsely fossiliferous intervals complicate age and environmental interpretations.

A marine dinoflagellate assemblage indicative of a Hauterivian to Barremian age is present from 1,539 m (5,050 ft) to 2,085 m (6,840 ft). This assemblage is characterized by *Cyclonephelium distinctum brevispinatum, Clathroctenocystis elegans, Dimidiadinium uncinatum, Omatia alaskaensis, O. butticula, Oligosphaeridium* cf. *O. complex, Prionodinium alaskense, P. alveolatum, Muderongia simplex, M. staurota, Gonyaulacysta serrata,* and *Gardodinium trabeculosum*. The presence of *Nelchinopsis kostromiensis* at 2,085 m (6,840 ft) suggests a possible Valanginian age. A calcareous nannoplankton assemblage of Hauterivian to Valanginian age containing *Cruciellipsis* cf. *C. cuvillieri, Calcicalathina* cf. *C. oblongata, Cyclagelospheara* sp., *Diazonatolithus lehmanni,* and *Nannoconus colomi* is pres-

Table 9. Late Cretaceous (Maestrichtian) foraminifers found between 1,402–1,539 m in the COST No. 1 well

Psammosphaera spp.	Guadryina tailleuri	Dorothia bulletta
Hippocrepina sp.	G. cf. G. austinana	Bathysiphon brosgei
Saccammina sp.	G. pyramidata	B. vitta
Gyroidinoides trujilloi	Hoglundina supracretacea	B. varans
G. nitidus	Osangularina cordieriana	B. californicus
G. globosa	Gavelinella whitei	Glomospira charoides corona
G. quadratus	G. stephensoni	Dentalina spp.
G . cf. G. bandyi	G. eriksdalensis	Nodosaria spp.
Pullenia spp.	G. nacatochensis	Lagena spp.
Bolivina incrassata	G. cf. G. henbesti	Fissurina spp.
B. cf. B. decurrens	Cribrostomoides cretaceus	Pseudonodosaria spp.
Lenticulina ovalis	Haplophragmoides kirki	Quinqueloculina sandiegoensis
L. cf. L. williamsoni	H. fraseri	Stilostomella pseudoscripta
L. cf. L. warregonensis	H. excavatus	Marginulina curvatura
Praebulimina kickapooensis	H. famosus	M. bullata
P. venusae	Reophax globosus	Sarcenaria triangularis
P. spinata	Trochammina boehmi	Marginulinopsis texasenis
P. cushmani	T. texana	Guttulina adhaerens
P. aspera	T. pilea	Pyrulina sp.
P. lajollaensis	Silicosigmoilina californica	Globulina lacrima
Pyramidina prolixa	Rzehakina epigona	

ent between 1,841 m (6,040 ft) and 2,134 m (7,000 ft).

The foraminiferal fauna present in the interval from 1,585 m (5,200 ft) to 2,106 m (6,910 ft) indicates an Hauterivian to Barremian age. The most significant fauna are listed in table 10.

Early Cretaceous paleobathymetry fluctuated twice from upper slope to inner to middle shelf depths, indicating two major periods of regression. The interval from 1,539 m (5,050 ft) to 1,585 (5,200 ft) represents an intertidal to middle shelf (0 to 100 m) (328 ft) depositional environment. Upper slope faunas are present from 1,585 m (5,200 ft) to 1,676 m (5,500 ft) and from 1,932 m (6,340 ft) to 2,106 m (6,910 ft). The strata between the two upper slope faunas generally reflect an inner or middle shelf paleoenvironment.

Few dinoflagellates or calcareous nannoplankton are present in the predominantly intertidal marine section below 2,143 m (7,030 ft). A nonmarine Neocomian to Late Jurassic microflora containing species of *Deltoidospora, Lycopodiumsporites, Osmundacites,* and *Taurocusporites segmentatus* is present from 2,160 m ((7,087 ft) to 2,417 m (7,930 ft). The exact position and nature of the Cretaceous-Jurassic contact could not be determined because of the absence of age diagnostic taxa. The hiatus may represent all of Berriasian time.

Late Jurassic

A Late Jurassic (Tithonian to Oxfordian) dinoflagellate assemblage characterized by *Gonyaulacysta cladophora, G. jurassica, Pareodina certaphora, Pluriarvalium osmingtonense, Scriniodinium crystallinum,* and *Sirmiodinium grossi* is present in the interval from 2,417 m (7,930 ft) to 3,776 m (12,387 ft; total depth). The calcareous nannoplankton assemblage contains species that are present in both the Cretaceous and Jurassic, although below 2,445 m (8,020 ft) forms with Jurassic affinities increase. The Jurassic paleoenvironment was predominately intertidal to inner neritic. The radiolarian fauna contains *Parvicingula* cf. *P. hsui, Hsuum* cf. *H. stanleyensis, Cenosphaera* spp., *Spongiodiscus* spp., and *Archeodictyomitre* cf. A. *rigida.* It is difficult to ascertain whether the radiolarians that sporadically occur in the Jurassic section are *in situ,* as reworked silicified and pyritized Late to Middle Jurassic radiolarians are present throughout the Mesozoic section.

Table 10. Early Cretaceous (Hauterivian into Barremian) foraminifers found between 1,585 to 2,106 m in the COST No. 1 well

Lenticulina muensteri	A. pachynota	Dorothia gradata
L. bronnii	Sarcenaria aff. S. triangularis	Textularia cf. T. klamathensis
L. saxonica	Marginulinopsis cf. M. collinsi	Haplophragmoides topagorukensis
L. gaultina	M. cf. M. gracilissima	H. cf. H. inconstans
L. discrepans	M. cf. M. cephalotes	Trochammina spp.
L. eichenbergi	Globulina prisca	Lingulina buddencanyonensis
L. heiermanni	Ramulina sp.	Planomalina buxtorfi
L. schloenbachi	Vaginulina sp.	Praebulimina cf. P. churchi
L. cf. L. guttata	Citharina sp.	Rheinholdella aff. R. dreheri
L. turgida	Rhizammina sp.	Hoeglundina anterior
L. ouachensis	Glomospira charoides corona	H. caracolla caracolla
Gavelinella andersoni	Dentalina spp.	Marssonella kummi
G. cf. G. barremiana	D. distincta	M. cf. M. trochus
Astacolus onoanus	D. aff. D. porcatulata	Gubkinella californica
A. calliopsis	D. gracilis	
	Bathysiphon sp.	

Petroleum Geochemistry

By George E. Claypool

INTRODUCTION

Four conventional cores (fig. 4), which were obtained from COST No. 1 well, were taken from the Herendeen Limestone (Lower Cretaceous) and the Naknek Formation (Upper Jurassic). The samples were taken from near the top, 1,541 m (5,055 ft) of the Herendeen Limestone and near the top, 2,112 m (6,930 ft), middle, and bottom, 3,756 m (12,387 ft) of the Naknek Formation. All depths represent drilled depths measured from the rig Kelly bushing.

The samples were analyzed to provide information on the content, type, and thermal maturity of the organic matter. The wet oxidation technique modified after Bush (1970) was used to determine the organic carbon content. These analyses were performed by Rinehart Laboratories, Arvada, Colo. Conventional source rock analyses (table 11) were also used to determine the organic carbon content, extractable organic matter, and kerogen. The saturated hydrocarbon fractions of the extractable organic matter were analyzed by gas chromatographic techniques (fig. 13). The MP-3 thermal analysis method was used to evaluate the content, type, and thermal maturity of the organic matter (table 12).

The amounts of organic carbon, concentration of C_{15+} extractable hydrocarbon, and content of gas, methane through butanes (C_1–C_4), have been analyzed by Geochem Laboratories (Van Delinder, 1977), and these contents are shown plotted against sample depth in figures 7 and 14.

In the sidewall core samples, the amount of organic carbon is generally less than 0.4 percent except for the samples of nonmarine rocks from depths of about 900 m (2,950 ft). The nonmarine samples contain as much as 1.44 percent organic carbon.

The concentration of C_{15+} extractable hydrocarbons was determined directly and was estimated from the weight of pentane-soluble extractable organic matter. The concentrations, determined by both methods, generally are less than 100 ppm for composite cuttings and for sidewall and conventional cores. The content of methane through butanes (C_1–C_4) of the drill cuttings is less than 0.01 standard volumes of gas per volume of rock. This low gas content decreases in both total concentration and C_2–C_4 content with increasing depth.

The organic matter was analyzed by three different methods to determine carbon isotopic composition and the capacity for generating hydrocarbons. The three methods, elemental hydrogen-to-carbon ratio of kerogen, the pyrolytic hydrocarbon yield per unit of organic carbon, and $\delta^{13}C$ values of kerogen and extractable organic matter, are com-

Table 11. Conventional source rock analysis of extractable organic matter and kerogen in core samples from COST No. 1 well

[Organic matter analyzed by Carlos Lubeck, U.S. Geological Survey, Lakewood, Colo.; kerogen analyzed by Core Laboratories, Dallas, Tex.]

Depth (m)	Depth (ft)	Lithology/ core no.	Extractable organic matter: Bitumen (ppm)	Total hydrocarbons (ppm)	Hydrocarbon/ organic carbon (%)	Saturates/ aromatics	Kerogen: Atomic H/C	TAI	Vitrinite reflectance (mean %)
1,644.4	5,395								
1,646.5	5,402	Shale/core 1	84	48	1.9	1.3	ND	1.7	.41
2,165.3	7,104	Shale/core 2	61	36	1.8	3.0	ND	1.7	.42
2,845.0	9,334	Shale/core 3	50	32	1.6	2.2	.74	2.0	.50
3,766.4	12,357	Shale/core 4	80	43	5.4	2.6	.79	2.5	.55
3,775.6	12,387	Siltstone/core 4	144	77	8.5	2.9	ND	2.5	.58

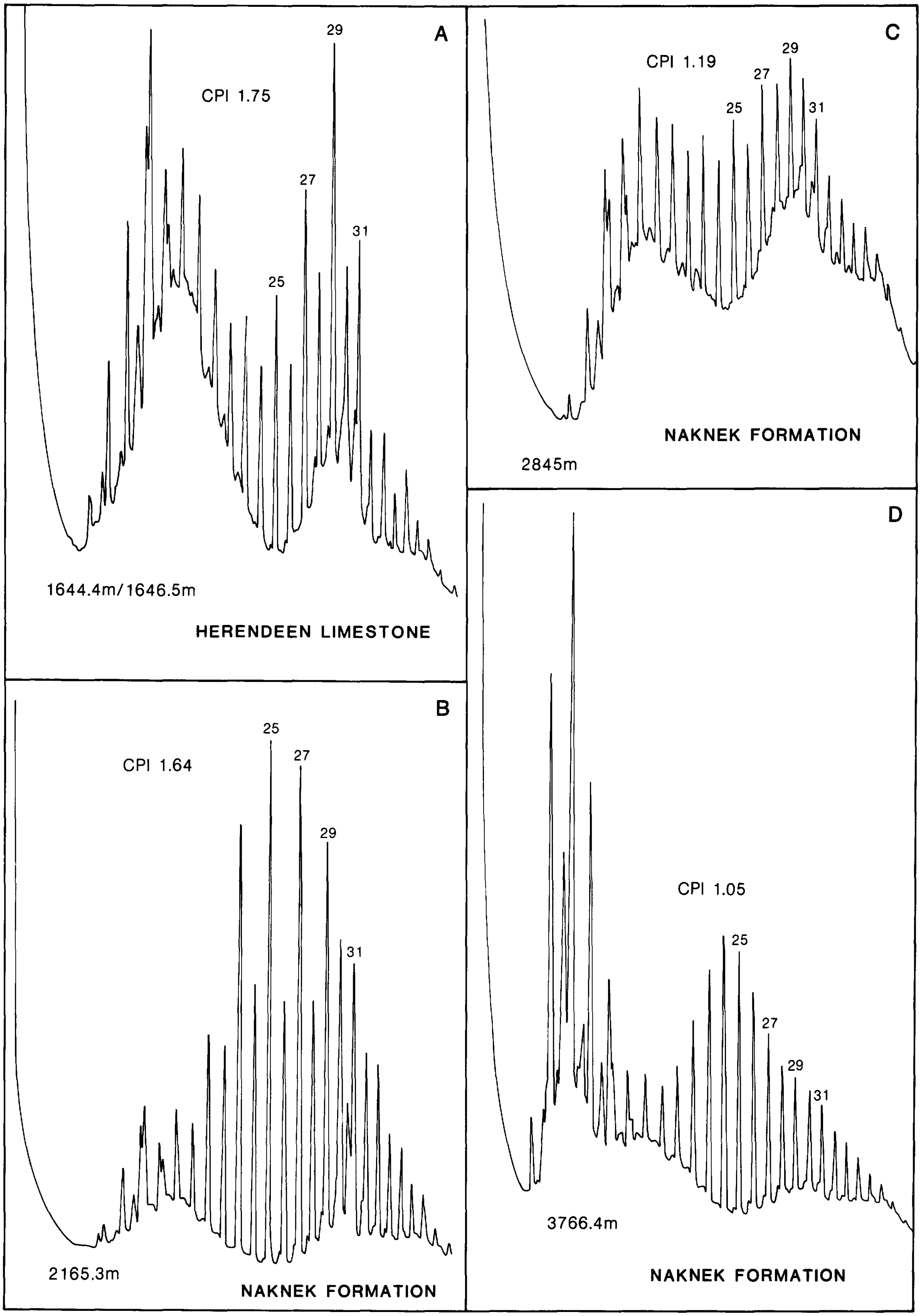


Figure 13. Gas chromatographic analyses of saturated hydrocarbons in samples from the COST No. 1 well, A through D with depths as indicated in table 11. CPI (carbon preference index) ranges from 1.75 to 1.05. Peak numbers refer to the number of carbon atoms for each *n*-paraffin compound.

Table 12. Thermal analysis of organic matter in the core samples from COST No. 1 well

[Thermal analysis (MP-3) by J. P. Baysinger, U.S. Geological Survey, Lakewood, Colo.; wet oxidation analysis of organic carbon by Rinehart Laboratories, Arvada, Colo.]

Depth interval (m)	Depth interval (ft)	Age	Organic carbon (OC) (weight %)	Total pyrolytic hydrocarbon yield (PHC) (weight %)	Volatile hydrocarbon content (VHC) (weight ppm)	Temperature of maximum pyrolysis yield (°C)	PHC/OC (%)	$\frac{PHC+VHC}{OC}$ (hydrocarbon index mg HC/g OC)	VHC/PHC (transformation ratio)
1,644.4	5,395	Early Cretaceous	0.65	0.062	35	475	9.6	90	0.06
1,646.8	5,403	Early Cretaceous	.41	.032	24	471	7.7	72	.08
2,165.3	7.104	Late Jurassic	.26	.020	21	481	7.8	69	.11
2,845.0	9,334	Late Jurassic	.20	.014	17	473	7.2	62	.12
3,766.4	12,357	Late Jurassic	.08	.009	27	480	12.2	79	.30
3,775.6	12,387	Late Jurassic	.17	.023	78	483	13.7	89	.34

pared and summarized in figure 15. Only five analyses of elemental hydrogen-to-carbon ratio of kerogen are available, but all analyses show that the organic matter is relatively hydrogen-deficient (H/C<1.0) even at shallow depths of burial where the organic matter is immature.

The pyrolytic hydrocarbon yield per unit of organic carbon, here defined as the total pyrolytic hydrocarbon yield minus the volatile hydrocarbon content normalized by organic carbon, is also low. The yield is from 62 to 90 mg HC/g OC, and its trend is not significantly related to depth. In the lower part of the well at 3,766.4 and 3,775.6 m (12,357 and 12,387 ft), the Upper Jurassic shales have slightly higher hydrocarbon to carbon ratios and pyrolytic hydrocarbon per unit of organic carbon than shales higher up in the well, even though the shales higher up are at a less advanced stage of thermal maturity. This fact may indicate that the organic matter in the lower part of the well originally was more rich in hydrogen than the organic matter higher up in the well. The fact may also indicate a difference in environment: possibly the organic matter in the lower part of the well was produced in a marine environment, but the amount preserved was too low to generate significant amounts of hydrocarbon.

The stable carbon isotope ratio, $\delta^{13}C$, primarily reflects the nature of the source material or the environment in which the organic matter was generated by photosynthesis; in addition, the differences in $\delta^{13}C$ among the kerogen, total extract, and the saturated hydrocarbons may indicate the maturity of the organic matter—the extent to which hydrocarbons have been generated from the organic matter. $\delta^{13}C$ expresses the stable carbon isotope ratio, $^{13}C/^{12}C$, in parts per thousand (per mil) deviations from the $^{13}C/^{12}C$ ratio of the PDB marine carbonate standard.

In the COST No. 1 well, the $\delta^{13}C$ values of kerogen range between −24 and −27 per mil. These values are consistent with organic matter derived from a mixed marine and nonmarine sediment.

The differences in values of $\delta^{13}C$ among the kerogen, total extract, and the saturated hydrocarbons changes with depth in the well. Above about 2,100 m (6,900 ft) in the well the saturated hydrocarbons are lighter than the total extract by 2-3 per mil, and the total extract is 1-2 per mil lighter than the kerogen. Below about 2,135 m (7,000 ft), the difference between the $\delta^{13}C$ values of saturated hydrocarbons and total extract decrease to about 1 per mil, but the difference between the total extract and the kerogen increases to about 2-2.5 per mil. This change probably reflects the increased maturity of organic matter in the lower part of the well. There the saturated hydrocarbons make up a greater proportion of the total extract, and the extractable organic matter is more petroleumlike in character.

Both the thermal analysis and gas chromatographic analysis of the saturated hydrocarbons show fairly consistent trends that indicate increasing thermal maturity with increasing depth (fig. 16). The transition from immature to mature hydrocarbon generation seems to be in the well interval from about 2,100-2,700 m (6,900-8,900 ft).

RESULTS AND DISCUSSION

The extractable organic matter of the Upper Jurassic and Lower Cretaceous rocks from the COST No. 1 well was measured by a variety of techniques to determine the character of its content, the amount present, and its degree of thermal maturity.

The organic carbon content in the core samples ranges from 0.08 to 0.65 weight percent (table 12). The organic carbon is more abundant in the upper part of the well than in the lower.

The core samples were also analyzed by the MP-3 thermal analysis method (Claypool and Reed, 1976). In this procedure, a small sample of rock is heated (40°C/min) in a flowing stream of helium. Using this procedure, measurements can be made of the total pyrolytic hydrocarbon yield, which is the total weight of hydrocarbons (or hydrocarbonlike compounds) given off during pyrolysis and distillation relative to the weight of the rock, the volatile

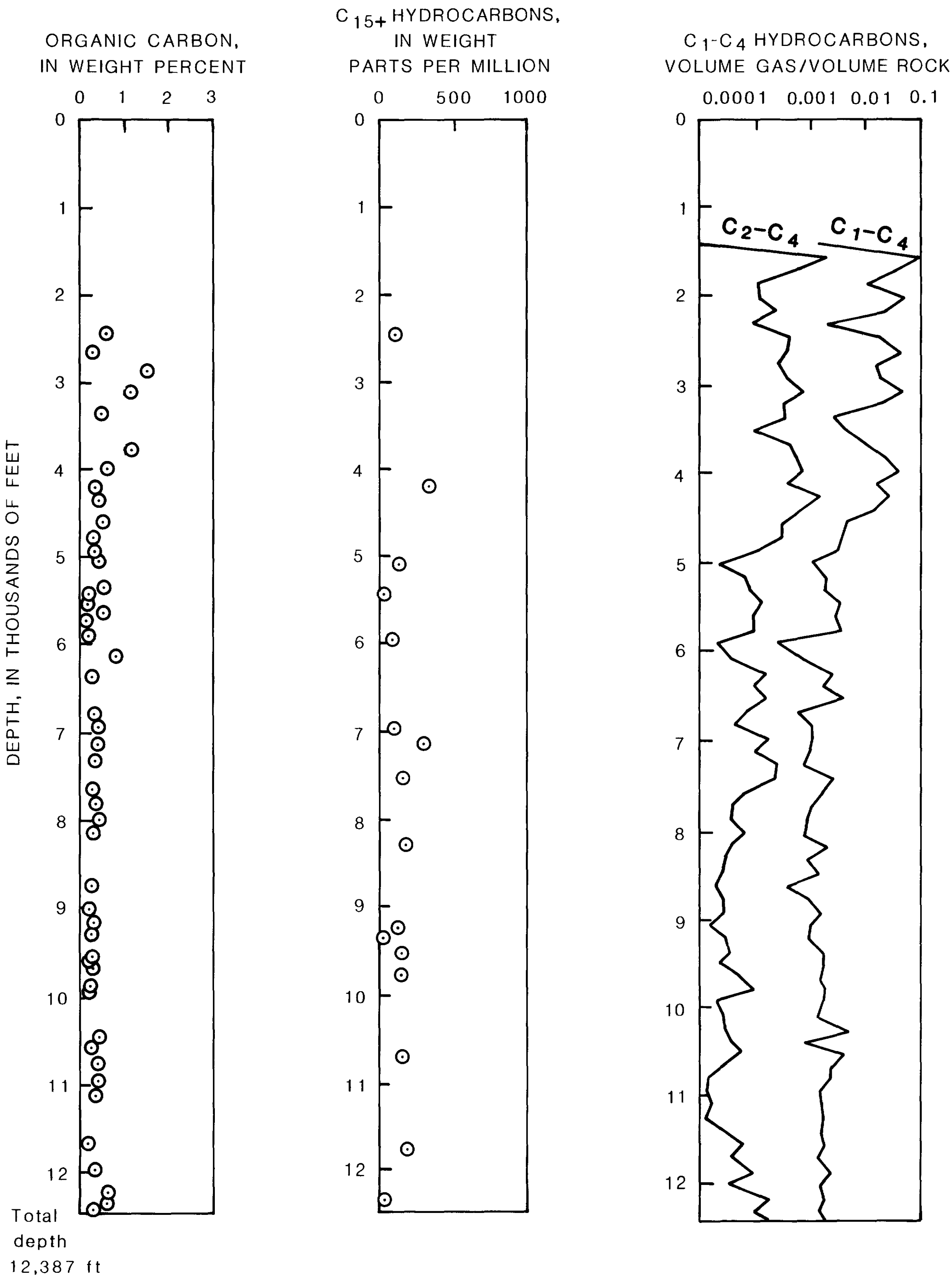


Figure 14. Summary and comparison of analyses of organic carbon and hydrocarbon contents of rocks in the COST No. 1 well. Data are from Van Delinder (1977).

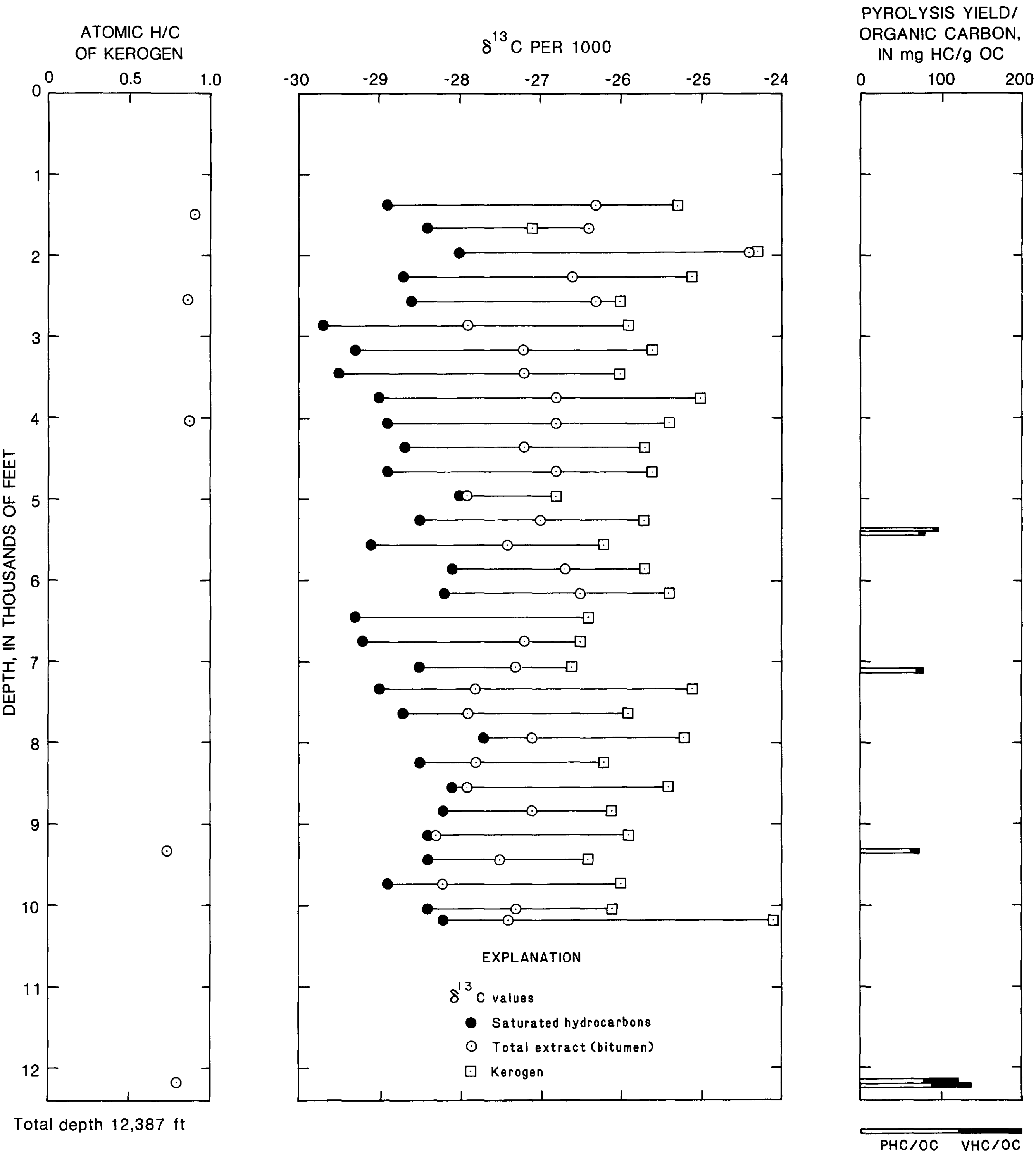


Figure 15. Summary and comparison of kerogen atomic hydrogen/carbon (H/C) ratios (Core Lab and Geochem data) as determined by COST No. 1 well group participant (Phillips Petroleum), $\delta^{13}C$ values of kerogen and extractable organic matter, and pyrolytic hydrocarbon yield normalized by organic carbon (USGS data, table 12) in rocks of the COST No. 1 well. $\delta^{13}C$ expresses the stable carbon isotope ratio, $^{13}C/^{12}C$, in parts per thousand deviations from the $^{13}C/^{12}C$ ratio of the PDB marine carbonate standard. PHC, pyrolytic hydrocarbon; VHC, volatile hydrocarbon; OC, organic carbon.

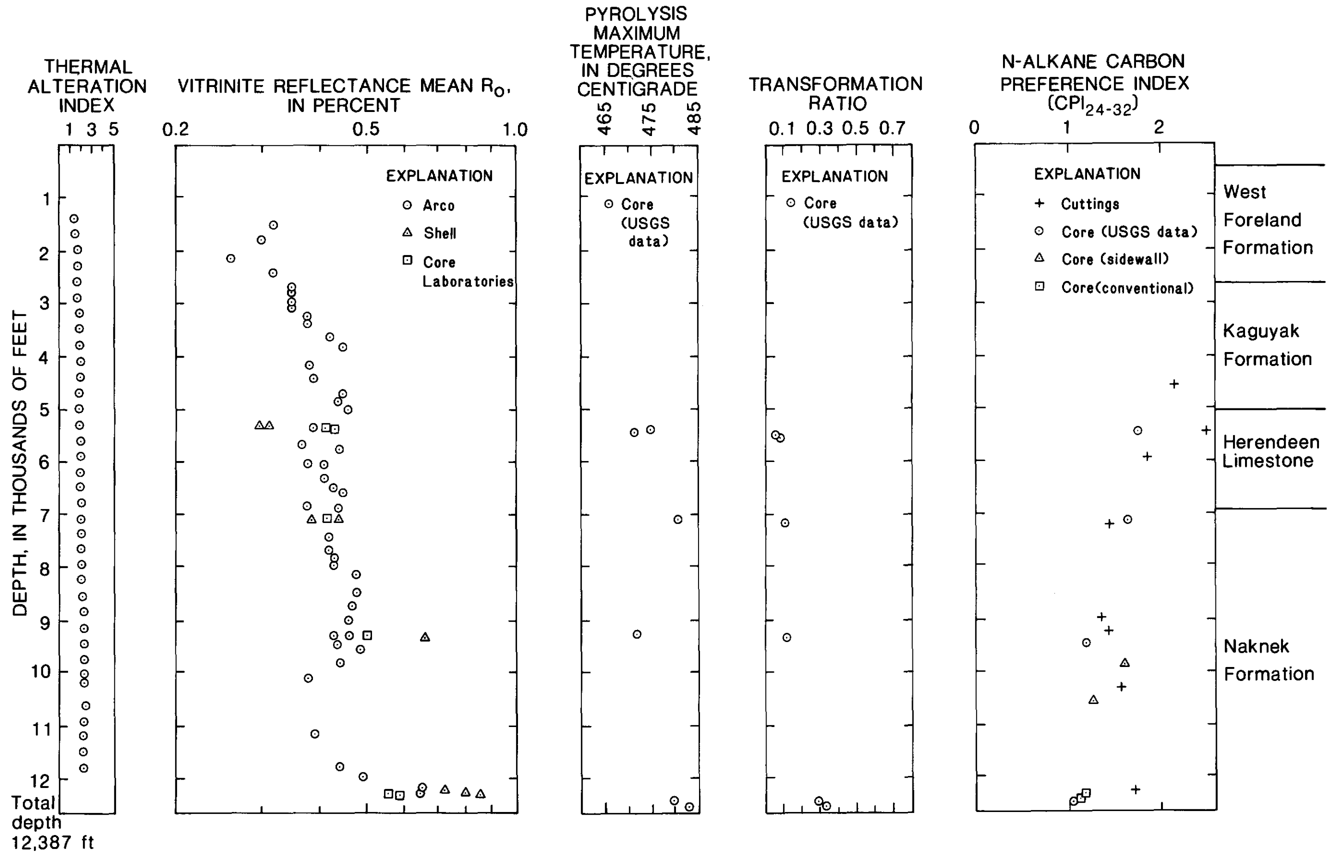


Figure 16. Summary and comparison of thermal alteration index (Van Delinder, 1977), vitrinite reflectance as determined by COST No. 1 well group participants and by Core Laboratories on USGS samples (table 11), temperature of maximum pyrolysis yield and transformation ratio (USGS data, table 12), and n-alkane carbon perference index (CPI_{24-32}) of organic matter in rocks of the COST No. 1 well.

hydrocarbon content, which is the portion of the total hydrocarbon yield produced by evaporation or distillation at lower temperatures, and the temperature of maximum yield, which is the temperature at which the yield of pyrolysis products is at a maximum. The results of the MP-3 thermal analysis are given in table 12.

The amount of total pyrolytic hydrocarbon yield, from 0.009 to 0.062 mg/g (table 12), falls short of the 2 mg/g that Tissot and Welte (1978, p. 447) define as the amount of oil-generating organic matter at an immature stage of thermochemical transformation necessarily present in a rock sample in order for it to be classified as a "potential oil source rock".

The total pyrolytic hydrocarbon yield per unit of organic carbon, from 7.2 to 13.7 mg HC/g OC, is relatively low. Interpreting thermal maturity from samples with low proportions of hydrogen-rich ("sapropelic") organic matter is usually questionable, but the results for these samples seem to be meaningful because they are corroborated by similar estimates of thermal maturity determined by other methods.

The volatile hydrocarbon-to-pyrolytic hydrocarbon ratio was determined for the core samples. This ratio is called the "transformation ratio" by Tissot and Welte (1978, p. 453) and the "production index" by Barker (1974). If the volatile hydrocarbon content is indigenous, then values of 0.1 or more indicate organic matter that has advanced to the oil-generating stage of thermal maturity. According to this interpretation, all the core samples below 2,165.3 m (7,104 ft) in the well are mature.

An empirical measure of thermal maturity, based on evidence collected in our laboratory, is provided by the temperature of maximum pyrolysis yield. We noticed that at a pyrolysis temperature of about 475°C the transition from an immature stage of thermal alteration to a mature stage of alteration occurs. By this criterion, the samples higher in the well are marginally mature and the lower samples are mature.

Analysis of the core samples by conventional source rock evaluation techniques (Claypool and others, 1978) produces results that indicate the organic matter was transformed to hydrocarbons to a more advanced degree than that indicated by thermal analysis.

The amounts of total extractable organic matter in the core samples (chloroform extractable bitumen) are low, from 50 to 144 ppm (table 11). Hydrocarbon concentrations, as determined by elution chromatography, range from 32 to 77 ppm. Vassoevich and others (1967) found that hydrocarbon concentrations in shales commonly average about 180 ppm. Therefore the hydrocarbon concentrations of the core samples of COST No. 1 well are below average for shales. The hydrocarbon content relative to organic carbon content in all of the core samples is greater than 1% or 10 mg HC/g OC, so that organic carbon has been transformed to hydrocarbons to an advanced degree.

The kerogen analyses generally substantiate the results of the thermal analyses. The atomic H/C ratios of less than 1 (table 11) confirm that the organic matter in the rocks at 2,845.0 m (9,334 ft) and 3,766.4 m (12,357 ft) are lacking in hydrogen.

The thermal alteration index and the vitrinite reflectance both increase consistently with increasing depth from 1,644.4 m (5,395 ft) to 3,775.6 m (12,387 ft). This is consistent with the increasing degree of thermal maturity with depth.

The alkane distributions of saturated hydrocarbon fractions of the extractable organic matter was determined by gas chromatography. Samples from shallower depths in the well have a distinct odd-numbered n-alkane predominance (figs. 13A and 13B). This feature is greatly reduced or absent in samples deeper in the well. This pattern is consistent with a transition from thermally immature to mature organic matter. The carbon preference index decreases with increasing depth, from 1.75 to 1.05 (fig. 13). This index, which Bray and Evans (1961) based on peak heights of n-alkanes with from 24 to 32 carbon atoms, also indicates a change from thermal immaturity to maturity.

CONCLUSIONS

The fine-grained Lower Cretaceous and Upper Jurassic rocks in COST No. 1 well contain a very low amount of organic matter compared to fine-grained rocks of this age worldwide, which average about 1 percent organic carbon. Moreover, the Mesozoic shales in this well contain much less organic matter than the Mesozoic sediments in the upper Cook Inlet, the North Slope, and in the other petroleum-producing areas of Alaska.

The section penetrated by COST No. 1 well does not contain prospective petroleum source rocks. Although the thermochemical transformation of the organic matter in the Mesozoic rocks is marginally mature to mature, the organic matter is dominantly of the type that has a poor oil-generating capacity. However, the prospect for petroleum of the lower Cook Inlet should not be judged on the data obtained from the COST No. 1 well alone. This well did not penetrate the shales of the Middle Jurassic—the source rocks for petroleum in the upper Cook Inlet (Magoon and Claypool, 1979, 1981). Migration paths from the Middle Jurassic rocks are crucial to the oil-generating system in the Cook Inlet basin.

Present-Day Geothermal Gradient

By Leslie B. Magoon

INTRODUCTION

By extrapolating from present-day subsurface temperatures, the threshold temperatures for various stages of hydrocarbon generation and sediment diagenesis can be approximated. Knowing the constant heat flux, burial depth at its historical maximum, and the known ages of the rock units, the past threshold temperatures for various stages of hydrocarbon generation and sediment diagenesis can be extrapolated from the present geothermal gradient. Unfortunately, the unique set of geologic and thermal conditions rarely occur in nature, and reliable temperature data is difficult to obtain. Even if this ideal situation occurs, the present-day geothermal gradient is an approximation.

Most borehole temperatures from exploratory wells are disequilibrium temperatures. Bottom-hole temperatures (BHT) are acquired when a well is logged; the BHT temperature is generally lower than the rock formation temperature because the drilling mud is uncirculated for only a few hours to a day or so while the well is logged. Other types of temperature data from exploratory wells, such as drill-stem test temperatures or temperature logs, may be more representative of rock formation temperatures than BHT temperatures because the drilling mud may be uncirculated for a longer period of time. More accurate temperature measurements are acquired after a hydrocarbon accumulation is discovered because of longer shut-in times.

Even if reliable subsurface temperatures are acquired, this data cannot be directly projected into the geologic past. The problem of how to determine the variations of the temperature gradient below lower Cook Inlet through geologic time still remains unsolved.

The problems in determining the present-day geothermal gradient of COST No. 1 well are complicated. In the COST No. 1 well, the Mesozoic section has many unconformities representing significant amounts of time. The COST No. 1 well is located off structure, north of the Augustine-Seldovia Arch, approximately 140 km (87 mi) southwest of Kenai and is drilled in a structural low and not in a structural high as most wells are. Moreover, the early Tertiary rocks penetrated near the surface in the well indicate that the geologic record for the Cenozoic is incomplete in the lower Cook Inlet basin. Therefore, the rocks in this area are no longer at maximum burial depth and have probably cooled since reaching their highest temperature. In the upper Cook Inlet just north of Kenai, a complete section of Late Cenozoic rocks is present, and it is probable that the entire Mesozoic and Cenozoic sections are very close to maximum burial depth.

In spite of these difficulties, I will try to determine (1) the present-day geothermal gradient for COST No. 1 well using well log data, (2) whether the geothermal gradient of COST No. 1 well in lower Cook Inlet basin compares favorably with the gradients in the upper Cook Inlet basin, and (3) how present subsurface temperatures in COST No. 1 well compare to the first occurrence of laumontite, the vitrinite reflectance data, and the thermal alteration index.

PRESENT-DAY TEMPERATURES

The temperature log data for the COST No. 1 well and the BHT for each log run are shown in figure 17. The four log runs, as recorded on the log headers (table 13), were made on June 12, June 27, August 20-21, and September 17-19, 1977. The temperature data is plotted in figure 17 and listed in table 14.

If the BHT and time since last mud circulation are recorded correctly on the well headers, then there is no difficulty in reconstructing the sequence of log runs and the BHT's. Unfortunately, not all the data was recorded for COST No. 1 well, so the data on the log headers do not agree with the data in table 14. The correct data, given to me by the log analyst, Forrest Baker, who witnessed the last log run, is given in table 14.

Bottom-hole Temperature

The first log run covered the well interval from 91 m (300 ft) to 405 m (1,327 ft) (table 13). The BHT for both runs was 19.4°C (67°F) (table 14). The second log run covered the interval from 404 m (1,325 ft) to 1,489 m (4,885 ft) (table 13). The three BHT's were for 43.9°C (111°F) (table 14).

The BHT's for both log runs one and two do not increase even though the time since mud circulation stopped does increase. Two explanations are possible: (1) the temperature of the mud is in thermal equilibrium with the formation temperature, or more likely (2) because of the size of the well hole, 26 in. and 17.5 in., there is too much mud in the hole to come to thermal equilibrium with the rocks in the formation in the short periods between mud circulation.

The BHT's of the third log run, for the interval from 1,475 m (4,840 ft) to 3,120 m (10,236 ft), ranged from 66.1°C (151°F) to 71.1°C (160°F). The BHT's for the first

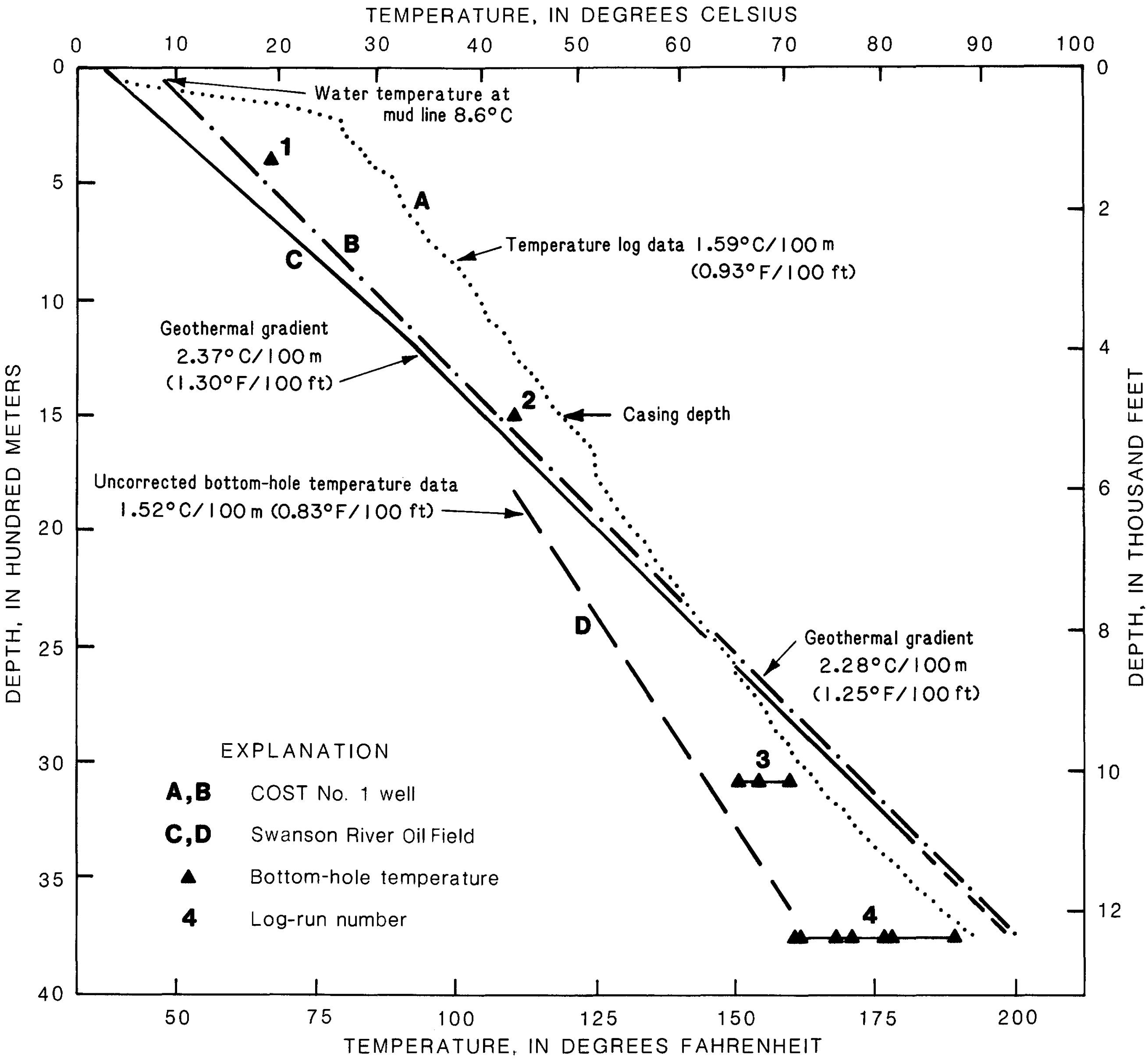


Figure 17. Temperature data for the COST No. 1 well and the Swanson River Oil Field. See table 14 for bottom-hole temperatures.

Table 13. Log runs for COST No. 1 well in 1977

[See tables 2 and 14 for additional information on logs]

Log run	Date	Depth interval			
		Top		Bottom	
		m	ft	m	ft
1	June 12, 1977	91	300	405	1,327
2	June 27, 1977	404	1,325	1,489	4,885
3	August 20-21, 1977	1,475	4,840	3,120	10,236
4	September 17-19, 1977	2,987	9,800	3,776	12,387

three log types increased 5°C during a 12-hour period. Unfortunately, the temperature data were not recorded for the LSS (long-spaced sonic) log; and this log run was made at the time when the time since mud circulation stopped was more than doubled.

The fourth log run covers the interval from 2,987 m (9,800 ft) to 3,776 m (12,387 ft) (table 13). Core number four was taken over an 11-hour period. The mud circulation continued until total depth was reached and stopped when the core barrel began to be withdrawn from the hole. From this time, seven different temperatures were acquired over the 57-hour period (table 14). The BHT's ranged from 71.7°C

Table 14. Temperature data for COST No. 1 well

[t_k is 11 hours. See figure 18]

Log run	Log type (see table 2)	Time since mud circulation stopped (hours)		Bottom-hole temperature °C	°F
1	DIL[1]	5	19.4	67	—
1	FDC	9	19.4	67	—
2	DIL/BHC	4.5	43.9	111	—
2	CNL/FDC	8	43.9	111	—
2	LSS	11.5	43.9	111	—
3	DIL	13.5	66.1	151	—
3	BHC	20.5	67.8	154	—
3	CN	[1]25.5	[1]71.1	160	—
3	LSS	38.5	—	—	—
4	BHC	10.5	[1]71.7	161	2.05
4	DIL	13.25	72.2	162	1.83
4	CNL/FDC	16.5	75.6	168	1.67
4	LSS	22	77.2	171	1.49
4	PL/ML	25.5	80.6	177	1.43
4	HDT	28	81.1	178	1.39
4	Temperature	[1,2]57	87.2	189	1.19

[1] Data provided by Forrest Baker, log analyst, who witnessed the fourth log run.

[2] Temperature log took 3 hours to run from the surface to total depth.

(161°F) to 87.2°C (189°F). The BHT's increase 15.5°C (60°F) over a 46.5-hour period. A maximum temperature of 92.4°C (198°F) was determined by a least squares linear regression. (The coefficient of determination, R^2, is 0.972).

The Horner temperature plot (Horner, 1951; Timko and Ferti, 1972; Dowdle and Coss, 1975) was made to estimate the equilibrium formation temperature (fig. 18). Except for the first data point, 71.7°C (161°F) at 10.5 hours, all the data support this maximum equilibrium formation temperature.

The BHT's from the first two log runs are probably not formation temperatures because of the short time since mud circulation stopped. The formation temperature was not calculated for the third log run because the mud circulation time after drilling to logging depth was not recorded. The formation temperature of 92.4°C (198°F), derived from making a plot of the data for the fourth log run, is considered the most reliable formation temperature for the COST No. 1 well.

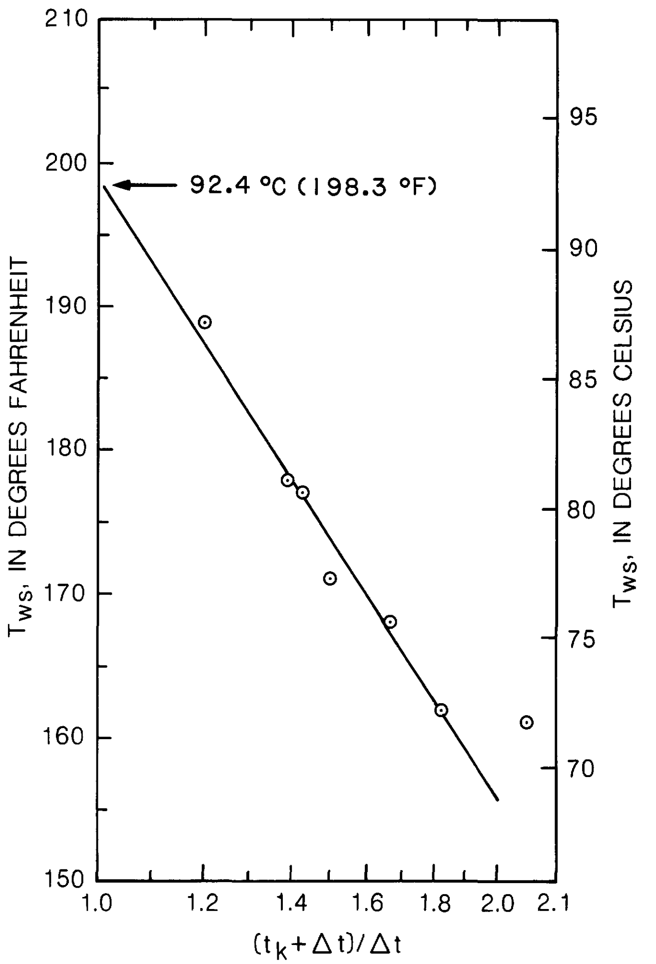


Figure 18. Horner temperature plot of the fourth log run for the COST No. 1 well. T_{ws} is the bottom-hole shut-in temperature measured at Δt. t_k is 11 hours.

Temperature Log

The relation of temperature to depth for COST No. 1 well and the Swanson River Oil Field (fig. 20) are plotted in figure 17. Using the temperature log, a temperature was plotted every 61 m (200 ft). The temperature gradient (A in fig. 17) below 240 m (322 ft), determined by a least squares linear regression, is 1.59°C/100 m (0.93°F/100 ft). The coefficient of determination, R^2, was plotted by using a temperature every 152 m (500 ft) from 300 m (985 ft) to 3,750 m (12,300 ft). It is 0.997. Using this geothermal gradient, the temperature at the KB (Kelly bushing) was found to be 22.2°C (71.7°F). This temperature is quite a bit higher than the 8.6°C that the measured water temperature is at the mud line (Miller and others, 1978).

The maximum temperature at total depth on the temperature log is 94.7°C. This temperature was measured, however, while the thermometer was at total depth for an unknown period of time (fig. 19). The temperature increased from 91°C (196°F) to 94.7°C (202°F) and asymptotically approached 95°C (203°F).

This maximum temperature of 94.7°C (202°F) agrees well with the formation temperature of 92.4°C (198°F) that was derived from a Horner plot (fig. 18).

Geothermal Gradient

The present-day geothermal gradient from the sea floor or mud line to total depth of the COST No. 1 well can be calculated by using either one of the formation temperatures;

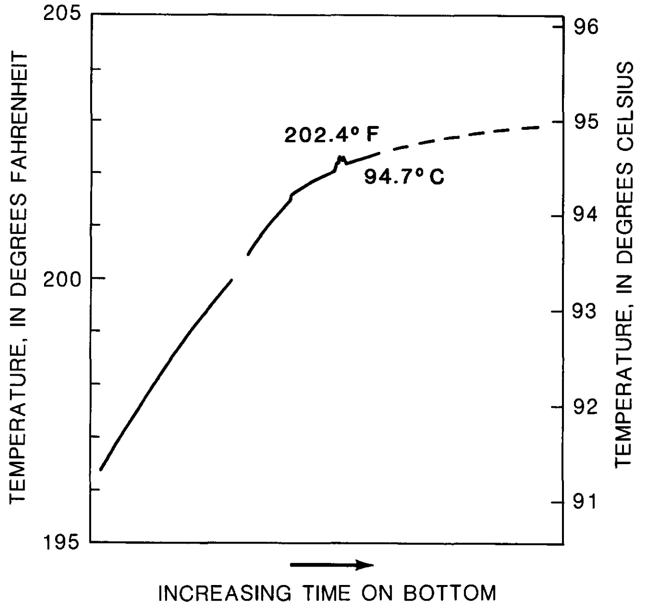


Figure 19. Temperature increased at total depth on the temperature log over an unknown time duration for the COST No. 1 well. The last recorded temperature is 94.7°C, and it asymptotically approached 95°C.

the 92.4°C derived from the Horner plot or the 94.7°C calculated from the temperature log. Miller and others (1978, fig. 2.8-2) found that the mudline temperature at the COST No. 1 well was 8.6°C during flood tide on September 20, 1977. By using the following figures:

96.0 m (315 ft) from KB = sea floor or mud line,
3,776 m (12,387 ft) = total depth of well,
8.6°C (47°F) = mudline water temperature, and
92.4°C (198°F) = formation temperature derived by Horner plot, the geothermal gradient is

$$\frac{92.4°C - 8.6°C}{3,776 \text{ m} - 96.0 \text{ m}} \times 100 = 2.28°C/100 \text{ m} \quad (1.25°F/100ft).$$

The geothermal gradient of profile B (fig. 17), 2.28°C/100 m (1.25°F/100 ft), is higher than the geothermal gradient of 1.59°C/100 m (0.93°F/100 ft) that was calculated from the temperature log of profile A. The temperatures along profile A (fig. 17) are probably not at thermal equilibrium because of the lack of long shut-in periods.

An example of an extremely long temperature survey is the one reported by Castano and Sparks (1974) in the Swanson River Oil Field. Temperatures recorded over a shut-in period of 100 days, after calculation, gave a geothermal gradient of 2.37°C/100 m (1.30°F/100 ft) and a surface temperature of 3.9°C (39°F) (Castano, oral commun., 1980). The geothermal gradient of the Swanson River Oil Field is profile C in figure 17. This geothermal gradient, 2.37°C/100 m (1.30°F/100 ft), compares well with the geothermal gradient calculated from the COST No. 1 well data, 2.28°C/100 m (1.25°F/100 ft).

In addition, a geothermal gradient was calculated from the uncorrected BHT data obtained from well log surveys run in the field, profile D in figure 17. The geothermal gradient of profile D, 1.52°C/100 m (0.83°F/100 ft), compares well with the geothermal gradient of profile A, 1.59°C/100 m (0.93°F/100 ft) that was calculated from the temperature log data of COST No. 1 well. Since the BHT data are comparable with the temperature log data, the temperature log data must not be equilibrium temperatures.

GEOTHERMAL GRADIENT OF THE AREA

The geothermal data in a basin generally has lower gradients for the thickest parts of the basin and higher gradients for the perimeter where the older rocks are closer to the surface. This relation is shown for the Great Valley of California on the Geothermal Map of North America (Kinney, 1976).

The west limb of the Cook Inlet basin is flanked by a batholith of Mesozoic and Cenozoic ages and five volcanoes: Mount Spurr, Redoubt Volcano, Iliamna Volcano, Augustine Volcano, and Mount Douglas (fig. 20). The geothermal gradient contours in upper Cook Inlet appear to reflect this heat source because the 2.7°C/100 m (1.6°F/100 ft) contour is located on the west near the heat source and the 2.1°C/100 m (1.2°F/100 ft) contour is located on the east farthest from the source. The highest geothermal gradient contour is closer to the batholith near Tyonek in upper Cook Inlet than it is to the batholith near Homer in the lower Cook Inlet.

The geothermal gradient in COST No. 1 well is lower than would be predicted from the regional trend (fig. 20; Kinney, 1976). The well is located a similar distance from the batholith as Tyonek, and it is also near an active volcano—Augustine Volcano, so one would expect the well to have a high geothermal gradient. Yet the geothermal gradient of the well is lower; it is very similar to the geothermal gradient of the Swanson River Oil Field.

THERMAL HISTORY

The thermal history or maximum temperature undergone by rocks can be inferred from the first occurrence of laumontite, from vitrinite reflectance, and from the TAI (thermal alteration index).

Laumontite

The first occurrence of laumontite recorded by Bolm and McCulloh (this volume) is at 1,891 m (6,205 ft) in the COST No. 1 well. It is also present in most samples from depths greater than 2,134 m (7,000 ft).

The present pressure and temperature of the rocks that the laumontite first occurs in is 184 bars at 50°C (122°F); this temperature is 30°C (86°F) too cool to form laumontite.

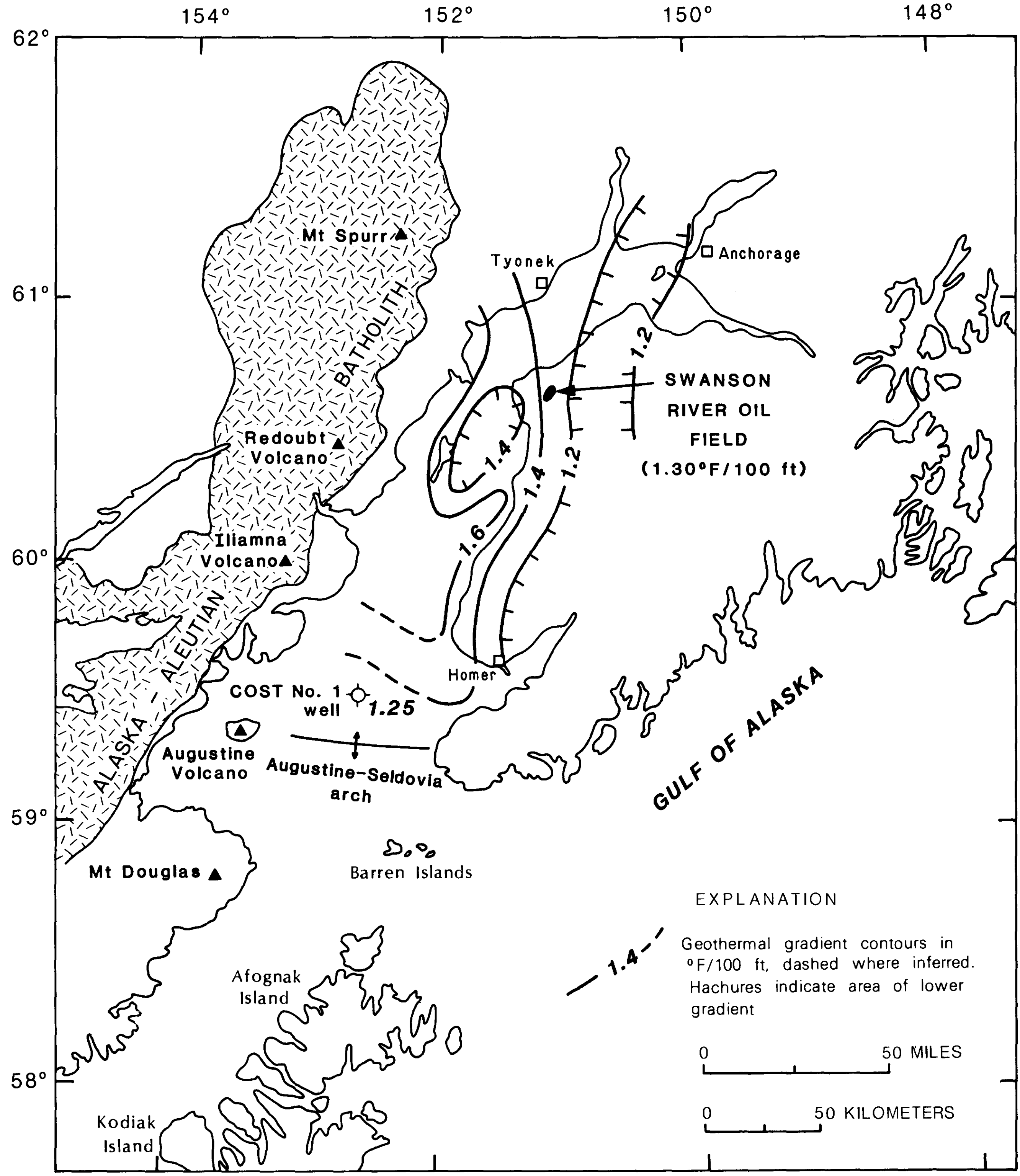


Figure 20. Geothermal gradient map of Cook Inlet (Kinney, 1976), location of the Swanson River Oil Field, COST No. 1 well, and the Alaska-Aleutian batholith. In upper Cook Inlet, the geothermal gradient on the west is much higher than that on the east. The COST No. 1 well gradient of 2.28°C/100 m (1.25°F/100 ft) compares with the eastern gradient.

Moreover, the entire T-P (temperature-pressure) profile for the COST No. 1 well is in the "fossil" laumontite field (fig. 21; McCulloh and others, 1978). If the rock section is not overpressured, then the first occurrence of laumontite is a fossil occurrence. Greater burial depths probably would not provide a T-P field conducive to the formation of laumontite, but a much higher heat flow, possibly from one or more of the many periods of plutonism, could provide the proper T-P field.

Vitrinite Reflectance Data

The vitrinite reflectance value is about 0.65 percent at total depth in the COST No. 1 well. The rocks there are at a present-day temperature of about 92-95°C, a temperature that is very close to the threshold of oil generation for source shales that have been buried for at least 30-40 m.y. (Connan, 1974). The vitrinite reflectance data obtained from conventional cores and sidewall cores substantiate these values. However, these reflectance values projected to the surface of the well are over 0.3 percent.

The vitrinite reflectance data determined by organic geochemical analysis by Simpson (1977) and Van Delinder (1977) (fig. 7) compare well with the vitrinite reflectance data determined by thermal analysis of organic matter supplied by Arco, Shell, and Core Laboratories (fig. 16).

Even though the overall vitrinite reflectance gradient seems to be reasonable, the evidence that the rocks in the well were uplifted and eroded argues against accepting them as true values. Furthermore, the surface reflectance values should be much higher than 0.3 percent, to fit in with the geothermal trend of the Cook Inlet basin.

Thermal Alteration Index

The TAI (thermal alteration index) of the rocks in the COST No. 1 well range from a low of 1.5 to a high of 2.6. The relations of the TAI and vitrinite reflectance scales are shown on figure 22 (Bayliss and Smith, [1980]). The TAI values indicate a much higher thermal history than the vitrinite reflectance values of the well. The stratigraphic evidence of uplift and erosion and the evidence of the first occurrence of laumontite in the well substantiate the TAI values and confirm the validity of the higher thermal history.

SUMMARY

Even though the COST No. 1 well temperature gradient of about 2.28°C/100 m (1.25°F/100 ft) is close to the Swanson River Oil Field gradient of 2.37°C/100 m (1.30°F/100 ft), the present-day geothermal gradient for the COST No. 1 well seems to be too low when compared to the geothermal trends in upper Cook Inlet. All the evidence from the stratigraphy of the rocks, the first occurrence of laumontite, and the TAI values indicate that the rocks in the COST No. 1 well were subjected to high temperature gradients before uplift and erosion. The vitrinite reflectance values, which are low, do not substantiate this inference.

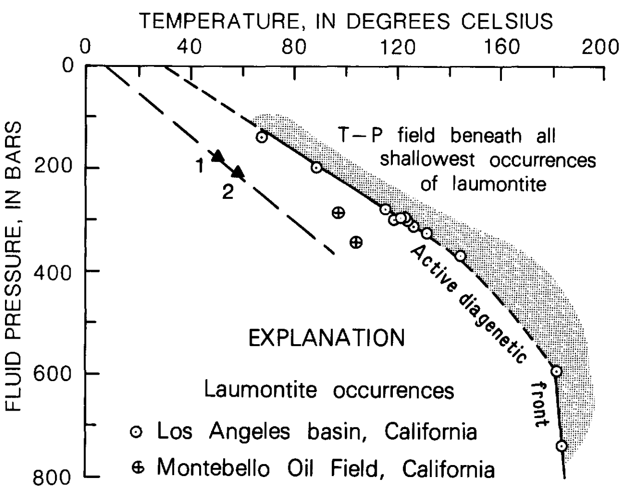


Figure 21. "Fossil" laumontite field. Figure modified from McCulloh and others (1978, fig.6). The dashed line with two solid triangles indicates the T-P (temperature-pressure) line for the COST No. 1 well. The entire well profile is in the "fossil" laumontite field. Triangle one indicates the laumontite at 1,891 m (6,205 ft) and triangle two is the laumontite at 2,134 m (7,000 ft).

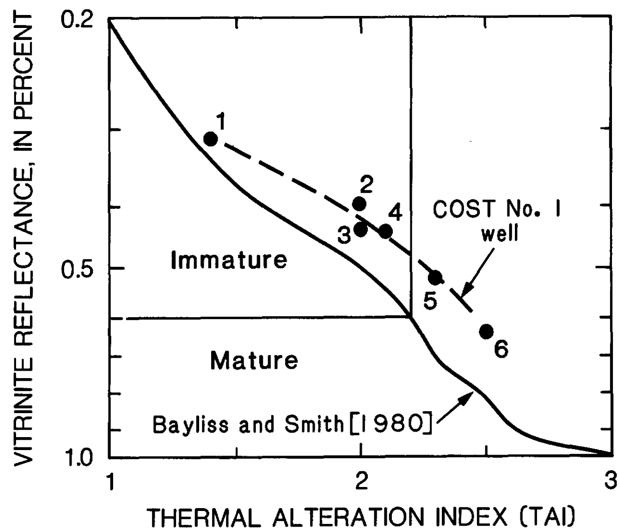


Figure 22. Cross reference of the TAI (1-3) scale to vitrinite reflectance (0.2-1.0 percent) (Bayliss and Smith, [1980]). TAI values indicate a much higher thermal history for the COST No. 1 well than does the vitrinite reflectance. Points (1 to 6) represent corresponding TAI and vitrinite reflectance values from 610 m (2,000 ft) to 3,660 m (12,000 ft) in intervals of 610 m.

Sandstone Petrography

By Hugh McLean

INTRODUCTION

The petrographic characteristics of sandstone beds penetrated in the COST No. 1 well are important in understanding the diagenetic influences on reservoir quality in this particular well and in the surrounding area.

Four conventional cores (table 3) and 101 sidewall core samples (table 15) were taken during drilling; one conventional core was cut from the Herendeen Limestone (Lower Cretaceous) and three cores were cut from the Naknek Formation (Upper Jurassic). Sidewall cores were taken from the interval between 545 m (1,788 ft) and 3,102 m (10,174 ft) (table 15), and include samples from the Naknek Formation, Herendeen Limestone, Kaguyak Formation (Upper Cretaceous), and West Foreland Formation (lower Tertiary).

Twenty thin sections were prepared from three of the conventional cores; the remaining sections were made from sidewall cores. Grain-mount thin sections were made from sidewall cores that were badly fractured or disaggregated. The classification system used to indicate sandstone composition in figure 23 is modified from Crook (1960) and Dickinson (1970).

The data shown in table 15 were compiled from petrographic reports prepared for the lower Cook Inlet COST No. 1 well in 1977 by: Paul R. Schluger, Mobil Oil Corporation, Denver, Colo.; E. W. Christensen, Chevron USA, Western Region, San Francisco, Calif.; T. J. Swiderski, Phillips Petroleum Company, Denver, Colo.; Laurel Babcock, AMOCO Production Company, Tulsa, Okla.; R. J. Kuryvial, Cities Service Company, Tulsa, Okla.; and by Hugh McLean, U.S. Geological Survey, Menlo Park, Calif.

PETROGRAPHIC ANALYSES

Naknek Formation (Upper Jurassic)

The Upper Jurassic Naknek Formation extends from 2,112 m (6,930 ft) to 3,776 m (12,387 ft) (fig. 4) from which 32 sidewall core samples (table 15) and three conventional cores were taken (table 3). The uppermost conventional core, 7.6 m (25 ft) long, cut from between 2,165.3 m (7,104 ft) and 2,173.5 (7,131 ft), consists entirely of sandstone. The middle core, 5.3 m (17.5 ft) long, cut from between 2,844.4 m (9,332 ft) and 2,850.5 m (9,352 ft) consists of interbedded sandstone and siltstone. The bottom core, 9.1 m (30 ft) long, cut from between 3,766.4 m (12,357 ft) and 3,775.6 m (12,387 ft), grades from sandstone to siltstone (table 3).

The average composition of 28 Naknek Formation sandstone thin sections is $Q_{24}F_{55}L_{21}$ (fig. 23). Most are fine- or medium-grained, with well sorted, subrounded grains. Samples however, between 2,145.8 m (7,040 ft) and 2,351.8 m (7,716 ft) consist of well rounded and very well sorted grains that may reflect winnowing, and possible deposition in a nearshore environment.

Framework grains are packed tightly together, resulting in predominantly long and concave-convex grain contacts. Laumontite replaces plagioclase grains and glassy parts of volcanic rock fragments, and also fills intergranular pore space. Original porosity and permeability may have been high, but have been substantially reduced by mechanical compaction and by precipitation of authigenic minerals.

Herendeen Limestone (Lower Cretaceous)

The Herendeen Limestone extends from 1,541 m (5,055 ft) to 2,112 m (6,930 ft). Approximately 5.5 m (18 ft) of core cut from 1,642.9 m (5,390 ft) to 1,649.6 m (5,412 ft) consists of interbedded sandstone and shale (table 3). Seven thin sections from conventional core and 32 thin sections from sidewall cores (tables 3 and 15) have an average composition of $Q_{36}F_{44}L_{20}$. Accessory minerals include green hornblende, biotite, epidote, and clinopyroxene. Rock fragments are mainly felsic and microlitic volcanics of intermediate composition. Metamorphic rock fragments include mica schist and quartzite.

Sandstone samples are fine-and medium-grained, with subrounded to subangular, well-sorted framework aggregates that are typically framework supported. Adjacent grains display combinations of both point and long contacts. Although alteration of framework grains is minimal, porosity and permeability are nevertheless reduced by mechanical compaction and by pore-filling authigenic clay minerals and calcite.

Samples from depths of 1,858.4 m (6,097 ft) and 1,877.9 m (6,161 ft) contain *Inoceramus* prisms, a typical fossil in the Herendeen Limestone.

Kaguyak Formation (Upper Cretaceous)

The Kaguyak Formation extends from 797 m (2,615 ft) to 1,541 m (5,055 ft) (fig. 4). Thin sections from 22 sidewall cores have an average composition of $Q_{23}F_{61}L_{16}$. Samples include a wide range of grain sizes including very fine, fine, medium, and coarse, which are typically poorly sorted and

Table 15. Sandstone petrography of COST No. 1 well

[Data compiled by R. M. Egbert, U.S. Geological Survey.]

Age	Core samples	Sample depth (ft)	Core No.	Q	F	L	Quartz	Chert	Feldspar K-spar	Feldspar Plag	Feldspar tot	Rock Frags VRF	Rock Frags URF	Rock Frags MRF	Other Bio	Other Hbl	Other tot	Ratios C/Q	Ratios P/F	Ratios V/L	Cement Cly	Cement Cal	Z	Matrix
Cenozoic	1 E	1,788		24	29	47	12	8	4	20		39					3	.40	.83	1	8	0	3	
	2 E	1,858		18	23	59	9	6	5	14		48					2	.40	.74	1	10	0	1	
	3 A	2,060		15	26	59	5	5	10	8		40			5		7	.50	.44	1	5			20
	4 E	2,230		16	23	61	5	7	5	12		46					3	.58	.71	1	10	0	4	
	5 A	2,274		32	13	55	18	5	6	4		40			2		2	.22	.40	1		5		20
	6 A	2,475		29	48	23	13	5	15	15		15			20		22	.28	.50	1	5			10
	7 E	2,506		27	44	29	17	2	2	29		20					4	.11	.94	1	8	0	3	
	8 A	2,594		23	35	42	14	3	15	10		30			5		8	.18	.40	1	5			15
Upper Cretaceous	9 E	2,972		9	21	70	5	2	2	15		57					3	.29	.88	1	10	0	1	
	10 E	3,100		17	16	67	9	5	2	11		54					2	.36	.85	1	6	0	3	
	11 E	3,427		39	55	6	30	0	8	35		5					2	0	.81	1	4	0	2	
	12 A	3,442		49	44	7	31	1	15	15		5			7		8	.03	.50	1			5	20
	13 E	3,460		16	78	6	12	0	7	52		5					3	0	.88	1	5	0	4	
	14 E	3,478		15	80	5	11	0	12	48		4					3	0	.80	1	2	0	5	
	15 A	3,486		27	63	10	19	0	20	25		7			4		4	0	.56	1	5			20
	16 A	3,508		17	53	30	10	1	15	20		20			2	1	3	.09	.57	95	5			25
	17 E	3,543		16	78	6	12	0	5	55		5					1	0	.92	1	4	0	4	
	18 A	3,553		25	70	5	15	0	15	25		2			7		7	0	.63	.67	5			30
	19 E	3,556		29	66	5	20	0	6	39		3					2	0	.87	1	4	10	4	
	20 A	3,587		16	79	5	9	0	20	25		3			15		18	0	.56	1	5			20
	21 E	3,664		30	65	5	22	0	7	40		4					2	0	.85	1	5	0	7	
	22 A	3,670		37	60	3	22	0	20	15		2			15		16	0	.43	1		5		20
	23 E	3,916		9	86	5	7	0	6	57		4					3	0	.90	1	10	0	8	
	24 A	3,974		25	38	37	20	0	15	15		29			1		1	0	.50	1		10		10
	25 E	4,078		21	67	12	12	3	7	42		9					2	.02	.86	1	6	5	4	
	26 A	4,080		12	58	30	8	0	20	20		20		1	1		1	0	.50	.95	10			20
	27 E	4,240		20	75	5	12	4	7	52		4					1	.25	.88	1	2	0	8	
	28 E	4,317		23	70	7	15	2	6	47		5					2	.12	.89	1	8	0	3	
	29 A	4,508		25	49	26	13	2	20	9		15			15		16	.13	.31	1		10		15
	30 E	4,520		28	65	7	18	2	5	41		5					2	.10	89	1	8	0	6	
Lower Cretaceous	31 B	5,120		6	51	43	4	—	0	35		30				8	16	—	1.0	1				15
	32 D	5,120		32	47	21	30	—			45		20			5	5	—	—	—				15
	33 C	5,130		17	48	35	14	0			40		29				1/17	0	—	.90				16
	34 B	5,210		14	57	29	10	—	0	39		20			5	15	21	—	1 0	1				10
	35 D	5,270		32	47	21	30	—			45		20			5	5	—	—	—				20
	36 D	5,350		44	28	28	40	—			25		25		10		10	—	—	—				14
	37 E	5,391	1	42	50	8	30	2	4	34		6					5	.06	.89	1	5	0	2	
	38 A	5,393	1	25	53	22	19	0	20	20		17			2		4	0	.50	1				11
	39 F	5,394	1	56	39	5	42	—		29		4			1	1	6	0	1.0	.99	15			
	40 B	5,396		29	60	11	26	—	7	46		7		3	4		6	—	.87	.70				5
	41 E	5,399	1	32	57	11	16	8	7	36		9					2	.33	.84	1	6	2	10	
	42 A	5,401	1	31	48	21	19	3	20	15		15			4		8	.14	.43	1		5		15
	43 F	5,403	1	39	41	20	26	0	1	28		10		2	6		2	0	.96	.81	23			
	44 E	5,404	1	30	51	19	17	2	6	26		12					11	.11	81	1	13	0	9	
	45 D	5,428		67	32	1	65	—			31		1				3	—	—			10		10
	46 C	5,472		15	70	15	15	0			70		15					0	High	High				
	47 D	5,505		58	21	21	55	—			20		20		5		5	—	—	—				10
	48 B	5,565		34	60	6	29	—	4	48		2		3	8		14	—	.92	.40				
	49 D	5,648		40	30	30	32	—			25		25		3	5	8	—	—	—				20
	50 B	5,692		18	62	20	14	—	1	46		13		2	9	10	19	—	.98	.87			5	2–20
	51 D	5,692		47	42	11	45	—			40		10			5	5	—	—	—			5	15
	52 B	5,713		33	55	12	27	—	2	43		9		1	8	10	18	—	.96	.90				
	53 C	5,713		25	45	30	23	0			41	28			1	7	8	0	—	—	2		4	21
	54 D	5,770		39	44	17	35	—			40		15		5		10	—	—	—		4	11	5
	55 B	5,839		35	43	22	29	—	5	30		10		8	10	6	16	—	.86	.56			x–5	2–3
	56 B	5,883		26	44	30	21	—	1	35		18		7	11	6	18	—	.97	.72				
	57 D	5,932		39	33	28	35	—			30		25		5	2	10	—	—	—			5	10
	58 B	5,962		29	57	14	25	—	2	47		9		3	8	3	14	—	.96	.75			x–3	x
	59 D	6,035		52	32	16	50	—			30		15		5		5	—	—	—		10		5
	60 B	6,097		38	42	20	28	—	0	31		13		2	7	1	8	—	1	87		1/15		2–10
	61 D	6,097		47	29	24	40	—			25		20		5		15	—	—	—		1/13		10
	62 D	6,125		66	22	12	55	—			18		10		15		17	—	—	—				40
	63 B	6,161		21	54	25	18	—	6	39		17		4	11		12	—	.87	.81		1/4		8–10
	64 B	6,205		37	49	14	29	—	4	34		6		5	9	2	12	—	.89	.55		4	x–7	
	65 B	6,302		39	49	12	37	—	6	40		9		2	5		5	—	.87	.82		1		
	66 D	6,385		50	22	28	45	—			20		25		5		10	—	—	—		1	4	
	67 B	6,404		42	45	13	40	—	7	36		10		2	4		5	—	.84	.83				
	68 C	6,404		54	16	30	51	0			15		28		1	4	o	0	—	0			3	13
	69 D	6,435		55	20	25	55	—			20		25		5		5	—	—	—		1/5		

angular to very angular. Most rock fragments (L) are volcanics that have altered to clay minerals that form pseudomatrix. Clay minerals also replace plagioclase and potassium feldspar. Porosity and permeability are mainly reduced by authigenic clays and traces of carbonate.

West Foreland Formation (lower Cenozoic)

The West Foreland Formation extends from 413 m (1,356 ft) to 797 m (2,615 ft). A total of 8 thin sections from sidewall cores from between 545 m (1,788 ft) and 790 m (2,594 ft) (table 15) have an average composition of $Q_{23}F_{30}L_{47}$. Accessory minerals include hornblende, biotite, epidote, and opaque minerals, and the assemblage of rock fragments is predominantly volcanic. Grains are fine and medium in size, angular to subangular in shape, and are poorly sorted. Framework grains tend to be surrounded by float in either a clay matrix or in calcite cement. In some samples, possible dissolution of calcite has increased porosity to nearly 20 percent (measured visually).

DISCUSSION

Sandstone porosity and permeability in the Kaguyak (Upper Cretaceous) and West Foreland Formations (lower

Table 15. Continued.

Age	Core samples	Sample depth (ft)	Core No.	Q	F	L	Quartz	Chert	Feldspar K-spar	Feldspar Plag	Feldspar tot	Rock Frags VRF	Rock Frags URF	Rock Frags MRF	Other Bio	Other Hbl	Other tot	Ratios C/Q	Ratios P/F	Ratios V/L	Cement Cly	Cement Cal	Z	Matrix
	70 B	7,040		10	74	16	8	—	2	59		10		3		5	5	—	.97	.77			x-2	12-13
	71 D	7,104		30	20	50	30	—			20		50					—	—	—			10	
	72 A	7,106	2	14	49	37	11	0	20	20		30			1		2	0	.55	1			12	5
	73 F	7,107	2	20	46	34	17	0	2	37		24		5			3	0	.93	.83			13	
	74 E	7,108	2	17	70	13	12	2	12	43		10					5	.14	78	1	5	0	8	
	75 A	7,110	2	20	58	22	11	3	15	25		15				12	1/18	.21	.63	1			10	3
	76 E	7,112		9	82	9	5	1	2	56		6					15	.17	.97	1	4	0	8	
	77 A	7,114	2	17	51	32	14	0	15	25		25				4	1/6	0	.63	1			12	3
	78 B	7,117		10	75	15	7	—	1	54		9		2		6	6	—	.98	.82			x	20-25
	79 E	7,117	2	19	71	10	12	3	5	50		8					6	.20	.91	1	5	0	9	
	80 A	7,124	2	17	51	32	10	3	20	20		25				2	2	.23	.50	1			16	4
Upper Jurassic	81 E	7,126	2	21	63	16	14	2	2	46		12						.13	.96	1				4
	82 E	7,128		13	73	14	10	1	2	56		12					3	.09	.92	1	4	0	6	
	83 A	7,129	2	11	43	46	8	1	15	20		38				4	4	.11	.57	1			10	4
	84 F	7,129	2	19	27	54	17	0	0	24		27	9	11	1	1		0	1	.58			10	
	85 B	7,716		11	73	16	8	—	1	53		10		2		5	5	—	.98	.83			20-25	
	86 D	8,376		37	42	21	35	—			40		20			5	5	—	—	—			2	13
	87 D	8,712		50	30	20	50	—			30		20					—	—	—		3	7	5
	88 B	8,855		27	68	5	21	—	0	52		2		2	7	12	21	—	1	.50			2-5	
	89 D	8,875		56	28	17	50	—			25		15		5	5	10	—	—	—				10
	90 B	8 972		28	68	4	17	—	0	41		2		0	4	16	30	—	1	1			7-10	3-5
	91 F	9,336	3	35	33	32	30	0	2	25		11	5	4		4	4	0	.93	.64			9	
	92 C	9,341	3	29	32	39	29	0			32		39					0	—	.80				
	93 F	9,344		35	59	6	15	0	2	24			0	0	2	4	4	0	.92	—			40	
	94 C	9,348	3	22	45	33	22	0			45		33					0	—	High				
	95 B	9,515		30	57	13	21	—	0	40		5		4	2	15	18	—	1	.56			12-15	
	96 D	9,515		64	24	12	55	—			20		10		2	10	12	—	—	—				15
	97 B	9,885		6	85	9	4	—	0	55		6		0		21	21	—	1	1			15-20	
	98 D	9,928		67	22	11	60	—			20		10			10	10	—	—	—				20
	99 B	10,091		9	77	14	6	—	1	52		10		0		18	18	—	.98	1			10-15	3-5
	100 B	10,145		4	68	28	3	—	3	49		21		0	2	11	14	—	.94	1			7-10	3-5
	101 D	10,174		22	44	33	20	—			40		30					—	—	—				25

Abbreviations and symbols:

A Mobil
B Chevron USA
C Phillips
D Amoco
E Cities Service
F USGS

Q = Quartz + Chert + Quartzite
F = Total feldspar
L = Total rock fragments
K-spar = Potassium feldspar
Plag = Plagioclase feldspar
tot = Total feldspar (plag and K-spar)
1/ = *Inoceramus* prisms

VRF = Volcanic rock fragments
MRF = Metamorphic rock fragments
URF = Undifferentiated rock fragments
Bio = Biotite
Hbl = Hornblende
tot = Total other minerals

C/Q = Chert/Quartz + Chert + Quartzite
P/F = Plagioclase/total feldspar
V/L = Volcanic rock fragments/total rock fragments
Cly = Clay
Cal = Calcite
Z = Zeolite
x = present in unknown amount
x-5 = up to 5%, estimated

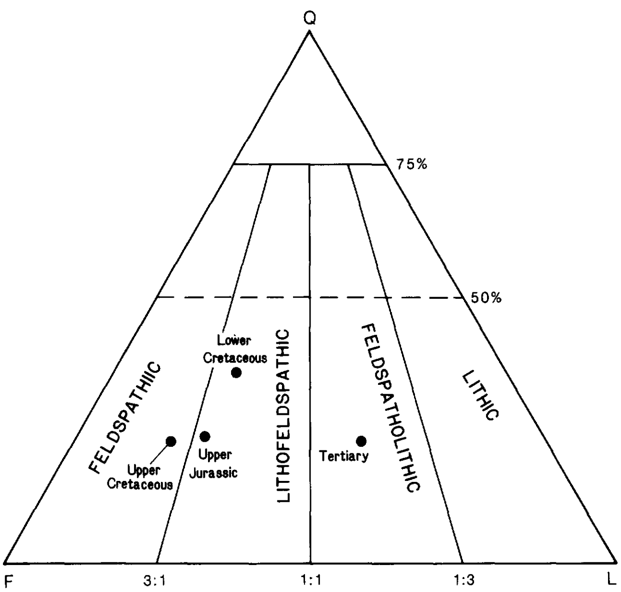


Figure 23. Averages of Q-F-L (quartz-feldspar-lithic fragments) for each formation. The classification presented is modified from Crook (1960) and Dickinson (1970). Quartz end member, Q, includes chert.

Tertiary) have been reduced mainly by the formation of authigenic clay matrix and by pseudomatrix derived from unstable volcanic rock fragments. Precipitation of authigenic zeolite cements and mechanical compaction of framework grains combine to reduce porosity and permeability even farther.

Although the lithofeldspathic sandstones of the Herendeen Limestone (Lower Cretaceous) and Naknek Formation (Upper Jurassic) contain low percentages of intergranular matrix, their framework grains are tightly compacted and locally cemented by laumontite and to a lesser extent by chlorite. Laumontite and heulandite together form as much as 7 weight percent of a sandstone sampled between 2,166.5 m (7,108 ft) and 2,171.0 m (7,126 ft), as measured by X-ray diffraction techniques. Samples from progressively greater depths reveal that laumontite increasingly replaces stilbite and(or) heulandite and that chlorite increasingly replaces montmorillonite.

Lower Cretaceous, Upper Cretaceous, and lower Tertiary sandstone samples all contain authigenic clay minerals and calcite cement. Intergranular pores of some Lower Cretaceous sandstone are filled with a mix of clay and calcite.

Upper Cretaceous sandstone typically contains authigenic clays derived from volcanic rock fragments, plagioclase, and potassium feldspar, and most samples contain at least a trace of carbonate cement. Lower Tertiary samples contain extensive amounts of clay matrix and(or) calcite cement, with as much as 20 percent visual porosity in one sample. Porosity and permeability of most Upper Cretaceous and lower Tertiary rocks are reduced mainly by precipition of authigenic clay minerals and to a lesser extent, by the formation of zeolite cement and by mechanical compaction.

Sandstone Diagenesis

By John G. Bolm[3] *and* Thane H. McCulloh[4]

INTRODUCTION

The purpose of this study was to determine the composition of the sandstones, their origin, and their porosity and permeability. Cuttings and core samples were obtained from between the depth intervals of 545.0 m (1,788 ft) and 3,775.6 m (12,387 ft) in the COST No. 1 well (table 3; fig. 4). From these samples 161 standard petrographic thin sections were prepared by companies that participated in the drilling of the well (table 4). The thin sections were loaned to the U.S. Geological Survey.

The compositions of the sandstones in the well indicate that they were derived from an igneous source terrane that had outcrops of both volcanic and plutonic rock types. Volcanic rock fragments and plagioclase feldspar, which are abundant in the sandstone samples, were most affected by the diagenetic changes.

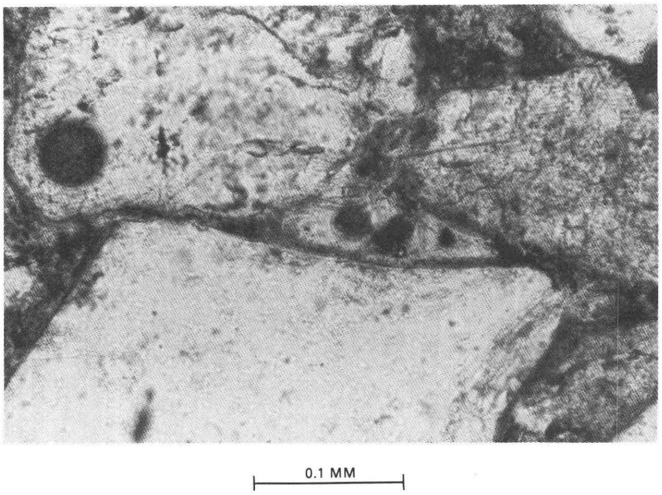


Figure 24. Authigenic clay lining in pore space at 1,060-m (3,478-ft) measured depth.

DIAGENETIC CHARACTERISTICS

Four kinds of diagenetic changes occurred to the sandstones in the COST No. 1 well: ductile deformation of volcanic rock fragments, formation of authigenic clay, formation of carbonate cement, and crystallization of laumontite.

Ductile Deformation of Volcanic Rock Fragments

Volcanic rock fragments have commonly undergone ductile deformation, and in some sandstones this has produced pseudomatrix as defined by Dickinson (1970, p. 702). The pseudomatrix is more abundant in sandstones having a high content of volcanic rock fragments than in sandstones having a low content of volcanic rock fragments, and it is more abundant in sandstones from deeper depths than it is in sandstones from shallower depths.

Authigenic Clay

Yellow to light green authigenic clay is present in many samples from the COST No. 1 well (fig. 24). In the shallowest sample from the well (545 m or 1,788 ft), the clay partly or completely coats framework grains; in deeper samples, clay coats are generally thicker and more widespread. Kuryvial (1977) determined by X-ray analyses that the clay consists of various combinations of montmorillonite and chlorite as discrete phases or mixed layer combinations. Samples with abundant volcanic rock fragments contain the most clay. Clay coatings were probably formed mainly from material derived from the chemical breakdown of volcanic rock fragments.

Carbonate Cement

Minor amounts of carbonate cement are present in a few samples. The cement fills intergranular spaces in some samples, and it is scattered in intergranular areas in others. Both sparry and microsparry carbonate are present. The sparry carbonate occurs as single crystals filling intergranular spaces several millimeters in diameter. Individual crystals of microsparry carbonate are 0.02-0.05 mm in diameter and are bounded by curved or wavy boundaries. The carbonate is probably of primary depositional origin, and the grain size of any particular occurrence probably has been determined by a balance of aggradational recrystallization associated with fluid flow and diminutional recrystallization associated with structural strain.

Laumontite

Although Kuryvial (1977) reported finding laumontite in samples from a depth as shallow as 1,643.2 m (5,391 ft),

[3]Minerals Management Service (Dept. of the Interior).

[4]Mobil Research and Development, Corp.

we first found laumontite at a depth of 1,891.3 m (6,205 ft). The method he used was X-ray analysis; ours was optical observation of thin sections. In our first sample, laumontite filled the intergranular spaces. Most of the sandstone samples from depths greater than 2,134 m (7,000 ft; fig. 25) contain laumontite; most of these samples also contain plagioclase that is partly to completely albitized. Release of calcium and aluminum from plagioclase during albitization together with chemical breakdown of volcanic rock fragments have undoubtedly contributed to the crystallization of laumontite.

Kuryvial (1977) also found other sodium and calcium zeolites besides laumontite present in samples from depths greater than 545 m (1,788 ft). He examined these zeolites with a scanning electron microscope and found evidence that they formed synchronously with the authigenic clay. Laumontite, however, crystallized after the clay formed, as is indicated by the presence of clay coats between framework clasts and laumontite pore-filling cements.

Porosity

In the upper half of the well, sandstone samples commonly have visible intergranular porosity. However, in most samples the pore spaces are lined with authigenic clay that obstructs pore throats and drastically reduces permeability. With depth, porosity decreases; framework grains are more tightly compacted and there is an increasing abundance of authigenic minerals. At 2,088 m (6,850 ft), there is a strong deflection in the resistivity, sonic velocity, and density curves on the geophysical logs (fig. 4); this deflection probably marks the base of significant intergranular porosity. Below this depth, fracture porosity is present in some samples. A sandstone sample from 2,847 m (9,340 ft) shows fractures that contain both oil and partial linings of laumontite (fig. 26).

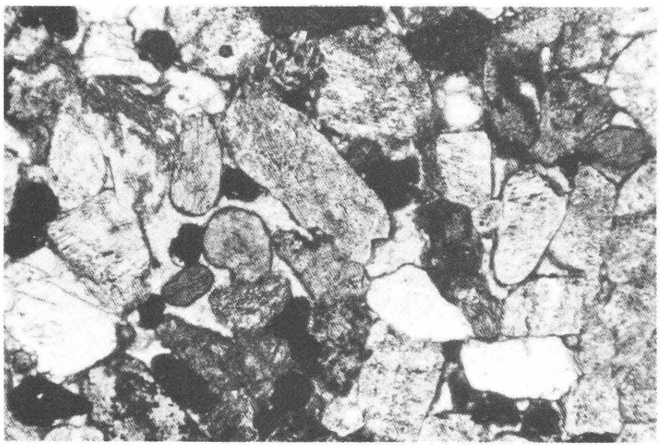


Figure 25. Laumontite filling in authigenic clay-lined pore space at 2,167.2-m (7,110-ft) measured depth. Note albitization of plagioclase.

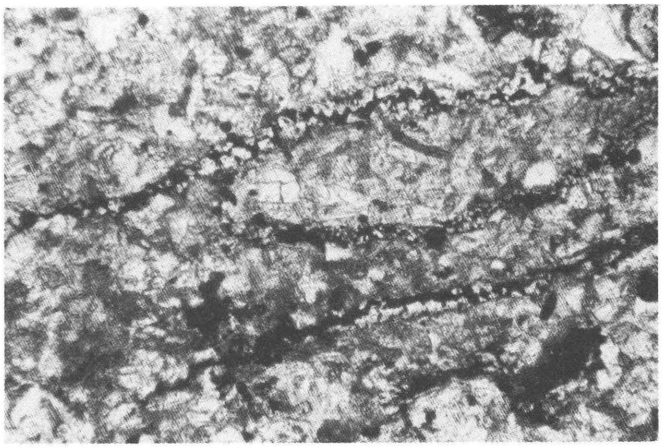


Figure 26. Oil in laumontite-lined fractures, 2,846.8 m (9,340 ft); measured depth.

DISCUSSION

Porosity and Permeability Reduction

The mineralogically immature sandstones in the COST No. 1 well are particularly susceptible to diagenetic processes because of their chemically unstable character. High temperatures from deep burial or from high geothermal gradients facilitate dissolution of unstable framework clasts and thus provide material for the precipitation of authigenic phases.

Clay or zeolite minerals precipitate in the intergranular pore spaces of sandstone because of changes in temperature, pressure, or pore-fluid composition subsequent to deposition. The crystallization of some zeolite minerals, such as stilbite and clinoptilolite, may cause only moderate reduction in the reservoir properties of sandstones, but the crystallization of the calcium zeolite laumontite causes a great reduction. Some diagenetic processes are slowed or prevented if petroleum flows into the sandstone reservoir before the alteration episode occurs, but evidence gained from several producing oil fields in California shows that the crystallization of laumontite is not inhibited in this way. Laumontite crystallizes in mineralogically immature sandstones whenever the appropriate conditions of temperature, pressure, and pore-fluid chemistry prevail whether the principal fluid is petroleum or water.

The laumontite in the COST No. 1 well is probably a product of an episode of thermal alteration that left a regional imprint throughout the Cook Inlet basin. Comparable alteration of Jurassic sandstones was observed during regional studies of the rocks of the Iniskin Peninsula on the west side of lower Cook Inlet (Detterman and Hartsock, 1966, p. 31). Laumontite also is present in rocks which crop out in the Kamishak Hills and Cape Douglas region. Several wells in the upper Cook Inlet basin contain laumontite, and Clark (1973) reported that laumontite was present in the rocks of the

McHugh complex in the Chugach Mountains east of Anchorage.

Most of the laumontite occurs in the mineralogically immature units of Jurassic and Cretaceous age, as in the COST No. 1 well; the youngest strata known to have been laumontitized belonged to the West Foreland Formation of Paleocene age that crops out near Cape Douglas. Evidently the upper surface of laumontitization (diagenetic front) is irregular and cuts discordantly across deformed strata and erosional unconformities. The thermal episode that partly controlled the formation of laumontite probably culminated in late Mesozoic or early Cenozoic time.

Exploration Considerations

Because of porosity and permeability reduction caused by laumontitization, sandstones of Jurassic, Cretaceous, and early Paleocene age are not highly prospective as reservoir rocks in Cook Inlet basin. However, information gathered from other oil fields suggests that there may be mitigating factors.

Artificial stimulation procedures may permit hydrocarbon production in some laumontitized reservoirs, but such techniques have not generally worked. In other sedimentary basins, where oil wells are drilled in mineralogically immature sandstones below the shallowest occurrences of authigenic laumontite, the wells have had low or noncommercial production rates initially. However, the production of oil may be improved in wells whose oil-saturated sediments are incompletely laumontitized by using a recently developed method of hydraulic fracturing (Lavery, 1961).

If parts of the lower Cook Inlet region were not subjected to the high thermal gradients required for the crystallization of laumontite, as the crosscutting character of the diagenetic front suggests, the sandstones in those areas may have retained sufficient intergranular porosity to be prospective. Several California oil fields, such as Santa Fe Springs, North Tejon, and Jacalitos, have producible reservoirs in strata that abruptly change laterally from destructively laumontitized rock to unaltered rock. Systematic mapping of the diagenetic front should identify potentially laumontite-free areas where reservoir quality should be better.

Studies of sandstone diagenesis in other petroliferous basins have provided evidence that the chemistry of the fluids in the rock pores may inhibit or prevent the formation of laumontite. Even though the temperature and pressure are suitable, if the pore solutions are saline ($\geqslant$ 3 percent) or contain high levels of dissolved carbonate species, carbonate minerals and kaolinitic clays will form instead of laumontite (McCulloh and Stewart, 1979); as a result, reservoir properties will not be so seriously reduced. Possibly this situation may apply to the lower Cook Inlet basin. During the laumontite-forming hydrothermal episode, lateral or vertical variations in the chemistry of the fluids in the rock pores may have inhibited the crystallization of laumontite in parts of the lower Cook Inlet basin.

Plutonism and Provenance—Implications for Sandstone Compositions

By Travis Hudson[5]

INTRODUCTION

In order to predict the kinds of sedimentary sequences in a well, the type of tectonic setting in the surrounding area must be identified first.

The provenance history of the forearc basin that includes Cook Inlet is revealed in the temporal, petrologic, and regional relations of southern Alaska plutonic rocks. The plutonic history indicates that provenance evolved from simple magmatic arc sequences in the early Mesozoic to a complicated composite of magmatic arc, recycled orogen, and continental block provenances in the late Cenozoic. Because three major provenance types are present, a complete range of sandstone framework modes is to be expected. Generally, Jurassic plutonism produced rocks with mafic to intermediate compositions, Cretaceous plutonism produced mostly intermediate compositions, and Tertiary plutonism produced felsic compositions. During provenance evolution, the amounts of metamorphic and plutonic rocks increased proportionally and the compositions of the younger plutons became more felsic, so the younger sandstones of the Cook Inlet basin are most likely to have quartzose framework modes.

For the purpose of this report, the provenance of the forearc basin is considered to be that part of southern Alaska south of, and including, the Aleutian-Alaska Range. This simplifying assumption focuses the discussion on the region proximal to the basin although it does not imply that other parts of Alaska could not have also been part of the provenance.

SOUTHERN ALASKA PLUTONISM

Plutonic rocks are very extensive in southern Alaska; all larger outcrops are shown in figure 27. The distribution, age, and setting of these rocks define several regional plutonic belts (Reed and Lanphere, 1973b; Hudson, 1979a), and these belts have important implications for southern Alaskan tectonic history (Hudson, 1979b,c; Hudson and others, 1979). Southern Alaska plutons (fig. 27) can be subdivided into the following groups or episodes of plutonic activity based on their age and geologic setting:

1. Late Triassic(?) and Early Jurassic (ca. 195 to 185 Ma) quartz diorite and tonalite in elongate deformed plutons are discontinuously exposed on northwestern Kodiak Island, the Barren Islands, and southern Kenai Peninsula. Some plutons intrude Upper Triassic sedimentary rocks that include volcanogenic sandstone and tuff. Because the K-Ar ages (about 193 Ma) on these plutonic rocks are all single mineral (hornblende) minimum ages, some could be slightly older.

2. Early Jurassic(?) gabbro, quartz diorite, and tonalite make up elongate and deformed plutons of the northern Chugach Mountains; the easternmost plutonic complex in this group (fig. 27) is mostly gabbro. The age of these poorly known plutons is uncertain. Because they share certain petrologic characteristics and a similar geologic setting with plutonic rocks on western Kodiak Island they may be Early Jurassic in age.

3. Middle and Late Jurassic (ca. 175 to 145 Ma) gabbro to granite but mostly quartz diorite, tonalite (including trondhjemite) and granodiorite make up large elongate batholithic complexes in the Aleutian Range and the Talkeetna Mountains. The batholiths locally intrude, and are regionally in spatial association with, Early Jurassic volcanogenic rocks of the Talkeetna Formation.

4. Late Jurassic (ca. 160 to 140 Ma) quartz diorite, monzodiorite, tonalite, and granodiorite are present in a large batholithic complex and some smaller plutons of the Chitina Valley area (Chitina Valley batholith of MacKevett, 1978). The plutons are known to have correlatives to the south east, and they apparently overlap in age and share some petrologic characteristics with Middle and Late Jurassic plutons to the west. Unlike Jurassic plutons to the west, however, spatially associated volcanogenic rocks have not been identified with plutons of the Chitina Valley area.

5. Middle Cretaceous (ca. 120 to 105 Ma) diorite to granite is present in shallow-seated small to moderate-sized plutons in the Nutzotin Mountains—correlative plutons have been identified to the southeast but not to the west. These plutons have local areas of extensive hydrothermal alteration and the volcanogenic rocks of the Lower Cretaceous Chisana Formation (Richter, 1976) are probably related to them.

6. Late Cretaceous and early Tertiary (ca. 75 to 50 Ma) gabbro to granite form many large plutons and coalescing batholithic complexes that make up a major part of the plutonic rocks in the Alaska Range and Talkeetna Mountains. Most of the more mafic rocks are $\geqslant$62 Ma old and tend to be located in the southern and eastern plutons of the group.

[5]ARCO Exploration Technology.

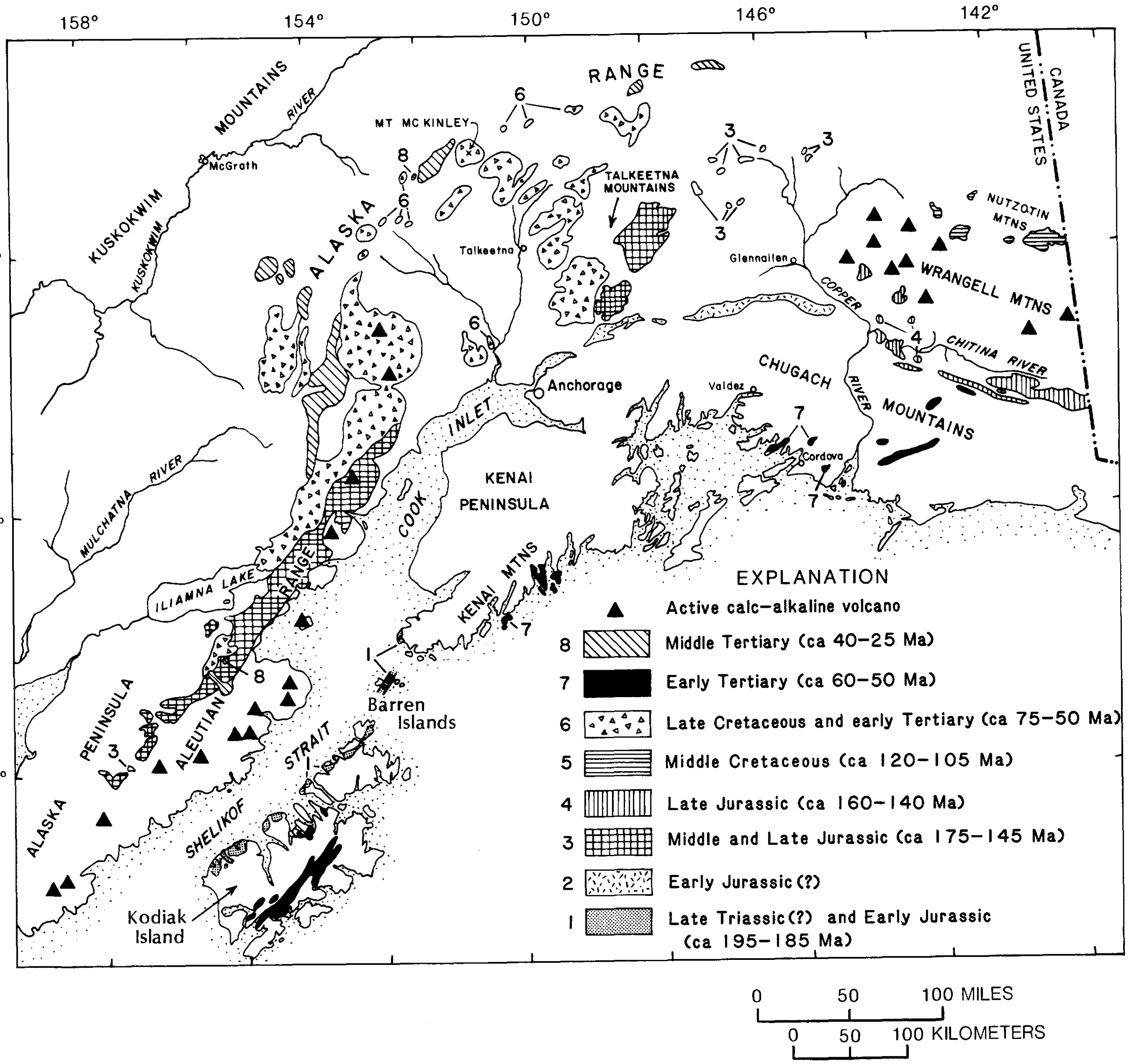


Figure 27. Principal groups of plutonic rocks in southern Alaska subdivided on the basis of their age and geologic setting. Subdivisions are keyed to the text and to figure 28 by age and number. A summary of the field petrology and age relations of these groups, based on the available literature, is presented in Hudson (1979a).

Related volcanic rocks probably developed although they have not been identified in many areas.

7. Early Tertiary (ca. 60 to 50 Ma) biotite tonalite, granodiorite, and granite in small to large plutons, are distributed along the Gulf of Alaska margin from Sanak Island on the west to Baranof Island on the east. These predominantly epizonal plutons are mostly granodiorite and granite; related volcanic rocks are not present. They are believed to have formed by melting of accreted terranes—an origin different from that for most other plutons in southern Alaska (Hudson and others, 1979).

8. Middle Tertiary (ca. 40 to 25 Ma) quartz diorite, tonalite, granodiorite, and granite, in small to large plutons, are scattered through the southern and central Alaska Range. Plutons of similar age are present on the Alaska Peninsula and possibly in eastern parts of southern Alaska. The plutons are commonly shallow-seated and in spatial association with subareal volcanic rocks.

The ternary diagrams in figure 28 summarize the petrologic variation in the groups of plutons outlined above. The diagrams show a general shift toward more felsic compositions from the older to the younger plutonic groups. The

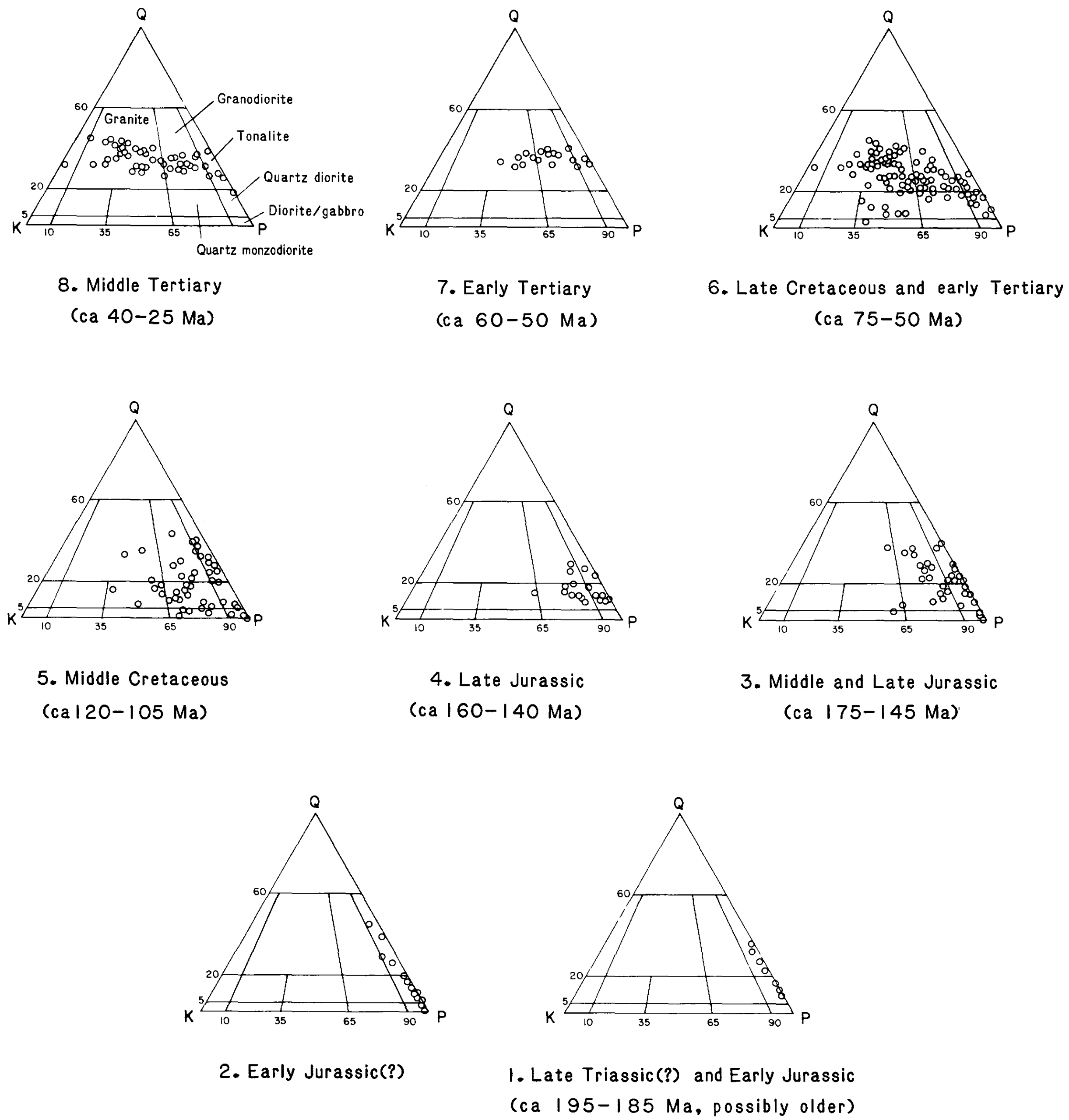


Figure 28. Ternary diagrams showing quartz (Q), K-feldspar (K), and plagioclase (P) ratios for groups of plutonic rocks shown in figure 27. Most of the granite in group 6 is early Tertiary in age. Group 2 includes a large proportion of gabbro. The classification scheme follows that suggested by the IUGS Subcommission on the Systematics of Igneous Rocks (Geotimes, 1973). Data for groups 1, 2, and 4 from Travis Hudson and J.G. Arth (unpub. data, 1980), group 3 from Reed and Lanphere (1973b), group 5 from Richter and others (1975), group 6 from Reed and Lanphere (1973b) and Reed and Nelson (1977), group 7 from Hudson and others (1979), and group 8 from Reed and Lanphere (1973b).

oldest rocks (Early Jurassic as presently known) make up a comparatively primitive suite with little or no K-feldspar. The voluminous Middle or Late Jurassic plutons display a shift to more intermediate compositions with development of quartz monzodiorite, granodiorite, and some large trondhjemite plutons. Petrologic variation becomes well-developed in the Cretaceous plutons and, although most of these are still of intermediate calc-alkaline character, granodiorite and granite are important parts of them. The Tertiary plutons, including the early Tertiary ones of group 6 (figs. 27 and 28), are dominantly granodiorite and granite. Thus, in a general sense, Jurassic plutonism produced mafic to intermediate compositions, Cretaceous plutonism produced mostly intermediate compositions, and Tertiary plutonism produced felsic compositions. These shifts in petrologic character, combined with specific considerations of the timing, extent, and impact of volcanic and metamorphic processes related to plutonism, indicate some general evolutionary changes in regional provenance during development of the Cook Inlet basin.

PROVENANCE EVOLUTION

There are two types of provenance evolution indicated by the plutonic history of southern Alaska. The first type includes those comparatively short-term changes that accompanied emplacement of a particular group of plutons. The second type includes those more gradual and longer term changes that took place as repeated episodes of plutonism affected the region.

Short- and Long-term Changes

Most of the individual groups of plutons identified in figure 27 and outlined above are believed to have formed as part of magmatic arcs that developed during episodes of plate convergence along the continental margin. Such plate convergent episodes generally modify the continental margin through sequential or overlapping cycles of tectonism, magmatism, and sedimentation that are marked by initial and ongoing volcanism, development of comagmatic and indirectly-related plutonism, and they culminate with uplift and erosion of the magmatic arc. Metamorphic and hydrothermal processes, accompanying regional tectonism and magma emplacement, recrystallize and mobilize large volumes of provenance material throughout this cycle. The plutonic history of southern Alaska indicates that such cycles were relatively short-term and affected the provenance marginal to the Cook Inlet forearc basin during at least four separate episodes: Late Triassic(?) and Early Jurassic (1, 2); Middle and Late Jurassic (3, 4); Late Cretaceous and early Tertiary (6, 7); and middle Tertiary (8). A fifth episode, ongoing today, is evidenced by widespread late Cenozoic volcanic rocks and the many active calc-alkaline volcanoes of the region (fig. 27).

The repetition of magmatic arc cycles and the shifting petrologic nature of plutonism combine to produce some longer-term changes in provenance character during development of the Cook Inlet forearc basin. The Jurassic provenance may have included the primitive magmatic (probably island) arc sequence (group 1, figs. 27 and 28) represented by the Late Triassic volcanogenic rocks and the Early Jurassic plutonic rocks of Kodiak Island, the Barren Islands, and Kenai Peninsula, but it was dominated by the magmatic arc rocks of the Aleutian Range and Talkeetna Mountains (group 3). Pre-Jurassic metasedimentary and metavolcanic rocks are locally a part of this arc but until the Late Cretaceous, the provenance was mostly volcanic and plutonic rocks of mafic to intermediate composition (fig. 28). The volume of plutonic rocks in southern Alaska virtually doubled in the Late Cretaceous and early Tertiary (groups 6 and 7). This increase, combined with widespread thermal and dynamothermal metamorphism, led to a composite provenance that, for the first time in the history of the forearc basin, included a high proportion of crystalline rocks. The Late Cretaceous plutonic rocks in part contained more quartz and K-feldspar than their predecessors, but it was during the Tertiary (groups 6, 7, and 8) that a large amount of felsic plutonic rocks were formed; the proportion of plutonic rocks increased by about a third in the Tertiary and these rocks were dominantly felsic in character. Through the Tertiary, the composite aggregate of diverse Mesozoic igneous, metamorphic, and sedimentary rocks that make up the bulk of the provenance became thoroughly welded by plutonism and metamorphism into what is now a relatively youthful but truly continentalized crust.

Therefore, provenance evolved over the long term from simple magmatic arc sequences in the early Mesozoic to a composite of regional sedimentary, metamorphic, and magmatic arc sequences in the late Mesozoic and Cenozoic. In effect, each succeeding magmatic arc increased the proportion of crystalline rocks in the provenance. It is against this background of long-term evolution that shorter-term changes, accompanying development of individual magmatic arcs, need to be considered. Consideration of the long- and short-term provenance changes together defines a history that should be reflected in the composition of Mesozoic and Cenozoic sandstones of the Cook Inlet forearc basin.

Implications for Sandstone Compositions

The influence of provenance on model framework compositions of sandstone has been summarized recently by Dickinson and Suczek (1979), who identified framework modes that have formed from three provenance types—magmatic arc, recycled orogen, and continental block provenances (fig. 29).

The Mesozoic and Cenozoic evolution of southern Alaska provenance, as indicated by the plutonic history of the region, involves the complicated interplay of all three provenance types. Even so, the following general implications of provenance evolution on sandstone composition in the Cook Inlet forearc basin can be made: (1) Late Triassic, Jurassic, and Early Cretaceous sandstones should reflect simple magmatic arc provenance and show Q-F-L modes changing from lithic to feldspathic compositions (fig. 29). Such changes have been identified qualitatively by stratigraphic studies (Burk, 1965; Detterman and others, 1965; Grantz and others, 1963) and in some cases quantitatively by sandstone modal studies (Egbert, this volume; McLean, 1979). (2) Late Cretaceous sandstones should reflect a composite provenance that includes magmatic arc and recycled orogen types. The continued dissection of Jurassic arcs would have helped

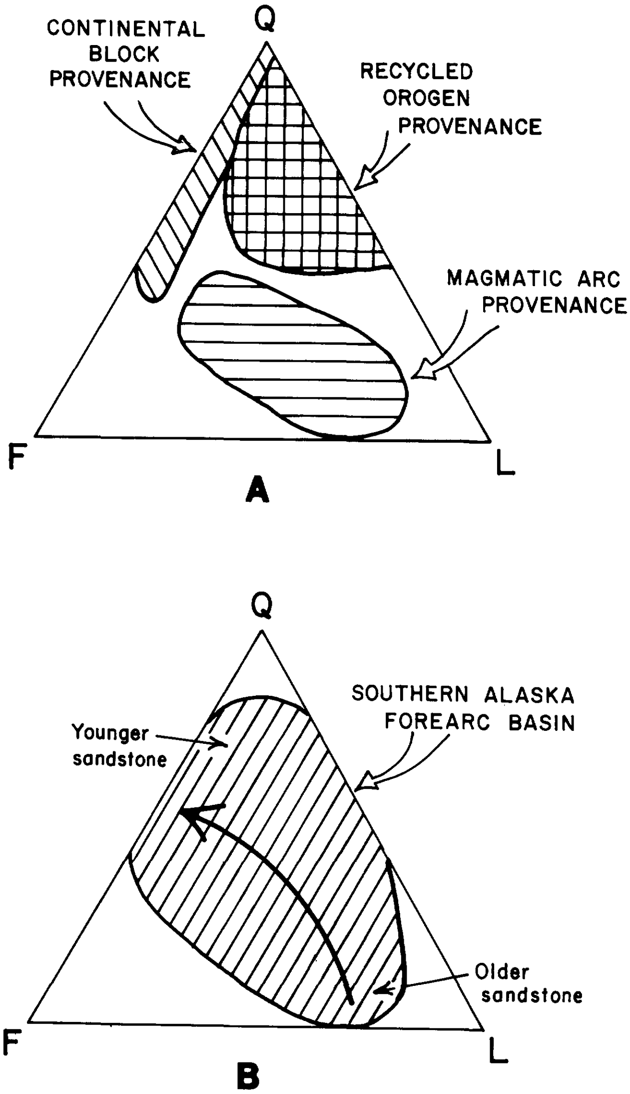


Figure 29. Relation of provenance on modal framework composition of sandstone. *A*, Ternary Q-F-L diagram showing framework mode fields from sandstones derived from different types of provenance (from Dickinson and Suczek, 1979, fig.1). *B*, Q-F-L diagram showing expected framework mode field for sandstones in the forearc basin of southern Alaska. Modal trend, from older to younger sandstones, is the expected general trend for the forearc basin that is suggested by provenance evolution.

produce quartzofeldspathic sandstone compositions but a new magmatic arc cycle should be evidenced in the Late Cretaceous with at least local development of volcanolithic sandstones (Magoon and others, 1980). (3) Tertiary sandstones should reflect an even more complicated composite provenance that includes all three types. The sandstones should be diverse and range from lithic to quartzose types. Volcanic, metamorphic, and sedimentary rock fragments could each dominate the lithic component in particular cases. Feldspar, commonly K-feldspar as well as plagioclase and quartz, could dominate framework modes of sandstones derived directly from plutonic terranes. In a very general sense, the Tertiary sandstones (assuming a derivation from a southern Alaska provenance) are the most likely to contain a significant K-feldspar and quartz component.

Figure 30 schematically illustrates the generalized framework grain ratios that are predicted by provenance evolution. The trend for the lithic volcanic (Lv) to total feldspar (F) ratio shows the initiation of each magmatic arc as distinct short-term shifts to higher ratios. These shifts to higher ratios are superimposed on a general trend of decreasing Lv to F ratios that reflect the predicted longer-term changes in provenance. The longer term changes should be more clearly shown by the ratio of total quartzose grains (Q) to total feldspar (F). The Q/F ratio should increase gradually while the dissected Jurassic arc is the principal provenance, then should increase more by the Late Cretaceous, and increase sharply through the Tertiary. The ratio of K-feldspar (K) to plagioclase (P) in the framework modes is the ratio that is most likely to reflect the development of felsic rocks in the provenance. This ratio is expected to be low in the Early to Middle Jurassic, increase slightly to a uniform volume in the Early and middle Cretaceous, and increase more rapidly by the Late Cretaceous. Like Q/F, K/P probably increased sharply through the Tertiary.

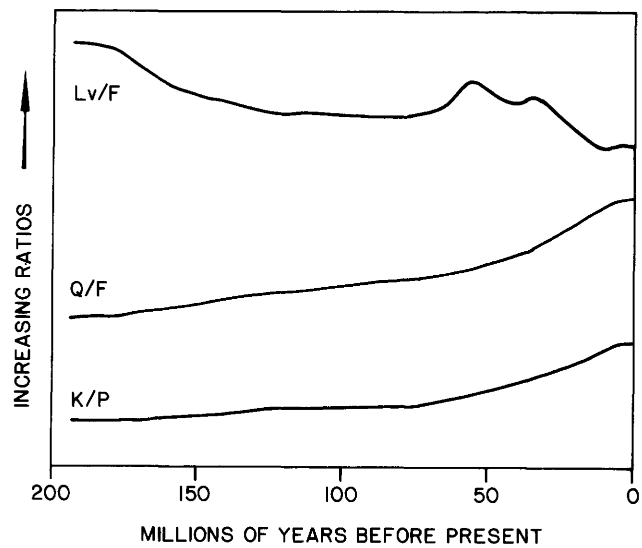


Figure 30. Schematic diagram showing possible evolutionary trends of average framework grain ratios in sandstones of the Cook Inlet forearc basin: lithic volcanic to total feldspar (Lv/F), total quartzose grains to total feldspar (Q/F), and K-feldspar to plagioclase (K/P) (symbology after Dickinson and Suczek, 1979). Models are based on the assumption of continuous erosion of source terranes and sedimentation in the basin.

CONCLUSION

The Mesozoic and Cenozoic plutonic history of southern Alaska provides insight into the provenance evolution for the forearc basin that includes Cook Inlet. This plutonic history indicates that provenance evolved from simple magmatic arc sequences in the Early Mesozoic to a complicated composite that includes magmatic arc, recycled orogen, and continental block provenance types in the late Cenozoic. Provenance with continental block characteristics is not widespread adjacent to Cook Inlet; it is mostly represented by those areas dominated by felsic plutonic rocks—these types of plutonic rocks were primarily emplaced in southern Alaska during the Tertiary.

Sandstone compositions in the forearc basin can be expected to reflect the changes in provenance and to show an increasing diversity from the early Mesozoic to late Cenozoic. Because all three major provenance types (fig. 29A) have developed in southern Alaska, a complete range of sandstone framework modes is to be expected (fig. 29B). However, the increasing proportion of metamorphic and plutonic rocks during provenance evolution combined with a shift to more felsic compositions in younger plutons suggests that younger sandstones of the Cook Inlet basin are the most likely to have quartzose framework modes. Although younger sandstones are expected to show an increasing diversity of composition, the general evolutionary trends shown in figure 29B are probably developed in the forearc basin.

Petrography, Provenance, and Tectonic Significance of Middle and Upper Jurassic Sandstone from Tuxedni Bay

By Robert M. Egbert[6]

INTRODUCTION

Modal analyses of 88 thin sections from Middle and Upper Jurassic sandstone in the Tuxedni Bay area, western Cook Inlet, show systematic changes in framework composition, hornblende content, and type of cement with stratigraphic position. The changes appear to reflect uplift and unroofing of the Alaska-Aleutian Range batholith in Jurassic time. Compaction and cementation, which have occluded all visible porosity in the sandstone, should be considered in evaluating the hydrocarbon-reservoir potential of Middle and Upper Jurassic sandstone in Cook Inlet.

The Middle and Upper Jurassic sequence in Tuxedni Bay is over 3,000 m (10,000 ft) thick, and includes the Middle Jurassic Tuxedni Group and Chinitna Formation and Upper Jurassic Naknek Formation (Detterman and Hartsock, 1966; Imlay and Detterman, 1973). I examined 21 thin sections from the Tuxedni Group, 23 thin sections from the Chinitna Formation (11 from the Tonnie Siltstone Member and 12 from the Paveloff Siltstone Member), and 44 thin sections from the Naknek Formation.

The sandstones were analyzed according to a modified classification system based on Crook (1960) and Dickinson (1970). An average of 470 points were counted for each thin section in order to obtain a minimum count of 300 framework grains (Q = quartz, F = feldspar, L = lithic fragments); these grains were used to determine framework composition (fig. 31). The Q-F-L populations were normalized to 100 percent. The remaining points counted were cements and accessory minerals that are shown on figure 31 as percentages of total constituents, including quartz, feldspar, and lithic fragments. In addition, secondary parameters in the form of ratios, C/Q (polycrystalline quartz to total quartz), P/F (plagioclase to total feldspar), and V/L (volcanic lithic to total lithic fragments) were calculated to aid in differentiating sandstone in the three stratigraphic units.

RESULTS

The average framework compositions (Q-F-L) change systematically up section from the Tuxedni Group through the Chinitna Formation and into the Naknek Formation, becoming progressively more feldspathic and less lithic. The quartz content remains nearly constant.

Quartz

All the sandstones studied contain less than 10 percent quartz, most of which is monocrystalline. However, in samples from the Tuxedni Group, quartz has features indicative of volcanic derivation (clear, unstrained, resorbed margins, or bleb inclusions), but the quartz in samples from the Chinitna and Naknek Formations has features indicative of plutonic or metamorphic derivation. Polycrystalline quartz, although not abundant, systematically decreases upward through the section from the Tuxedni Group to the Naknek Formation (see C/Q ratios, fig. 31). Most of the polycrystalline quartzose fragments probably represent silicified volcanic detritus.

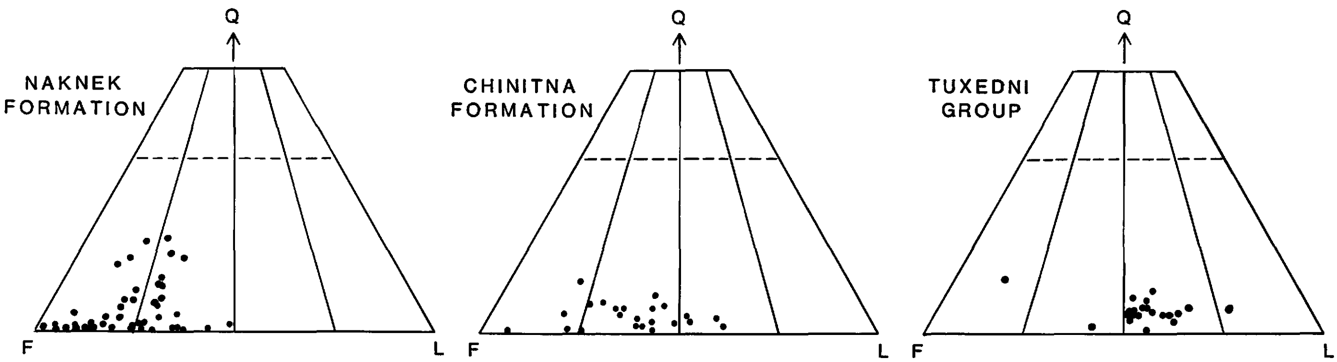
Feldspar

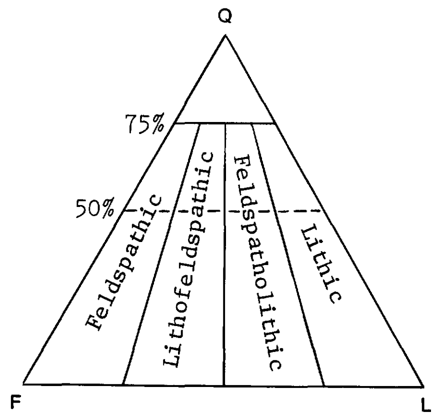
Feldspars are the most abundant mineral grains in the sandstone and increase in abundance from an average of 43 percent of the framework grains in the Tuxedni Group to 73 percent in the Naknek Formation. Plagioclase, the dominant feldspar, averages greater than 90 percent of the feldspar population throughout the stratigraphic section (see P/F ratios, fig. 31). The plagioclase is highly altered and is mostly albitized and(or) replaced by laumontite.

Lithic

The lithic fragment populations decrease up section as the feldspar populations increase. Lithic fragments average 51 percent in the Tuxedni Group, 35 percent in the Chinitna Formation (43 percent in the Tonnie Siltstone Member and 29 percent in the Paveloff Siltstone Member), and 21 percent in the Naknek Formation. Most of the lithic fragments are volcanic grains of intermediate composition. V/L ratios decrease slightly up section; this decrease can be related to the appearance of plutonic rock fragments in the upper part of the Chinitna Formation and in the Naknek Formation.

[6]SOHIO Petroleum Company.





Compositon	Naknek Formation (N 44)	Chinitna Formation Paveloff Sts. Mbr. (N 12)	Chinitna Formation Tonnie Sts. Mbr. (N 11)	Tuxedni Group (N 21)
Q	6	5	4	6
F	73	66	53	43
L	20	29	43	51
C/Q	.06	.11	.12	.27
P/F	.96	.96	.96	.92
V/L	.84	.93	.90	.96
Hornblende (%)	11	7	0	0
Chlorite (%)	4	11	12	17
Laumontite (%)	10	5	1	2

Figure 31. Q-F-L ternary diagrams and compositional data of sandstone from Tuxedni Bay. Sandstone classification after Crook (1960) and Dickinson (1970). N, number of thin sections; Q, quartz; F, feldspar; and L, lithic fragments; C, polycrystalline quartz; P, plagioclase; V, volcanic lithic fragments.

Accessory Minerals

Accessory minerals include: hornblende, epidote, biotite, and opaque minerals. Hornblende, which is absent or present in only trace amounts in samples from the Tuxedni Group and Tonnie Siltstone Member of the Chinitna Formation, is the dominant accessory mineral in the Paveloff Siltstone Member of the Chinitna Formation and in the Naknek Formation, averaging 7 and 11 percent respectively.

Intergranular Spaces

Three types of cement, chlorite, laumontite, and calcite, fill intergranular spaces in the sandstones. Chlorite is ubiquitous in the Tuxedni Group and in the lower part of the Chinitna Formation, apparently forming from the chemical breakdown of the abundant volcanic rock fragments. Laumontite is a common cement in the upper part of the Chinitna Formation and is the dominant cement in the Naknek Formation; laumontite probably formed in response to chemical alteration of plagioclase that is abundant in these units. Sampling was biased towards noncalcareous sandstone in order to obtain accurate modal analyses because calcite can replace framework grains. However, though calcite-cemented sandstone was found in all units, it was not common. No porosity was observed in any of the sandstone. Initial pore space has been totally occluded by compaction and deformation of volcanic lithic grains, and by chlorite, laumontite, and calcite cements.

DISCUSSION

Sandstone of the Tuxedni Group was derived largely from a volcanic terrane as indicated by the high percentages of volcanic lithic grains and volcanic quartz. Several important changes in sandstone composition occur between the two members of the Chinitna Formation. The Tonnie Siltstone Member is volcanic-lithic rich, is virtually devoid of hornblende, and has chlorite as the dominant cement, whereas the overlying Paveloff Siltstone Member is much more feldspathic (less lithic rich), contains an average of 7 percent hornblende, and has laumontite as a common cement in addition to chlorite (fig. 31). These differences indicate a change from a dominantly volcanic source for the Tonnie Siltstone Member to a mixed volcanic/plutonic provenance for the Paveloff Siltstone Member. Sandstone of the Naknek Formation was derived mainly from a plutonic source, as indicated by the high percentages of feldspar and hornblende.

The composition of sandstone from the Tuxedni Group and Chinitna and Naknek Formations is directly related to Jurassic tectonic events in south-central Alaska. During the Early Jurassic, 1,800 to 2,700 m (6,000-9,000 ft) of volcanic and volcaniclastic rocks (Talkeetna Formation) accumulated in the area of the present-day Alaska-Aleutian Range forming a volcanic arc at least 800 km (500 mi) long (Detterman and Hartsock, 1966; Reed and Lanphere, 1973a). During the Middle to Late Jurassic, gabbro to granite but mostly quartz diorite, and tonalite to granodiorite of the Alaska-Aleutian Range batholith intruded the Early Jurassic volcanic arch sequence and older rocks (Detterman and others, 1965; Hudson, this volume). Uplift and erosion of the ancestral Aleutian Range in the Middle Jurassic shed volcanic detritus into the adjacent Cook Inlet forearc basin—the deposits represented by the Tuxedni Group. Continued uplift and erosion of the Aleutian Range in the late Middle Jurassic partially unroofed the Alaska-Aleutian Range batholith, and both volcanic and plutonic detritus was being deposited in the adjacent basin; these deposits are represented by the Chinitna Formation. By Late Jurassic time, when rocks of the Naknek Formation were being deposited, the Alaska-Aleutian Range batholith was mostly unroofed, thereby supplying dominantly plutonic detritus to the Cook Inlet basin. These conclusions are consistent with previous detailed work by Detterman and Reed (1980). They base their conclusions mainly on comparison of age and composition of conglomerate clasts in the Naknek Formation to underlying units. I suggest, however, that the Alaska-Aleutian Range batholith was unroofed earlier—during the deposition of the Paveloff Siltstone Member of the Chinitna Formation.

Framework Geology and Sandstone Composition

By Leslie B. Magoon *and* Robert M. Egbert[7]

INTRODUCTION

The purpose of this paper is to review the stratigraphic history and tectonic evolution of the Cook Inlet forearc basin in order to understand the evolution of the sandstone composition so that potential hydrocarbon reservoirs can be predicted.

The tectonic evolution of the Cook Inlet-Shelikof Strait area and adjacent areas is complex because the areas are a part of the northern Pacific margin that has been the site of continuous convergence throughout the Mesozoic and Cenozoic eras. The Cook Inlet forearc basin is bounded on the northwest by the Alaska-Aleutian Range and the Talkeetna Mountains and on the southeast by Kodiak Island and adjacent islands, the Barren Islands, and the Chugach Mountains. The main discussion will focus on the rock units and tectonic elements of the Cook Inlet-Shelikof Strait area, which includes the Alaska Peninsula from Puale Bay northeast to the Matanuska Valley (fig. 32). If pertinent, rock units and tectonic elements adjacent to this area also will be discussed.

The stratigraphic and structural history of each rock unit will be summarized; all the available information on sandstone composition will be summarized; and the implications of sandstone composition and provenance in relation to the tectonic evolution and development of a hydrocarbon reservoir will be discussed. The parallel change in composition of the plutonic bodies of southern Alaska (Hudson, this volume) to that of the sandstones of the Cook Inlet forearc basin, and in some instances, to that of the sandstones of the accreted terranes, will be demonstrated.

The stratigraphic history will include discussions on: the early Mesozoic geologic framework of the Cook Inlet forearc basin northwest of the Border Ranges fault, the Mesozoic and Cenozoic accreted terranes southeast of the Border Ranges fault, and the Mesozoic Peninsular terrane within the Cook Inlet forearc basin that overlaps the Border Ranges fault. Information from the lower Cook Inlet COST No. 1 well, as well as other wells, measured sections, and plutonic bodies, is incorporated in this discussion.

The compositions of the sandstones in the Cook Inlet forearc basin have an important bearing on the development of hydrocarbon reservoirs in the Cook Inlet-Shelikof Strait area. New data and data from many other sources, modal analyses, and petrographic descriptions of approximately 700 sandstone samples from the Cook Inlet-Shelikof Strait and adjacent areas, are included here. The petrographic data are summarized in figure 33 and in tables 16 and 17.

Dickinson's (1970) classification is used for the sandstone, and his classification with modifications from Crook (1960) is used for subquartzose sandstone. If the published data did not conform to the conventions of Dickinson (1970), the data was recalculated and this is noted in tables 16 and 17.

The sandstones are classified using three primary grain parameters: Q (quartz), F (feldspar), and L (lithic fragments). To further differentiate the sandstones, secondary parameters in the form of ratios, C/Q (polycrystalline quartz to total quartz), P/F (plagioclase to total feldspar), and V/L (volcanic lithic to total unstable lithic fragments) are listed in tables 16 and 17 and discussed in the text. New point-count data and the published point-count data of Egbert and Magoon (1981) were made by counting at least 300 framework grains (quartz, feldspar, and lithic fragments) following the method of Dickinson (1970). All the sandstone from the Cook Inlet-Shelikof Strait and adjacent areas is subquartzose ($Q<75$) and is classified using the following system: feldspathic ($F/L>3$), lithofeldspathic ($3>F/L>1$), feldspatholithic ($3>L/F>1$), and lithic ($L/F>3$).

By applying the techniques of Dickinson and Suczek (1979), the compositions of the sandstones in the forearc basin are related to those of the plutonic bodies and of the accreted terranes, thus two provenance terranes, a magmatic arc and a recycled orogen, are identified in the Cook Inlet-Shelikof Strait area from the Q-F-L (quartz-feldspar-lithic) ternary diagrams.

GEOLOGIC FRAMEWORK

Rocks of the Cook Inlet-Shelikof Strait are part of a belt of Mesozoic and Cenozoic sedimentary rocks that extend northeastward to the Matanuska Valley and southwestward along the Alaska Peninsula and Shelikof Strait (figs. 32, 34, 35). Four major northeast-trending geologic features flank the Cook Inlet-Shelikof Strait area; the Alaska-Aleutian Range batholith and the Bruin Bay and Castle Mountain faults are on

[7] SOHIO Petroleum Company.

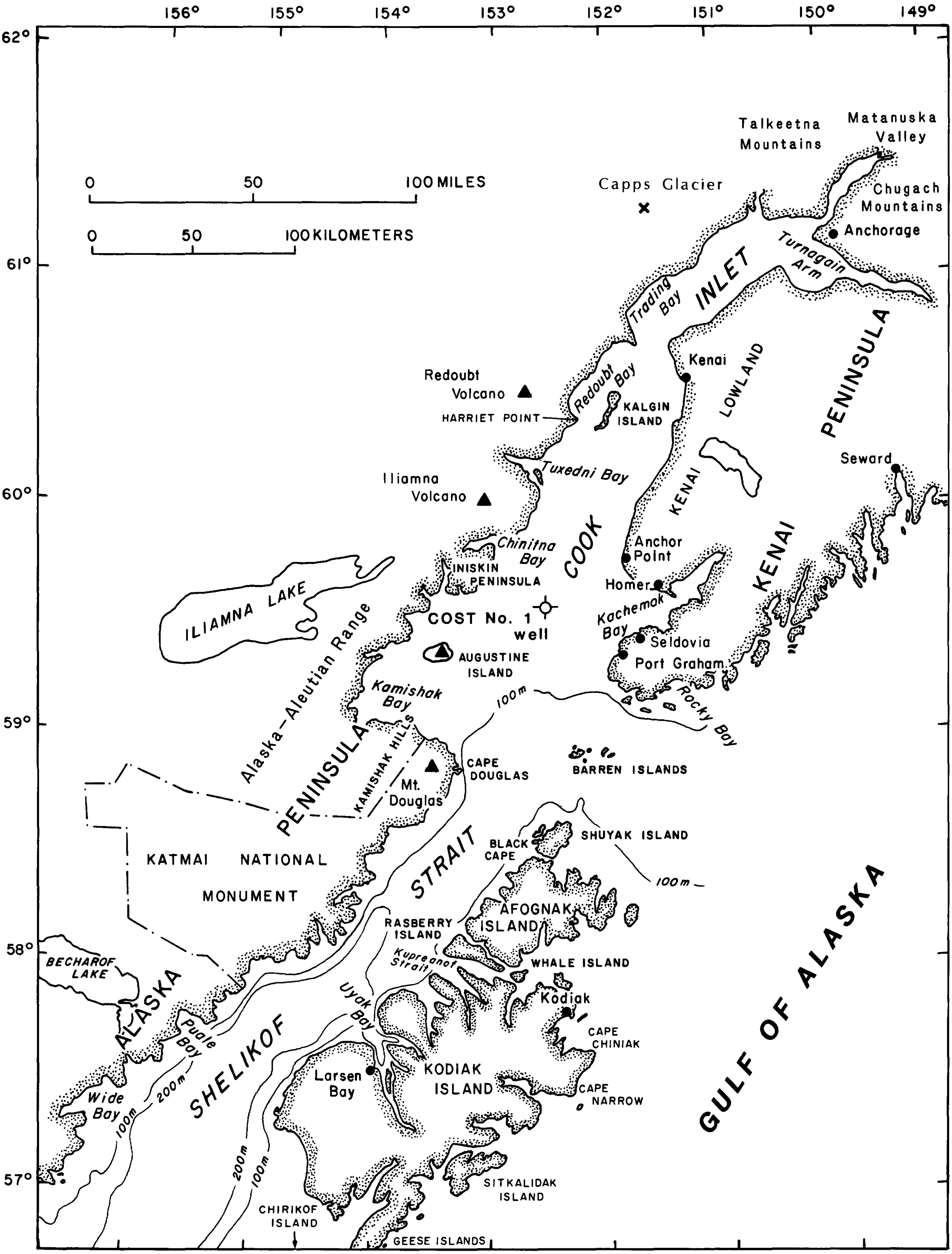


Figure 32. Geographic names and geomorphic features in Cook Inlet, Shelikof Strait, and adjacent areas. The COST No. 1 well is located in lower Cook Inlet.

the northwest side of the Cook Inlet-Shelikof Strait area, and the Border Ranges fault and the accreted terranes are on the southeast side. The Mesozoic rocks of the Cook Inlet-Shelikof Strait area may be more than 10,750 m (35,250 ft) thick; the continental Cenozoic rocks are as much as 7,000 m (25,000 ft) thick (figs. 37, 38).

The Mesozoic sequence of the Cook Inlet-Shelikof Strait area, together with the Alaska-Aleutian Range batholith, constitute the Peninsular terrane of Jones and Silberling (1979) (fig. 36). The Cenozoic rocks that overlie the Peninsular terrane are not designated a terrane name. On the southeast side of the Border Ranges fault, the tectonic terranes comprise the Kachemak (Triassic rocks), Chugach, and Prince William terranes (Jones and Silberling, 1979).

Alaska-Aleutian Range Batholith

The Alaska-Aleutian Range batholith, exposed on the northwest side of the region, is composed of a series of elongate plutonic belts that extend from the Becharof Lake area on the Alaska Peninsula northeast to the Talkeetna Mountains (fig. 34). These calc-alkaline plutonic belts Hudson (1979a,c) has designated the Aleutian Range-Talkeetna Mountains belt (ca. 175-145 Ma), the Alaska Range-Talkeetna Mountains belt (ca. 75-50 Ma), and the Alaska Range belt (ca. 40-25 Ma). The ages of the plutonic belts in figure 30 are those of Hudson (this volume). Three intrusive episodes are indicated by concordant mineral ages on hornblende and biotite pairs: (1) Middle and Late Jurassic plutons emplaced between 176 and 154 Ma, (2) Late Cretaceous and early Tertiary plutons emplaced between 83 and 58 Ma, and (3) middle Tertiary plutons emplaced between 38 and 26 Ma (Reed and Lanphere, 1969, 1972, 1973a,b; Lanphere and Reed, 1973).

Bruin Bay and Castle Mountain Faults

The Bruin Bay fault (fig. 34), a high-angle reverse fault, can be traced along the northwest side of the Alaska Peninsula and Cook Inlet basin for 500 km (300 mi). The fault plane dips 60° northwest in Kamishak Bay. Just north of Chinitna Bay, stratigraphic throw across the fault is as much as 3 km (1.9 mi); and here beds on the west, granitic rocks and rocks as old as Early Jurassic are juxtaposed against sedimentary strata as young as Middle Jurassic (Detterman and Hartsock, 1966).

The Castle Mountain fault, an extension of the Lake Clark fault, can be traced for over 200 km (125 mi), from the north end of the Bruin Bay fault, northeast through the Susitna River Valley to the southeast flank of the Talkeetna Mountains. The fault apparently has large right-lateral strike-slip displacement. The Aleutian Range-Talkeetna Mountains belt has been displaced by about 150 km (95 mi).

Vertical offset has occurred along both the Bruin Bay and Castle Mountain faults; the Cook Inlet-Shelikof Strait block dropped relative to the northwest block.

Border Ranges Fault

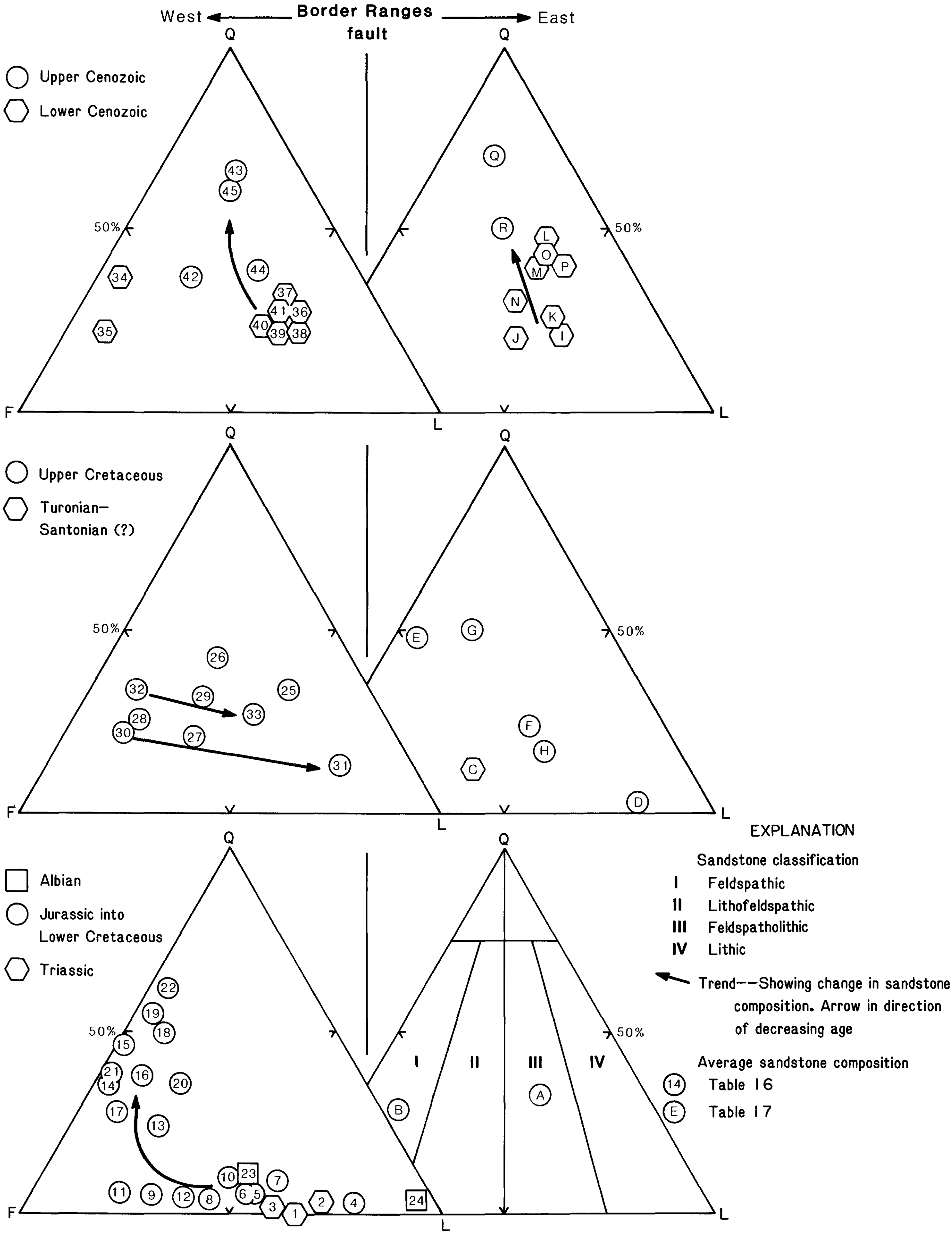
The Border Ranges fault, a major tectonic feature in southern Alaska, extends from southeastern Alaska (MacKevett and Plafker, 1974), throughout southern Alaska (Plafker and others, 1977; Fisher, oral commun., 1980), at the surface near Anchorage, Seldovia, and on the northwest side of Kodiak Island and adjacent islands. The part of the Border Ranges fault near Anchorage is designated the Knik fault zone by Clark (1972); the fault near Seldovia is designated the Seldovia fault by Fisher and Magoon (1978). The Seldovia fault is interpreted to extend northeast through Homer, beneath the Kenai lowland to connect with the Knik fault, and southwest through the Barren Islands to Kodiak Island and adjacent islands. The fault is overlapped at the surface by Tertiary (Neogene) sedimentary rocks in the Kenai lowland northeast toward Anchorage. However, in the areas of Matanuska Valley, Seldovia, Kodiak Island and adjacent islands, the Border Ranges fault separates the moderately deformed Mesozoic sequence, Peninsular terrane of Cook Inlet-Shelikof Strait on the northwest, from the severely deformed rocks, Chugach and Prince William terranes, on the southeast.

Kodiak-Seldovia Schist Terrane

The schist terrane, or glaucophane-bearing rock assemblage, was first recognized by Martin and others (1915) on the Kenai Peninsula and was described and dated in more detail by Forbes and Lanphere (1973). Later it was designated the Kodiak-Seldovia schist terrane by Moore and Connelly (1979). Similar schist terranes have been identified on Kodiak Island and adjacent islands (Carden and others, 1977), east of Anchorage (Clark, 1972), and in the northern Chugach Mountains (Winkler and others, 1980).

The terrane contains a variety of metamorphic rocks, marble, metachert, blueschist, and greenschist, in addition to quartz-mica schist. The original sediments of this terrane, marble and metachert, should predate the K-Ar ages that range from 192 to 181 Ma (Forbes and Lanphere, 1973) or Early Jurassic time; in fact, Permian fusilinids were identified from limestone east of Anchorage (Clark, 1972). Although the blueschist mineralogy suggests a low-temperature, high-pressure metamorphic event, the greenschist mineralogies suggest that a higher temperature event formed the schist (Forbes and Lanphere, 1973; Carden and others, 1977).

On the Kenai Peninsula, the schist terrane is separated from the Mesozoic shelf deposits by the Port Graham fault on the northwest (Carden and others, 1977) and is separated


West
Border Ranges fault
East
Q
F
L
50%
Upper Cenozoic
Lower Cenozoic
Upper Cretaceous
Turonian–Santonian (?)
Albian
Jurassic into Lower Cretaceous
Triassic
I
II
III
IV
EXPLANATION
Sandstone classification
I Feldspathic
II Lithofeldspathic
III Feldspatholithic
IV Lithic
Trend––Showing change in sandstone composition. Arrow in direction of decreasing age
Average sandstone composition
14 Table 16
E Table 17

from the Kachemak (Triassic rocks) and Chugach terranes by the Border Ranges fault on the southeast (Plafker and others, 1977). In the northern Chugach Mountains, the schist terrane has been, in part, tectonically incorporated into the McHugh Complex (Winkler and others, 1980). On Kodiak Island and adjacent islands, the schist terrane is bounded on the east by the Border Ranges fault and on the west by the Kodiak-Kenai plutonic belt.

Kodiak-Kenai Plutonic Belt

The Kodiak-Kenai plutonic belt, ca. 195-185 Ma, (Hudson, 1979b; fig. 27, this volume) extends from the Seldovia area southwest to Kodiak Island; it includes the Afognak pluton (Hill and Morris, 1977). The K-Ar age of the plutonic body on the Barren Islands is 187 Ma (Cowan and Boss, 1978); and on Kodiak Island and adjacent islands the age ranges from 193 to 184 Ma (Carden and others, 1977).

The structural relation of the Kodiak-Kenai plutonic belt to the Kodiak-Seldovia schist terrane is unclear. In the Seldovia area the rock units are geographically separated (Carden and others, 1977). The similarity in K-Ar age and close geographic proximity of the pluton to the schist terrane leads Carden and others (1977) to infer that emplacement of the pluton did not create the schist, but the two rock units "experience(d) a similar crystallization and cooling history". The pluton is in intrusive contact with the Mesozoic shelf rocks on Kodiak and the Barren Islands (Carden and others, 1977; Cowan and Boss, 1978; Connelly and Moore, 1979).

ACCRETED TERRANES

The severely deformed Mesozoic and Cenozoic rocks southeast of the Border Ranges fault can be subdivided into two fault-bounded terranes (Jones and Silberling, 1979; Jones and others, 1984)—the Chugach terrane, and the Prince William terrane (fig. 36).

Chugach Terrane

The Chugach terrane (Berg and others, 1972) lies southeast of the Border Ranges fault (fig. 36). It consists of the Triassic rocks and the melange and flysch sequences. The melange consists of the McHugh and Uyak Complexes and the deformed flysch sequences consist of the Cape Current terrane, the Valdez Group, and the Kodiak and Shumagin Formations.

Triassic Rocks

The chert and ellipsoidal lavas that are mapped east of the Border Ranges fault and along the south shore of Kachemak Bay (Martin and others, 1915, pl. III; Magoon and others, 1976b) constitute the Triassic rocks (fig. 36). A Triassic age has been assigned to the rocks on the basis of the stratigraphic relations of the nearby units (Martin and others, 1915, p. 61) and on the paleontologic evidence. A radiolarian assemblage, recovered from chert on Yukon Island in Kachemak Bay by E. A. Pessagno in 1975, was assigned a Late Triassic age (Jones and others, 1977, p. 2572). This chert unit was found to be in thrust-fault contact with the McHugh Complex by J. S. Kelley (Magoon and others, 1976b). Other workers have included the Triassic rocks in the Seldovia Bay Complex (Cowan and Boss, 1978) or in the McHugh Complex (Plafker and others, 1977).

McHugh and Uyak Complexes

The McHugh and Uyak Complexes consist of metasedimentary and metavolcanic rocks in the Chugach Mountains near Anchorage (Clark, 1972, 1973), on the Kenai Peninsula (Kelley, 1977b), and on the northwest part of Kodiak Island and adjacent islands (Connelly, 1978; Connelly and Moore, 1979) (fig. 34).

Quantitative modal analyses of sandstone are limited for the McHugh Complex. Clardy (1974) described one sample from the McHugh east of Anchorage as having a modal composition of $Q_{33}F_{25}L_{42}$. Nineteen sandstone samples from the Uyak Complex on the Kodiak Island and adjacent islands have an average modal composition of $Q_{29}F_{61}L_{10}$ (Connelly, 1978). Plagioclase to total feldspar ratios (P/F), which range from 1.0 to 0.91, indicate that nearly all the feldspar is plagioclase. The very high ratios of volcanic lithic to total lithic fragments (V/L) indicate a volcanic source terrane.

Quartz from both the McHugh and Uyak Complexes is present in moderate amounts. Polycrystalline to total quartz ratios (C/Q) are low, therefore most of the quartz is monocrystalline. Connelly (1978) concluded that the monocrystalline quartz was mainly of volcanic derivation. However, Connelly (1978) described several samples of "chert-clast wackes" from the Uyak Complex as having high polycrystalline quartz to total quartz ratios.

Figure 33. Q-F-L ternary diagrams for sandstones from Upper Triassic through upper Cenozoic rocks of the Cook Inlet forearc basin northwest of the Border Ranges fault and of the accreted terranes southeast of the fault. Average Q-F-L values are plotted; numbers and letters refer to samples listed in tables 16 and 17.

Table 16. Petrography of sandstone samples from northwest of Border Ranges fault

[Sandstone classification of Dickinson (1970) with modifications from Crook (1960). Sample numbers are referred to in QFL plots, fig. 33]

Sample Number	Formation	Area	Age	Reference	Sandstone classification	Average Q	Average F	Average L	Average C/Q	Average P/F	Average V/L	N
45	Tyonek Formation	Middle Ground Shoal Field	Oligocene-middle Miocene	Stewart (1976)	Feldspatholithic	61	19	20	0.17	0.46	0.20	2
44	Hemlock/Tyonek Undifferentiated	Cape Douglas	Oligocene-middle Miocene	Lankford and Magoon (1978)	Feldspatholithic	39	24	37	.0	--	--	12
43	Hemlock Conglomerate	Middle Ground Shoal Field	Late Oligocene	Stewart (1976)	Feldspatholithic	66	15	19	.14	.50	.21	4
42	Tsadaka Formation	Matanuska Valley	Late Oligocene	Clardy (1974)	Lithofeldspathic	37	40	23	.14	.78	26	12
41	West Foreland Formation	Cape Douglas	Paleocene-Early Eocene	Lankford and Magoon (1978)	Feldspatholithic	29	22	49	.0	.95	.98	12
40	West Foreland Formation	COST No. 1 Well	Paleocene-Early Eocene	Kuryvial (1977), Schluger (1977)	Feldspatholithic	23	30	47	.33	.62	1.0	8
39	West Foreland Formation	Pan American West Foreland No. 1	Paleocene-Early Eocene	Stewart (1976)	Feldspatholithic	22	27	51	.15	.87	.79	4
38	Wishbone Formation	Matanuska Valley	Paleocene-Early Eocene	Clardy (1974)	Feldspatholithic	23	22	55	.23	.72	.89	43
37	Chickaloon Formation	Matanuska Valley	Paleocene	Clardy (1974)	Feldspatholithic	30	22	48	.18	.74	.73	16
36	Chickaloon Formation	Matanuska Valley	Paleocene	Winkler (1978)	Feldspatholithic	28	20	52	.21	.96	.86	8
35	Arkose Ridge Formation	Matanuska Valley	Paleocene	Clardy (1974)	Feldspathic	22	68	10	.06	.72	.28	4
34	Arkose Ridge Formation	Matanuska Valley	Paleocene	Winkler (1978)	Feldspathic	28	20	52	.05	.92	.71	20
33	Kaguyak Formation Upper Part	Cape Douglas	Late Cretaceous (Maestrichtian)	Lankford and Magoon (1978)	Feldspatholithic	27	31	42	.0	.90	.82	12
32	Kaguyak Formation Lower Part	Cape Douglas	Late Cretaceous (Maestrichtian)	Lankford and Magoon (1978)	Feldspathic	34	55	11	.0	--	89	8
31	Kaguyak Formation Upper Part	COST No. 1 Well	Late Cretaceous (Maestrichtian)	Schluger (1977)	Lithic	13	18	69	.33	.87	1.0	2
30	Kaguyak Formation Lower Part	COST No. 1 Well	Late Cretaceous (Maestrichtian)	Kuryvial (1977), Schluger (1977)	Feldspathic	22	64	14	.06	.71	.99	20
29	Kaguyak Formation	Saddle Mountain	Late Cretaceous (Maestrichtian)	Magoon, Griesbach and Egbert (1980)	Lithofeldspathic	32	40	28	.04	.59	.67	5
28	Matanuska Formation Upper Part	Matanuska Valley	Late Cretaceous (Campanian-Maestrichtian)	Grantz (1964)	Feldspathic	26	58	16	.11	.97	--	3
27	Matanuska Formation Upper Part	Matanuska Valley	Late Cretaceous (Campanian-Maestrichtian)	Clardy (1974)	Lithofeldspathic	21	48	31	.23	.81	.68	5
26	Chignik Formation	Alaska Peninsula	Late Cretaceous (Campanian)	Fairchild (1977)	Lithofeldspathic	43	31	26	.16	.31	73	1/69
25	Chignik Formation	Alaska Peninsula	Late Cretaceous (Campanian)	Burk (1965)	Feldspatholithic	34	19	47	--	--	--	2/7
24	Matanuska Formation Lower Part	Matanuska Valley	Early Cretaceous (Albian)	Grantz (1964)	Lithic	4	4	92	.0	.75	(high)	1/2
23	Unnamed	Alaska Peninsula	Early Cretaceous (Albian)	Egbert (this volume)	Feldspatholithic	11	40	49	.03	.99	.97	4
22	Herendeen Limestone	Alaska Peninsula	Early Cretaceous (Hauterivian-Barremian)	Burk (1965)	Feldspathic	62	33	5	--	--	--	2/2
21	Herendeen Limestone	Cape Douglas	Early Cretaceous (Hauterivian-Barremian)	Lankford and Magoon (1978)	Feldspathic	38	59	3	.0	.77	.64	7
20	Herendeen Limestone	COST No. 1 Well	Early Cretaceous (Hauterivian-Barremian)	Babcock (1977), Christensen (1977), Kuryvial (1977), Schluger (1977), Swiderski (1977)	Lithofeldspathic	36	44	20	.06	.88	83	37
19	Staniukovich Formation	Alaska Peninsula	Late Jurassic-Early Cretaceous (late Kimmeridgian-Valanginian)	Burk (1965)	Feldspathic	55	41	4	--	--	--	2/7
18	Staniukovich Formation	Alaska Peninsula	Late Jurassic	Franks and Hite (1980)	Feldspathic	48	42	10	--	--	--	--
17	Naknek Formation	Puale Bay	Late Jurassic	Egbert (this volume)	Feldspathic	28	63	9	.0	.90	.66	3
16	Naknek Formation	Alaska Peninsula	Late Jurassic	McLean (1979)	Feldspathic	38	52	10	--	--	--	42
15	Naknek Formation	Alaska Peninsula	Late Jurassic	Burk (1965)	Feldspathic	47	52	1	--	--	--	4
14	Naknek Formation	Cape Douglas	Late Jurassic (Kimmeridgian)	Lankford and Magoon (1978)	Feldspathic	36	60	4	.0	.97	.75	11
13	Naknek Formation	Cost No. 1 Well	Late Jurassic (Kimmeridgian)	Babcock (1977), Christensen (1977), Kuryvial (1977), Schluger (1977), Swiderski (1977)	Lithofeldspathic	24	55	21	.08	.87	.88	28
12	Naknek Formation	Iniskin-Tuxedni Region	Late Jurassic	Franks and Hite (1980)	Lithofeldspathic	4	58	38	--	--	--	--
11	Naknek Formation	Tuxedni Bay	Late Jurassic (Oxfordian-early Kimmeridgian)	Egbert and Magoon (1981)	Feldspathic	6	73	21	.06	.96	.84	44
10	Shelikof Formation	Puale Bay	Middle Jurassic (Callovian)	Egbert (this volume)	Lithofeldspathic	9	46	45	.04	.97	.95	13
9	Chinitna Formation Paveloff Siltstone	Tuxedni Bay	Middle Jurassic (Callovian)	Egbert and Magoon (1981)	Lithofeldspathic	5	66	29	.11	.96	.93	12
8	Chinitna Formation Tonnie Siltstone	Tuxedni Bay	Middle Jurassic (Callovian)	Egbert and Magoon (1981)	Lithofeldspathic	4	53	43	.12	.96	.90	11
7	Kialagvik Formation	Puale Bay	Middle Jurassic (early-middle Bajocian)	Egbert (this volume)	Feldspatholithic	8	35	57	.23	.95	.94	6
6	Tuxedni Group	Tuxedni Bay	Middle Jurassic (Bajocian-Bathonian)	Egbert and Magoon (1981)	Feldspatholithic	6	43	51	.27	.92	.96	21
5	Talkeetna Formation	Puale Bay	Early Jurassic (Hettangian-early Sinemurian)	Egbert (this volume)	Feldspatholithic	6	42	52	.0	.97	.98	3
4	Talkeetna Formation (Pogibshi Formation, Kelley 1980)	Kenai Peninsula	Early Jurassic (Hettangian-early Sinemurian)	Kelley (1980)	Lithic	3	20	77	(low)	1.0	1.0	114
3	Unnamed	Puale Bay	Late Triassic	Moore and Connelly (1979)	Feldspatholithic	2	39	59	--	--	--	2/3
2	Shuyak Formation	Kodiak Island	Late Triassic	Moore and Connelly (1979)	Feldspatholithic	3	27	70	--	--	--	2/6
1	Unnamed	Kenai Peninsula	Late Triassic	Moore and Connelly (1979)	Feldspatholithic	0	35	65	--	--	--	2/5
						2	34	64	0.10	1.0	0.9	3/14

1/ Recalculated from original data.
2/ Estimated percentages from QFL ternary diagrams in reference (no tabular data present in reference).
3/ Triassic sandstone from Puale Bay, Kodiak Island, and the Kenai Peninsula averaged together by Moore and Connelly (1979).

Q = Quartz + Chert + Quartzite
F = Total feldspar
L = Total rock fragments
C/Q = Chert/Quartz + Chert + Quartzite
P/F = Plagioclase/Total feldspar
V/L = Volcanic rock fragments/Total rock fragments
N = number of samples

Clark (1972, 1973) was uncertain about the age of the McHugh Complex; she considered it to be Late Jurassic and(or) Cretaceous. Recently radiolarians were recovered from the chert at the type locality of the McHugh Complex, and Karl and others (1979) assigned the radiolarians an Early Cretaceous (Valanginian) age. Connelly and Moore (1979) found that the Uyak Complex on Kodiak Island and adjacent islands contained fossils ranging in age from Paleozoic to

Table 17. Petrography of sandstone samples from southeast of Border Ranges fault

[Sandstone classification of Dickinson (1970) with modifications from Crook (1960). Letter refers to QFL plots, fig. 33]

Letter	Formation	Area	Age	Reference	Sandstone classification	Average Q	F	L	Average C/Q	P/F	V/L	N
R	Narrow Cape Formation	Kodiak Island	Late Oligocene(?)-middle Miocene	Winkler (1979)	Lithofeldspathic	50	26	24	0.25	0.75	0.47	3
Q	Narrow Cape Formation	Kodiak Island	Late Oligocene(?)-middle Miocene	Lyle and others (1977)	Lithofeldspathic	70	18	12	—	.75	.47	3
P	Sitkinak Formation	Kodiak Island	Oligocene	Winkler (1979)	Feldspatholithic	40	16	44	.34	.98	.75	4
O	Sitkinak Formation	Kodiak Island	Oligocene	Lyle and others (1977)	Feldspatholithic	45	18	37	—	.90	.75	5
N	Sitkinak Formation	Kodiak Island	Oligocene	Stewart (1976)	Feldspatholithic	30	33	37	.12	.84	.28	1
M	Sitkalidak Formation	Kodiak Island	Eocene-Oligocene	Stewart (1976)	Feldspatholithic	40	22	38	.25	.81	.41	7
L	Sitkalidak Formation	Kodiak Island	Eocene-Oligocene	Lyle and others (1977)	Feldspatholithic	46	17	37	—	.90	.75	4
K	Sitkalidak Formation	Kodiak Island	Eocene-Oligocene	Winkler (1979)	Feldspatholithic	26	26	48	.16	.91	.74	3
J	Ghost Rocks Formation	Kodiak Island	Paleocene-Eocene	Winkler (1979)	Feldspatholithic	21	37	42	.08	.92	.95	8
I	Ghost Rocks Formation	Kodiak Island	Paleocene-Eocene	Lyle and others (1977)	Feldspatholithic	23	25	52	—	.92	.95	2
H	Shumagin Formation	Shumagin Island	Late Cretaceous (Maestrichtian)	Moore (1973)	Feldspatholithic	17	32	51	.15	.97	.96	61
G	Kodiak Formation	Kodiak Island	Late Cretaceous (Maestrichtian)	Connelly (1978)	Lithofeldspathic	50	33	17	.3	1.0	—	5
F	Kodiak Formation	Kodiak Island	Late Cretaceous (Maestrichtian)	Winkler (1979)	Feldspatholithic	24	32	44	.10	.95	.96	3
E	sliver wacke	Kodiak Island	Late Cretaceous (Maestrichtian)	Connelly (1978)	Feldspathic	48	47	5	.20	1.0	—	6
D	Valdez Group	Chugach Mountains	Late Cretaceous (Maestrichtian)	Clardy (1974)	Lithic	3	17	80	.80	1.0	.90	1
C	Cape Current terrane	Shuyak-Afognak Islands	Late Cretaceous (Turonian-Santonian?)	Connelly (1978)	Lithofeldspathic	12	52	36	.2	1.0	1.0	7
B	Uyak Complex	Kodiak Island	Middle Permian(?)-Early Cretaceous (Valanginian)	Connelly (1978)	Feldspathic	29	61	10	.3	1.0	1.0	19
A	McHugh Complex	Chugach Mountains	Middle Permian(?)-Early Cretaceous (Valanginian)	Clardy (1974)	Feldspatholithic	33	25	42	.06	.91	.74	1

Q = Quartz + Chert + Quartzite
F = Total Feldspar
L = Total rock fragments

C/Q = Chert/Quartz
P/F = Plagioclase/total feldspar
V/L = Volcanic rock fragments/total rock fragments

N = number of samples

Early Cretaceous; however, they believed the petrologic and stratigraphic data indicated an Early Cretaceous (late Valanginian to Aptian) age.

The sandstone compositions of these two rock complexes are considered to be correlative (table 17; fig. 34). The McHugh and Uyak Complexes are inferred to represent oceanic crust, abyssal floor, and trench deposits of a subduction complex (Plafker and others, 1977; Connelly and Moore, 1979).

Cape Current Terrane

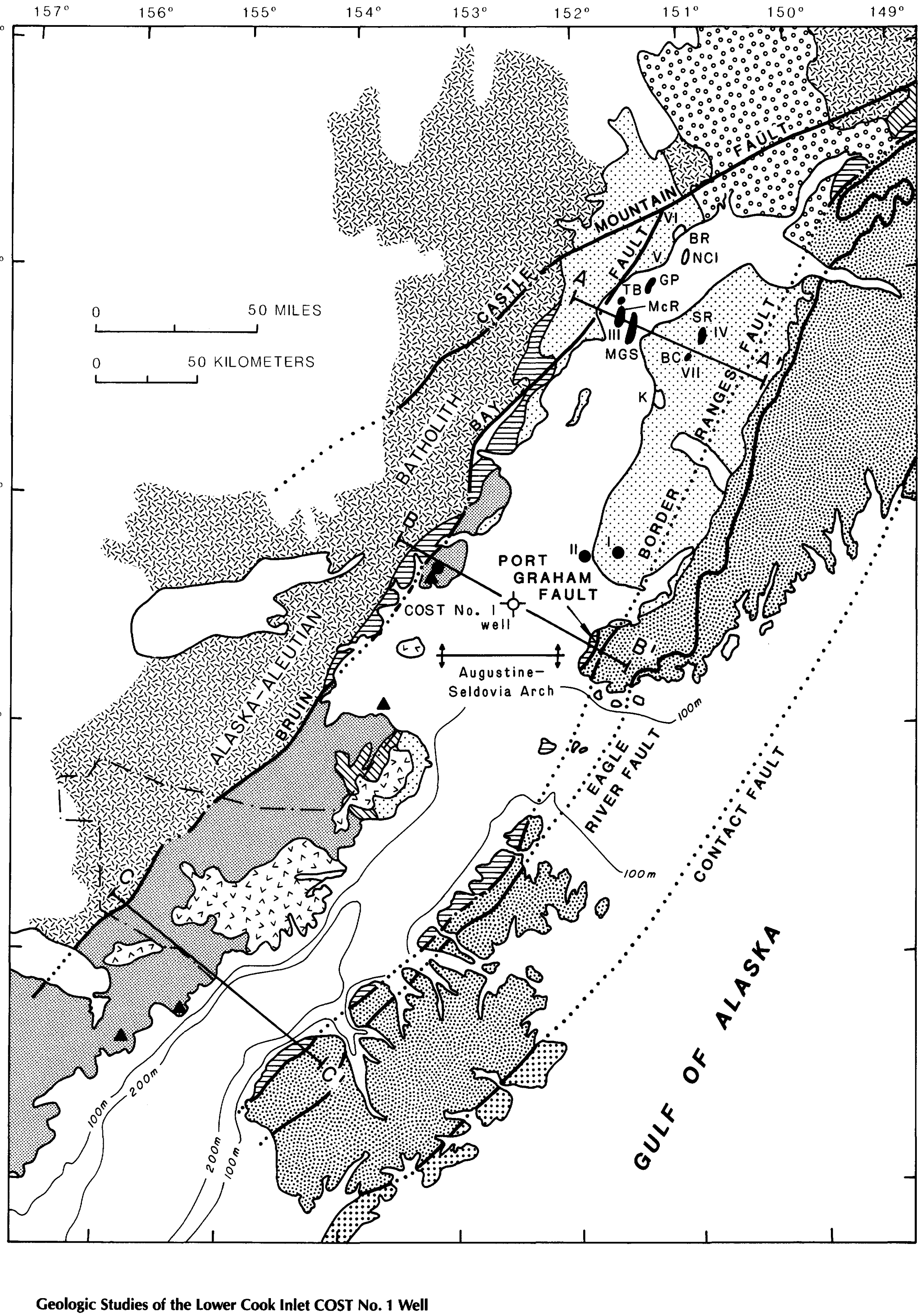
The Cape Current terrane is between, and in fault contact with, the Uyak Complex and the Kodiak Formation (Connelly and Moore, 1979). This terrane (Connelly, 1978) consists dominantly of lithofeldspathic sandstone with minor amounts of pillow lava and pelagic limestone that dip steeply to the northwest (Connelly, 1978).

Sandstones from the Cape Current terrane are lithofeldspathic with an average modal composition of $Q_{12}F_{52}L_{36}$ (table 17; fig. 34; Connelly, 1978). Quartz content is low, and the low polycrystalline quartz to total quartz ratios (C/Q) indicate that most of the quartz is monocrystalline. Plagioclase to total feldspar ratios (P/F) of 1 indicate that all the feldspar in the Cape Current sandstones is plagioclase. A volcanic source area can be inferred because the ratio of volcanic lithic to total lithic fragments (V/L) is 1. The rock composition of the Cape Current terrane is inferred to be mostly medium- to thick-bedded turbidites, and like the McHugh and Uyak Complexes, the Cape Current terrane is thought to be part of a subduction complex.

The age of the Cape Current terrane, which Connelly and Moore (1979) based on paleontologic data, is Late Cretaceous (Turonian-Santonian?).

Valdez Group and Kodiak and Shumagin Formations

The correlative rock units of the Valdez Group, the Kodiak and Shumagin Formations, and the "extraformational slivers wacke" of Connelly (1978) are located on the Kenai Peninsula, Kodiak Island, and Shumagin and Sanak Islands southwest of Kodiak Island (fig. 34). The rock units consist of deformed and metamorphosed flysch sequences of sandstone, siltstone, shale, and some conglomerate. The McHugh and Uyak Complexes and the Cape Current terrane structurally overlie the Valdez Group and the Kodiak Formation, and they, in turn, structurally overlie younger rocks. However, on Kodiak and adjacent islands, fault-bounded outliers or klippe of the Kodiak Formation overlie the Uyak Complex (Connelly and Moore, 1979).



157°
156°
155°
154°
153°
152°
151°
150°
149°
62°
61°
60°
59°
58°
57°
0 50 MILES
0 50 KILOMETERS
MOUNTAIN FAULT
CASTLE MOUNTAIN FAULT
BORDER RANGES FAULT
PORT GRAHAM FAULT
BRUIN BAY
ALASKA-ALEUTIAN BATHOLITH
COST No. 1 well
Augustine-Seldovia Arch
EAGLE RIVER FAULT
CONTACT FAULT
GULF OF ALASKA
A
A'
B
B'
C
C'
BR
NCI
GP
TB
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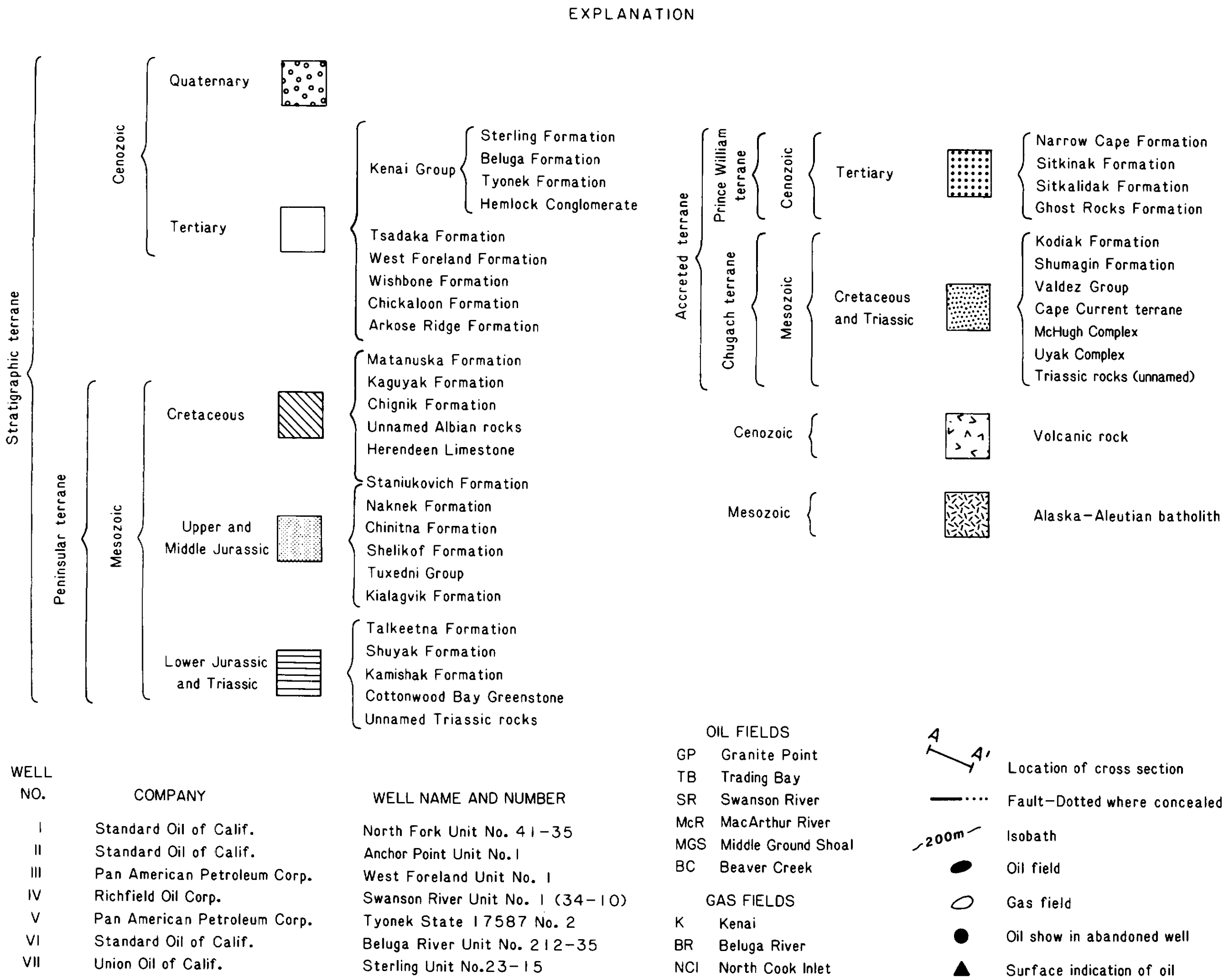


Figure 34. Generalized geologic map of Cook Inlet, Shelikof Strait, and adjacent areas (modified from Beikman, 1978). The COST No. 1 well is located in lower Cook Inlet. Cross sections A-A′, B-B′, and C-C′ are shown in figure 35. Indication of oil in wells and at the surface are shown around lower Cook Inlet and on the Alaska Peninsula.

These rock units are in thrust-fault contact with both older and younger rocks. In the Anchorage area, the thrust fault is designated the Eagle River fault (Clark, 1972; Tysdal and Case, 1979); in the Seldovia area, the Chugach Bay fault (Cowan and Boss, 1978); and in the Kodiak Bay area, the Uganik thrust (Connelly and Moore, 1979). For all these areas, Beikman (1978) designated the name Eagle River fault (fig. 34).

Fossil evidence indicates that these three rock units are correlatives, however, the sandstones in these rock units have significantly different compositions. Moreover, some of the determinations of the average modal sandstone compositions from the same rock unit made by different workers (table 17) do not agree closely. Although Moore (1973) and Winkler (1979) determined similar average modal compositions for the Shumagin and Kodiak Formations of $Q_{17}F_{32}L_{51}$ and $Q_{24}F_{32}L_{44}$, respectively, Connelly (1978) determined the average modal sandstone compositions for the Kodiak Formation and the "extraformational slivers wacke" of the Kodiak Formation incorporated within the Uyak Complex to be $Q_{50}F_{33}L_{17}$ and $Q_{48}F_{47}L_5$, respectively. Connelly's sandstone samples are much more rich in quartz and poor in lithic fragments than those of Moore (1973) and Winkler (1979).

One sandstone sample from the Valdez Group, described by Clardy (1974), differs from the sandstone in all the other units. Its modal composition of $Q_3F_{17}L_{80}$, which is poor in quartz and feldspar and rich in volcanic lithic fragments, is opposite to that of the Kodiak and Shumagin Formations.

The quartz content seems to be variable in the Upper Cretaceous rocks east of the Border Ranges fault. The low ratios of polycrystalline quartz to total quartz indicate that most of the quartz is monocrystalline except for one sample from the Valdez Group which contains 80 percent poly-

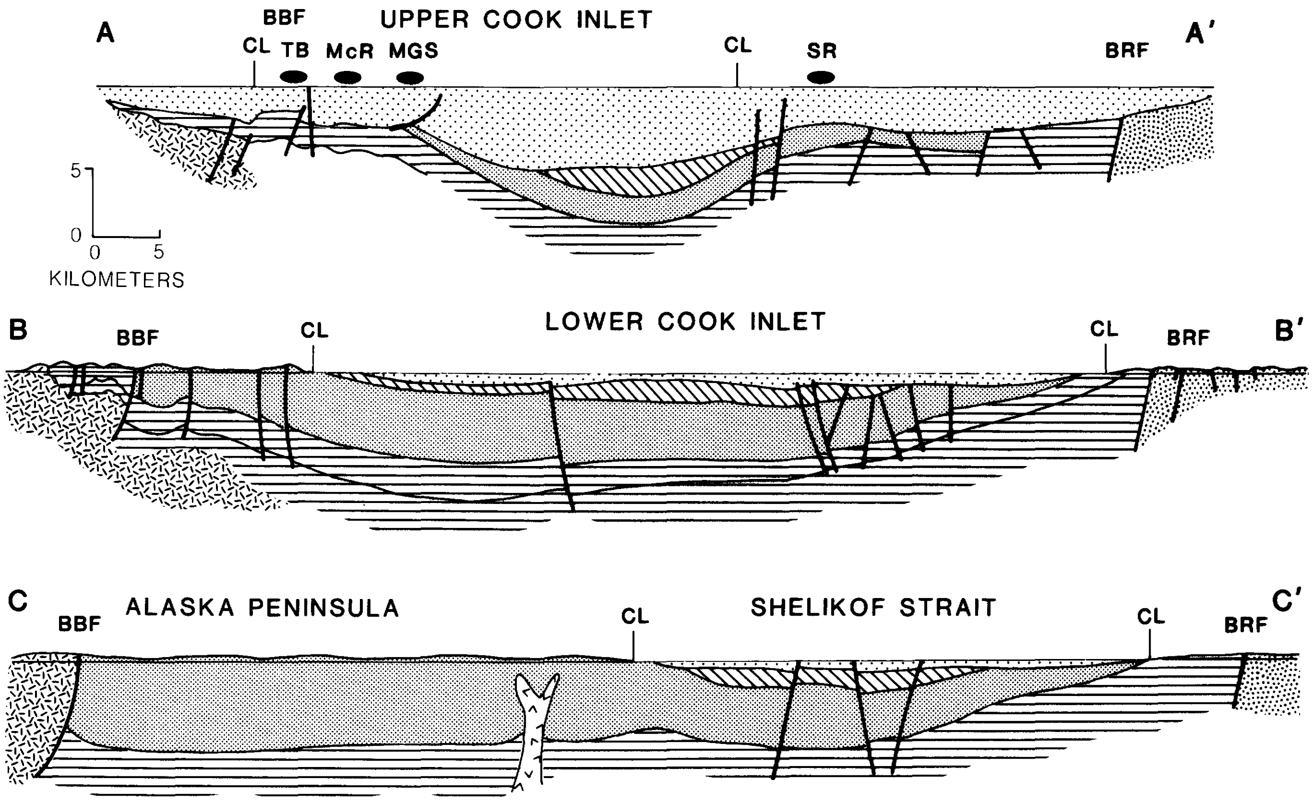


Figure 35. Geologic cross sections A-A′ (modified from Boss and others, 1976) through upper Cook Inlet, B-B′ (modified from Fisher and Magoon, 1978) through lower Cook Inlet, and C-C′ through the Alaska Peninsula and the Shelikof Strait. Cross section C-C′ is conceptual except for onshore surface geology. BBF, Bruin Bay fault; BRF, Border Ranges fault; CL, coastline. Refer to figure 34 for location of cross sections and explanation of other symbols.

crystalline quartz. Winkler (1979) suggested that much of the polycrystalline quartz represents silicified volcanic rock fragments.

The very high ratios of volcanic lithic to total lithic fragments (V/L) indicate that the volcanic rocks were derived from a predominantly volcanic terrane.

The plagioclase to total feldspar ratios (P/F) are very high in the Upper Cretaceous sandstone east of the Border Ranges fault, so in those sandstones almost all the feldspar is plagioclase.

Work by Jones and Clark (1973) showed that the age diagnostic fossils of the Valdez are latest Cretaceous.

Prince William Terrane

The Prince William terrane consists of the Cenozoic rocks south of the Chugach terrane and is separated from the Chugach terrane by the Contact fault (Jones and Silberling, 1979) (fig. 36). Four formations, the Ghost Rocks, Sitkalidak, Sitkinak, and Narrow Cape Formations, make up the terrane.

Ghost Rocks Formation

The Ghost Rocks Formation crops out in a long belt on the east side of Kodiak Island and extends from Cape Chiniak on the northeast to the Geese Islands on the southwest. The formation is bounded by faults between the older Kodiak Formation on the northwest and the younger Sitkalidak Formation on the southeast. The strata consists mostly of highly deformed shale, argillite, and mudstone that contain isolated, thin-bedded turbidites (Nilsen and Moore, 1979).

Sandstones from the Ghost Rocks Formation are generally feldspatholithic with average modal compositions of $Q_{21}F_{37}L_{42}$ (Winkler, 1979) and $Q_{23}F_{25}L_{52}$ (Lyle and others, 1977). The content of quartz is relatively low and that of volcanic lithic fragments high. The low ratios of polycrystalline quartz to total quartz (C/Q) indicate that most of the quartz is monocrystalline. The high ratios (>0.90) of plagioclase to total feldspar (P/F) indicate that most of the feldspar is plagioclase. Both the high ratios of volcanic lithic to total lithic fragments and the high percentages of total lithic fragments indicate a predominantly volcanic source area.

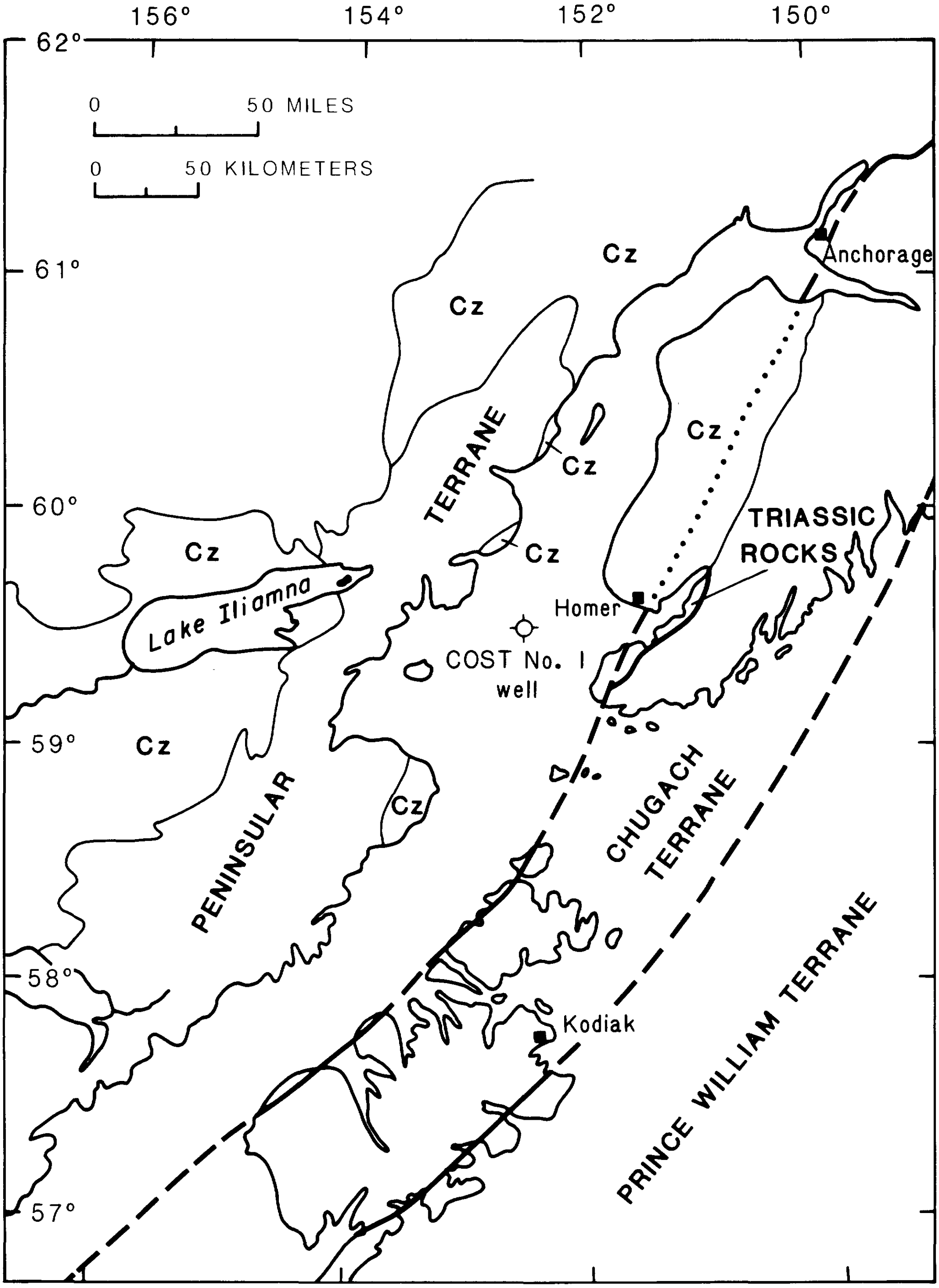


Figure 36. Major terrane boundaries in the Cook Inlet region. Terrane boundaries dashed where queried, dotted where buried under younger sediments. Cz stands for Cenozoic post-accretionary cover deposits. (Modified from Jones and others, 1984).

Moore (1969) considered the Ghost Rocks Formation, on the basis of lithologic and paleontologic evidence, to be Paleocene and Eocene in age.

Although the sedimentary and tectonic relations of the Ghost Rocks Formation are not well understood, Nilsen and Moore (1979) think that the sediments may have been deposited in a basin plain or slope environment.

Sitkalidak Formation

The Sitkalidak Formation consists of interbedded sandstone and shale that forms a thick series of turbidites. The rocks crop out in separate areas along the southeastern parts of Kodiak, Sitkalidak, and Sitkinak Islands (off south tip of Kodiak Island). On Sitkinak Island it is separated from the

Sitkinak Formation by faults; on Kodiak Island it is faulted from the older Ghost Rocks Formation; on Sitkalidak Island, it is conformably overlain by the Sitkinak Formation; and at Cape Narrow (at the northeast end of Kodiak Island), it is overlain unconformably by the Narrow Cape Formation. At its type section in eastern Sitkalidak Island, Moore (1969) estimated the formation to be about 3,000 m (10,000 ft) thick.

Sandstones from the Sitkalidak Formation (table 17) are generally feldspatholithic with average modal compositions of $Q_{26}F_{26}L_{48}$ (Winkler, 1979), $Q_{46}F_{17}L_{37}$ (Lyle and others, 1977), and $Q_{40}F_{22}L_{38}$ (Stewart, 1976). The moderate amounts of quartz present are mostly monocrystalline, as indicated by the polycrystalline quartz to total quartz ratios (C/Q). Polycrystalline quartz is about twice as abundant in the Sitkalidak Formation as in the Ghost Rocks Formation.

The ratios of plagioclase to total feldspar (P/F), which range from 0.81 to 0.91, indicate that most of the feldspar is plagioclase in the Sitkalidak Formation. K-feldspar, also present, is slightly more abundant in the Sitkalidak than in older units. Volcanic lithic to total lithic fragment ratios (V/L), which range from 0.41 to 0.75, indicate that volcanic lithic fragments are not the important framework grains. Most of the lithic fragments are sedimentary rock fragments, and there are lesser amounts of metamorphic rock fragments.

The sandstone and shale of the Sitkalidak Formation were deposited in middle and outer submarine fan environments in the Eocene and Oligocene (Nilsen and Moore, 1979).

Sitkinak Formation

Small isolated outcrops of the Sitkinak Formation are exposed on Kodiak Island, Sitkalidak Island, Sitkinak Island, and Chirikof Island (southwest from Kodiak Island). The Sitkinak Formation consists of two distinct sedimentary deposits—marine and nonmarine facies. The marine facies on Sitkalidak Island consists of interfan channel conglomerate and slope facies siltstone and shale (Nilsen and Moore, 1979); these beds conformably overlie the Sitkalidak Formation and are faulted against the Ghost Rocks Formation (Nilsen and Moore, 1979). The nonmarine facies on Sitkinak Island consist of conglomerate, sandstone, and siltstone with some coal and carbonaceous shale; this unit is faulted against the Sitkalidak Formation. The siltstone and fine-grained sandstone strata contain abundant fossil plants of Oligocene age (Moore, 1969).

Sandstone, generally feldspatholithic (table 17) from the Sitkinak Formation, have average modal compositions of $Q_{30}F_{33}L_{37}$ (Stewart, 1976), $Q_{45}F_{18}L_{37}$ (Lyle and others, 1977), and $Q_{40}F_{16}L_{44}$ (Winkler, 1979). Quartz is present in moderate amounts. The low ratios of polycrystalline quartz to total quartz (C/Q) indicate that most of the quartz is monocrystalline. However, polycrystalline quartz is slightly more abundant in the Sitkinak Formation than in the Sitkalidak Formation.

The high ratios of plagioclase to total feldspar, ranging from 0.84 to 0.98, indicate that plagioclase is the most abundant feldspar. The content of potassium feldspar is as low in the Sitkinak Formation as it is in the Sitkalidak Formation.

A great diversity in type of lithic fragments is present, as indicated by the range from 0.28 to 0.75 of volcanic lithic to total lithic fragments. Sedimentary and metamorphic lithic fragments make up a significant part of the total lithic fragment assemblage, but generally volcanic lithic fragments are more abundant.

Narrow Cape Formation

The Narrow Cape Formation, at its type locality at Narrow Cape on eastern Kodiak Island, consists of silty sandstone and siltstone and sedimentary breccia and conglomerate. The formation rests with angular unconformity on the Sitkalidak and Ghost Rocks Formations. A smaller outcrop on Sitkinak Island has a general lithology similar to that at Narrow Cape. The Narrow Cape Formation here is disconformable with the Sitkinak Formation. The exposures at both places contain abundant fossils; however, at Narrow Cape the fossils indicate an early and middle Miocene age, and at Sitkinak Island, they indicate a late Oligocene or early Miocene age (Allison and Addicott, 1976). The strata represent marine shelf deposits.

Sandstone from the Narrow Cape Formation is lithofeldspathic with average modal compositions of $Q_{70}F_{18}L_{12}$ (Lyle and others, 1977) and $Q_{50}F_{26}L_{24}$ (Winkler, 1979). Quartz content is higher in this formation than in the older formations. The low ratios of polycrystalline quartz to total quartz (C/Q) indicate that most of the quartz is monocrystalline. The Narrow Cape Formation contains similar percentages of polycrystalline quartz (as much as 25 percent of the total quartz) as the Sitkinak Formation.

Plagioclase to total feldspar ratios (P/F), which average 0.75, indicate that most of the feldspar is plagioclase and that 25 percent of the total feldspar assemblage is K-feldspar. Of the lithic fragment assemblage, 48 percent is sedimentary, 47 percent are volcanic, and 5 percent are metamorphic rock fragments. The Narrow Cape Formation has the greatest diversity in types of lithic fragments than any other formation east of the Border Ranges Fault.

Peninsular Terrane

Moderately deformed upper Paleozoic and Mesozoic sedimentary rocks at least as old as Permian are present within the confines of the basin framework (fig. 36). The Permian rocks (Hanson, 1957) are known from only one small area near Puale Bay, so they will not be discussed here; only the Mesozoic rocks will be discussed in this section. Formerly these Mesozoic sedimentary rocks were designated the Matanuska-Wrangell terrane (Berg and others, 1972), but they are now renamed the Peninsular terrane (Jones and Silberling, 1979). The age, general lithology, and stratigraphic relations of these rocks are shown on figure 37. The important distinction between this terrane and the previous terranes is that the stratigraphic units are deposited one on top of another and many stratigraphic units are separated by unconformities, whereas most of the previously discussed terranes are in fault contact and become progressively younger southward from the Border Ranges fault to the Aleutian trench.

Upper Triassic Rocks

On the northwest side of lower Cook Inlet, Upper Triassic rocks are exposed in scattered outcrops on both sides of the Bruin Bay fault from Tuxedni Bay to Kamishak Bay. At the head of Tuxedni Bay, unnamed Upper Triassic rocks, as much as 395 m thick (1,300 ft; fig. 37), consist of metamorphosed limestone, tuff, chert, sandstone, shale, and basaltic lava flows (Detterman and Hartsock, 1966). West of the Bruin Bay fault in the Kamishak Bay area, the Upper Triassic mafic-volcanic rocks of the Cottonwood Bay Greenstone presumably underlie the fossiliferous limestone, chert, and tuff of the Kamishak Formation (Detterman and Reed, 1980). The Cottonwood Bay Greenstone is probably more than 600 m thick (2,000 ft; fig. 37), and a composite thickness for the three members of the Kamishak Formation is as much as 1,290 m thick (4,230 ft; fig. 37; Detterman and Reed, 1980).

In the Puale Bay area unnamed Upper Triassic rocks, as much as 800 m thick (2,625 ft; fig. 37), consist of fossiliferous limestone and volcanic agglomerate intruded by basaltic dikes and sills (Imlay and Detterman, 1977). On the southeast side of lower Cook Inlet, unnamed Upper Triassic rocks exposed northwest of the Border Ranges fault on the Kenai Peninsula consist of fossiliferous limestone, fine-grained tuffs, and a few thin sandstone beds (Martin and others, 1915; Moore and Connelly, 1979).

Unnamed Upper Triassic rocks at least 600 m thick (2,000 ft; fig. 37) depositionally overlie undeformed pillow basalts on the westernmost island of the Barren Islands (Cowan and Boss, 1978). These rocks, which contain Late Triassic fossils, consist of gently folded greenish tuff, tuffaceous sandstone, minor black siliceous mudstone, and chert (Cowan and Boss, 1978). On the northwestern part of the Kodiak Islands, pillowed greenstones are overlain by fossiliferous volcaniclastic turbidites of the Upper Triassic Shuyak Formation (Connelly, 1978).

Sandstones within Upper Triassic rocks from widely spaced areas around Cook Inlet and Shelikof Straits have similar compositions (table 16, fig. 33). The sandstones are lithic and feldspatholithic and are distinctly poor in quartz. Average modal compositions determined by Moore and Connelly (1979) are $Q_0F_{35}L_{65}$ from the Kenai Peninsula, $Q_3F_{27}L_{70}$ from the Shuyak Formation, Kodiak Island, and $Q_2F_{39}L_{59}$ from Puale Bay.

Polycrystalline quartz to total quartz ratios (C/Q) are all low, therefore most of the quartz is monocrystalline. Plagioclase to total feldspar ratios (P/F) of one indicate that plagioclase is the only feldspar present. The very high ratios of volcanic lithic to total lithic fragments (V/L) reflect the lithic nature of the sandstones and indicate a prominent volcanic source terrane.

Two assumptions need to be made to reconstruct the generalized paleogeology of the Late Triassic rocks: (1) the structural grain of the Triassic is parallel to the Kodiak-Kenai plutonic belt of Late Triassic(?)-Early Jurassic age; and (2) the Triassic rocks, on both sides of the Cook Inlet-Shelikof Strait west of the Border Ranges fault, are genetically related but are not fragments of other land masses that were later welded together. If these assumptions are true, then the northwest and southeast flanks of the basin can be compared. Shallow-water shelf carbonates and agglomerates occur on the northwest flank compared to turbidite sandstones and siltstones on the southeast flank; mafic igneous flows, sills, and dikes with a few pillow basalts occur mainly on the northwest compared to many pillow basalts on the southeast; chert occurs on both flanks. In other words, the Late Triassic rocks formed a broad volcanic Island arc that included shallow-water carbonates, turbidites, mafic volcanic rocks, and chert.

Lower Jurassic Rocks

Lower Jurassic rocks are exposed on both sides of Cook Inlet. On the northwest side, the outcrop belt is as much as 15 km (10 mi) wide and is cut in several places by the Bruin Bay fault. South of Tuxedni Bay, unfossiliferous Lower Jurassic rocks dip generally southeast and consist of poorly bedded volcanic agglomerates, breccias, and lava flows of the Talkeetna Formation (Detterman and Hartsock, 1966). In the Iniskin-Tuxedni area the formation is as much as 2,575 m (8,500 ft) thick (fig. 37).

Near Seldovia, fossiliferous Lower Jurassic strata consist of a pyroclastic sequence that is about 4,000 m (13,000 ft) thick (fig. 37; Kelley, 1978). Three lithofacies were mapped from bottom to top: a graded pyroclastic lithofacies with each graded sequence as much as 50 m (165 ft) thick, a pyroclastic debris-flow and fossil-bearing turbidite lithofacies, and a reworked volcaniclastic lithofacies with coal beds as much as 4 m (15 ft) thick (Kelley, 1978). On the basis of lithology and age, the rocks near Seldovia have been assigned to the Talkeetna Formation (Magoon and others, 1976b). Lower Jurassic rocks are not exposed northwest of the Border Ranges fault on Kodiak Island (Connelly and Moore, 1979) or on the Barren Islands.

On the northwest coast of Shelikof Strait in Puale Bay, as much as 555 m (1,820 ft) (fig. 36) of sparsely fossiliferous

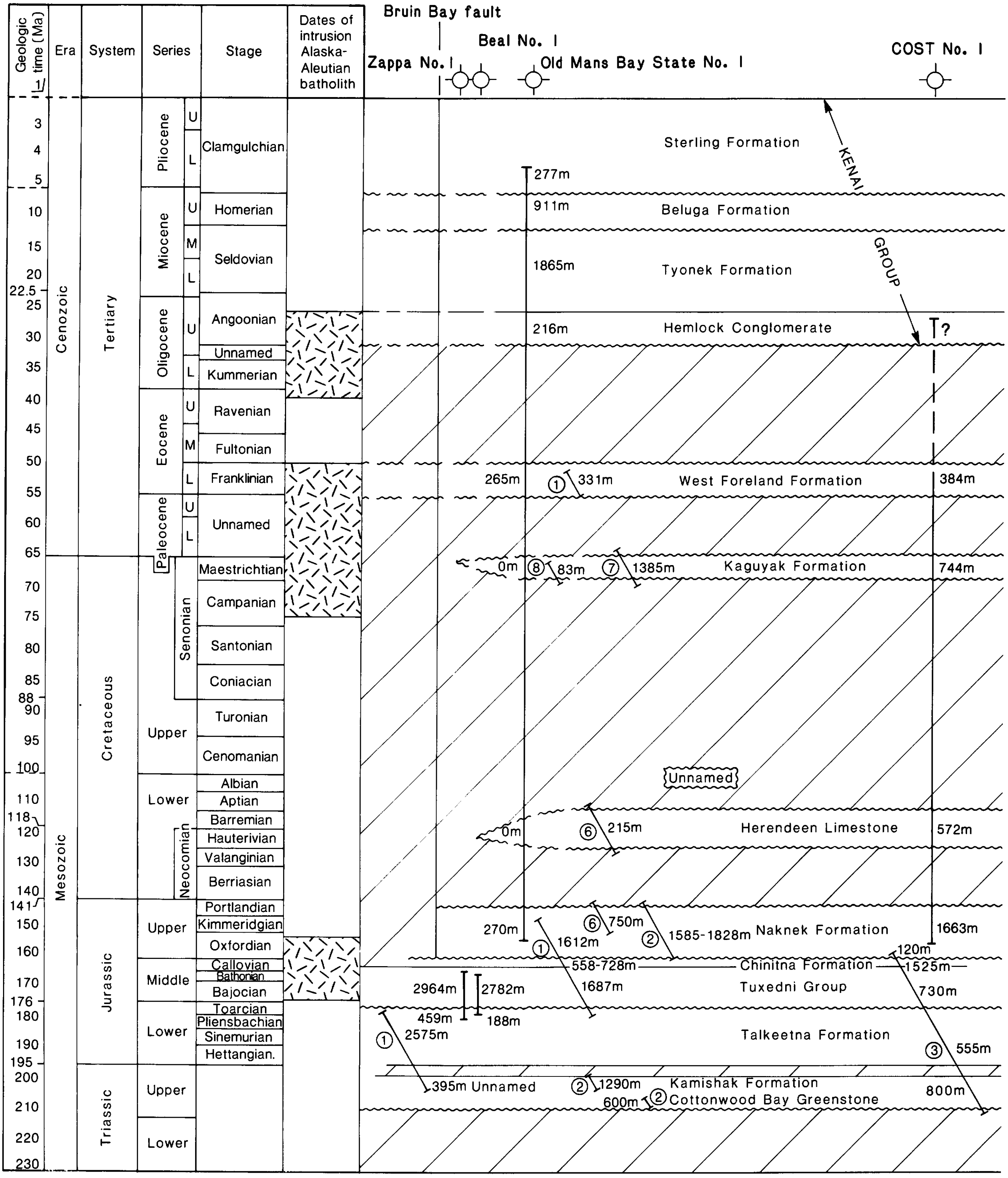
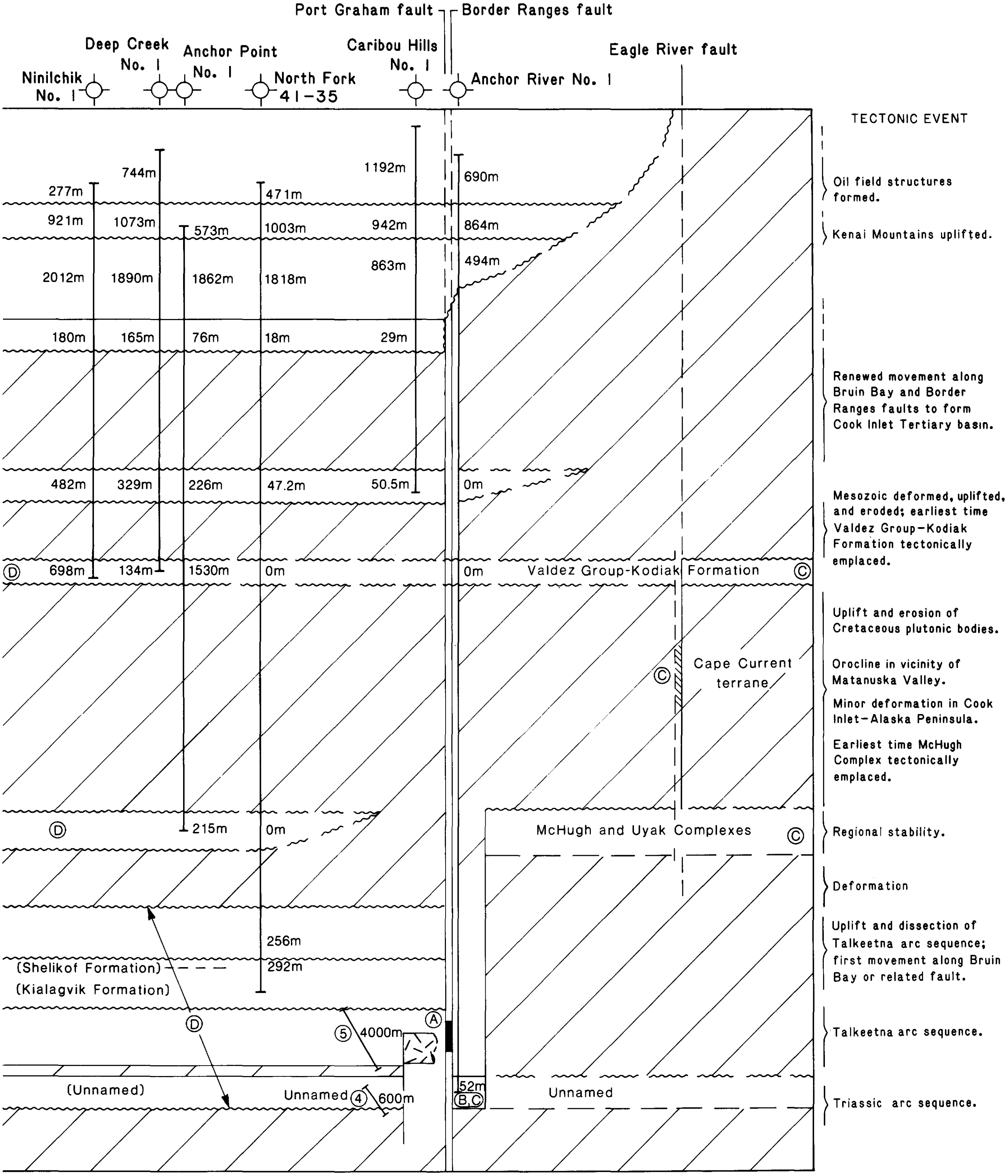


Figure 37. Time-stratigraphic chart through COST No. 1 well coincident with B-B′. Wells (vertical lines) and measured sections (diagonal lines) are projected parallel to the Alaska-Aleutian Range. The thickness of each rock unit is placed to the right of the well or outcrop. The circled numbers refer to the references for the measured sections: (1) Detterman and Hartsock (1966), (2) Detterman and Reed (1980), (3) Kellum and others (1945), Imlay and Detterman (1977), and the authors of



unpublished information, (4) Cowan and Boss (1978), (5) Kelley (1978), (6) Magoon and others (1976a), (7) unpublished section, and (8) Magoon and others (1980). Letters refer to (A) Seldovia schist terrane, (B) Kachemak terrane (Triassic rocks), (C) Chugach terrane, and (D) Peninsular terrane. Hachure lines indicate time of nondeposition or erosion.

Lower Jurassic volcaniclastic sandstone, conglomerate, and limestone are exposed (Imlay and Detterman, 1977). According to Detterman (oral commun., 1980), Lower Jurassic rocks of Puale Bay are very similar to the Talkeetna Formation in the Talkeetna Mountains.

The presence of the Lower Jurassic Talkeetna Formation on both sides of Cook Inlet, in some offshore areas (Boss and others, 1976; Fisher and Magoon, 1978), and in the Puale Bay area suggests that this unit is continuous beneath Cook Inlet and Shelikof Strait.

Lower Jurassic sandstones from widely spaced areas in Cook Inlet and Shelikof Strait and adjacent areas are similar and they are also similar to sandstones in the underlying Upper Triassic sequences. The Lower Jurassic sandstones are generally volcanic lithic rich, reflecting a primary volcanic nature of associated rocks interbedded with the sandstones. Average modal compositions from the Puale Bay area and from the Kenai Peninsula are $Q_6F_{42}L_{52}$ (Egbert, this volume) and $Q_3F_{20}L_{77}$ (Kelley, 1980), respectively.

The sandstones are distinctly quartz poor with low polycrystalline quartz to total quartz ratios (C/Q) indicating that most of the quartz that is present is monocrystalline. The quartz has features indicative of volcanic derivation: clear, unstrained, resorbed margins or bleb inclusions. Plagioclase to total feldspar ratios (P/F) are high (0.97 to 1.0); the high ratios indicate that almost all the feldspar is plagioclase. Volcanic lithic to total lithic fragment ratios (V/L), which are also high (0.98 to 1.0), reflect the volcanic lithic rich nature of the sandstones and indicate an extensive volcanic source terrane.

Middle Jurassic Rocks

Unconformably overlying the Lower Jurassic volcaniclastic rocks is a thick sequence of Middle Jurassic marine sedimentary rocks. These rocks are exposed only on the west side of Cook Inlet and on the Alaska Peninsula east of the Bruin Bay fault. In the subsurface, 292 m (960 ft) of Middle Jurassic rock has been penetrated in the North Fork 41-35 well on the Kenai lowland (fig. 37).

Middle Jurassic rocks are divided, in upward order, into the Tuxedni Group and the Chinitna Formation in the Cook Inlet area and into the Kialagvik and the Shelikof Formations on the Alaska Peninsula.

Tuxedni Group and Kialagvik Formation

The Tuxedni Group, Bajocian to Callovian in age, includes as many as six formations and ranges in thickness from 536 to 2,748 m (1,760 to 9,015 ft) in the Iniskin-Tuxedni area (Detterman and Hartsock, 1966, pl. 5). According to Detterman and Hartsock (1966, pl. 5), the thickness of the Tuxedni Group on the Chisik Island-Tuxedni Bay section measures 1,687 m (5,535 ft) (fig. 37), is abundantly fossiliferous and contains 35 percent sandstone and 65 percent siltstone with minor amounts of tuff. All the sediments were deposited in a shallow marine shelf environment.

The Kialagvik Formation, Toarcian and Bajocian in age and in part correlative to the Tuxedni Group, crops out along the north shore of Puale Bay on the Alaska Peninsula (Imlay and Detterman, 1977). The unit is at least 730 m (2,400 ft) thick (fig. 37), is sparsely fossiliferous and contains 10 percent sandstone-conglomerate and 90 percent siltstone representing submarine slope-channel fill and slope deposits, respectively.

Sandstones from the Tuxedni Group and Kialagvik Formation from widely spaced areas have similar compositions. The sandstones are feldspatholithic with average modal compositions of $Q_6F_{43}L_{51}$ (Egbert and Magoon, 1981) and $Q_8F_{35}L_{57}$ (Egbert, this volume) from the Tuxedni Group and Kialagvik Formation respectively. The sandstones are quartz poor with low polycrystalline quartz to total quartz ratios indicating that most of the quartz is monocrystalline. The quartz, mostly of volcanic origin, was probably derived from the underlying volcanic and volcaniclastic Talkeetna Formation.

The high (0.92-0.95) plagioclase to total feldspar ratios (P/F) indicate that most of the feldspar is plagioclase. The high ratios of volcanic lithic to total lithic fragments (V/L) reflect the lithic-rich nature of the sandstones and also their derivation from an extensive volcanic source terrane (Talkeetna Formation).

Chinitna and Shelikof Formations

The Chinitna Formation of Callovian age, has two members, and ranges in thickness from 558 m (1,830 ft) at the Chisik Island-Tuxedni Bay section to 728 m (2,375 ft) in the Iniskin-Tuxedni area (fig. 37; Detterman and Hartsock, 1966, pl. 5). The Chisik Island-Tuxedni Bay section contains 10 percent sandstone-conglomerate and 90 percent siltstone. These rocks represent submarine channel fill conglomerate and slope facies siltstone and thin-bedded turbidite sandstone of the forearc basin.

The Shelikof Formation, of Callovian age and a correlative unit to the Chinitna Formation, overlies the Kialagvik Formation in the Puale Bay area (Kellum and others, 1945; Imlay and Detterman, 1977). Here the Shelikof Formation is at least 1,525 m thick (5,000 ft) (fig. 37), is sparsely fossiliferous, and contains 80 percent sandstone and 20 percent siltstone. These rocks mainly represent submarine fan deposits.

Sandstones from the Chinitna and Shelikof Formations are generally lithofeldspathic with average modal compositions of $Q_5F_{59}L_{36}$ and $Q_9F_{46}L_{45}$, respectively (Egbert and Magoon, 1981; Egbert, this volume). Quartz content is low in both units; the low polycrystalline quartz to total quartz ratios indicate that most of the quartz is monocrystalline. Present in only minor amounts, the polycrystalline quartz probably represents silicified volcanic detritus.

Feldspars are the most abundant framework grains in the Chinitna and Shelikof Formations. The high plagioclase to total feldspar ratios (P/F) indicate that most of the feldspar is plagioclase. Lithic fragments are the second most abundant framework grains; the high volcanic lithic to total lithic fragment ratios (V/L) indicate a predominantly volcanic source terrane. The high feldspar content may indicate plutonic source areas in addition to volcanic sources. Hornblende becomes a dominant accessory mineral in the Shelikof Formation and in the upper part of the Chinitna Formation, however, its virtual absence in underlying units indicates the unroofing of the Jurassic plutonic rocks.

Upper Jurassic Rocks

Naknek Formation

The Naknek Formation of Oxfordian to Tithonian age unconformably overlies the Chinitna and Shelikof Formations. The Naknek Formation crops out from the Alaska Peninsula to Tuxedni Bay and is also present in the Matanuska Valley. It has greater areal exposure than the underlying or overlying rocks. The depositional environment of the Naknek Formation varies from fluvial, alluvial and shallow marine deposits to deep-marine channel, slope, and submarine fan deposits.

In the Iniskin-Tuxedni area, as much as 1,612 m (5,285 ft) of the Naknek is exposed and the outcrops represent four members (fig. 37; Detterman and Hartsock, 1966) and in the Kamishak Bay area, the thickness ranges from 1,585 to 1,828 m (5,200 to 5,995 ft) (fig. 37; Detterman and Reed, 1980). The Naknek Formation does not crop out on the southeast side of the basin, but 256 m (840 ft) of Upper Jurassic rocks were penetrated in the North Fork 41-35 well and 1,663 m (5,455 ft) were penetrated in the COST No. 1 well (fig. 36). Along the Alaska Peninsula, the Naknek varies in thickness and may be as much as 3,050 m (10,000 ft) thick (Burk, 1965).

Sandstones from the Naknek Formation on the Alaska Peninsula are all generally feldspathic with moderate amounts of quartz and average modal compositions of $Q_{28}F_{63}L_9$ (Egbert, this volume), $Q_{38}F_{52}L_{10}$ (McLean, 1979), $Q_{36}F_{60}L_4$ (Lankford and Magoon, 1978), and $Q_{47}F_{52}L_1$ (Burk, 1965). These rocks are similar to sandstones penetrated in the COST No. 1 well that have an average modal composition of $Q_{24}F_{55}L_{21}$ (McLean, this volume). This composition contrasts to Naknek sandstones exposed in the Iniskin-Tuxedni region that are distinctly quartz poor but still feldspathic; they have average modal compositions of $Q_6F_{73}L_{21}$ (Egbert and Magoon, 1981) and $Q_4F_{58}L_{38}$ (Franks and Hite, 1980).

Although there is a distinct contrast in quartz content between the Naknek exposed on the Alaska Peninsula to that exposed in the Iniskin-Tuxedni area, the polycrystalline quartz to total quartz ratios are all similar and indicate that almost all of the quartz is monocrystalline. Plagioclase to total feldspar ratios (P/F), which are all high, indicate that most of the feldspar is plagioclase, however K-feldspar is more abundant in the Naknek Formation than in the underlying units. Potassium feldspar in the Naknek Formation, which averages 13 percent of the total feldspar population, is most abundant in samples from the COST No. 1 well.

Volcanic lithic to total lithic fragment ratios (V/L) are high in the Naknek Formation but are lower than the ratios in underlying units; this variation indicates greater diversity in the source area. Plutonic, sedimentary, and metamorphic lithic fragments account for the remaining lithic fragment population.

Upper Jurassic and Lower Cretaceous Rocks

Staniukovich Formation

The Staniukovich Formation of Late Jurassic (Kimmeridgian) through Early Cretaceous (Valanginian) age crops out on the southwest end of the Alaska Peninsula where it conformably overlies the Naknek Formation. The formation is unknown in the Cape Douglas area and areas farther northeast. The Staniukovich Formation is as much as 549 m (1,800 ft) thick and consists mainly of marine sandstone and siltstone (Burk, 1965).

Two sandstone samples described by Burk (1965) are feldspathic; their average modal composition, $Q_{55}F_{41}L_4$, is similar to the average modal composition, $Q_{48}F_{42}L_{10}$, of Franks and Hite (1980). The sandstone samples in the Staniukovich are more quartz rich than those in the underlying Naknek Formation and are nearly compositionally mature.

Lower Cretaceous Rocks

Herendeen Limestone

Lower Cretaceous (Valanginian to Barremian) rocks crop out in many areas from the Matanuska Valley and Wrangell Mountains in the north (Grantz and others, 1966; MacKevett, 1976, 1978) to Port Moller-Herendeen Bay area on the Alaska Peninsula in the south (Atwood, 1911; Burk, 1965; Molenaar, 1980).

In this area, thick beds of the Naknek Formation (91+ m; 300+ ft), Staniukovich Formation (550 m; 1,800 ft), and Herendeen Limestone (152 m; 500 ft) (Burk, 1965; Jones, 1973) seem to be substantial evidence that sedimentation was continuous from Late Jurassic through Early Cretaceous; however, Molenaar (1980) demonstrates an unconformity between Lower Cretaceous and Upper Jurassic strata in the Chignik area 160 km (100 mi) to the northeast.

In the Kamishak Hills, 215 m (700 ft) of Lower Cretaceous rock (Herendeen Limestone) unconformably overlies Upper Jurassic strata (Jones and Detterman, 1966; Jones, 1973; Magoon and others, 1976a, 1978). The beds consist of 7 percent sandstone and 93 percent siltstone and are rich in *Inoceramus* fragments. These bioclastic fragments occur in very high concentrations and are described as limestone in this predominantly siltstone rock unit.

In the subsurface, Lower Cretaceous rocks were depicted by Boss and others (1976) in a cross section through Cook Inlet basin north of Kalgin Island. On the Kenai Lowland 215 m (700 ft) of Lower Cretaceous rocks (Herendeen Limestone) were penetrated in the Anchor Point No. 1 well and 572 m (1,875 ft) were penetrated in the COST No. 1 well (fig. 37, table 16).

The Lower Cretaceous Nelchina Limestone crops out east of the Matanuska Valley (Grantz and others, 1966) and in the Wrangell Mountains (MacKevett, 1976, 1978). The similarity of both the Herendeen and Nelchina Limestones, in age and lithology, has been acknowledged by many workers. In the Wrangell Mountains the undeformed Lower Cretaceous rocks unconformably overlie much older severely deformed rocks (MacKevett, 1976, 1978).

Sandstone from the Lower Cretaceous sequences are generally feldspathic and lithofeldspathic with average modal compositions of $Q_{62}F_{33}L_5$ from the Alaska Peninsula (Burk, 1965), $Q_{38}F_{59}L_3$ from the Cape Douglas area, (Lankford and Magoon, 1978) and $Q_{36}F_{44}L_{20}$ from the COST No. 1 well (McLean, this volume). Quartz content is similar to the upper part of the underlying Naknek and Staniukovich Formations reflecting increased compositional maturity from underlying units.

Polycrystalline quartz to total quartz ratios are very low; the low ratio indicates that most of the quartz is monocrystalline. Plagioclase to total feldspar ratios (P/F) are high but K-feldspar ranges from 12 to 23 percent of the total feldspar populations. Volcanic lithic to total lithic fragment ratios (V/L) are moderately high, but total lithic fragment populations are low.

Unnamed Albian Rocks

Rocks of Albian age have been reported from the Matanuska Valley (Grantz, 1964) and Wrangell Mountains (Jones, 1973). Fossils collected recently by the authors on the Alaska Peninsula, which were identified by D. L. Jones, indicate that Albian rocks are also present on the Alaska Peninsula. The fossils were collected north of the Katmai River from rocks in fault contact with the Naknek Formation.

Albian sandstone samples from the Matanuska Valley and on the Alaska Peninsula are lithic and feldspatholithic with average modal compositions of $Q_4F_4L_{92}$ and $Q_{11}F_{40}L_{49}$ respectively (Grantz, 1964; Egbert, this volume). These compositions are in sharp contrast to the more feldspathic nature of the Lower Cretaceous (Valanginian to Barremian) and Upper Jurassic sandstone.

Polycrystalline quartz to total quartz ratios (C/Q) are very low. Plagioclase to total feldspar ratios (P/F) are high, however K-feldspar accounts for 25 percent of the total feldspar population from samples from the Matanuska Valley and account for only 1 percent of the total feldspar from the Alaska Peninsula. The very high volcanic lithic to total lithic fragment (V/L) and total lithic fragment populations from both areas possibly reflect local but prominent volcanic sources during the Albian.

Upper Cretaceous Rocks

Upper Cretaceous (Campanian and Maestrichtian) rocks in the Cook Inlet area north of Kalgin Island are assigned to the Matanuska Formation; south of Kalgin Island, they are assigned to the Kaguyak Formation. Magoon and others (1976b) and Fisher and Magoon (1978) suggested the latitude at Seldovia as an arbitrary boundary separating these two formations, but that suggestion was prior to drilling the COST No. 1 well (Magoon and Claypool, 1979, 1981) and recognizing the Saddle Mountain outcrop northeast of Chinitna Bay (Magoon and others, 1980) and the Augustine Island outcrop (Buffler, 1976; Detterman and Reed, 1980). In addition, the continuity or mapability of Upper Cretaceous rocks south of Kalgin Island to the Katmai River can be demonstrated using reflection seismic data (Fisher and Magoon, 1978), well control, and outcrop patterns.

The Kaguyak Formation (Keller and Reiser, 1959) crops out in the Kamishak Hills-Cape Douglas area where 1,385 m (4,545 ft) of rock unconformably overlies Lower Cretaceous and Upper Jurassic strata (fig. 37). In upward succession this formation consists of a thin shallow-marine basal conglomerate (5 m; 16 ft) that grades upward into thick sandstones (32 m; 105 ft), bioturbated gray siltstone (600 m; 1,970 ft), and turbidite sandstone interbedded with siltstone (460 m; 1,500 ft). The COST No. 1 well penetrated 744 m (2,325 ft) of the Kaguyak Formation. In addition, 83 m (275 ft) of Upper Cretaceous nonmarine sandstone, conglomerate, and coal are exposed northwest of the COST No. 1 well; the Upper Cretaceous rocks unconformably overlie Upper Jurassic rocks near Saddle Mountain in the Iniskin-Tuxedni area (Magoon and others, 1980).

On the Kenai Lowland, several wells penetrated the Kaguyak Formation, including the Anchor Point No. 1 well, which penetrated 1,530 m (5,000 ft) of Upper Cretaceous strata (figs. 34 and 37, table 16).

In the Matanuska Valley at least 1,250 m (4,100 ft) of Campanian and Maestrichtian rocks of the Matanuska Formation are exposed (Grantz, 1964). In this area the Matanuska Formation is composed of claystone, siltstone, sandstone, and conglomerate, and the rocks have features indicative of deposition from turbidity currents (Grantz, 1964).

South of Wide Bay on the Alaska Peninsula (fig. 32), the Upper Cretaceous rocks are known as the Chignik Formation (fig. 37) and consist dominantly of sandstone with lesser amounts of conglomerate, siltstone, shale and mudstone.

Depositional environments represented within the formation range from fluvial to marine (Burk, 1965; Imlay and Detterman, 1977; Fairchild, 1977; Molenaar, 1980).

Sandstones from the Matanuska, Kaguyak, and Chignik Formations are of variable composition, ranging from lithic to feldspathic with intermediate quartz content. Sandstones from the Kaguyak Formation are represented by two compositional modes. In the Cape Douglas area and in the COST No. 1 well, the lower part of the Kaguyak Formation has average modal compositions of $Q_{34}F_{55}L_{11}$ (Lankford and Magoon, 1978) and $Q_{22}F_{64}L_{14}$ (McLean, this volume) respectively. Similarly, sandstone from the Kaguyak Formation near Saddle Mountain, which has been correlated with the lower part of the Kaguyak Formation penetrated in the COST No. 1 well (Magoon and others, 1980), has an average modal composition of $Q_{32}F_{40}L_{28}$.

In contrast, sandstones from the upper part of the Kaguyak Formation from the Cape Douglas area and COST No. 1 well have average modal compositions of $Q_{27}L_{31}F_{42}$ and $Q_{13}F_{18}L_{69}$, respectively; these compositions reflect increased volcanic lithic detritus from source areas in the latest Cretaceous.

Stratigraphically located sandstone samples were not collected from the Matanuska Formation, however, Grantz (1964) and Clardy (1974) indicate average modal compositions of $Q_{26}F_{58}L_{16}$ and $Q_{21}F_{48}L_{31}$, respectively; these compositions are similar to the modal compositions of the lower part of the Kaguyak Formation.

Sandstone samples from the Chignik Formation are mostly lithofeldspathic and feldspatholithic with average total quartz percentages higher than in the Kaguyak and Matanuska Formations. Average modal compositions from the Chignik are $Q_{43}F_{31}L_{26}$ (Fairchild, 1977) and $Q_{34}F_{19}L_{47}$ (Burk, 1965).

Quartz content is variable from the Kaguyak, Matanuska, and Chignik Formations, but the low ratios of polycrystalline quartz to total quartz (C/Q) indicate that most of the quartz is monocrystalline. Plagioclase to total feldspar ratios (P/F), although variable in the three formations, generally are lower in the three formations than in the underlying units; this variability indicates increased K-feldspar content (as much as 41 percent of the total feldspar from the Kaguyak Formation and 69 percent from the Chignik Formation, table 16). The moderate to high ratios of volcanic lithic to total lithic fragment (V/L) reflect a prominent volcanic source, but plutonic and sedimentary sources are also indicated.

CENOZOIC SEDIMENTARY ROCKS

The early Cenozoic sequence (ca. 50-65 Ma) includes the Arkose Ridge, Chickaloon, West Foreland, and Wishbone Formations (fig. 37). The late Cenozoic sequence (ca. 0-30 Ma) includes the Kenai Group (Hemlock Conglomerate and Tyonek, Beluga, and Sterling Formations) and Quaternary rocks.

Lower Cenozoic Rocks

Arkose Ridge and Chickaloon Formations

The Arkose Ridge Formation crops out north of the Castle Mountain fault north of the Matanuska Valley. The age of this unit has not been established, but it is considered Late Cretaceous by Csejtey and others (1977) and Early and Late(?) Cretaceous by Grantz and Wolfe (1961) and Paleocene by Magoon and others (1976b) (fig. 38). The outcrops of the Arkose Ridge have not been correlated with the subsurface units, so at present it cannot be considered a regional unit.

The Chickaloon Formation, Paleocene in age (Magoon and others, 1976b), consists of volcanic lithic sandstone, siltstone, and coal. The Chickaloon crops out south of the Castle Mountain fault in the Matanuska Valley and can be correlated into the subsurface from here to west of the Susitna River (Alaska Geological Society, 1969c, 1970a, b). The Chickaloon is of regional importance inasmuch as it extends into the subsurface and is compositionally similar to and correlates, in part, with the West Foreland and Wishbone Formations.

Sandstone from the Arkose Ridge and Chickaloon Formations are feldspathic and feldspatholithic, respectively. Average modal sandstone compositions from the Arkose Ridge Formation are $Q_{37}F_{57}L_6$ (Winkler, 1978) and $Q_{22}F_{68}L_{10}$ (Clardy, 1974), whereas average modal compositions from the Chickaloon Formation are $Q_{28}F_{20}L_{52}$ (Winkler, 1978) and $Q_{30}F_{22}L_{48}$ (Clardy, 1974). Arkose Ridge sandstone compositions reflect the composition of granitic and local metamorphic rocks that are directly below stratigraphically whereas the sandstone compositions of the Chickaloon Formation indicate a volcanic source in part, however the sandstones also contain a heavy mineral population high in epidote and garnet that partly reflects a metamorphic source terrane (Kirschner and Lyon, 1973; Clardy, 1974).

Both the Arkose Ridge and Chickaloon Formations have moderate amounts of quartz and low polycrystalline quartz to total quartz ratios, however polycrystalline quartz in Chickaloon samples, which is three to four times more abundant than in samples from the Arkose Ridge Formation, may be silicified volcanic rock fragments.

Plagioclase to total feldspar ratios, which are moderate to high, indicate that most of the feldspar is plagioclase, but as much as 28 percent of the feldspar is K-feldspar in both units (Clardy, 1974). Volcanic lithic to total lithic fragment ratios are low to moderate in the Arkose Ridge Formation and high in the Chickaloon Formation, and total lithic fragments are much higher in the Chickaloon Formation than in the Arkose Ridge Formation.

West Foreland and Wishbone Formations

The type section of the West Foreland Formation, as designated by Calderwood and Fackler (1972), is the section

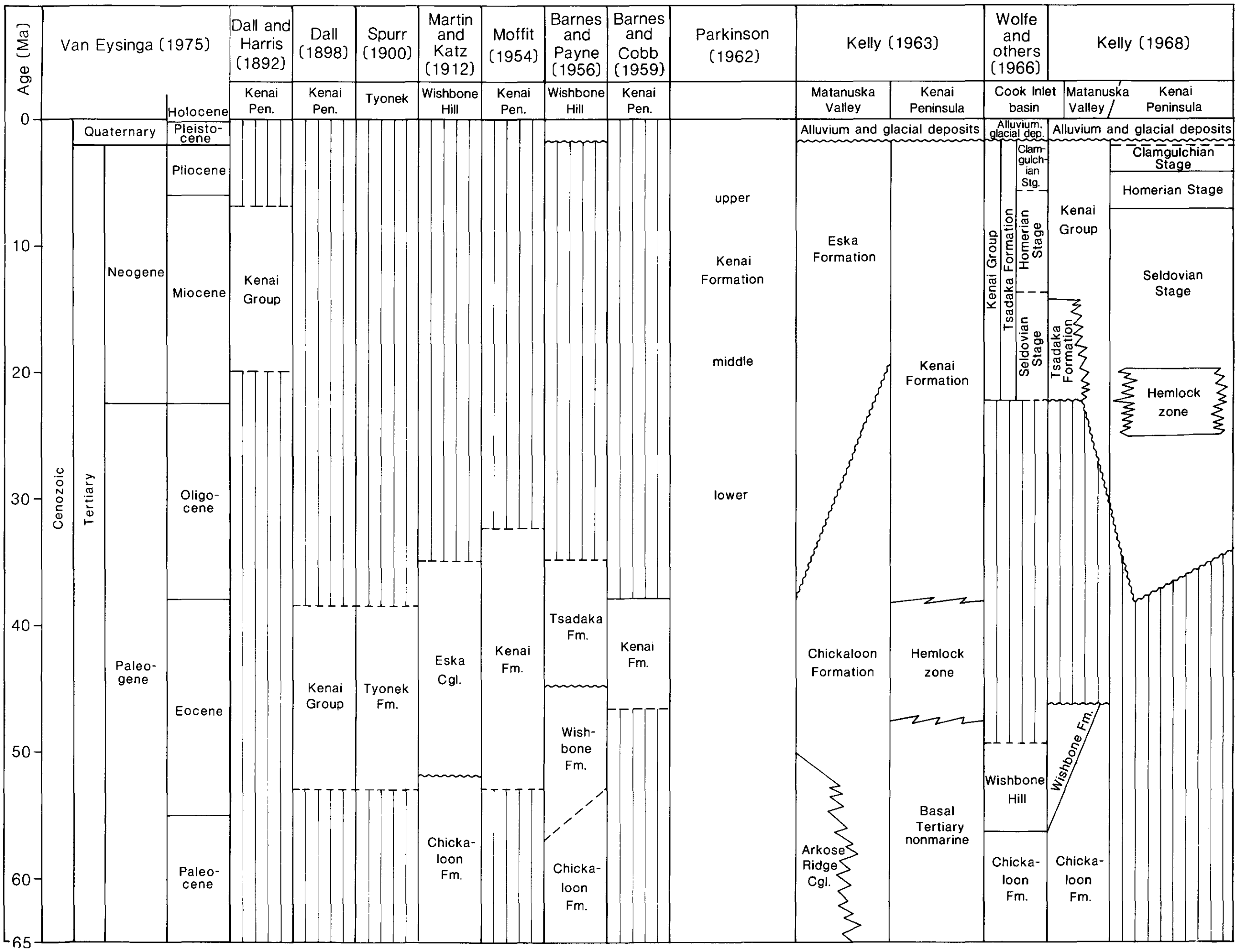


Figure 38. Tertiary correlation chart for the Cook Inlet forearc basin. The chart shows the evolution of stratigraphic nomenclature for the Cook Inlet area from the Matanuska Valley to Cape Douglas. The names formally proposed by Calderwood and Fackler (1966, 1972) for each rock unit are unchanged, but the ages vary from author to author.

penetrated between 3,237.0 to 3,508.3 m (10,617 to 11,507 ft) in the Pan American West Foreland No. 1 well (fig. 34; table 16). The lithology is described as "A tuffaceous siltstone-claystone unit containing a few conglomeratic sandstone and thin coal beds" (Calderwood and Fackler, 1972). Other workers (Adkison and Newman, 1973; Adkison and others, 1975a,b; Boss and others, 1976; Hite, 1976; Magoon and others, 1976a) describe the lithology of this unit as variable but tuffaceous, and much of the composition reflects the Mesozoic basement rock.

Hartman and others (1972) made isopach maps of the West Foreland Formation using industrial well information. The isopach map indicates that the West Foreland Formation thickness ranges from 0 m on the basin periphery to more than 600 m (2,000 ft) in the basin center. Kirschner and Lyon (1973) and others (Clardy, 1974; Boss and others, 1976; Magoon and others, 1976b) correlated this unit with outcrops on the west flank of the basin and to the Wishbone Formation in the Matanuska Valley.

The age of the West Foreland Formation is late Paleocene and early Eocene (Magoon and others, 1976b). Previous age assignments ranged from Oligocene (Crick, 1971; Kirschner and Lyon, 1973; Clardy, 1974) to Paleocene (Clardy, 1974; Boss and others, 1976). The age is based on leaf fossils and palynomorphs from localities in the Cape Douglas, East Glacier Creek, and Capps Glacier areas (Magoon and others, 1976b). A similar age is indicated for the Wishbone Formation in the Matanuska Valley.

The heavy mineral composition of the West Foreland Formation is variable, but it usually contains substantial amounts of epidote and hornblende (Kelley, 1973, 1977a; Hite, 1976). The Wishbone Formation has a heavy mineral composition comparable to the underlying Chickaloon Formation that is high in epidote and garnet; the garnet apparently comes from a local source in the Talkeetna Mountains. The contact between the Chickaloon and Wishbone Formations on Wishbone Hill is gradational. However, the lower Cenozoic rocks are bounded by unconformities.

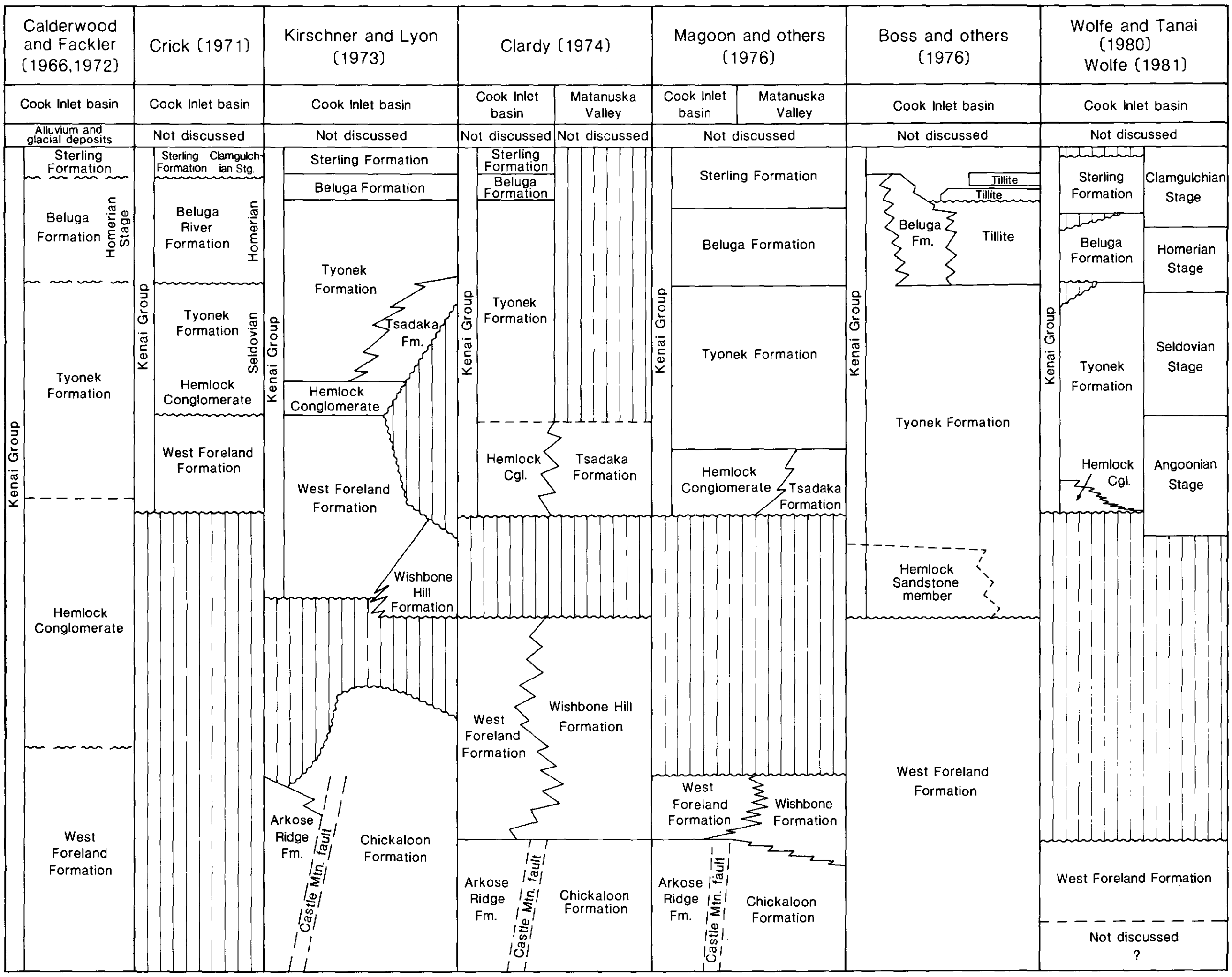


Figure 38. Continued.

The depositional environments of the West Foreland, Chickaloon, and Wishbone Formations are similar; all are nonmarine-fluvial units derived from local source terranes (Kirschner and Lyon, 1973; Clardy, 1974; Hite, 1976). Conglomerate on the west flank of the Cook Inlet indicates proximity to the source terrane. Coalescing alluvial fans from the northwest flank spread southeastward. Ash from volcanic eruptions covered the entire area, in some places burying trees in growth position as at East Glacier Creek; locally, coal swamps developed.

Sandstones from the Wishbone and West Foreland Formations are feldspatholithic, similar to the Chickaloon Formation. The average modal composition for the Wishbone Formation is $Q_{23}F_{22}L_{55}$ (Clardy, 1974) and for the West Foreland Formation average modal compositions are $Q_{22}F_{27}L_{51}$ (Stewart, 1976), $Q_{23}F_{30}L_{47}$ (Schluger, 1977; Kuryvial, 1977), and $Q_{29}F_{22}L_{49}$ (Lankford and Magoon, 1978).

The ratios of polycrystalline quartz to total quartz (C/Q) ranged from zero to moderate (0.33) for the two units indicating that most of the quartz is monocrystalline. The polycrystalline quartz that is present probably represents silicified volcanic fragments (Lankford and Magoon, 1978).

Plagioclase to total feldspar ratios (P/F), which are moderate to high (0.62 to 0.95), indicate that most of the feldspar is plagioclase, but as much as 30 percent of the total feldspar is K-feldspar in some areas (table 16). The percentages of lithic fragments are high for the Wishbone and West Foreland Formations and reflect prominent volcanic source terrane.

Upper Cenozoic Rocks

Kenai Group

The Kenai Group, first proposed by Calderwood and Fackler (1972), consisted, in ascending order, of the West Foreland Formation, Hemlock Conglomerate, Tyonek Formation, Beluga Formation, and Sterling Formation (fig. 38). The West Foreland Formation was later excluded from the

Kenai Group because of a major unconformity between the two units (Clardy, 1974; Boss and others, 1976; Magoon and others, 1976b). The Kenai Group now represents almost continuous continental deposition from the Hemlock Conglomerate through the Sterling Formation, but each formation reflects a different source terrane or depositional environment.

The stratigraphic committee of the Alaska Geological Society (1969a-d, 1970a,b) correlated the Kenai Group, which at that time included the West Foreland Formation, by making a series of stratigraphic cross sections throughout the Cook Inlet basin. Hartman and others (1972) made an isopach map of the Kenai Group and Quaternary rocks using industrial well information, and Kirschner and Lyon (1973) correlated the subsurface units of the Kenai Group with the outcrop units. The outcrops of equivalent units of the Cook Inlet basin from the Matanuska Valley to Cape Douglas, which have been correlated and dated, represent two stratigraphic sequences—an early Cenozoic sequence and a late Cenozoic sequence (Kirschner and Lyon, 1973; Clardy, 1974; Magoon and others, 1976b); the two sequences are separated in time by a 20 m.y. hiatus.

Hemlock Conglomerate and Tsadaka Formation

The type section of the Hemlock Conglomerate, as designated by Calderwood and Fackler (1972), was penetrated from 3,392.4 to 3,566.2 m (11,697 to 12,890 ft) in the Richfield Swanson River No. 1 (34-10) and is described as "conglomeratic sandstones and conglomerates." The detailed description includes coal and siltstone. Boss and others (1976) described the "Hemlock sandstone member" as a blanket sandstone that consists of 50 to 70 percent sandstone with the remainder siltstone and a few thin coal seams. Similar descriptions of the Hemlock Conglomerate were made by Crick (1971), Hartman and others (1972), and Adkison and Newman (1973).

The Hemlock Conglomerate crops out in the Cape Douglas and Harriet Point areas. In the Matanuska Valley, correlative rocks are known as the Tsadaka Formation (Magoon and others, 1976b). The Hemlock Conglomerate thickens from 0 on the periphery of the basin to 244 m (800 ft) in the center of the basin (Hartman and others, 1972). In the subsurface, two other thick sections are shown: (1) a section near the west flank at Trading Bay (374 m; 1,225 ft) of the Hemlock Conglomerate, and (2) a section near the Castle Mountain fault (448 m; 1,470 ft)—a lateral equivalent of the Bell Island Sandstone. Coal in the Hemlock Conglomerate is concentrated along both flanks of the basin in the vicinity of Trading Bay and the Kenai Lowlands (Hite, 1976).

The age of the Hemlock Conglomerate and the Tsadaka Formation is late Oligocene (Clardy, 1974; Magoon and others, 1976b); the age is based on leaf fossils and palynomorphs in the Cape Douglas and Harriet Point areas and in the Matanuska Valley (Magoon and others, 1976b). Recent studies by Wolfe and Tanai (1980) show that the Hemlock Conglomerate is of early Oligocene age. Previous age designations ranged from Eocene to Miocene (Crick, 1971; Adkison and Newman, 1973; Kirschner and Lyon, 1973; Boss and others, 1976; fig. 38).

The heavy mineral composition is high in garnet and epidote (Kelley, 1973; Kirschner and Lyon, 1973; Hite, 1976). Clardy (1974) indicates that the Tsadaka Formation, a lateral equivalent of the Hemlock Conglomerate, is high in epidote.

The depositional environments of the Hemlock Conglomerate are fluvial-deltaic to estuarine (Hartman and others, 1972; Kirschner and Lyon, 1973; Boss and others, 1976; Hite, 1976). The lower contacts of both the Hemlock Conglomerate and Tsadaka Formation are sharp unconformities, whereas the upper contact of the Hemlock Conglomerate with the Tyonek Formation has been depicted as an unconformity (Hite, 1976) or a gradational boundary (Crick, 1971; Kirschner and Lyon, 1973; Boss and others, 1976; Magoon and others, 1976b).

Sandstones of the Hemlock Conglomerate and the Tsadaka Formation are generally feldspatholithic and lithofeldspathic. Average modal compositions are variable for the two units, but the quartz content is greater for both units than it is in the underlying units. The Tsadaka Formation has an average modal composition of $Q_{37}F_{40}L_{23}$ (Clardy, 1974), whereas the Hemlock Conglomerate has an average modal composition of $Q_{66}F_{15}L_{19}$ (Stewart, 1976), and the undifferentiated Hemlock Conglomerate and Tyonek Formation has an average modal composition of $Q_{39}F_{24}L_{37}$ (Lankford and Magoon, 1978).

The very low ratios of polycrystalline quartz to total quartz (C/Q) for both units indicate that most of the quartz is monocrystalline. Plagioclase to total feldspar ratios range from 0.78 for the Tsadaka Formation to 0.50 for the Hemlock Conglomerate; this variability indicates that K-feldspar averages 22 and 50 percent of the total feldspar from the Tsadaka Formation and Hemlock Conglomerate, respectively (Stewart, 1976; Clardy, 1974).

Volcanic lithic to total lithic fragment ratios (V/L) are low for both the Tsadaka Formation (0.26) and Hemlock Conglomerate (0.21); these low ratios completely contrast with all the other underlying units. Metamorphic and plutonic rock fragments, in subequal proportions, account for most of the lithic fragment populations.

Tyonek Formation

The type section of the Tyonek Formation, as designated by Calderwood and Fackler (1972), was penetrated from 1,310.6 to 3,642.4 m (4,300 to 11,947 ft) in the Pan American Tyonek State 17587 No. 2 well. The lithology is described as "massively bedded sandstones and thicker coal beds which contrast with the more thinly bedded sandstones, claystones, and thin lignitic coal beds of the overlying Beluga Formation." Crick (1971), Hartman and others (1972), Adkison and Newman (1973), Kirschner and Lyon (1973), and Hite (1976) give similar lithologic descriptions.

The Tyonek Formation crops out in the Cape Douglas, Harriet Point, and Susitna River areas (Magoon and others, 1976b). In the subsurface this unit thickens from 0 on the periphery of the basin to more than 2,134 m (7,000 ft) in the center of the basin (Hartman and others, 1972). A sandstone/shale ratio map indicates that in the Trading Bay area, the unit is more than 50 percent sandstone (Hartman and others, 1972).

The age of the Tyonek Formation, late Oligocene to middle Miocene, is based on leaf fossils and on palynomorphs in the Cape Douglas, Harriet Point, and Capps Glacier areas (Magoon and others, 1976b). Wolfe and Tanai (1980), however, believe that the age of the Tyonek Formation ranges from early Oligocene to middle Miocene.

The depositional environment of the Tyonek is described as fluvial, deltaic, and estuarine (Hartman and others, 1972; Kirschner and Lyon, 1973), or as alluvial (Boss and others, 1976; Hite, 1976). In outcrops at Capps Glacier, near Seldovia, and in the subsurface of the Kenai Lowland where the Hemlock is missing, the Tyonek Formation unconformably overlies the West Foreland Formation. The upper contact of the Tyonek Formation with the Beluga Formation is described as gradational and intertonguing (Kirschner and Lyon, 1973; Boss and others, 1976; Hayes and others, 1976) or as an unconformity (Crick, 1971; Calderwood and Fackler, 1972).

The heavy mineral concentrations for the Tyonek Formation and underlying Hemlock Conglomerate are high in garnet and epidote (Kelley, 1973, Hite, 1976; C. E. Kirschner and others, written commun., 1979). These units are also thick in the subsurface near the Matanuska Valley. These rocks compare in both age and lithology to the Nenana coal-bearing rocks farther north, and the wide distribution of the rocks suggest that both rock sequences had source areas in interior Alaska or western Canada, northeast of the present Alaska Range (Wahrhaftig and others, 1969; Kirschner and Lyon, 1973; Buffler and Triplehorn, 1976). From late Oligocene to middle Miocene time, one or more river systems brought garnet-rich sediments from interior Alaska or Canada through the Nenana and Susitna River areas to the Trading Bay and Matanuska Valley areas.

Sandstones from the Tyonek Formation are generally feldspatholithic with an average modal composition of $Q_{61}F_{19}L_{20}$ (Stewart, 1976). Quartz content is relatively high, and a low polycrystalline quartz to total quartz ratio (C/Q) indicates that most of the quartz is monocrystalline. Plagioclase to total feldspar ratios are low (<0.50); K-feldspar averages 54 percent of the total feldspar population. Volcanic lithic to total lithic fragment ratios are low for the Tyonek Formation; the ratios are similar to those of the underlying Hemlock Conglomerate and Tsadaka Formation that have high percentages of metamorphic and plutonic rock fragments.

Beluga Formation

The type section of the Beluga Formation, as designated by Calderwood and Fackler (1972), was penetrated between 1,100.3 to 2,365.3 m (3,610 to 7,760 ft) in the Standard Oil Company of California Beluga River No. 1 (212-35) well, and "consists of thin intercalated beds of claystone, sandstone, siltstone, and lignitic to subbituminous coal." Similar descriptions were given by Crick (1971), Hartman and others (1972), Adkison and Newman (1973), Adkison and others (1975b), Boss and others (1976), and Hayes and others (1976).

The Beluga Formation crops out in cliffs near Homer and northeast of Trading Bay (Magoon and others, 1976b). In the subsurface, this unit thickens from 0 on the basin edge where it is truncated by the Sterling Formation to as much as 1,525 m (5,000 ft) in the basin axis under the Kenai Lowland (Hartman and others, 1972).

The age of the Beluga Formation, based on leaf fossils and palynomorphs from outcrops north of Trading Bay and north of Kachemak Bay, is late Miocene (Magoon and others, 1976b) or middle and late Miocene according to Wolfe and Tanai (1980). The upper contact with the overlying Sterling Formation is considered to be unconformable by some workers (Crick, 1971; Calderwood and Fackler, 1972; Hayes and others, 1976), transitional in part by Kirschner and Lyon (1973), and intertonguing by Boss and others (1976). A high epidote content is typical of the Beluga Formation (Kirschner and Lyon, 1973; Hite, 1976; Biddle, 1977).

The depositional environment is believed to have been alluvial fans (Kirschner and Lyon, 1973; Hayes and others, 1976) or glacial deposits (Boss and others, 1976). Both depositional models designate the Chugach terrane on the southeast as the primary source of sediments with a secondary source of sediments from the north (Hartman and others, 1972). In late Miocene time, the Alaska Range became a prominent topographic feature on the north that cut off drainage from interior Alaska (Wahrhaftig and others, 1969; Kirschner and Lyon, 1973; Buffler and Triplehorn, 1976). After the Chugach terrane on the southeast was elevated and eroded, it provided epidote-rich sediments to the Cook Inlet basin.

Sterling Formation and Quaternary Rocks

The type section of the Sterling Formation, as designated by Calderwood and Fackler (1972), was penetrated from 320.0 to 1,688.6 m (1,050 to 5,540 ft) in the Union Oil Company Sterling Unit No. 23-15 well, and it is described as "a thick sequence of massive sandstones, conglomeratic sandstones, and interbedded claystones." Other authors give a similar description; 50 to 75 percent or more of the section is medium grained, well to fairly well sorted, and slightly conglomeratic sandstone (Crick, 1971; Boss and others, 1976; Hayes and others, 1976). Sandstones are composed of quartz, plagioclase, biotite, and glassy volcanic rock fragments (Hayes and others, 1976). Hornblende, hypersthene, and some epidote are the major heavy minerals (Kirschner and Lyon, 1973; Hayes and others, 1976; Hite, 1976; Biddle, 1977). Primary and secondary porosity are as much as 30 percent (Boss and others, 1976; Hayes and others, 1976).

The Sterling Formation crops out in the cliffs of the Kenai Lowland. An isopach map of the formation and the Quaternary age rocks in the subsurface reveals that these rocks are more than 3,050 m (10,000 ft) thick (Hartman and others, 1972). The age of the Sterling Formation, late Miocene and Pliocene (Magoon and others, 1976b; Wolfe and Tanai, 1980), is based on leaf fossils and palynomorphs.

The depositional environment was alluvial. The primary source terrane was the Alaska-Aleutian Range batholith to the northwest (Kirschner and Lyon, 1973; Boss and others, 1976; Hayes and others, 1976), but the Chugach terrane was and still is a contributor of some sediment (Hartman and others, 1972). Throughout the Pliocene and Quaternary and even up to the present, volcanic material was erupted over the entire basin.

TECTONIC EVOLUTION

The northern Pacific margin has been the site of continuous convergence throughout the Mesozoic and Cenozoic eras; the Cook Inlet-Shelikof Strait and adjacent areas are a part of this margin. Many authors have discussed the tectonic evolution of various parts of southern Alaska in relation to a convergent margin model (Burk, 1965; Plafker, 1969; MacKevett and Plafker, 1974; Moore and Connelly, 1977; Plafker and others, 1977; Fisher and Magoon, 1978; Hudson, 1979a, b,c). Three major geologic elements are included in many of these models: the magmatic arc, the forearc basin, and the accreted terranes (table 18). In general, the magmatic arc, represented by the Alaska-Aleutian batholith, and the subduction zone, whose present location is the Aleutian trench, are directly or indirectly responsible for the temporal, compositional, and spatial relations of the intervening rocks of the forearc basin and accreted terranes.

Beck and others (1980) distinguished two types of tectonic (tectonostratigraphic) terranes. First, the "stratigraphic terranes wherein major contacts between principal lithic subdivisions are depositional". The Peninsular terrane and the Cenozoic sedimentary rocks fall into this category (fig. 36). Second, "disrupted terranes wherein major contacts between principal lithic subdivisions are faults". The Chugach and Prince William terranes (fig. 36) fall into this category.

These stratigraphic terranes of the forearc basin, which include the Peninsular terrane and the Cenozoic sedimentary rocks, seem to be genetically linked to the intrusive bodies that make up the Alaska-Aleutian batholith. The more difficult relationship to demonstrate is the connection between the stratigraphic terranes of the forearc basin to the disrupted or accreted terranes seaward of the Border Ranges fault. There, the rocks are highly deformed, lack adequate fossil control, and are bounded by faults.

Table 18. Magmatic arcs, stratigraphic terranes, and accreted terranes of Cook Inlet–Shelikof Strait area

[Numbers and letters in parentheses refer to figure 33 and tables 16 and 17]

Episode	Magmatic arc (plutonic belt)	Stratigraphic terrane (unconformity bounded)	Accreted terrane (fault bounded)
Post-Eocene	Alaska-Aleutian Range (granite to granodiorite)	Hemlock Conglomerate and Tyonek Formation (43-49) Tsadaka Formation (42)	Narrow Cape Formation (Q, R)
Pre-Oligocene	Alaska Range-Talkeetna Mountains Belt (granite to quartz diorite)	West Foreland Formation (39-41) Wishbone Formation (38) Chickaloon Formation (36, 37) Arkose Ridge Formation (34, 35)	Sitkinak Formation (N-P) Sitkalidak Formation (K-M) Ghost Rocks Formation (I, J)[1]
Late Cretaceous	Alaska Range-Talkeetna Mountains Belt (granite to quartz diorite)	Kaguyak Formation (29, 33)[3] Matanuska Formation (part) (27-28)[3] Chignik Formation (25, 26)[3]	Kodiak and Shumagin Formations (F-H)[2] Slivers wacke (E)[2] Valdez Group (D)[2]
Late Early and early Late Cretaceous	Not represented	Matanuska Formation (Albian part, 24)[3] Unnamed Albian rocks (23)[3]	Cape Current terrane (C)[2]
Early Jurassic into Early Cretaceous	Aleutian Range-Talkeetna Mountains Belt (granodiorite to quartz diorite)	Herendeen Limestone (20-22)[3] Staniukovich Formation (18, 19)[3] Naknek Formation (11-17)[3] Shelikof and Chinitna Formations (8-10)[3] Tuxedni Group and Kialagvik Formation (6, 7)[3] Talkeetna Formation (4, 5)[3]	McHugh and Uyak Complexes (A, B)[2]
Permian(?) to Early Jurassic	Kodiak-Kenai belt (tonalite-quartz diorite)	Shuyak Formation (2)[3] Unnamed (1, 3)[3] Unnamed Permian rocks[3]	Kachemak terrane[2] Kodiak-Seldovia schist terrane(?)

[1] Prince William terrane
[2] Chugach terrane
[3] Peninsular terrane

Paleomagnetic data from both the stratigraphic and disrupted terranes strongly suggest that southern Alaska is a conglomeration of terranes that originated in a more southerly latitude and subsequently moved north to finally collide or accrete in southern Alaska (Packer and Stone, 1974; Jones and others, 1977; Hillhouse, 1977; Stone, 1979). The petrographic data and depositional history of the sandstones in the Cook Inlet basin and adjacent terranes do not preclude this interpretation, but the Cook Inlet evidence does constrain the interpretation. For example, sandstones in the Cook Inlet basin and from adjacent accreted terranes that are of the same age and composition as the sandstones of southern Alaska may well have had the same source areas. However, we feel that the terranes of southern Alaska need not have evolved in their present location, and therefore they are not necessarily in conflict with the paleomagnetic data.

The development of the magmatic arc, the forearc basin (stratigraphic terrane), and accreted terrane (disrupted terrane of the Cook Inlet-Shelikof Strait and adjacent areas) can be discussed in terms of the tectonic cycle. Each cycle represents one episode in the development of the crust adjacent to this convergent margin (Hudson, this volume); each succeeding episode affects the crust landward of the trench. The crust, which ranged from near oceanic to continental in composition, evolved in six episodes that took place over the following time span: (1) Permian(?) through Early Jurassic; (2) Early Jurassic into Early Cretaceous; (3) late Early and early Late(?) Cretaceous; (4) Late Cretaceous; (5) early Cenozoic, and (6) late Cenozoic. The rocks of episodes 1 and 2, and 4 and 5 may overlap temporally, but they are different geologically, whereas the rocks of episode 3 are different temporally but are poorly represented geologically.

According to this model, a complete tectonic cycle goes through three stages of development; first, plutonism and volcanism construct a magmatic arc along a convergent margin; second, the tectonic forces associated with the convergent margin and magmatic arc interact to form the outer arc ridge, shelf, slope, trench, and abyssal plain. Finally uplift and erosion dissect the magmatic arc and the outer arc ridge, and the eroded sediments fill the arc basins, shelf, slope, and trench, and then spill onto the abyssal plain. Throughout the cycle, tectonism, magmatism, and sedimentation proceed at varying intensities. Present-day evidence for the existence of the cycle include: (1) a plutonic belt with radiometric age dates that correspond to the cycle; (2) evidence for coeval extrusive volcanic activity of calc-alkaline composition; (3) undeformed sedimentary rocks bounded by unconformities (stratigraphic terrane) whose provenance is the magmatic arc and whose age, from fossils or radiometric age dates, is similar to the plutonic belt, and (4) accreted (disrupted) terrane(s), bounded by faults, whose age based on fossils is no younger than the undeformed sedimentary rocks of the forearc basin and whose rocks were probably deformed towards the end of the cycle. The disrupted terrane need not evolve adjacent to nor be intimately associated with the stratigraphic terrane. The time needed to complete a stage in the tectonic cycle is called an episode.

Permian(?) through Early Jurassic Episode

The first episode took place during the Triassic, but fossil evidence suggests it may have extended back into the Permian(?) and forward into the Early Jurassic. The magmatic arc is represented by the Kodiak-Kenai plutonic belt, the extrusive activity by the pillow basalts and greenstones, and the erosion of the volcanic terrane is shown by the lithic-rich turbidite sandstones (numbers 1 through 3 on table 16 and fig. 33). Behind or adjacent to the arc, biothermal carbonate reefs were periodically inundated by volcanic agglomerates. The accretionary wedge may be represented by the Triassic rocks in Kachemak Bay or by the Kodiak-Seldovia schist terrane, but the latter rocks may not be related to the rocks of the accretionary wedge because the schist is presently defined as being inboard of the Border Ranges fault.

Early Jurassic into Early Cretaceous Episode

The second episode, which took place from Early Jurassic through Early Cretaceous, is the most complete, longest, and best understood. The magmatic arc is represented by the Aleutian Range-Talkeetna Mountain plutonic belt, the extrusive activity is represented by the volcanogenic Talkeetna Formation, and the unroofing of the magmatic arc is exquisitely shown by the change in composition of the sandstone (numbers 4 through 22 in table 16 and fig. 33) and conglomerate in the middle Jurassic through Lower Cretaceous sedimentary rocks of the Peninsular terrane. The change in sandstone composition compares closely with the magmatic arc provenance of Dickinson and Suczek (1979). The fault-bounded accretionary terrane may be represented by the McHugh and Uyak Complexes because its youngest age is Aptian. The compositions of the sandstone within this terrane are variable (letters A and B in table 17 and fig. 33), but the terrane is inadequately sampled. The rock sample from the Chugach Mountains is more quartz rich compared with the lithic content than any other rocks involved in this episode from the Peninsular terrane, but the rock samples from Kodiak Island do compare fairly well with rocks of the same age in the Peninsular terrane.

Late Early and Early Late(?) Cretaceous Episode

The third episode, which occurred during the late Early and early Late(?) Cretaceous, is poorly represented in the rock record. The middle Cretaceous plutons, which are located in the Nutzotin Mountain on the USA-Canadian border, probably are not represented in the immediate vicinity of the Cook Inlet; the only rocks in the forearc basin are lithic-rich sandstones of Albian age (numbers 23 and 24 in table 16 and fig. 33). The accreted terrane is represented by the younger Cape Current terrane that occurs on the Shuyak and Afognak Islands which are questionably of Turonian-Santonian age (letter C in table 17 and fig. 33).

Late Cretaceous Episode

The fourth episode, which occurred during the Late Cretaceous, is well represented in the rock record and isolated by unconformities. Although the plutonic belt contains intrusive bodies of both ages, the Late Cretaceous episode is considered distinct from the early Cenozoic episode because a major unconformity occurs at the base of the early Cenozoic rocks. The unconformity at the Late Cretaceous-early Cenozoic boundary, the most important structural unconformity because the Mesozoic rocks were folded and truncated before the Cenozoic rocks were deposited, separates the two episodes. The magmatic arc is represented, in part, by the Alaska Range-Talkeetna Mountain plutonic belt of granite to quartz diorite composition. The composition of the Upper Cretaceous sandstone (numbers 30 and 32 in table 16 and fig. 33) reflects the reworking of the underlying feldspathic-rich rocks and deeply dissected magmatic arc of the second episode, but eventually the sandstone composition becomes more lithic rich high in the section. The primary extrusive volcanic rock of the Late Cretaceous may have been reworked into the lithic-rich sandstones in the upper part of the Kaguyak Formation in the COST No. 1 well (number 31 in table 16 and fig. 33) and in the Cape Douglas area (number 33 in table 16 and fig. 33). In general, Upper Cretaceous sandstones are more quartz rich than the underlying Mesozoic units (numbers 25 through 33 in table 16 and fig. 33). The accreted terrane contains sandstones ranging from those having few volcanic-lithic fragments (letter E in table 17 and fig. 33) to those having abundant volcanic-lithic fragments (letter D in table 17 and fig. 33). From a petrographic study of rock fragments from Upper Cretaceous sandstone of the Chugach terrane, Zuffa and others (1980) concluded that the sandstone was derived primarily from a volcanic arc with secondary inputs from a magmatic arc, a subduction complex and recycled sedimentary debris. To date (1981), the range in compositions of the sandstones in the forearc basin and accreted terrane does not preclude that the provenance is the same for both and that the accreted terrane may be farther from the source than the forearc basin.

Early Cenozoic Episode

The fifth episode, which occurred during the early Cenozoic, includes the same plutonic belt as the previous episode. These early Cenozoic stratigraphic units of the forearc basin unconformably overlie the Mesozoic rocks and the accreted terrane seaward of the Border Ranges fault. The composition of the sandstone is approximately 50 percent lithic (numbers 36 through 41 in table 16 and fig. 33) except for the Arkose Ridge Formation, which contains very few lithic fragments (numbers 34 and 35 in table 16 and fig. 33). The Ghost Rocks Formation of the accreted (Prince William) terrane, (letters I and J in table 17 and fig. 33), is very similar in composition to the lithic-rich sandstone. In addition, the Sitkalidak and Sitkinak Formations (letters K through P in table 17 and fig. 33), which are more quartz rich than the lithic-rich sandstone, also contain a lot of lithic material.

Late Cenozoic Episode

The last episode, which is still going on today, is demonstrated by the granitic to granodioritic plutonic rocks exposed in the Alaska Range and the stratigraphic terrane by the late Cenozoic Kenai Group; however, there is no evidence of an accretionary terrane. Provenance of the lower part of the Kenai Group sedimentary rocks in the forearc basin (numbers 42 through 45 in table 16 and fig. 33) is more quartz rich in the lower part than in the upper part; the plutonic body follows the same trend as the sedimentary rocks (Hudson, this volume). Heavy-mineral content (garnet and epidote) suggest that the provenance for the Hemlock Conglomerate and Tyonek Formation is from the interior of Alaska. High concentrations of epidote and volcanic-lithic fragments in the Beluga Formation suggest that the provenance is the Kenai Peninsula after the Alaska Range was uplifted. The provenance for the Sterling Formation and Quaternary rocks is probably the Alaska-Aleutian Range, and to a lesser degree, the Kenai Peninsula. Except for today's active volcanism, there is no evidence of a plutonic body with K-Ar age dates that correlate with the Kenai Group and Quaternary rocks.

Conclusions

By Leslie B. Magoon

1. The COST No. 1 well was drilled in 65 m (214 ft) of water and penetrated 3,776 m (12,387 ft) of sedimentary rocks in the Alaska Outer Continental Shelf block 489 about midway between the Iniskin Peninsula on the northwest and the Kenai Peninsula on the southeast. The ages of the sedimentary units were determined by wireline logs and the classification of Foraminifera, Radiolaria, calcareous nannoplankton, and marine and terrestrial palynomorphs. The section from 413 m (1,356 ft) to 797 m (2,615 ft) is Cenozoic. The underlying section, from 797 m (2,615 ft) to 2,112 m (6,930 ft), is Cretaceous; at 1,541 m (5,055 ft) the section is divided into Upper and Lower Cretaceous rocks. The bottom section, from 2,112 m (6,930 ft) to 3,775.6 m (12,387 ft), is Upper Jurassic (Oxfordian through Tithonian). The base of this section probably was not penetrated so the 1,663 m (5,455 ft) thickness is probably a minimum. The top of this unit is controversial. Drill cutting samples indicate that the top is at 2,109 m (6,918 ft), 2,112 m (6,928 ft), or 2,135 m (7,003 ft). Paleontologic evidence indicates that the top is at 2,109 m (6,918 ft) or 2,417 m (7,928 ft). I place the top at 2,112 m (6,928 ft), just below the abundant *Inoceramus* fragments and just above the first occurrence of laumontite.

The West Foreland Formation, of lower Cenozoic age, extends down to 797 m (2,615 ft). The sediments are sandstone, siltstone, coal, and some conglomerate. Modal analyses of the sandstone indicate that it is feldspatholithic with an average composition of $Q_{23}F_{30}L_{47}$. The Kaguyak Formation (Upper Cretaceous), from 797 m (2,615 ft) to 1,541 m (5,055 ft) contains marine and nonmarine sediments. The feldspathic sandstone has an average composition of $Q_{23}F_{61}L_{16}$. The Herendeen Limestone (Lower Cretaceous) contains sandstone, siltstone, shale, and abundant *Inoceramus* fragments from 1,541 m (5,055 ft) to 2,122 m (6,930 ft). The lithofeldspathic sandstone has an average composition of $Q_{36}F_{44}L_{20}$. The bottom section, the Naknek Formation (Upper Jurassic), down to 3,776 m (12,387 ft), is dominantly siltstone, shale, and sandstone. The average composition of the lithofeldspathic sandstone is $Q_{24}F_{55}L_{21}$.

The West Foreland Formation, the shallowest unit sampled, has a minimum thickness of 384 m (1,259 ft). Paleontologic data indicate Mesozoic rocks were reworked into a nonmarine environment. The organic carbon content of the unit is low and the section is thermally immature. No hydrocarbon shows were indicated. The Kaguyak Formation is 744 m (2,440 ft) thick and includes three sandstone bodies that are potential hydrocarbon reservoirs. Paleontologic and lithologic evidence indicate two prograding sedimentary sequences that prograde seaward from upper bathyal to nonmarine. Although the organic carbon content is as much as 1.07 weight percent, the kerogen is low in oil-prone material and lacks an adequate thermal history to generate oil. Two different hydrocarbon shows were reported in this unit. The Herendeen Limestone is 572 m (1,875 ft) thick. Foraminiferal data indicate middle bathyal to inner neritic marine environments. The organic carbon content is low, and the thermal history is insufficient to generate hydrocarbons. Only a few hydrocarbon indications were reported. Reservoir properties of the sandstones are poor. The deepest rock unit penetrated, the Naknek Formation, is at least 1,663 m (5,457 ft) thick. Even though the rock is thoroughly cemented with laumontite, it contained most of the hydrocarbon shows. Since the strata, mostly sandstone and siltstone, is low in organic content, and the organic matter is not the type to generate oil, the oil must have migrated into the area of the well bore from another part of the basin where mature oil-prone source rocks are present.

2. Information about the environmental geology of the lower Cook Inlet basin is limited; and no quantitative information has been collected from the upper Cook Inlet basin.

A number of geologic features and processes have been identified that may pose problems to engineering installations in the lower Cook Inlet and along the adjacent coastline. Strong earthquakes have caused major damage to the area by ground failure, surface warping, and tsunamis. Four active volcanoes on the west side of lower Cook Inlet are andesitic, so they can have violent eruptions. Very little is known about the swift bottom currents and sandwaves that have broken pipelines in the upper Cook Inlet.

3. The seismic horizons were determined by comparing the measured seismic reflections with the calculated reflections from the COST No. 1 well. Horizon A, at 900 m (2,950 ft) depth in the well, is near the top of the Upper Cretaceous rocks. Horizon B is at the depth of 2,005 m (6,575 ft) in the well. That depth represents the Cretaceous-Jurassic contact where the rocks no longer have intergranular porosity but are cemented with calcite and laumontite. The third horizon, C, is 1,400 m (4,600 ft) below the bottom of the well and about 3,100 m (10,200 ft) below the top of the Upper Jurassic rocks. It represents the contact between the top of the Middle Jurassic rocks and the base of the Upper Jurassic.

4. The paleontology and biostratigraphy are based on detailed analysis of foraminifers, marine and terrestrial palynomorphs, calcareous nannoplankton, and Radiolaria. Eocene fossils from 413 to 552 m (1,356 to 1,810 ft) represent a predominantly nonmarine depositional environment in a warm temperate climate. The Paleocene rocks from 552 to 799 m (1,810 to 2,620 ft) are characterized by a palynomorph assemblage containing *Paraalnipollenites confusus*. Well developed Late Cretaceous (Maestrichtian) microfossil assemblages, from 799 to 1,539 m (2,620 to 5,050 ft), indicate nonmarine and marine intervals. Sparse but diagnostic assemblages of Early Cretaceous Hauterivian to Valanginian(?) microfossils, from 1,539 to 2,417 m (5,050 to 7,930 ft), indicate a marine depositional environment whose paleobathymetry fluctuated twice from upper slope to middle-shelf water depths. Late Jurassic (Tithonian to Oxfordian) microfossils, from 2,417 to 3,776 m (7,930 to 12,387 ft), indicate an intertidal to inner neritic marine depositional environment.

5. The COST No. 1 well does not contain prospective petroleum source rocks. The organic carbon content, which ranges from 0.08 to 0.65 weight percent, is more abundant in the upper part of the well than in the lower. The thermal maturity, however, increases with increasing depth. The transition from immature to mature hydrocarbon generation seems to be from 2,100-2,700 m (6,900-8,900 ft) in the well.

The Mesozoic sediments in the COST No. 1 well contain much less organic matter than the Mesozoic sediments in the upper Cook Inlet and the North Slope in Alaska. Although the thermochemical transformation of the organic matter in the Mesozoic rocks is marginally mature to mature, the organic matter is dominantly of the type that has a poor oil-generating capacity. However, because the COST No. 1 well did not penetrate the source rocks for petroleum in the upper Cook Inlet—the shales of the Middle Jurassic—the prospect for petroleum in the lower Cook Inlet should not be judged only on the data obtained from the COST No. 1 well. The oil-generating system in the Cook Inlet basin is probably made up of migrating paths from the Middle Jurassic rocks.

6. The present-day geothermal gradient for the COST No. 1 well is 2.28°C/100 m. Even though this gradient is close to that of the Swanson River oil field gradient of 2.37°C/100 m, the gradient is too low when compared to the geothermal trends in the upper Cook Inlet. The evidence from the stratigraphy of the rocks, the first occurrence of laumontite, and the TAI values indicate that the rocks in the well were subjected to high temperature gradients before uplift and erosion. The low vitrinite reflectance values do not substantiate this inference.

7. The compositions of the sandstones in the COST No. 1 well indicate that they were derived from an igneous source terrane which had outcrops of both volcanic and plutonic rock types. The shallowest samples are volcaniclastic sandstone. The West Foreland Formation of lower Cenozoic age contains feldspatholithic sandstone with an average composition of $Q_{23}F_{30}L_{47}$. The Kaguyak Formation (Upper Cretaceous) contains feldspathic sandstone with an average composition of $Q_{23}F_{61}L_{16}$. Both the Herendeen Limestone (Lower Cretaceous) and Naknek Formation (Upper Jurassic) contain lithofeldspathic sandstone with average modal compositions of $Q_{36}F_{44}L_{20}$ and $Q_{24}F_{55}L_{21}$, respectively.

8. The diagenetic changes most affected the volcanic rock fragments and plagioclase feldspar that are abundant in the sandstone samples. Sandstone diagenesis increases with increasing depth in the COST No. 1 well. Pseudomatrix is more common in the deeper sandstones than in the higher sandstones. Authigenic clay, montmorillonite and chlorite, increases with depth, and some of it formed before laumontite crystallization. Laumontite is present in most sandstone samples from depths greater than 2,134 m (7,000 ft) where most plagioclase is partly to completely albitized and intergranular porosity is destroyed.

The major cause for the reduction of porosity and permeability in the COST No. 1 well is due to the formation of authigenic clay matrix and pseudomatrix. The minor cause is that of compaction and diagenesis.

The sandstones of the West Foreland Formation (lower Cenozoic) have a porosity of nearly 20 percent. The porosity and permeability of the sandstone of the Herendeen Limestone (Lower Cretaceous) has been reduced by compaction and pore fillings of clay and calcite. The original porosity of the sandstone of the Naknek Formation (Upper Jurassic) was probably high but is now substantially reduced by compaction and by precipitation of authigenic minerals (laumontite).

9. The Middle Jurassic sandstones of the Tuxedni Group were derived largely from a volcanic terrane. Important differences in composition occur between the Tonnie Siltstone Member of the Chinitna Formation and the overlying Paveloff Siltstone Member; the lower member is volcanic-lithic rich, is virtually devoid of hornblende, and is cemented mostly with chlorite; and the upper member is less lithic-rich (more feldspathic), contains an average of 7 percent hornblende, and is cemented with laumontite as well as chlorite.

The cementation and compaction of the sandstones in the Tuxedni Bay area in the western Cook Inlet should be considered when evaluating the hydrocarbon-reservoir potential of the Middle and Upper Jurassic sandstone in Cook Inlet.

The new data about the composition of the sandstones from the Tuxedni Group and Chinitna and Naknek Formations provide evidence that the Alaska-Aleutian Range batholith was unroofed during the deposition of the Paveloff Siltstone Member of the Chinitna Formation. This event would have happened earlier than previously thought.

10. Eight separate episodes of plutonism in southern Alaska may have affected or have affected the provenance history of the forearc basin that includes Cook Inlet. The petrologic variations of the plutons representing these eight episodes reveal a general trend to higher felsic composition

from the older to the younger plutonic groups. Generally, Jurassic plutonism produced mafic to intermediate compositions, Cretaceous plutonism produced mostly intermediate compositions, and Tertiary plutonism produced felsic compositions.

Both short-term and long-term plate-convergent episodes have affected the provenance of the Cook Inlet forearc basin. Four relatively short-term episodes that affected the Cook Inlet basin occurred during the Late Triassic(?) and Early Jurassic, Middle and Late Jurassic, Late Cretaceous and early Tertiary, and middle Tertiary. Widespread upper Cenozoic volcanic rocks and the presence of many calc-alkaline volcanoes in the region are evidence that a fifth episode is taking place now.

Over the long term, the provenance evolved from simple magmatic arc sequences in the early Mesozoic to a composite of regional sedimentary, metamorphic, and magmatic arc sequences in the late Mesozoic and Cenozoic. In effect, each succeeding magmatic arc increased the proportion of crystalline rocks in the provenance. The simple magmatic arc provenance of the Upper Triassic, Jurassic, and Lower Cretaceous produced sandstones changing from lithic to feldspathic compositions. The sandstones in the Upper Cretaceous should demonstrate a composite provenance that includes magmatic arc and recycled orogen types, and, after a new magmatic arc cycle began in the Late Cretaceous, local development of volcanolithic sandstones.

Late Cenozoic sandstones should demonstrate a complex composite provenance that includes magmatic arc, recycled orogen, and continental block provenance types. The diverse sandstones should range from lithic to quartzose types.

The development of three major provenance types in southern Alaska will produce a complete range of sandstone framework modes. However, the younger sandstones of the Cook Inlet basin are the most likely to have quartzose framework modes because the increasing proportion of metamorphic and plutonic rocks during provenance evolution occurred as the compositions in younger plutons became more felsic.

11. Only the sandstones from the Lower Jurassic through the Lower Cretaceous changed compositions in the way Dickinson and Suczek (1979) predicted for magmatic arc provenances. In the forearc basin, the Upper Cretaceous sandstones change composition from a feldspathic to a feldspatholithic sandstone with very little change in quartz content; this change is the reverse of the kind of change expected in a magmatic arc provenance and more like the dissection of the previous magmatic arc provenance. The changes in the Cenozoic sandstones in the forearc basin and the accreted terranes also are those of a magmatic provenance; the sandstones were all feldspatholithic but they increased in quartz content very rapidly as they decreased in age, undoubtedly demonstrating the more felsic provenance and indicating that the drainage system reached into interior Alaska.

Only in the Cenozoic sandstones was the quartz content high enough to provide adequate petroleum reservoirs consistently. The Upper Jurassic sandstone would have been a good petroleum reservoir before the laumontite filled all the pores in the rocks.

12. Considering all the data, only three sandstone beds of Upper Cretaceous age are potential hydrocarbon reservoirs in the COST No. 1 well. These rocks, however, are not the source rocks for the petroleum in the upper Cook Inlet. COST No. 1 well did not penetrate the shales of the middle Jurassic, so the question of whether potential prospective petroleum accumulations are present in the lower Cook Inlet basin still remains unanswered.

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