UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GEOLOGIC FRAMEWORK OF LOWER COOK INLET, ALASKA

By

Michael A. Fisher *and* Leslie B. Magoon

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ABSTRACT

Three seismic reflectors are present throughout the lower Cook Inlet basin and can be correlated with onshore geologic features. The reflections come from unconformities at the base of the Tertiary sequence, at the base of Upper Cretaceous rocks, and near the base of Upper Jurassic strata.

A contour map of the deepest horizon shows that Mesozoic rocks are formed into a northeast trending syncline. Along the southeast flank of the basin, the northwest-dipping Mesozoic rocks are truncated at the base of Tertiary rocks.

The Augustine-Seldovia arch trends across the basin axis between Augustine Island and Seldovia. Tertiary rocks thin onto the arch from the north and south. Numerous anticlines, smaller in structural relief and breadth than the Augustine-Seldovia arch, trend northeastward parallel to the basin, and intersect the arch at oblique angles.

The stratigraphic record shows four cycles of sedimentation and tectonism that are bounded by three regional unconformities in lower Cook Inlet and by four thrust faults and the modern Benioff zone in flysch rocks of the Kenai Peninsula and the Gulf of Alaska. The cycles are called, from oldest to youngest, the early Mesozoic, the late Mesozoic, the early Cenozoic and the late Cenozoic.

Data on organic geochemistry of the rocks from one well suggest that Middle Jurassic strata may be a source of hydrocarbons. Seismic data show that structural traps are formed by northeast-trending anticlines and by structures formed at the intersections of these anticlines

with the transbasin arch. Stratigraphic traps may be formed beneath the unconformity at the base of Tertiary strata and beneath unconformities within Mesozoic strata.

INTRODUCTION

Lower Cook Inlet is located in south-central Alaska between lat $58^{\circ}45'$ and $60^{\circ}30'$ N. and between long 151° and 154° W. (fig. 1). Geographic features on the perimeter of the area are the Aleutian Range on the northwest, Kalgin Island on the northeast, the Kenai Peninsula on the east, the Barren Islands on the southeast, and the Kamishak Hills-Cape Douglas area on the south. Augustine Island, a prominent active composite volcano, is in the southwestern part of lower Cook Inlet. Lower Cook Inlet is part of a large bay that is nearly surrounded by mountains except where it opens southeastward into the Gulf of Alaska and southward into Shelikof Strait. In anticipation of oil and gas lease sales in lower Cook Inlet, the U.S. Geological Survey acquired geological and geophysical data to study the geologic framework and petroleum geology of this area. These data were included in the lower Cook Inlet environmental impact statements (Alaska Outer Continental Shelf Office, 1976a, b) and are being made available to other government agencies and the public.

The submerged lands of Cook Inlet are owned by both the State of Alaska and the Federal Government. Upper Cook Inlet, owned by the State of Alaska, is a well-developed petroleum province with estimated recoverable reserves of more than 1.1 billion barrels of oil and more than 8.3 trillion cubic feet of dry gas (Blasko, 1974;

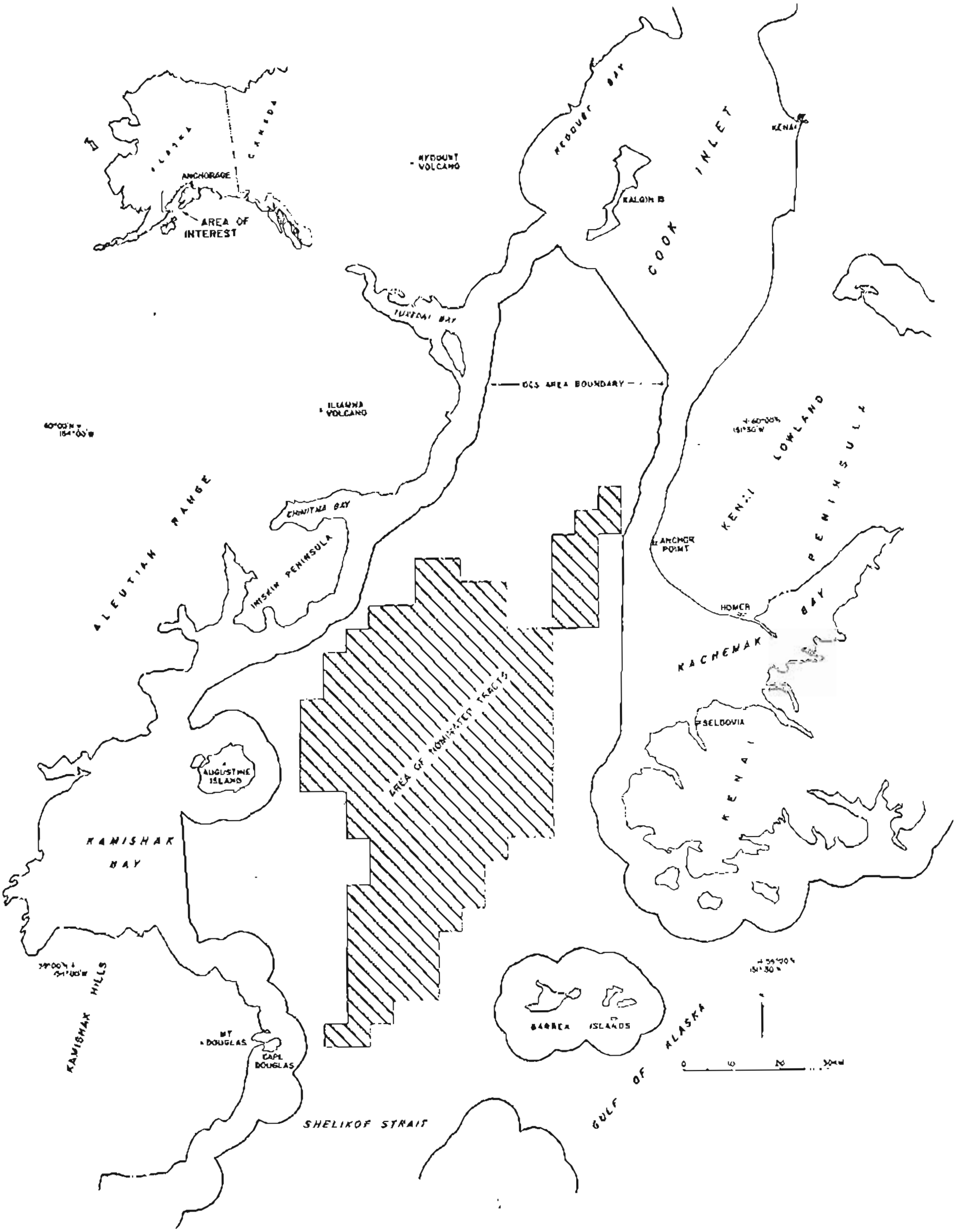

Fig. 1--Geographic features and area nominated of lease sale, lower Cook Inlet.

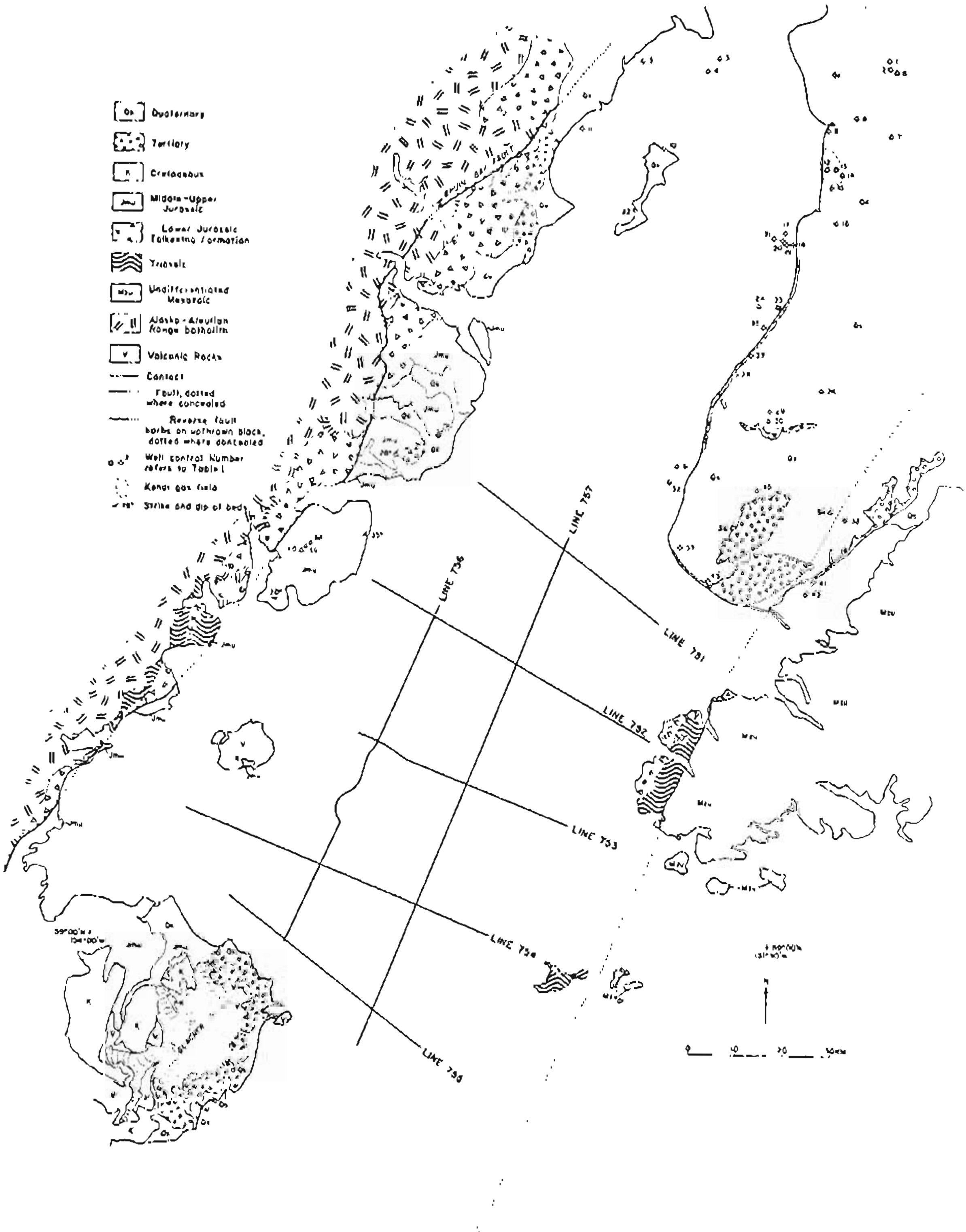

Fig. 2--Geologic map of lower Cook Inlet showing the seismic grid, well locations and the Kenai gas field.

Oil and Gas Journal, 1975; Alaska Division of Oil and Gas, 1976). The Outer Continental Shelf (OCS) area of lower Cook Inlet, owned by the Federal Government, has been subdivided into tracts, 120 of which have been selected for a lease sale that may be held in 1977 (Oil and Gas Journal, 1977) (fig. 1). All the selected tracts are in less than 200 m of water. The undiscovered recoverable resources of this area are estimated to be between 0.3 to 1.4 billion barrels of oil and 0.6 to 2.7 trillion cubic feet of gas (Magoon, Adkison, and others, 1976).

Information on Cook Inlet exists in several forms. A bibliography of geological literature on Cook Inlet was published by Maher and Trollman (1969). A summary of the stratigraphy and structure of upper Cook Inlet was written by Kirschner and Lyon (1973). Boss, Lennon, and Wilson (1976) described the geology of the Middle Ground Shoal oil field, located about 25 km northwest of Kenai. A geologic map was compiled for Cook Inlet and the surrounding area (Magoon, Adkison, and Egbert, 1976). The subsurface geology of upper Cook Inlet and the Kenai lowland is generally known from exploratory wells. Three of nine exploratory wells on the Iniskin Peninsula were drilled recently enough for information to be available (Detterman and Hartsock, 1966; Blasko, 1976).

Until recently, little if any geologic information that pertained directly to offshore lower Cook Inlet was publicly available. Much of the onshore geology, however, can be extended offshore using geological and geophysical techniques. To accomplish this extension, the geology of areas around Cape Douglas and Seldovia was mapped (Magoon, Adkison, and Egbert, 1976), and offshore seismic data were collected.

Under contract to the U.S. Geological Survey, Western Geophysical, Inc. collected 480 km of 36-fold seismic data in the first week of July 1975 (Fisher, 1976). A 2,700-m streamer with 72 arrays of hydrophones, a rectangular array of six Aquapulse guns (propane, oxygen, and air exploded inside a rubber boot), and DDS-888 digital instruments made up the seismic system. Seismic records were sampled at a two-millisecond rate for at least six seconds. Shotpoints were located using a combined Raydist-RPS navigational system with a potential positional accuracy of 15 m. Swift tidal currents, current-borne debris, and crab pots caused delays during field operations. The seismic data were processed by Petty-Ray Geophysical, Inc. Most of the problems encountered during processing stemmed from strong water-bottom and peg-leg multiples that interfered with both accurate velocity analysis and efficient deconvolution.

Tracklines 751 through 755 (fig. 2) were planned to be perpendicular to the expected trend of offshore structural axes. Lines 756 and 757 completed the grid, which has a line spacing of about 30 km. The northernmost line, 751, is a tie line between the proposed locations of the Phillips Petroleum Co. Chinitna A-1 well and the Shell Oil Co. Kachemak 1 well. The nominal streamer towing depth, 12 m, required that line 751 be terminated on the northwest 2 km from the Phillips Petroleum Co. well. A phalanx of crab pots stopped line 751 about 1 km northwest of the Shell Oil Co. well.

Line 752 provides an offshore cross section of the structure between the Iniskin and Kenai Peninsulas. The southern seismic profiles, lines 754 and 755, allow the geology of the Kamishak Hills-Cape Douglas area to be projected offshore.

In the discussion that follows, background data on the geologic framework of lower Cook Inlet are presented in this order: (1) stratigraphy, (2) interpreted seismic horizons, and (3) velocity data. These data are then merged to show basin configuration and structural trends. The concluding discussion reconstructs the geologic history and explores the petroleum potential of this province.

GEOLOGY

Geologic Setting

Rocks of lower Cook Inlet are part of a belt of Mesozoic and Tertiary sedimentary rocks that extend northeastward into upper Cook Inlet and southwestward down the Alaska Peninsula and Shelikof Strait. Along this belt, Mesozoic rocks may exceed 12,000 m in thickness; continental Tertiary rocks are as much as 7,000 m thick (fig. 3). Four major northeast-trending geologic features that flank Cook Inlet are the Alaska-Aleutian Range batholith and the Bruin Bay fault on the northwest side, and the Seldovia fault and the undifferentiated Mesozoic terrane on the southeast side (fig. 2).

The Alaska-Aleutian Range batholith is exposed in the northwest part of this area; it is mostly quartz diorite. Although there are younger plutons, the bulk of the batholith was emplaced between about 176 and 154 m.y. ago (Reed and Lanphere, 1969, 1972, 1973a, b).

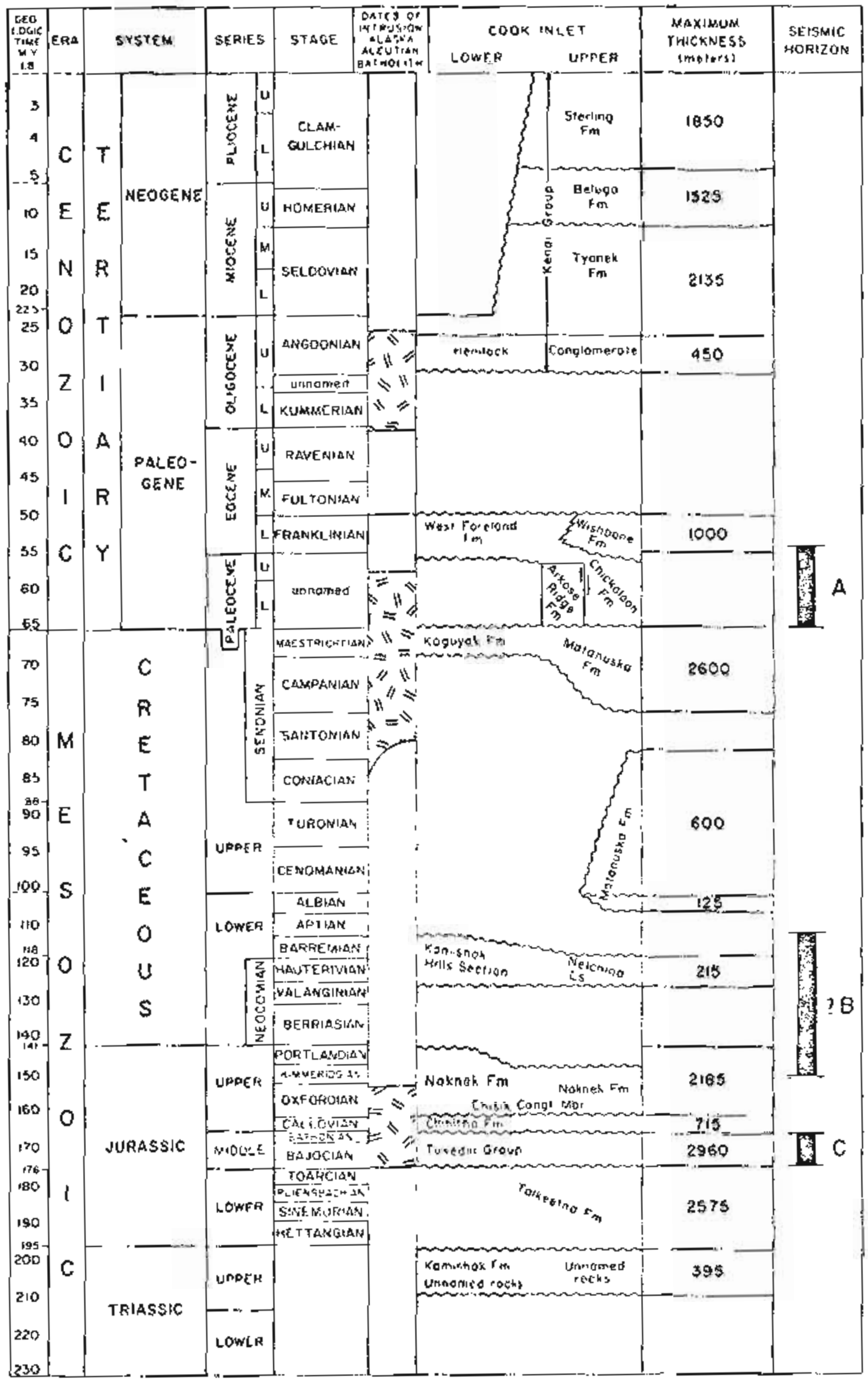

Fig. 3--Stratigraphic column of Cook Inlet basin showing thickness of stratigraphic units and the probable range in age of the three seismic reflectors. Geologic time-table modified after van Eysinga, 1975; Tertiary stages from Wolfe, 1977, in press.

The Bruin Bay fault, a high-angle reverse fault, can be traced along the northwest side of the lower Cook Inlet basin for 215 km. In Kamishak Bay the fault plane dips 60° northwest. Just north of Chinitna Bay, stratigraphic throw across the fault is as much as 3 km; granitic rocks and rocks older than Middle Jurassic on the west are juxtaposed against sedimentary strata younger than Early Jurassic on the east (Detterman and Hartsock, 1966).

A fault seen at the surface near Seldovia is interpreted to extend to the northeast through Homer and beneath the Kenai lowland, and to the southwest through the Barren Islands. This fault is designated the Seldovia fault. In the Kenai lowland the fault is overlapped by Tertiary sedimentary rocks, but in the Seldovia area, it separates Mesozoic shelf deposits on the west from Mesozoic flysch deposits on the east. Associated with the Seldovia fault is a glaucophane-bearing rock that was first recognized by Martin, Johnson, and Grant (1915). Forbes and Lanphere (1973) described this rock as a blueschist facies of Late Triassic or Early Jurassic age.

The Mesozoic melange and flysch deposits on the east side of the Seldovia fault are represented by the McHugh Complex and by rocks questionably assigned to the Valdez Group. The McHugh Complex includes metasedimentary and metavolcanic rocks in the Chugach Mountains near Anchorage (Clark, 1972a, 1973) and on the Kenai Peninsula (Martin and others, 1915). The age of the McHugh is uncertain but is considered to be Late Jurassic and (or) Cretaceous by Clark (1972a, 1973). Moore and Connelly (1976, 1977) consider the McHugh to be part of a tectonic melange emplaced as a subduction complex in late Mesozoic time, Plafker, Jones, and Pessagno (1977) consider the McHugh to be an Early Cretaceous and possibly older melange emplaced with the Valdez(?) Group before latest Cretaceous time. The Valdez(?) Group consists of highly deformed and metamorphosed sandstone, siltstone, shale, and some conglomerate (Clark, 1972a). From fossils the age of part of this unit is Maestrichtian (Jones and Clark, 1973).

Rocks at least as old as Triassic occur with these major geologic features. These rocks are discussed below from oldest to youngest. Unconformities or abrupt lithologic changes that may create significant seismic reflections are also mentioned.

Stratigraphy

Upper Triassic rocks.--On the northwest side of lower Cook Inlet, rocks of Late Triassic age occur in scattered outcrops on both sides of the Bruin Bay fault from Kamishak Bay (R. L. Detterman and B. L. Reed, unpub. data) to Tuxedni Bay (Detterman and Hartsock, 1966). At the head of Tuxedni Bay, Upper Triassic rocks are as much as 395 m thick and consist of metamorphosed limestone, tuff, chert, sandstone, shale, and basaltic lava flows (Detterman and Hartsock, 1966). On the southeast side of lower Cook Inlet, Upper Triassic rocks exposed west of the Seldovia fault consist of fossiliferous marine limestone and fine-grained tuffs (Martin and others, 1915). Upper Triassic rocks are also exposed on the westernmost island of the Barren Islands.

Lower Jurassic rocks.--Rocks of Early Jurassic age are exposed on both sides of the inlet. On the northwest side, the outcrop belt is as much as 15 km wide and is cut in several places by the Bruin Bay fault. South of Tuxedni Bay, Lower Jurassic rocks dip generally to the 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 thick. Near Seldovia, Lower Jurassic strata consist of volcanic tuff, agglomerate, and breccia and interbedded marine sandstone, shale, and limestone (Martin and others, 1915; Forbes and Lanphere, 1973). Using the 30° northwest dip of the strata, Martin, Johnson, Grant (1915) estimated the thickness of the rocks to be 300 m. On the basis of lithology and age, the rocks near Seldovia are assigned to the Talkeetna Formation (Magoon, Adkison, and Egbert, 1976). Two wells in Redoubt Bay and two on the Iniskin Peninsula penetrate the Talkeetna Formation (fig. 2; table 1). The presence of this formation on both sides of lower Cook Inlet and in some offshore areas (Boss and others, 1976) suggests that the formation is continuous beneath the inlet.

The Talkeetna Formation is poorly bedded and made up of rock fragments of different sizes, shapes, and compositions. Its heterogeneity suggests that the unit may be a poor transmitter of seismic energy, but its upper contact may be a good reflector.

Middle and Upper Jurassic rocks.--Unconformably overlying the Lower Jurassic volcaniclastic rocks are the thick Middle and Upper Jurassic marine sedimentary rocks. These rocks are exposed only on the west side of lower Cook Inlet, east of the Bruin Bay fault, but

Well No.	Company	Well Name and Number	Total Depth Location Sec.	T.	R.	Deepest Rock Unit	Fig. 2 T.D.*	Fig. 9 Top Jtk*	Fig. 11 Base Tertiary*
1	Marathon Oil Co.	Beaver Creek Unit No. 4	34	7N	10W	Twf	4,808		X
2	Marathon Oil Co.	Beaver Creek No. 1	34	7N	10W		2,738		
3	Pan American Petroleum Corp.	Redoubt Shoal State 22064 No. 1	26	7N	14W	Twf	4,367		X
4	Tenneco Oil Co.	State Lease 36465 No. 1	34	7N	14W	Twf	4,237		X
5	Standard Oil Co. of Ca.	Kustatan Unit No. 43-30	30	7N	15W	Jtk	3,218	3,163	3,163
6	Marathon Oil Co.	Beaver Creek No. 2	3	6N	10W	Twt	4,737		X
7	Union Oil Co. of Ca.	Sterling Unit No. 23-15	15	5N	10W	Twf	4,453		
8	Union Oil Co. of Ca.	Kenai Unit No. 41-2	2	5N	11W	Tks	1,730		
9	Union Oil Co. of Ca.	Kenai Unit No. 13-8	8	5N	11W	Tkb	1,667		
10	Hunt Oil Co.	Kalgin Island State No. 1	22	5N	15W	Jurassic	4,410	X	4,286
11	Atlantic Richfield Co.	Drift River State No. 1	11	5N	17W	Jtk	1,631	1,509	1,509
12	Union Oil Co. of Ca.	Kenai Unit No. 14-6	6	4N	11W	Twf	4,558		X
13	Union Oil Co. of Ca.	Kenai Deep Unit No. 1	6	4N	11W	Tkh	2,989		
14	Union Oil Co. of Ca.	Kenai Unit Hemlock No. 1	8	4N	11W	Twf	4,457		X
15	Union Oil Co. of Ca.	Kenai Unit No. 41-19	19	4N	11W		1,695		
16	Union Oil Co. of Ca.	Cohoe No. 1	8	3N	11W	Twf	4,705		X
17	Mesa Petroleum Co.	Kasilof State Unit No. 2	19	3N	12W	Tkt	2,415		
18	Union Oil Co. of Ca.	Kasilof State No. 2	29	3N	12W	Tks	2,009		
19	Union Oil Co. of Ca.	Kasilof State No. 1	29	3N	12W	Twf	4,885		X
20	Union Oil Co. of Ca.	Kasilof Unit No. 1	30	3N	12W	Tkb	1,659		
21	Standard Oil Co. of Ca.	Cape Kasilof No. 1	25	3N	13W		4,250		
22	Hunt Oil Co.	Old Mans Bay State No. 1	2	3N	16W	Jurassic	3,794	X	3,533
23	Standard Oil Co. of Ca.	Falls Creek Unit No. 1	1	1N	13W	Twf	4,121		X
24	Marathon Oil Co.	Clam Gulch State 29715 No. 1	3	1N	13W	Twf	4,536		X
25	Standard Oil Co. of Ca.	Falls Creek Unit No. 2	22	1N	13W	Tkt	2,459		
26	Pan American Petroleum Corp.	USA Edna Mae Walker No. 1	35	1S	12W	Twf	4,602		X
27	Union Oil Co. of Ca.	Ninilchik No. 1	6	1S	13W	Km	4,504		3,821
28	Mobil Oil Corp.	Ninilchik Unit No. 1	24	1S	14W	Km	3,805		3,600
29	Standard Oil Co. of Ca.	Deep Creek No. 1	15	2S	13W	Km	4,140		3,998
30	Superior Oil Co.	Happy Valley Unit No. 31-22	22	2S	13W	Km	3,939		3,874
31	Pennzoil Co.	Starichkof State Unit No. 1	22	3S	15W	Twt	2,653		X
32	Pennzoil Co.	Starichkof State No. 1	33	3S	15W	Km	3,671		2,654
33	Standard Oil Co. of Ca.	Anchor River No. 1	29	4S	11W	Mz	1,646		1,593
34	Gulf Oil Corp.	South Caribou Hills Unit No. 1	24	4S	12W	Twf	2,491		X
35	Standard Oil Co. of Ca.	North Fork Unit No. 11-4	4	4S	13W	Km	3,459		3,347
36	Standard Oil Co. of Ca.	North Fork Unit No. 41-35	35	4S	14W	Jurassic	3,667	X	3,177
37	Standard Oil Co. of Ca.	Anchor Point Unit No. 1	10	5S	15W	Cretaceous	4,404	X	2,659
38	Iniskin Bay Association	IBA No. 1	8	5S	23W	Jt	2,598	X	0
39	Iniskin Unit Operators	Beal No. 1	17	5S	23W	Jtk	2,848	2,660	0
40	Alaska Consolidated Oil Co.	Antonio Zappa No. 1	18	5S	23W	Jtk	3,278	2,815	0
41	Halbouty Alaska Oil Co.	Fritz Creek No. 1	4	6S	12W	Mz	1,109		1,029
42	Texaco, Inc.	Coal Bay State 17612 No. 1	8	6S	12W	Mz	1,208		1,201
43	Occidental Petroleum Corp.	South Diamond Gulch Unit No. 1	6	6S	14W	Tkh	3,099		X

X Significant well control for respective map.

* Datum is sea level. Depth is in meters.

Table 1--Well data.

they have been penetrated by two wells located on Kalgin Island, by three wells on the Iniskin Peninsula, and probably by one well on the Kenai lowland. Thus, these rocks are probably continuous under the inlet.

Middle and Upper Jurassic rocks are divided, in upward order, into the Tuxedni Group, the Chinitna Formation, and the Naknek Formation. The Tuxedni Group, of Middle and Late Jurassic age, consists of alternating beds of fossiliferous graywacke, sandstone, and siltstone. In the Iniskin-Tuxedni region the Tuxedni is as much as 2,960 m thick (Detterman and Hartsock, 1966). The Chinitna Formation, of Late Jurassic age, unconformably overlies the Tuxedni Group. The Chinitna is mostly dark-gray marine siltstone with large concretions and is as much as 715 m thick in the Iniskin-Tuxedni area (Detterman and Hartsock, 1966). The Naknek Formation, of Late Jurassic age, unconformably overlies the Chinitna Formation and has greater areal exposure than the underlying rocks; it crops out from the Kamishak Hills to Tuxedni Bay. In the Iniskin-Tuxedni region the Naknek is as much as 1,435 m thick (Detterman and Hartsock, 1966) and is composed of fossiliferous marine conglomerate, sandstone, and siltstone. The part of the Naknek exposed along the coast in Kamishak Bay is approximately 750 m thick (Magoon, Adkison, and Egbert 1976) and is younger than the part of the Naknek exposed in the Iniskin-Tuxedni region (Imlay and Detterman, 1973). The combined thickness of the two parts of the Naknek in these two areas exceeds 2,185 m (fig. 3).

Unconformable contacts in the Middle and Upper Jurassic strata may be good seismic reflectors.

Lower Cretaceous rocks.--In the lower Cook Inlet area, 215 m of Lower Cretaceous rock unconformably overlies Upper Jurassic strata in the Kamishak Hills (Jones and Detterman, 1966; Jones, 1973; Magoon, Adkison, and others, 1976). The beds consist of siltstone and sandstone that are rich in *Inoceramus* fragments. A subsurface occurrence of Lower Cretaceous rocks is depicted by Boss, Lennon, and Wilson (1976) in a cross section through Swanson River oil field, located northeast of Kenai. Lower Cretaceous strata are probably penetrated by a well at Anchor Point and thus may be present in a large area of offshore lower Cook Inlet. This unit is bounded by unconformities that may be good seismic reflectors.

Upper Cretaceous rocks.--Upper Cretaceous rocks in the Cook Inlet basin south of the latitude of Seldovia are assigned to the Kaguyak Formation; north of Seldovia, they are assigned to the Matanuska Formation. The Kaguyak Formation (Keller and Reiser, 1959) crops out in the Kamishak Hills-Cape Douglas area where 1,385 m of rock unconformably overlies Lower Cretaceous rocks. In upward succession this formation consists of shallow-marine sandstone, bioturbated gray siltstone, and turbidite sandstone and siltstone. On the Kenai Lowland many wells penetrate the Matanuska Formation (table 1). Kirschner and Lyon (1973) outline the subcrop of Upper Cretaceous strata from the Matanuska Valley to Kachemak Bay. The structural cross section of Boss, Lennon, and Wilson (1976) depicts the subsurface distribution of Upper Cretaceous rocks east of Middle Ground Shoal; the authors also indicate that these rocks outcrop on the northwest side of Cook Inlet. The Matanuska Formation outcrops in the Matanuska Valley northeast of Anchorage (fig. 3; Grantz, 1960, 1964; Grantz and Jones, 1960; Jones, 1964, 1967; Jones and Grantz, 1967). The widespread distribution of Upper Cretaceous rocks around the Cook Inlet basin strongly suggests that these rocks are present in the subsurface in lower Cook Inlet.

Tertiary rocks.--Tertiary rocks of lower Cook Inlet are all nonmarine and consist of the West Foreland Formation and the overlying Kenai Group. The conglomeratic West Foreland Formation, of late Paleocene and early Eocene age, includes much tuffaceous and volcaniclastic material. In outcrop, this unit unconformably overlies progressively younger rocks from north to south along the northwest side of lower Cook Inlet: west of Redoubt Bay it overlies Lower Jurassic rocks; north of Chinitna Bay it overlies Upper Jurassic rocks; near Cape Douglas it overlies Upper Cretaceous rocks and attains a maximum thickness of 1,000 m. The West Foreland Formation is penetrated by wells on the Kenai lowland (table 1).

The Kenai Group, of Oligocene to Pliocene age, is composed of conglomerate, sandstone, siltstone, and coal. Exposures are found west of Redoubt Bay, near Cape Douglas, and overlapping the Seldovia fault in the Kenai lowland and near Seldovia. Tertiary rocks of unknown age occur on the Barren Islands (J. S. Kelley, oral commun., 1975). Well data indicate that the total Tertiary (7,000 m) and

Quaternary sequence is more than 7,600 m thick north of Kenai (Hartman and others, 1972), whereas outcrop data obtained near Cape Douglas show that Tertiary rocks are about 1,850 m thick. The widespread unconformity between Mesozoic and Tertiary rocks is probably a good seismic reflector.

SEISMIC DATA

Interpreted Horizons

Three areawide reflecting horizons were correlated throughout the seismic grid. These horizons, labeled A, B, and C, are shown in a northwest-trending cross section (fig. 4). The cross section is seismic line 755, located just north of Cape Douglas, and is included as an example of the best data from this survey.

The quality of seismic data acquired in lower Cook Inlet is relatively poor primarily because a very reflective water bottom produces bothersome multiples. In places, the third or fourth water-bottom multiple is strong enough to interfere with interpretation. The nearly horizontal events in the first second of record (fig. 4) that are especially noticeable southeastward from shotpoint (SP) 600 are water-bottom multiples. Above the A horizon, shallowest of the three interpreted, primary reflections are conformable with the A horizon.

The A horizon dips generally to the southeast from its termination at the seafloor. Like the sea bottom, this horizon is a strong reflector that produces troublesome multiples. Between SP 600 and SP 1000, events below the A horizon that dip to the southeast are water-layer multiples of the A horizon. At about 2.2 s, below SP 900,

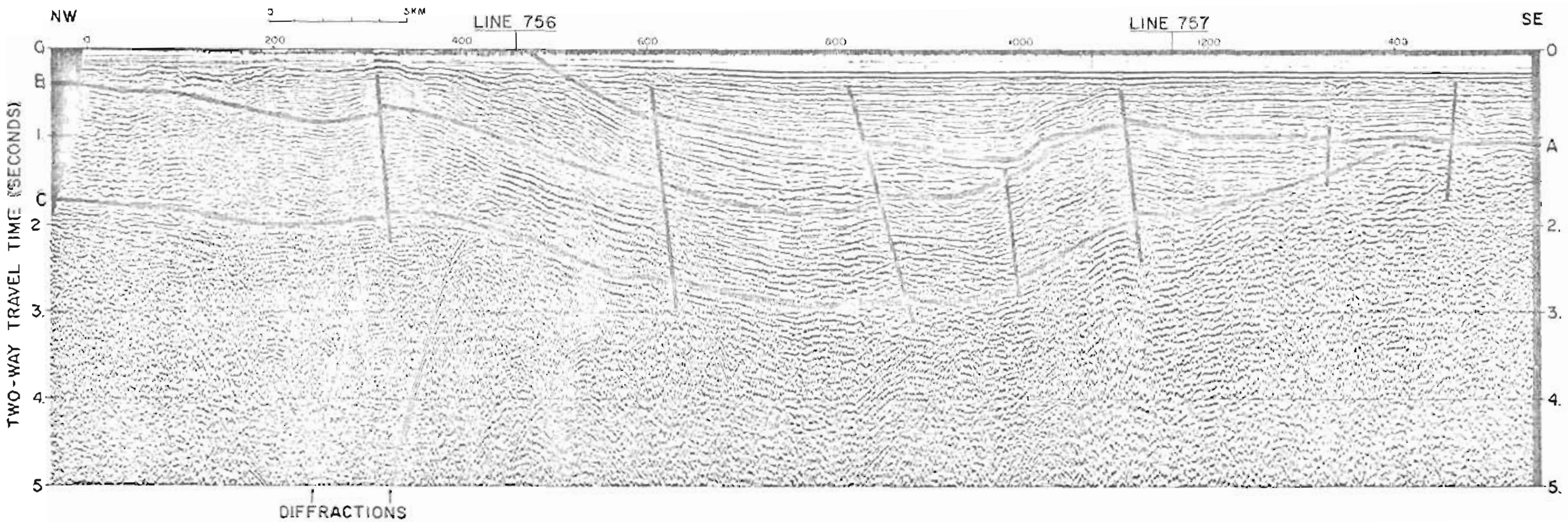

Fig. 4--Seismic line 755, just north of Cape Douglas (fig. 2) with the A, B, and C horizons interpreted. This profile, some of the highest quality seismic data obtained in this survey, shows some of the problems of interpreting seismic data from lower Cook Inlet.

one multiple of the A horizon appears to have the following raypath: seismic source, A horizon, sea surface, A horizon, hydrophone. About 0.2 s later, the first water-layer multiple of this multiple occurs. These examples show the variety and the strength of multiples that make the data from lower Cook Inlet difficult to interpret.

In figure 4, reflectors in the interval between the A and B horizons are conformable with the B horizon. This interval thins toward the southeast up to the truncation of the B horizon by the A horizon. The apparent rapid thickening of this interval northwest of SP 600 may be partly due to the effects of low velocities in strata in the first 0.5 s of traveltime. Angular discordance of strata across the B horizon is evident east of Augustine Island; elsewhere, the strata appear conformable.

The C horizon is the deepest reflector that can be correlated throughout the lower Cook Inlet area, but correlation is difficult in some places because the reflection is fragmented. Especially south of a line between Augustine Island and Seldovia, the C horizon forms the acoustic basement. North of this line, faint reflections are locally returned from what appears to be a layered sequence below the C horizon. Therefore, depth to the C horizon probably represents a minimum thickness of sedimentary rock in lower Cook Inlet. Except for the localized occurrences of deep reflections, no information is returned from below the C horizon, and the structure of the underlying strata cannot be determined.

The diffracted events in the northwest part of line 755 (fig. 4) are examples of such events that occur throughout the seismic grid. Their origin is not known, but they may result from near-bottom features such as channels or glacial erratics.

Velocity Interpretation

Seismic data are presented in relation to two-way traveltime, and traveltime must be converted to depth. The needed velocity information was obtained from the stacking of common-depth-point (CDP) seismic records. Stacking velocities were converted to interval velocities by use of the Dix formula (Dix, 1955). Horizontal and planar reflectors are required for correct application of the Dix formula, and these requirements are violated to some degree nearly everywhere. In addition, strong water-layer reverberations made accurate velocity computation difficult. For these two reasons, the computed interval velocities are not suitable for detailed stratigraphic interpretation or correlation but can be used for approximate conversion of seismic traveltime to depth.

Interval velocity curves were computed at 21 locations scattered throughout the seismic grid, and in places, considerable variation was found between adjacent curves. The averaging procedure used to extract trends from the velocity data involved first grouping similar curves together. The curves fell into four groups, and the interval velocity curves within each of the four groups were then averaged (fig. 5). The resulting four averaged curves illustrate gross trends in the velocity data; each of the four summarizes velocity information over a rather large geographic area, here called a velocity domain

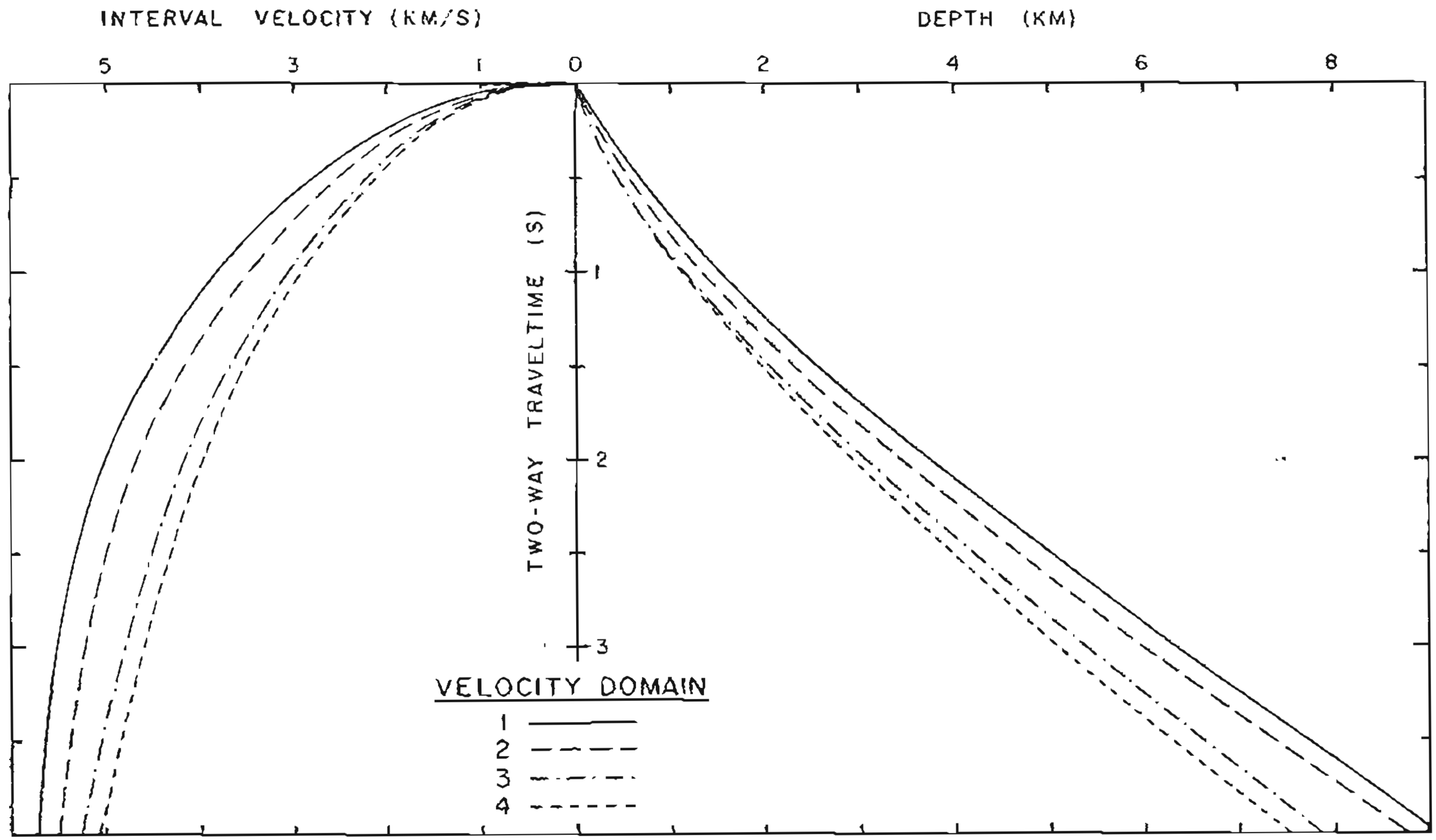

Fig. 5--Averaged interval-velocity and companion time-depth curves computed for each of the velocity domains.

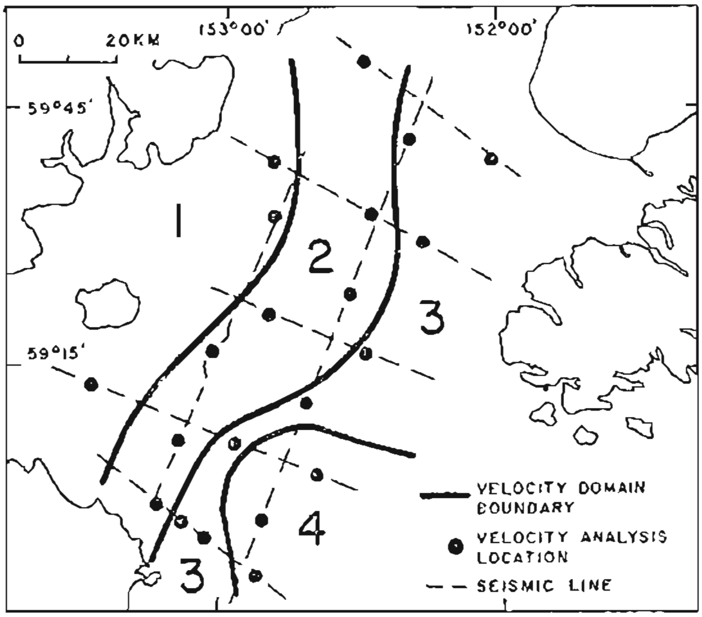

Fig. 6--Velocity domains interpreted from the interval-velocity curves. One velocity and one time-depth curve summarize velocity and depth relations in each domain. Domain one is characterized by the highest velocities, domain four by the lowest. The velocity domains generally parallel the axis of the lower Cook Inlet basin.

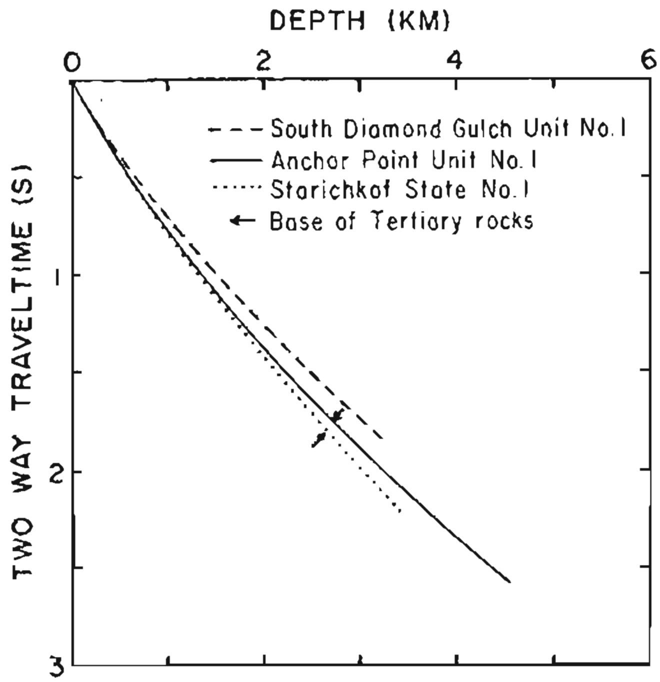

Fig. 7--Time-depth curves computed from sonic logs obtained in wells near the south end of the Kenai lowland. The curve from the Anchor Point well is used to convert two-way time to the A horizon to depth.

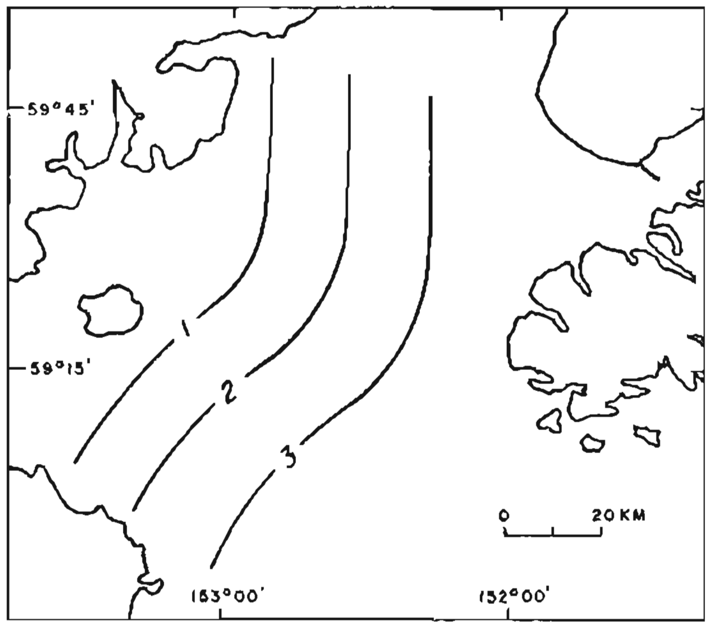

Fig. 8--Placement of velocity functions used to approximate the velocity gradient across lower Cook Inlet. This gradient is used to convert two-way traveltime to the C horizon to depth. Numbers refer to the velocity domains.

(fig. 6). Time-depth curves were computed from the four averaged velocity curves. Since seismic profiles in this paper are presented with two-way traveltime as the vertical dimension, an idea of implied thickness or depth can be obtained by using the geographically appropriate time-depth curve.

Velocity domain one (fig. 6) is characterized by the highest interval velocities of the four domains. The northeastward prolongation of domain one can be explained geologically. The large embayment surrounding Augustine Island is rimmed by Middle and Upper Jurassic rocks (fig. 2). The rocks on the Iniskin Peninsula and around Kamishak Bay generally dip southeast into the inlet and are probably at a shallow depth offshore. The northwest end of line 755 (fig. 4) shows that relatively old, presumably high-velocity strata are at or near the seafloor and dip southeast in Kamishak Bay. The northwest end of line 754 shows the same relation of beds as line 755 and, in addition, has a velocity curve that belongs to domain one. The rocks in Kamishak Bay, therefore, seem to have a general northeast strike, and the extension of domain one to the northeast from line 755 is along the strike.

Velocity domain two is characterized by intermediate velocities. The decrease in velocities from domain one to domain two is geologically related to the presence of rocks as young as Tertiary near Cape Douglas and north of Chinitna Bay. The high-velocity rocks of domain one are buried progressively deeper to the southeast by younger, lower velocity rocks as shown on seismic line 755 (fig. 4). The boundaries of domain two emphasize the general zonation of the velocity domains subparallel to the axis of the Cook Inlet basin. Near the Iniskin Peninsula, domain two trends north; it then curves around, finally trending northeast near Cape Douglas. The apex of the curve lies near a line connecting Augustine Island and Seldovia.

Velocity domains three and four are characterized by the lowest velocities. On line 755, these domains coincide with the thickest accumulation of sedimentary rock above the A horizon. The high reflectivity of the A horizon may result from the contrast between the low seismic velocity in the strata above the A horizon and the high velocity in the strata of domains one and two below it. The high-velocity strata are progressively truncated southeastward by the A horizon in the southeast half of line 755. The velocity curve of domain four should increase markedly below the A horizon, but the velocity analyses show consistently slow velocities below this horizon. Triassic and Lower Jurassic rocks are exposed west of Seldovia and on the Barren Islands, so high-velocity domains are expected to reappear in these areas, but no velocity data are available to confirm their reappearance.

An estimate of seismic velocities in Tertiary rocks can be obtained from other types of data. Sonic logs from wells on and near the Kenai lowland are publicly available. Conversion of depth to two-way traveltime was done from logs in three wells: (1) Starichkof State No. 1 (32 on table 1 and fig. 2), (2) Anchor Point Unit No. 1 (No. 37), and (3) South Diamond Gulch Unit No. 1 (No. 43). Visual comparison of the time-depth curves from the three wells (fig. 7) shows that the curves are close together and that there is a velocity gradient from low velocities in the Starichkof well to high velocities in the South Diamond Gulch well. The curve from the Anchor Point well is an average of the three curves and is used to convert time to depth in Tertiary rocks.

Plots of the time-depth data from the Anchor Point well suggest a curve of the form $z=at^2+bt$. The curve was fit using a least-squared-error routine. The results of the fit are: $z=0.29t^2+1.17t$, where t is two-way traveltime, in seconds, and z is one-way depth, in kilometers. Comparison of the time-depth curves obtained from the Anchor Point well and in velocity domain three show that a greater depth is obtained from well data than from seismic velocities.

BASIN CONFIGURATION

Deep Basin Form

Velocity curves (fig. 5) from domains one, two and three were applied to the areas delineated in figure 6, creating a velocity gradient used to convert two-way traveltime to the C horizon to depth (fig. 8). Depths to the C horizon and the top of the Talkeetna Formation were contoured to show the present-day configuration of Mesozoic rocks in lower Cook Inlet (fig. 9).

Depth to the top of the Lower Jurassic Talkeetna Formation was contoured partly because it is economic basement for petroleum. It also is easily identified in exposures and in wells; the Talkeetna is a red or green volcaniclastic rock, whereas the overlying Tuxedni

Group is composed of siltstone and sandstone. The Talkeetna Formation crops out on both sides of lower Cook Inlet, and on both sides the strata dip toward the inlet. The zero line on the northwest side is the exposed contact of the Talkeetna with the overlying Middle and Upper Jurassic Tuxedni Group or Tertiary rocks. In the Seldovia area the top of the Lower Jurassic is not exposed onshore but presumably exists offshore to the west. Of four wells near Kalgin Island (fig. 9), the Talkeetna Formation is present in the western two; the eastern two penetrate only the Middle Jurassic. Two of three wells on the Iniskin Peninsula pierce the top of the Talkeetna Formation; the third stops just above the base of the Tuxedni Group. Outcrop data and well control indicate that the top of the Talkeetna Formation on the northwest flank of the basin trends northeast and dips southeast. On the Kenai lowland, Tertiary rocks truncate and unconformably overlie Mesozoic rocks. Two wells near Anchor Point penetrate the Mesozoic (fig. 9). Rocks of Cretaceous age are present in the lower third of the well at Anchor Point (No. 37, Anchor Point Unit No. 1). The other well (No. 36, Northfork Unit 41-35), the shallower of the two, was drilled into Middle(?) and Upper Jurassic rocks; the Talkeetna Formation was not penetrated. From the relations in these wells a pattern is suggested: the farther east the well, the older the rock subjacent to the Tertiary strata. Hence, the truncated top of the Talkeetna Formation should lie some distance to the east of these wells.

Without a well located on a seismic line, it is difficult to

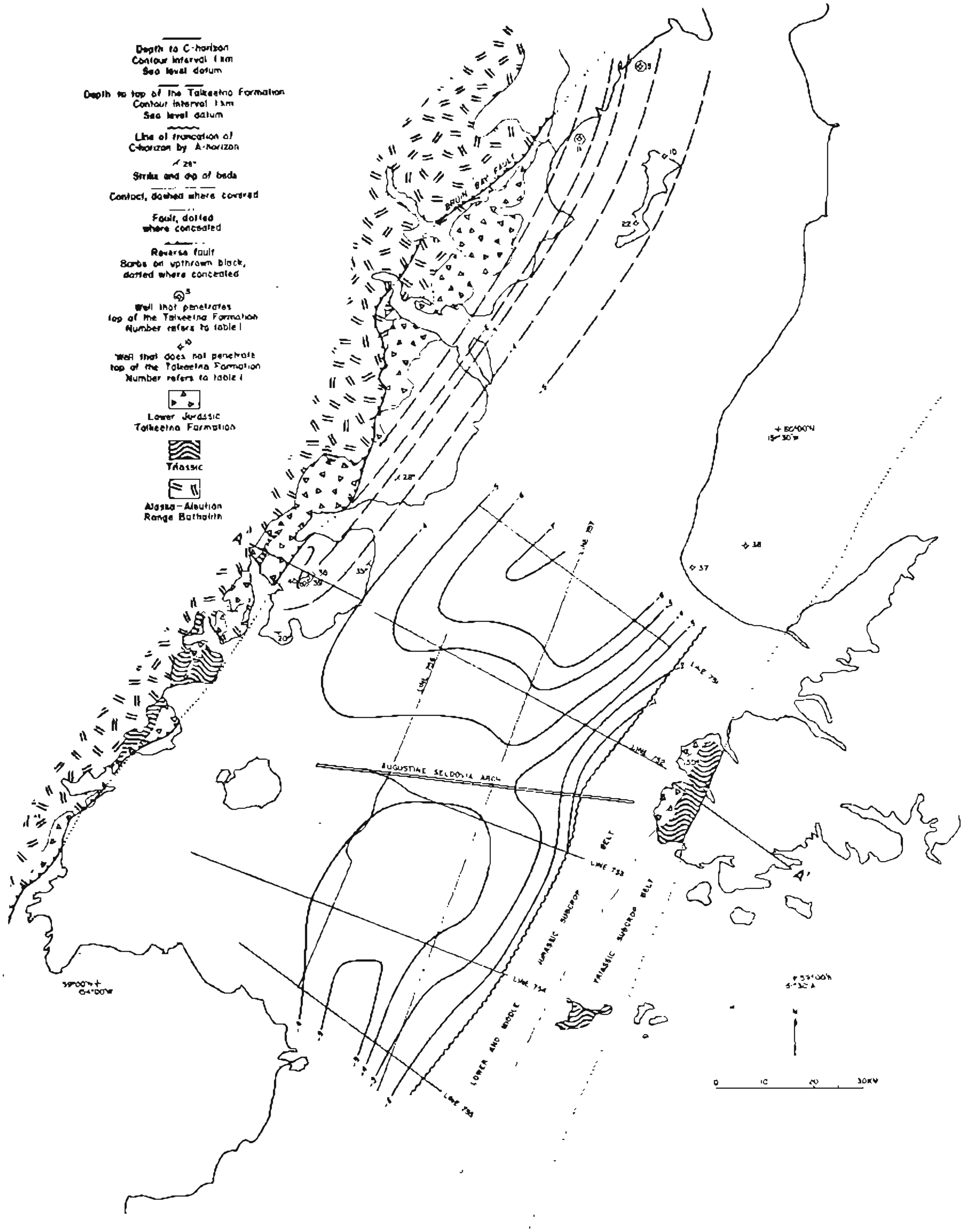

Fig. 9--Structure contours showing present-day geometry of Mesozoic strata. Depth to C horizon (Middle Jurassic) shown by solid lines, depth to the Talkeetna Formation by dashed lines.

determine the geologic interface that correlates with the C horizon. The critical depth conversion at the northwest end of line 752 is only approximate, because velocity data there are of marginal quality and the velocity curve of domain one is an averaged curve. The C horizon seems to correlate with some part of the Middle Jurassic strata, perhaps near the top of the Tuxedni Group (fig. 3). Truncation of the C horizon along the southeast side of lower Cook Inlet can be projected as a straight line into the Kenai lowland and is found to lie just east of wells numbered 36 and 37 (fig. 9). This relation also suggests that the C horizon represents some part of the Middle Jurassic strata.

The depth contours on the C horizon show a broad transbasin arch between a northeast- and a southwest-plunging syncline. The arch trends S. 80° E. between Augustine Island and the Kenai Peninsula near Seldovia and is called the Augustine-Seldovia arch. The arch becomes broader and flatter toward Augustine Island and may not persist west of the island; the structure is shaped like a megaphone with its broad end pointed west. The arch apparently brings old high-velocity rocks close to the surface and causes the southeastward bulge of the velocity domains (fig. 6).

The Augustine-Seldovia arch divides the area into two oppositely plunging synclines. The northern syncline trends about N. 45° E. In this syncline the greatest depth to the C horizon is about 7 km. South of the arch the other syncline trends S. 35° W. near the crest of the arch. Farther south near Cape Douglas, it trends S. 15° W.

Here the C horizon is buried by about 5 km of sedimentary rock. On the crest of the Augustine-Seldovia arch on line 757, the C horizon is about 3 km deep, and structural relief of the arch at the C horizon is about 2 km , measured from the crest of the arch to the trough of the syncline near Cape Douglas.

The contours on the C horizon show that the east to southeast dips of the Jurassic strata on the east coast of the Iniskin Peninsula continue offshore. A subsidiary syncline outlined in the contours lies about 10 km offshore from the Iniskin Peninsula. Dips on the south coast of the Iniskin Peninsula are nearly south-southeast, indicating that the subsidiary syncline probably extends southwestward between the Iniskin Peninsula and Augustine Island.

A cross section (fig. 10, A-A' on fig. 9) drawn through the Iniskin Peninsula, across the inlet along line 752, and through the Kenai Mountains shows the relation of the C horizon to the Middle Jurassic rocks on the Iniskin Peninsula and the truncation of the C horizon by the A horizon. Reflections from the offshore seismic profile were converted to depth using velocity functions located as shown in figure 10.

The stratigraphic position of the B horizon is either near the base of Lower Cretaceous strata or, more likely, near the base of Upper Cretaceous strata. The cross section shows that the B horizon is more or less conformable with the C horizon and that all units except the Tertiary thin from the Iniskin Peninsula to the Kenai Peninsula.

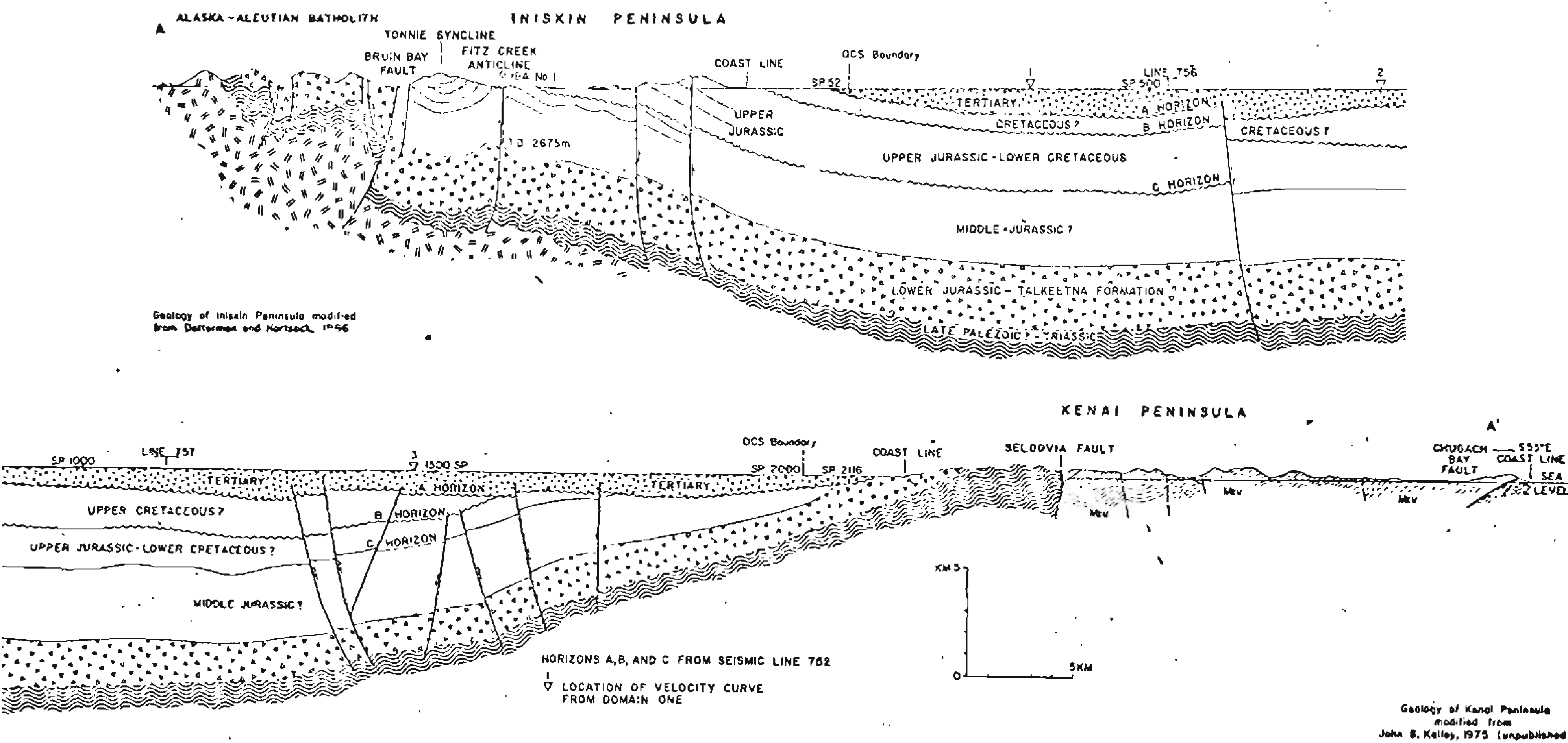

Fig. 10--Structure section from Iniskin Peninsula to Kenai Peninsula. Onshore data is from outcrop and well control, offshore data is from seismic line 752. Location of section is shown on figure 9.

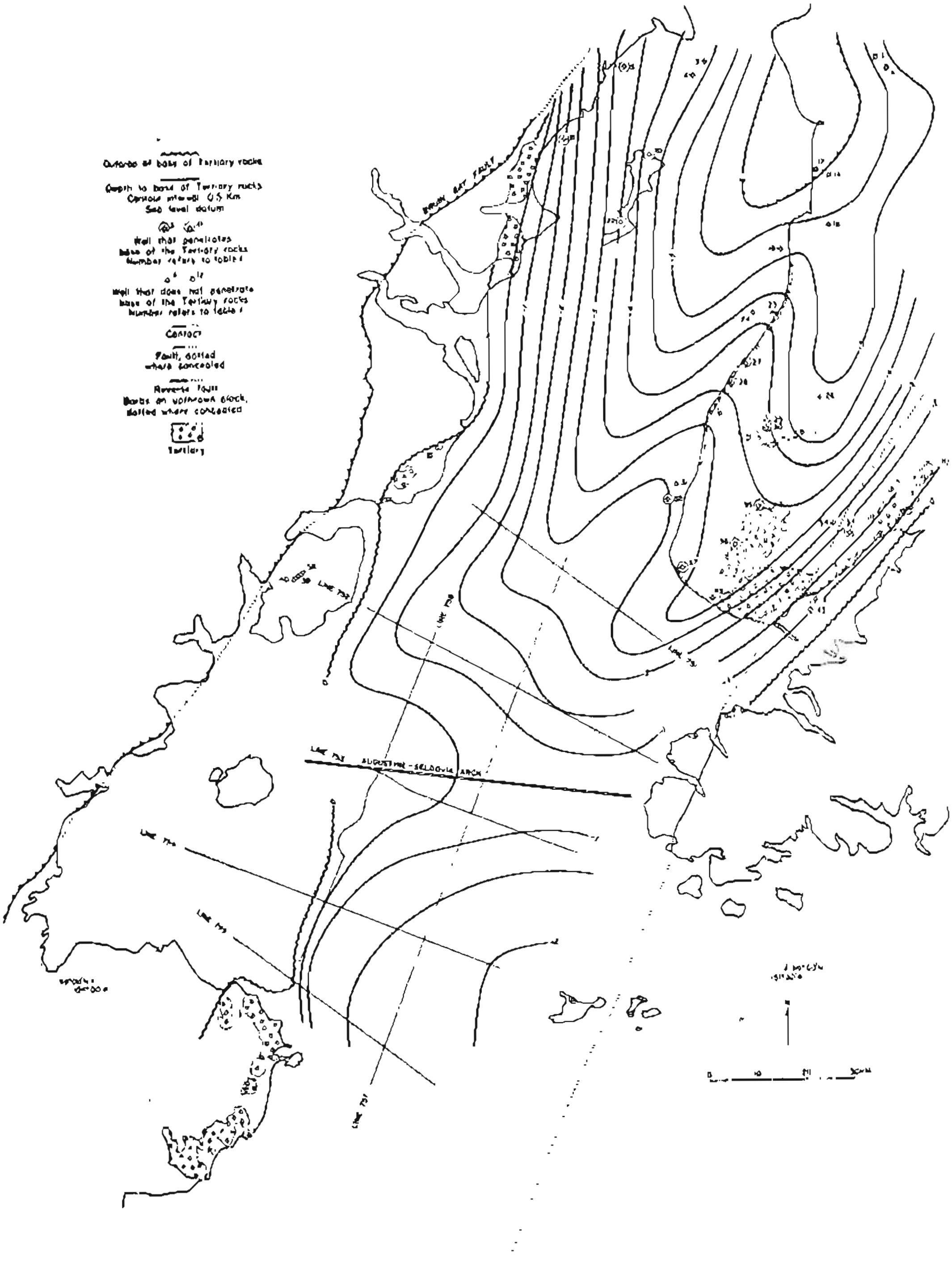

Fig. 11-- Structure contours showing depth to the base of Tertiary strata (A horizon).

Shallow Basin Form

The map showing the shallow basin form (fig. 11) depicts the configuration of the Tertiary rocks in lower Cook Inlet. Two-way traveltime to the A horizon was converted to depth using sonic log data from the Anchor Point Unit No. 1 well. The greatest error in depth conversion probably occurs in the area of velocity domain four.

The geologic interface that correlates with the A horizon is interpreted to be at the base of Tertiary strata. This correlation is based primarily on outcrop data and partly on well control and reflection character or appearance. In the area around Chinitna Bay the outcrop pattern of the A horizon conforms to the outcrop pattern of Tertiary rocks. The Iniskin Peninsula has no exposures of Tertiary rocks, and the A horizon terminates at the seafloor just seaward of the peninsula. On the north side of Chinitna Bay the West Foreland Formation is exposed and contours of the A horizon show that about 0.5 km of strata remain above the A horizon offshore from the exposures. In this area also, the conglomerate of the early Tertiary West Foreland Formation overlies sandstone of the Naknek Formation, resulting in a lithologic contrast that may return a strong reflection. Thus, the projected outcrop of the A horizon seems to be correlative with the exposed base of the Tertiary rocks.

Twenty kilometers northwest of Cape Douglas, lower Tertiary conglomerate unconformably overlies interbedded sandstone and siltstone of the Upper Cretaceous Kaguyak Formation. This lithologic difference could give rise to the acoustic impedance contrast necessary to generate the very strong A horizon reflection. The correlation of the A horizon with the base of the Tertiary rocks in this area is less precise. The contact between the Upper Cretaceous and Tertiary rock units onshore is horizontal and at an elevation of 150 m, but the A horizon on line 755 dips southeast and outcrops under about 60 m of water 12 km east of the onshore exposures. The structural complexities associated with igneous intrusion and faulting in the Mount Douglas area may explain the unconformity pattern, or less likely, the A horizon reflection may come from an interface above the base of the Tertiary rocks.

At the southeast end of line 752, the A horizon rises toward a Tertiary outcrop near Seldovia (fig. 8), where the Kenai Group unconformably overlies Lower Jurassic rocks. North of Seldovia, wells on the Kenai lowland indicate that the base of the Tertiary is about 3 km deep and dips northeast. Fifteen kilometers southwest of Anchor Point the A horizon is about 2.5 km deep. The northeast dip of the A horizon and the distance between the seismic line and the onshore wells makes a correlation of the A horizon with the base of the Tertiary rocks seem reasonable. In summary, inferences made with varying degrees of confidence and based on evidence from localities scattered around lower Cook Inlet support the interpretation that the A horizon is at the base of the Tertiary strata throughout lower Cook Inlet.

The shape of the shallow part of the basin is shown by contours that are based on well control in the north and derived from seismic data in the south (fig. 11). The configuration shown is similar to that shown by Hartman, Pessel, and McGee (1972) and Kirschner and Lyon (1973) for the Cook Inlet Tertiary basin. The zero edge of the Tertiary strata on the northwest side is located using outcrop and well data.

The crest of the Augustine-Seldovia arch at the A horizon coincides with the crest at the C horizon. At the A horizon, the basin north of the arch is divided into two arcuate troughs that trend south and curve around to trend southwest near the arch. The eastern trough dies rather quickly as it approaches the Augustine-Seldovia arch; the western trough coincides with a trough in the C horizon and trends between the Iniskin Peninsula and Augustine Island. Gravity data (Barnes, 1976) show that the western trough continues farther southwest than indicated on either the A or the C horizon. The Tertiary rocks thin between the two troughs. Line 751 shows that the thinning is caused by both anticlinal deformation and reverse faulting. The contour interval used on the map of the C horizon (fig. 9) is too large to depict this anticline clearly, but line 751 shows that it is there. The anticline extends from upper Cook Inlet southwestward, following the coastline of the Kenai lowland, into lower Cook Inlet. South of the Augustine-Seldovia arch, the contours suggest that the A horizon dips generally to the southeast, except where local structures east of Cape Douglas interrupt that dip. The greatest thickness of Tertiary strata in the south is in the area west of the Barren Islands.

Cenozoic strata are more than 6 km thick near Kenai, about 0.6 km thick at the crest of the Augustine-Seldovia arch on line 757, and about 1.7 km thick just east of Cape Douglas. Structural relief across the Augustine-Seldovia arch on the A horizon is at least 1.1 km, measured between the crest of the arch and the area near Cape Douglas.

LOCAL STRUCTURE

Selected offshore structures are shown on four segments of the seismic lines (fig. 12). The shallow (A), intermediate (B), and deep (C) horizons are indicated on all the seismic profiles; in addition, miscellaneous horizons, shown with an "M" prefix, illustrate other reflectors which have not been correlated between profiles. The horizontal distance scales of all the profiles are the same; the vertical time scales are also equal.

The first seismic profile is from line 757 just northeast of the intersection with seismic line 753. The profile transects the Augustine-Seldovia arch and is nearly perpendicular to the axis. The A horizon is more symmetrically folded than the C horizon; at the deep horizon, the arch is asymmetric with steeper dips on the north flank than on the south flank. The southern limb of the arch, within the limits of this profile, barely dips south, but the dip increases south of this segment of the seismic line. Near the crest is a prominent unconformity where the M1 horizon is truncated by the B horizon. A similar unconformity was not seen on the south flank, but, because of gentle dips, it may be lost in seismic noise or reflection overlap. The unconformity is evidence for uplift and erosion in this area during the time the

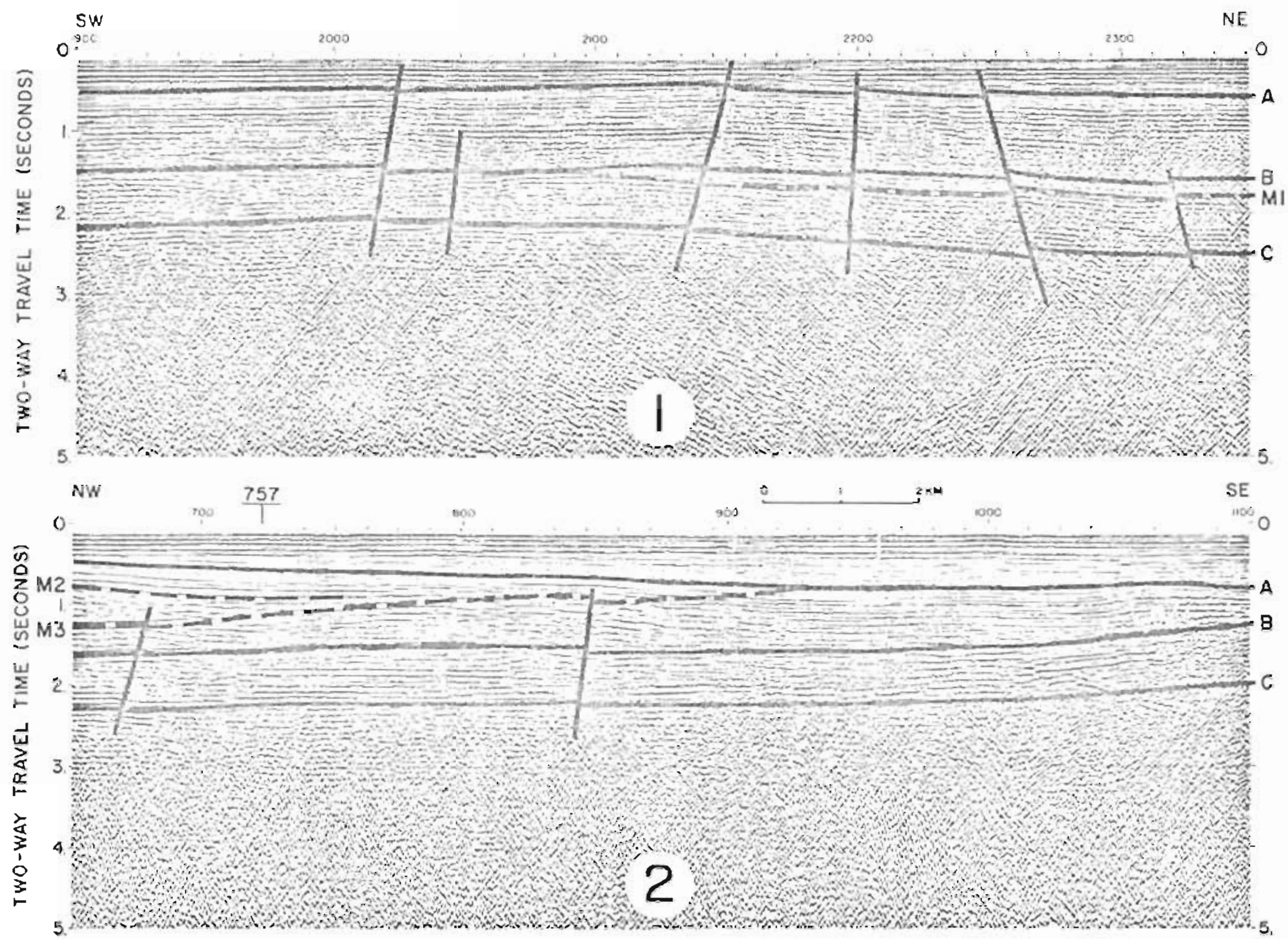

Fig. 12--Selected offshore geologic features in lower Cook Inlet (figure 12 continued).

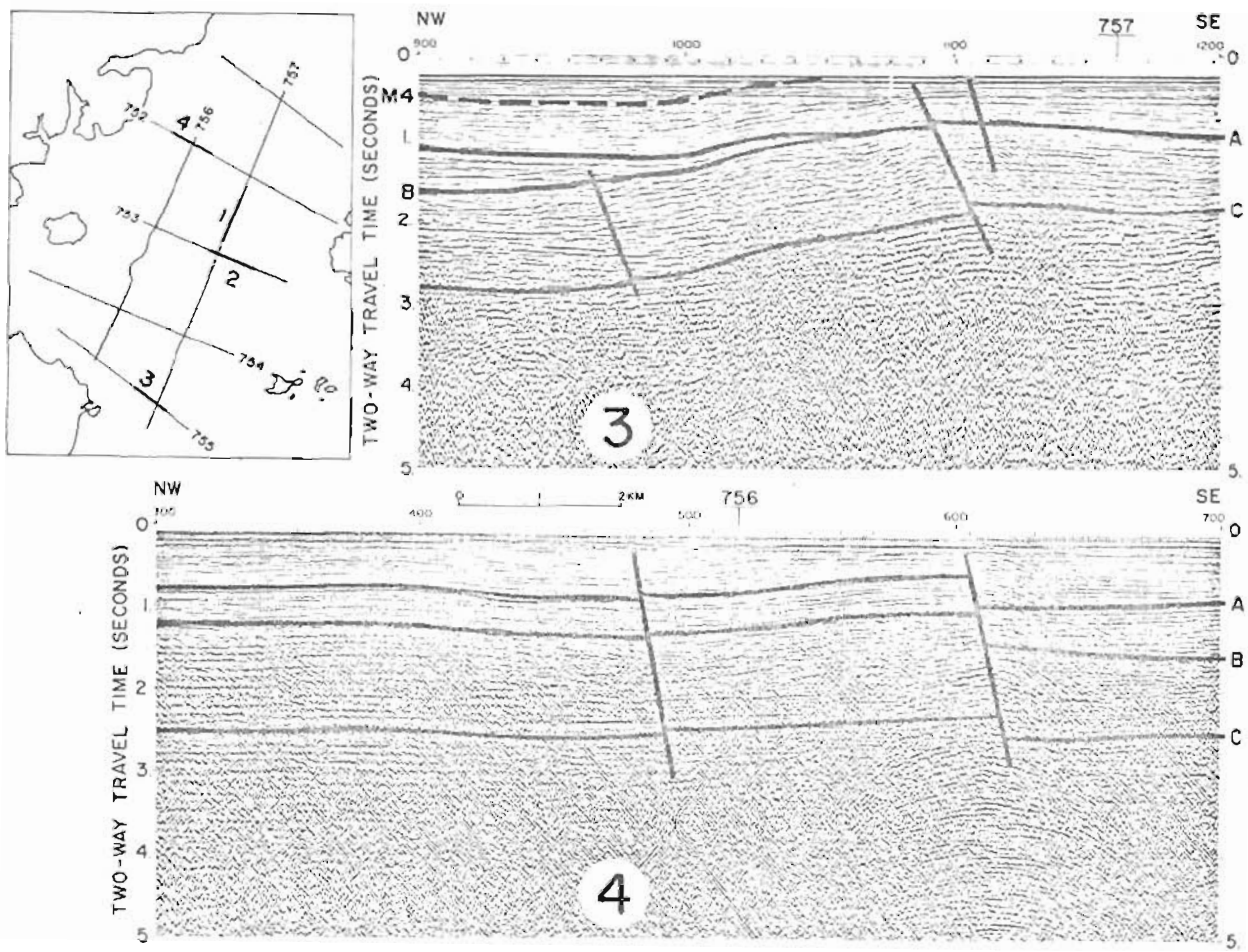

Fig. 12--(continued)--Selected offshore geologic features in lower Cook Inlet.

B horizon was formed. Two-way traveltime between horizons B and C decreases southwestward, and time-depth curve two suggests that the stratigraphic interval between them thins from 1.9 to 0.8 km. There does not appear to be as much thinning of the interval between the A and B horizons. Four of the six faults in this profile appear to break shallow strata; the remaining two offset only reflections below the A horizon. All are high-angle reverse faults except for the one at SP 2200, which is nearly vertical. Faults that are to the south of the nearly vertical fault dip south; those to the north dip north. The fault near SP 2250 appears to show increasing displacement downward, which suggests the fault has moved several times throughout its history.

The second seismic profile is from line 753 near the intersection with line 757. The A horizon rises smoothly to the northwest, but the B and C horizons dip in the opposite direction. Southeast of the profile, the B and C horizons are truncated by the A horizon. Events below the B horizon are conformable, as are events above the A horizon. Between the A and B horizons, however, the configuration of the reflection is more complex: the M2 horizon laps onto the M3 horizon, and the seismic time interval between the M3 and B horizons increases uniformly southeastward to the fault in the middle of the profile.

The third seismic profile is from line 755 east of Cape Douglas at the intersection of line 757. Three high-angle reverse faults, an unconformity, and an anticline are interpreted from this profile. The A and M4 horizons are concordant and show that anticlinal deformation extends upward to the seafloor. The B and C horizons are parallel. The A horizon truncates the B horizon in the middle of the profile, and, toward the southeast end of the profile, the time interval between the A and C horizons gradually decreases. Southeast of profile three, the A horizon truncates the C horizon (fig. 4). All of these seismic horizons are folded into an asymmetric anticline with the steeper flank on the northwest side.

The fourth seismic profile is located near the Iniskin Peninsula on line 752 at the intersection of line 756. Crests of two anticlines observed on the A horizon are at SP 400 and SP 600. Folding involves even the shallowest reflectors, as it does in many other folds. The syncline between the two anticlines is the syncline that trends southwest seaward of the Iniskin Peninsula and probably extends between the peninsula and Augustine Island. The normal fault at SP 600 has a large throw compared to other faults in lower Cook Inlet.

The four seismic profiles show that folding of the northeast-trending anticlines occurred some time after the close of the Mesozoic Era; there does not appear to be evidence for an earlier period of folding. In contrast, there is evidence for at least two periods of faulting, and possibly three if the fragmentary nature of the C horizon reflection is due to faulting.

A map showing the structural axes and faults in lower Cook Inlet was drawn using seismic data and evidence from outcrops and wells (fig. 13). Only structures between the two major flanking faults, the Bruin Bay and the Seldovia, are included. The numerous northeast-trending anticlines in lower Cook Inlet are all smaller in both width and relief than the Augustine-Seldovia arch, and some intersect the arch at oblique angles. The offshore anticlines are depicted as having long continuous axes; more seismic data across these axes probably would show a series of closed anticlines or domes that are aligned with or perhaps en chelon with the axes drawn. Folds near seismic-line intersections and onshore from surface data suggest a northeast structural grain. All structures trend approximately northeast on the Iniskin Peninsula (Detterman and Hartsock, 1966), near Kamishak Bay (Magoon, Adkison, and Egbert, 1976), and on the southern part of the Kenai lowland near Homer and Anchor Point (Kirschner and Lyon, 1973). Axes that diverge from the general northeast trend are found along the south shore of Kamishak Bay, where trends of onshore folds rotate from N. 20^{o} E. on the west to N. 80^{o} E. at Cape Douglas. Offshore structures near this area, however, appear to maintain an approximate N. 45^{o} E. trend. Igneous intrusion around Mount Douglas may account for the rotation of axial trends onshore and for the difference between onshore and offshore structural trends. Just north of the Augustine-Seldovia arch, offshore folds trend N. 45^{o}E. Near Kenai the folds trend N. 15^{o} E., reflecting the S-curve of structures in the Cook Inlet basin (Kirschner and Lyon, 1973; Tysdal, 1976).

Faults in lower Cook Inlet are difficult to correlate across the 30-km-square grid of seismic lines. Seismic data south of the Augustine-Seldovia arch are good enough to allow tentative correlations

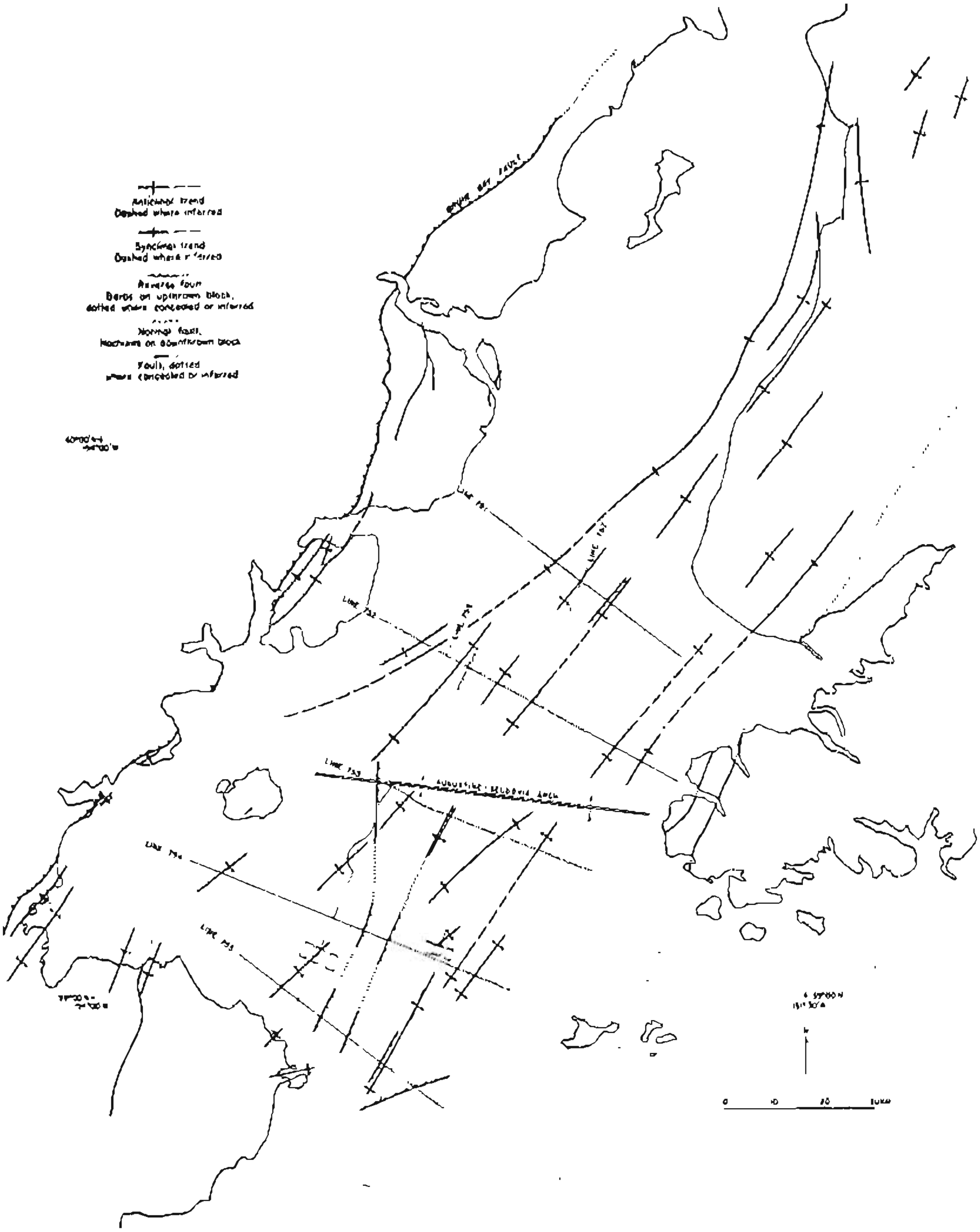

Fig. 13--Structural axes and faults in lower Cook Inlet. Structural data outside the seismic grid is taken from Kirschner and Lyon (1973), Tysdal (1976), Detterman and Hartsock (1966), Detterman and Reed (unpub. data), and Magoon, Adkison, and Egbert (1976).

between interpreted faults. North of the arch, the quality of the data is lower; the faults are not connected between the lines, and the apparent absence of faults north of the arch (fig. 13) reflects the lack of data. Most of the reverse faults of lower Cook Inlet that are interpreted from seismic data can be described as high-angle faults that are upthrown on the southeast, a sense of movement opposite to that of the Bruin Bay fault.

A few normal faults are mapped in lower Cook Inlet. A large normal fault is shown on figure 10, profile 4, and two small grabens with an uncertain east-west strike are shown on the map (fig. 13) on lines 756 and 757. Pre-Tertiary rocks in the Swanson River anticline of upper Cook Inlet are broken by normal faults transverse to the axis of the fold (Kirschner and Lyon, 1973). In lower Cook Inlet, most normal faults also seem to be related to anticlines but are not confined to pre-Tertiary rocks.

SUMMARY OF SEISMIC INFORMATION

A regional picture of the present-day structure of lower Cook Inlet is provided by a fence diagram constructed from the seismic profiles (fig. 14). A regional angular unconformity extends along the southeast margin of the lower Cook Inlet basin. The angular discordance is developed where the A horizon progressively truncates the B and C horizons to the southeast. From northwest to southeast below the unconformity, northeast-trending belts of progressively older strata subcrop against the A horizon. The inferred locations of the Middle and Lower Jurassic and the Upper Triassic subcrop belts

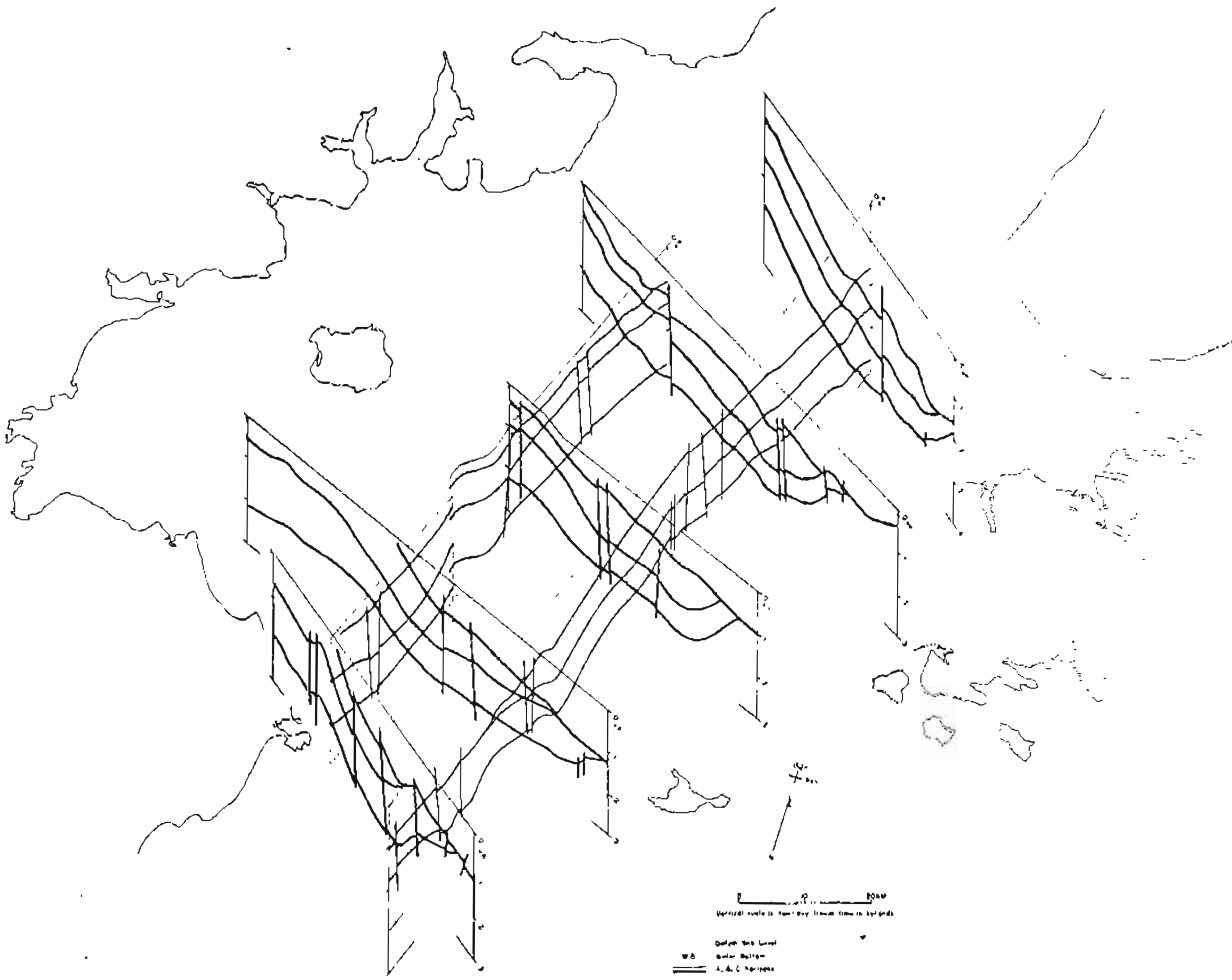

Fig. 14--Fence diagram constructed from seismic profiles showing regional unconformity at base of Tertiary rocks (A horizon), Augustine-Seldovia arch, and numerous faults. Datum of vertical dimension is two-way traveltime in seconds; a tick mark at both ends of each profile indicates time to the water bottom (WB).

lie southeast of the truncation of the C horizon (fig. 9). The southeast progression of subcrop belts ends at the Seldovia fault, where Upper Triassic rocks are in fault contact with Mesozoic flysch deposits (fig. 10).

The Augustine-Seldovia arch is evident in line 757, about midway along the line. Asymmetry of the dips of the north and south flanks is apparent; the north flank dips toward the very thick upper Cook Inlet Tertiary sequence that lies north of the fence diagram. The south flank dips less steeply than the north flank toward a shallow Tertiary sequence east of Cape Douglas. Line 756 shows that the arch is broader and structural relief decreases westward from line 757; the arch may die out near Augustine Island.

GEOLOGIC HISTORY

Lower Cook Inlet is part of the tectonically active northern Pacific continental margin. Mount Douglas, Iliamna and Redoubt Volcanoes, and Augustine Island are volcanoes that have all been active in Quaternary time; Augustine Island erupted in early 1976, and Iliamna steams continually. These volcanoes form a small part of the long Alaska-Aleutian volcanic arc that extends southwest and northeast of the Cook Inlet area.

In the general area of Cook Inlet, earthquakes of varying intensities have been part of the written record since 1912 (Magoon, Adkison, Chmelik, and others, 1976) and have been recorded by instruments since 1966 (Lahr, oral commun., 1977). Most of the earthquakes emanate from a northwest-dipping Benioff zone that underlies the Cook Inlet area (Lahr and others, 1974).

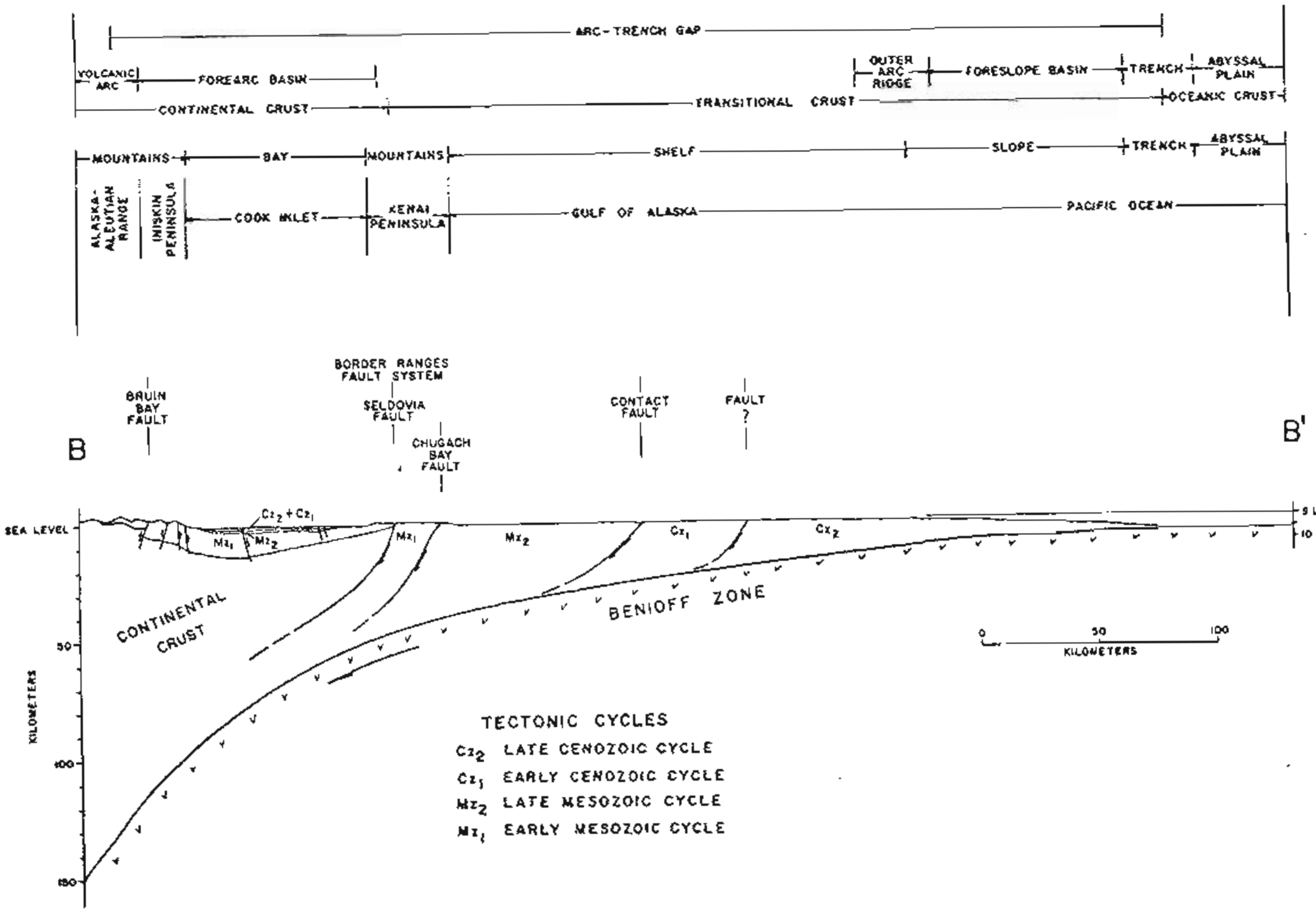

Fig. 15--Present structure between Alaska-Aleutian Range batholith and Gulf of Alaska. The cross section is modified from Plafker (1969, 1972) and Thompson (1976) to portray the present-day structure of the arc-trench gap from the top of the Benioff zone up to the surface. The top of the Benioff zone is drawn through computer-derived locations of hypocenters (J. C. Lahr, written commun., 1976). The extension of granitic continental crust to the southeast side of Cook Inlet and the subsurface geometry of faults are conjectural.

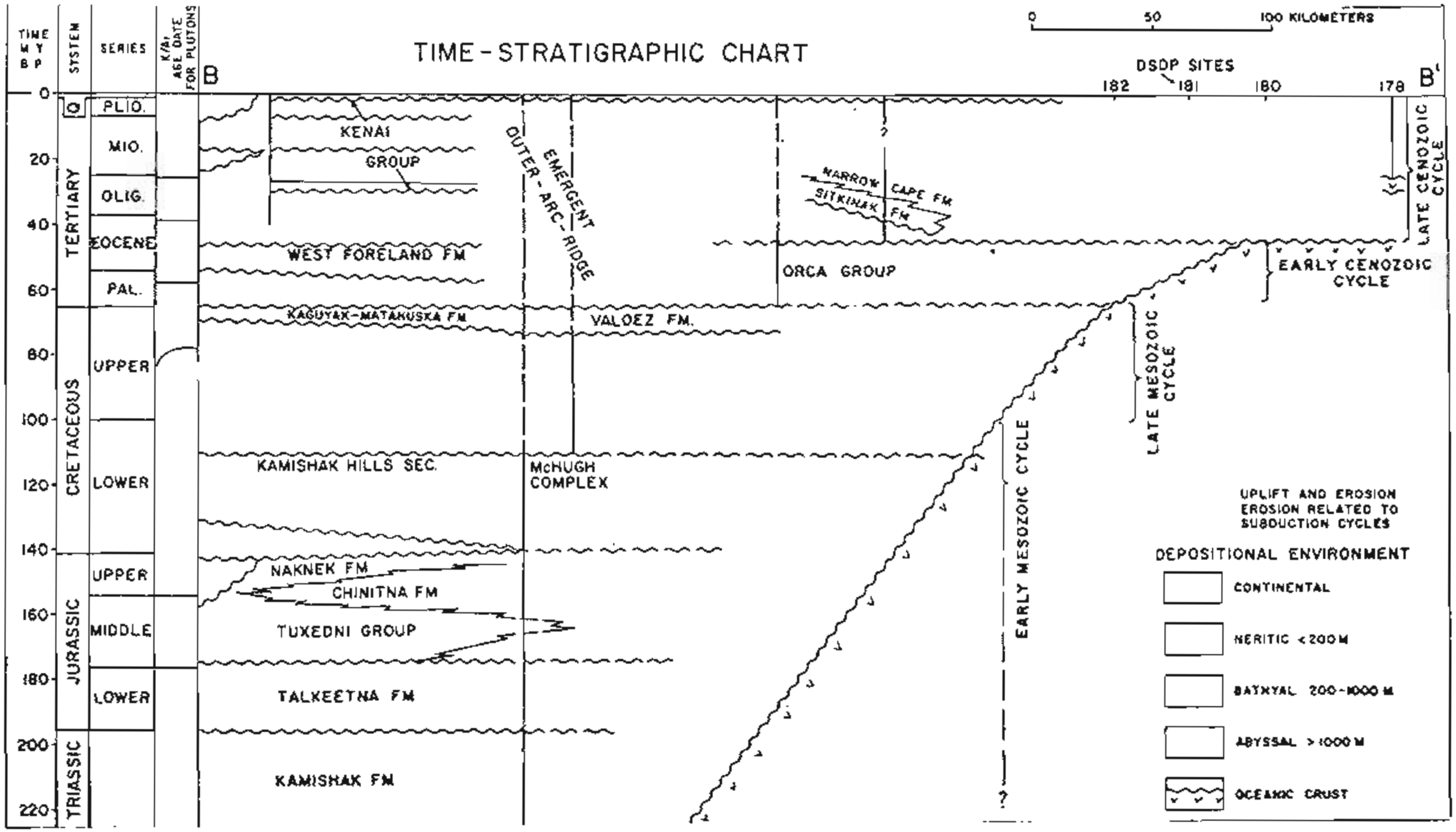

Fig. 16--Time-stratigraphic chart shows tectonic cycles that affected the Cook Inlet area. Depositional environments that range from continental to pelagic to abyssal are shown by patterns. Age of oceanic crust for late Cenozoic cycle from Pitman and Hayes, 1968.

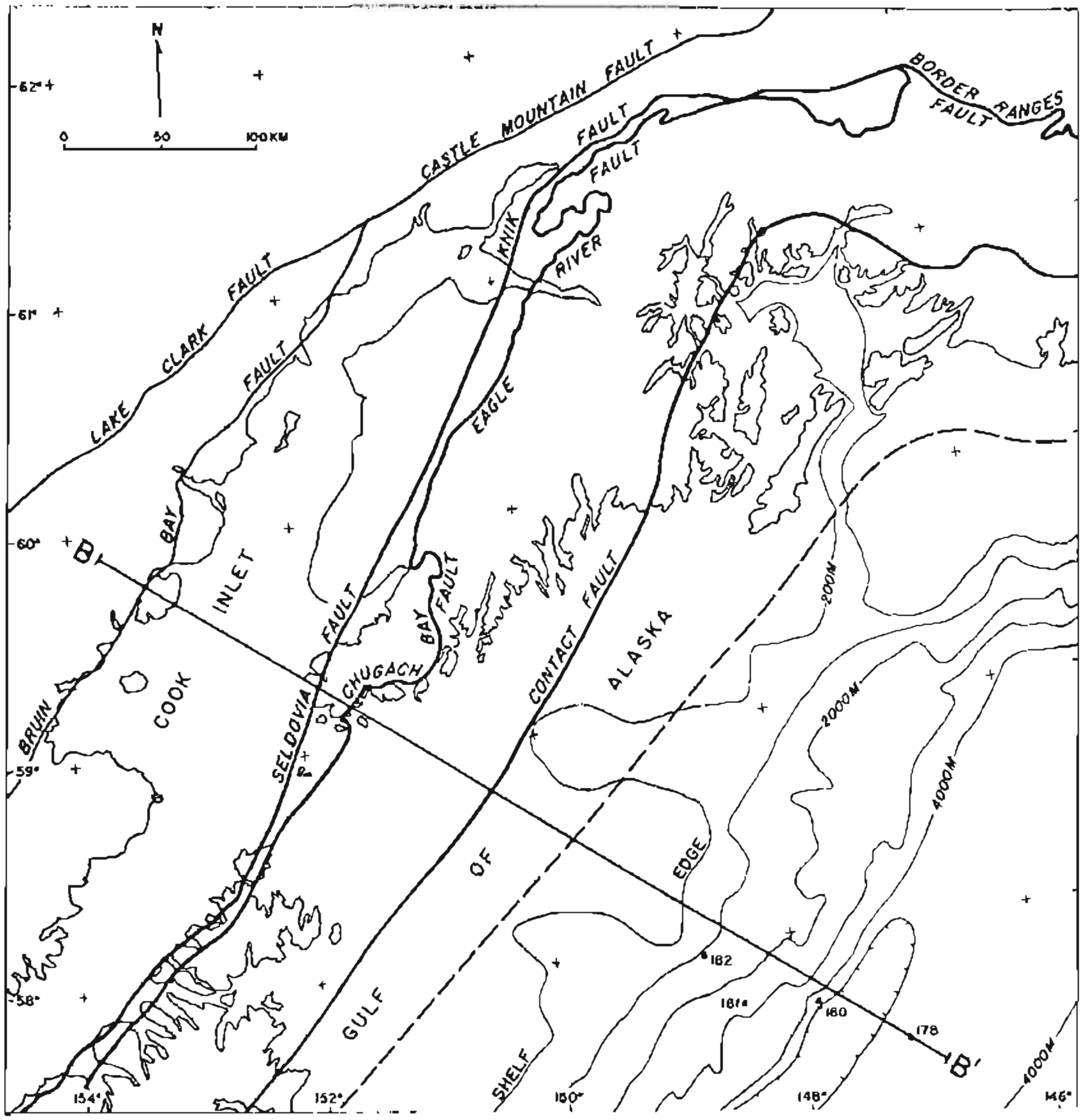

Fig. 17--Major faults in Cook Inlet and Gulf of Alaska. B-B', line of cross section and time-stratigraphic chart (figs. 15 and 16). The index map is compiled from geologic maps prepared by Beikman (1974a, b), Connelly and others (1977), Cowan and Boss (1977), Detterman and others (1976), King (1969), MacKevett and Plafker (1974), Magoon, Adkison, and Egbert (1976), Plafker (1969), Plafker, Jones, and Pessagno (1977), and Winkler (1976).

Plafker (1969, 1972) demonstrated the degree and type of deformation associated with the 1964 Alaska earthquake. Between the Aleutian trench and volcanic arc, the Cook Inlet area and the Kenai Peninsula subsided and the floor of the Gulf of Alaska rose. Plafker (1972) suggested that the Pacific plate is being thrust under the North America plate at the Aleutian trench. Cross section B-B' (fig. 15) portrays the present-day structure of the arc-trench gap.

With modification, the present-day tectonic model can be projected back into the Mesozoic. Many authors (for example, Burk, 1965; Moore, 1975; MacKevett and Plafker, 1974; and Plafker and others, 1977) have suggested such a reconstruction. The terminology and arc-trench models used in this discussion came from Bally (1976), Dickinson (1970, 1973), Seely, Vail, and Walton (1974), and others.

The strata in lower Cook Inlet are divided into four units by three regional unconformities (fig. 16). The age ranges within the units, in upward order, are: Late Triassic to Barremian, Maestrichtian, late Paleocene through early Eocene, and late Oligocene through Holocene. On the Kenai Peninsula and in the Gulf of Alaska, deformed melange and flysch sequences that are approximately the same ages as the units in the lower Cook Inlet are bounded by thrust faults, not by unconformities. The thrust faults are, from oldest to youngest, the Seldovia fault, the Chugach Bay fault, the Contact fault, a postulated unnamed fault, and the modern Benioff zone (fig. 17). The unconformities and thrust faults bound rock units that define four cycles of sedimentation and deformation, herein named the early Mesozoic, late Mesozoic, early Cenozoic and late Cenozoic cycles (Plafker, 1969, 1972).

Generally these cycles start with volcanic activity, emplacement of a pluton, and end with uplift of the area of the magmatic arc. Sedimentary rocks representative of much of the cycle are preserved in the arc-trench gap. Slope and trench rocks that were deposited towards the end of the cycle are preserved between thrust faults. These rocks were probably tectonically emplaced as the trench moved seaward.

The early Mesozoic cycle started with subduction and associated volcanism, continued with emplacement of a batholith, uplift, and ended with a stable shelf. The age of the older boundary of the early Mesozoic cycle in both shelf and flysch rocks is unclear, but Permian rocks at Puale Bay on the Alaska Peninsula (Burk, 1965) suggest volcanic activity that may be related to subduction, so the older boundary may be of late Paleozoic age. In lower Cook Inlet, the older boundary may be at the base of the Upper Triassic. The Border Ranges fault system (MacKevett and Plafker, 1974; Plafker and others, 1977), which includes the Knik and Seldovia faults, is the older boundary in melange rocks; it is between continental crust made of rocks as old as late Paleozoic(?) on the north and transitional crust made of deformed deep-marine Mesozoic rocks on the south. The age of the younger boundary in shelf rocks is based on the age of the unconformity at the top of Early Cretaceous rocks found in the Matanuska Valley (Grantz, 1960; Jones and Detterman, 1966; Jones, 1973), in the Kamishak Hills, and near Herendeen Bay on the south end of the Alaska Peninsula (Jones and Detterman, 1966). In flysch rocks, the Chugach Bay fault is the younger boundary and is interpreted to be younger than radiolarian chert in the Uyak Formation (Moore, 1969) of the Kodiak Islands. The chert is dated as late Valanginian to Hauterivian (Moore and Connelly, 1977).

The present distance between the Mesozoic volcanic arc and the outcrop of the McHugh Complex, about 125 km, suggests that the arc-trench gap during the early Mesozoic cycle was narrower than the arc-trench gap of today which is about 450 km wide. The extensive volcaniclastic rocks of the Early Jurassic Talkeetna Formation indicate that an active volcanic arc was located coincidently with the modern one. By Middle Jurassic time the Alaska-Aleutian Range batholith was emplaced into Triassic and older rocks. The occurrence of Jurassic quartz diorite plutons on the Kenai Peninsula on the Barren Islands (Cowan and Boss, 1977), and on the Kodiak Islands (Hill and Morris, 1977) suggests that the Alaska-Aleutian Range batholith extends under Cook Inlet as far as the Seldovia fault, forming competent continental crust. Only low-amplitude folds occur in the Cook Inlet basin on the west side of the Seldovia fault, whereas highly deformed and faulted rocks occur on the east side of the fault. The batholith may act as a buttress that protects the Cook Inlet rocks from severe deformation.

The lack of volcaniclastic rocks dating from Middle and Late Jurassic time suggests that the arc became quiescent. Uplift, probably related to vertical movement of the batholith, made the area of the volcanic arc a source of sediment that was shed onto a shelf, so that the Talkeetna Formation provided material for the Tuxedni Group and the Chinitna Formation. The batholith was finally unroofed at the beginning of deposition of the Naknek Formation, as shown by the Chisik Conglomerate Member, at the base of the Naknek, which contains the first occurrence of abundant plutonic cobbles (Detterman and Hartsock, 1966).

In the Kamishak Hills, Lower Cretaceous rocks deposited toward the end of the early Mesozoic cycle contain shallow-marine sandstone and siltstone rich in *Inoceramus* fragments. Similar rock units, the Herendeen Limestone on the south end of the Alaska Peninsula (Burk, 1965; Jones and Detterman, 1966; Jones, 1973) and the Nelchina Limestone northeast of the Matanuska Valley (Grantz, 1960; Jones and Detterman, 1966; Jones, 1973), demonstrate the geographic extent of the stable shelf implied by the high percentage of bioclastic material in the rocks.

Around lower Cook Inlet no plutons or volcaniclastic rocks date from the Early Cretaceous; apparently subduction waned or ceased altogether.

The slope and trench deposits of the early Mesozoic cycle are now the Uyak Formation of the Kodiak Islands (Moore, 1969; Moore and Connelly, 1977) and the McHugh Complex. The source area for these rocks was mainly the adjacent shelf and magmatic arc. Beginning in late Triassic time the melange was subducted; toward the close of Barremian time, some melange may have been accreted to the continent.

The McHugh Complex, Lower Cretaceous and possibly older, was emplaced as a melange before deposition of the Valdez(?) Group.

Subduction and emplacement of plutons during the early Mesozoic cycle created the blueschist facies that is attached to the continental plate along the Seldovia fault. On the Kenai Peninsula, the blueschists are dated at about 190 m.y. (Forbes and Lanphere, 1973); schists on the Kodiak Islands are dated at 170.0 ± 5.5, and 187.6 ± 5.6 from co-existing crossite and white mica, and 161.4 ± 19.4 m.y. from crossite (Carden and others, 1977). Age dates from a pluton on the Barren Islands, 187 ± 14 m.y., (Cowan and Boss, 1977) and from the Afognak pluton, 188.5 ± 5.7 m.y., (Hill and Morris, 1977) are about the same as the age dates of the schists. Mesozoic thermal events may have reset the ages of the schists (Plafker and others, 1974). Ultramafic complexes occur along the Knik fault (Clark, 1972a, b) and the Seldovia fault (Martin and others, 1915). The blueschists and ultramafic complexes are probably fragments of continental and oceanic crust respectively (George Plafker, oral commun., 1977).

The late Mesozoic cycle is the second period of sedimentation and deformation and occurred during the Late Cretaceous. The older boundary of the late Mesozoic cycle is the same as the younger boundary of the early Mesozoic cycle: in shelf rocks the boundary is the unconformity at the base of Late Cretaceous rocks; in flysch rocks it is the Chugach Bay fault. The younger boundary of the late Mesozoic cycle is the unconformity at the top of Late Cretaceous shelf rocks, the Matanuska and Kaguyak Formations; in flysch rocks, the boundary is the Contact fault.

No rocks of Aptian through Companian age are found in the Cook Inlet area except in the Matanuska Valley where older units of the Matanuska Formation exist (Grantz, 1960, 1964; Jones, 1964, 1967). On the Alaska Peninsula similar rocks are as old as Campanian (Burk, 1965). The unconformity from Aptian into Campanian time represents more than 40 m.y., the longest break in the geologic record in the Cook Inlet basin. The unconformity is exposed on the south end of the Alaska Peninsula (Burk, 1965; Jones and Miller, 1976) and in the Kamishak Hills (Jones and Detterman, 1966; Jones and Miller, 1976; Magoon, Adkison, and Egbert, 1976). Rocks of Maestrichtian age were deposited on a deepening shelf; the basal sandstone, deposited in a near-shore environment, is overlain by bioturbated siltstone that is in turn overlain by turbidite sandstone and siltstone.

Rocks in the Cook Inlet area were eroded and redeposited on the slope and in the trench as the Valdez Group and the Kodiak Formation. All fossils found in the Valdez indicate a Maestrichtian age for these flysch rocks (Jones and Clark, 1973).

In Late Cretaceous time, plutonic rocks that yield age dates between 65 and 83 m.y. (Reed and Lanphere, 1973b) intruded the Alaska-Aleutian volcanic arc and may indicate that early in this period sub-subduction occurred at the trench. Sediments eroded from the shelf and slope were evidently subducted after being deposited in a trench that formed seaward of the McHugh Complex. When subduction waned or ceased in Campanian time, transgression of the sea preserved sediments on the shelf, slope and trench. The Kaguyak and Matanusak Formations are rocks deposited on the shelf and the Valdez Group was emplaced against the McHugh Complex, before deposition of the Orca Group, increasing the width of transitional crust.

Seismic data show that a prism of rock on the north flank of the Augustine-Seldovia arch is terminated at the crest of the arch (fig. 12, first profile), implying uplift along the arch. A similar prism is not found on the south flank, which suggests that during this cycle the arch may have been a hinge line that was onlapped by Maestrichtian rocks.

The older boundary of the early Cenozoic cycle, the third period of sedimentation and deformation, is the same as the younger boundary of the late Mesozoic cycle: in shelf rocks the boundary is the unconformity at the base of the West Foreland Formation; in flysch rocks it is the Contact fault. The younger boundary in forearc-basin rocks is the unconformity at the top of the West Foreland Formation; in flysch rocks, named the Orca Group, the boundary is a postulated fault near the shelf edge. In the Cook Inlet basin, the change from the late Mesozoic cycle to the early Cenozoic cycle is marked by an abrupt change from the marine shelf environment of the Kaguyak and Matanuska Formations to the nonmarine forearc-basin environment of the early Tertiary West Foreland Formation.

Throughout much of the early Cenozoic cycle, plutons whose ages range from 65 through 58 m.y. intruded the Mesozoic volcanic arc (Reed and Lanphere, 1973b), and plutons dated from 65 through 41 m.y. intruded the Mesozoic and outer-arc ridge (Hudson and others, 1977; Kienle and Turner, 1976). Volcanism along the Alaska-Aleutian volcanic arc contributed debris to the forearc basin, but perhaps not to the area seaward of the outer-arc ridge. Subduction occurred in early Paleocene time which probably uplifted the Cook Inlet basin, creating a site for deposition of continental rocks. After a period of erosion, the volcaniclastic West Foreland Formation was deposited. Seaward of the outer-arc-ridge, on the shelf and slope, the Ghost Rocks and Sitkalidak Formations were deposited. The Orca Group was deposited on the slope and in the trench, and was emplaced against the Valdez Group before deposition of the Oligocene and younger rocks.

The fourth and last cycle, the late Cenozoic, began with the intrusion of a pluton into the Mesozoic magmatic arc. Radiometric age dates on the intrusive body range from 38 to 26 m.y. (Reed and Lanphere, 1973b). Extensive volcanic activity occurred northwest of the magmatic arc (Reed and Lanphere, 1973a). The older boundary of this cycle in forearc-basin rocks is at the base of the Hemlock Conglomerate; in flysch rocks it is the postulated fault. The younger boundary in forearc-basin strata is the present land surface; the modern Benioff zone is the boundary in flysch rocks. In the forearc basin, the late Cenozoic cycle is represented by the nonmarine Kenai Group, which had a complex depositional history (Kelley, 1963, 1968; Kirschner and Lyon, 1973; Hite, 1975; Hayes and others, 1975; Magoon, Adkison, and others, 1976). The Kenai Peninsula and the Kodiak Islands separated sedimentation in the forearc basin from that in the Gulf of Alaska. Some rocks of the late

Cenozoic cycle have been accreted to the Orca Group between the postulated fault and the modern Benioff zone. At DSDP sites 181 and 182, Pleistocene strata were penetrated that have been interpreted as accreted rocks because they are highly compacted and dewatered (Kulm and others, 1973; von Huene and others, 1971). Other rocks of the late Cenozoic cycle were deposited on the shelf over transitional crust formed by accreted rocks of this and older cycles.

Undeformed trench sediments penetrated in DSDP 180 (Kulm and others, 1973) and undeformed abyssal plain sediments in DSDP 178 (Kulm and others, 1973) and DSDP 183 (Creager and others, 1973; Scholl, 1974; Stewart, 1976) are not part of the late Cenozoic cycle because these sediments are seaward of the accreted rocks of the inner slope.

Folding of northeast-trending anticlines occurred late in the late Cenozoic cycle, as indicated by deformation of strata near the seafloor and the lack of seismic evidence for multiple phases of growth of folds. Burk (1965) determined a Pliocene age for deformation on the Alaska Peninsula, and the Cook Inlet area may have been affected by that deformation. The most pronounced thinning of strata across the Augustine-Seldovia arch occurs in strata of Tertiary age. Deformation along the arch may have begun in Cretaceous time, but it seems to have climaxed in Tertiary time.

PETROLEUM GEOLOGY

Petroleum in upper Cook Inlet is contained within Tertiary reservoirs. From 1957 to the beginning of 1976, 677 million barrels of oil have been produced; 80 percent of the production has come from the Hemlock Conglomerate. Lower Cook Inlet contains Tertiary rocks that are probably important to the petroleum resource potential of this area, and parts of the Mesozoic must also be considered prospective petroleum reservoirs. To appreciate this, a model of petroleum generation and migration must be presented.

Geochemical data suggest that the source rock for petroleum in Cook Inlet is in the marine Middle Jurassic through Cretaceous strata, not in the nonmarine Tertiary sequence or the volcaniclastic Lower Jurassic Talkeetna Formation, which is considered to be economic basement. On the Iniskin Peninsula, wells penetrate Middle Jurassic strata that are rich in organic carbon (fig. 18). Thus, attention is focused on Middle Jurassic strata as hydrocarbon source rocks in lower Cook Inlet.

Generally a source rock rich in organic debris must be heated to a minimum temperature for a minimum time before oil and gas are generated and expelled (Hood, 1974, 1975). In lower Cook Inlet, upper Mesozoic strata, the most likely source beds, were probably not covered with sufficient overburden to generate petroleum until buried by Tertiary rock. In upper Cook Inlet the oil apparently was generated in late Tertiary or Quaternary time, which suggests that the present configuration of the basin may have controlled the direction of oil migration. Tertiary overburden south of the Augustine-Seldovia arch is thin and may be insufficient to initiate generation of oil.

The unconformity at the base of the Tertiary rocks plays an

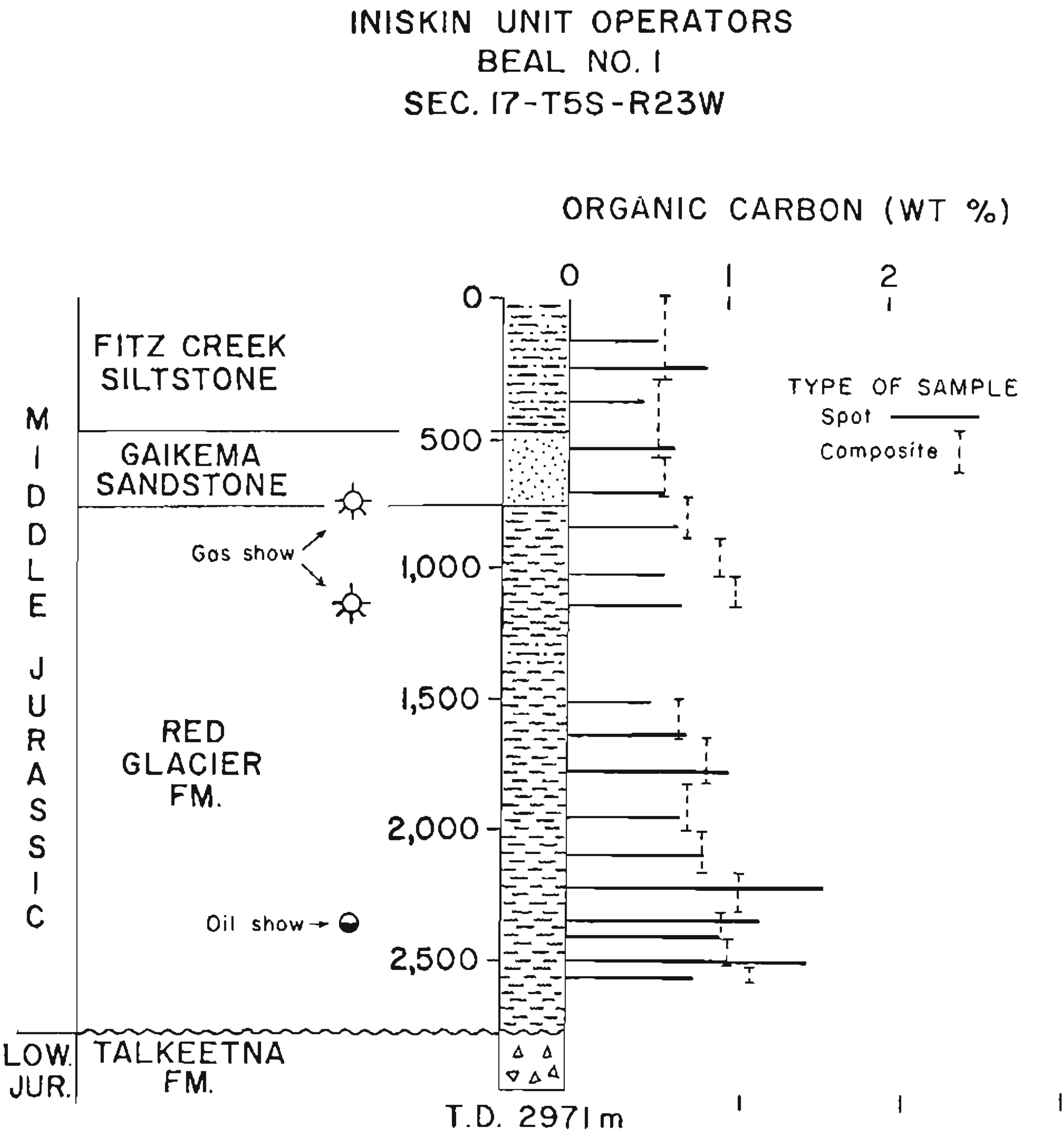

Fig. 18--Organic-carbon content of rocks, Beal No. 1 well.

important role in the migration of hydrocarbons in lower Cook Inlet because it cuts across all units of the Mesozoic. A cross section through Middle Ground Shoal (Boss and others, 1976) shows an upper Mesozoic source rock immediately beneath Tertiary reservoirs. Oil from upper Mesozoic strata apparently migrated upward across the unconformity and into Tertiary strata. If the unconformity were not present, oil would have remained trapped in the Mesozoic rocks. In wells on the Iniskin Peninsula, oil shows are found in Middle Jurassic rocks. If adequate reservoirs exist in upper Mesozoic rocks in lower Cook Inlet, enough oil may have accumulated for them to be considered prospective targets.

Tertiary rocks thin considerably south of upper Cook Inlet; in places they are less than 0.25 km thick at the crest of the Augustine-Seldovia arch. Although the base of the Tertiary strata is found at increasingly greater depths south of the crest of the arch, the section remains relatively thin; it is only 2 km thick near the Barren Islands. The thinness of the Tertiary rocks suggests that the most likely target for oil exploration south of the transbasin arch is Mesozoic strata. Exposures of a friable sandstone of the Naknek Formation on Augustine Island and about 40 km northwest of Cape Douglas are probably connected in the subsurface beneath Kamishak Bay and may be a significant reservoir. Cretaceous strata include marine sandstone units that may contain beds that could serve as reservoirs.

In lower Cook Inlet, petroleum may have accumulated in structural, stratigraphic, and combination traps. One type of structural trap may form where northeast-trending anticlines intersect the Augustine-Seldovia arch. One structure of this type is located just north of the intersection of seismic lines 753 and 756; another may be located near the intersection of seismic lines 753 and 757. The exact shape of structures formed at the nearly perpendicular intersections is unknown because of the coarse seismic grid, but they could be domes. The location of such structures astride the crest of the arch is important because the arch is a transbasin structure that could be the site of accumulation of oil that migrated with updip from the southern part of lower Cook Inlet or southward from the upper Cook Inlet petroleum province. The arch may have existed in pre-Tertiary time; it would have been an important updip barrier if petroleum had been generated in Mesozoic time south of the arch.

Another type of structural trap is found along the crests of the northeast-trending anticlines, for example, the faulted anticline on line 751, just east of line 757 (fig. 13), that appears to extend a considerable distance into upper Cook Inlet. The crests (fig. 13) are probably lineations along which individual anticlines are separated by structurally low areas. Some of these individual structures may be large enough to entrap commercial quantities of petroleum. Most of these anticlines appear to be young, because in many places folds extend upward through the Tertiary rocks and are truncated at or near the seafloor.

Stratigraphic and combination traps may be formed across unconformities. These traps could contain important reserves because of their number and extent, but structural traps are likely to be tested first. The prominent angular unconformity across the A horizon extends along the southeast side of the basin, is at shallow depth in many places, and could offer sites for stratigraphic or combination traps. The possible lack of a good seal above the subcropping Mesozoic strata may be a negative factor. At Cape Douglas, the Tertiary West Foreland Formation consists of a thick sequence of conglomerate that may be too permeable to form a good seal. Onshore near Seldovia, however, the upper part of the Kenai Group, which is generally finer grained than the West Foreland Formation, directly overlies the upturned Mesozoic strata and may seal them better than the lower Tertiary conglomerate. Offshore to the west of Seldovia the extent of the West Foreland Formation is not known, but the unconformity may be overlain by the upper part of the Kenai Group, and stratigraphic or combination traps may exist there.

Away from the transbasin arch combined stratigraphic and structural traps may exist where strata in the subcropping Mesozoic rocks are deformed into northeast-trending anticlines that strike at low angles across the subcrop belts. A cross section through such a trap (fig. 12, profile 2) shows that within the extent of the anticline, a thickness of Mesozoic strata is truncated, and petroleum migrating updip within the thickness of strata might be trapped in only part of the total closure of the fold. Late Cretaceous siltstone overlying sandstone of Early Cretaceous age at Cape Douglas may be a particularly effective barrier to vertical migration of petroleum from older rocks.

Petroleum may be forced to migrate updip along the base of the siltstone; hence, stratigraphic traps filled with oil from Jurassic and Early Cretaceous sandstone may lie southeast of the subcrop belt of the siltstone.

The Augustine-Seldovia arch trends at nearly right angles to the subcrop belts. In the offshore area around Seldovia, the arch exhibits its greatest structural relief and provides north-south closure. Where combined with the northwest dip of Mesozoic rocks, the structure of the arch may form a trap at the base of Tertiary strata.

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