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Coalbed Methane Prospects of the Upper Cook Inlet

by

C.E. Barker, J.G. Clough, and T.A. Dallegge

February 2001

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Opportunities in Alaska
Coalbed Methane Workshop

Coalbed Methane Prospects of the Upper Cook Inlet

A Field Trip Organized by
C.E. Barker, J. G. Clough and T.A. Dallegge

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Coalbed Methane Prospects of the Upper Cook Inlet

Field Trip Guidebook Compiled by
C.E. Barker, J. G. Clough and T.A. Dallegge

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Coalbed Methane Prospects of the Upper Cook Inlet

Field trip, Thursday, March 2, 2000

Schedule

8:00 Distribution of field trip materials, then board bus.

8:15 Bus departs Sheraton Anchorage Hotel, Anchorage, Alaska March 2, 2000. Proceed west on 5th Ave from hotel, turn north onto I street, left (westbound) onto 3rd avenue.

8:30 Stop 1: Viewing platform at Resolution Park. This viewpoint overlooks Cook Inlet with great views of Cook Inlet, Mt. Spurr, etc. Proceed eastbound on 4th Avenue to video stop.

8:45 Stop 2: Video of 1964 earthquake in the Bus from the vantage point where the video was taken, Video courtesy of Rod Combellick (DGGS).

9:00 Travel from Anchorage to Eagle River, Alaska via Glenn Highway

9:30 Stop 3: Bus arrives AK Geological Materials Center, Fish Hatchery Rd., Eagle River, AK. (907) 696-0079. Half of bus departs at GMC while other half remains aboard, continuing on Skyline Drive Loop (weather permitting).

AT GMC (-1 hour for each group)
introduction and greeting by John Reeder, Curator.

Dallegge will discuss ash potential content of AK-94 and Deep Creek #I wells in relation to Ph.D. research concerning stratigraphic study of coals from the Kenai Group and implications to CBM.

General discussion of the AK-94 well, project and core in terms of CBM properties, discuss Flores et al. marine influence hypothesis and other comments.

Skvline Drive Loop (-1 hour for each oroupj
Proceed back to Old Glenn Hwy and go west to Eagle Loop Rd, turn left (south) proceed to Skyline Dr., go left follow winding road up hill, road turns into upper Skyline Drive then Golden Eagle Dr. Exit bus at dead end, short walk (caution icy surfaces).
Regional Overview of Cook Inlet Geology in terms of CBM (Bob Swenson)

Relationship between Cook Inlet and interior basins and implications to CBM (Chet Paris)

Bus returns to GMC and change over occurs for second group

12:00 Bus departs via Glenn Highway and Park Highway to Wasilla, AK

12:30 Lunch at Best Western at Lake Lucille, 1300 Lake Lucille Dr. Wasilla 99654, AK. (907) 373-l 776

14:00 Depart for Pioneer Project, Vine Road wells, west of Wasilla, Alaska

14:15 Pioneer Project: Overview and discussion by Rob Downey, Dan Seamount, and Charley Barker

14:45 Depart to Houston Project, Discussion by Dave Lappe

15:10 Depart for Best Western at Lake Lucille

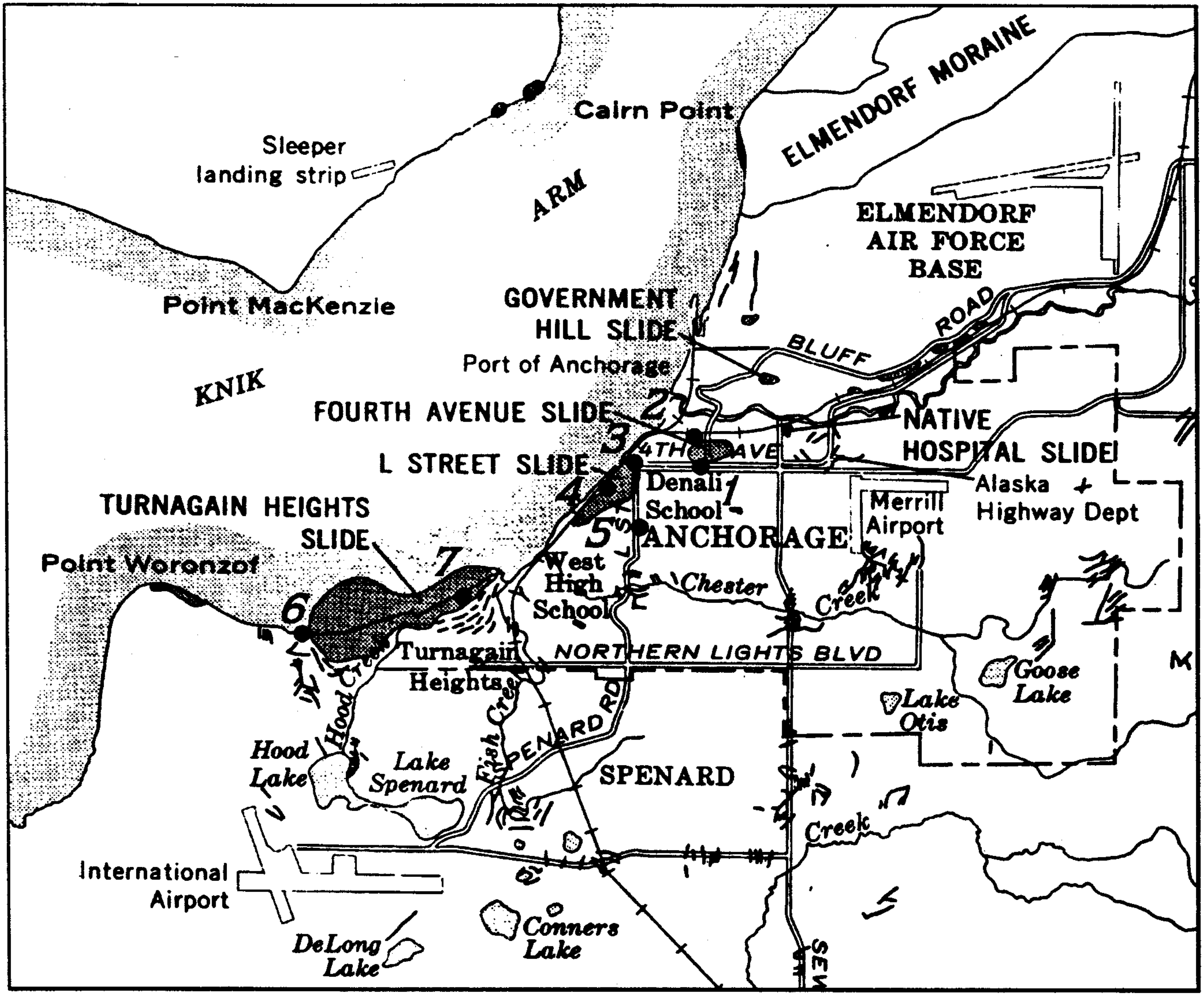
15:30 Restroom and Coffee Break at Best Western at Lake Lucille. Overview of field trip. Additional question and answer period.

16:00 Depart for Anchorage.

16:50 Arrive Sheraton, Anchorage.

Table of Contents for Submitted Papers

Papers are listed in order of topic presented on field trip and separated by color dividers.



Major landslides and ground cracks in the downtown Anchorage area resulting from the 1964 M_w 9.2 earthquake. Numbered points indicate field trip stops.

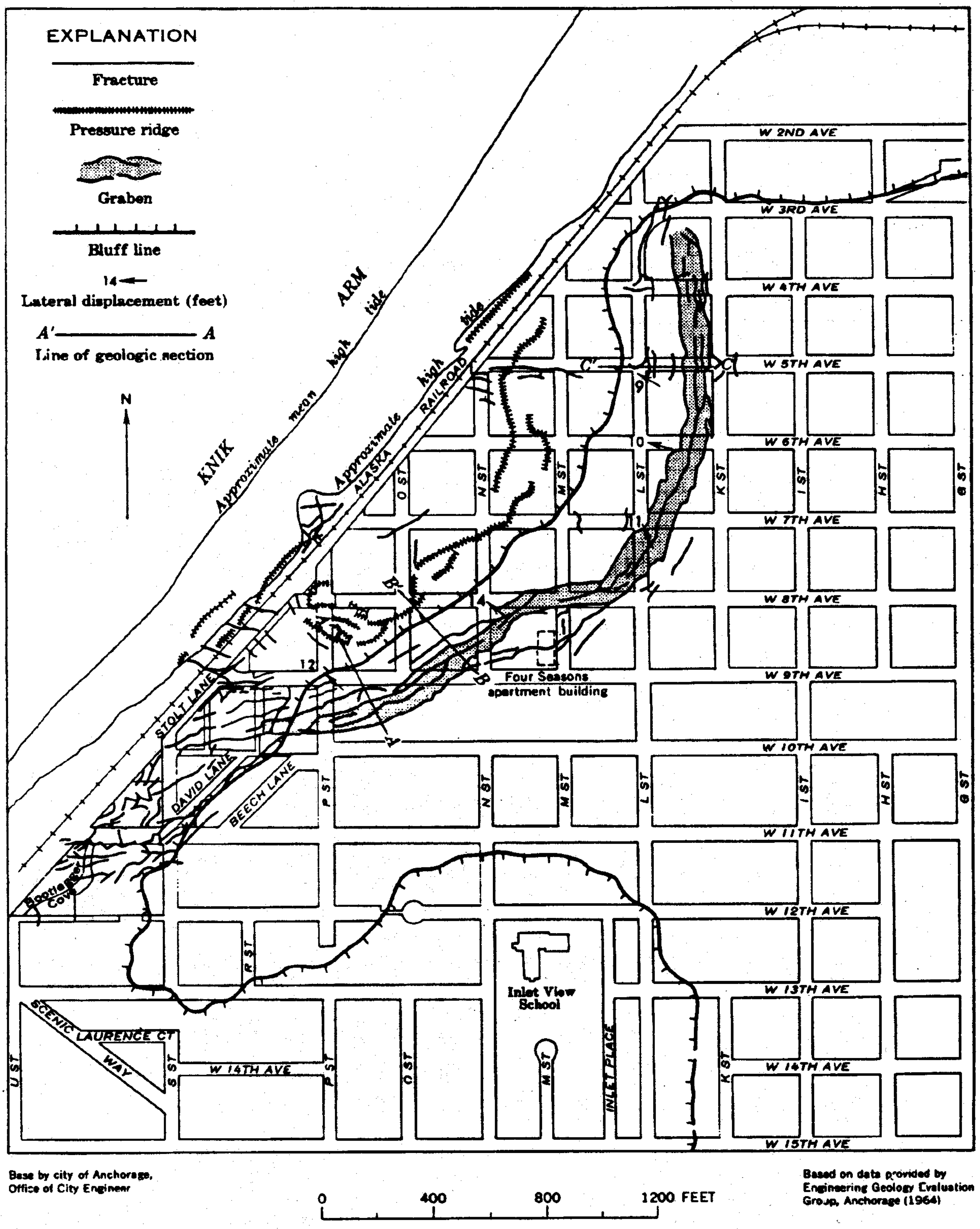
Modified from Hansen, W.R., 1965, Effects of the earthquake of March 27, 1964, at Anchorage, Alaska: U.S. Geological Survey Professional Paper 542-A, figure 1.

ANCHORAGE EARTHQUAKE SOURCES

	Maximum magnitude	Closest distance to rupture	Average return period
INTERPLATE THRUST			
Shallower than -20 km	9¼ - 9½	75 km	600-800 yr
Deeper than -20 km	8	40-50 km	unknown
SUBDUCTED PLATE	7-7½	>40 km	unknown
OVERRIDING PLATE			
Border Ranges fault	7½ ?	<10 km	> 10,000 yr ?
N. Cook Inlet fold belt	7 ?	<10 km	unknown
Castle Mountain fault	7½ - 7¾	40 km	1,000 yr ?
Susitna River zone	7%	60 km	unknown
Volcanic axis	6	130 km	unknown
Other sources	7%	<10 km	unknown

modified from Combellick, RR., and Lahr, JC., 1996, Earthquake potential and hazards in southcentral Alaska [abs.] : Geological Society of America Abstracts with Programs, v.28, no. 5, p. 56-57.

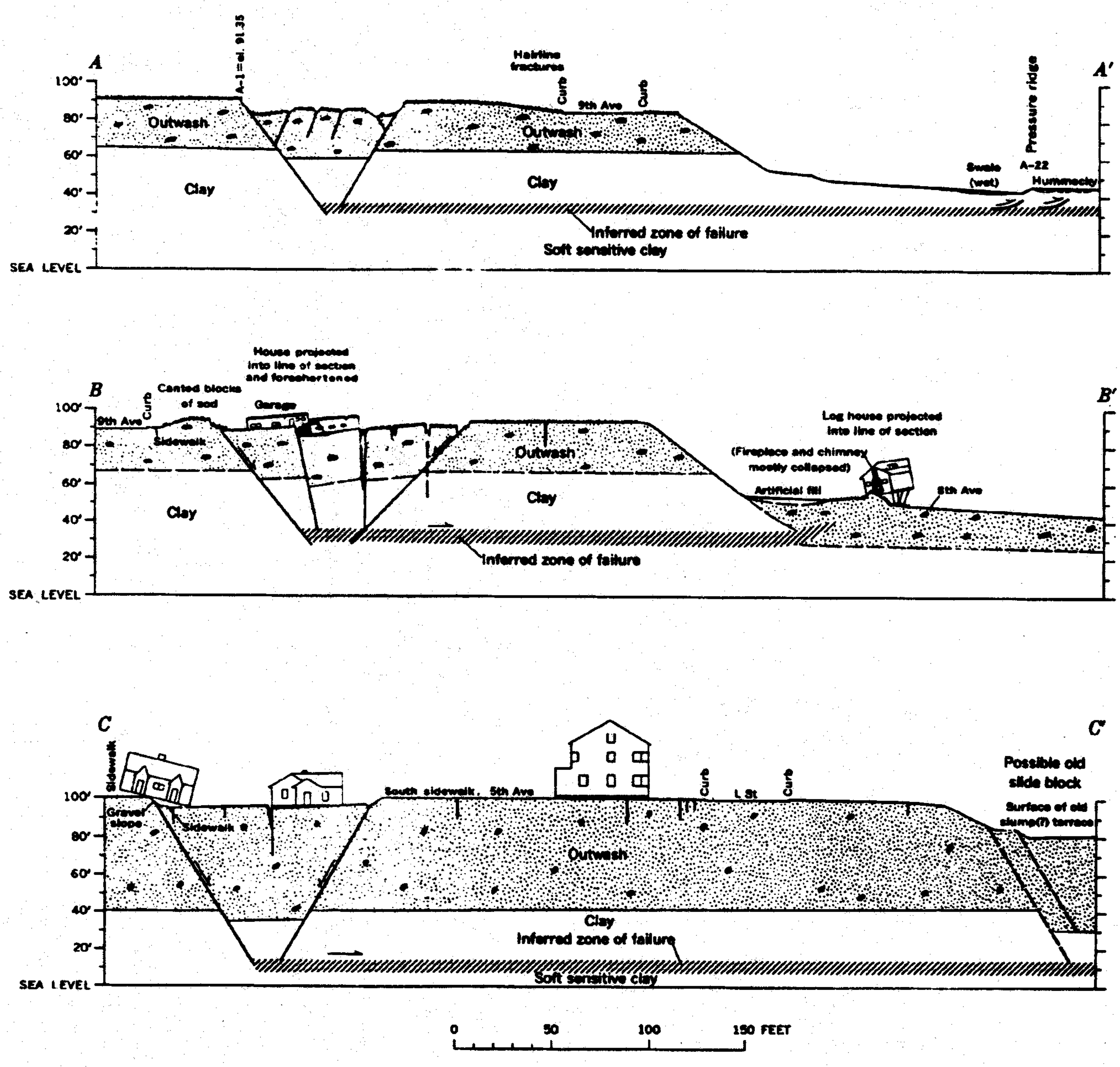
L Street Slide



27.—L Street slide area, Anchorage, Alaska. Geologic cross sections are shown in figure 30.

from Hansen, W.R., 1965, Effects of the earthquake of March 27, 1964, at Anchorage, Alaska: U.S. Geological Survey Professional Paper 542-A. See figure 30 for cross sections.

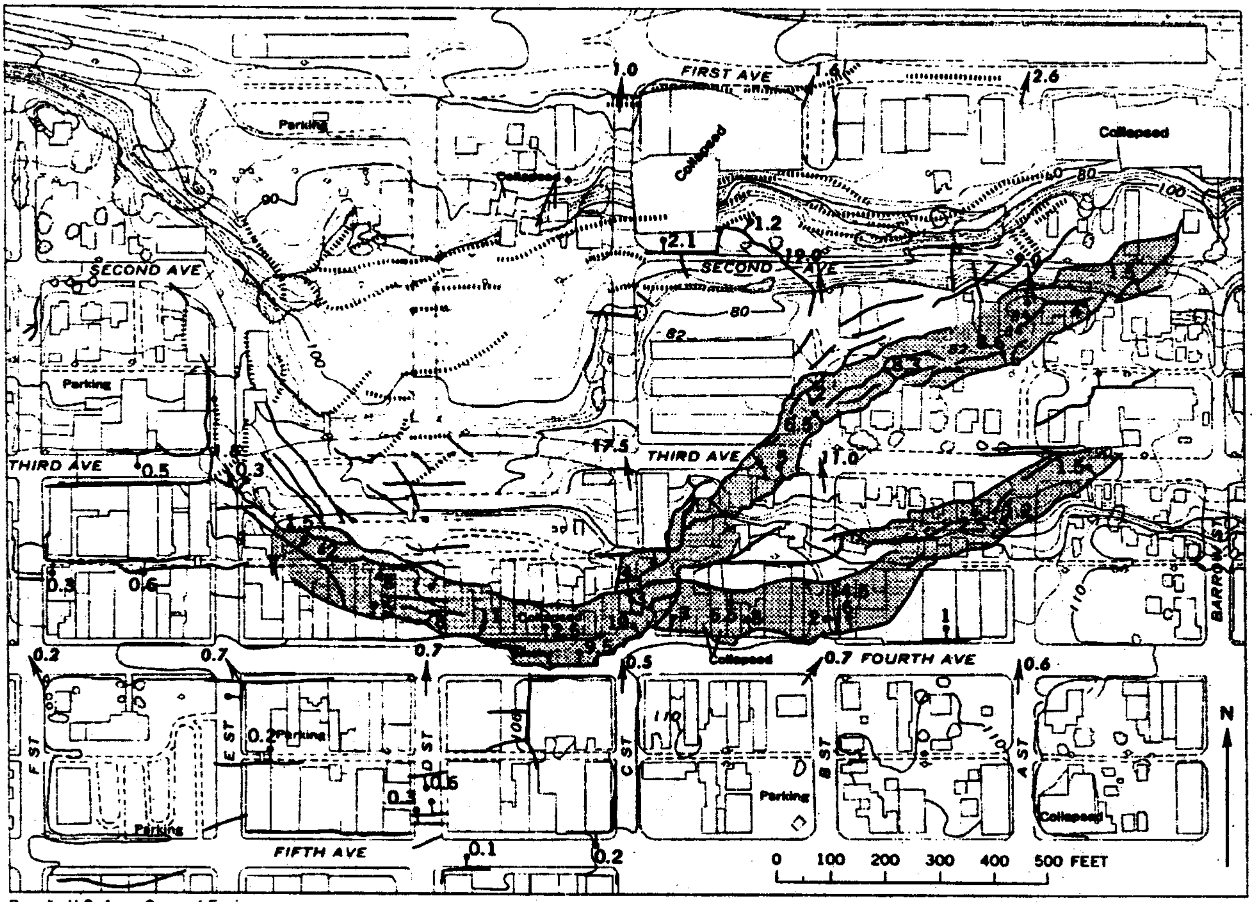
L Street Slide



30.—Geologic section through the L Street slide. In section C–C' the toe of the slide is to the right of C'.

from Hansen, W.R., 1965, Effects of the earthquake of March 27, 1964, at Anchorage, Alaska: U.S. Geological Survey Professional Paper 542-A.

4[th] Avenue Slide



Base by U.S. Army Corps of Engineers

Compiled from aerial photographs and data taken from reports of Engineering Geology Evaluation Group (1964) and Shannon and Wilson, Inc. (1964)

EXPLANATION

1.5

Fracture, showing downthrown side and displacement in feet

Pressure ridge

Graben

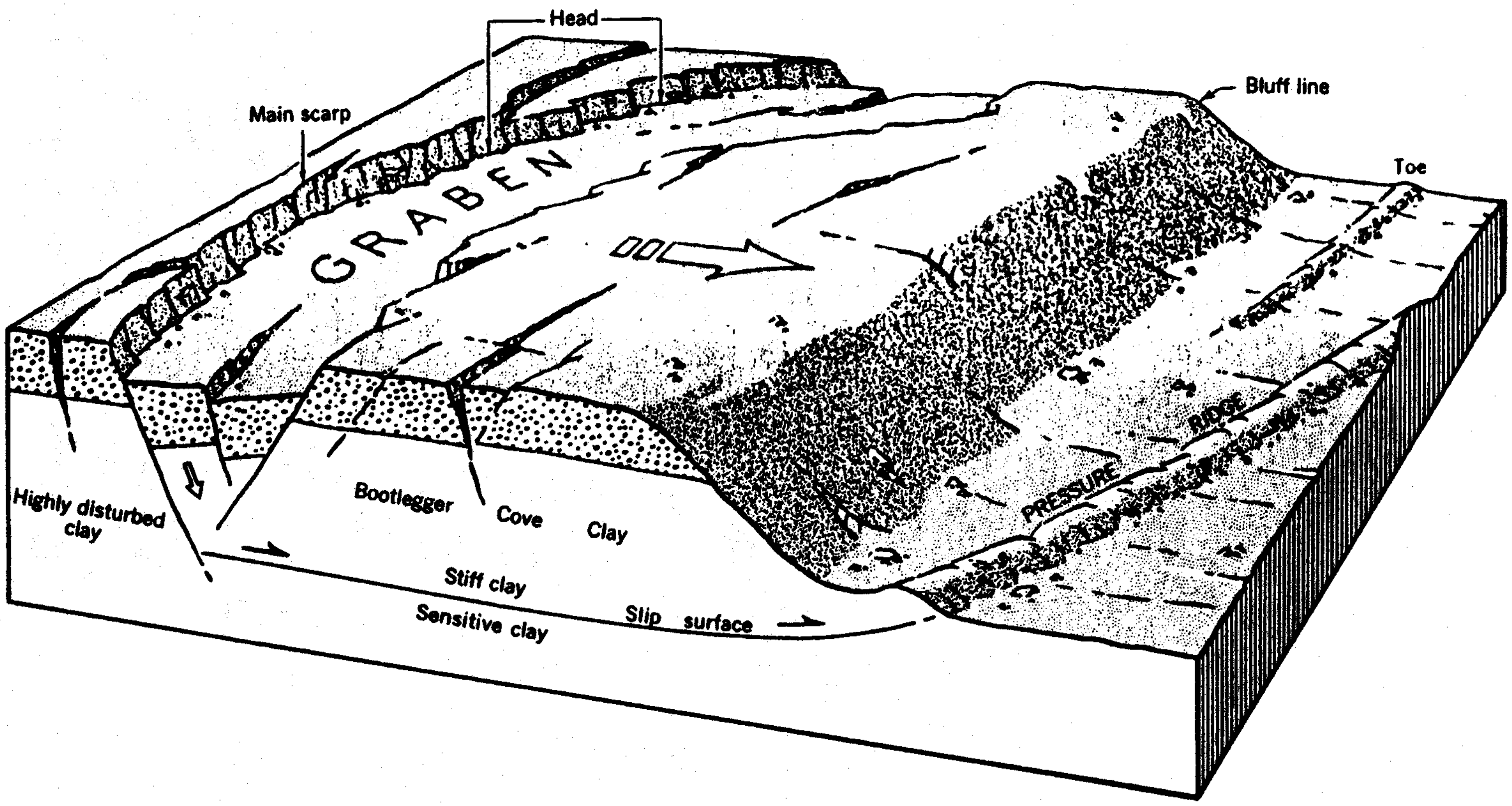
9.0

Lateral displacement of bench mark, in feet. New position at point of arrow. No appreciable movement since earthquake

26.—Fourth Avenue landslide area, Anchorage, Alaska.

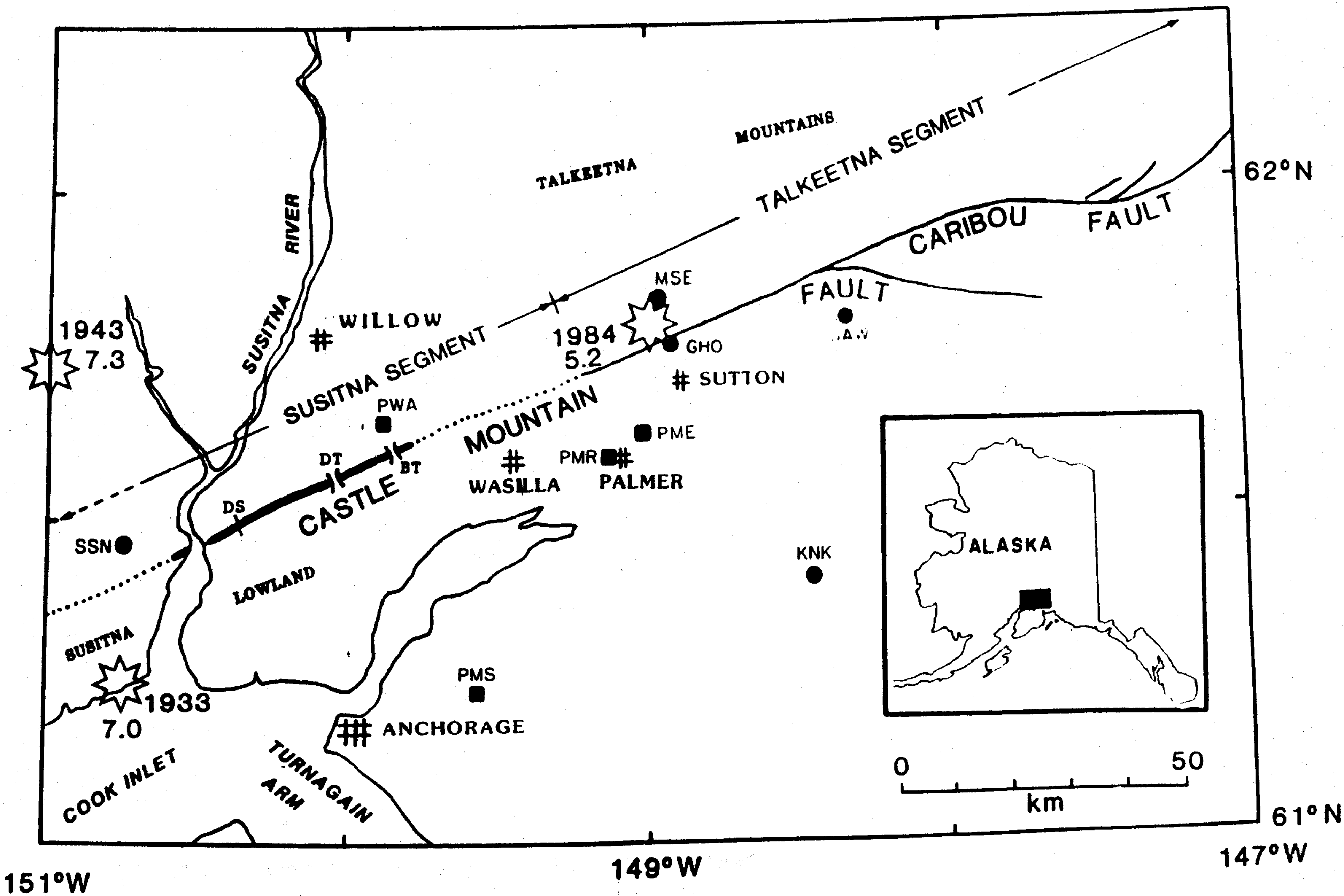
from Hansen, W.R., 1965, Effects of the earthquake of March 27, 1964, at Anchorage, Alaska: U.S. Geological Survey Professional Paper 542-A.

from Hansen, W.R., 1965, *Effects of the earthquake of March 27, 1964, at Anchorage, Alaska:* U.S. Geological Survey Professional Paper 542-A.



24.—Block diagram of a translatory slide.

4th Avenue Slide


TALKEETNA
MOUNTAINS
TALKEETNA SEGMENT
CARIBOU
FAULT
FAULT
62° N
SUSITNA RIVER
RIVER
WILLOW
1943
7.3
MSE
1984
5.2
GHO
SUTTON
SUSITNA SEGMENT
PWA
MOUNTAIN
PME
PMR
DT
BT
WASILLA
PALMER
CASTLE
DS
SSN
LOWLAND
KNK
ALASKA
SUSITNA
1933
7.0
PMS
ANCHORAGE
0
50
km
COOK INLET
TURNAGAIN
ARM
61° N
151°W
149°W
147°W

LATE-WISCONSIN EVENTS IN THE UPPER COOK INLET REGION, SOUTHCENTRAL ALASKA

by
Richard D. Reger,[1] Rodney A. Combellick,[1] and Julie Brigham-Grette [2]

ABSTRACT

New evidence and reconsideration of previously published evidence for late-Wisconsin events in the upper Cook Inlet region support the conclusions of Schmoll and others (1972) against criticism by Williams (1986). Nine new radiocarbon dates strongly confum the late-Wisconsinan age of the Bootlegger Cove Formation. We document Elmendorf age glacial advances in Knik Arm, Turnagain Ann, and elsewhere in southcentral Alaska as evidence that the Elmendorf advance was of regional significance and not a local aberration.

INTRODUCTION

Shoreline bluffs along Knik Arm and Turnagain Arm in upper Cook Inlet (fig. 1) expose well-preserved evidence of glacial and marine events late in the Naptowne glaciation(3). This complex record has been studied by many workers during the past 45 years, commonly with conflicting interpretations. The purpose of this article is to present new evidence related to these controversies.

HISTORY OF INVESTIGATIONS

The late-Pleistocene stratigraphic framework in the Anchorage area has been understood since the pioneering work by Miller and Dobrovolny, although the ages of various units have been controversial. They (1959, p. 35) first defined the Bootlegger Cove clay(4) as the silty clay that underlies most of the lowland in the vicinity of Anchorage and is conspicuously exposed in the bluffs along Knik Arm (fig. 1). They recognized that this formation overlies and interfingers with relatively coarse-grained glaciodeltaic deposits in southwest Anchorage (fig. 2). Dominant dip directions, decreasing grain size toward the east and southeast, and the presence of elastic coal convinced Miller and Dobrovolny (1959, p. 31) that the glaciodeltaic complexes in the Point Woronzof-Point Campbell area and on nearby Fire Island are related to glacial ice that entered the Anchorage lowland from the west or northwest. Clearly, they are, at least in part, the same age as the interlingering Bootlegger Cove Formation (BCF).

Till and outwash of the late-Naptowne Elmendorf advance overlie BCF in the Anchorage area (fig. 2). Miller and Dobrovolny (1959, p. 48) found local, 0.5- to O.6-m-thick oxidation zones in the uppermost BCF beneath outwash alluvium of the Elmendorf advance. They interpreted these zones as part of a weathering profile and, because of the thickness of the zones, concluded that a significant amount of time passed between BCF deposition and formation of the Elmendorf moraine. At that time they believed that the Elmendorf moraine marked the maximum extent of the Naptowne glaciation in the Anchorage area. They (1959, p. 84-86) attributed the glaciodeltaic complex and BCF to the late Knik glaciation, and they assigned an early Wisconsinan age to them. However, Cederstrom and others (1964) contended that Miller and Dobrovolny (1959) misinterpreted the temporal significance of permeable zones of groundwater staining between BCF and deposits of the Elmendorf advance in the Anchorage area. Cederstrom and his colleagues (1964, p. 41) argued that the BCF-is not much older than the Elmendorf moraine.

The environment of deposition of the BCF has also been the subject of some debate. Miller and Dobrovolny (1959, p. 44-45) acknowledged the presence of marine fossils in colluvium derived from BCF exposures but believed that the dominant evidence, including numerous dropstones and large erratics and varvelike laminations in some facies, supported a model of glaciolacustrine deposition..However, Schmidt (1963) discovered marine mollusks, foraminifera, and ostracodes in place in BCF and proposed that the environment of deposition was at least in part marine. Most other workers agreed that BCF was deposited in conditions of variable salinity, ranging from lacustrine to marine, with variations in glacier proximity (Karlstrom, 1964; Cederstrom and others, 1964, Trainer and Waller, 1965; Hansen, 1965). In 1967, Hopkins reported foraminifera and marine ostracodes throughout BCF and fairly abundant marine mollusks in the middle

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2-Department of Geology and Geography, Box 35820, University of Massachusetts at Amherst, Amherst, Massachusetts 01003-5820.
3-Named by Karlstrom (1953,1964) for a series of moraines in the vicinity of Sterling, then called Naptowne. in eastcentral Kenai lowland.
4-Renamed Bootlegger Cove Formation by Updike and others (1982) because clay is not the dominant grain size in most of the unit. For clarity, in this report we use the term "Bootlegger Cove Formation" even if the original references cited used the term "Bootlegger Cove clay."

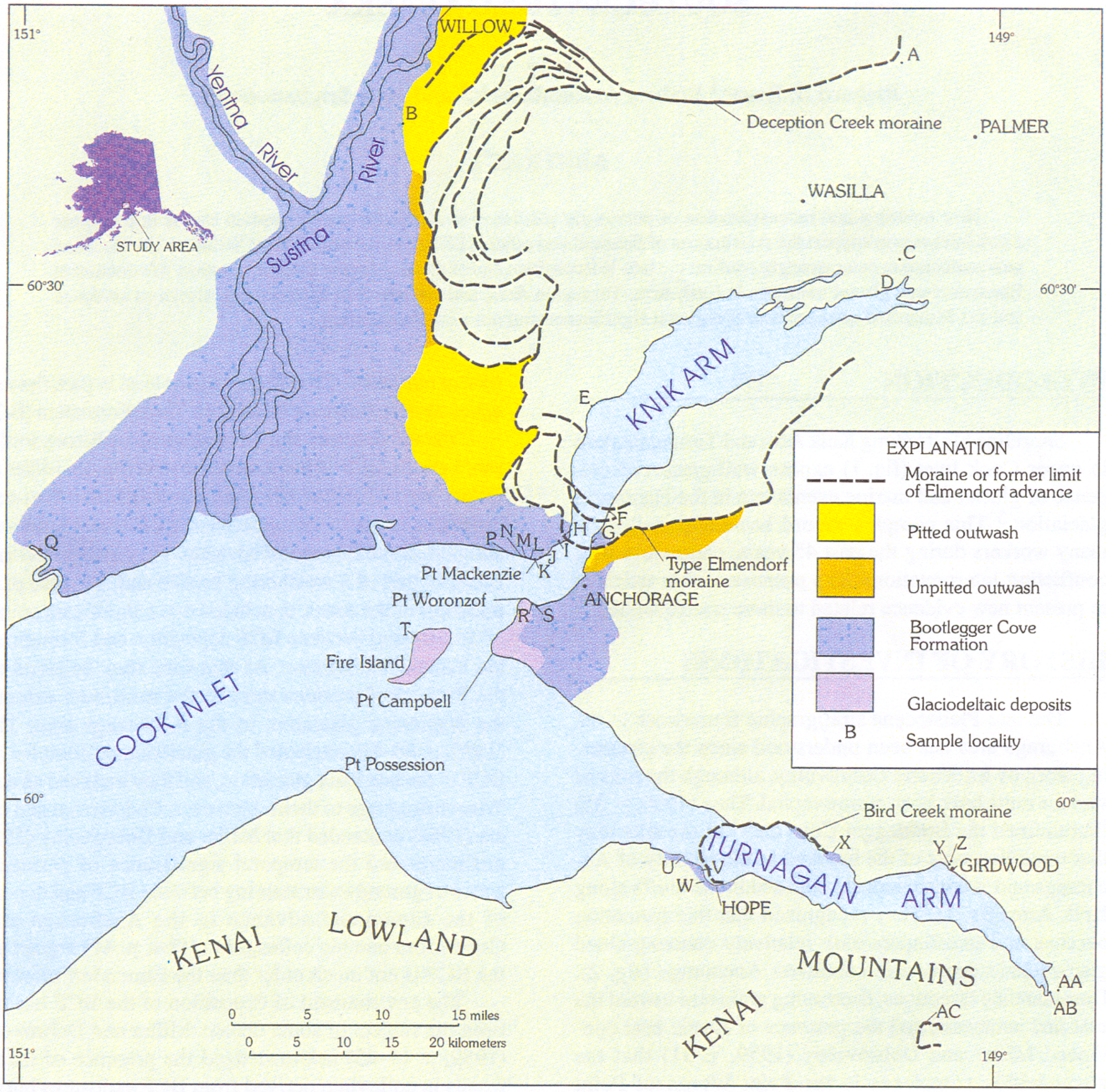

Figure 1. *Map showing sample localities and associated geologic units in the upper Cook Inlet region. (Modified slightly from Reger and Updike, 1983, sheet 1.)*

of the formation. He attributed the BCF to a marine invasion of upper Cook Inlet, which he named the Woronzofian transgression. The foraminifera indicate normal salinities during deposition of the lower BCF and low salinities during deposition of the upper BCF. Hopkins (1967, p. 82–83) recognized that isostatic and tectonic changes significantly affected the Woronzofian transgression in the Anchorage area.

Thus, BCF has been variously attributed to (1) the late Knik glaciation (Miller and Dobrovolny, 1959), (2) the late Knik and early Naptowne glaciations (Karlstrom, 1964; Trainer and Waller, 1965), and (3) a mid-Naptowne interstadial transgression (Hopkins, 1967). Karlstrom first attempted an absolute date of marine shells from the BCF and obtained a ^{230}Th age of 33,000–48,000 yr. In a key paper, Schmoll and others (1972) presented the results of radiocarbon analyses of four collections of marine shells from the upper BCF at three localities in the Anchorage area (fig. 1, localities H, J, and S) and uranium-series analyses of collections from two localities (fig. 1, localities J and S). The most reliable results indicate that the four shell samples range in age from 13,690 ± 400 to 14,900 ± 350 ^{14}C yr B.P. and average 14,160 ± 400 ^{14}C yr B.P. For the first time, the radiocarbon data provided solid evidence (1) that shell-bearing diamictons from separate exposures in the Anchorage area are close to the same age and (2) that, at its type locality, the Woronzofian transgression was a late-glacial submergence event (Hopkins, 1973).

After 1972, geologic mapping and additional radiocarbon dates helped clarify the late Wisconsin glacial history of the upper Cook Inlet region (Kachadoorian and others, 1977; Schmoll and Yehle, 1983, 1986; Reger and Updike, 1983; Ulery and Updike, 1983; Bartsch-Winkler and Schmoll, 1984; Schmoll and others, 1984; Updike and Ulery, 1986). The known distribution of BCF in the upper Cook Inlet region has been extended northwest as far as 60 km inland from Cook Inlet, west to lower Beluga River, and east into Turnagain Arm (fig. 1).

Recently, our work along Knik Arm and Turnagain Arm and elsewhere in the Cook Inlet region has concentrated on late Pleistocene and Holocene deposits and histories (Combellick, 1991, 1993, 1994; Combellick and Reger, 1994; Reger and Pinney, in press). These studies both confirm and challenge previous interpretations and provide important data on late Naptowne–Holocene events in the vicinities of Knik Arm and Turnagain Arm.

KNIK ARM EVIDENCE

The stratigraphy that we have seen is consistent with a model of deglaciation of the Anchorage area just prior to the Elmendorf glacial advance (Reger and Updike, 1983). Glaciodeltaic deposits in the southwest Anchorage–Fire Island area (figs. 1 and 2) formed when the pre-Elmendorf glacier stagnated and melted, discharging debris-laden streams into upper Cook Inlet, where deltaic deposits interfinger with BCF, the upper part of which is dated as old as 14,900 ± 350 ^{14}C yr B.P. (fig. 1 and table 1, loc. S). The presence of numerous dropstones, some block sized, especially in the lower BCF (Miller and Dobrovolny, 1959) is evidence that a calving glacier fronted in the same waters just prior to 14,900 ^{14}C yr B.P. The mass of the pre-Elmendorf glacier that occupied the Anchorage lowland depressed the land at least 86 m. This minimum depression is based on the difference between the highest level of BCF there and the worldwide sea-level curve about 14,000 ^{14}C yr B.P. (Reger and Pinney, in press) and implies that the pre-Elmendorf glacier was at least 258 m thick in the Anchorage lowland.[5]

Previously unpublished atomic-mass-spectrometer (AMS) dates for five collections of marine mollusk shells and barnacle plates from BCF just beyond the limit of the Elmendorf advance on the west side of Knik Arm support previous dating of the shell-rich zone of the BCF by Schmoll and others (1972) (fig. 1 and table 1, locs. I, K, M, N, and P). An AMS date of 13,470 ± 120 ^{14}C yr B.P. (table 1, loc. N) provides the youngest known age for the BCF in the type area.

[5]Based on the assumption that local bedrock and sediments with a density of 2.7 gm/cm^3 or greater are displaced downward at least 86 m by glacial ice with a density of 0.9 gm/cm^3. The upper Cook Inlet area in the vicinities of Knik Arm and Turnagain Arm has been tectonically lowered at rates of 0.13 to 0.3 cm/yr for at least 2,000 to 4,000 yr (Combellick, 1991, 1994). The long-term effect is to decrease the apparent maximum elevation of the BCF there, also decreasing the apparent isostatic depression. For this reason, and because former sea level was at least as high as the present highest exposure of BCF, our estimate is a minimum value.

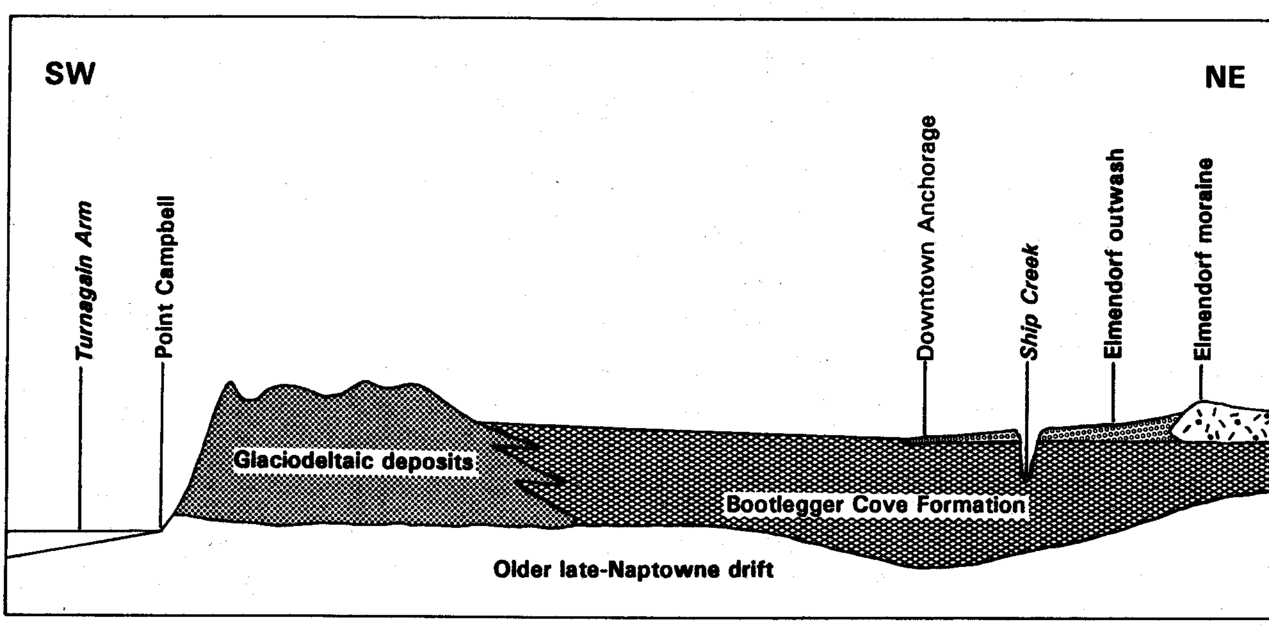

Figure 2. *Sketch of late Naptowne stratigraphy in the Anchorage area. (Generalized from Miller and Dobrovolny, 1959; Hansen, 1965; Schmoll and others, 1972; Schmoll and Barnwell, 1984; Updike and Ulery, 1986; and Yehle and others, 1991.)*

Table 1: Radiocarbon and calibrated ages and significance of selected organic samples in the upper Cook Inlet region

(next 4 pages)

Sample A locality	Material and stratigrapllic context	Chronological significance	Radiocarbon age b (14C yr BP.)	and 1range c (cal yr B.P.)	Source
A	Silty peat with scattered wood fragmets from base of 0.9-m-thick layer underlying 1.2-m-thick silty alluvial-fan sand and overlying gravelly sand deposited in ice-marginal bedrock channel	Minimum age for thinning of Elmendorf-age glacier blocking mouth of Little Susitna River canyon north of Palmer	9,155 +/ 215 (GX-5019)	10,040 9,650-10,860	Reger and Updike (1983, loc. C)
B	Organic silt 0.1 to 0.2 m below top of 1.0-m-thick silty and sandy peat underlying O.6-m-thick woody sphagnum peat and overlying 0.4-m-thick organic silt on top of sandy gravel at base of scarp cut into pitted outwash of Elmendorf age during estuarine transgression	Minimum age for outwash from Elmendorf-age moraine to east and cutting of scarp by glacio-estuarine waters in which BCFd deposited in Red Shirt Lake area	10,720 +/- 460 (GX-6041)	12,650 10,990-13,580	Reger and Updike (1983, loc. I)
C	Organic silt from depth of 7.7 m in estuarine deposits	Minimum age for recession of Elmendorf age glacier from upper Knik Arm	11.400 +/- 720e (GX-15241)	13,310 11,050-15,180	Combellick (1990, 1991, borehole KA6)
D	Organic silt from depth of 8.5 m in estuarine fjord filling	Minimum age for recession of Elmendorf-age glacier from upper Knik Arm	8,850 +/- 20fg (GX-15229)	9,880 9,520 - 10,030	Combellick (1990, 1991, borehole KA1)
E	Organic silt from depth of 3.8 m in estuarine deposits	Minimum age for recession of Elmendorf-age glacier from Goose Bay area, middle Knik Arm	9,255 +/- 420g (GX-15294)	10,210, 10,260, 10,280 9,400-l 1,670	Combellick (1990,1991 borehole KA4B)
F	Peat from base of paludal deposit overlying postglacial alluvium	Minimum age for recession of glacier from type Elmendorf moraine in lower Knik Arm	9,760 +/- 350 (W-2936)	10,970 lO,OlO-12,380	Yehle and others (1990,loc. 3)
G	Basal organic swamp deposits overlying till of type Elmendorf moraine	Minimum age for recession of glacier from type Elmendorf moraine in lower Knik Arm	12,350 +/- 350 (W-2589)	14,440 13,580-15,520	Yehle and others (1990, 1991, loc. 4)
H	Peat from beneath colluvium overlying till of type Elmendorf moraine	Minimum age for Elmendorf advance in lower Knik Arm	11,690 +/- 300 (W-2375)	13,630 13,000-14,370	Schmoll and others (1972, loc. F), Spiker and others (1977, p. 346)

H	Mollusk shells from macrofossil-rich zone in BCF	Dates middle or upper sublittoral glacioestuarine environment in which BCF deposited in lower Knik Arm	13,750 +/- 500 (W-2389)	15,9600 14,430-17,200	Schmoll and others (1972, loc. D), *Spiker* and others (1977, p. 346)
I	Hiatella arctica shells from 6 m below top of BCF and 0.3 m above pre- Elmendorf diamicton	Dates BCF in lower Knik Arm and minimum age for recession of pre-Elmendorf glacier from lower Knik Arm	14,308 +/- 14Ofg (AA-2226)	16,670 16,310-17.020	This study
J	Mollusk shells from macrofossil-rich zone of BCF	Dates middle or upper sublittoral glacioestuarine environment in which BCF deposited in Point MacKenzie area	14,300 +/- 350 (W-2367)	16,670 15,740-17,490	Schmoll and others (1972, loc. C), Spiker and others, 1977, p. 346)
K	Balanus plates from 1- to 2-cm-thick medium-coarse sand layers interbedded with clayey silt in upper BCF overlain by up to 5 m of fan-delta sand	Dates upper BCF at Point MacKenzie	14,100 +/- 90 fg (GX-19989)	16,420	This study
L	Organic silt from beneath 1.8 m-thick peat overlying 3-m-thick fan-delta sand above BCF	Minimum age for recession of pre-Elmendorf glacier and emergence from glacioestuarine waters in which BCF deposited at mouth of Knik Arm	12,250 +/- 140 (BETA-5580)	14,300 13,940-14,720	Reger and Updike (1983, p. 202)
M	Mya *truncata shells* from dropstone-rich diamicton 3 m below top of BCF	Dates upper BCF west of Point MacKenzie	14,078 214fg (GX-20128)	16,390 15,810-16,930	This study
N	*Mya trmcata* shells from silty clay facies of BCF 1 m above contact with ice-stagnation deposits of pre-Elmendorf age	Dates BCF at mouth of Knik Arm	13,470 +/- 120fg (AA-2227)	15,550 15,140-15,920	This study
P	Mya *truncata* shells from interbedded medium sand and silt layers up to 20 cm thick 6 m below top of BCF	Dates upper BCF west of Point MacKenzie	13,994 +/- 90 fg (GX-20127)	16,290	This study

a- See figure 1 for locations of sample sites.
b- based on Libby half-life for radiocarbon (5,570 yr) and referenced to AD. 1950.
c- Rounded to nearest 10 yr. Combines standard deviation in radiocarbon age and a conservative laboratory error multiplier of 2 to compensate for possible unreported laboratory errors (Stuiver and Pearson. 1986).
d- BCF = Bootlegger Cove Formation.
e- Because disseminated organic material. which could include very fine-grained detrital coal, was dated, this age could be spuriously old
f- Atomic-mass-spectrometer date.
g- Sample corrected for natural isotopic fractionation based on ^{13}C content.

Sample locality	Material and stratigraphic context	Chronological sigaiflcance	Radiocarbon age (14C yr B.P.)	Calibrated mean age and 1 range (cal yr B.P.)	source
Q	Shells in glacioestuarine silt and clay of BCF	Dates BCF in lower Beluga River area	14,350 +/- 200 (W-4292)	16,730 16,220-17,210	Schmoll and Yehle (1983, loc. B; 1986. loc. B5), Schmoll and others (1984, loc. B5)
R	Peat from base of 2.4-m-thick bed overlying 3 m of sand that overlies 1.8 to 3 m of BCF	Minimum age for emergence from glacioestuarine waters in which BCF deposited in Point Woronzof area	11,600 +/- 300 (W-540)	13,530 12,920-14,250	Rubin and Alexander (1960, p. 165), Miller and Dobrovolny (1959, p. 68, pl. 9). Schmoll and others (1972, loc. E)
S	Mollusk shells from macrofossil-rich zone of BCF	Dates middle or upper sublittoral glacioestuarine environment in which BCF deposited in Point Woronzof area	13,690+/-400 (W-2151)	15,870 14,620-16,900	Sullivan and others (1970. p. 333), Schmoll and others (1972, loc.A)
S	Mollusk shells from macrofossil-rich zone of BCF	Dates middle or upper sublittoral glacioestuarine environment in which BCF deposited in Point Woronzof area	14,900 +/- 350 (W-2369)	17,370 16,540-18,130	Schmoll and others (1972,loc. B), Spiker and others (1977, p. 346)
T	Peat from base of I.8 m-thick bed overlying BCF	Minimum age for emergence from glacioestuarine waters in which BCF deposited in Fire Island area	11,450 +/- 150 (BETA-5581)	13,360 13,060-13,710	Reger and Updike (1983, p. 202)
U	*Macoma balthica* shells from 3-m-thick. dropstone-rich, thin-bedded sand in upper BCF overlain by 3 m of colluvium	Dates upper BCF just beyond Ehnendorf maxium west of Hope in Turnagain Arm	13,718 +/- 160fg (GX-20129)	15,910 15,420-16,350	This study
V	*Hiatella arctica* and *Macoma balthica* shells from colluvium derived from BCF	Dates BCF and nearby Elmendorf-equivalent advance in Hope area	14,160 +/- 140fg (GX-16529)	16,500 16,130-16,850	This study

W	*Hiatella arctica* shells from colluvium derived from BCF	Dates BCF and nearby Elmendorf-equivalent advance in Hope area	14,200 +/- 100fg (GX-17133)	16,550 16,280-16,810	This study
X	Mollusk shells from colluvial bedrock rubble incorporating reworked BCF	Dates BCF and maximum age for Elmendorf-equivalent advance in upper Turnagain Arm	13,900 +/- 400 (W-2919)	16,160 14,940-17,150	Schmoll and Yehle (1983, loc. A; 1986, loc. B4), Bartsch-Wmkler and Schmoll(l984)
X	*Macoma balthica* shells from BCF incorporated into till of Elmendorf-age advance	Dates BCF and maximum age for Elmendorf-equivalent advance in upper Turnagain Arm	14,290 +/- 140fg (GX-16524)	16,660 16,300-17,000	This study
Y	Organic silt from depth of 16.8 m in estuarine deposits	Minimum age for recession of Elmendorf-age glacier from Girdwood area	10,375 +/- 310 (GX-15215)	12,260 10,970-12,920	Combellick (1990,1991. borehole TAl)
Z	Compressed wood and peat from beneath diamicton and estuarine silt and clay and overlying bedded deltaic gravel	Minimum age for recession of Elmendorf-age glacier from Girdwood area and deposition of BCF in upper Turnagain Arm	10,180 +/-350 (W-2302)	11,920 10,480-12,810	Bartsch-Winkler and Schmoll (l984)
AA	Wood fragments from laminated silt near depth of 93 m in estuarine deposits	Minimum age for recession of Elmendorf-age glacier from head of Turnagain Arm	8,230 +/- 100 (-)	9,210 8,960-9,440	Bartsh-Winkler and others (1983), Bartsh-Winkler andSchmoll (1984)
AB	Organic silt from depth of 15.4 m in estuarine deposits	Minimum age for recession of Elmendorf-age glacier from head of Turnagain Arm	10,730 +/- 525 (GX-15224)	12,660 10,940-13,740	Combellick (1990, 1991, borehole TA8)
AC	Peat from depth of 1.8 m in organic sediments ponded behind outer end moraine	Minimum age for readvance of glaciers from Tincan Creek and Lyons Creek valleys after recession of Elmendorf-age glacier from upper Turnagain Arm	9,850 +/- 390 (GX-10649)	11,000 10.020-12,560	This study

a- See figure. 1 for locations of sample sites.
b- Based on Libby half-life for radiocarbon (5,570 yr) and referenced to A.D. 1950.
c- Rounded to nearest 10 yr. Combines standard deviation in radiocarbon age and a conservative laboratory error multiplier of 2 to compensate for possible unreported laboratory errors (Stuiver and Pearson, 1986).
d-BCF = Bootlegger Cove Formation.
e-Because disseminated organic material, which could include very finegrained detrital coal, was dated, this age could be spuriously old
f-Atomic-mass-spectrometer date.
g-Sample corrected for natural isotopic fractionation based on 13C content.

Northwest of Point MacKenzie is a large outwash fan that is genetically related to the type Elmendorf moraine, which Schmoll and others (1972) bracketed between 11,690 +/- 300 14C yr BP (table 1,loc. H) and 13,750 +/- 400 14C yr BP. (table 1,loc. S) (fig. 1). This fan is unmodified and clearly postdates the Woronzofian transgression. However, scarps that truncate early Elmendorf outwash and end moraines related to the Deception Creek moraine near Willow were cut west of Wasilla during the Woronzofian transgression (fig. 1,loc. B). These physiographic relations are evidence that the Woronzofian transgression at least in part postdates the early phase of the Elmendorf advance. The main erosion scarp there is older than a basal peat, which dates 10,720 +/- 460 14C yr B.P. (table 1,loc. B).

Radiocarbon dating of basal freshwater peats that overlie BCF provides minimum ages for isostatic rebound of the Anchorage lowland from beneath estuarine waters in which BCF was deposited. These dates range from 11,450 +/- 150 14C yr B.P. (table 1,loc. T) to 12,350+/- 350 14C yr B.P. (table 1,loc. G). We speculate that land emergence began generally just after culmination of the Elmendorf glacial advance, which in Knik Arm probably occurred about 13,500 14C yr B.P. in response to the interaction of eustatic, isostatic; and tectonic conditions (fig. 3).

Not long after the culmination of the Elmendorf advance, the expanded glacier system from lower Matanuska and Knik valleys developed a negative budget. The final phase of the Naptowne glaciation is characterized by ice stagnation and retreat, widespread meltwater activity, and rapid downcutting by streams (Reger and Updike, 1983). Radiocarbon dates of organic sediments from deep boreholes in paludal and estuarine deposits provide minimum ages for deglaciation of Knik Arm (fig. 1, lots. C, D, E, and F). A generalized time-distance curve, tentatively based on available physiographic and stratigraphic evidence, indicates that by 11,400 14C yr B.P. the Elmendorf glacier had retreated at least 47 km from the terminal moraine just north of Anchorage (fig. 3). However, the northeastern end of this curve is based on a single radiocarbon date of organic silt in estuarine deposits, and we are suspicious that this date is spuriously old because of possible contamination by very fine-grained detrital coal (table 1,loc. C). Pitting of low terraces of the Matanuska River near Palmer is evidence that stagnant glacial ice, probably from Knik Glacier, existed there until quite late, perhaps into the early Holocene (Reger and Updike, 1983, p. 230). A date of 9,155 +/- 215 14C yr BP (table 1,loc. A) for basal peat in an ice-marginal channel at the mouth of the upper canyon of Little Susitna River provides a minimum age for deglaciation there (fig. 1 and table1, loc. A),

TURNAGAIN ARM EVIDENCE

Kachadootian and others (1977) described a complex stratigraphy along the southern shore of Turnagain Arm in the vicinity of Hope that resulted from a late-Wisconsin glacial advance westward down the shallow fjord. During this episodic advance, the glacier overrode its own outwash as well as associated deltaic and marine sediments. According to their model (p. B50), the advance terminated about 2 km west of Hope, where the upper limit of the massive terminal moraine stands at a modem elevation of 83 m. Although they did not mention the presence of marine fossils in the oldest exposed sediments and provided no radiocarbon ages, the authors correlated the basal deposits with the BCF.

In 1982, in discontinuous exposures through the dense alder vegetation for about 5 km along the southern shore of Tumagain Arm west of Hope, we observed a fine-grained, undeformed diamicton that contains marine shells, many unbroken, and is locally rich in cobbles and boulders, especially in the upper part of the unit (fig. 1,locs. U, V, and W). We did not find the thick morainal diamicton that Kachadoorian and others (1977, p. B49) reported overlies outwash, deltaic deposits and the BCF there, but exposures were very limited in extent. We measured the top of the fossiliferous unit at between 3 and 12 m above the high-tide line. AMS ages for marine mollusk shells in the undeformed diamicton west of Hope are 13,718+/-160 14C yr B.P. (table 1, lot. U), 14,160 +/- 140 14C yr B.P. (table 1, lot. V), and 14,200 +/- 100 14C yr B.P(table 1, lot. W). These ages confirm correlation of this fossiliferous deposit with type BCF in the Anchorage area by Kachadoorian and others (1977, p. B49).

During our traverse, we noted that there is a contrast in the degree of deformation of BCF east and, west of Hope. About 1 km east of Hope, shells in the clay-rich BCF diamicton are rare and severely crushed. Farther east we could not find fossils in the BCF. Our impression was that the deformation is pervasive and widespread throughout the unit there, which argues against local deformation by grounding ice bergs. In contrast, the BCF west of Hope is undeformed. We propose that the glacier that advanced westward down Turnagain Arm during deposition of the upper BCF was grounded at least during low tides as far west as Hope. The undeformed nature of the BCF and the presence of unbroken marine-mollusk shells west of Hope are evidence that floating, not grounded ice was the source of the large clasts in the upper BCF there. We suggest that the BCF accumulated in glacioestuarine waters there as a result of (1) the rainout of material from turbid sediment plumes related to efflux jets emerging from beneath the nearby glacier and (2) dropstone deposition from the floating terminal zone of the tidewater

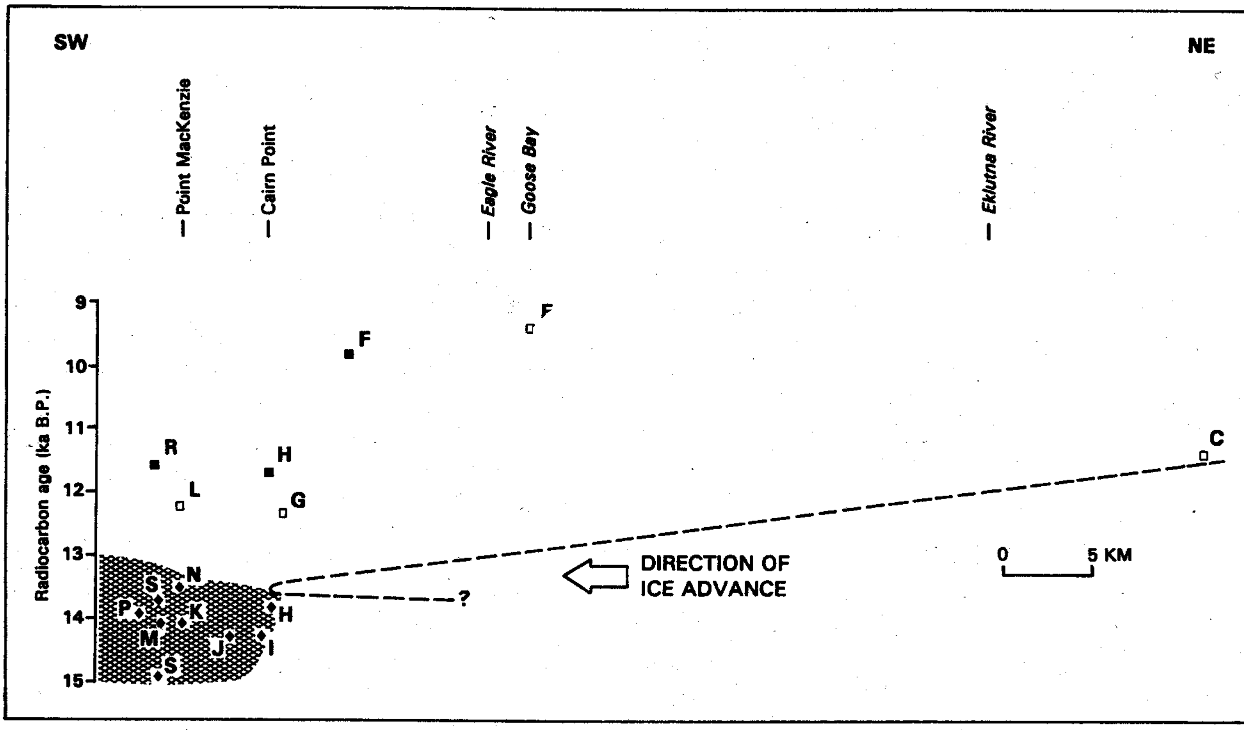

Figure 3. *Tentative time-distance curve for Elmendorf advance in Knik Arm. Letters refer to locations in figure 1 and table 1. Symbols:* □ = *organic silt,* ■ = *peat,* ♦ = *shell, BCF = Bootlegger Cove Formation.*

glacier, an ice shelf, or from debris-laden, melting ice bergs (Eyles and McCabe, 1989). We correlate the terminal position at Hope with the Bird Creek moraine, which is reported to overlie BCF on the northern shore of Turnagain Arm (Bartsch-Winkler and Schmoll, 1984; Schmoll and others, 1984, fig. 7; and Schmoll and Yehle, 1986, fig. 5), and with the type Elmendorf moraine (fig. 1).

In 1982, we also revisited the shell-bearing diamicton at Mile 99.5 Seward Highway, where Dobrovolny and Schmoll discovered and dated crushed marine shells at 13,900 ± 400 ^{14}C yr B.P. (table 1, loc X). The highway-cut exposure there was about 15 m above the high-tide line before subsequent highway realignment destroyed it. Dobrovolny and Schmoll interpreted the exposure to be colluvial bedrock rubble that incorporated reworked BCF (Schmoll and Yehle, 1986, p. 205). We suggest that the Mile 99.5 exposure can also be interpreted as BCF that was overridden by a glacier that advanced westward into estuarine waters of Turnagain Arm. The shells could have been preserved there in the lee of the bedrock shoulder, although perhaps badly broken as we found them, if the overriding glacier was partially floating. Our collection of severely fragmented *Macoma balthica* shells from that locality has an AMS age of 14,290 ± 140 ^{14}C yr B.P. (table 1, loc X). The weighted average age of our collection and that of Dobrovolny and Schmoll is 14,245 ± 270 ^{14}C yr B.P., which is essentially the same age as shells preserved in BCF near Hope, 8 km to the west (fig. 1).

Their interpretation of the Mile 99.5 exposure and a tenuously extrapolated age of about 14,000 ^{14}C yr B.P. for basal sediments in the thick fjord fill at the head of Turnagain Arm (Bartsch-Winkler and others, 1983) (fig. 1, loc. AA) convinced Bartsch-Winkler and Schmoll (1984) and Schmoll and Yehle (1986) that Turnagain Arm was free of glacial ice about 14,000 ^{14}C yr B.P. However, we question the estimate of about 14,000 ^{14}C yr B.P. for the age of basal sediments in the >303-m-thick fill at the head of Turnagain Arm. Their estimate is based on an assumed sedimentation rate that was derived from four radiocarbon samples, the oldest of which is 8,230 ± 100 ^{14}C yr B.P. (table 1, loc AA) at a depth of only 93 m in the thick fill (Bartsch-Winkler and others, 1983, fig. 11). In our opinion, the actual sedimentation rate probably varied considerably, especially between depths of 90 m and the base of the thick fjord fill in that part of the section deposited in late glacial time, when sedimentation rates were undoubtedly much higher than Holocene rates. Our skepticism is reinforced by the presence of a clay and rock unit, which is probably till, at a depth of 210–225 m in the 305-m water well at that location (Bartsch-Winkler and others, 1983, fig. 10).

A simplified and tentative time-distance curve (fig. 4) reflects our belief that the Elmendorf advance in Turnagain Arm terminated about 14,000 ^{14}C yr B.P in shallow estuarine waters at Hope. West of Hope, diamictons of this age probably accumulated in glacioestuarine conditions.

Undoubtedly, waxing and waning of the trunk glacier in Turnagain Arm were interrupted by minor still-stands and even reversals. The stratigraphy preserved along the southern shore of Turnagain Arm just east of Hope records these events (Kachadoorian and others, 1977). By 10,730 ± 525 ^{14}C yr B.P. (table 1, loc. AB), ice had retreated at least 44 km up Turnagain Arm. A date of 10,180 ± 350 ^{14}C yr B.P. (table 1, loc. Z) is a minimum age for a post-Elmendorf delta at a present elevation of about 12 m in the Girdwood area. Peat in organic sediments ponded against a small terminal moraine in Turnagain Pass (Combellick, 1984) dates 9,850 ± 390 ^{14}C yr B.P. (table 1, loc. AC). The age of the peat demonstrates that glaciers had retreated nearly to the heads of tributary valleys in the nearby Kenai Mountains and then readvanced just before the end of the Naptowne glaciation (fig. 4).

OTHER EVIDENCE

Reger and Updike (1983) proposed that simultaneous expansion of glaciers from lower Matanuska and Knik valleys resulted in the Elmendorf advance. Williams (1986) dated a basal peaty silt overlying till in a depression filling <0.2 km from the terminus of Matanuska Glacier at the head of Matanuska valley about 73 km east-northeast of Palmer. Samples of the organic silt date 13,100 ± 60 ^{14}C yr B.P. (USGS-2175) and 12,210 ± 210 ^{14}C yr B.P. (BETA-11174), which provides a local minimum limiting age for the late Naptowne retreat of Matanuska Glacier. These dates encouraged Williams (1986, p. 87) to question dating of the type Elmendorf moraine at Anchorage and to challenge interpretations of stratigraphic relations between BCF and deposits of the Elmendorf advance (Schmoll and others, 1972; Reger and Updike, 1983; Schmoll and Yehle, 1986). Evidence presented in this report reaffirms the previous interpretations. We emphasize that Matanuska Glacier was not the only source of ice in lower Matanuska valley. Several large tributary glaciers entered middle Matanuska valley from the Talkeetna Mountains to the north. Although the floor of upper Matanuska valley is deeply scoured bedrock and no obvious ice limits have been identified during casual observations, ice-stagnation and associated glaciofluvial deposits related to former glaciers in the middle and lower valley are mentioned in guidebooks of the area (Reger and Updike, 1983; Clardy and others, 1984). We further contend that radiocarbon dates from Kenai Peninsula, Chugach Mountains, St. Elias Mountains, and southeastern Alaska, which Williams (1986) cited as evidence against our dating and interpretation of the late-Naptowne

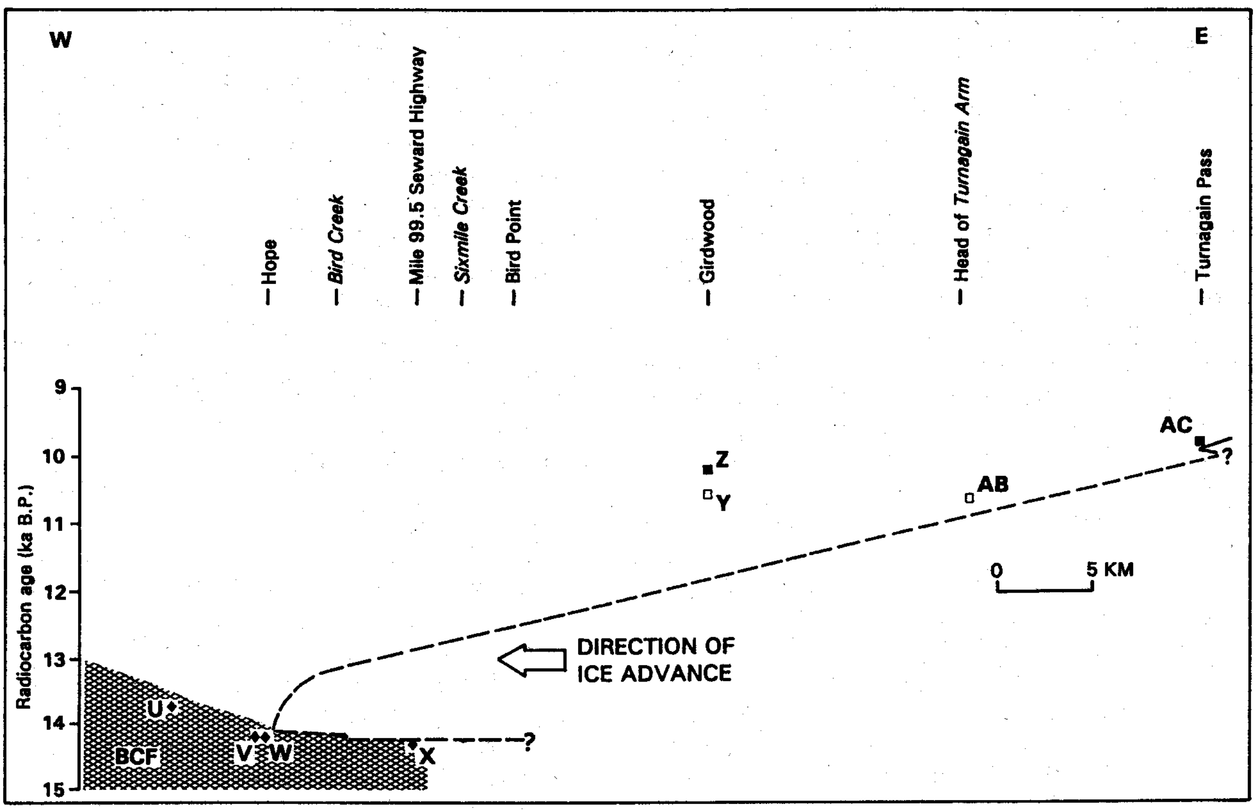

Figure 4. *Tentative time-distance curve for Elmendorf advance in Turnagain Arm. Letters refer to locations in figure 1 and table 1. Symbols: □ = organic silt, ■ = peat, ♦ = shell, BCF = Bootlegger Cove Formation.*

record in the Anchorage area, actually relate to pre-Elmendorf deposits and events. This is certainly the case at Hidden Lake in the eastcentral Kenai lowland, where the lake basin was deglaciated at the end of the pre-Elmendorf Skilak stade of the late Naptowne glaciation (Reger and Pinney, in press).

Evidence in the upper Cook Inlet region demonstrates that the Elmendorf advance in the Anchorage area was not an isolated late Naptowne event as suggested by Williams (1986). After considering physiographic and stratigraphic evidence, Reger and Pinney (in press) attribute range-front ice limits in many valleys in the western Kenai Mountains to the Elmendorf advance. In the Valdez area, Wilber and others (1991) found physiographic and stratigraphic evidence that Port Valdez became ice free at the end of the Skilak stade. They correlated a subsequent glacial advance that built moraines at the mouths of tributary valleys with the Elmendorf advance. Reger (1991) published a minimum age of 11,820+/-560 14C yr BP. (GX-10,789) for the readvance of ice out of the valley of Allison Creek on the southern shore of Port Valdez and correlated that event with the Elmendorf advance in upper Cook Inlet.

CALIBRATION OF RADIOCARBONDATES

To this point in this paper we have not complicated our presentation by introducing calibrated radiocarbon dates. However, past variations in radiocarbon content of the atmospheric and marine reservoirs introduced significant errors in the radiocarbon time scale. Available calibration programs, although not yet perfected, at least partly correct these errors as far back as 18,760 14C yr BP (21,950 cal yr BP.) (Stuiver and Reimer, 1993). For terrestrial samples, detailed calibrations are based on changes in the radiocarbon contents of dendrochronologically-dated tree rings; for marine shells in the time range of our study, corrections are based on uranium-thorium and radiocarbon dating of corals.

Clearly, if we are to keep the sequence of late Naptowne events in upper Cook Inlet in proper perspective, we need to consider the effects of calibration on radiocarbon ages related to these events. In table 1 we list both radiocarbon and calibrated dates and relate them to significant events in upper Cook Inlet. We ignore small potential errors that are due to local variations in the 14C content of the estuarine waters of Cook Inlet. And we do not compensate for possible errors up to 400 14C yr due to comparison of 11 dates that are corrected for fractionation, based on their 13C contents, with 20 dates that are not corrected for fractionation.

When we compare mean ages, the main effect of converting radiocarbon ages to calibrated (calendar) ages is to extend back in time the Holocene and late Naptowne events in upper Cook Inlet. According to the calibrated time scale provided by CALIB 3.0 (Stuiver and Reimer, 1993), the oldest dated event, deposition of the shell-rich zone in the type area of the BCF, occurred between 15,140 and 18,130 cal yr BP (table 1, locations N and S). Interfingering relations between the glaciodeltaic complex and BCF indicate that stagnant ice existed in the south Anchorage-Fire Island area at the same time. The type Elmendorf moraine was built between 13,000 and 17,200 cal yr B.P. (table 1, loc. H). In Turnagain Arm, shell-bearing BCF was deposited between 14,940 and 17,000 cal yr B.P. (table 1, lots. U, V, W, and X), and the Elmendorf advance down Tumagain Arm culminated shortly after. The land surface in the Anchorage area rebounded out of Cook Inlet waters before freshwater peats began accumulating there between 13,060 and 15,520 cal yr B.P. (table 1, locs. T and G). The latest Naptowne advance in Turnagain Pass ended between 10,020 and 12,560 cal yr BP. (at lo) (table 1, loc. AC).

CONCLUSIONS

Recently acquired evidence reaffirms previous dating of the upper BCF in the Anchorage area and supports previous interpretations of the stratigraphy and history by Schmoll and others (1972). Reger and Updike (1983), and Schmoll and Yehle (1983). The BCF was deposited during and after deposition of a glaciodeltaic complex in the south Anchorage-Fire Island area and just before the height of the type Elmendorf advance about 13,500 14C yr BP. (roughly 16,200 cal yr B.P.). We concur with previous correlations of shell-bearing glacioestuarine deposits in Tumagain Arm with the type BCF (Schmoll and Yehle, 1983,1986; Schmoll and others, 1984). However, we believe there is strong evidence for an Elmendorf-equivalent advance in Turnagain Arm that culminated in shallow estuarine waters at Hope about 14,000 14C yr BP (about 16,270 cal yr B.P.).By about 9,85014 C yr B.P. (11,000cal yr BP.) tributary glaciers in Tumagain Arm had receded nearly to the heads of source valleys and then readvanced slightly. Comparison with late Naptowne events elsewhere in southcentral Alaska indicates that the Ehmendorf advance was regionally significant and not a local aberration as suggested by Williams (1986).

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R. Foster, Curator for Invertebrate Collections, University of Alaska (Fairbanks) Museum. Thoughtful reviews by Thomas D. Hamilton (USGS) and Jeffrey T. Kline (DGGS) helped clarify this paper. Radiocarbon ages were determined by University of Arizona (AA), Beta Analytic (BETA), Geocbron Laboraties (GX), and United States Geological Survey (W) (table 1).

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Introduction to Tertiary Tectonics and Sedimentation in the Cook Inlet Basin

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Introduction

Tertiary rocks of the Cook Inlet Basin record the geology of an active plate boundary and associated cycles of deposition in a forearc setting. Beginning with the subduction of the Kula oceanic plate and spreading center, Cenozoic tectonics were the driving force of a complex geologic system that in places accumulated over 25,000 feet of non-marine stratigraphy. Variation in uplift histories of adjacent tectonic blocks provided both sediment input and stress needed for formation of structures that accumulated both gas and liquid hydrocarbons.

The regional Tertiary stratigraphic column is separated into 5 distinct non-marine lithologic units. These formations are regionally time transgressive and represent laterally equivalent facies that were deposited in a elastic dominated basin. The current depositional model suggests that alluvial fans carried sediment off the uplifting margins and provided the bulk of sediment influx. A migrating axial fluvial system produced an environment for the thick accumulation of sandstone, siltstone, and coal near the. basin center. Plio/Pleistocene tectonic activity caused dramatic change in the deposystem and contributed to uplift that exposed the Tertiary stratigraphy.

The ideas presented in this paper come from years of research by many scientists within the oil industry, government and academia. Much of the recent work contains proprietary information and cannot be presented here. However, it is the author's hope that this general outline will provide the reader with a basic understanding of the geology of the Cook Inlet region. A reference list of research papers is included for more detailed models and data .

Cook Inlet Basin

The Tertiary Cook Inlet Basin can be defined as an elongate, northeast trending, fault-bounded forearc basin that extends from the Matanuska Valley south along the Alaskan Peninsula (see Plate II). Although the basin geometry appears relatively straight forward, dramatic geologic variation is evident along trend. For example, variation in uplift/subsidence rates along the basin axis has greatly affected thickness of the present Tertiary section. Where preserved in the Kenai area, Eocene through Pliocene sediments are up to 25,000 feet thick whereas Tertiary strata over the Seldovia Arch thins to less than 1500 feet in thickness.

Figure 1 shows the present-day geometry and location of major basin-bounding faults that have controlled much of the tectonic history. The Bruin Bay and Castle Mountain fault zones make up the northern and northwestern boundaries and separate the uplifted volcanic arc complex from the Tertiary depocenter. Much of the deformation along the northwest margin of the basin was related to motion on these faults and resulted in structural traps for hydrocarbon accumulation.

The Border Ranges Fault to the southeast separates the Tertiary basin from the Chugach Terrane. This tectonic block is an emergent accretionary prism composed of metasedimentary and metaigneous rocks abducted at the plate boundary. Continued subduction/abduction processes along the Aleutian Trench caused thermal alteration, rotation, and uplift of these rocks during the Late Cretaceous (figures 3 & 4).

Both the Chugach and Peninsular/Wrangellia geologic terranes, adjacent to the Tertiary Basin, provided detritus for the thick sedimentary package. Variation in mineralogy, depositional style, and accumulation rates of the Tertiary stratigraphy record changes in uplift of these terranes and understanding the tectonic histories has been critical in deciphering the geology of the Cook Inlet.

Tectonic History

Evidence for active tectonism in the Cook Inlet region spans back to the Late Triassic with onset of subduction and~change from shelfal carbonates of the Kamishak Formation to oceanic arc volcanism and sedimentation of the Talkeetna Formation (Wang, 1988). It is not clear how subduction was initiated, but the change in depositional patterns was dramatic. Nearly all Cook Inlet sedimentation following this event can be related to deposition in a foreland/forearc setting with episodic uplift and erosion to the north. Unroofing of the arc-related highlands provided sediment for Mesozoic forearc deposits which presently make up the 'basement' for the Tertiary basin.

Figure 2 is a general stratigraphic column relating the tectonic events with stratigraphy. Periodic uplift and pulses of deformation created numerous unconformities and change of depositional environments from marine to non-marine. The Late Cretaceous marks the final emergence of the basin with a marked unconformity at the Paleocene and Early Eocene boundaries. All subsequent deposition was non-marine and derived from both the volcanic arc to the northwest and the exposed accretionary prism to the southeast.

The Aleutian Subduction Zone was also undergoing dramatic changes during the Early Tertiary. Figure 3 is a cartoon depiction of the overall geometry of the plate boundary well into its evolution. Morphologic and geologic variation of the down-going slab had the greatest influence on basin evolution, including local and regional tcctonism of the overriding plate. Subduction of the Kula Plate and spreading center in Early Eocene is thought to be the driving force for the early Tertiary deformation and increased tectonism (Byrne, 1979, Pavlis, 1982). Thermal effects associated with that event can be observed throughout southern Alaska and include near-trench plutonism and gold-quartz vein mineralization.

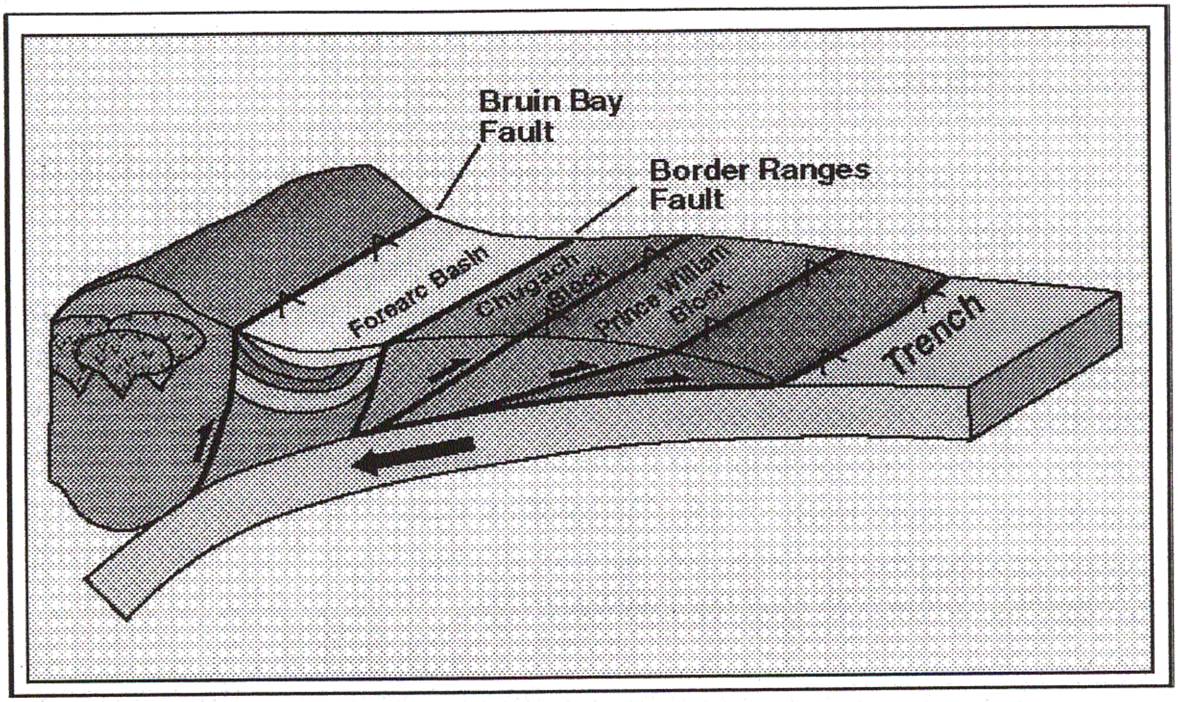

Figure 3: General tectonic configuration of Cook Inlet Basin and associated subduction zone (From Doherty, et.al., 1994)

Following Kula spreading ridge subduction, the Cook Inlet basin underwent a phase of rapid subsidence and deposition resulting in a very thick section of non-marine sandstone, coal, and siltstone. Although there are numerous unconformities in the section, this subsidence and depostional environment continued until the end of Pliocene time when the latest phase of tectonism deformed the basin margins. Many of these recent folds are tight asymmetric anticlines associated with transpressional strain from right lateral motion on the northern basin-bounding faults. This lateral stress could be associated with accretion/collision of the Yakutat continental block (Figure 4) during Late Tertiary.

Figure 4 is a generalized tectonic map which shows the modern elements of the Southern Alaska tectonic boundary and Cenozoic stratigraphy. Understanding the distribution of structures, volcanic centers, and non-marine depocenters has been critical in deciphering the history of the basin as a whole.

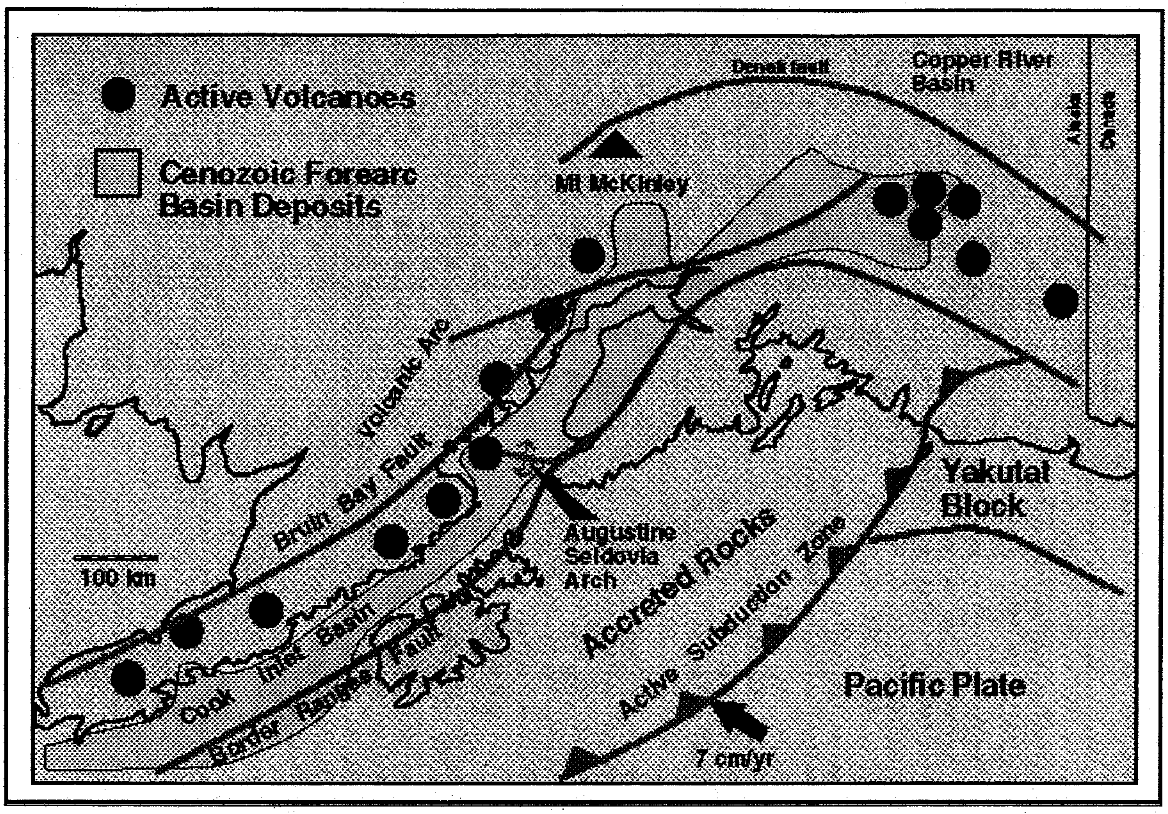

Figure 4: Present day tectonic framework and Cenozoic forearc basin deposits (from Doherty et.al., 1994)

Tertiary Statigraphy

The Tertiary section is as thick as 25,000 feet near the northern basin axis and thins radically to both the basin edges, as well as to the south towards the Augustine-Seldovia Arch. Unit identification, age control, and facies relationships within the units has undergone many iterations and is based on both outcrop and well data.

Tertiary rocks were first identified as the "Kenai group" by Dall and Harris in 1892 and further refined by Parkinson in 1962 using well control from the Swanson River Field. Calderwood and Fackler, 1972, studied five widely separated "type" well logs and elevated the "Kenai" to Group status. Based on their correlation, they assigned five formation names that are retained in the present nomenclature. Much work has been done since that time to refine the stratigraphy and age assignments, and provide depositonal models to better understand the distribution of facies.

As mentioned in the previous section, subduction of the Kula oceanic plate and spreading center dominated the Early Tertiary tectonics and initiated the final phase of non-marine clastic deposition within the basin. The generally angular unconformity at the base of the Tertiary section separates Mesozoic stratigraphy from overlying Paleocene/Eocene volcaniclastic rocks. The amount of stratigraphic section missing at this boundary varies widely and ranges from Eocene on Jurassic, to Paleocene on Cretaceous. Figure 5 is a generalized stratigraphic column for the Tertiary Cook Inlet.

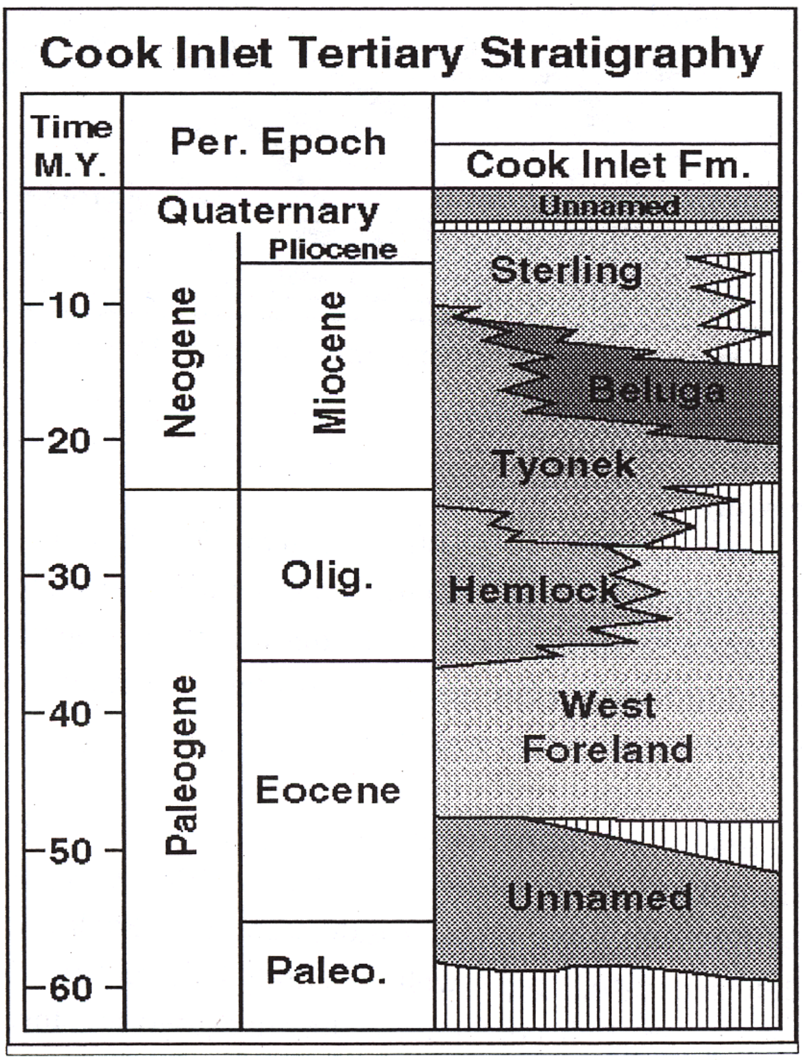

Figure 5: Generalized Cook Inlet Tertiary Stratigraphy

The formal lithologic units include the Sterling, Beluga, Tyonek, Hemlock and West Foreland Formations, all of which are non-marine. Identification of these units has historically been based on lithologic character and well log correlation. Recent research by ARC0 personnel suggests that many of the lithologic units are time transgressive, laterally correlative facies related to a dynamic non-marine depositional system. More details concerning this research will be published at a later date. (also see Flores and others, this volume)

The oldest Tertiary units in the inlet outcrop in the Matanuska Valley and contain four distinct non-marine facies of Paleocene/Eocene age. .These formations are the Tsdaka, Wishbone, Chickaloon and Arkose Ridge. The lateral extent of these units, and distribution of Paleocene strata in the subsurface is limited (Magoon and Claypool, 1979) and record initial Tertiary uplift and cessation of Mesozoic depositional patterns. The Paleocene section is shown as un-named in the basin-wide stratigraphic section.

The Eocene/Oligocene West Foreland Formation is tuffaceous sand and conglomerate that, with the exception of the localized 'un-named' Paleocene unit, makes up the basal part of the inlet-wide Tertiary section. The dominant lithic component of the coarse facies is volcaniclastic which coincides with increased volcanism associated with subduction of the Kula spreading.center. The West Foreland and overlying Hemlock Conglomerate are often hard to distinguish because of their similar lithology and log character and are primarily distinguished by mineralogical variation.

The Hemlock Conglomerate overlies the West Foreland and is an important oil reservoir for the inlet . This unit is Oligocene in age and comprised predominantly of fine to coarse grained sandstone and conglomerate. Dominant mineralogies within the sands are quartz, feldspar, and metamorphic/plutonic rock fragments which explains the increase in reservoir quality. The fine grained facies of this unit are siltstone and tuffaceous siltstone which locally contain coal beds.

The Tyonek Formation-is very similar to the overlying Beluga and is composed of abundant coal, siltstone, and massive sandstone of Oligocene and Miocene age. Unlike the Beluga facies however, coal beds within the Tyonek are relatively high quality, sub-bituminous to bituminous, and often regionally continuous. The similarities in lithology between this unit and the Beluga Formation can make it difficult to identify a distinct contact. The base of the Tyonek Formation is gradational with the Hemlock and placed at the first occurrence of thick, coarse sand and conglomerate with a general lack of coal.

The Miocene Beluga formation is a thick (> 3000 ft,) siltstone rich unit with common interbeds of channelized muddy sandstone, coal, and tuff. Lithic components of the coarser facies, in contrast with the overlying Sterling, are dominated by metamorphic rock fragments and quartz (Curry et.al., 1993). Beluga coals tend to be thin (< 5 feet), lignitic to sub-bituminous, and regionally discontinuous. Much of the gas produced in the Inlet to date has been from Sterling and Beluga reservoirs. The base of the Beluga Formation can be hard to consistently identify on logs and is placed at the top of the first thick (> 10 feet) coal.

The Miocene-Pliocene Sterling Formation is the youngest non-glacial unit in the inlet, and with the exception of the uplifted basin edges, is the predominant submarine outcrop. The Sterling is a friable, fine to coarse grained cross-bedded sandstone deposited in stacked channels with associated mud drapes and siltstone facies with local thin coals. Outcrop of this unit can contain as much as 80% sand and well logs show a very distinct blocky character. Mineralogically, the sandstone contains abundant volcaniclastics, common glass shards, quartz and feldspar. The base of the Sterling Formation is a regional unconformity and picked at the first occurrence of abundant coal and loss of massive sands.

Depositional Model

A depositional model for the above described units involves a rapidly subsiding non-marine basin with sediment sources from both the north and south. Figure 6 depicts this model and shows local and regional aspects of the system (McGowen and Doherty, 1994). The coarsest grained facies were deposited proximal to the source by an alluvial fan system which carried sediment out into the basin from both the arc and accretionary complex margins. Location of these fans was related to uplift on the basin bounding faults.

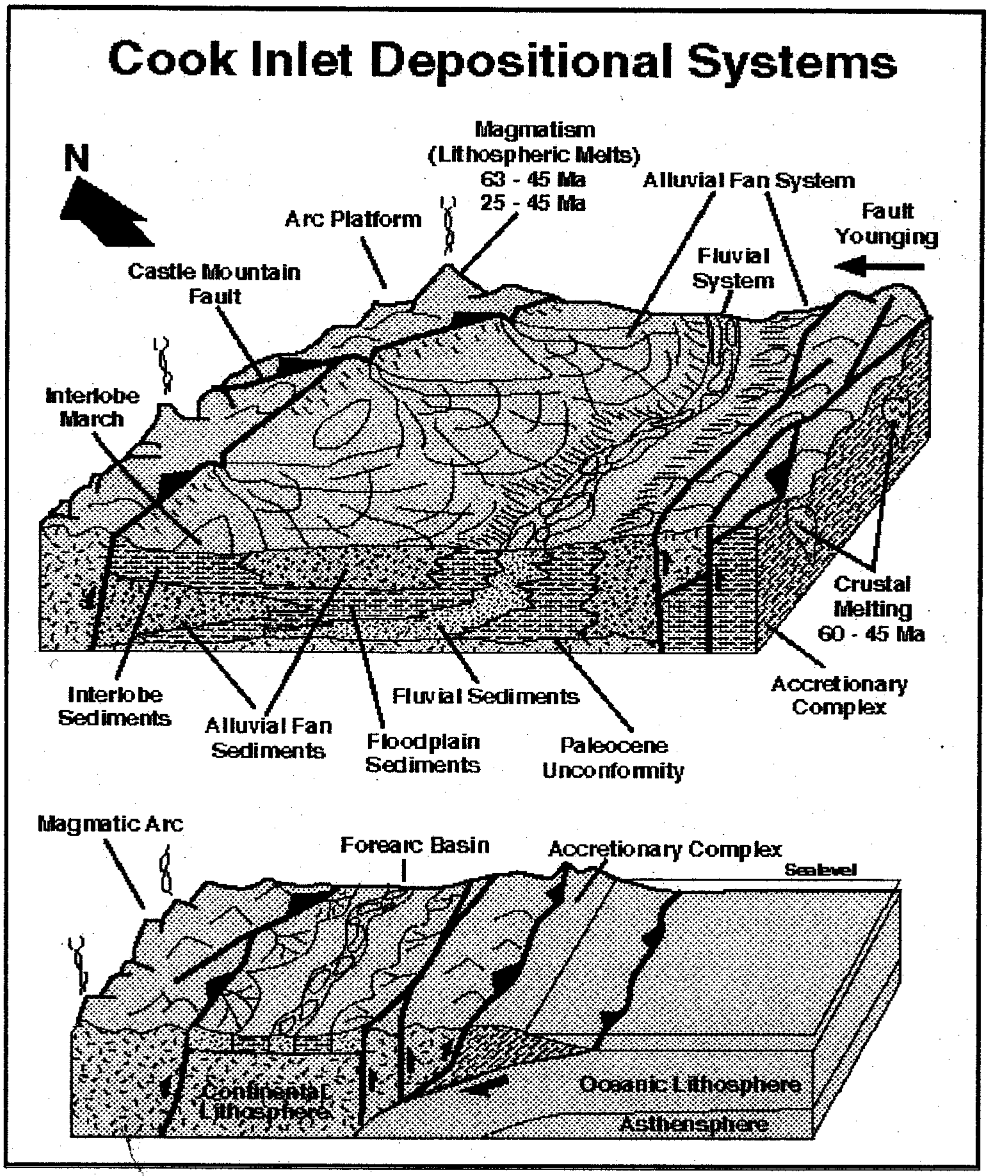

Figure 6: Cook Inlet Depositional systems model (From McGowen, et. al., 1994)

The distal portions of the fans were later reworked by an axial-fluvial system that migrated across the basin floor in relation to sediment input and topography. The fluvial system,provided mixing of the various mineralogies, was dominantly fine grained, and moved sediment out into the flood plain areas. Swamps, marshes and flood basins provided the biotic material that produced the ubiquitous coal horizons. The final product of this depositional system is the thick package of clastics and coal that defines the non-marine Tertiary of the Cook Inlet.

Summary

Tertiary rocks of the Cook Inlet Basin record the geology of an active plate boundary and associated cycles of deposition in a forearc setting. Beginning with the subduction of the Kula oceanic plate and spreading center, Cenozoic tectonics were the driving force of a complex geologic system that in places accumulated over 30,000 feet of non-marine stratigraphy. Variation in uplift histories of adjacent tectonic blocks provided both sediment input and stress needed for formation of structures that accumulated both gas and liquid hydrocarbons maturing at depth.

The Tertiary stratigraphic column is separated into 5 distinct lithologic units. These formations are regionally time transgressive and represent laterally equivalent facies that were deposited in a clastic dominated basin. The current depositional model suggests that alluvial fans carried sediment off the uplifting margins and provided the bulk of sediment influx. A migrating axial fluvial system produced an environment for the thick accumulation of siltstone and coal near the basin center. Increased tectonism in Plio/Pleistocene time shut the deposystem down and helped create the geologic snapshot that is observed today.

The list of scientists that have worked this basin and provided critical information is much too extensive to provide here, but special recognition should be given to Joe McGowen, Dave Doherty, Mike Gardner, Dave Bannan, Bill Grether, Bud Simpson, Richard Curry, Steve Bergman, David Hite, Kris Meisling, Paul Daggett, Jeff Corrigan, Ken Helmhold and many others.

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A Potential Method for Assessing Coalbed Methane Resources Using High-Resolution Chronostratigraphy, Vitrinite Reflectance and Burial History Modeling, Cook Inlet, AK

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Introduction

The Kenai Group within the Cook Inlet Basin, south-central Alaska, contains a substantial record of terrestrial sedimentation and regional volcanism throughout most of Tertiary time. Due to the abundance of well-preserved plant leaves, the Kenai Group has been designated the type section of three Neogene provincial paleobotanical stages: the Seldovian, Homerian, and Clamgulchian (Wolfe et al., 1966; Wolfe and Toshimasa, 1980 Tertiary plant-bearing strata from Alaska, Pacific northwest and eastern Russia are correlated on the basis of these stages (Wolfe and Toshimasa, 1980; Wolfe, 1994). In addition, these units are a source of oil and gas production and contain a valuable, under-developed coal resource that has significant coalbed methane potential. Thus, understanding the geologic history of the basin is important from an economic as well as paleontological standpoint. The purpose of this paper is to outline a proposed method for determining stratigraphic relations and coalbed methane potential for the Cook Inlet Basin.

Abundant stratigraphic information exists in the form of cores, well logs and scattered surface outcrops from the Cook Inlet Basin. Because the surface outcrops are incomplete, scattered throughout the basin, and covered by heavy vegetation, the construction of stratigraphic models has been primarily from well data. Correlation of isolated outcrops within the Cook Inlet Basin has been problematic and poorly documented despite the abundant work done to date. Over two-thirds of the entire Tertiary section is known only from subsurface well information Currently, there is some debate about whether the units in the Kenai Group are time-transgressive (Swenson, 1997) (Fig. 1). Part of the problem is that type sections for the formations of the Kenai Group are defined based on cuttings and subsurface electric log characteristics with some palynologic and heavy mineral analyses (Calderwood and Fackler, 1972; Hite, 1976). These units are then projected to surface exposures (Adkison et al., 1975) but the lack of diagnostic characteristics of individual units and the lack of age controlling fossil material hampers clearly defined correlations. Attempts to correlate outcrop and well data are further hindered by stratigraphic complexity produced by the braided and meandering fluvial systems that deposited the Kenai Group sediments. Many attempts have been made to correlate strata locally and regionally but thus far, these studies have had limited success, even over short intervals.

Deposition of the Kenai Group is believed to have taken -30 Ma, however the age control for this is poor. Imprecise K-Ar and fission track ages have been assigned to the upper parts of the group (Fig. 2; Triplehom et al., 1977; Turner et al., 1980), representing only 7 million years of deposition. Much of the older portion of the group, mostly seen in well samples, has only one limiting radiometric age control point. The remainder is dated by pollen genera and leaf species with relatively long ranges. No vertebrate mammal material has been documented within these units (Dorr, 1964; McClellan and Giovannetti, 1979). Therefore, the best available

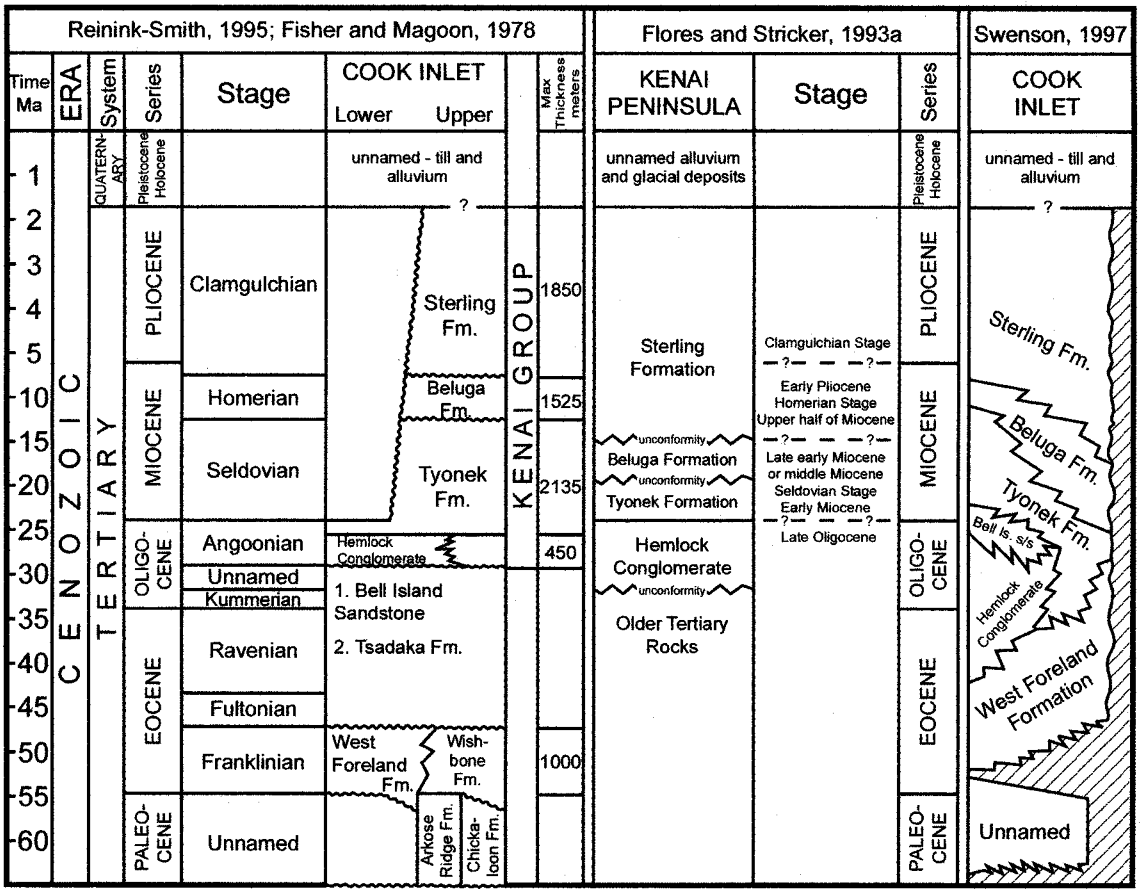


Figure 1. Time stratigraphic chart of Cenozoic units in Cook Inlet Basin showing three stratigraphic models. Note - Tertiary series boundaries have been adjusted to 1999 Geoloogical Society of America time scale; time chart not to scale for the interval 0-5 Ma.

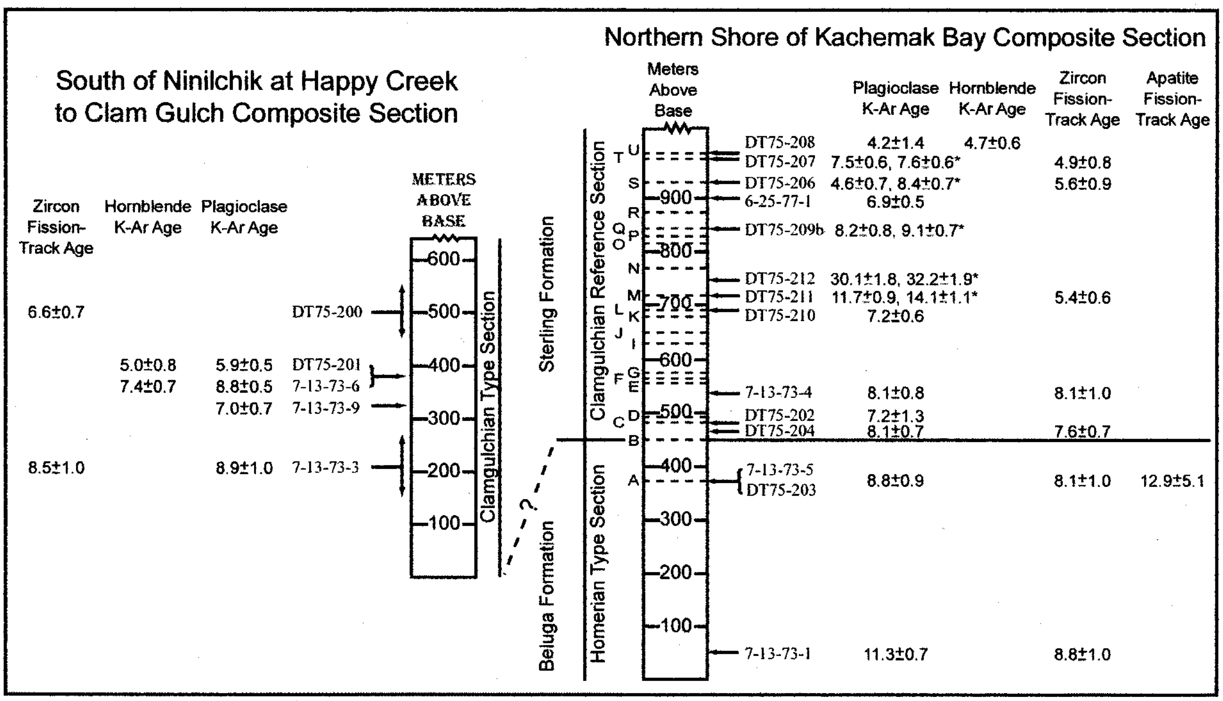


Figure 2. Comparison of all available absolute dates for the Beluga and Sterling Formations, Kenai Peninsula. Letters on Kachemak Bay section correspond to designated coal bed names of Barnes and Cobb (1959). Dates with asterisk (*) were attributed to apparent detrital contamination and not used in final interpretation (Turner et al., 1980). Adapted and modified from Triplehorn et al. (1977) and Turner et al. (1980).

dates are based on long-ranging botanical fossils and imprecise K-Ar data, leaving the age of the Tertiary section poorly documented.

Current approaches to chronostratigraphy involve integration of several techniques. The $^{40}Ar/^{39}Ar$ method has been used to precisely date type-sections for many litho-, bio-, and chronostratigraphic units throughout the world and, when coupled with palynology and other paleobotanical methods, can be used to correlate units across broad regions and identify lateral variations in geologic units (e.g. Deino et al., 1990; Berggren et al., 1995; Larson and Evonoff, 1998, Dallegge, 1999). The abundant coal-bearing units of the Kenai Group contain ash beds (partings) within the coal seams (Adkison et al., 1975; Kremer and Stadnicky, 1985; Reinink-Smith 1987 1989 1990, 1995). Reinink-Smith (1987) has reported over 98 ash beds in coals from the Kehai Lowland (Fig. 3). The goal of this research is to use these ash layers to establish a chronostratigraphic framework for a continuous section of the upper Kenai Group along the northern shore of Kachemak Bay and then apply it to subsurface core material and other outcrop locations in the Cook Inlet Basin.

Once this chronostratigraphic framework is in place, the thermal history of the basin can be evaluated. Thermal maturation information can be placed in proper stratigraphic succession allowing for the creation of basin-wide, maturity isopach maps showing areas of potential coalbed methane generation and storage.

Geologic Background

Cook Inlet Basin

The Cook Inlet Basin (Fig. 3) is an elongate (110 km x 320 km), northeast-trending, fault-bounded forearc basin. The basin begins north of Anchorage in the Matanuska Valley and trends south along the Alaska Peninsula (Kelley, 1985; Swenson, 1997). The basin is bounded on the north by the Castle Mountain Fault system and to the northwest by the Bruin Bay Fault system and the magmatic Aleutian arc. The Chugach Terrane and associated Chugach Mountains and Border Ranges Fault Zone abut the southeastern side of the basin. The northwest-southeast trending Augustine Seldovia Arch separates the basin into two depocenters, upper and lower. Over 8500 meters of Tertiary sediments occupy the basin, 6000 meters of which belong to the Kenai Group (Crick, 1971; Fisher and Magoon, 1978).

Kenai Group

Dall and Harris (1892) first used the term "Kenai Group" for coal-bearing strata in the Cook Inlet area. Barnes and Cobb (1959) measured multiple sections and described the coal-bearing units, applying the name Kenai Formation to sediments on the Kenai Peninsula. Calderwood and Fackler (1972) elevated the Kenai Formation to group status and described and defined five formations (West Foreland, Hemlock Conglomerate, Tyonek, Beluga, and Sterling formations, see Fig. 1) based on subsurface type sections. These type sections are distinguished by electric log characteristics and well cuttings, with supporting palynology and heavy mineral analyses. Fisher and Magoon (1978) removed the West Foreland Formation because it did not meet the original description of a "coal-bearing unit."

Several studies have examined the sedimentology of the Kenai Group. The depositional setting includes braided, anastomosing, and meandering stream systems on a broad alluvial plain (Hayes et al., 1976; Hite, 1976, 1985; Rawlinson, 1979, 1984; Kremer and Stadnicky, 1985; Flores and Stricker, 1992; Flores and Stricker, 1993a, 1993b; Flores et al., 1997). This fluvial

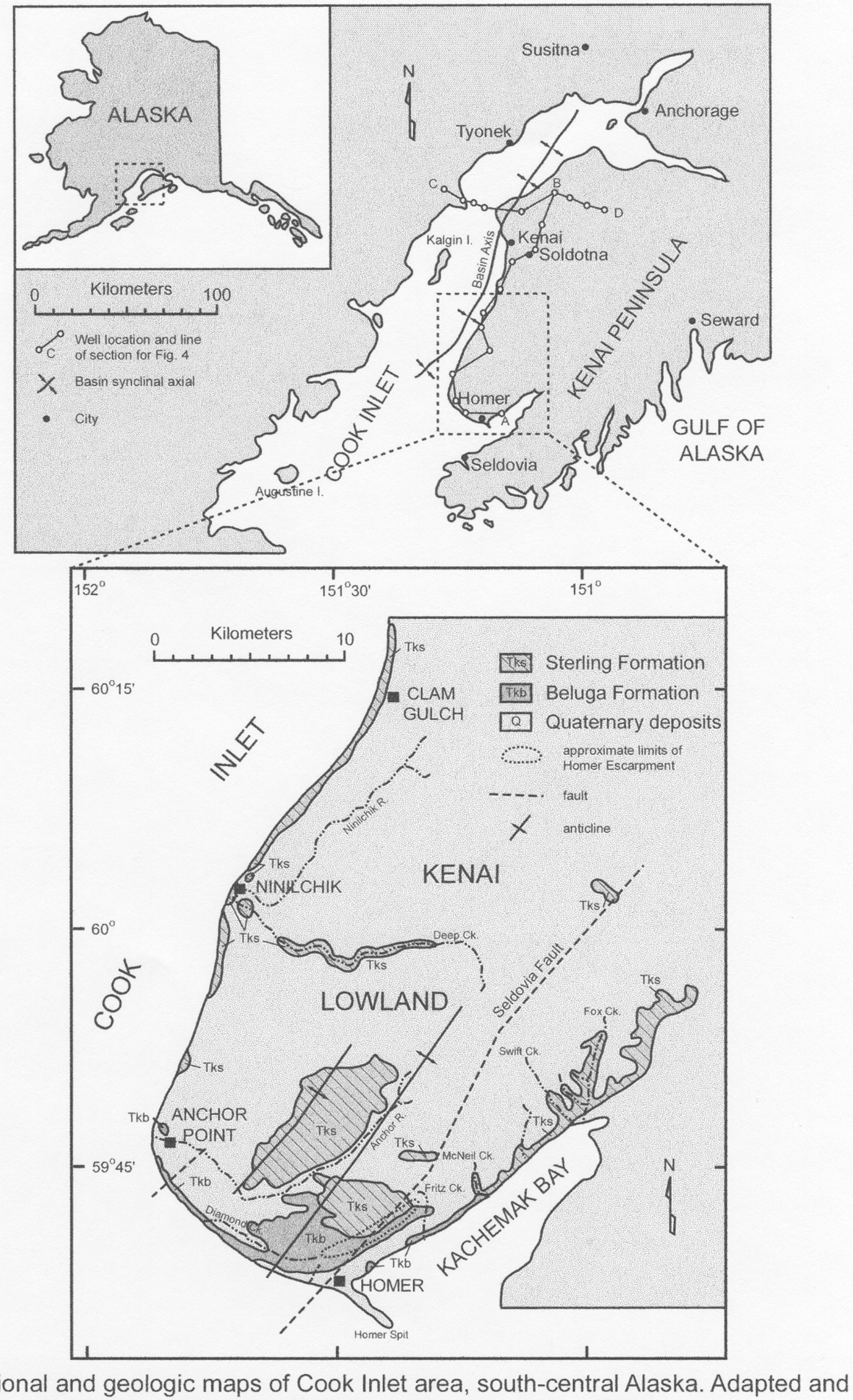


Figure 3. Regional and geologic maps of Cook Inlet area, south-central Alaska. Adapted and modified from Lueck et al. (1987); Reinink-Smith (1990); Flores et al. (1997).

setting produced laterally discontinuous beds of interfingering sandstone, siltstone, conglomerate, and coal.

Problems to be Addressed

Although the Kenai Group has been the subject of repeated sedimentological and paleontolological investigations, problems with dating, correlation of outcrops, subsurface continuity, and paleobotanical assessment are unresolved. Development of an integrated chronostratigraphic framework for these units is proposed in order to resolve existing correlation difficulties.

Chronology

Three provincial paleobotanical stages with type sections in the Kenai Group are used for local and regional correlations (Wolfe et al., 1966; Wolfe, 1994; For'yanova, 1985), but their ages remain poorly constrained. All but one of the published K-Ar dates occur within the stratigraphic section equal to the upper Beluga and lower Sterling formations. Thus only one sixth of the total stratiyaphic thickness, or about 7 of the -30 million years, is represented by existing radiometric dates. Furthermore, the precision of the K-Ar ages is generally greater than 0.5 Ma, and reversals occur throughout the dated stratigraphic section (Fig. 2). Several chronohorizons were disregarded due to apparent detrital contamination (Turner et al., 1980). These poor dates may be the result of the inherent problems of dating plagioclase using the K-Ar technique. The deposits along the western edge of the Kenai Peninsula have been assigned to the Clamgulchian Stage (Fig. 3). However, the radiometric data suggests they belong to the Homerian Stage, based on the dated Homerian/Clamgulchian boundary in Kachemak Bay (Fig. 2). No radiometric data is currently available for the subsurface.

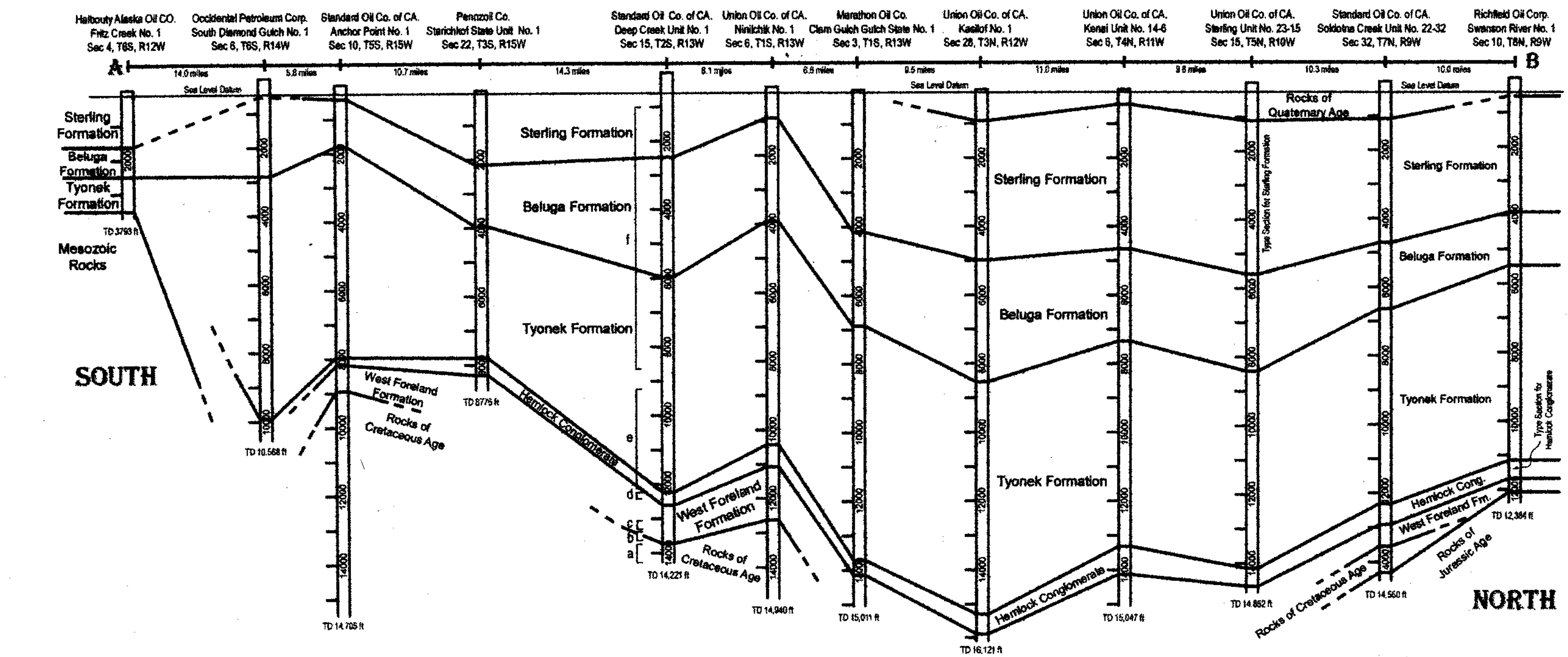
Apatite and zircon fission-track data have been published in conjunction with the K-Ar data (Turner et al., 1980). In many cases, these fission-track data disagree with plagioclase and hornblende K-Ar ages from the same ash bed (Fig. 2).

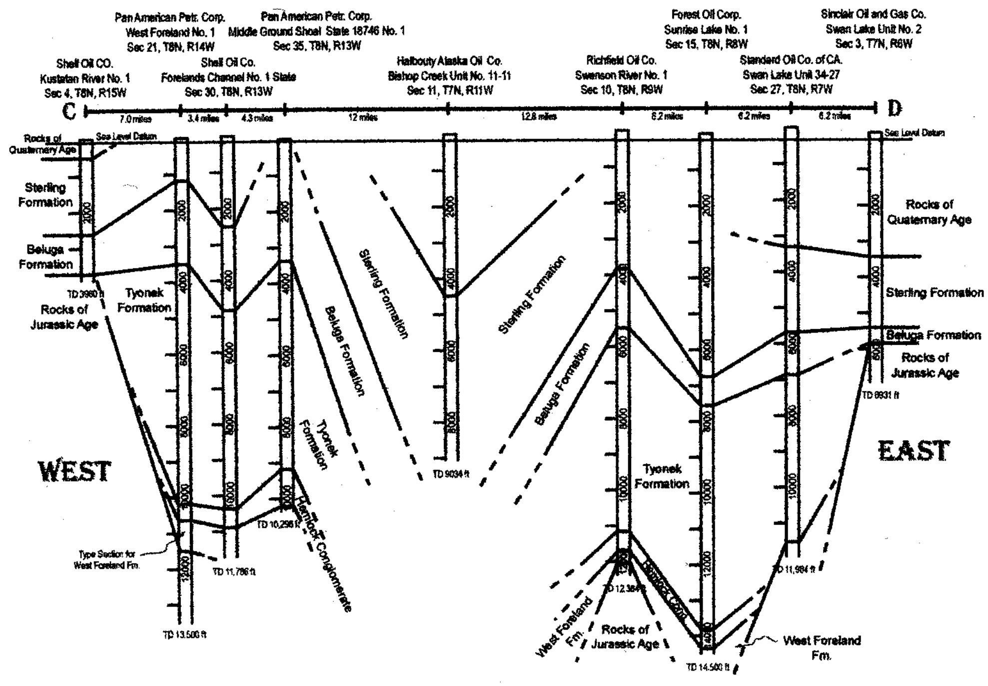
Additional dates are based on the distribution of fossil leaves, fruits, and pollen. However, many of the palynomorphs are long-ranging genera found in all three of the paleobotanical stages (Wolfe et al., 1966). The ranges of fossil leaves are determined by comparison with distant localities that have better age control. Because plants migrate in response to climate changes, the first and last appearances of plant species may vary widely between sites. Hence, ages based upon the ranges of leaf species are approximate at best (Wolfe et al., 1966; Wiggins and Hill, 1987).

Correlation

> "One of the primary problems in the Tertiary of the Cook Inlet is the lack of tools for rapid and widespread correlation. The absence of marine fossils and rapid lateral facies changes are the chief deterrents to effective correlations. Gross lithologic characteristics, such as thick coals in the Tyonek, are the only guide." Hite (1976, p, 13)

Due to the fluvial nature of the deposits, units of the Kenai Group are laterally discontinuous. Lenticular sand bodies and lateral facies changes complicate attempts to correlate surface outcrops, even over short distances. Hence correlation of outcrops and subsurface well logs over long distances has proven extremely problematic, despite the battery of physical and





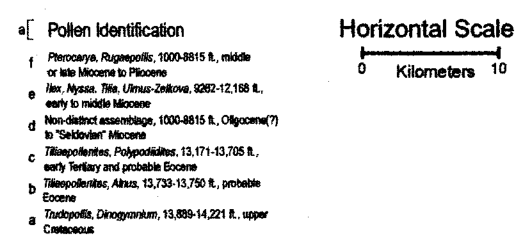


Figure 4. Generalized version of Carter and Adkison (1972, Plates 1 and 2) well-to-well correlation of the Kenai Group based on electric well logs, cutting logs, and palynology. Self-potential, resistivity, and gamma curves were not included on this small scale modification but are available on original report. See Figure 3 for location of wells.

biological correlation techniques employed by various researchers. Studies of heavy mineral concentrations in subsurface wells (Kirschner and Lyon, 1973; Hite, 1976) suggest that assemblages are not correlative across the depositional basin. Furthermore, formation boundaries identitied by heavy mineral assemblages generally do not coincide with boundaries established by log correlations and palynological analyses (Hite, 1976).

Attempts to correlate coalbeds locally and across the Kenai Peninsula (Barnes and Cobb, 1959; Adkison et al., 1975; Hite, 1976; Reinink-Smith, 1989, 1995) have shown that most coalbeds are lenticular or split into multiple seams. Others have been removed by erosion, In some sections, erosion has removed overlying units until a resistant coal seam was reached. The erosional surface then migrates along the surface of that coal bed. The unconformity created by subsequent deposition is difficult to recognize without careful lateral inspection of the outcrop (Triplehom, pers. comm, 1999). Thus, different aged coals can be placed in apparent stratigraphic continuity, and lateral correlation of coalbeds based on thickness, is suspect.

Ash bed partings from coal seams across the Kenai Peninsula have been analyzed by X-ray diffraction (XRD), geochemical techniques (Direct Current Plasma spectrometer [DCP], inductively coupled plasma spectrometer [ICP], X-ray fluorescence [XRF], and electron microprobe), and petrographic methods (optical and scanning electron microscope [SEMI) in an attempt to achieve regional correlations (Reinink-Smith 1987, 1989, 1990, 1995). These analyses of whole-rock, coarse-fraction, trace elements, and glass were combined with stratigraphic relations, inertinite content of coals, and results of prior studies in order to correlate between outcrop sections. Reinink-Smith (1989, 1995) successfully correlated local outcrops, but she was unable to achieve correlation of regional Kenai Peninsula outcrops, with one possible exception. A diagnostic pumice-fragment ash bed in the Sterling Formation extends from the southeast shore of Cook Inlet to the northern end of Kachemak Bay (Fig. 3) (Reinink-Smith, 1989, 1995). Despite the distinctive appearance of this ash bed, whole-rock elemental analyses and prior published isotopic dates from isolated exposures were found to disagree (Reinink-Smith, 1995) casting doubt on the reliability of this ash for long-distance correlations.

Basin-wide correlation has also been attempted by comparison of electric logs (Fig. 4) (Kelley, 1963; Calderwood and Fackler, 1972; Carter and Adkison, 1972). Such e-log correlations are successful only at the formation level and they commonly have poor resolution near the edges of the basin, where facies changes are abrupt. Calderwood and Fackler (1972) noted that the contact between the Beluga and Sterling formations is dificult to distinguish in some areas. Along the northeastern margin of the basin, the Beluga Formation is missing entirely or cannot be distinguished from the Sterling Formation (Kirschner and Lyon, 1973). Furthermore, Carter and Adkison (1972) noted that electric logs from the upper Sterling Formation and overlying Quatemary deposits are very similar. Thus the top of the Sterling Formation is difficult to resolve by means of e-log data

Structural features within the Kenai Peninsula exacerbate correlation difficulties. Formation contacts in the subsurface vary several thousand feet between wells separated by distances of ten miles or less (Fig. 4; Carter and Adkison, 1972, Plate 2). The east-west trending synclinal structure, apparent on Figure 4, further complicates interpretation of subsurface data. This synclinal form parallels mapped anticlines on the Kenai Peninsula (Fig. 3), suggesting a north-south compressional regime. This is not consistent with the current north-south trending forearc basin interpretation (Fisher and Magoon, 1978; Kelley, 1985; Magoon and Anders, 1992; Swenson, 1997). Furthermore, exposed surface faults with small or undetermined amounts of displacement have been noted (Barnes and Cobb, 1959; Adkison et al., 1975; Reinink-Smith, 1989, 1995). These faults are supported by geophysical and structural studies (Parkinson, 1962; Kirschner and Lyon, 1973; Beikman, 1974; Fisher and Magoon, 1978; Flores and Stricker, 1992; Magoon and Anders, 1992; Swenson, 1997). The Seldovia fault (Fig. 3) is particularly problematic, in that it separates the western side of the Kenai Peninsula from the eastern portion of Kachemak Bay, rendering physical correlation across this zone virtually impossible (Beikman, 1974; Reinink-Smith, 1990).

Projection of the subsurface Kenai Group type-sections into outcrop is encumbered by the myriad problems that attend long-distance correlations. Adkison et al. (1975) projected type sections of the Beluga and Sterling formations into outcrop at Kachemak Bay. These correlations were based on previous studies, including lithologic criteria (Calderwood and Fackler, 1972), paleobotanical stages (Wolfe et al. 1966), isopach maps (Hartrnan et al., 1972), and surface maps (Kirschner and Lyon 1973). Adkison et al. (1975) determined the location of the Beluga/Sterling Formation contact by projecting surface features shown on a geologic map (Barnes and Cobb, 1959) to depth, without mapping the contact in the field. This method produces acceptable results, placing the boundary between the Beluga and Sterling formations at approximately the same level as the boundary between the Homerian and Clamgulchian stages (Wolfe et al., 1966) (Figs. 1,2). However, these results are in conflict with radiometric ages of Sterling Formation outcrops on the west side of the Kenai Peninsula. In this location, the radiometric ages of these deposits suggest they are partially of Homerian age (Fig. 2).

The abundance of conflicting age data suggests that formations of the Kenai Group are substantially time-transgressive (Fig. 1). Swenson (1997) supports this hypothesis, citing several internal ARC0 reports. Flores and Stricker (1993a) go so far as to place all of the Beluga Formation within the Seldovian Stage, contradicting all previous interpretations (Fig. 1). However, the existing chronostratigraphic framework is too inaccurate to confirm or deny the time-transgressive nature of Kenai Group formations.

Goal of the Project and Research Method

The goal of this project is to determine if the methane generation and storage potential of Cook Inlet Basin can be modeled by incorporating high-resolution chronostratigraphy, thermal maturation studies, and burial history reconstruction. In order to complete this study, two components must be evaluated. (1) Methane stored in coalbeds can be modeled if the burial history, rank of the coals (i.e., volume of gas generated), shallow structure (gas traps), and depth to the coals (pressure acting to hold gas in) are known. Changes in burial depth, erosion rates, and geothermal gradient affect the distribution of vitrinite reflectance (Ro) values, methane formation, and potential storage in coalbeds. Therefore, a complete understanding of the stratigraphic relations is necessary to adequately assess methane production. (2) The stratigraphic architecture of the Kenai Group is complex and little age control has been reported (Fig. 2). We propose construction of a detailed chronostratigraphic framework for the portion of the Kenai Group exposed along the northern shores of Kachemak Bay on the Kenai Peninsula (Fig. 3). Multiple ash partings in coalbeds have been reported from this section (Triplehorn et al., 1977; Turner et al., 1980; Reinink-Smith, 1987, 1990). By using precise $^{40}Ar/^{39}Ar$ dating, we will be able to obtain dates with a precision of approximately 0.05 Ma throughout the exposed section. Subsurface samples will be gathered from multiple cores and cuttings housed at the Alaska Geological Materials Center in Eagle River, AK and the USGS Core Library in Denver, CO. Two cores in particular, the Deep Creek # 1 well and the AK 94CBM- 1 have published occurrences of coal and volcanic ash as well as palynological data and coal quality analyses (Adkison and Newman, 1973; Flores et al., 1997). These samples will be analyzed in order to place the subsurface sections within the chronostratigraphic framework defined by the outcrop data. Samples from other areas of the Kenai Lowland and Cook Inlet area will also be correlated with these dated sections.

$^{40}Ar/^{39}Ar$ dating will focus on ash bed partings located in coal seams. These partings are often less than a cm in thickness as observed in outcrop. Microscopic examination of the coal seams from cores will be necessary to find these ash partings. Multiple $^{40}Ar/^{39}Ar$ age determinations from several coal seams per well or per outcrop and the published age data from K-Ar and palynology will be used to establish chronohorizons that will allow for the creation of high-resolution correlation diagrams. These diagrams will identify shallow structures that may be potential gas traps, Published seismic and structural information will be used to further constrain these diagrams across the basin.

A thermal stratigraphic framework will be developed by measuring vitrinite reflectance values. Samples will be collected from coalbeds and coaly fossils found in cores and outcrops. The vitrinite reflectance data will provide the rank and maximum burial depth of the coals. Given the published geothermal gradient, current depth to and quality of the coals, and the rank and maximum burial depth as determined from this study, the potential gas generation will be assessed using BasinMod software.

Once both detailed high-resolution frameworks are complete, the criteria necessary for coal bed methane generation and storage are known. The thermal framework will then be superimposed on the chronostratigraphic framework to determine current areas of potential gas storage. This available information will then be used to create basin-wide, maturity isopach maps showing areas of potential coalbed methane generation and storage.

These factors make the Cook Inlet Basin an ideal setting to document and test a high-resolution chronostratigraphic and thermal maturation model for coalbed methane resource assessment.

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Coalbed Methane Potential for Alaska and Drilling Results for the Upper Cook Inlet Basin

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ABSTRACT

Alaska's estimated coal reserves exceed 5.5 trillion short tons or nearly 1/2 of the U. S. total. Based on analysis performed during this study, I have concluded that these coals could contain up to 1,000 tcf of gas. Most of these coals range in age from Cretaceous to Tertiary and rank from bituminous to subbituminous. This study uses coal rank, present-day burial depth, seam thickness and structure as criteria to evaluate thirteen of Alaska's most promising coal basins. Much of the Cook Inlet, Susitna, North Slope, Middle Tanana, Nenana, Yukon Flats, North Aleutian, Seward Peninsula, and Copper River Basins contain thermally immature coals (Ro<0.5%) with low methane potential. The Upper and Lower Koyukuk, Kobuk, Gulf of Alaska, and the Alaska Peninsula Basins contain bituminous coals with moderate potential for local gas usage. Thermal maturity and coal isopach maps indicate that the Matanuska Valley area of the Cook Inlet Basin and the western foothills belt of the North Slope Basin contain abundant, bituminous, coalbeds up to 50 feet (15 m) thick. These coals have high potential for methane production at depths between 500 and 6,000 feet (150 and 1,800 m). Gas content of coal seams from the first core hole (AK-94CBM-1) drilled in the state to evaluate coalbed methane support this conclusion for the northern portion of Cook Inlet Basin. Coals penetrated by this well show increasing gas content with depth ranging from 63 scf/ton (1.96 cc/g) at 521 feet (159 m) to 245 scf/ton (7.66 cc/g) at 1,236 feet (377 m) on a dry, ash free basis.

INTRODUCTION

Alaska contains vast, lightly explored coal resources that underlie approximately 9% of the land area (Figure 1). Hypothetical coal resources exceed 5.5 trillion short tons, about half of the total United State's coal resources [1]. Most of the coal is Cretaceous to Tertiary in age and bituminous to subbituminous in rank. The North Slope and Cook Inlet Basins contain both subbituminous and bituminous rank coals and constitute the largest coal resources in the state (Figures 1 and 2). The Upper and Lower Koyukuk, Kobuk, Alaska Peninsula and the Gulf of Alaska Basins all contain bituminous coals (Figures 1 and 2). Subbituminous and lignite coals are found in the Susitna, Middle Tanana, Nenana, North Aleutian, Seward Peninsula and Copper River Basins (Figures 1 and 2).

Near-surface coal has been commercially utilized and studied in Alaska for over 100 years and most of the surface coal occurrences have been mapped and studied. Deep coal resources have received considerably less attention. This study focuses on the coal at deeper depths. Information from petroleum production and exploration wells, gravity surveys and surface studies are integrated to provide a coalbed methane resource estimate for Alaska and coalbed methane potential for Alaska's coal basins. Since gas content analyses are available only for the State of Alaska core hole (AK-94CBM-1) in Cook Inlet Basin, established indirect methods using data such as depth, rank and composition [2, 3 and 4] were used to estimate Alaska's coalbed methane resource. The available data suggests that Alaska's coal could contain over 1,000 trillion cubic feet (tcf) of gas. If only 10% is recoverable, the resource would triple the current proven conventional gas reserves for Alaska.

NORTHERN ALASKA PROVINCE

The Northern Alaska Province (North Slope)(Figure 3) contains the largest coal resource in Alaska with hypothetical reserves of 4 trillion short tons [1]. The coals underlie a 400 mile long by 150 mile (640 km by 240 km) wide area (approximately 60,000 square miles (154,000 sq km)). While coals range in age from Mississippian to Tertiary, the primary coal resources occur in the Lower Cretaceous Corwin Formation of the Nanushuk Group (Figure 4).

The North Slope is one of the most thoroughly explored basins in Alaska. Coal was exploited by whaling ships in the late 1800's along the Chukchi Sea coast and the first coal investigation was conducted by Collier [5] in 1906 in that same area. Early explorers also occasionally exploited natural oil seeps for fuel. Oil and gas exploration was initiated in 1919 by geologists of the U. S. Geological Survey and it was this early survey work that led to the establishment of the Naval Petroleum Reserve No. 4 (now National Petroleum Reserve in Alaska (NPRA)) in 1923. Between 1943 and 1953, early exploratory drilling by the Navy in NPRA found three oil and six gas accumulations. In 1967, the super giant Prudhoe Bay Field was discovered in the central North Slope by ARCO-Humble. This field is now expected to yield 12 billion barrels of oil and eventually over 23 tcf of gas.

The North Slope data base includes more than 350 oil and gas exploratory wells, 2,500 development wells and seismic data from near the Canadian border to the Chukchi Sea. Since NPRA was established, systematic geologic investigations have proceeded on the North Slope and the Brooks Range that include mapping and sampling the coals. Extensive coal studies have been done on Native lands in the area west of NPRA, where large, exploitable deposits are located near tidewater, but lack the infrastructure to commence mining operations.

Mississippian Coal

Mississippian coals are found in the Kapaloak Formation on the Lisburne Peninsula and in the regionally extensive Kekiktuk Formation (Figure 4). The Kapaloak Formation outcrops over a 45 mile (72 km) long belt trending north-south across the Lisburne Peninsula (Figure 3) and contains low-volatile bituminous to semianthracite coals up to 11 feet (3.4 m) thick. A minimum of 13 coal beds have been identified in outcrop along 2,200 feet (670 m) of measured section [6] that is extensively faulted and folded [7].

The presence of the Kekiktuk Formation has been documented across most of the North Slope. It has been described in detail from outcrops in the Brook Range [8] and is the primary petroleum reservoir at the Endicott Field located on the east side of the Prudhoe Bay Complex (Figure 3). In the Endicott Field, multiple, thick (greater than 10 feet (3 m)) coal seams with an average Ro of 0.6% occur at depths greater than 9,500 feet (2,900 m)(Figure 5). Several wells in NPRA have encountered coal beds as thick as 5 feet (1.5 m) in the Kekiktuk Formation [9]. Only minor, thin Kekiktuk Formation coal occurrences are found in the Brooks Range outcrop belt.

Coalbed Methane Potential. The structurally complex and high rank Kapaloak Formation coals on the Lisburne Peninsula may provide gas for local village or mining use. The Kekiktuk Formation coals are generally too deep to be viable for coalbed methane production.

Lower Cretaceous Coal

Most of the coal resources in Alaska are found in the Cretaceous Corwin and the Chandler Formations of the Nanushuk Group (Figure 4) [9]. Both the Corwin and Chandler Formations are dominantly nonmarine strata that were deposited in two separate, but simultaneous prograding delta systems (Corwin delta of western NPRA and Umiat delta of eastern NPRA) [10]. The Corwin Formation contains abundant coal seams up to 20 feet (6 m) thick that underlie most of western and central NPRA and extend farther west under the Chukchi Sea [11]. These coal seams have been documented in outcrop along the Kukpowruk River [12] to the west of NPRA and in wells drilled in NPRA. The Kaolak -1 penetrated 255 feet (78 m) of coal in over 4,500 feet (1,370 m) of Nanushuk section and the Meade -1 encountered 130 feet (40 m) of coal in 2,000 feet (610 m) of Nanushuk Group section. Individual coal beds in these wells reach 20 feet (6 m) with up to 26 coal beds exceeding 5 feet (1.5 m) thick. Mapping by Sable and Stricker [9] shows that the coal-bearing interval lies between the surface and 6,000 feet (1,830 m) in western NPRA (Figure 5). In eastern NPRA, the Chandler Formation contains abundant coals similar to those found in the Corwin Formation. The coal-bearing interval of the Chandler Formation is less than 2,000 feet (610 m) deep (Figure 5). Coal rank increases from north to south, to the foothills of the Brooks Range, and also increases with depth. Most of the coal is high-volatile bituminous with a mean Ro of 0.7% [9].

Coalbed Methane Potential. The area of western NPRA, to the Chukchi Sea coast, has high coalbed methane potential and large possible gas reserves (Figure 5). These coals are in a relaxed tectonic stress regime. The area has been uplifted and stripped of overburden which may allow for open fractures and cleats. In the western NPRA area, the depth to the base of the Nanushuk Group coals exceeds 2,500 feet (760 m), placing a substantial portion of the coal section below permafrost. In eastern NPRA, most of the Nanushuk Group coals lie at depths less than 2,000 feet (610 m), placing them near or in the permafrost zone. It is currently uncertain what effects permafrost and cold temperatures will have on gas flow from these coals.

Upper Cretaceous and Tertiary Coal

The Upper Cretaceous Colville Group and the Tertiary Sagavanirktok Formation (Figure 4) contain substantial coal with coaly intervals and coal beds as thick as 50 feet (15 m) [13 and 14]. However, most beds are thinner and lower in rank than the Nanushuk Group coals. The rank of these coals range from lignite A to subbituminous B. The nonmarine Prince Creek Formation of the Colville Group occurs mostly in northeast Alaska and overlies the Nanushuk Group. The Sagavanirktok Formation conformably overlies the Colville Group [15] and occurs generally northeast of NPRA. In NPRA, distribution of the Sagavanirktok Formation is limited to the northeast corner and northern coastal areas, where it reaches a maximum thickness of 1,500 feet (460 m). East of NPRA, the formation thickens to over 7,000 feet (2,130 m) adjacent to the Arctic National Wildlife Refuge (ANWR)(Figure 3).

Coalbed Methane Potential. The Upper Cretaceous and Tertiary coals represent a large, low rank coal resource that probably contain large gas reserves. However, because of the low rank of these coals and cold subsurface temperatures (permafrost), they have low potential for coalbed methane production.

COOK INLET-SUSITNA PROVINCE

With hypothetical resources exceeding 1.5 trillion short tons, the Cook Inlet-Susitna Province (Figures 2 and 6) constitute the second largest coal resource in the state. The province covers an area of approximately 14,000 square miles (36,000 sq km), which is bounded by the Kenai Mountains to the east, the Aleutian Range to the west, and extends north to the Alaska Range and the Talkeetna Mountains. Unlike many other areas of the state, portions of the Cook Inlet-Susitna Province are road accessible.

The first major commercial oil discovery in Alaska was made 16 miles (26 km) northeast of Kenai (Figure 6) at Swanson River Field in 1957. Subsequent oil and gas discoveries have produced over 1.2 billion barrels of oil and 5.5 tcf of gas. Seismic, well and production data from within the basin provide an extensive data base which greatly decreases coalbed exploration risk. Additionally, Cook Inlet oil and gas production has created an infrastructure which may enable near term gas development.

Cook Inlet Basin

The Cook Inlet Basin is located in the arc-trench gap between the volcanoes of the Alaska-Aleutian Range and the Aleutian trench. Over 25,000 feet (7,600 m) of Tertiary continental deposits unconformably overlie mostly marine Mesozoic rocks [16]. Although coal is found in the entire Tertiary section, the Oligocene to Miocene Tyonek and the Paleocene Chickaloon Formations (Figure 7) have the highest coalbed methane potential. The Tyonek Formation is widespread across Cook Inlet Basin. Large coal fields have been mapped where it crops out on the west side of Cook Inlet. The Chickaloon Formation is limited to the northeast portion of the Cook Inlet Basin.

Cook Inlet Basin forms a large trough with the basin axis located just west of Kenai and roughly paralleling the current shoreline (Figure 6). Because of post-depositional uplift of the basin margins, older rocks with higher thermal maturity are exposed on the basin margins, while rocks of similar age and thermal maturity occur at significant depths along the axis of the basin. For example, an Ro of 0.6% is reached at a depth of 15,000 feet (4,600 m) near the axis of the basin and at 5,000 feet (1,500 m) near the basin edge (Figure 6). Holocene uplift has brought the thick coals of the Tyonek and the Chickaloon Formations near the surface, making some of the onshore areas of the Cook Inlet basin attractive for coalbed methane exploration.

In 1994, the State of Alaska funded a core hole to sample Tyonek Formation coals near Wasilla, located in the northern portion of Cook Inlet Basin. The core hole (AK-94CBM-1) was drilled on a previously identified prospect [17] (Figure 8) located between the towns of Palmer and Houston and near roads and gas pipelines. In this area, the Tyonek Formation is estimated to have a total thickness in excess of 4,000 feet (1,220 m) with cumulative coal thickness exceeding 100 feet (30 m). High-volatile bituminous coals are expected to be present at depths ranging form 500 to 6,000 feet (150 to 1,800 m).

AK-94CBM-1 was drilled to a total depth of 1,245 feet (380 m), continuously coring the Tyonek Formation from the surface casing shoe at 354 feet (380 m) to total depth. Eighteen seams of high-volatile C bituminous coal were encountered with the thickest being 6.5 feet (3.0 m) and a cumulative thickness of 41 feet (12.5 m). Thirteen of these coal seams were sampled for gas content using 38 gas desorption canisters. Gas content ranges from 63 scf/ton (1.96 cc/g) to 245 scf/ton (7.66 cc/g). Gas content and vitrinite reflectance generally increase with depth, while moisture decreases. Coal moisture contents are low, ranging from 9.02% at 521 feet (159 m) to 4.82% at 1,236 feet (377 m). Gas analyses show that carbon isotopes become slightly heavier with depth indicating an increase in the thermogenic/biogenic gas ratio. The range of -49.3 to -43.2 $\delta^{13}C$ for methane encountered here is indicative of coalbed gas that has both biogenic and thermogenic sources. Gas composition is 98% methane with minor amounts of CO_2 and N_2. Due to cost constraints, the drilling program was designed solely to acquire coal samples for analysis and therefore the well was not flow tested. Porosity and permeability measurements have not been obtained. From visual analysis, coal cleat and fracture density is widely spaced with vertical fractures occurring 1 to 3 inches (2.5 to 7.6 cm) apart. Calcite coating was noted on some of the fracture surfaces which may lower effective permeability. Almost no fractures were noted in the clastic rocks. Figure 9 outlines the coal analyses from core samples for this well.

The coal-bearing Chickaloon Formation occurs only in the Matanuska Valley area north of Palmer (Figure 8). These coals have been mined from 1914 to 1968. Geologists with the Bureau of Mines and the U. S. Geological Survey [18] have mapped the extent of these coals in detail using outcrop, mining and core hole data. Most of the coal is confined to the upper 1,400 feet (426 m) of the Chickaloon Formation, which is greater than 3,000 feet (914 m) thick [18]. The coal in the Chickaloon Formation ranges in rank from high-volatile bituminous to anthracite. Coal beds up to 34 feet (10 m) thick and laterally continuous for up to 5 miles (8 km) have been mapped in faulted synclines that increase in structural severity to the east [18 and 19]. The presence of coalbed gas has been documented by mine explosions which occurred in 1937 and in 1957. In the 1937 incident, a violent methane and dust explosion in the Evan Jones Mine, located 12 miles (19 km) north of Palmer, killed 14 men. The 1957 incident was another methane and dust explosion in the same mine, killing 5 men.

Barnes and Payne [18] estimate that over half of the coal reserves lie beneath 1,000 to 2,000 feet (305 to 610 m) of overburden. Bituminous rank coal at shallow depths and the methane gas problems associated with mining combine to make the Matanuska Valley area highly prospective for coalbed methane production.

Coalbed Methane Potential. High gas content (up to 245 scf/ton at 1,200 feet (366 m) deep) and large coal resources (hypothetical coal resources exceeding 1.5 trillion short tons), indicate that Cook Inlet Basin contains large gas reserves. Conventional gas production, infrastructure and a local market make near term coalbed gas production possible. The uplifted margins of the basin constitute the best plays.

Cook Inlet coal is very similar to coal found in the Powder River Basin where economical flow rates have been accomplished. However, several significant questions need to be answered to determine the economics of coalbed production from within the basin. These include determination of production flow rates for gas as well as formation water.

Susitna Basin

The Susitna Basin underlies a lowland north of Cook Inlet between the Talkeetna Mountains to the east and the Alaska Range to the north and west (Figures 6 and 8). The Castle Mountain Fault and the Susitna Arch separates the shallower and younger Susitna Basin from the Cook Inlet Basin to the south (Figure 8). The dextral Castle Mountain Fault has offset Mesozoic rocks over 60 miles (97 km) and has almost a 2 mile (3.2 km) vertical throw [20]. The Tertiary coal-bearing section exceeds 13,400 feet (4,080 m) and consists of rocks equivalent to the Sterling, Beluga and upper part of the Tyonek Formations (Kirschner, unpublished report).

Nine exploratory wells have been drilled, plugged and abandoned in the basin, seven of which were drilled near the Castle Mountain Fault. The Trail Ridge -1 was drilled in a deeper part of the basin to 13,708 feet (4,178 m) and encountered Tyonek Formation coals with good gas shows from 11,700 feet to 13,708 feet (3,566 m to 4,178 m). The Tyonek Formation outcrops around the margins of the basin and contains subbituminous coal seams over 20 feet (6 m) thick. One reported seam on Sunflower Creek, located on the northwest side of the basin, measured 55 feet (16.8 m) thick [21].

Coals and sandstones north of the Castle Mountain Fault in the Houston area (Figure 8), where a small coal deposit was mined episodically between 1917 and 1952, appear to have high levels of gas. Five oil and gas exploration wells (Rosetta -1 through Rosetta -4A) and three U. S. Bureau of Mines (USBM) core holes drilled near Houston, encountered gassy coals (Figure 8). The USBM core holes, drilled in 1951, flowed small quantities of gas, possibly from coal seams. The Rosetta wells were drilled between 1954 and 1963 and encountered gas shows while drilling coals and sandstones. In spite of being plugged and abandoned, Rosetta -3 still has some gas escaping from around the surface casing. Some shallow water wells near the Castle Mountain Fault also flow small quantities of gas. Gas analysis results are similar to those from the coals cored in AK-94CBM-1. Gas analyses from a water well located six miles (10 km) north of Wasilla, indicated the gas to be 98% methane, 2% N_2 and the carbon isotope for methane -46.4 $\delta^{13}C$.

Coalbed Methane Potential. Susitna Basin is a smaller, shallower extension of Cook Inlet Basin. Like Cook Inlet Basin, the uplifted basin margins constitute the best potential for gas targets. The area along the Castle Mountain Fault is also highly prospective. This basin lacks the infrastructure of roads and pipelines, however, gas could be exploited for local use or pipelines could be built to connect with the existing gas distribution system in the Cook Inlet Basin.

ALASKA PENINSULA PROVINCE

The Alaska Peninsula contains two distinct coal-bearing basins. Coals in the Cretaceous basin are bituminous rank and the Tertiary (North Aleutain Basin) coals are of bituminous, subbituminous and lignite ranks. The two coal basins have different structural and depositional histories and are separated by a regional angular unconformity. The Cretaceous coal accumulated in an arc-trench gap setting while most of the Tertiary coal-bearing deposits are in a back-arc setting [22].

Cretaceous Basin

All Cretaceous coal occurs in the Upper Cretaceous Coal Valley Member of the Chignik Formation [22]. The Chignik Formation subcrops from Wide Bay in the north to the Herendeen Bay-Pavlof Bay in the south, an area over 200 miles (322 km) long and 50 miles (80 km) wide (Figure 10). The strata is moderately folded and faulted with dips varying from 20 to 35 degrees. The Coal Valley Member is laterally discontinuous in this area. The thickest deposits are found near Herendeen Bay (1,250 feet (381 m)), while this member is absent at other localities. Coal deposition was also variable. An aggregate thickness of 26 feet (7.9 m) of coal [19] was found in one 200-foot (61 m) thick section in the Herendeen Bay area. Other sections within the area contain little coal [23]. Coal beds average 3 feet (0.9 m) thick (the thickest 8 feet (2.4 m)), contain 12 percent ash and have a high (90 percent) vitrinite content. The vitrinite reflectance values of these high-volatile bituminous coals range from 0.57% to 1.76% Ro.

In the subsurface, the Chignik Formation has been penetrated by at least four deep oil and gas wells (Figure 10). The Phillips, Big River A-1 penetrated 27 thin coal seams (maximum thickness of 6 feet (1.8 m) over a 1,345-foot (410 m) interval. The Pan Am, Hoodoo Lake Unit -2 encountered 18 thin coals (maximum thickness of 8 feet (2.4 m)) and the Cities, Painter Cr. -1 encountered 9 coal seams (maximum thickness of 9 feet (2.7 m)). Only the Pan Am, David River 1-A did not encounter any coal seams in the Chignik Formation. All the wells that encountered coals had excellent mudlog gas shows. Coal samples from the

Hoodoo Lake Unit -2 well at depths greater than 8,000 feet (2,438 m), and the David River 1-A at depths between 8,500 to 10,250 feet (2,590 to 3,124 m) (above the Chignik Formation in the overlying Tolstoi Formation) are high-volatile to low-volatile bituminous rank. The Cities Service, Painter Creek -1 encountered a medium-volatile bituminous coal at 1,018 feet (310 m) [24]. Coals of similar rank are found in outcrops at Chignik and Herendeen Bay, indicating that these areas have undergone considerable uplift since maximum burial. The permeability of the cleat system could be enhanced in the uplifted areas.

Coalbed Methane Potential. Cretaceous coal underlies a significant area of the Alaska Peninsula. The variability of the coal development and discontinuous nature of the thin coal beds make subsurface exploration for coalbed methane difficult, particularly for large scale operations. However, if a local energy source is the objective and large reserves and high productivity wells are not necessary, the Chignik Formation coals are viable gas targets for villages towns such as Chignik Lake and Chignik Lagoon.

Tertiary Coal

Alaska Peninsula Tertiary coal occurs in the Tolstoi (Paleocene to Eocene), Stepovak (Oligocene), and Bear Lake (Miocene) Formations. In general, the Bear Lake and Stepovak Formation coals are lignitic to subbituminous rank. Tolstoi Formation coals range from medium- to low-volatile bituminous rank. Most of the coal seams are less than 3 feet (0.9 m) thick. The Bear Lake Formation coals crop out in the area south of Herendeen Bay and on Unga Island (Figure 10). On the north side of the Alaska Peninsula, most of the Tertiary coal-bearing strata subcrop in an area which is over 250 miles (400 km) long and extends at least 35 miles (56 km) offshore to the North Aleutian Cost well in the North Aleutian Basin (Figure 10). Minor to good gas shows are associated with these coals. For example, the Gulf, Port Heiden Unit -1 shows greatly increased mudlog gas in the coaly section in the Bear Lake Formation from depths of 4,000 feet to 5,000 feet (1,219 m to 1,524 m). The mudlog gas levels increased from 20 ppm to over 250 ppm in some of the coal seams. Over this interval, the Port Heiden well encountered approximately 23 coal seams, most of which were less than 5 feet (1.5 m) thick. The David River 1-A well encountered Bear Lake Formation subbituminous coals at similar depths and the Hoodoo Lake Unit -1 penetrated lignitic coals to 5,000 feet (1, 524 m) and subbituminous coals to the well's total depth of 8,049 feet (2,453 m) in the Stepovak Formation [24]. This trend is consistent to the north, where the General Petroleum, Great Basins -1 encountered immature rocks with an average Ro of 0.29% for the Bear Lake Formation and an average Ro of 0.51% for the Stepovak Formation. The Hoodoo Lake Unit -2 encountered a gassy coal section in the Tolstoi Formation between 5,800 feet and 6,500 feet (1,768 m and 1,980 m). Based on the mudlog, this well encountered coal seams to 20 feet (6 m) thick with good mudlog gas shows and trace oil shows. The coal is described as lignitic to subbituminous in rank and is shaly. The rank of these coals must be higher than described in the mudlog since McLean [24] reports the vitrinite reflectance values average 1.15 % (medium-volatile bituminous) for this interval. Geophysical logs do not verify the thick coals noted on the mud log. This may be due to the shale interbeds and/or the nature of the shaly coal beds. The David River 1-A well encountered thin, high-volatile to low-volatile bituminous coal seams between the depths of 8,500 feet and 10,400 feet (2,590 m and 3,170 m) [24].

Coalbed Methane Potential. Structurally high areas where the Tolstoi Formation coals are found above 5,000 feet (1,524 m) in depth have the highest potential. Coal seams in the Bear Lake and Stepovak Formations are too low rank to have good gas potential.

GULF OF ALASKA PROVINCE

The Gulf of Alaska Province consists of the northern Gulf of Alaska onshore area of southern Alaska and is composed of amalgamated tectonic terranes that resulted from both Mesozoic and Cenozoic plate interactions [25]. The Tertiary coal-bearing rocks are found in the Yakutat terrane, the most recently arrived terrane. This terrane is presently moving north with the Pacific plate, colliding with and subducting beneath southern Alaska [26], subjecting the entire area to intense compressional stresses. The tectonism has caused the intense fold and fault deformation present in the Bering River Field [27].

Most of the coal in the Gulf of Alaska Province is found within the Eocene to Early Oligocene Kulthieth Formation [28 and 26]. The coals found in the Bering River Field area (Figure 11) are low-volatile bituminous to meta-anthracite and occur in deformed lenses up to 60 feet (18 m) thick. The coal seams are lenticular both from intense structural deformation and stratigraphic thinning (27) (Merritt, 1986). Coal seams up to 6 feet (1.8 m) thick are found in the Duktoth River District in the Robinson Mountains about 50 miles (80 km) east of the Bering River Field (Figure 11). Thin coal seams are encountered over a much broader and less deformed area in the subsurface from the Bering River field to the Yakutat Bay area, however, none of the thick coal seams found at the Bering River field have been encountered in the subsurface. Onshore exploratory wells (Figure 11) encountered both coal-bearing fluvial and marine strata based on the presence of sparse outer neritic to upper bathyal benthic microfauna in the Kulthieth Formation [29]. Reconstruction of the Kulthieth depositional system indicates that a series of deltas probably deposited sediments directly into a deep marine basin with rapid lateral changes in paleobathymetry [25].

Coalbed Methane Potential. The coals in the Gulf of Alaska Province are subject to intense compressional stress and severely deformed. These coals may be too metamorphosed and compressed to be viable gas targets. However, suitable coalbed methane plays may be found in structurally less deformed areas between the Bering River Field and the coast line.

YUKON-KOYUKUK PROVINCE

The Yukon-Koyukuk Province of western interior Alaska is characterized by maturely-eroded and heavily-vegetated terrain with most of the coal found in outcrops along the Yukon, Koyukuk, and Kobuk Rivers. Three poorly defined coal basins (Upper Koyukuk, Lower Koyukuk, and Kobuk) (Figure 12) have been identified in this province by Merritt and Hawley [1]. Cretaceous and Tertiary volcanic and sedimentary rocks [30] were deposited in a highly mobile basin complex subject to repeated volcanism and plutonism [31]. Up to 25,000 feet (7,620 m) of Cretaceous sedimentary rocks have been documented in this province [31]. This assemblage consists of marine volcanic graywacke and mudstone turbidites overlain by a westward prograding assemblage which includes coal-bearing deltaic deposits at least 10,000 feet (3,048 m) thick [32]. Patton [31] concluded the coal-bearing beds were deposited along a broad shallow trough extending along the eastern margin of the province.

Upper Koyukuk Basin

The thickest coal seams in the Yukon-Koyukuk Province are found in the Tramway Bar Field in the Upper Koyukuk Basin. The Tramway Bar Field is located 35 miles (56 km) above Bettles on the Middle Fork of the Koyukuk River (Figure 12). At this field, three coal seams with thicknesses of 17.5 feet, 3 feet and less than 1 foot (5.3, 0.9, and 0.3 m) have been mapped. These coals are steeply dipping, high-volatile B bituminous, with 38% ash and 6% moisture content [33]. Although these are the only significant coal outcrops in the Upper Koyukuk Basin, abundant coal float has been reported on the John River north of Bettles [34].

Coalbed Methane Potential. The Upper Koyukuk Basin contains bituminous rank coals that could provide gas for local use. Widely scattered outcrops, little surface data, lack of continuity of coal seams, and the structural complexity of the area make drilling targets very elusive.

Lower Koyukuk Basin

Lower Koyukuk Basin coals consist primarily of scattered coal occurrences between Ruby and Anvik on the Yukon River [35] (Figure 12). However, coals in this basin possibly extend much farther south than Anvik as bituminous coals have been reported on the lower Yukon River and Kuskokwim Rivers and Nelson and Nunivak Islands [34]. Between 1890 and 1903, some of these coal occurrences were mined to supply fuel for the steam-powered boats of the Yukon River. The area near Nulato supported several small scale mines in what is now referred to as the Nulato Field. These coals are typically thin (less than 4 feet (1.2 m) thick), high-volatile C bituminous and occur in the Late Cretaceous Kaltag Formation [36]. The thickest coal seam, an 11-foot (3.4 m) bed, is located 12 miles (19 km) upriver from Galena [37]. Thin coal seams were reported at this location by Collier [35] and Chapman [38].

In 1960, the Nulato Unit -1 was drilled to 12,000 feet (3,658 m) and is the only deep well to be drilled in this basin. This well was drilled on a north-east trending surface anticline and penetrated only Cretaceous rocks, yielding little information on the coal-bearing section. Sample descriptions indicate only minor coal was encountered and cores show dips greater than 60 degrees and abundant fractures and brecciation. The entire succession is over mature with respect to oil generation [39] with vitrinite Ro values ranging from 2.62% near the surface to over 4.0% at 6,100 feet (1,859 m) measured depth.

Coalbed Methane Potential. The entire area has undergone moderate to severe structural deformation with some of the coal seams sheared and dipping at steep angles. The complex structure, combined with very limited outcrop control, make predicting reservoir continuity and drillable targets impossible. Gas from bituminous coals for local village usage along the lower Koyukuk and Yukon Rivers may be obtained provided viable drilling targets can be delineated.

Kobuk Basin

Kobuk Basin coals consist of scattered, high-volatile C bituminous occurrences along a 120 mile (193 km) stretch of the Kobuk River between Kiana and Kobuk [21] (Figure 12). Some of these coals were sampled by Clough and others [40] on the west end of the known coal deposition in the Hockley Hills-Singauruk River (near Kiana) areas. Clough and others [40] noted some coal seams up to 6 feet (1.8 m) thick with most of the coal thickness less than 2 feet (0.6 m). Ash contents are high, reaching values of 60%. While the area is slightly less deformed than the Upper and Lower Koyukuk Basins, bed dips exceeding 40 degrees are common. Because of the lack of well and seismic data, no subsurface information on the extent of coal beds is available in this area.

Coalbed Methane Potential. The Kobuk basin lacks the outcrop and subsurface data (well and seismic) to fully evaluate the gas potential of its coals. However, bituminous coals in the basin may be viable exploration targets if they can be demonstrated to subcrop near villages now dependent on imported oil for heating and electricity.

NENANA PROVINCE

The Nenana coal trend is located north of the Alaska Range and includes fields located in the Minchumina, Middle Tanana, and Nenana Basins (Figure 13). These Tertiary coal bearing basins form a discontinuous belt from the Jarvis Creek Field near Big Delta on the east, through Healy, Lignite Creek, and Suntrana Coal Fields in the central portion, to the Farewell-Little Tonzona area (Minchumina Basin) to the southwest. The entire trend extends over 200 miles (320 km) and is over 30 miles (50 km) wide. The coals in these areas are mostly Oligocene to Miocene in age and are subbituminous C or B in rank.

Minchumina Basin

The Minchumina Basin is probably a complex of small, extensional basins [41]. Scattered Tertiary nonmarine sedimentary rocks crop out along stream valleys and river bluffs adjacent to the Alaska Range on the eastern edge of the basin. No subsurface data is available in this area and therefore mapping the lateral extent of coals is problematic. Most outcrops lie along the Farewell Fault Zone and are steeply [42]. The Farewell Fault separates the Minchumina Basin from the Alaska Range. To the west, away from the Farewell Fault, it is conceivable that the dips of these rocks could flatten into the subsurface. Coals in this area range from subbituminous A to high-volatile C bituminous and ash content ranges from 4% to over 26%. Seam thicknesses up to 20 feet (6 m) and multiple coal seams over 3 feet (0.9 m) thick have been mapped [43]. One subbituminous coal seam over 100 feet (30 m) thick has been reported from the Farewell-Little Tonzona Field [44].

Coalbed Methane Potential. The Minchumina Basin contains coal similar to that found in Cook Inlet Basin. Known coal occurrences dip steeply along the major dextral faults in the area. Without subsurface control, the extent and depth to these Tertiary coals is unknown and locating viable coalbed methane targets will be difficult. If found, the coalbed gas could be a useful fuel for local village use.

Nenana Basin

The Nenana Basin contains over 3,000 feet (914 m) of nonmarine Tertiary coal-bearing rocks which unconformably overlie Precambrian and Paleozoic metamorphic rocks. The Nenana Basin is the most explored of the three basins in the Nenana Province and contains a large coal resource (Figures 2 and 13) with coal seams up to 60 feet (18 m) thick. Most of the coal in this basin is subbituminous and is comparable in overall quality to coals found in the Cook Inlet and Wyoming's Powder River Basins [27]. Although the Healy Creek, Suntrana, and Lignite Creek Formations of the Usibelli Group all have significant coal deposits, most exploitable coal is contained within the Suntrana Formation [27]. The Lignite (Hoseanna) Creek Field near Healy is the only active coal mine in Alaska. Here, multiple coal seams that average 20 feet (6 m) thick are being mined from the Suntrana Formation.

Coalbed Methane Potential. The Nenana Basin contains thick coals that are similar to those found in Cook Inlet Basin. If the gas contents are comparable to those in Cook Inlet Basin, these coals could be good gas objectives. This basin contains coalbed methane targets located along the state's road system between Nenana and Healy and in the Big Delta area.

Middle Tanana Basin

The Middle Tanana Basin lies just north of the Nenana Basin and contains about 10,000 feet (3,050 m) of late Cenozoic fill [45 and 41]. Two oil and gas exploratory wells have been drilled in the Middle Tanana Basin. The Unocal, Nenana -1 and the Arco, Totek Hills -1 (Figure 13) were drilled near the margin of the basin. These wells drilled through the Tertiary section, encountering metamorphic basement rocks at 2,090 feet (789 m) and 3,163 feet (963 m) respectively. Both wells encountered coal, with the Totek Hills -1 well encountering numerous coal seams up to 10 feet (3 m) thick. The nonmarine Tertiary sequence in this basin penetrated by these wells consists of the Usibelli Group, which has been described from outcrops in the Nenana Basin to the south. Coals penetrated by both wells produced only minor mudlog gas shows. Cutting descriptions for the wells indicate the coals to be lignite to subbituminous and the section to be poorly to moderately consolidated. Higher rank coals could be encountered in the deeper parts of the Middle Tanana Basin. Stanley and others [46] estimate the top of the oil window (Ro of 0.6%) to be at depths exceeding 4,500 feet (1,370 m).

Coalbed Methane Potential. Wells in the Middle Tanana Basin encountered lignite to subbituminous coal. Higher rank (high-volatile bituminous) coal is projected to be below 4,500 feet (1,370 m) and is probably too deep for good coalbed methane production. Geologically, the low-rank coals are poor to moderate methane drainage targets, although the basin's proximity to the large Fairbanks market makes it attractive from an economic perspective.

NORTHERN YUKON PROVINCE

The Northern Yukon Province encompasses lower to middle Tertiary coal-bearing sedimentary rocks found in the Eagle and Rampart Troughs and the Yukon Flats Basin (Figure 13). Outcrops are scarce in this region occurring only in recently eroded bluffs and stream cutbanks. The area extends west over 400 miles (640 km) from the Canadian border along the Yukon River. Coal rank for the area ranges from lignite A to subbituminous C, though a few localities containing bituminous coal have been reported [47].

Eagle Trough

The Eagle Trough (Tintina Trench) is a northwest-trending basin that lies along the Tintina Fault Zone (Figure 13). This basin is estimated to contain as much as 9,500 feet (3,000 m) of Tertiary fill [48] in the vicinity of the Tintina Fault Zone. The basin contains subbituminous coals, although some coals have been tectonically upgraded in rank near the Tintina Fault Zone [47]. Although coal seams thicker than 30 feet (9 m) have been reported, most seams have a thickness less than 3 feet (0.9 m). In outcrop, many coal beds are highly fractured and steeply dipping [34].

Coalbed Methane Potential. The Eagle Trough contains mainly subbituminous coals which may be too low in rank to be good gas prospects. Gas for local use may be found in areas near faulting where the coal rank is higher and coal fractures may be better developed.

Rampart Trough

The Rampart Trough is a southwest-trending basin that lies along the Kaltag Fault. Tertiary fill in the trough is estimated to be as much as 6,500 feet (2,000 m) [41] (Figure 13). Coals found in the basin are dominantly subbituminous in rank and generally less than 5 feet (1.5 m) thick. Most of the mapped coal occurrences in the Rampart Trough are found adjacent to the Kaltag Fault and are very tectonically disturbed [47]. As in the Eagle Trough, some of the coals are bituminous in rank due to tectonic rank upgrading along major faults.

Coalbed Methane Potential. The Rampart Trough coals have low gas potential because of their low rank (subbituminous). Near faulting, where coals are fractured and have a higher rank, coalbed methane targets may be more attractive.

Yukon Flats Basin

Covering over 8,500 square miles (22,000 sq km), the Yukon Flats Basin is the largest Tertiary basin in Interior Alaska [47] (Figure 13). The basin is a half-graben complex with about 2 to 3 miles (3 to 5 km) of nonmarine Tertiary fill [49]. The only subsurface control in this large basin is a proprietary oil company seismic survey, shallow core holes, and a 1,200-foot (366 m) core hole drilled in 1994 at Fort Yukon by the U. S. Geological Survey. Bedrock outcrops are rare with the only exposures found along the margins of the basin. These limited exposures indicate coal-bearing rocks probably underlie most of the Yukon Flats Basin. Barker and Goff [47] report augering about 20 feet (6 m) of coal with a rank from lignite A to subbituminous B. The USGS Fort Yukon well encountered a 21+ feet (6.4 m), Middle Miocene, lignitic coal bed at a depth of 1,260 feet (384 m) (Gary Stricker, personnel communication, 1994). The core sample released a significant amount of gas when brought to the surface. This resulted in the termination of drilling (Tom Ager, personnel communication, 1994).

Coalbed Methane Potential. The known coals of Yukon Flats Basin are too low in rank for good gas production. However, higher rank coals found closer to the surface along the uplifted basin margins may have high gas potential.

SEWARD PENINSULA PROVINCE

Lignite and subbituminous coal-bearing rocks of Cretaceous and Early Tertiary age occur in isolated, structurally controlled coal fields on the Seward Peninsula [50] (Figure 12). Some of the coal beds are impressive in thickness reaching 80 feet (24 m) at Chicago Creek Field and 180 feet (55 m) at Grouse Creek [7]. The Tertiary section at Chicago Creek Field is generally less than 200 feet (61 m) thick and unconformably overlies quartz-mica schist of lower Paleozoic or Proterozoic age. Lignite beds in the Unalakleet area are generally less than 2 feet (0.6 m) thick and also dated as early Tertiary [31].

Both the Socal, Cape Espenberg -1, drilled on the north side of the Seward Peninsula, and the Socal, Nimiuk Point -1, drilled south of Kotzebue (Figure 12), penetrated a coal-bearing section in the Selawik Basin. The coal-bearing section penetrated by the wells is Upper Pliocene to lower Pleistocene in age [51] and thermally immature with Ro values less than 0.4%, distinguishing it from the Paleocene coals found in outcrop at Chicago Creek Field [52]. These wells reached total depth in schistose metasandstone and marble that likely correlate with pre-Mississippian schists and marble exposed on the Seward Peninsula. Both wells failed to penetrate the Cretaceous and early Tertiary coal-bearing rocks that outcrop on the Seward Peninsula, possibly indicating that the Seward Peninsula coal-bearing strata occurs as local, isolated basins.

Coalbed Methane Potential. Coals in the Seward Peninsula, Selawik, and Unalakleet areas are too low in rank for good gas production.

OTHER COAL-BEARING AREAS

Southeast Alaska

High-volatile B Bituminous [53] coal occurs near Angoon on the Kootznahoo Inlet (Admiralty Island) throughout an area of about 40 square miles (100 sq km) [54] (Figure 1). The coals are high sulfur, dirty, discontinuous and thin. The prominent structural dip of the rocks in the area is 45 degrees to the southeast. Coal with similar characteristics crops out near Murder Cove at the southern tip of Admiralty Island. Small, isolated outcrops of Tertiary lignite also are present on Prince of Wales, Kuiu, and Kake Islands [34].

Coalbed Methane Potential. The Kootznahoo Inlet coals on Admiralty Island are the only coals in southeast Alaska that hold even low gas potential. However, these coals are thin, discontinuous, dirty and structurally complex, making them unlikely targets.

Copper River

The Copper River Basin (Figure 11) occupies a lowland area in south-central Alaska between the Talkeetna and the Wrangell Mountains. Coal occurs throughout the 3,000 feet (914 m) of nonmarine Tertiary sedimentary basin fill. The coals penetrated in the wells and found in outcrops on the basin margins are lignites. Ten exploratory oil and gas wells have been drilled in the basin. The thickest Tertiary section penetrated in the northeast portion of the basin by Salmon Berry Lake -1 and Rainbow Federal -1 and -2 wells (Figure 11). A high thermal gradient on the eastern side of the basin near the Neogene and Quaternary Wrangell Mountain volcanoes may be present and upgrade the rank of coal in this area. However, coal outcrops in the Wrangell Mountains (Figure 11) are reported to be lignite [1] and Ro values of Tertiary sediments are generally less than 0.4% in the eastern portion of the basin near the Wrangell Mountains.

Coalbed Methane Potential. The Copper River Basin coals are too low in rank to have good gas potential.

DISCUSSION

Neither a proven reserve base or an export market for coalbed methane has been established in Alaska. However, preliminary analysis suggests that coalbed methane represents a huge, untapped state resource. As Alaska's conventional oil and gas reserves decline, it is critical to locate and identify and catalog potential deposits that can contribute to long term growth. In addition, identifying future energy resources is essential for land use planning.

This report's evaluation of Alaska's coalbed methane potential is based primarily upon the current limited knowledge of the basins and is calibrated with analogs from producing coalbed methane basins, primarily in the lower 48 states. It must be noted, however, that coal is a complex, heterogeneous material that defies simple analysis and comparisons. Predictions of Alaska's coalbed methane potential is fraught with pitfalls and ultimately only exploration drilling and long term well testing can provide definitive results.

For large scale coalbed methane production (involving several tcf) to take place in Alaska, it will have to compete with other gas sources for export to Pacific Rim markets. The economics involved with using coalbed methane as a local energy source may be much more favorable. Alaska's remote communities are currently dependent on large deliveries of diesel fuel for heating and electrical generation. Some areas pay the equivalent of $10 to $15 per mcf in fuel costs. The potential for spills during water-borne transportation of petroleum products is well known, and regulators are making it increasingly expensive. Additionally, using gas for local consumption would eliminate the large oil storage facilities (large enough to sustain the village through the entire winter) that each village must maintain, thus eliminating the potential for oil spills and pollution of ground and surface water. Wells producing 30 mcf per day, that in other situations would be uneconomic, could fill the energy needs of many of Alaska's rural communities.

CONCLUSIONS

Alaska's enormous coal resources provide many opportunities for coalbed methane exploration. Both Northern Alaska (North Slope) and Cook Inlet-Susitna Provinces contain thick coal sequences that hold large coalbed methane resources. The onshore areas in the Matanuska Valley and the uplifted basin margins of Cook Inlet Basin provide the highest potential for near term, large scale coalbed methane development. Large scale coalbed methane development on the North Slope is currently not feasible due to a lack of infrastructure. Bituminous coals in the Upper and Lower Koyukuk, Kobuk, Gulf of Alaska and Alaska Peninsula Basins could provide gas for the rural communities that depend on diesel fuel for power generation. Subbituminous and lignite coals in the North Slope, Cook Inlet, Susitna, Middle Tanana, Nenana, Yukon Flats, North Aleutian, Seward Peninsula and Copper River Basins could provide more opportunities for gas production provided hydrologic conditions and gas contents are suitable.

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Figure 1. Alaska coal basins and coal occurrences [1].

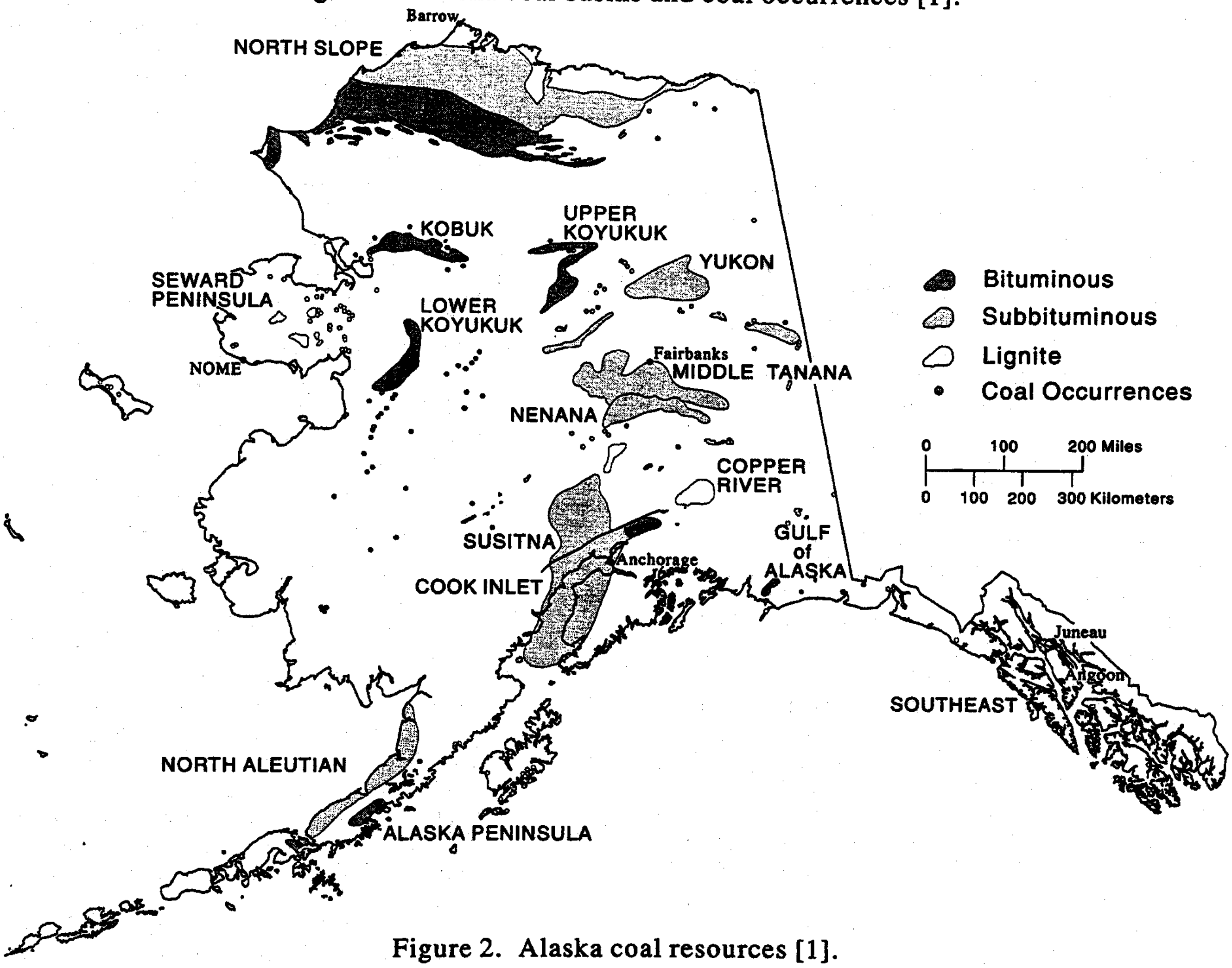


Figure 2. Alaska coal resources [1].

RANK OF COAL	BASIN	HYPOTHETICAL RESOURCES (Billion short tons)
BITUMINOUS COAL		
	North Slope	2,500
	Cook Inlet	500*
	Alaska Peninsula	3
	Gulf of Alaska	4
	Upper and Lower Koyukuk	1
	Kobuk	1
SUBBITUMINOUS COAL		
	North Slope	1,500
	Cook Inlet	1,000
	Nenana	15
	Susitna	3
	Tanana	45
	Yukon	1
	North Aleutian	No Estimate
LIGNITE COAL		
	Copper River	No Estimate
	Seward Peninsula	0.1

*Includes subsurface for Cook Inlet Basin from well data and Matanuska field coals.

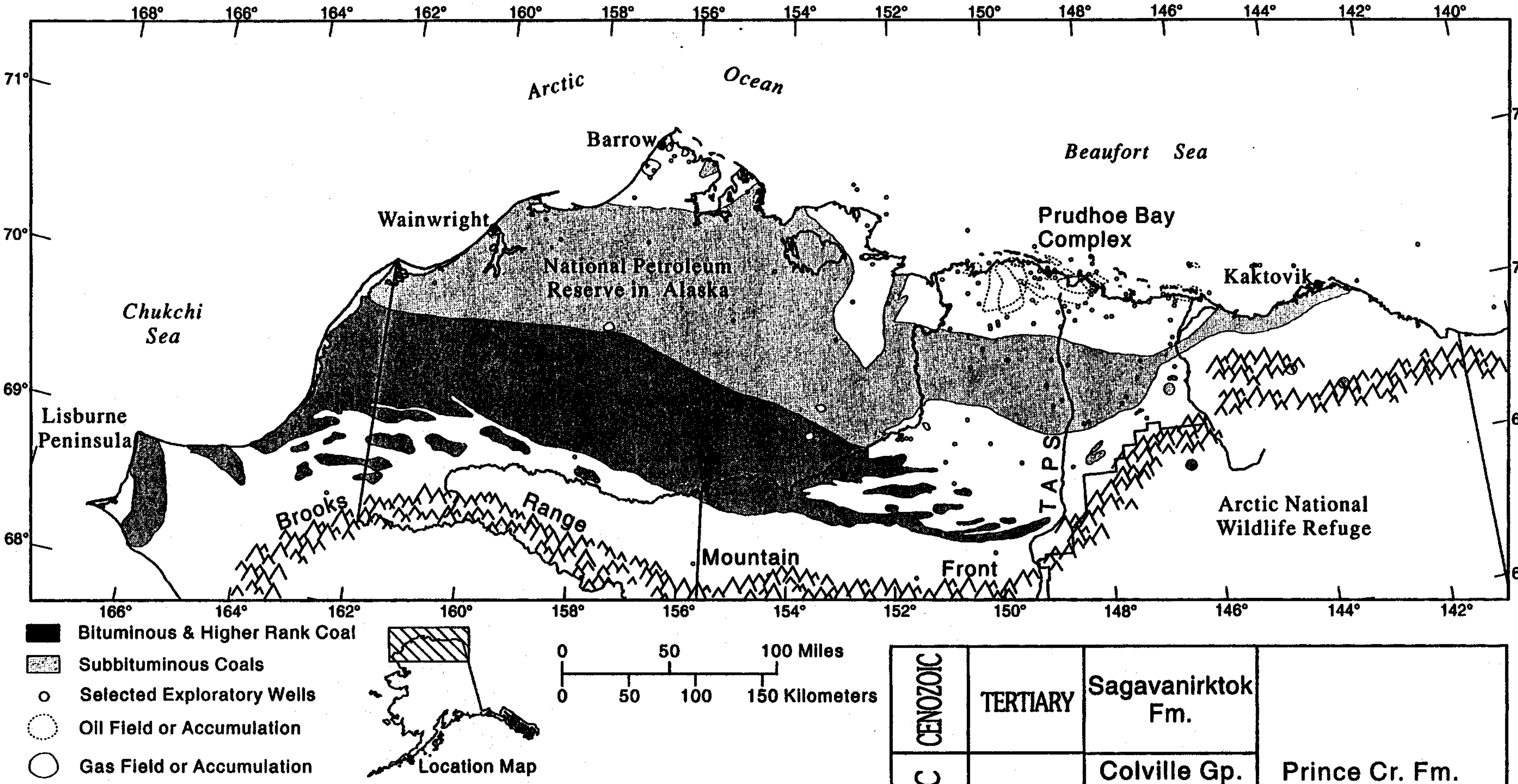


Figure 3. Extent of Northern Alaska Province (North Slope) coals [1].

CENOZOIC	TERTIARY	Sagavanirktok Fm.	
MESOZOIC	CRETACEOUS	Colville Gp.	Prince Cr. Fm.
		Nanushuk Gp.	Corwin Fm.
		Kuparuk Fm.	
	JURASSIC	Kingak Fm.	
	TRIASSIC	Sadlerochit Gp.	
PALEOZOIC	PERMIAN	Lisburne Gp.	
	PENN.		
	MISS.	Endicott Gp.	Kekiktuk Fm.
	DEVONIAN		Kapaloak Fm.

Figure 4. North Slope generalized stratigraphic column.

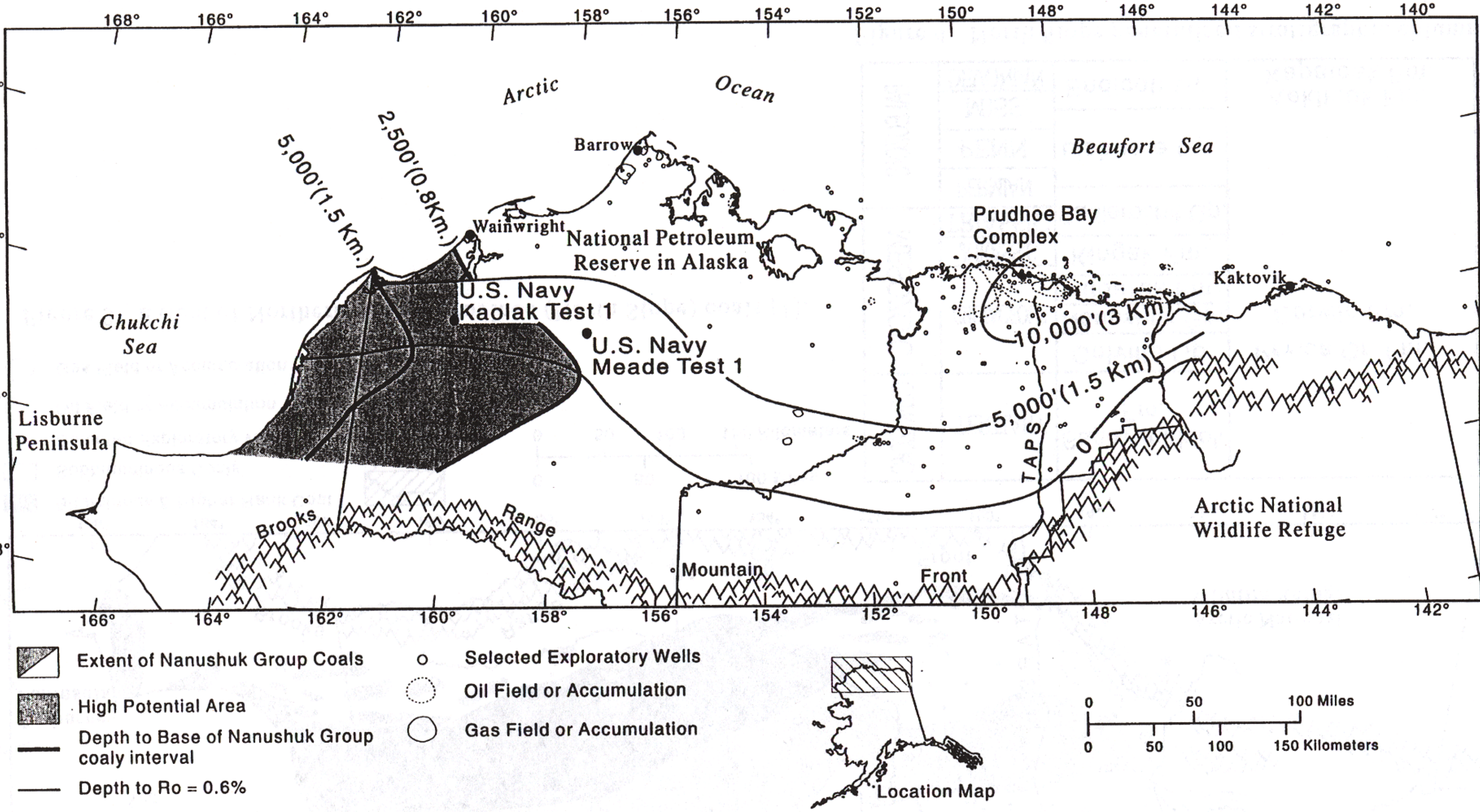


Figure 5. Extent of Nanushuk Group coals [9] and area of high coalbed methane potential.

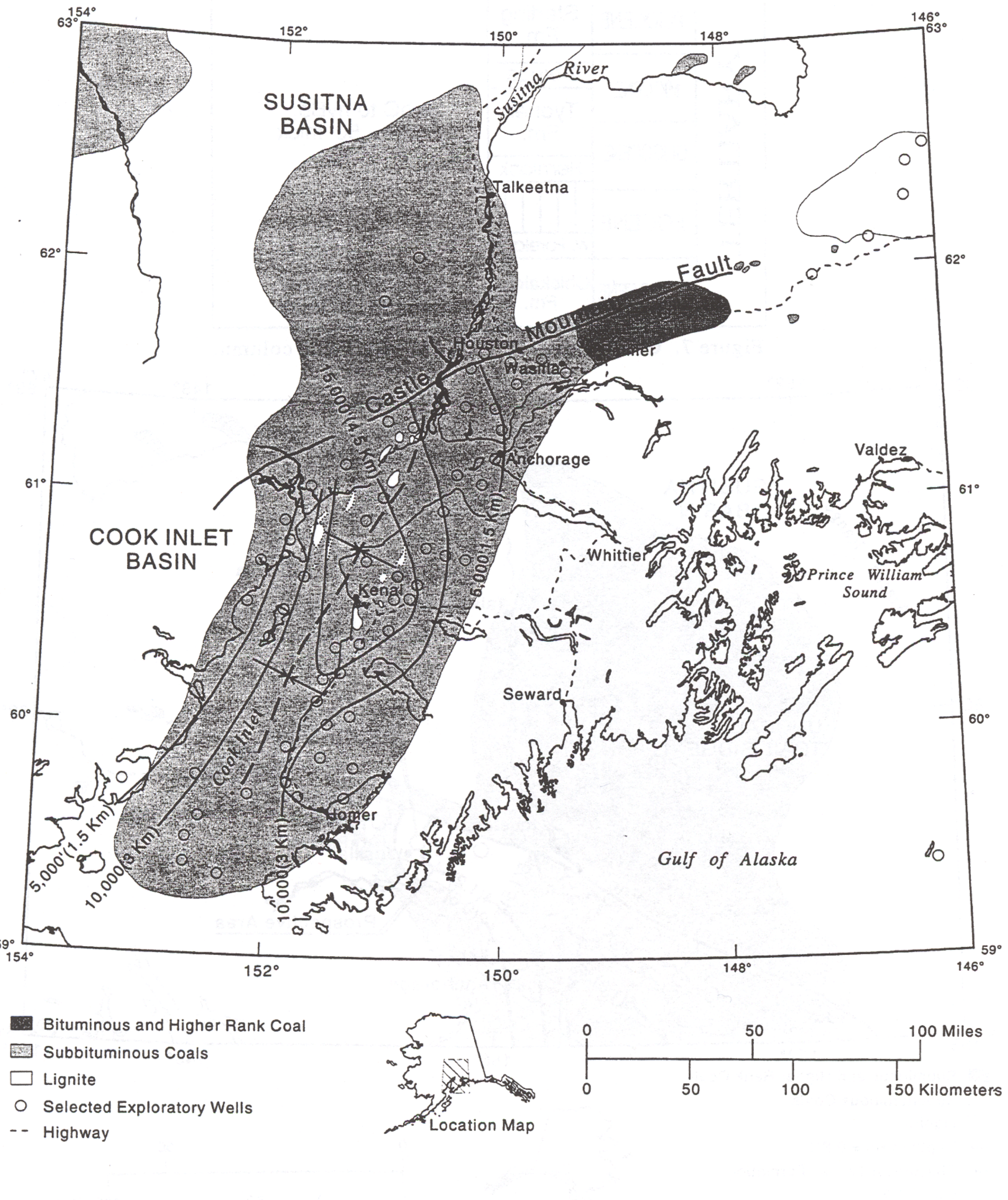


Figure 6. Extent of Cook Inlet-Susitna Province coals [1] showing the basin axis and contours showing depth to Ro = 0.6%.

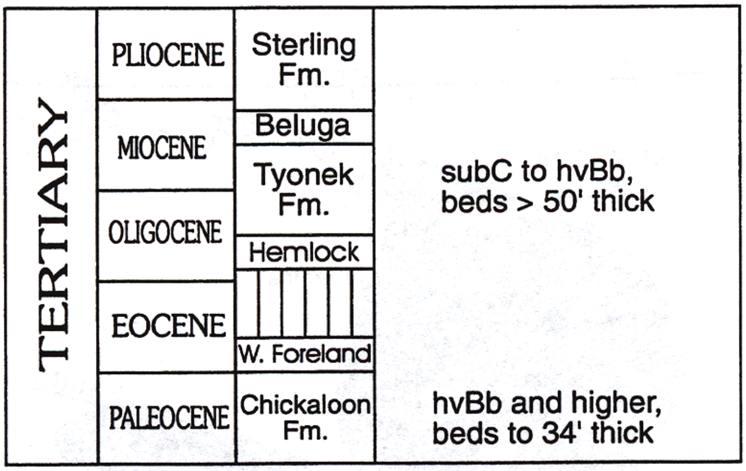


Figure 7. Cook Inlet generalized stratigraphic column.

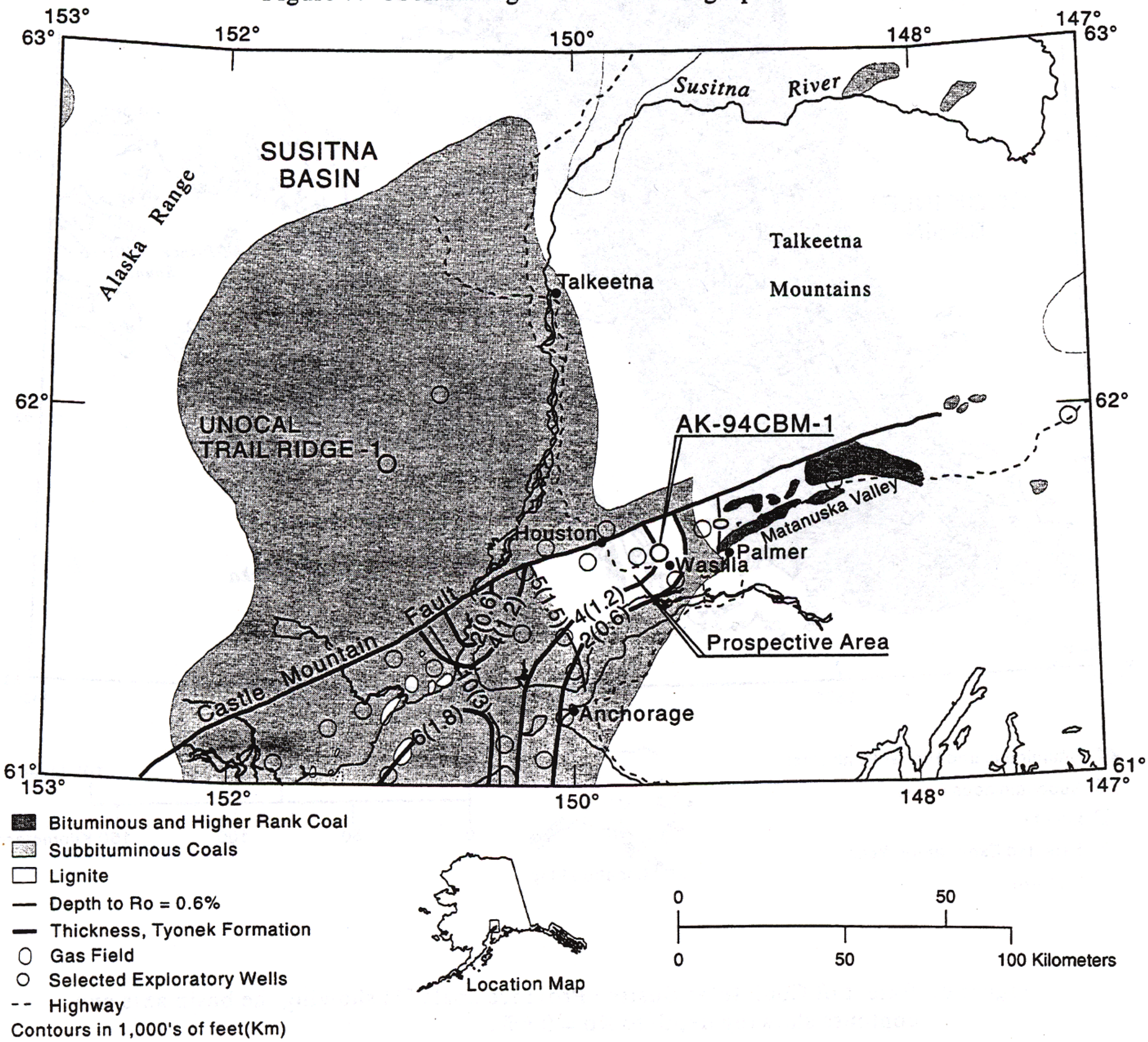
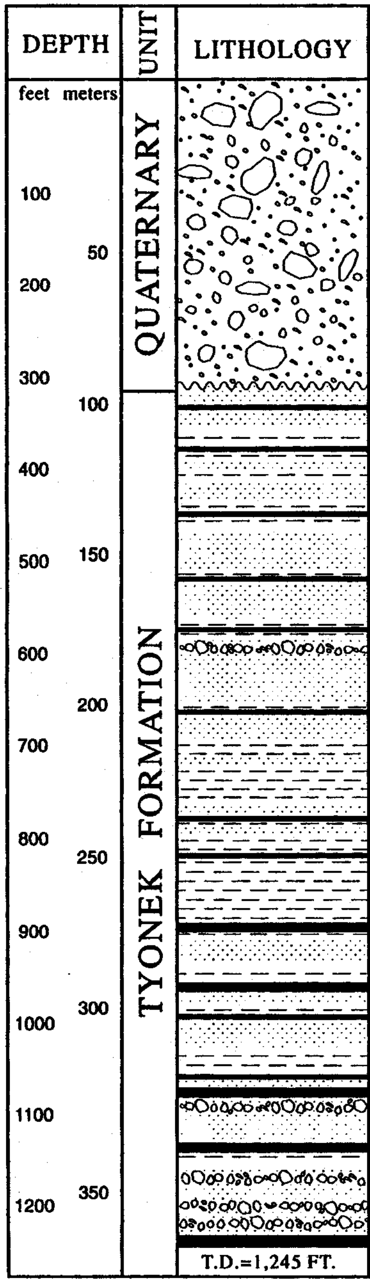
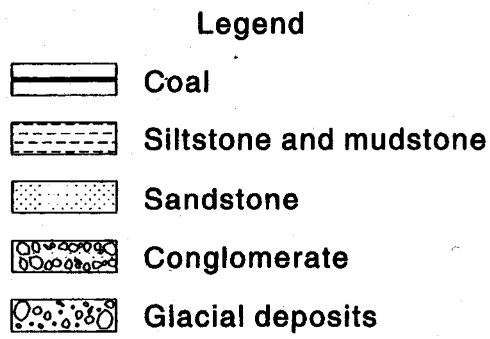


Figure 8. Extent of Susitna and upper Cook Inlet coals [1] showing Tyonek Formation thickness, depth to Ro = 0.6% and prospective area for Tyonek Formation coals.





Seam No.	Gas (DAF) cm^3/gram	Gas (DAF) scf/ton	Moisture %	Ash %	Volatile Matter %	Fixed Carbon %	Ro %	$\delta^{13}C$
1	1.96	63	9.02	8.47	33.80	48.71	0.48	
2	4.14	132	7.13	19.60	32.78	40.49		
3	4.99	160	7.43	11.80	34.34	46/43		-48.9
4	5.31	170	7.96	8.26	34.55	49.23	0.47	
5	5.16	165	5.06	49.80	21.93	23.21		-49.3
6	5.54	177	6.02	14.30	33.84	45.84	0.56	-48.3
7	4.42	141	6.15	26.84	29.47	37.54		-47.0
8	5.94	190	7.17	5.57	37.50	49.76	0.52	
9/10	5.10	163	6.25	14.62	35.18	43.95		
11	5.73	183	5.53	40.18	23.42	30.87		
12	5.72	183	5.23	44.74	22.85	27.18	0.58	-43.3
13	7.66	245	4.82	42.00	30.15	23.03	0.58	-44.0

Figure 9. Coal analyses for AK-94CBM-1.

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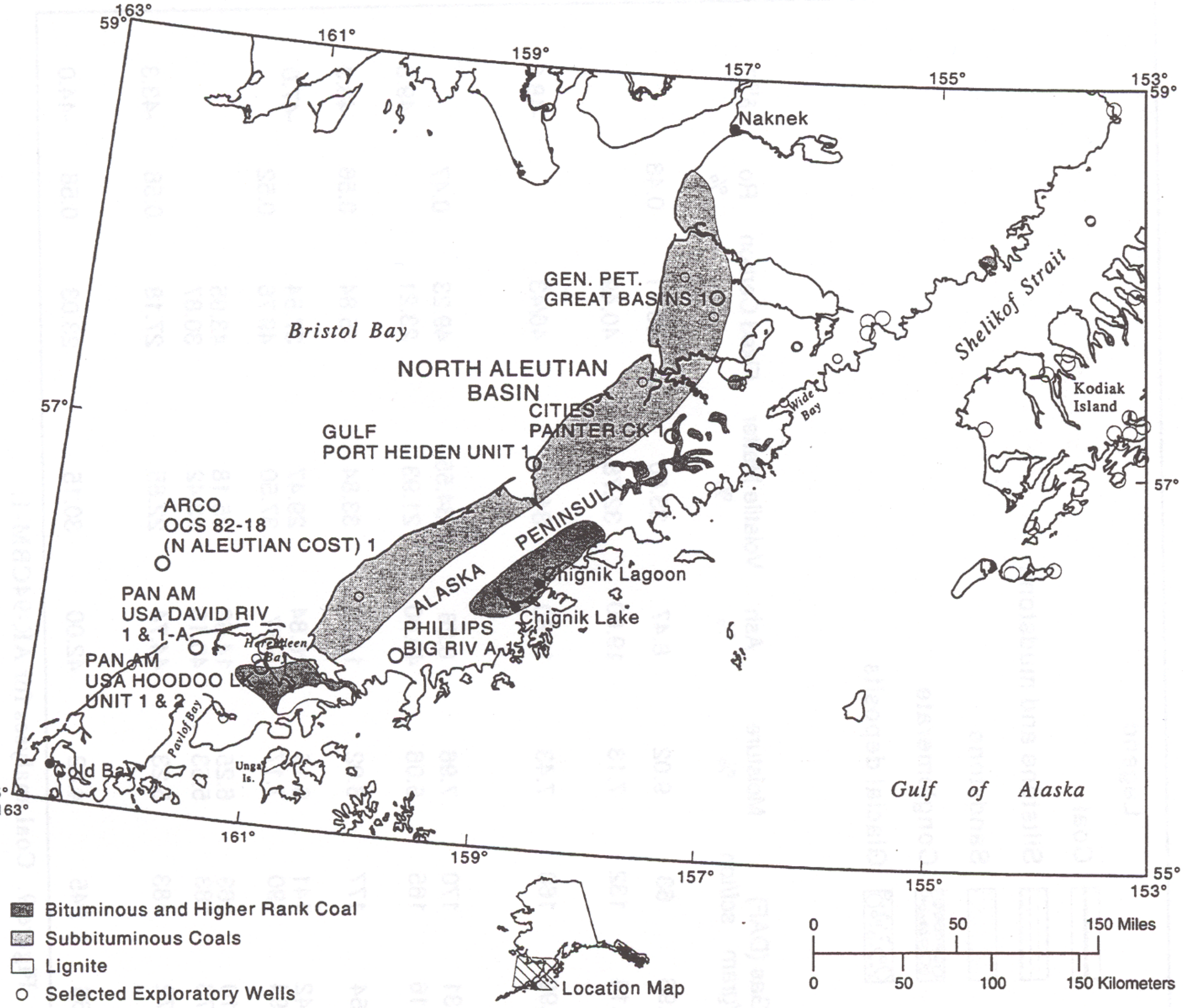

Figure 10. Extent of Alaska Peninsula Province coals [1].

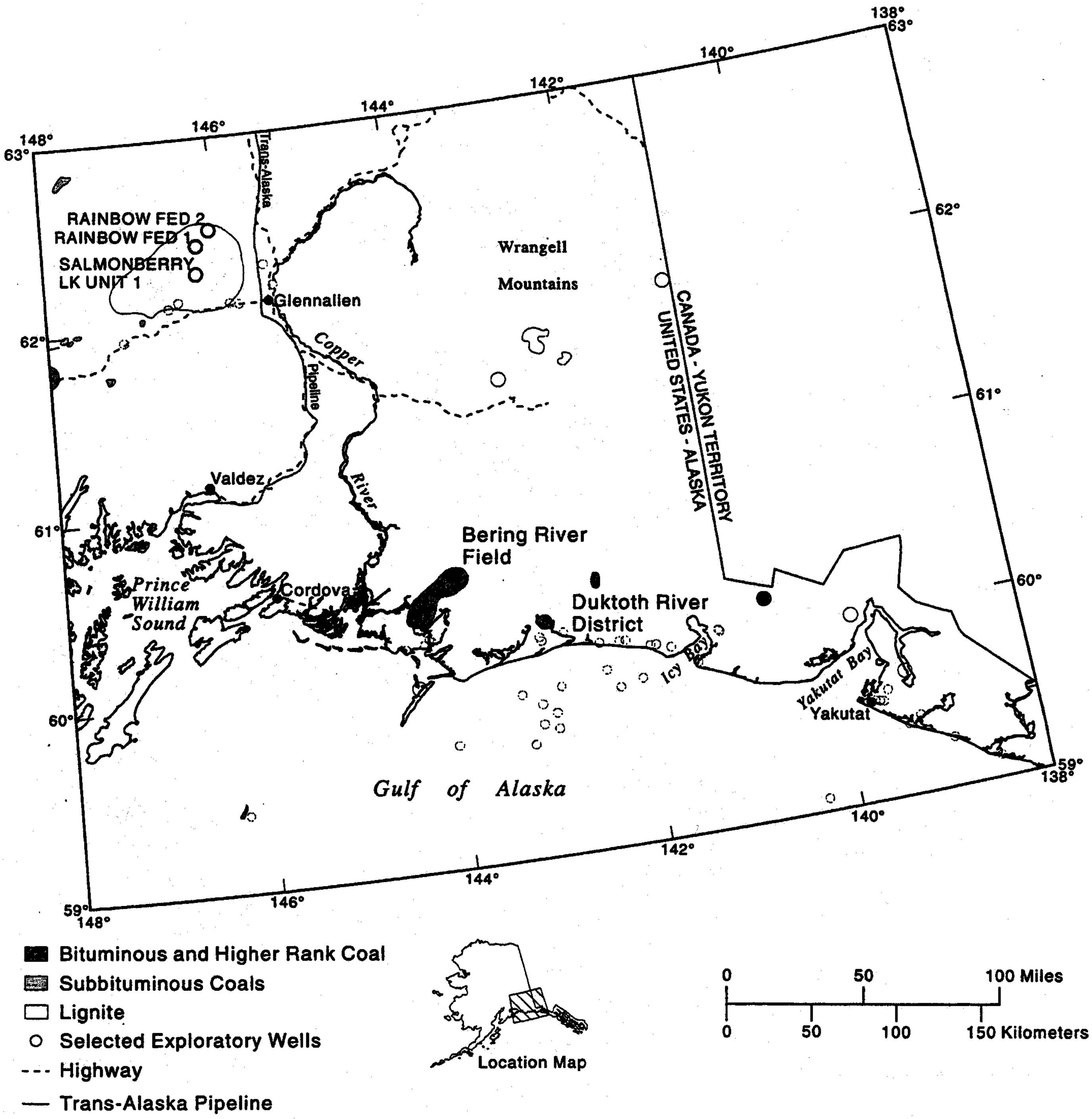

Figure 11. Extent of Gulf of Alaska Province coals and the Copper River Basin [1].

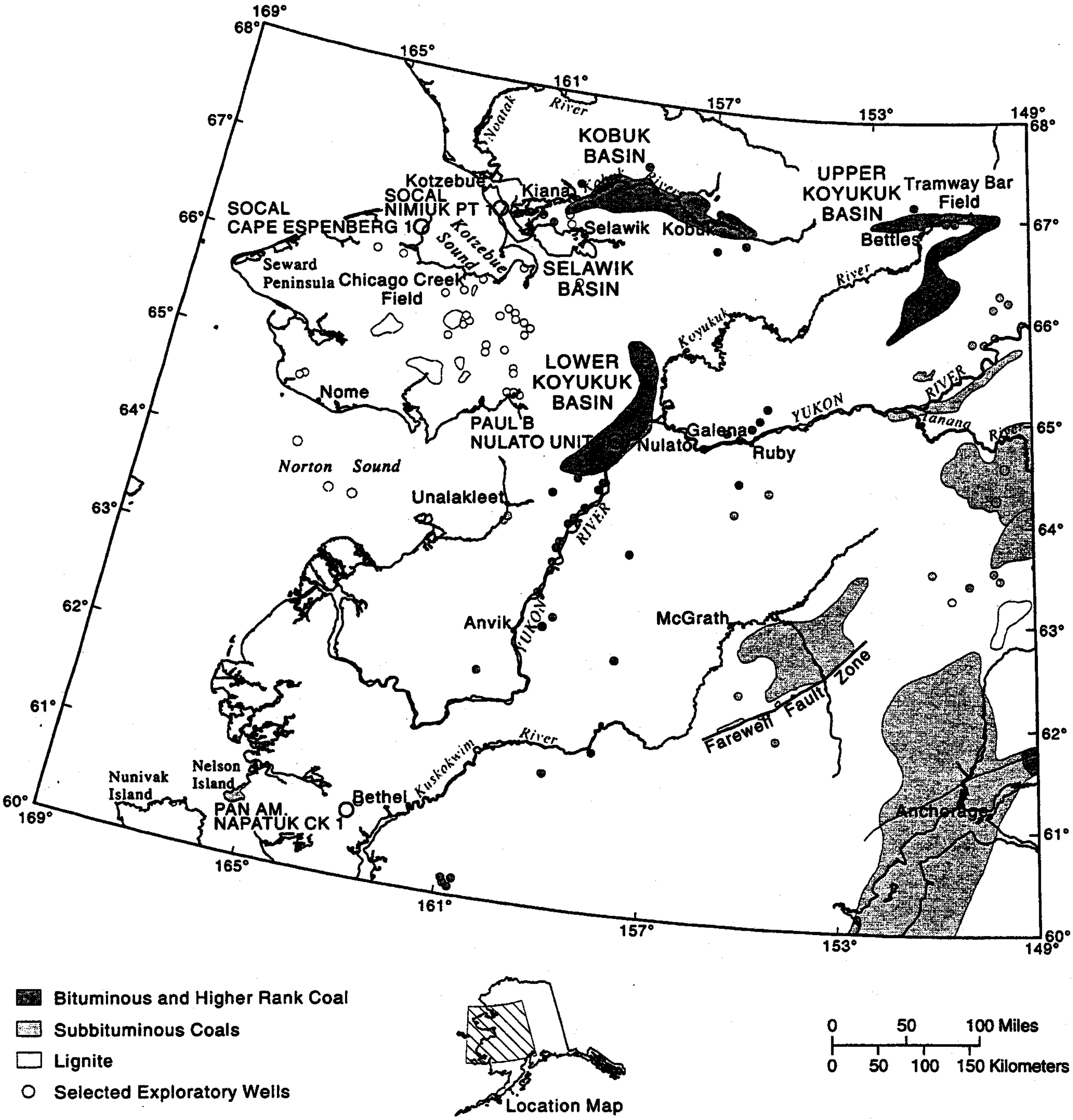

Figure 12. Extent of Yukon-Koyukuk and Seward Peninsula Provinces [1].

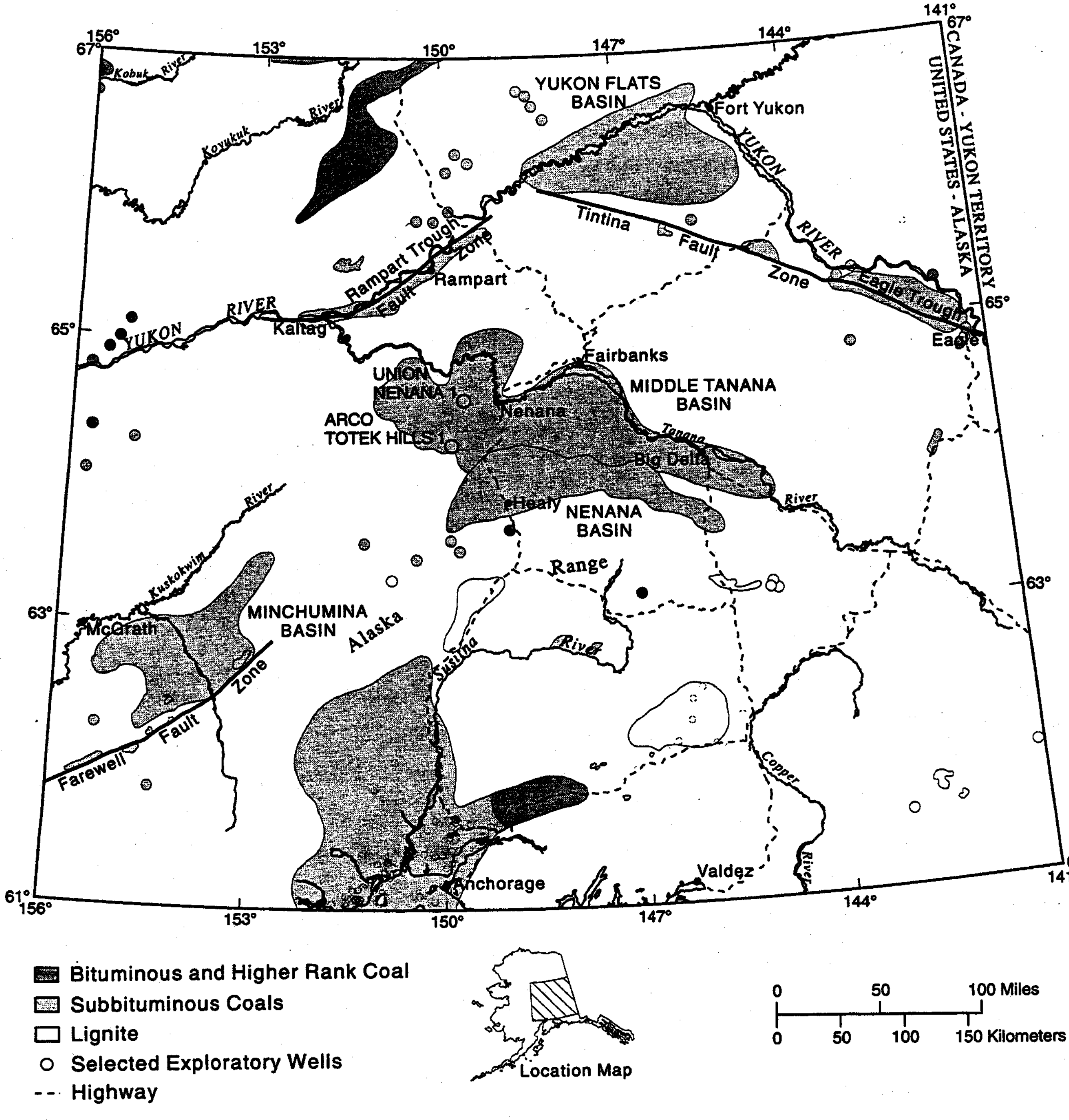

Figure 13. Extent of Nenana Province and Northern Yukon Province coals [1].

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Core Lithofacies Analysis and Fluvio-Tidal Environments in the AK 94 CBM-1 Well, Near Wasilla, Alaska

By Romeo M. Flores, Mark D. Myers, Gary D. Wicker, and Julie A. Houle

Abstract

The AK 94 CBM-1 well penetrated and cored, from 108 to 378 m, the Tyonek Formation (Miocene-Pliocene) near Wasilla, Alaska. Baaed on core and well-log descriptions, the Tyonek Formation consists of two major lithofacies types: fluvial dominated and tidallike. The upper (97 m thick) and lower (107 m thick) parts of the core consist of fluvial-dominated lithofacies occasionally interbedded with thin intervals of tidallike litbofaties, whereas the middle part (67 m thick) of the core predominantly contains tidallike lithofacies. Coal beds are mainly associated with the fluvial-dominated lithofacies where they were deposited in freshwater mires developed mainly on abandoned fluvial channel belts and subordinately on distal flood plains. In contrast, only thin coal lenses are present within the tidallike lithofacies, where they are associated with paleosols, well-drained mires, and freshwater lakes.

Sedimentary and biogenic structures suggest that the tidallike lithofacies formed in intertidal to subtidal environments. The most compelling evidence for this interpretation is the common occurrence of lenticular and flaserlike beds; foresets with reactivation surfaces; and rhythmic, mud-draped, bipolar ripple laminae. In addition, associated trace fossils of possibly *Thalassinoides, Chondrites, Teichicnus, Gyrolithes, Planolites,* and *Paleophycus,* as well as synaeresis cracks, support a tidal influence. These sedimentary structures are interbedded with heavily bioturbated units, suggesting subaqueous deposition. Alternatively, the only subaqueous fluvial setting that could produce most of these sedimentary structures is in a freshwater lacustrine setting with ebb and flow processes. Some of these tidallike deposits contain the freshwater lacustrine alga *Pediastrum* reported by Nichols (1998).

The alternating fluvial-dominated and tidallike lithofacies are similar to lithofacies found in the Tyonek Formation in the Chuitna drainage basin by Flores and others (1994, 1997). The discovery of these Tyonek tidallike lithofacies in the Chuitna River drainage basin and near Wasilla in the Upper Cook Inlet suggests that brackish water processes may have deposited part of the Tertiary coal-bearing deposits. Previous interpretations have limited these rocks to a nonmarine origin. If our interpretation of these rocks is correct, it requires their reevaluation and suggests that the generally accepted paleogeographic reconstructions of the Tertiary Cook Inlet Basin may need revision with respect to the location and distribution of marine-influenced sedimentation. However, if these rocks were deposited in freshwater lakes, the depositional processes that created these tidallike sedimentary structures need to be better documented.

Introduction

The Cook Inlet Basin (fig. 1) contains the second largest (the largest is the North Slope) amount of hypothetical coal resources in Alaska (Stricker, 199 1). These coal resources are contained in the Oligocene to Pliocene Kenai Group (fig. 2) (Calderwood and Fackler, 1972), which is as much as 7,617 m thick in the offshore Cook Inlet Basin. The hypothetical coal resources of the basin exceed 1.5 trillion short tons of which 500 billion short tons are found onshore (Stricker, 1991; Smith 1995).

The coal-bearing Kenai Group includes, from bottom to top, the Hemlock Conglomerate, and the Tyonek, Beluga, and Sterling Formations (fig. 2). These formations consist of interbedded conglomerate, sandstone, siltstone, mudstone, coal, and carbonaceous shale. Coals are mainly found in the Tyonek, Beluga, and Sterling Formations; however, the thickest coals are found in the Tyonek and Beluga.

The depositional environment of the Kenai Group has generally been interpreted as a nonmarine continental setting (Hite, 1976; Hayes and others, 1976). More specifically, the Beluga and Sterling Formations were interpreted as deposits of braided and meandering streams. Flores and Stricker (1993), and Flores and others (1994, 1997) reinterpreted the Beluga and Sterling Formations to be mixed anastomosed, meandering, and braided streams. In this setting, the thick and thin coal beds accumulated in raised mires and low-lying swamps, respectively. The Tyonek Formation has generally been interpreted as braided-stream deposits (McGee, 1972; Adkison and others, 1975; Dickinson and Campbell, 1978; Dickinson and others, 1995). However, tidallike deposits of the Tyonek in the Chuitna River drainage basin (fig. 1) were reported by Flores and others (1994, 1997).

The purpose of this paper is to report additional evidence for tidallike deposits in the Tyonek Formation near Wasilla (fig.

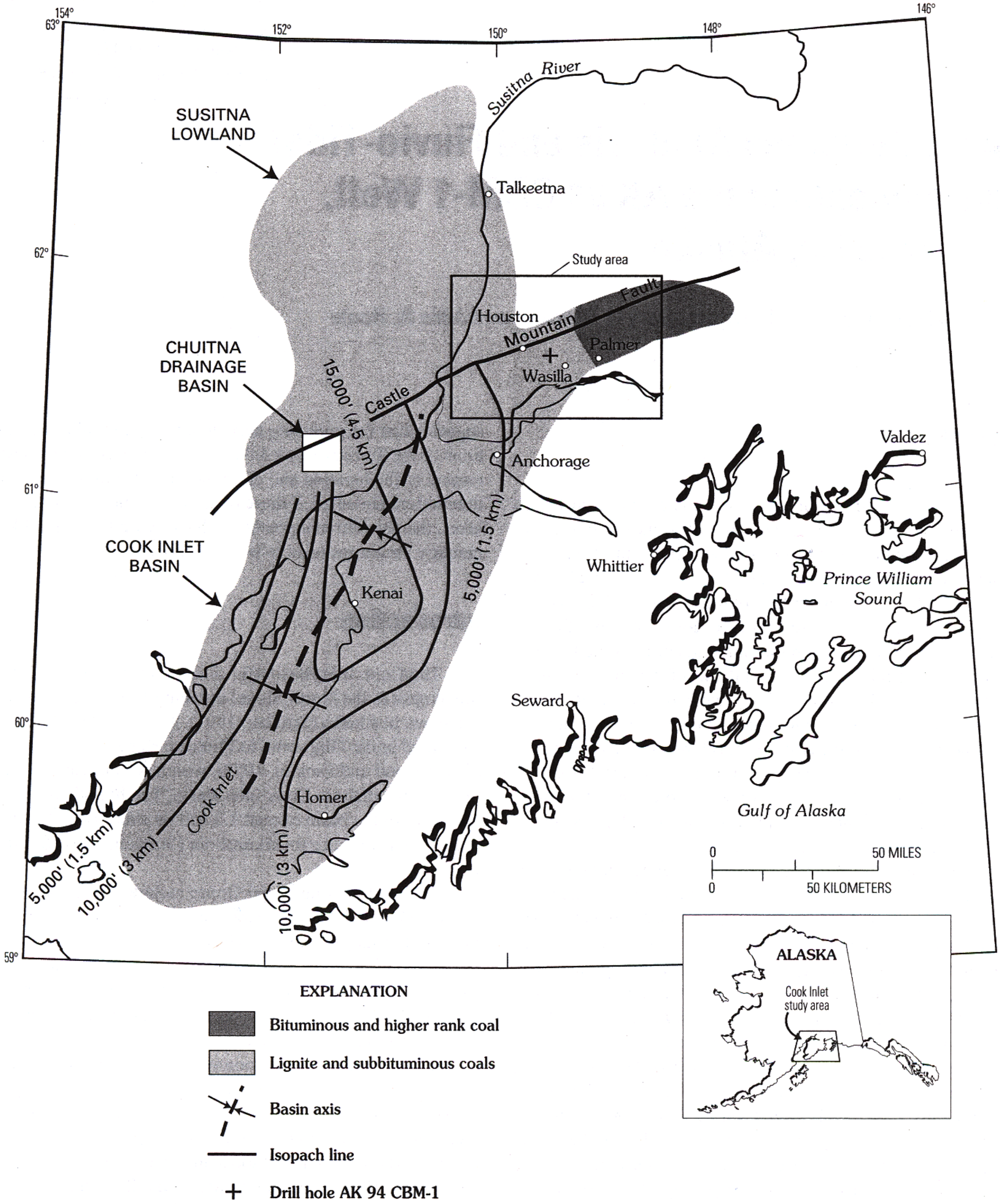


Figure 1. Offshore and onshore Cook Inlet Basin in south-central Alaska. Modified from Smith (1995).

1), which is about 161 km northeast of the Chuitna River drainage basin. These deposits were described from cores of the AK 94 CBM-1 well that was drilled for a coal-bed methane prospect by the Alaska Department of Natural Resources (Smith, 1995). This paper includes detailed lithofacies analysis, sedimentology, and interpretation of the depositional environments, which were not previously performed by Smith (1995).

Geologic Setting

The AK 94 CBM-1 well was drilled in 1994 at a location about 4.2 km northwest of Wasilla on the northeast margin of the Cook Inlet Basin (fig. 3). The northeast margin of the basin forms a northeast-trending trough bounded by the Castle

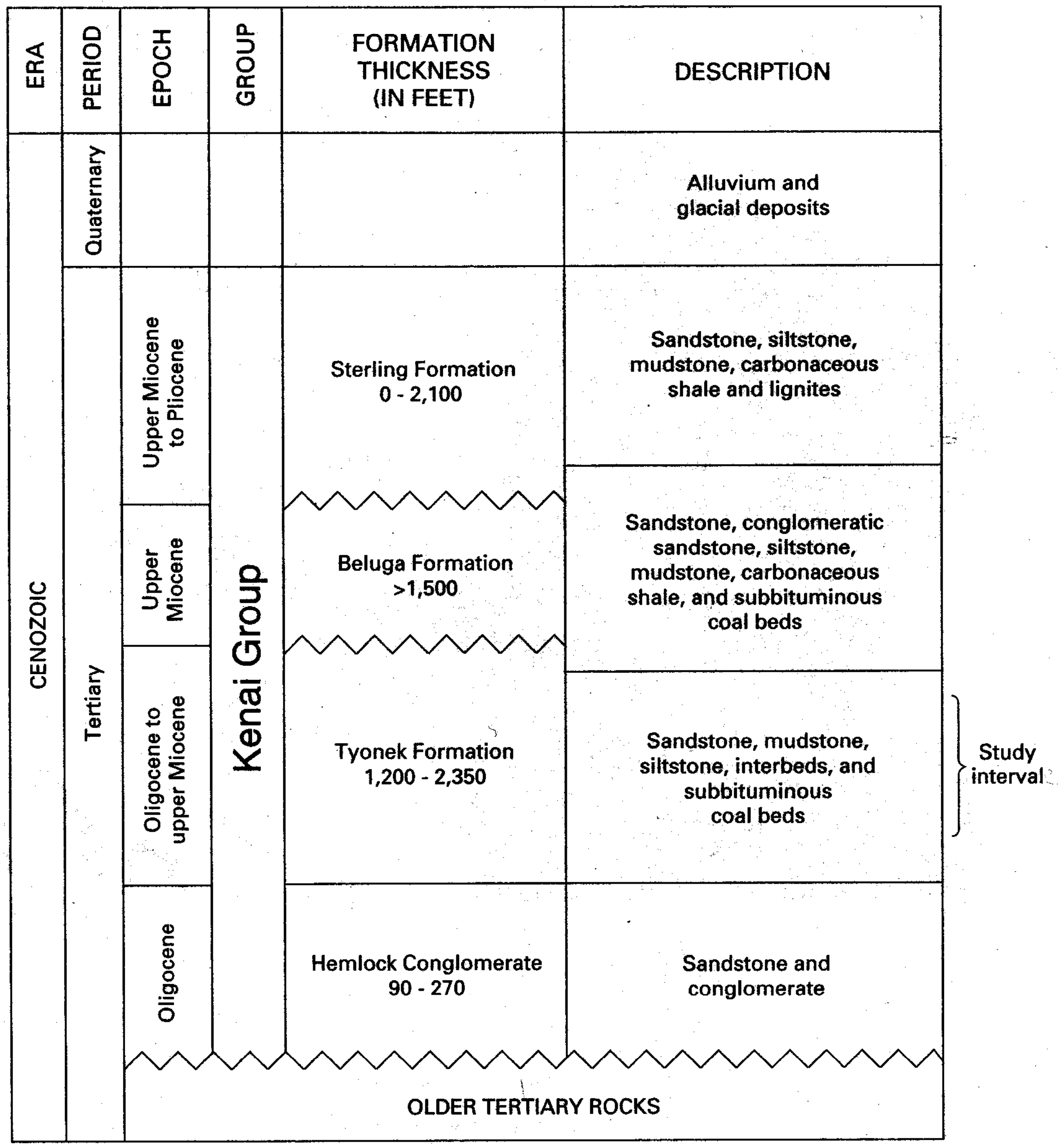


Figure 2. A general stratigraphic column showing the coal-bearing formations of the Kenai Group and the study interval in the Tyonek Formation in the upper Cook Inlet.

Mountain fault and Talkeetna Mountains on the north and the Chugach Mountains on the south (fig. 3). The western part of the trough, which is 40.2 km wide and 121 km long, contains the Tyonek Formation; in this area, it is more than 1,219 m thick and contains a cumulative thickness of greater than 30.5 m of coal beds at depths from 152 to 1,828 m (Smith, 1995). Smith (1995) reported that these coals are high-volatile bituminous with vitrinite reflectance (R_o) values ranging from 0.6 to 1.2 percent (fig. 3).

Johnsson and others (1993) reported that coals in the Kenai Group in the northern Cook Inlet Basin range from 0.2 to 0.9 percent R_o in depths from 30.5 to 2,742 m. Post-depositional uplift of the northern margin of the basin exposed older rocks (Paleocene to Oligocene) with high thermal maturity. For example, Paleocene to Eocene rocks, which contain high-volatile bituminous and anthracite coals, are exposed in the Matanuska Valley (Anonymous, 1990). Coal mines in this area have emitted methane gas, which caused outbursts and explosions in 1937 and 1957 (Barnes and Payne, 1956; Smith, 1995).

The high-thermal-maturity Tertiary coals, particularly in the northern margin of the Cook Inlet Basin, have been targeted for coal-bed methane exploration. Smith and Clough (1993) identified the Wasilla area as a prospect because of its proximity to infrastructure, including gas pipelines. This led to the drilling of the AK 94 CBM-1 well by the Department of Natural Resources, State of Alaska, to test for the presence of coal-bed methane in the Tyonek Formation (Smith, 1995). This test well will serve as an important guide to future coal-bed gas measurements and resource estimates of Tertiary coal-bearing rocks in the Cook Inlet Basin.

Previous Work Performed on the AK 94 CBM-1 Well

The AK 94 CBM-1 well was drilled to a total depth of 379 m, and a continuous core of the Tyonek Formation was

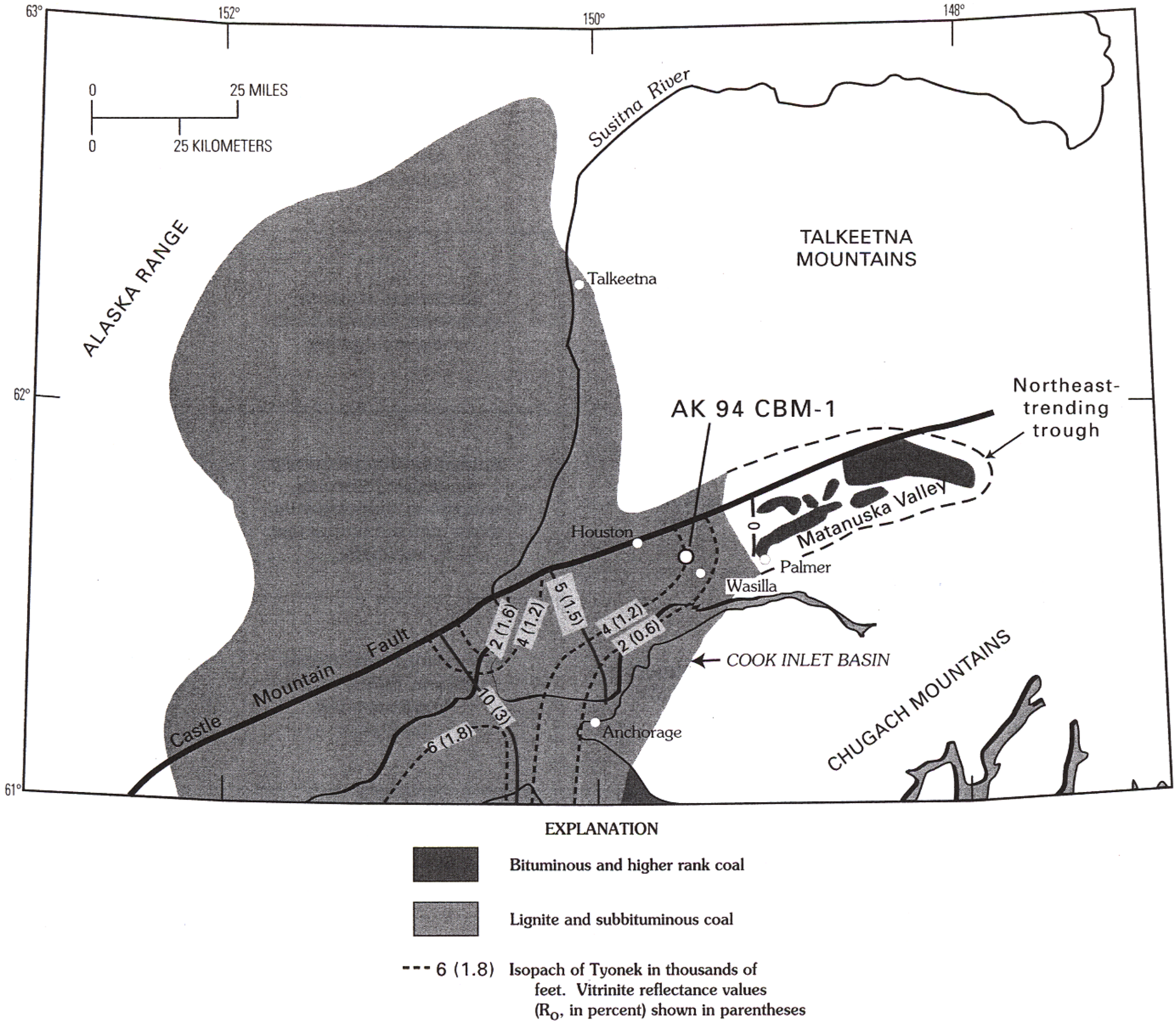


Figure 3. Upper Cook Inlet Basin showing location of the AK 94 CBM-1 well; coal rank in the Matanuska Valley; and coal rank, R_o, and thickness of the Tyonek Formation. Modified from Smith (1995).

recovered from 108 to 379 m (Smith, 1995). The depths from 0 to 108 m were cased; however, rock samples indicate that the interval is composed of Quaternary glacial conglomerate. A suite of geophysical logs (e.g., gamma ray, density, spontaneous potential, and resistivity) was also run to evaluate the Tyonek rocks. The drilling project was mainly designed by Smith (1995) to collect samples from Tyonek coal beds that were greater than 0.6 m thick for proximate and geochemical analyses, and gas desorption. Thus, only coal beds that are less than 0.3 m thick were left in the core for detailed description. Smith (1995) noted that the coal beds are thick (as thick as 2.9 m) at depth and their cumulative thickness is about 12.5 m.

Out of the total of 18 coal beds drilled in the Tyonek Formation, 13 beds were sampled for gas content. Proximate analysis of these coals indicates an as-received moisture content of 4.8 to 9.02 percent, volatile matter of 5.57 to 22.85 percent, fixed carbon of 23.03 to 48.71 percent, and ash yield from 5.57 to 44.74 percent. In general, moisture and fixed carbon increased with depth. Gas content ranges from 63 ft^3/short ton at standard temperature and pressure (STP) for coal beds at a shallow depth (152 m) to 245 standard ft^3/short ton at STP for coal beds at a great depth (366 m). Carbon isotopes of the coal-bed gases range from –49.3 to –43.3 ‰ (per mil) $\delta^{13}C$, with slightly heavier isotope values at depth, indicating both a thermogenic and biogenic origin of the coal-bed gas. Composition of this gas is 90 percent methane with minor amounts of CO_2 and N_2. Vitrinite reflectance values range from 0.47 to 0.58 percent and generally increases with depth (Smith, 1995).

Lithostratigraphy of the AK 94 CBM-1 Core

Smith (1995) described the general lithology of the AK 94 CBM-1 core, from 379 to 108 m depth, as consisting of interbedded coal, mudstone, siltstone, sandstone, and conglomerate. Our detailed description of this 271-m-thick interval of 7.6-cm-diameter core included thickness, lithology, color, grain size, sorting, mineral composition, nature of contact, sedimentary structures, trace fossil content, and biological constituents (figs. *4A-4C).*

In order to summarize the lithofacies association of the core, the Tyonek interval is divided into lower, middle, and upper parts based on the grain size, abundance, and thickness of diagnostic lithologic types. The lower part (fig. *4A),* from 379 to 272 m, is 107 m thick and consists of abundant conglomeratic sandstones and thick (0.3-2.9 m) coals and carbonaceous shales. The middle part (fig. 4B), from 272 to 205 m, is 67 m thick and is composed of abundant mudstone, siltstone, fine-grained sandstone, and sparse, thin (8.9 cm to 0.3 m) coal and carbonaceous shale. The upper part (fig. 4C), from 205 to 108 m, is 97 m thick and comprises abundant medium- to coarse-grained sandstones and thin to thick (l-3.5 ft or 0.3-l m) coal and carbonaceous shale.

The gamma-ray curve measures the natural radioactivity of rock types caused by absorption of thorium by clay minerals, potassium content of clay minerals (mainly illite, and uranium fixed by associated organic matter (Doveton, 1994). In general, low levels of radioactivity are observed in sandstone and siltstone, which is attributed to the amount of clay minerals, potassium feldspar, mica, and heavy minerals. Coal displays much lower gamma radiation compared to these rock types and is readily identifiable by the g&a-ray log curve. Density and resistivity curves were also used to identify the coal beds. Responses of both gamma-ray and spontaneous-potential logs are indirectly related to sediment grain size and may be used as a vertical grain-size profile (Galloway, 1968; Selley, 1978).

A comparison of the gamma-ray and spontaneous-potential logs of the conglomerates and sandstones have significantly different patterns (see fig. *4A). The* gamma-ray log curve displays serrated cylindrical and bell shapes (rightward excursions). However, the spontaneous-potential log curve shows smooth cylindrical to combined smooth and serrated bell shapes (leftward excursions). The better definition of the spontaneous potential is probably due to changes in grain size of the sandstone. The cylindrical-shaped curve suggests uniform vertical grain size of the sandstone and the bell-shaped curve indicates fining upward.

lower Part of the Core

The lower part (379-272 m) of the Tyonek interval (see fig. 4A) is dominated by medium- to coarse-grained sandstone and conglomerate, which make up as much as 60 percent of the total rock volume. The sandstones occur as fining-upward beds that are from 0.6 to 4.6 m thick and display erosional bases (fig. 5). The sandstones are light gray and show a "salt-and-pepper" texture (Krynine, 1950); light minerals consist mainly of quartz. The dark color is due to the presence of chert and other rock fragments (e.g., metamorphic and volcanic). Sedimentary structures consist of trough crossbeds that are 7.6 cm to 0.3 m in height (fig. 5). These structures are interbedded by a few planar crossbeds (0.3 m in height) with steep foresets (fig. 5). Asymmetrical and climbing ripple laminations (7.6-cm- to 0.6-m-thick units) cap the trough and planar crossbedded units (fig. 6).

The conglomerates, which make up less than 5 percent of the total rock volume, have erosional bases and occur as 7.6-cm- to 0.6- m-thick beds (figs. *4A* and 5). They are gray and composed of rounded to subrounded pebbles and cobbles of quartz, black chert, and volcanic rock fragments. They are commonly framework supported, and a few are matrix supported. The framework-supported conglomerates exhibit clast imbrication.

Forty percent of the lower part of the Tyonek interval (fig. *4A)* consists of interbedded, very fine to fine-grained sandstone, siltstone, mudstone, coal, and carbonaceous shale (fig. 7). Sandstones have sharp basal contacts, are gray in color, and vary from 0.3 to 1.5 m thick. They are mainly ripple laminated, lenticular and flaserlike bedded (with bipolar ripple laminae), and are vertically burrowed by nondescript trace fossils. Siltstones are gray, a few centimeters to 0.4 m thick, ripple laminated, burrowed, and are commonly interbedded with the sandstones. Mudstones are dark gray to black, depending on the amount of macerated plant content, and vary from 0.3 to 8.2 m thick. They are massive to crudely laminated, vertically and horizontally burrowed, and contain whole shells of bivalve mollusks or pelecypods. These bivalves are articulated, 3.8 cm wide and 6.3 cm long, and resemble a unionid clam in shape. Root marks, defined by vertical branchlike tubules lined by carbonaceous matter, are common in the sandstones, siltstones, and mudstones. Coal beds vary from 15.2 to 2.9 m in thickness (fig. *4A).* They contains vitrinite bands indicating woody composition. They are commonly interbedded with carbonaceous shales, which vary from a few centimeters to 0.3 m thick. Carbonaceous shales are fissile and contain a mixture of mud and macerated plant fragments. Root marks are a common bioturbation feature in the carbonaceous shale.

Middle Part of the Core

The middle part (272-205 m) of the Tyonek interval (fig. 4B) is dominated by abundant fine-grained sandstones (fig. 8), which make up as much as 55 percent of the total rock volume. Sandstones display sharp to erosional bases and uniform grain size from bottom to top; they are from 0.3 to 7.9 m thick and are light gray and show a "salt-and-pepper" texture. Sedimentary structures consist mainly of foresets that range from 23 to 25 cm in height and are separated by clay-draped reactivation surfaces. Trough crossbeds, 8-15 cm in height, are common, but planar crossbeds, as much as 15 cm in height, and convolutions are rare. Lenticular bedding (0.25-0.64 cm thick) and flaserlike ripple laminations are very common (fig. 8A). Ripple sets in the flaserlike laminations are bipolar and draped by burrowed mudstones (fig. 8B). The sandstones are heavily bioturbated, and the accompanying sedimentary structures have been partly to completely destroyed. Vertical burrows in the form of escape and branching structures are very common. Escape structures are 1.3 cm high and 2.5 cm wide, and the branching vertical burrows (e.g., *Thalassinoides-like)* are *5-8* cm wide and 1.5 m long (fig. 9). The branching burrows were open and passively infilled by overlying sand (fig. 9). Plant bioturbation in the form of root marks is rare.

The gamma-ray and spontaneous-potential logs of the sandstones have significantly different patterns (fig. 48). The gamma-ray log curve displays mainly a serrated bell shape (rightward excursions). However, the spontaneous-potential log curve shows combined smooth and serrated bell shapes and funnel

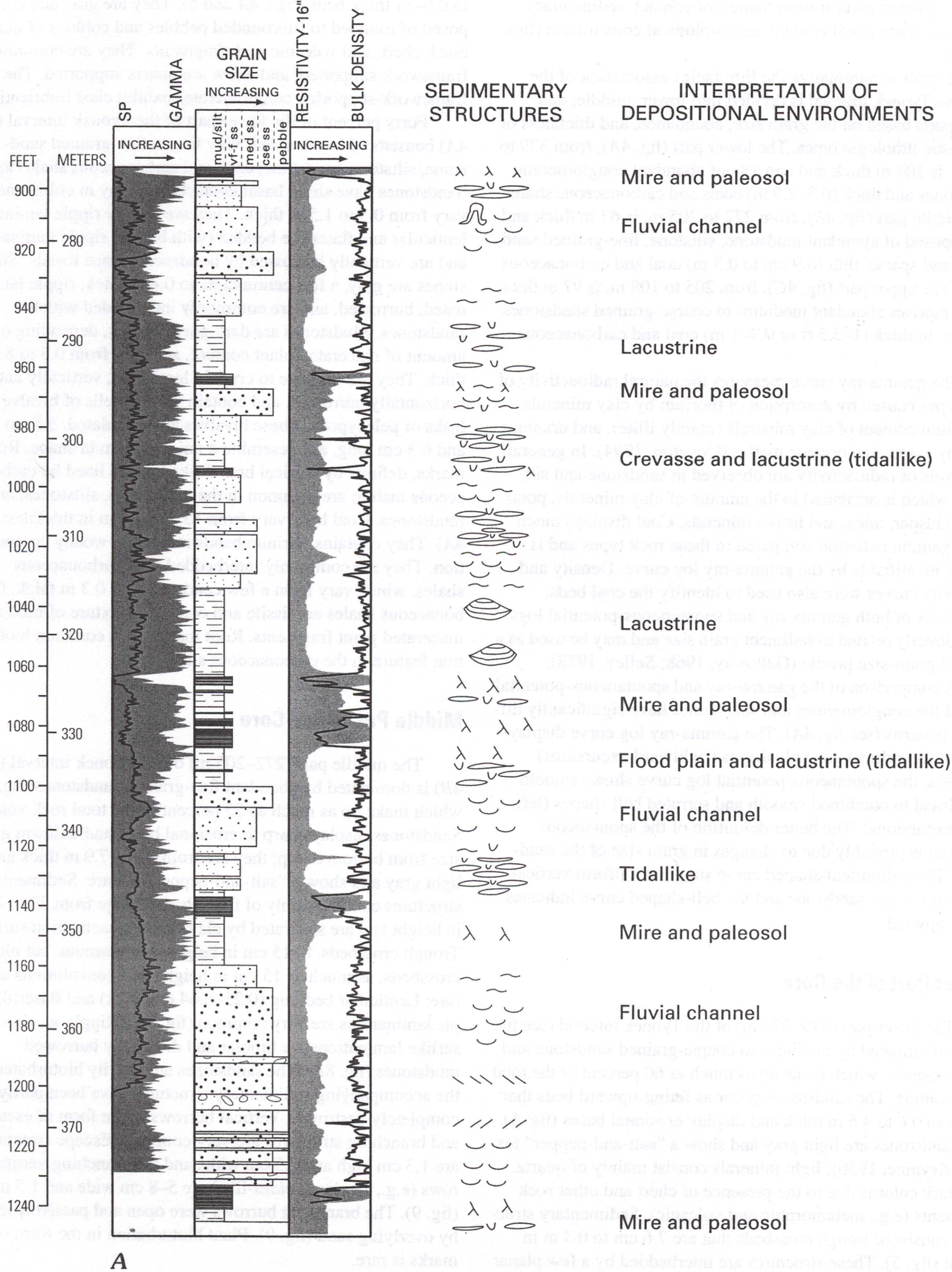


Figure 4A. Lithostratigraphy, geophysical logs, and lithofacies variation of the lower part (379–272 m) of the AK 94 CBM-1 core.

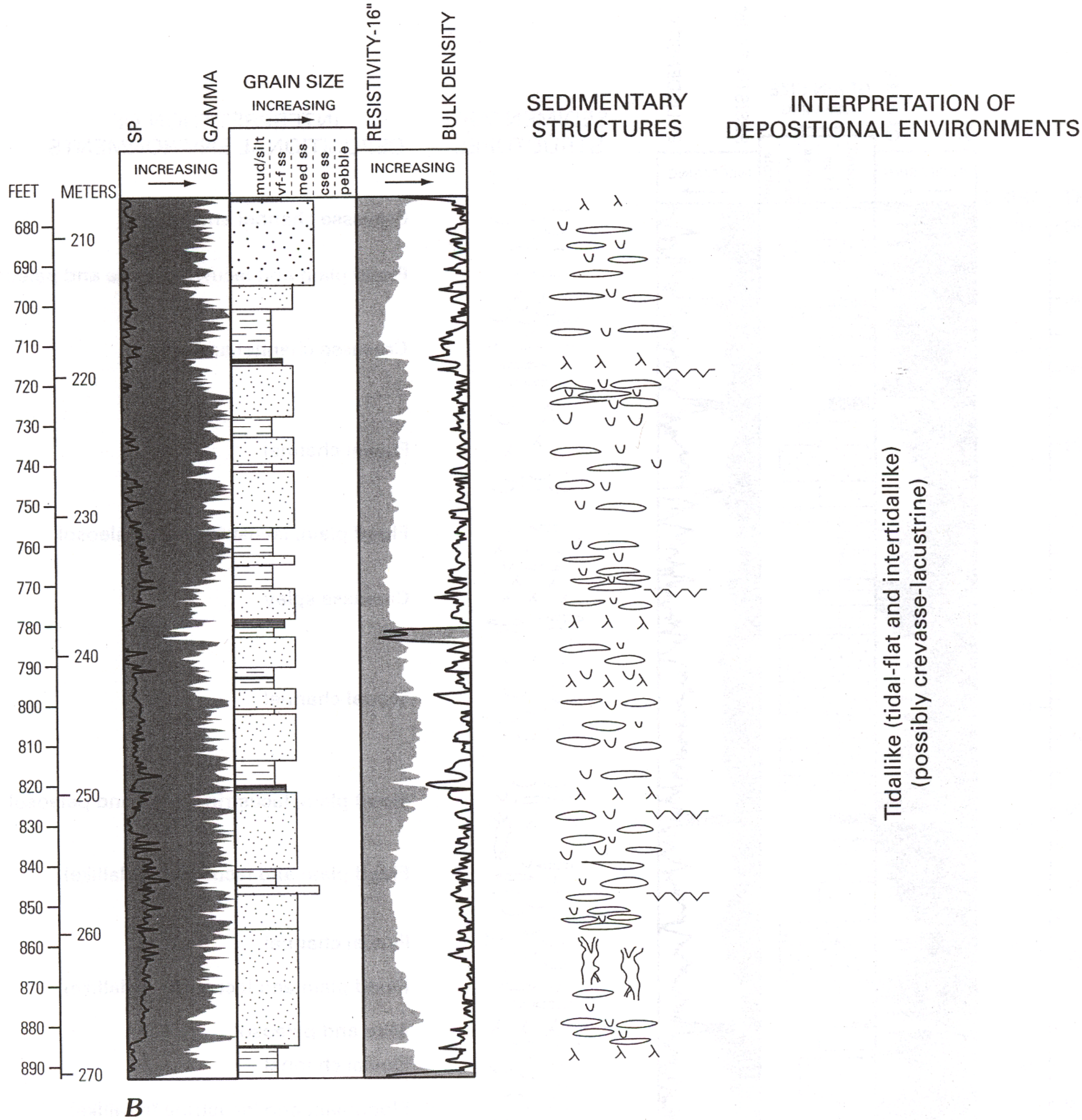


Figure 4*B*. Lithostratigraphy, geophysical logs, and lithofacies variation of the middle part (272–205 m) of the AK 94 CBM-1 core.

shapes (leftward excursions). The spontaneous-potential log curve is probably due to fining-upward grain size of the sandstone. The funnel shape curve of the spontaneous potential curve suggests coarsening-upward vertical grain size of the sandstone.

Forty-five percent of the total rock volume of the middle part of the Tyonek interval (fig. 4*B*) is composed of siltstone, mudstone, carbonaceous mudstone, and coal (fig. 10). The siltstones and mudstones are light to dark gray and are commonly intercalated, making up units as much as 2.7 m thick. These units are commonly lenticular and (or) flaser bedded with lenses of siltstones draped by mudstones. Wispy lenses or "starved ripples" in siltstones are also common. Siltstone lenses are as much as 0.6 cm thick and are vertically burrowed by trace fossils—the burrows include small oval burrows of possibly *Chondrites* and *Teichicnus* (Pemberton and Wightman, 1992; Beynon and Pemberton, 1992) at 264.3–264.4 m. Possible trace fossils of *Planolites* and *Paleophycus* (Pemberton and Wightman, 1992; Beynon and Pemberton, 1992) are found at 264.5 m. A *Thalassinoides*-like (Pemberton and Wightman, 1992; Beynon and Pemberton, 1992) trace fossil (fig. 9) is found at 263.4–262.9 m. The mudstones are heavily bioturbated vertically by wormlike or spiroform burrows (possibly *Gyrolithes*) that are 1 mm in diameter and 1.3 cm long. These burrowed horizons are commonly associated with mud and synaeresis cracks. Discrete units of black,

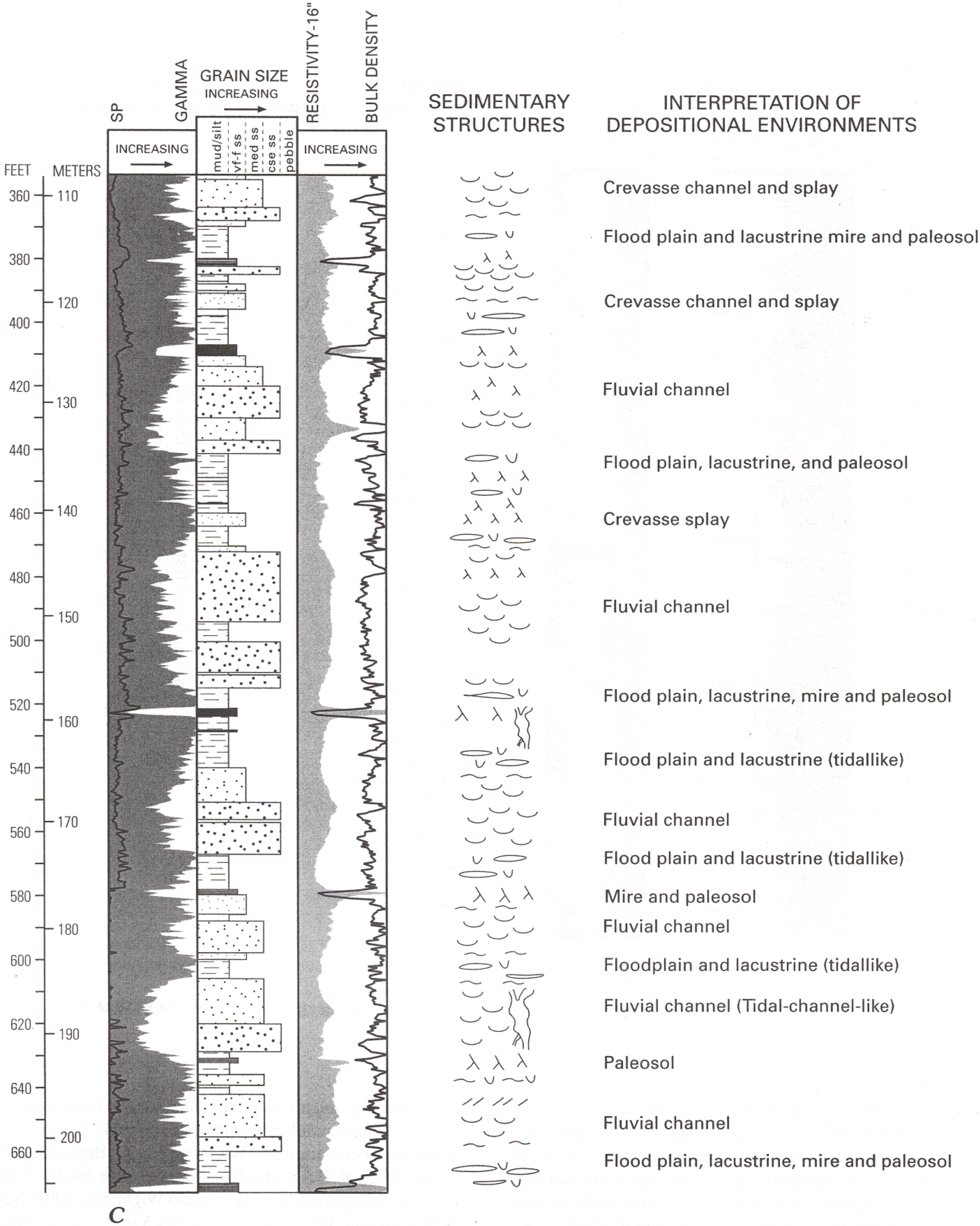
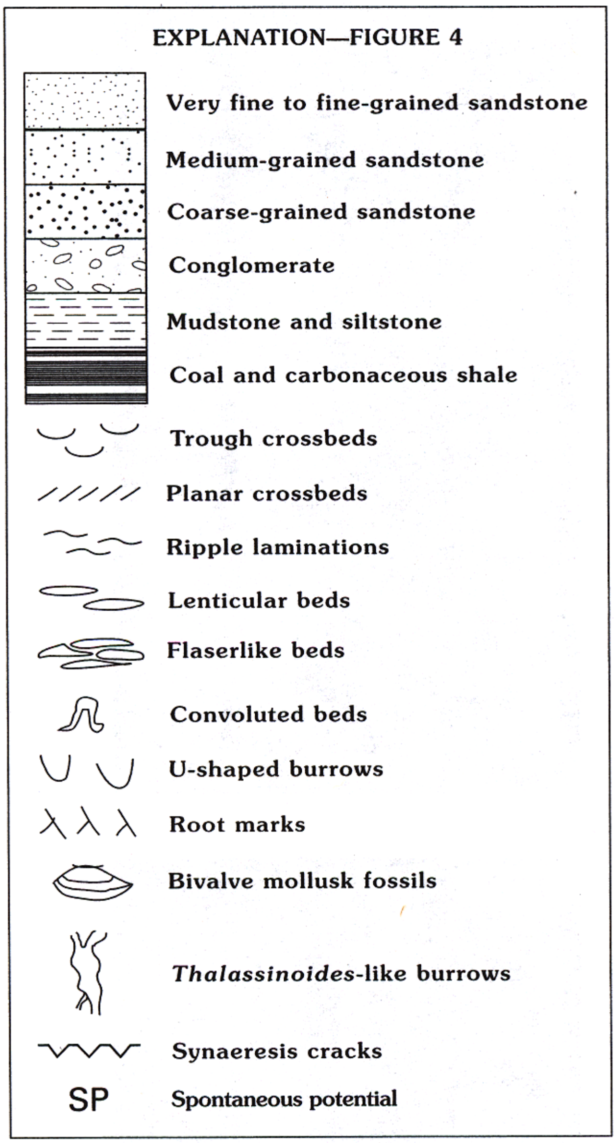


Figure 4*C*. Lithostratigraphy, geophysical logs, and lithofacies variation of the upper part (205–108 m) of the AK 94 CBM-1 core.

carbonaceous mudstones are as much as 0.6 m thick and are bioturbated by plant rootlets associated with yellow mottles. These mudstone units are interbedded with thin, vitrain-rich, coaly layers that are as much as 8.2 cm thick.



Upper Part of the Core

The upper part (205–108 m) of the Tyonek interval (fig. 4*C*) is dominated by fine- to coarse-grained sandstones, which make up about 55 percent of the total rock volume, and commonly by thin coal beds. The sandstones occur as fining-upward beds that are from 4.6 to 9.1 m thick and display sharp to erosional bases (fig. 11). The sandstones are light gray and show a "salt-and-pepper" texture. Sedimentary structures commonly consist of trough crossbeds that are as much as 0.3 m in height (fig. 11). Massive beds as much as 1.8 m thick are commonly interbedded with the trough crossbeds. Planar crossbeds (as much as 1.5 cm in height) and slump structures are sparse. Asymmetrical and climbing ripple laminations in units as much as 0.6 m thick cap the fining-upward sandstones. Bioturbation by trace fossils and plants is common. Trace-fossil burrows are vertical (fig. 11) and branchlike or *Thalassinoides*-like and are as much as 10 cm in diameter and 0.5 m long. Carbonaceous plant root marks are common in the upper part of the fining-upward sandstones. The root marks are both younger and older than the vertical burrows.

The gamma-ray log curve (fig. 4*C*) displays serrated-bell and cylindrical shapes (rightward excursions). The spontaneous-potential log curve shows combined smooth- and serrated-bell and cylindrical shapes and funnel shape (leftward excursions). The spontaneous-potential log curve is probably due to uniform vertical and fining-upward grain size of the sandstones. These vertical grain-size variations of the sandstones are reflected by the gamma-ray log curves. The funnel shape curve of the spontaneous potential curve suggests coarsening-upward vertical grain size of the sandstones.

Forty-five percent of the upper part of the Tyonek interval (fig. 4*C*) consists of siltstone, mudstone, coal and carbonaceous shale (fig 12). Siltstones are light gray, a few centimeters to 1.4 m thick, contain very fine grained sandstone lenses (lenticular bed), and are rippled, rooted, and burrowed (fig. 11). Mudstones are gray to black, depending on the amount of carbonaceous matter content, and vary from 0.3 to 2.7 m thick (fig 12). They are massive to crudely laminated, rippled (lenticular beds and "starved ripples"), rooted, and vertically burrowed. Vertical burrows in the mudstones are 0.6 to 2.5 cm in diameter, more than 8 cm long, and sand-infilled. Carbonaceous root marks penetrate these branchlike vertical burrows. Coal and carbonaceous shales are interbedded, forming units as thick as 0.9 m. Coals are brightly banded, indicating woody composition. Carbonaceous shales are commonly rooted (fig. 12).

LOWER PART OF THE CORE

Lithofacies Associations and Sequences

Lithofacies associations of the Tyonek Formation may be recognized as a depositionally related group of lithofacies that occur together. Lithofacies sequences of the Tyonek Formation are recognized as a series of lithofacies that pass vertically from one lithofacies to another.

Three thick, fining-upward sandstone units occur as lithofacies sequences in the lower part of the Tyonek interval (fig. 4*A*), from bottom to top, 376–353 m, 344–334 m, and 287–273 m. These 12- to 23-m-thick sandstones consist of stacked, multiple scoured units, each of which fines upward. The fining-upward sandstones at 376–353 m are associated with erosionally based conglomerates that are either singular or stacked units. This lithofacies association is mainly found at 374.6–362.7 m, where the conglomerates occur. In addition, pebble floats are associated with erosionally based sandstones in the middle part of the succession. The fining-upward sandstones at 287–272 m are associated with some conglomerates that mark erosional bases below the sandstones.

The fining-upward sandstone lithofacies sequences are interbedded, from bottom to top, with lithofacies associations consisting of coal, carbonaceous shale, sandstone, siltstone, and mudstone at 379–376 m, 353–344 m, 334–287 m, and 273–272 m. The lithofacies association at 379–376 m consists mainly of coal and carbonaceous shale underlain by mudstone and siltstone, which are rooted, burrowed, lenticular bedded, and rippled. The lithofacies association at 353–344 m includes, from bottom to top, a rooted mudstone capped by vitrinite lenses, coal

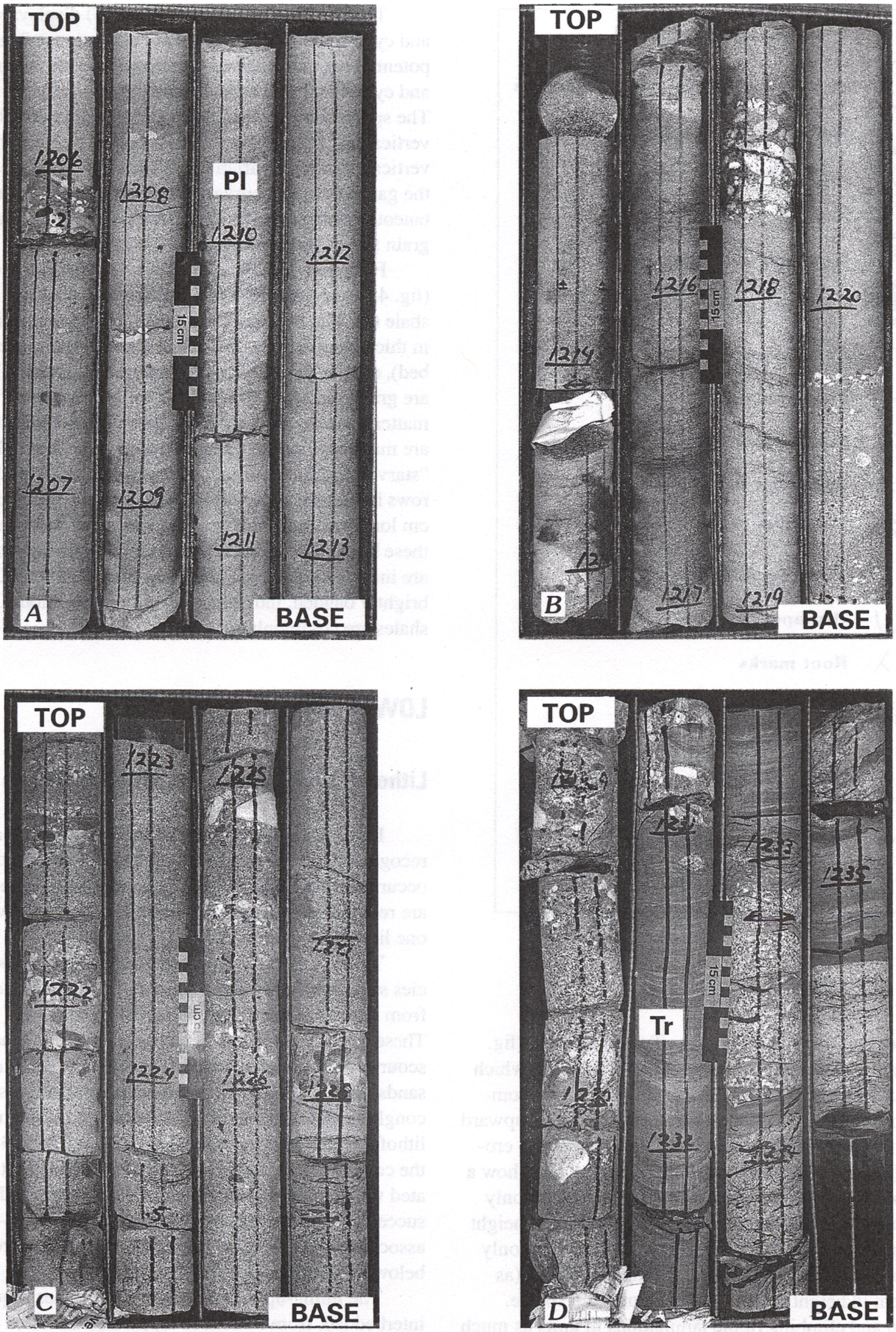


Figure 5. Stacked, erosionally based, fining-upward sandstones interbedded with conglomerates from 376.4 to 367.4 m in the lower part of the core (photos *A*, from 376.3 to 369.9 m; *B*, from 369.9 to 372.2 m; *C*, from 372.2 to 374.6 m; and *D*, from 374.6 to 376.8 m). Trough (Tr) and planar (Pl) crossbeds in the fining-upward sandstones from 375.6–375.0 m and 371.8 to 367.7 m, respectively. Numbers on core show depth in feet. To convert from feet to meters multiply by 0.304 (note centimeter scale on photo).

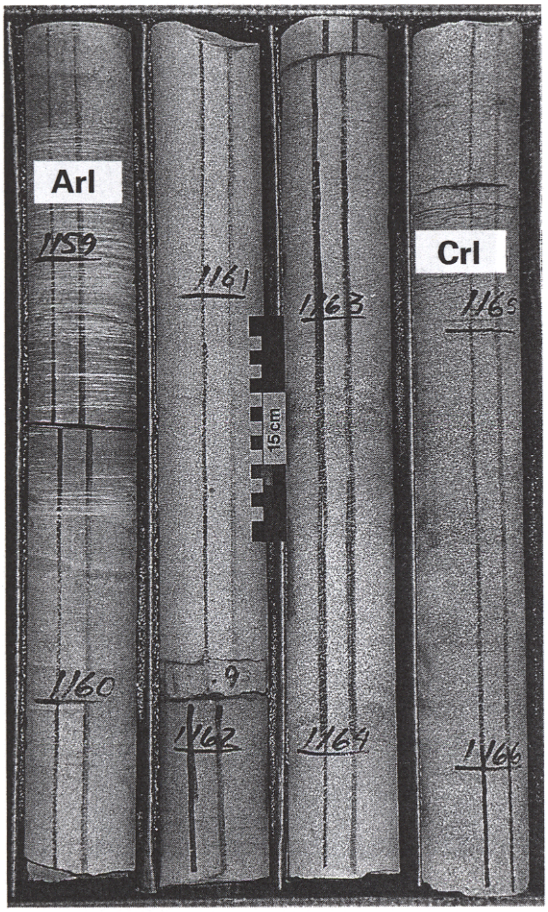


Figure 6. Climbing ripple laminations (Crl) interbedded with asymmetrical ripple laminations (Arl) that cap the stacked, fining-upward sandstones from 355.2 to 353.1 m in the lower part of the core. Numbers on core show depth in feet. To convert from feet to meters multiply by 0.304 (note centimeter scale on photo).

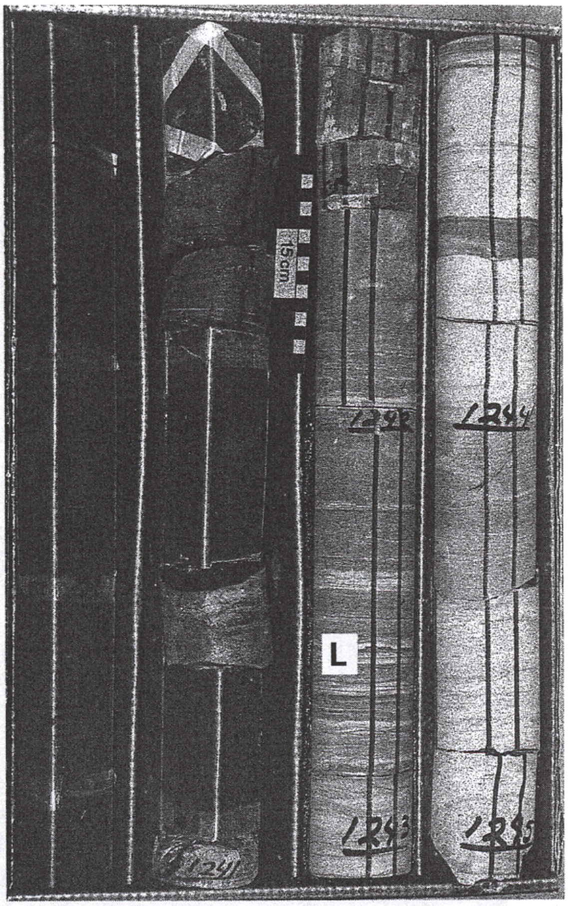


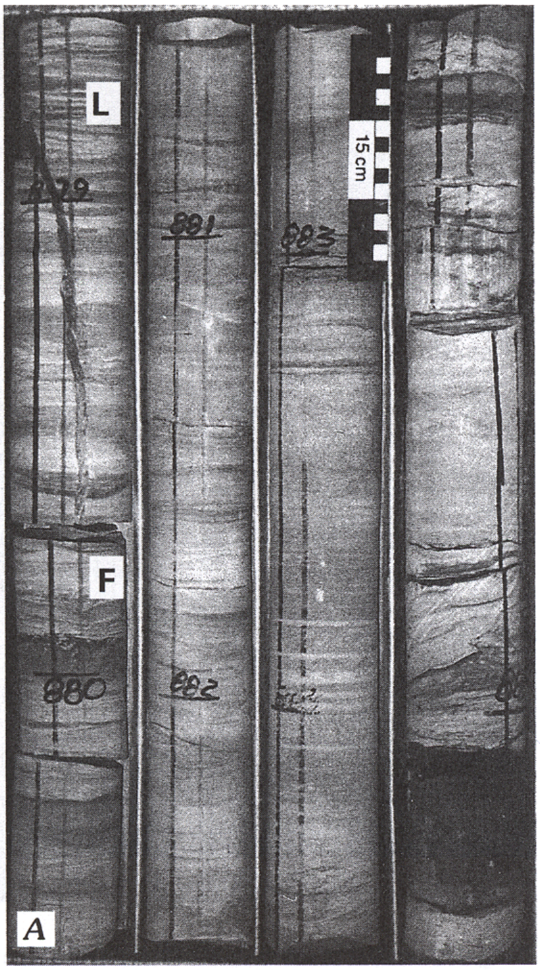
Figure 7. Interbedded coal, carbonaceous mudstone, siltstone, and sandstone from 379.3 to 377.1 m in the lower part of the core. A part of the coal bed is missing and was sampled for analysis (378–377). L, lenticular bedding. Numbers on core show depth in feet. To convert from feet to meters multiply by 0.304 (note centimeter scale on photo).

and carbonaceous shale, and interbedded burrowed mudstone; tonstein; fining-upward, rippled-burrowed sandstone; and siltstone. The lithofacies association at 334–287 m consists of coal and rooted carbonaceous shale interbedded with lenticular-bedded, mud-draped (flaserlike) sandstone, siltstone, and mudstone in the lower part. A massive mudstone containing bivalve mollusks interbedded with a multi-erosional, 7.3-m-thick, fining-upward sandstone occurs in the middle part. A lithofacies association of coal and carbonaceous shale interbedded with mudstone and stacked, multi-erosional, 1.5- to 3.3-m-thick, fining-upward sandstone occurs in the upper part. The lithofacies association at 273–272 m consists mainly of coal and carbonaceous shale. A mudstone at 260.4 m (below a coal) analyzed by Nichols (1998) for palynomorphs yielded the freshwater alga *Pediastrum* and common conifer pollen.

Interpretation

The thick, fining-upward sandstone sequences are interpreted as deposits of major fluvial channels. The stacked, multiple scoured units represent deposits of shallow (thin) to deep (thick) subchannels. The thin, erosionally based conglomerates are interpreted as channel-floor and gravel-bar deposits similar to braided streams (Webb, 1994). Pebbles in the sandstone reflect debris-flow deposits. The lithofacies association of sandstone and conglomerate suggests that the major fluvial channels were braided, consisting of subchannels that were aerially separated by gravel bars (Best and Bristow, 1993). The fining-upward sandstones floored by conglomerates indicate channel-fill during waxing to waning channel flows (Allen, 1965).

The coal and carbonaceous shale lithofacies associations are interpreted as mire deposits in freshwater environments as indicated by the alga *Pediastrum*. The massive mudstones containing bivalve mollusks or pelecypods suggest deposition in a subaqueous, probably freshwater, lacustrine environment. The lithofacies association of mudstone with lenticular-bedded, mud-draped sandstone, siltstone, and mudstone reflects deposition either in a wave-influenced flood plain crevasse and lacustrine environment, or tidallike environment. The thin, fining-upward sandstone lithofacies sequence is interpreted as deposits



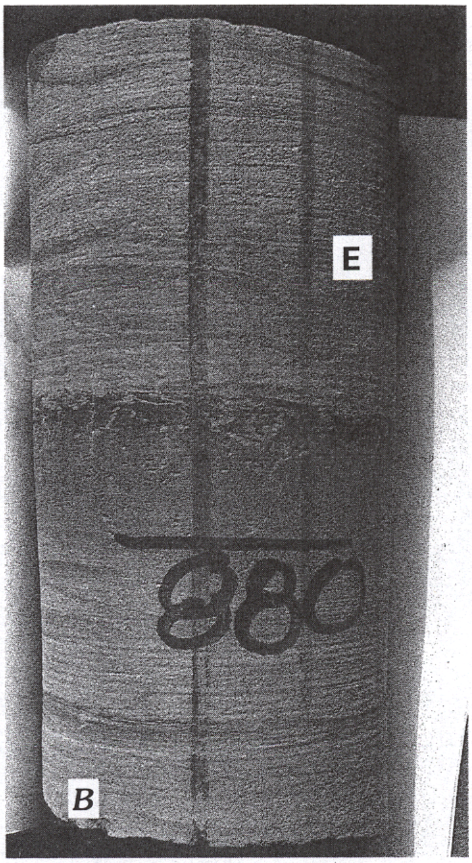


Figure 8. *A*, Siltstones, mudstones, and silty sandstones containing lenticular (L) and flaserlike (F) beds underlain by a thin coal and carbonaceous shale lithofacies from 270.1 to 267. 9 m. *B*, Flaserlike beds with bipolar ripple sets draped by burrowed mudstone lenses and a mudstone exhibiting synaeresis or shrinkage cracks (SC). E, escape structure. Numbers on core show depth in feet. To convert from feet to meters multiply by 0.304 (note centimeter scale on photo).

of minor, sinuous or meandering fluvial channels that drained the mires, flood plains, and lacustrine environments (Miall, 1996). They also served as minor drainages that were laterally contemporaneous to the major braided fluvial channels in the alluvial plain.

MIDDLE PART OF THE CORE

Lithofacies Associations and Sequences

The lithofacies association in the middle part of the core consists mainly of erosionally based, thick, heavily bioturbated, fine-grained sandstones at 272–242 m (fig. 4*B*). The fine-grained sandstones are mainly lenticular, wispy, and flaserlike bedded and contain subordinate crossbed foresets with clay-draped reactivation surfaces and opposed foresets in ripple laminae. These sedimentary structures are partly destroyed by "tidallike" burrows and U-shaped escape burrows. The fine-grained sandstones are associated with minor siltstones and mudstones that are commonly lenticular and flaserlike bedded. Lithofacies association of minor amounts of rooted carbonaceous mudstones with the siltstones and mudstones are at 250–249 m and 243–242.8 m.

The lithofacies association from 242–205 m of the middle part of the core is mainly composed of sharp-based, thin, heavily bioturbated, fine-grained sandstones. These are commonly lenticular and flaserlike bedded with the mud-drapes being burrowed. These sedimentary structures are locally rhythmic and are commonly destroyed by vertical burrows and root marks. Root marks are in the form of yellow mottles. The fine-grained sandstones are commonly associated with thin to thick siltstones and mudstones. The siltstones and mudstones in this lithofacies association are characterized by lenticular, wispy, and flaserlike beds that are almost destroyed by vertical burrows and root marks. The root marks and mottled structures are associated with thin coal and carbonaceous mudstones. A rooted carbonaceous mudstone analyzed for palynomorphs by Nichols (1998) yield abundant pine and hemlock pollen.

Interpretation

The lithofacies association in the middle part of the core is very similar to that described as tidallike deposits by Flores and others (1997) in core from the Chuitna drainage. The thin to thick, erosional- to sharp-based, fine-grained sandstone

Figure 9. Siltstones, mudstones and silty sandstones displaying lenticular beds (L) and a *Thalassinoides*-like burrow (B) from 265.4 to 262.9 m. Numbers on core show depth in feet. To convert from feet to meters multiply by 0.304 (note centimeter scale on photo).

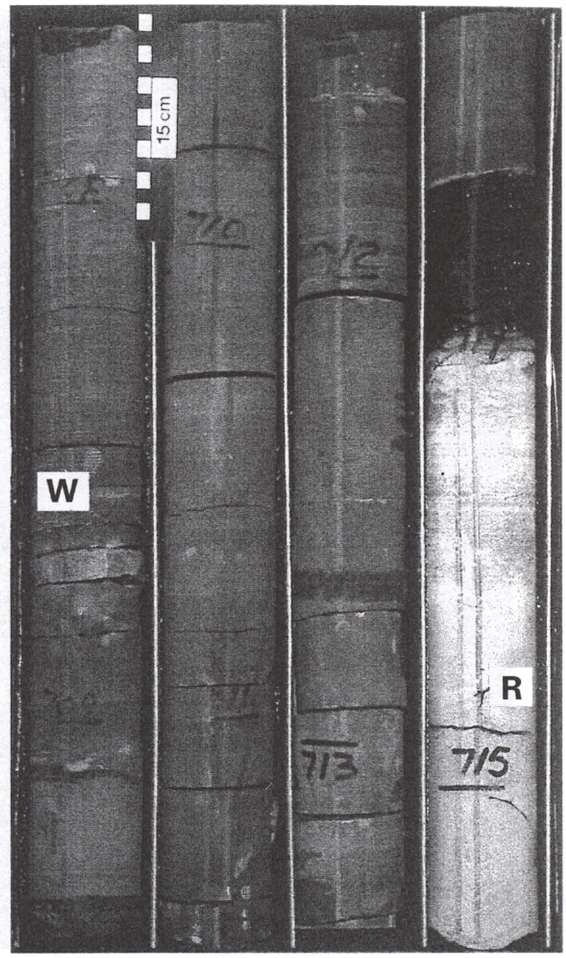


Figure 10. Mudstones, siltstones, carbonaceous shales, and coals from 217.8 to 215.7 m in the middle part of core. W, wispy structure. R, root mark. Numbers on core show depth in feet. To convert from feet to meters multiply by 0.304 (note centimeter scale on photo).

lithofacies are interpreted by Flores and others (1997) as deposits in tidal-channel to tidal-flat-like environments similar to sediments described by Evans (1975), Visser (1980), Reinson (1989), Nio and Yang (1991), Flores and Johnson (1995), and Flores and Sykes (1996). The *Thalassinoides*-like burrows suggest that these lithofacies associations were influenced by brackish or marine water. However, MacKenzie (1975) suggested that the same burrows may have been generated by some species of clams. If this is correct, we suggest that these clams may be similar to the unionid bivalve mollusks found in the mudstones in the lower part of the core, interpreted to be deposited in a large flood-plain freshwater lake. The tidallike deposits may have been deposited in crevasse splays and reworked by burrowing animals as well as ebb-and-flow processes. The presence of burrowed lenticular and flaserlike beds in the sandstone and siltstone, and in the wispy beds, indicates intertidal-subtidal-like environments (Reineck and Wunderlich 1968). The opposed bipolar ripple laminae and development of reactivation surfaces probably reflects successive tidallike ebb and flow. The possible trace fossils *Thalassinoides*, *Chondrites*, *Teichicnus*, *Gyrolithes*, *Planolites*, and *Paleophycus* reflect brackish-marine influence and may support tidallike deposition of the associated rocks (Pemberton and Wightman, 1992; Beynon and Pemberton, 1992). Furthermore, the presence of synaeresis or shrinkage cracks support the idea of large fluctuations in salinity (Burst, 1965). The rooted and mottled mudstone lithofacies are interpreted as paleosols or millisols (Retallack, 1988). The coal and carbonaceous mudstone lithofacies associated with the paleosols suggest deposition either in low-lying or well-drained mires. Retallack (1988) recognized this coal and carbonaceous mudstone lithofacies as a form of paleosol or histosol.

Upper Part of the Core

Lithofacies Associations and Sequences

The upper part of the core from 205–108 m is dominated by lithofacies sequences of erosional-based, fining-upward (medium to fine) sandstone (fig. 4*C*). The sandstone commonly displays branching *Thalassinoides*-like vertical burrows. The thick, fining-upward sandstones are found at 201–125 m. At these depths, the sandstones are commonly associated with

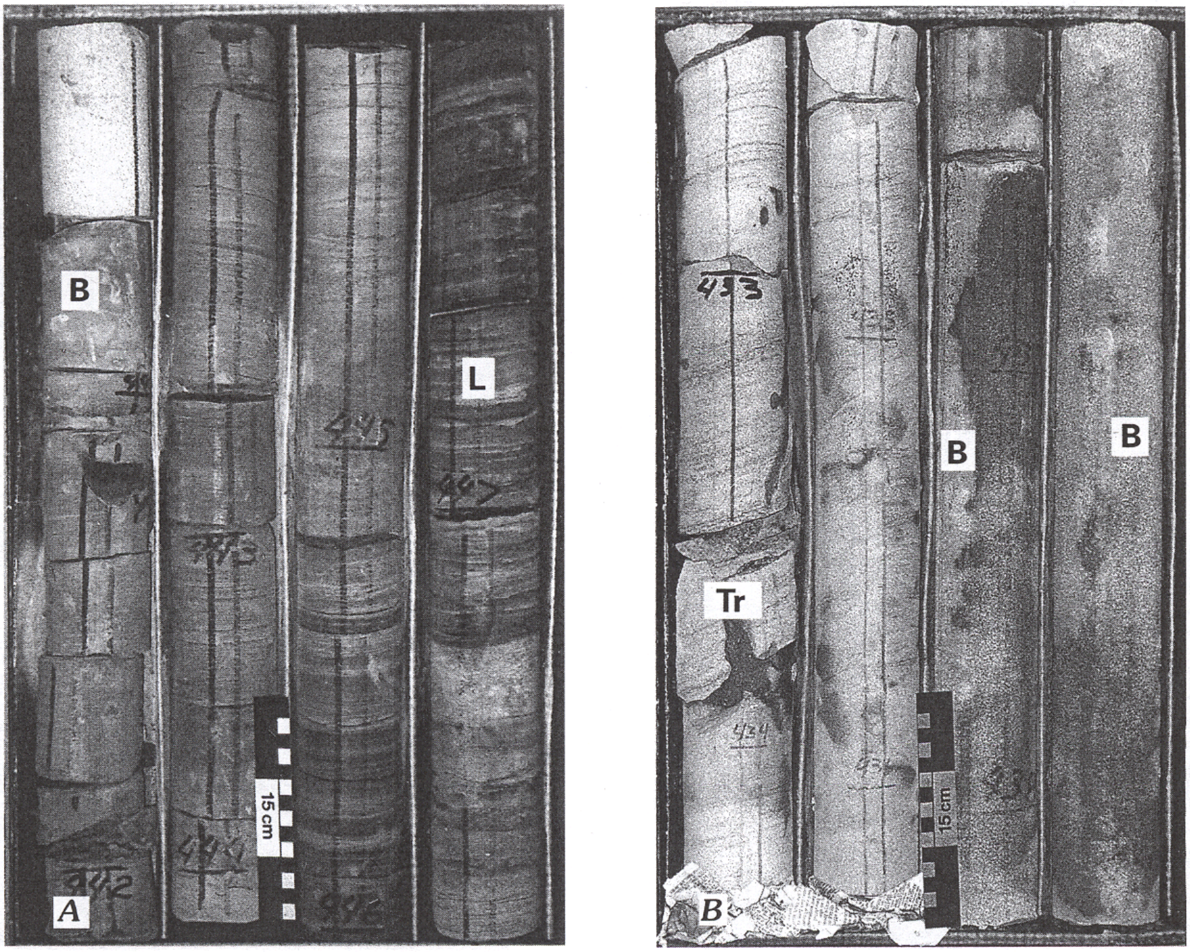


Figure 11. *A*, Burrowed mudstones and siltstones from 149.6–134.5 m, and *B*, sandstones containing trough crossbeds (Tr) and burrows (B) from 134.5–132.1 m. Numbers on core show depth in feet. To convert from feet to meters multiply by 0.304 (note centimeter scale on photo).

coarsening-upward lithofacies sequences of rippled ("starved") mudstones and burrowed, lenticular, flaser-bedded siltstones, and sandstones. In addition, thick coals and carbonaceous shales are interbedded with these lithofacies associations. Mudstones at 174.6 m and 202 m (above coals), analyzed by Nichols (1998) for palynomorphs, yielded the freshwater alga *Pediastrum* and common conifer pollen. Thin fining-upward sandstone lithofacies sequences are found at 120–117 m. Thin coal and rooted carbonaceous shales and mudstones cap the fining-upward sandstone lithofacies sequences. These lithofacies sequences are underlain by coarsening-upward lithofacies sequences of burrowed mudstones, and rippled siltstones and sandstones.

Interpretation

The thin to thick, fining-upward sandstone lithofacies sequences are interpreted as fluvial channels. Because these channels exhibit *Thalassinoides*-like burrows, it suggests reworking of the fluvial sediments by either crustaceanlike organisms typical of tidal-flat-like settings (Reineck, 1967) or some species of pelecypods (MacKenzie, 1975). The tidal influence may be indicated by the lenticular and flaser-bedded units. The coarsening-upward lithofacies sequences of mudstones, siltstones, and sandstones represent fluvial aggradational complexes (e.g., crevasse channels and splays) in subaqueous floodplain or freshwater lacustrine environments. Thus, the fluvial channels overlying these coarsening-upward lithofacies sequences may represent crevasse channels that were reoccupied by flow-through systems. The coal and carbonaceous shales and rooted mudstones are interpreted as mire and paleosol deposits on abandoned deposits of these flow-through channel systems. These mires were inundated by freshwater lakes, as indicated by the presence of the freshwater alga *Pediastrum*.

Summary and Conclusions

The Tyonek interval in the AK 94 CBM-1 well contains interbedded fluvial-dominated and tidallike lithofacies. The fluvial-dominated lithofacies are found in the lower and upper parts of the core. The tidallike lithofacies are found in the middle part of the core; however, tidallike lithofacies are associated with the fluvial-dominated lithofacies. These alternating fluvial-dominated and tidallike lithofacies are similar to lithofacies found in the Tyonek Formation in the Chuitna drainage basin described by Flores and others (1994, 1997).

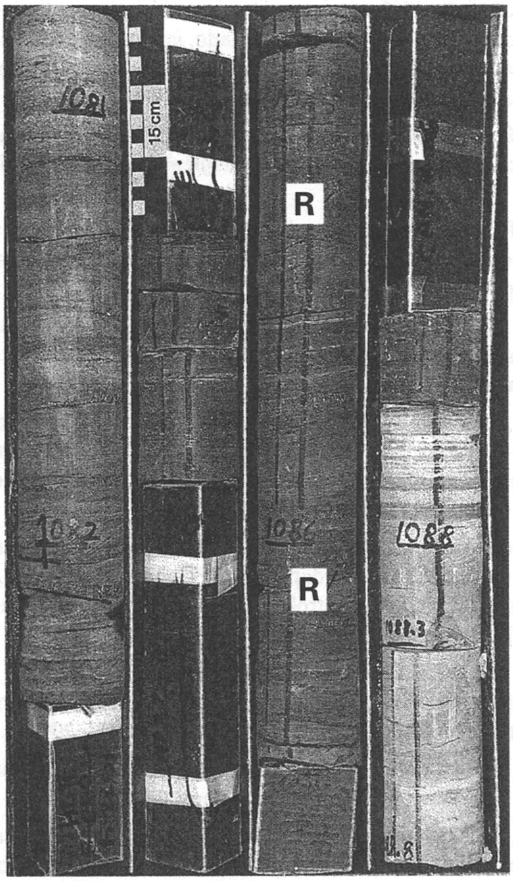


Figure 12. Siltstones and mudstones interbedded with carbonaceous shales and coals (removed for analysis) from 329.4 to 331.9 m. Mudstones are mainly rooted (R). Numbers on core show depth in feet. To convert from feet to meters multiply by 0.304 (note centimeter scale on photo).

The coal beds are mainly associated with the fluvial-dominated lithofacies. Here, the coal beds formed in freshwater mires developed mainly on abandoned fluvial channel belts and, subordinately, on distal flood plains. Paleosols and well-drained mires, forming only thin coal lenses, are associated with the tidallike lithofacies. The tidallike lithofacies are interpreted to form in intertidal-subtidal-like environments. Perhaps the most compelling characteristics of these tidallike lithofacies are the lenticular and flaserlike beds; foresets with reactivation surfaces; and rhythmic, mud-draped, bipolar ripple laminae. Associated trace fossils (*Thalassinoides*-like, *Chondrites*, *Teichicnus*, *Gyrolithes*, *Planolites*, and *Paleophycus*) and synaeresis cracks with these lithofacies support a brackish-marine influence (Burst, 1965; Pemberton and Wightman, 1992; Beynon and Pemberton, 1992). Subaqueous deposition is suggested by sedimentary structures that are laced with heavy bioturbation. The only subaqueous fluvial setting that is equivalent to a tidallike setting in which most of these sedimentary structures may be formed is possibly in a freshwater lacustrine setting with ebb-and-flow processes, possibly driven by wind storms.

The discovery of these Tyonek tidallike lithofacies near Wasilla and in the Chuitna River drainage basin (Flores and others, 1994, 1997) in the upper Cook Inlet suggests that the processes that formed them are more prevalent and widespread than originally thought. Another interpretation could be that tidallike processes in freshwater lakes in fluvial-dominated environments, particularly in the Cook Inlet Basin, have been overlooked. It is an enigma that these lithofacies have not been found associated with fluvial-dominated lithofacies of the Kenai Group during previous studies. The generally accepted paleogeographic reconstructions of the Tertiary Cook Inlet Basin may need to be revised with respect to the paleogeography and distribution of brackish-marine-influenced sedimentation. Thus, based on this study and previous work by Flores and others (1994, 1997), the estuarine and marine environments that existed during deposition of the Tyonek are probably found in the southern and central part of the Cook Inlet Basin.

Acknowledgments

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PIONEER COAL BED METHANE PROSPECT, MATANUSKA VALLEY, ALASKA

Dan Seamount- Geologist
Rick Cross- Landman
George Buck- Engineer

INTRODUCTION

Despite Alaska's tremendous coal resource, there has to date been no development of coal bed methane in the state. The Pioneer Unit encompasses a substantial coal bed methane **(CBM)** prospect located in the lower Matanuska Valley on the northern end of Cook Inlet. Unocal is seeking knowledgeable partners to appraise and, if successful, develop these potentially large reserves.

The Pioneer prospect targets Tertiary Tyonek coal bed methane **(CBM)** potential in the lower Matanuska Valley on the northern end of Cook Inlet (Figure 1). It encompasses the area two to fourteen miles south of Houston, Alaska. Wasilla (population 4,635) is located on the NE end of the prospect. Residential use of the area is sporadic to moderate. Total population of the encompassing 24,000 square mile Matanuska borough is close to 52,000 people.

The nearest significant gas fields are Ivan River, Beluga River, (1TCF Rec.) and North Cook Inlet (2.25 TCF) from 30 to 50 miles to the southwest. Production is from sandstones within the Tertiary Sterling, Beluga, and Tyonek Formations. Total recoverable gas reserves in northern Cook Inlet is approximately 8TCF. Geochemical studies indicate that the more than 6TCF gas is biogenic and sourced from intervening coal seams (Claypool, Threlkeld. and Magoon, 1980).

While the possibility of conventional sandstone and conglomerate reservoirs exists in the prospect area, the testing of **coal bed methane (CBM)** potential is the project's **primary objective.** Abundant coal has been recognized in the stratigraphic section throughout Cook Inlet Basin with estimates of up to 245 TCFG total gas in place (Stricker and Flores, 1996). Success in the project could lead to expanding the play into the rest of Cook Inlet.

The area of highest potential is included in the 72,000 acre Pioneer Unit. Examinations of drill cuttings, core, wireline log and mudlog data from the area indicate a substantial coal volume with encouraging coal maturity and gas content. Additional supporting evidence include gas flows from shallow water wells which are open to coal seams and significant methane shows from coal seams in deeper wells exploring for conventional oil and gas reservoirs. Uncertainties regarding the CBM potential are due to scarcity of data both from low well density and direct measurements (such as gas and water production rates, adsorption/desorption isotherms, formation pressures, and permeabilities).

Seamount, D.T., Cross, R., and Buck, G., 1997, Geologic And Engineering Report To Accompany Application For Approval For Unitization Of The Pioneer Unit, State Of Alaska, December 10, 1997; on file at State of Alaska, Department of Natural Resourses, Division of Oil and Gas

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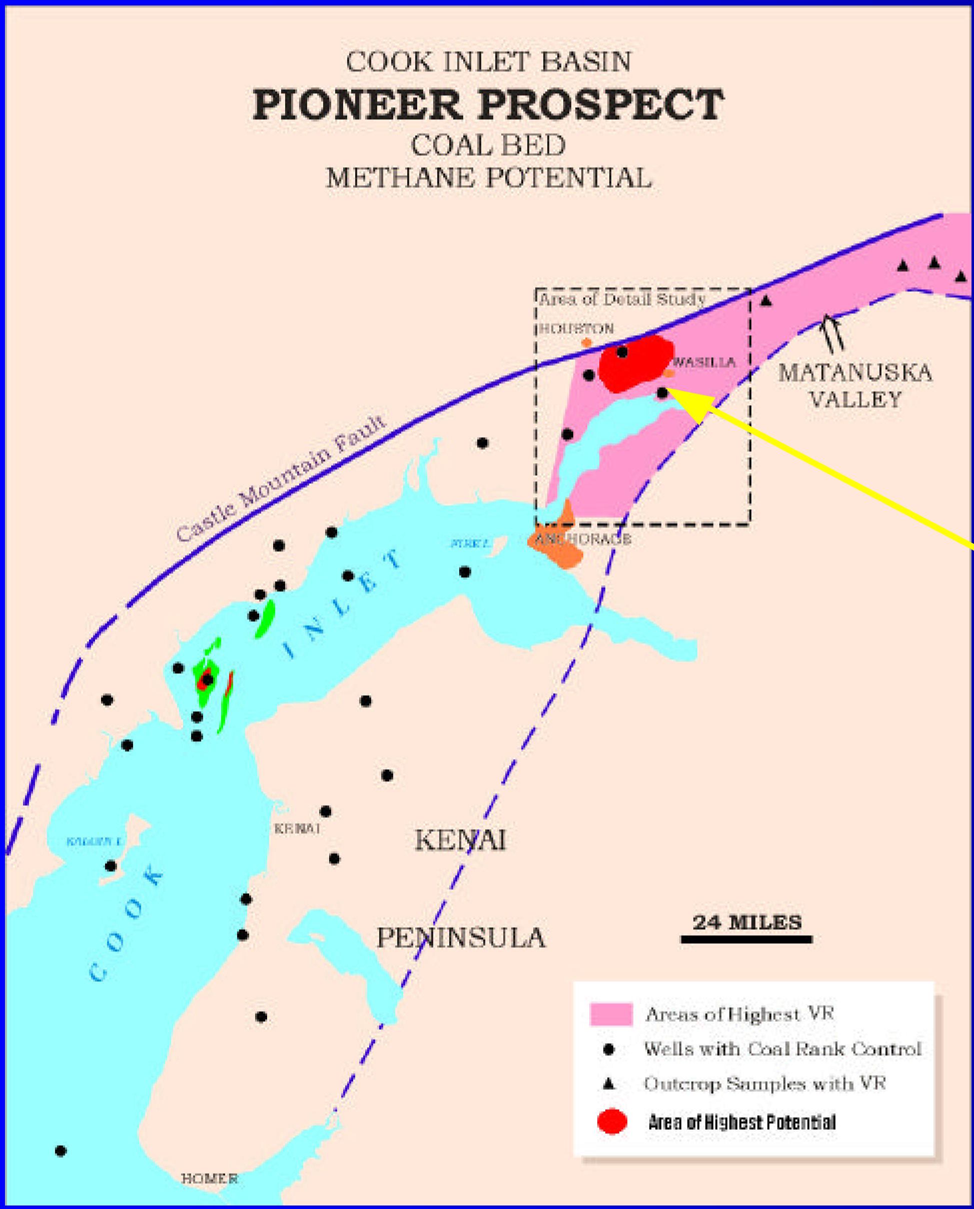


- Located in NE Cook Inlet in area of maximum coal maturity
- Testing 72,000 acres (.8% of Coal Basin)
- If successful, could extend to rest of the Basin

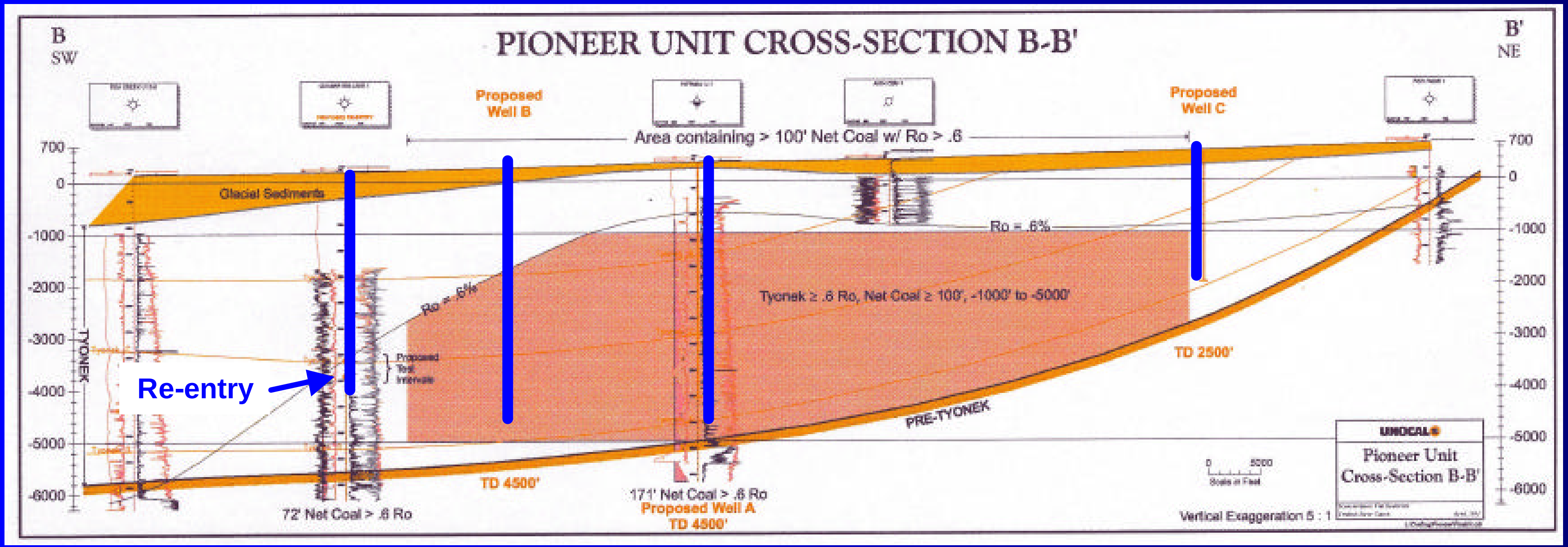
Even though exploration in the Matanuska Valley began in 1951 and continued sporadically throughout the last 45 years, well control in the area is sparse. Only 26 wells have been drilled in this northernmost edge of Cook Inlet- a density of less than one well per township. All walls were drilled to test for conventional sandstone or conglomerate reservoirs. Gas and oil shows were encountered in virtually all of the wells. Moderate to strong hydrocarbon shows were recorded in most coals and many of the conventional reservoirs penetrated. Three of the wells adjacent to the unit area and one within it flowed gas during tests of sandstones. One well reportedly blew out. However, production has yet to be established. Also, no coal seams were purposely tested for CBM potential in any of the wells.

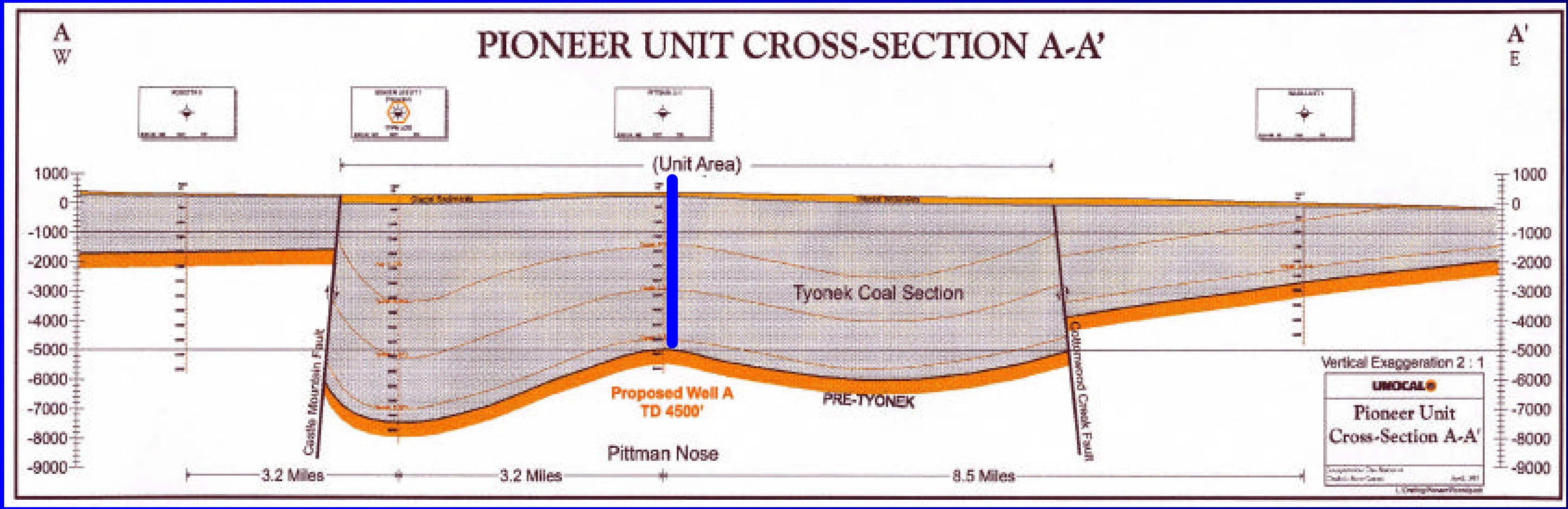
In 1994 the DNR used a USGS rig to core drill the AK-94CBM-1 test hole to 1245' in the northern central portion of the unit area. Evaluation of the coal cores for gas content and vitrinite reflectance suggested promising CBM potential {Smith, 1995)

The Matanuska Valley has the highest population growth rate in the state. A 20" pipeline exists within 5 miles of the prospect and extends throughout an area of 300,000~ people (Anchorage, Matanuska Valley, and Kenai Peninsula) and industrial users including fertilizer and LNG facilities.

Elevations in the unit area are generally less than +600' sea level. The topography is somewhat irregular due to past glacial events. Moraine and deposits range up to 500' thick and kettle ponds and lakes are very common.

The total gas in place for the 72,000 acre area of highest potential could be as high as 3.6 TCFG'.





Cross-section View of Proposed Program

STRATIGRAPHY

The Sterling, Beluga, and Upper Tyonek Formations (Figure 3) are absent in the prospect area due to erosion resulting in glacial sediments directly overlying the Lower Tyonek.

The fluvial/alluvial Miocene lo Oligocene Tyonek formation (Figure 3) contains up to 30+ coal seams from 1000' to 6500' in the unit area. Gross thickness of the Tyonek is extremely variable ranging from less than 2000' on the uplifted sides of the bounding Castle Mountain and Cottonwood Creek Faults (discussed below) to more than 5000' (>7500 in some areas) in the prospect area. The large variations are due to erosion in uplifted areas. The number of coal seams varies somewhat from well to well. The Pittman #I and the Beaver Lakes State #1 (Figure 4) are considered typical and contain 29 and 36 seams respectwely. The seams, which are the primary targets, each range from 5' to 30' in thickness. Typical thickness is 8'. Total net coal thickness ranges from 0' to more than 300' between -1000' and -5000' sub-sea (Figure 5). Coal seams less than 5' thick which were not vertically within 50' of a coal seam of at least 5' in thickness were not counted.

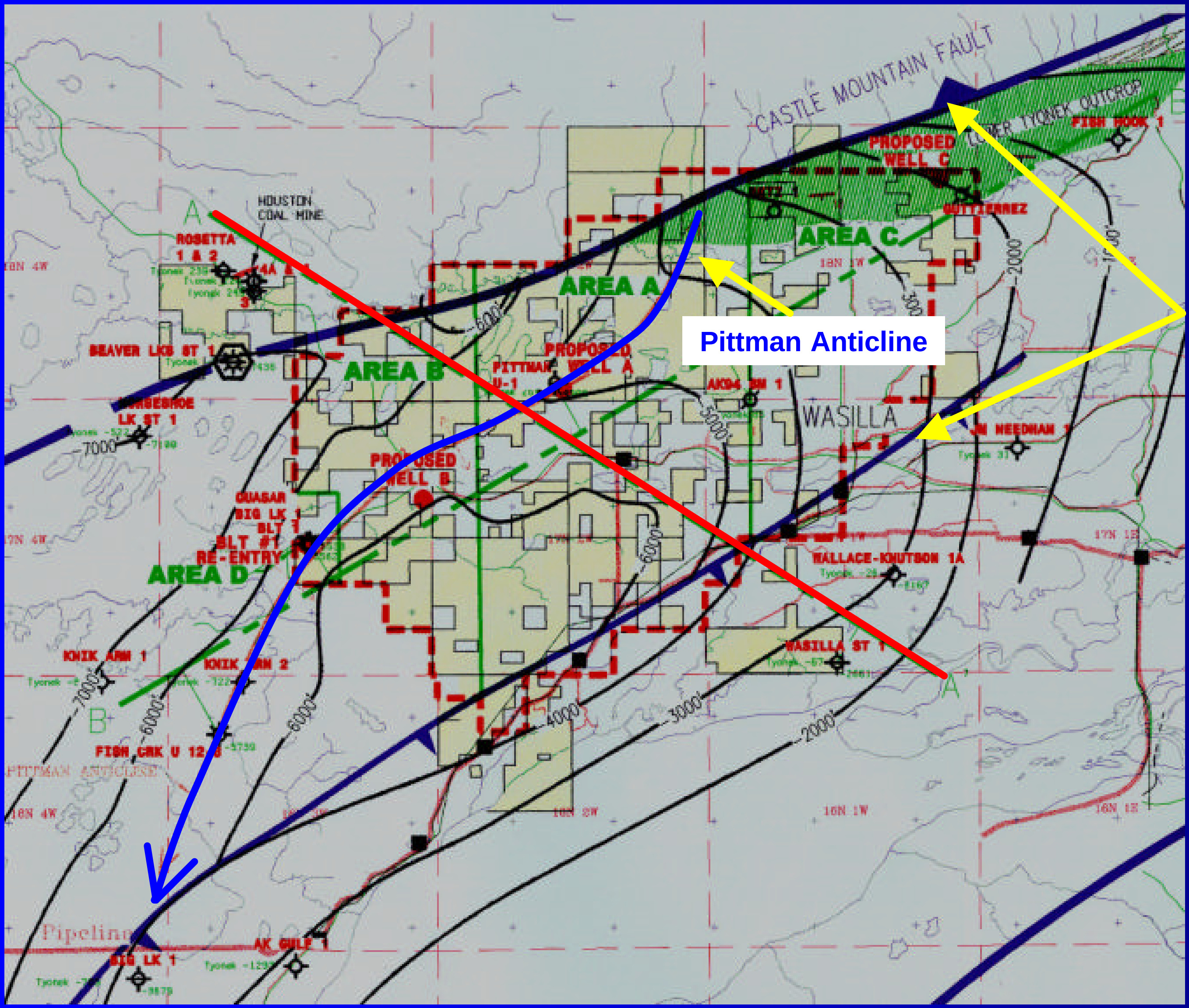
Because of extensive cover by Quaternary sediments, Tyonek coal outcrops are rare. A few road accessible coat seams are present in very localized exposures along the Little Susitna River a few miles to the north and in the Eagle River valley 18 miles to the south (Barnes and Sokol, 1959).

Only eight wells have been drilled in the vicinity of the unit and hence, individual coal seam continuity can not be assured. However, the presence of coal is certain because of the abundance of seams encountered in every well.

Secondary targets are intervening Tyonek sandstones and conglomerates, and a Hemlock equivalent oil conglomerate. Although many shows of gas and oil have been encountered, the few productlon tests have indicated a permeability problem. Massive fracture stimulation, such as performed in the tight gas sands of the Rocky Mountains, would probably be required to test the economic potential of the conventional reservoirs.

STRUCTURE AND TRAPPING

In evaluating the prospect, only coal seams between -5000's~ and -1000 ss were considered. It was assumed that permeability is too low for economic flow rates deeper than 5000' and reservoir pressure is too low above -1000'. However, recently we became aware that shallow CBM production is very significant in a number of basins in the Rocky Mountains, the Appalachians, and other areas. More study should be pursued to determine if the shallow seams in the prospect really should be ignored.



- Bounded by two active reverse faults
- Pittman Anticline bisects the unit

Base Tyonek Structure

The **area of highest** CBM potential in Cook Inlet appears to be located in the unit area in **a large footwall fault block** bounded on the NW and SE by two major reverse/lateral faults (Figures 6 & 7).

The **Castle Mountain Fault** with thousands of feet of vertical displacement and significant horizontal displacement (Dotter-man et al, t 974) forms the prospect's NW boundary. Exploration in the area was initiated on the Castle Mountain hanging wall block in the early 1950's when the U.S. Bureau of Mines drilled four shallow drill holes (<lOOO') in an unsuccessful search for economic coat mine sites. One of the holes-USBM DH #2 flowed gas and water from 587' from Tyonek sands or coals. The gas was analyzed as mostly methane (74%) and nitrogen (25%) with a heating value of 763 Btu/ft3. Anchorage Gas and Oil company offset the drill holes with the deeper Rosetta wells (1100' to 6109' TD), The Rosetta 3 encountered gas and water flow from 1220' to 1393' but an Interrupted DST (and probably low gas prices) discouraged development. Oil and gas shows were also encountered in the underlying Mesozoic "basement". Although the tests were encouraging, less than 50' of net coal thickness is estimated for the Castle Mountain hanging wall fault block (Figure 5).

The **Cottonwood Creek Fault** (identrfied from reflection seismic) with approximately 1900' of vertical displacement forms the prospect's SE boundary. The thin Tyonek section and some of the underlyrng basement in the hanging wall block were penetrated by five wells from 1963 to 1966 with discouraging results.

While vitrinite reflectance (maturity) IS relatively higher on the hanging wall blocks, the blocks have been uplifted to the extent that most of the coal bearing Tyonek Formation has been eroded, leaving little to exploit (Figure 5).

Strata in the prospective footwall block dip away from both faults, possibly setting up fault traps in the conventional reservoirs or causing fault enhancement of cleating in the coals.

The **Pittman Nose** is a south westerly plunging anticline which trends through the center of the footwall fault block. Four wells were drilled on the anticline, all of which had strong gas shows in the coal seams as well as in the conventional reservoirs (Figure 8). Oil shows were recorded in the Hemlock equivalent conglomerates in Unocal's Pittman 1 well drilled in 1962. Uneconomic rates of gas (57mcfd) were recovered from Tyonek sandstones in the most recent well (ARC0 BLT 1) drilled in 1992 on the edge of the prospect. Perhaps, modem fracture stimulation would result in an economic well. Axial stresses may enhance coat cleating along the crest where depth to the base of the Tyonek formation is less than 6000'.

Coincident synclines are present on either side of the Pittman **nose.** The syncline axes and possible flexing on the flanks of the nose may be other sites of enhanced cleating.

COAL BED METHANE POTENTIAL

Coal bed methane is an unconventronai resource which was not generally considered as an economic objective in the U.S. until the 1980's. The only positive method to determine CBM productivity of an area is to production test the seams. Then well cost, production rates of both gas and water, bottom hole pressure, reservoir continuity, and relative permeability can give confidence in determining economics.

The **primary objectives** of the project **are** the **25 to 35 sub-bituminous "B" to bituminous coal seams** contained within the Tyonek Formation between -1000' and -5000' sub-sea in the footwall fault block.

Gas reportedly has flowed from a! least two wells (Guttierrez #I and Betz #I) drilled for water on the eastern edge of the unrt area from above 250' depth. It is assumed that the source of the gas was the Tyonek Coal encountered in the wells. The drillers log of the Guttierrez well lists 1 1 coal seams from 1' to 16' in thickness between 67' and 258'. The well was reported to have built up to 14.5 psi pressure overnight and then took three to four hours to "blow down" Gas flow supported a flare for days until the owner extinguished it. Gas from the Beletz well was used to de-ice a culvert.

In the prospect area (as well as anywhere in Alaska), no coal seams have ever been properly production tested and much still must be learned about the CBM potential. However, gas was recovered during wireline tests from two shallow intervals in one well- the Lum Lovely Beaver Lakes State #1 well (Figure 4) located on the western synclinal edge of the footwall block. Spiked high resistivity signatures and sample descriptions **suggest that the zones are coal seams.** The upper test at 1666' recovered 16.6 **cfg** and calculations suggested a potential for 1.2MMCFD, The zone at 1777' produced **8.2 cf of methane.** Neither test recovered water.

Coal maturity, measured by Vitrinite reflectance (Ro), is an indicator of gas generation within coals {Jones et al., 1988). Studies in the lower 48 have indicated that coals with Ro between .72% and 1.2% are optimal for CBM production (Jones et al., 1988 and Meissner, 1984). However, Unocal (and other companies) have produced CBM in the San Juan Basin of New Mexico from coals with Ro **<** .5%. Unocal studies have shown that coal maturity in Cook Inlet is highest in the area of the unit. In order to focus specifically on the most prospective area, vitrinite reflectance data from drill cuttings were measured from 10 wells in the area (Appendix 1).

In 1994 the Alaska DNR used a USGS rig to core drill the AK-94CBM-1 test hole (Smith, 1995). A continuous core was cut in Tyonek from the base glacial at 354' to TD at 1245'. The section drilled contained 18 coal seams, 13 of which, were analyzed for gas content, cleat density , and vitrinite reflectance. Cleats were widely spaced with vertical fractures occurring 1" to 3" apart. Porosity and permeability were not measured. Gas content (ash free} and vitrinite reflectance (Ro) respectively increased from 63 scf/ton and .48% at 521' to 245 scf/ton and 58% at 1236'. Stable carbon isotope &13C analyses of the methane ranged from -48.9 per mil in the shallow samples to -44.0 per mil at 1236' suggesting more thermogenic influence with depth. This differs from analyses of produced gases from conventional reservoirs to the south with values of -63 to -56 per mil which indicate less mature biogenic gas generation (Claypool, Threlkeld. and Magoon. 1980). High-pressure methane adsorption analyses was performed on four of the seams (Appendix 3).

The data from the 10 wells and the DNR core hole were used to create a vitrinite reflectance map (Figure 9) which shows depth to Ro = .6% (arbitrary Ro cutoff for mature/non-mature coals). The map and cross-section A-A' (Figure 10) demonstrate that the depth of mature coals becomes progressively shallower to the northeast.

The vitrinite reflectance map (Figure 9), net coal thickness map (Figure 5), and direct counting from well logs were combined to map net coal thickness of coals with Ro> .6 between -1000' and -5000' (Figure 11). The area of highest potential has been high graded by assigning a cutoff thickness of 100'. The total area of highest CBM potential within the Pioneer Unit is approximately 55,500 acres,

RESOURCE

The core from DNR well AK94CBM-1 provided the only direct **gas** content measurement of a Cook inlet coal. The deepest measurement in the well was shallower than the assumed cut off depth of -1OOO's used in mapping the resource.

The deepest measured gas content was 24Sscf/ton (ash free) at -845'sl. Average ash content was 24%.

The following calculation is made based on the following additional assumptions:

Ro increases to 250scf/ton by · 1 000'sl and reaches 350scfAon by -5000'sl
Average GIP= 300scf/ton
Net coal th= 100' (assume than not all coal w/ Ro>.6% will be productive)
Area= 640 acres
Density= 2039 tons/ac-ft (1.5gm/cc)
GIP/sq mile= Average GIP - Density . Net Coal th . Area * (l- Average ash content)

Gas in place= 29.7 BCF/square mile

The area of highest potential mapped is 55,500 acres (Figure 9 and Table 1). If it is assumed that not all coal w/Ro>.6% is pay and use 100' as an average pay, total estimated gas in place is 2.6TCF. Assuming all coal is pay (average 137') results in total gas in place of 3.6TCF for the area.

Recoverable cannot be reasonably estimated until pilot wells are drilled and tested.

PLAN OF EXPLORATION AND DEVELOPMENT

The unit requirements mandate that the Pioneer Unit be evaluated in two phases, a pre-pilot exploratory phase. and the pilot exploratory program phase.

Pre-pilot Phase:

For the purpose of the pre-pilot phase the unit area is subdivided into areas “A”, “B”, “C”, and “D” as shown on Figure 11. The unit aggreement requires the drilling of three exploration wells to minimum depths of 2,500’ (MD), one in each of areas “A”, “B”, and “C”. However, because of depths to promising coal seams, Unocal would probably require that two of the wells be drilled to 4,500’ for a more complete evaluation of the project. Coal seams will be cored in at least two wells and measurements of gas yield, absorption, cleat density, RO, and permeabilities will **be** made. Fracture stimulations and production tests will be attempted on at least two wells. Area “D” on the western edge of the unit will be tested by the re-entry of the BLT #I well and the stimulation of selected intervals. The drilling and initial testing of these areas will be complete by September 1,1999. Any area not drilled and/or tested in the case of Area “D” will be excluded from the unit area.

In some cases, up to 18 months of additional well testing and analyses is required after running casing to determine CBM productivity, Therefore, it is expected that the well testing an evaluation phase will be completed by March 1, 2001.

Pilot Program *Phase:*

If encouraging results are obtained in the pre-pilot program, a pilot program of additional five wells would be drilled and completed to depths in excess of 2,000’ by January 1, 2003. The consequence of not completing the pilot program will result in the contraction of the unit to participating areas of production.

Full Field Development

Total project development could range from 200 to 400 wells, A more detailed project description can be provided al request.

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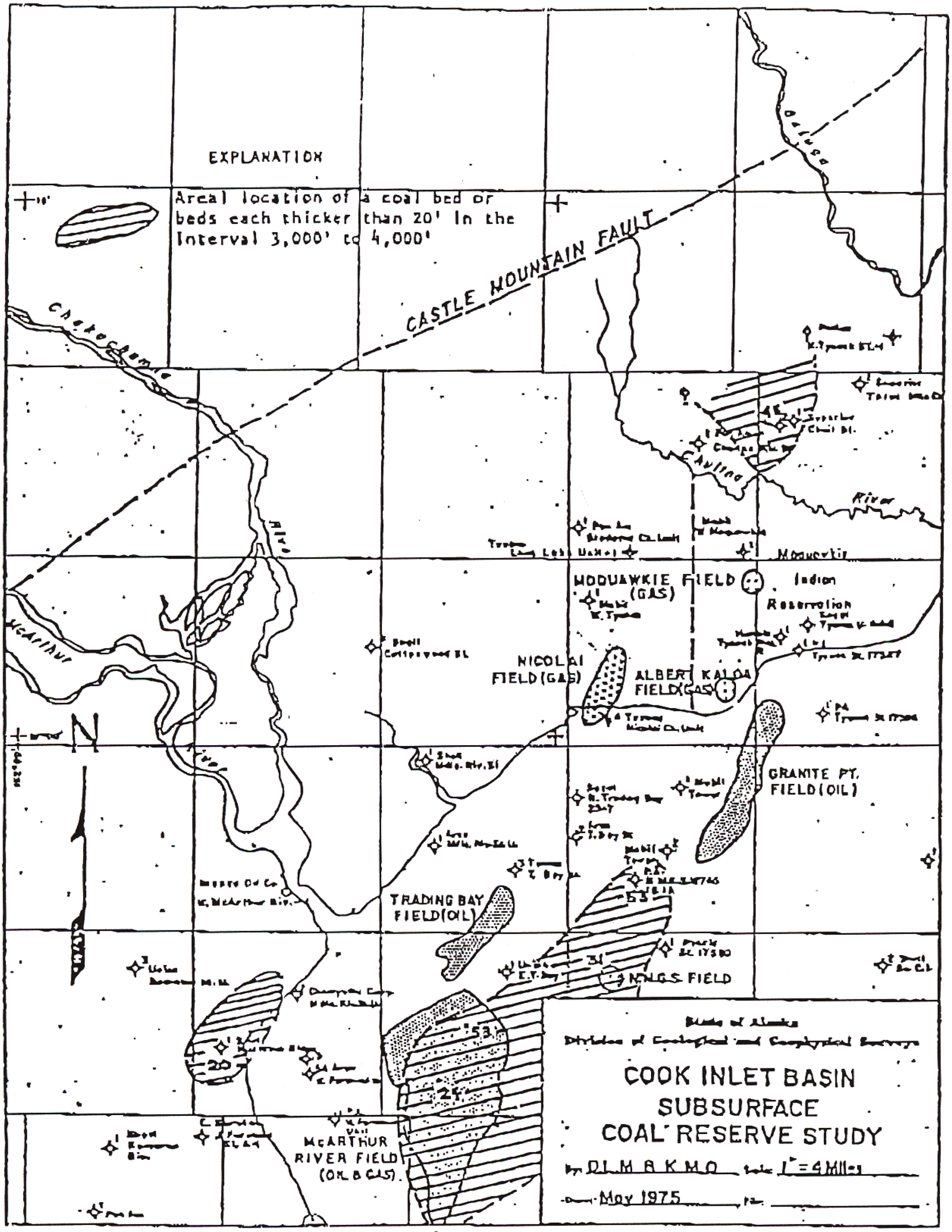
SEAMS THICKER THAN 20 FEET
3000 to 4000 ft.



McGee and O'Connor, 1975

FIGURE 43

SEAMS THICKER THAN 20 FEET
4000 to 5000 ft.

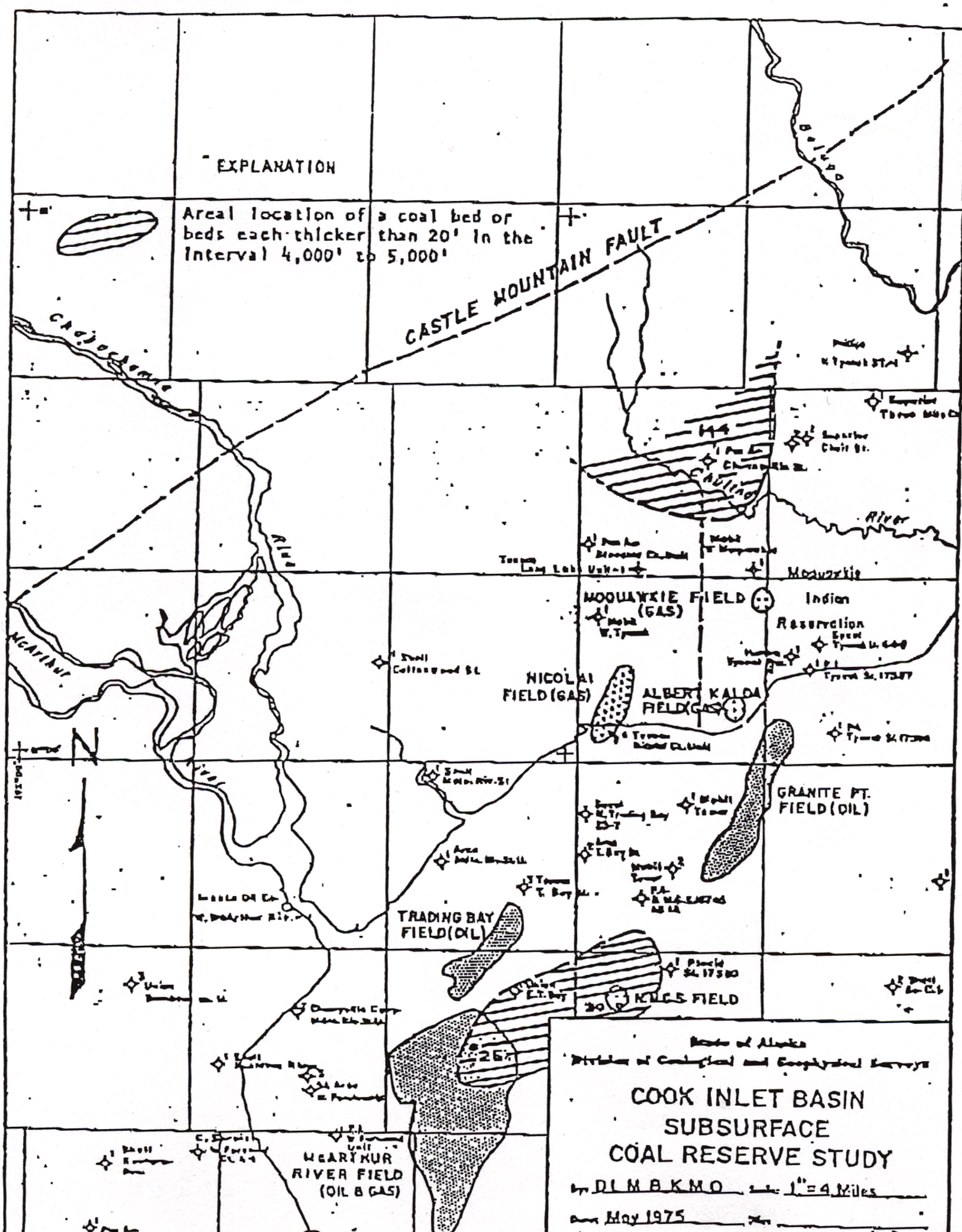


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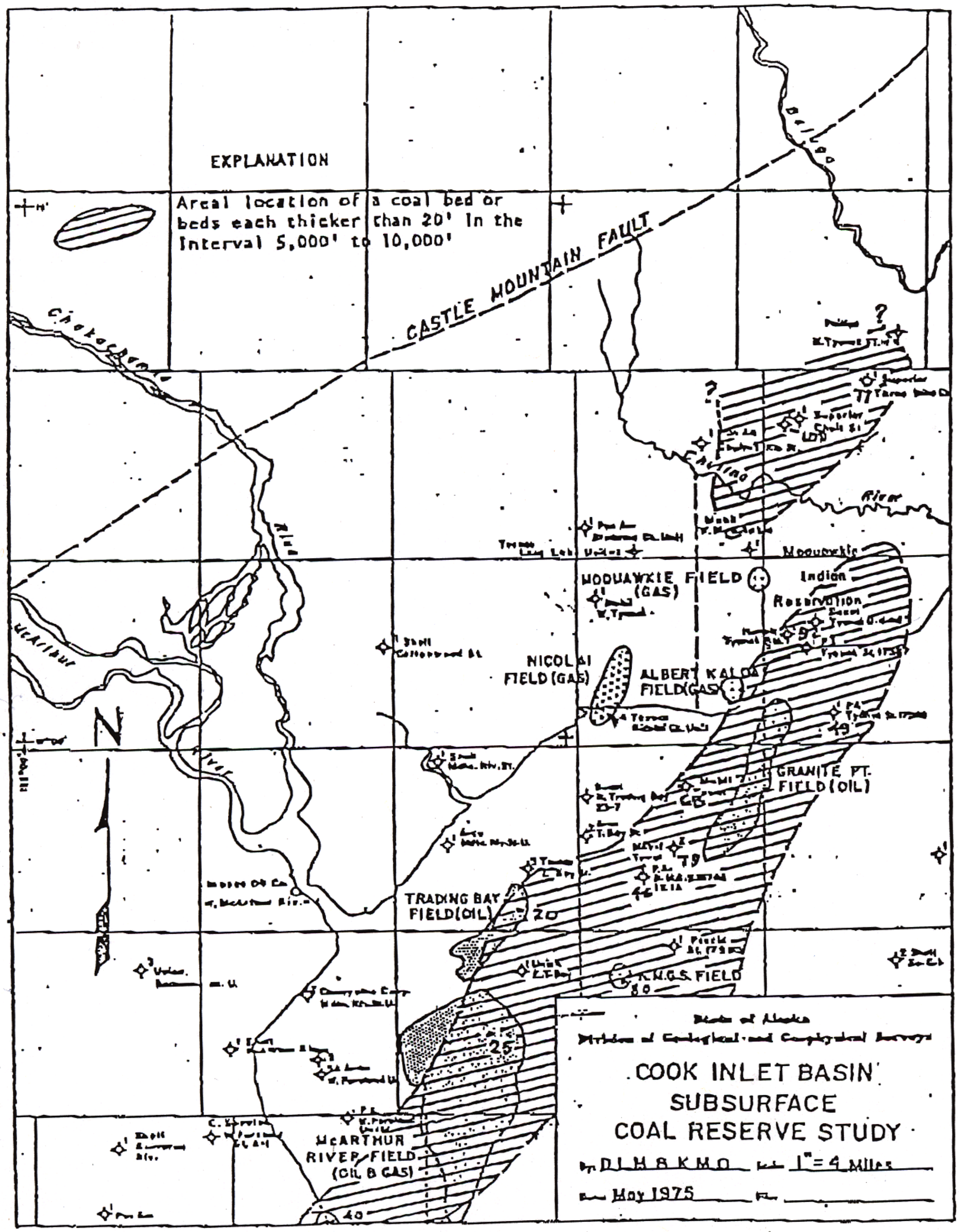
FIGURE 44

SEAMS THICKER THAN 20 FEET
5000 to 10000 ft.



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Chapter 37

Economic Alaskan coal deposits

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INTRODUCTION

Alaskan coal is a large untapped national resource that probably exceeds 40 percent of the total coal resources in the United States. Estimates by various authors of the total tonnage of Alaska's coal resources have increased over the years along with our knowledge of Alaskan coal geology. Recent estimates of Alaska's coal resources are as large as 5,600 billion short tons of hypothetical coal resources (Wood and Bour, 1988; Merritt and Hawley, 1986; Ferm and Muthig, 1982; McGee and Emmel, 1979). Averitt (1975) estimated that the conterminous United States contains 3,700 billion short tons. In Alaska, little is presently exploited. In 1989, the only active coal mine in the state had an annual production of 1.5 million short tons (Green and Bundtzen, 1989). Future use of Alaskan coal, in all probability, will be hydrocarbon feedstock and export to Pacific rim countries and small-scale mining for local consumption.

Wood and Bour (1988) listed 50 coal fields and coal occurrences in Alaska (Plate 7, in pocket) ranging in age from Mississippian to early Tertiary. McConkey and others (1977, p. 91–97) ranked Alaska's coal fields according to the likelihood of development in the following order: Nenana (including Jarvis Creek), Beluga, Matanuska, Herendeen Bay (including Chignik), northern Alaska, and Bering River (Fig. 1). The state of Alaska and various private energy companies, in the last several years, have investigated most of the forementioned fields; those activities are summarized in a series of annual reports (U.S. Geological Survey, 1982 through 1988). Based on McConkey and others' (1977) ranking of the coal fields and on data from government and private industries studies, this chapter focuses on the above-mentioned fields. For each of these fields, I discuss the known geology, tectonic setting, environments of coal deposition, paleoclimate, and coal quality and quantity. For a more extensive review of the geology of Alaskan coal, see Wahrhaftig and others (1991).

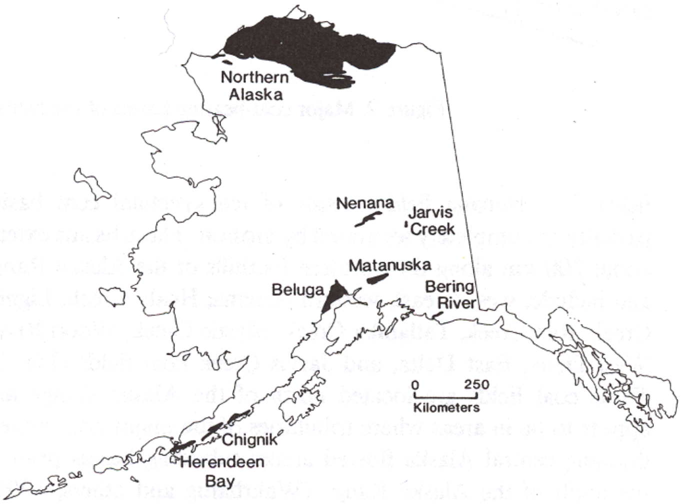

Figure 1. Index map showing locations of coal fields mentioned in this report.

NENANA, BELUGA, MATANUSKA COAL FIELDS

The Nenana, Beluga, and Matanuska coal fields are three of many isolated occurrences of coal-bearing rocks in southern and central Alaska. These fields may be depositionally related to a large river system that drained much of central Alaska and emptied into the Gulf of Alaska through the Cook Inlet. The large coal basins of the Cook Inlet, Susitna Lowlands, and Matanuska Valley (Fig. 1) appear to be located where this large river system flowed into Cook Inlet and joined the Pacific.

The Cook Inlet basin lies on the site of an arc-trench gap (Moore, 1974) between the Mesozoic magmatic arc represented by the Lower Jurassic Talkeetna Formation and Middle Jurassic Talkeetna batholith on the north and the ancient Pacific Ocean crust on the south where the Kenai and Chugach Mountains are located. A thick, mainly terrigenous sequence of Middle Jurassic to Late Cretaceous strata accumulated on this shelf and lies unconformably beneath the coal-bearing Tertiary sedimentary rocks (Kirschner and Lyon, 1973; Fisher and Magoon, 1978). Within the Cook Inlet region, only the Healy Creek, Beluga, and Matanuska coal fields are considered economically important (Plate 7 and Fig. 2).

Nenana coal field

More than half the coal mined in Alaska has been produced from the Nenana coal field (the rest is mostly from the Matanuska

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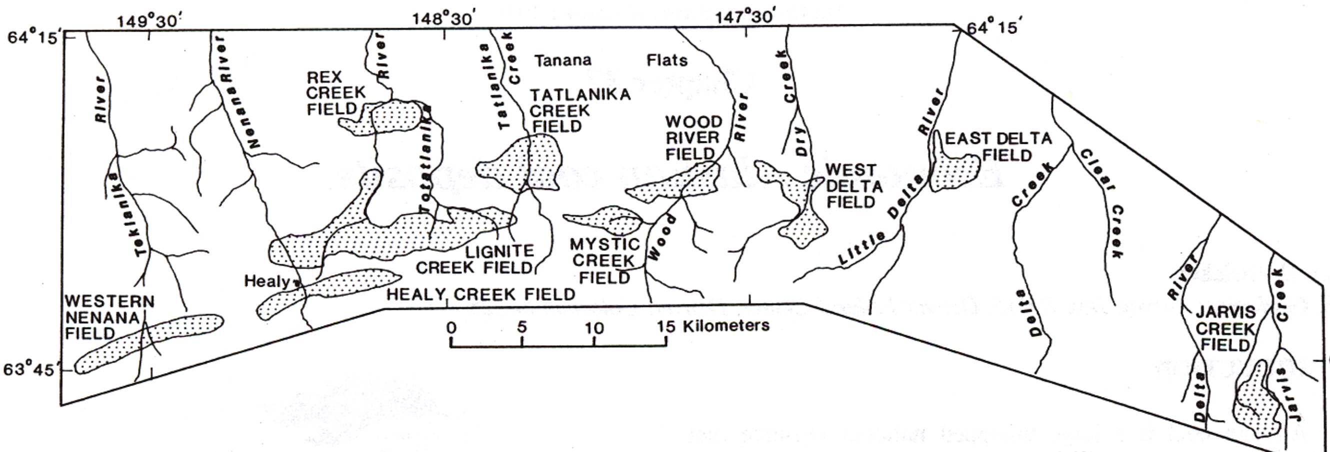

Figure 2. Major coal-bearing basins of the Nenana region (after Wahrhaftig and others, 1969).

field). The Nenana field consists of ten synclinal coal basins partially or completely separated by erosion. These basins extend about 200 km along the northern foothills of the Alaska Range and include, west to east, western Nenana, Healy Creek, Lignite Creek, Rex Creek, Tatlanika Creek, Mystic Creek, Wood River, West Delta, East Delta, and Jarvis Creek coal fields (Fig. 2). These coal fields are located north of the Alaska Range and appear to lie in areas where tributaries of the major river system draining central Alaska flowed across subsiding basins prior to the uplift of the Alaska Range (Wahrhaftig and others, 1991). The coal occurs in the Usibelli Group (Wahrhaftig, 1987), a sequence of five formations of poorly consolidated continental sedimentary rocks of late Eocene and early to late Miocene age (Fig. 3). The same coal-bearing units have been identified in all the synclinal basins in the Nenana coal field.

The oldest unit in the Usibelli Group is the Healy Creek Formation (Fig. 3), a fluvial sequence of lenticular beds of poorly sorted and basally scoured lenticular sandstone, conglomerate, siltstone, and claystone with coals that thicken, split, and pinch out abruptly. These sediments were deposited by migrating braided streams (Stanley and others, 1989). The Healy Creek Formation was deposited on a surface having a few hundred meters of relief; as a result, the thickness of the formation, as well as the number of coal beds, varies markedly. The coals are as thick as 20 m and have been mined extensively in underground and surface mines, both hydraulically and by truck and shovel.

Overlying the Healy Creek Formation is the Sanctuary Formation (Fig. 3), a thinly laminated shale (possibly varved) 40 m thick. This non-coal-bearing unit, which is assigned to the middle Miocene (Wolfe and Tanai, 1980), accumulated in a large, shallow lake.

The overlying Suntrana Formation, of middle Miocene age (Wolfe and Tanai, 1980), is as thick as 400 m and consists of 6 to 12 fining-upward sequences of conglomerates and cross-stratified sandstones overlain by mudstones, and finally, by coals as thick as 20 m. Stanley and others (1989) have interpreted the coarse clastics as having been deposited in stacked, high-energy fluvial channels and the mudstones as having been deposited in the quiet water of abandoned channels. The Suntrana Formation coals, when compared to the underlying Healy Creek Formation coals, are thicker and more laterally persistent. Alaska's only active coal mine is presently surface mining three seams in the Suntrana Formation.

Overlying the Suntrana Formation is the Lignite Creek Formation of middle Miocene age (Fig. 3). This unit, 150 to 240 m thick, is a multicycled, fining-upward sequence, similar to the underlying Suntrana Formation. The Lignite Creek Formation differs from the Suntrana; it has different sandstone lithology, fewer mud-filled abandoned channels, and thinner (typically less than 1.5 m), less laterally persistent coals.

The uppermost formation assigned to the Usibelli Group is the non-coal-bearing Grubstake Formation. This dark gray, laminated shale and claystone is interpreted to have accumulated in a lake formed by the damming of south-flowing streams by uplift of the Alaska Range (Wahrhaftig and others, 1969).

Wolfe and Tanai (1980), in studies of the flora in southern and south-central Alaska, report that the vegetation and trees in the Cook Inlet region and as far north as the Nenana coal field belong to a mixed northern hardward forest. They suggest that the mean annual temperature for this region was 6 to 7°C, with a temperature range of 26 to 27°C.

The total sulfur content of coals in the Usibelli Group ranges from 0.03 to 0.3 percent (Affolter and Stricker, 1987c), a content that ranks it among the lowest of any United States coal. Apparent rank ranges from lignite A to subbituminous B, with the mode being subbituminous C. Ash-content arithmetic mean is 12.6 percent (range of 6.5 to 37.5 percent), and heat-of-combustion (Btu/lb) mean is 8,030 (range of 6,130 to 9,210; Affolter and others, 1981).

Resources are: 1 billion short tons identified and 2 billion hypothetical for Healy Creek; 4.9 billion short tons identified and 7 billion short tons hypothetical for Lignite Creek; and 8 billion short tons identified and 14 billion short tons hypothetical for Nenana coal field (Merritt and Hawley, 1986).

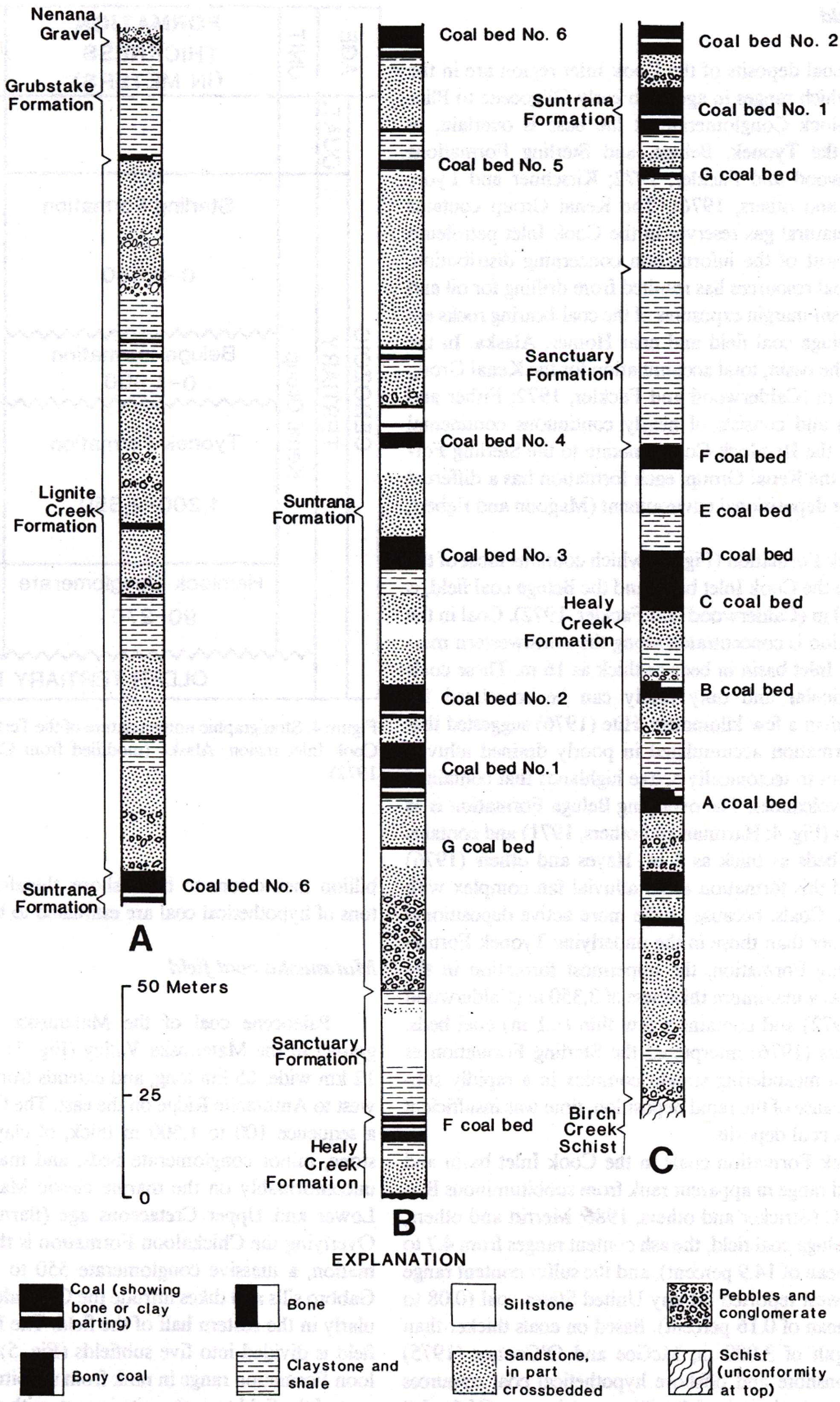

Figure 3. Type section of the Usibelli Group at Suntrana, Alaska (from Wahrhaftig and others, 1969; Wahrhaftig, 1987).

Beluga coal field

The main coal deposits of the Cook Inlet region are in the Kenai Group, which ranges in age from early Oligocene to Pliocene. The Hemlock Conglomerate at the base is overlain, in succession, by the Tyonek, Beluga, and Sterling Formations (Fig. 4; Calderwood and Fackler, 1972; Kirschner and Lyon, 1973; Magoon and others, 1976). The Kenai Group contains petroleum and natural gas reserves in the Cook Inlet petroleum province, and most of the information concerning distribution, lithology, and coal resources has resulted from drilling for oil and gas. Excellent basin-margin exposures of the coal-bearing rocks are found in the Beluga coal field and near Homer, Alaska. In the deepest part of the basin, total accumulation for the Kenai Group exceeded 7,800 m (Calderwood and Fackler, 1972; Fisher and Magoon, 1978) and consists of nearly continuous continental deposition from the Hemlock Conglomerate to the Sterling Formation. Within the Kenai Group, each formation has a different source terrane or depositional environment (Magoon and Egbert, 1986).

The Tyonek Formation (Fig. 4), which contains most of the coal resources in the Cook Inlet basin and the Beluga coal field, is as thick as 2,300 m (Calderwood and Fackler, 1972). Coal in the Tyonek Formation is concentrated along the northwestern margin of the Cook Inlet basin in beds as thick as 16 m. These coals are highly lenticular and only rarely can be correlated for distances more than a few kilometers. Hite (1976) suggested that the Tyonek Formation accumulated in poorly drained alluvial lowlands adjacent to tectonically active highlands that contained sporadic active volcanoes. The overlying Beluga Formation is as thick as 1,500 m (Fig. 4; Hartman and others, 1971) and contains numerous coal beds as thick as 2 m. Hayes and others (1976) have interpreted this formation as an alluvial fan complex with braided streams. Coals, because of the more active depositional system, are thinner than those in the underlying Tyonek Formation. The Sterling Formation, the uppermost formation in the Kenai Group, has a maximum thickness of 3,350 m (Calderwood and Fackler, 1972) and contains a few thin (<1 m) coal beds. Hayes and others (1976) interpreted the Sterling Formation as the product of a meandering stream complex in a rapidly subsiding basin. Because of the rapid deposition, time was insufficient to develop thick coal deposits.

The Tyonek Formation coals in the Cook Inlet basin and Beluga coal field range in apparent rank from subbituminous B to subbituminous C (Stricker and others, 1986; Merritt and others, 1987). In the Beluga coal field, the ash content ranges from 4.7 to 46.5 percent (mean of 14.9 percent), and the sulfur content range is one of the lowest reported for any United States coal (0.08 to 0.33 percent, mean of 0.16 percent). Based on coals thicker than 0.6 m to a depth of 3,000 m, McGee and O'Connor (1975) estimated the onshore and offshore hypothetical coal resources for the Cook Inlet basin to be 1.2 trillion metric tons. Of the 1.2 trillion metric tons, Affolter and Stricker (1987b) estimated 800 billion metric tons to be offshore; therefore, 400 billion metric tons of hypothetical coal are estimated to be onshore.

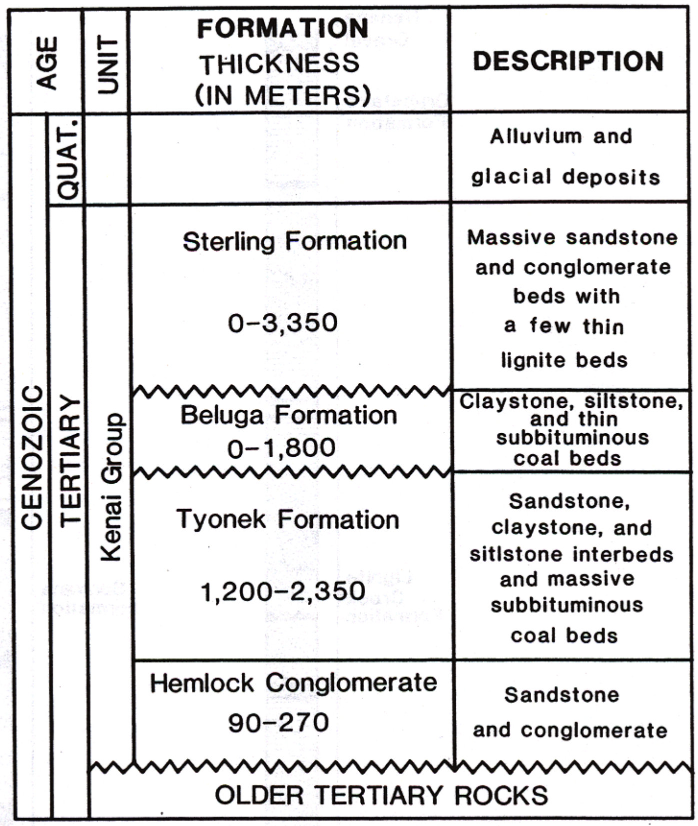

Figure 4. Stratigraphic nomenclature of the Tertiary Kenai Group, upper Cook Inlet region, Alaska (modified from Calderwood and Fackler, 1972).

Matanuska coal field

Paleocene coal of the Matanuska coal field occupies a graben in the Matanuska Valley (Fig. 5). The coal field is 9 to 12 km wide, 65 km long, and extends from Moose Creek on the west to Anthracite Ridge on the east. The Chickaloon Formation, a sequence 100 to 1,500 m thick, of claystone, siltstone, sandstone, minor conglomerate beds, and many beds of coal, rests unconformably on the marine clastic Matanuska Formation of Lower and Upper Cretaceous age (Barnes and Payne, 1956). Overlying the Chickaloon Formation is the Wishbone Hill Formation, a massive conglomerate 550 to 600 m thick (Fig. 6). Gabbro sills and dikes intrude the Chickaloon Formation, particularly in the eastern half of the field. The Matanuska Valley coal field is divided into five subfields (Fig. 5). Coals of the Chickaloon Formation range in rank from subbituminous in the western part of the field to anthracite in east, with a mean of high-volatile A bituminous coal. The Anthracite Ridge coals are associated with numerous dikes and sills and have been upgraded in rank as a result of localized heating. Total sulfur content ranges from 0.2 to 1.5 percent, with a mean of 0.45 percent (Barnes and Payne, 1956; Waring, 1934).

Historically, the Matanuska coal field has been one of two major fields (the other being Nenana) to have produced coal in Alaska. From 1915 to 1967, most of the production was from the Wishbone Hill district. Mining essentially ended when the Alaskan Railroad switched to diesel-electric engines and the Anchorage area military bases converted from coal to Cook Inlet gas-generated electric power. Resources for the Matanuska coal field have been estimated by various workers since 1906. Recently, Merritt and Belowich (1984) estimated a total of 380 million short tons of coal remaining in the Matanuska Valley.

HERENDEEN BAY AND CHIGNIK COAL FIELDS

The Upper Cretaceous Chignik Formation in the Chignik and Herendeen Bay coal fields (Fig. 7) on the Alaska Peninsula accumulated near an arc-trench gap (Burk, 1965). The coal fields are separated by about 160 km, and each is approximately 100 km^2 in size. Coals have been identified in the 500-m-thick Coal Valley Member (of Burk, 1965) of the Chignik Formation (Fig. 8). The Coal Valley Member is part of a cyclic, nearshore, marine-to-nonmarine, coal-bearing sequence (Deeterman, 1978). The coals accumulated in littoral and overbank-swamp environments as part of a fluvial to deltaic depositional system near an arc-trench gap (Dickinson, 1974). Mancini and Deeter (1977) suggested that during accumulation of the Coal Valley Member the Alaska Peninsula was characterized by a narrow shelf facing a major trench. The Chignik Formation is coal bearing only between Herendeen Bay and Hook Bay, indicating that sedimentation, subsidence, and climate were amenable for development and preservation of peat-accumulating swamps only in the Herendeen Bay–Chignik areas.

The late Campanian plant assemblage from the Alaska Peninsula near Herendeen Bay and Chignik was that of a microphyllous, broad-leaved evergreen forest (Wolfe and Upchurch, 1987). This plant assemblage indicates there was no precipitation deficit during the deposition of the Coal Valley Member. Wolfe and Upchurch (1987) estimate a mean annual temperature of 12°C with a mean annual range of 8°C for this region during the late Campanian.

Upper Cretaceous coal that accumulated in this arc-trench gap environment on the Alaska Peninsula has a low resource potential because the peat-accumulating swamps were not large and the ash content is high. The elevated tectonic activity in this depositional system has resulted in coals of relatively high rank. Conwell and Triplehorn (1978) and Gates (1944) reported that the coals in the Herendeen Bay and Chignik fields are high in ash (mean, 20 percent; range, 5 to 51 percent), low in sulfur (mean, 0.7 percent; range, 0.27 to 2.75 percent), and have a mean apparent rank of high-volatile B bituminous coal. Because of the narrow deposition shelf upon which peat was able to accumulate, hypothetical coal resources in the Herendeen Bay and Chignik fields are estimated by Merritt and McGee (1986) to be only 360 million short tons.

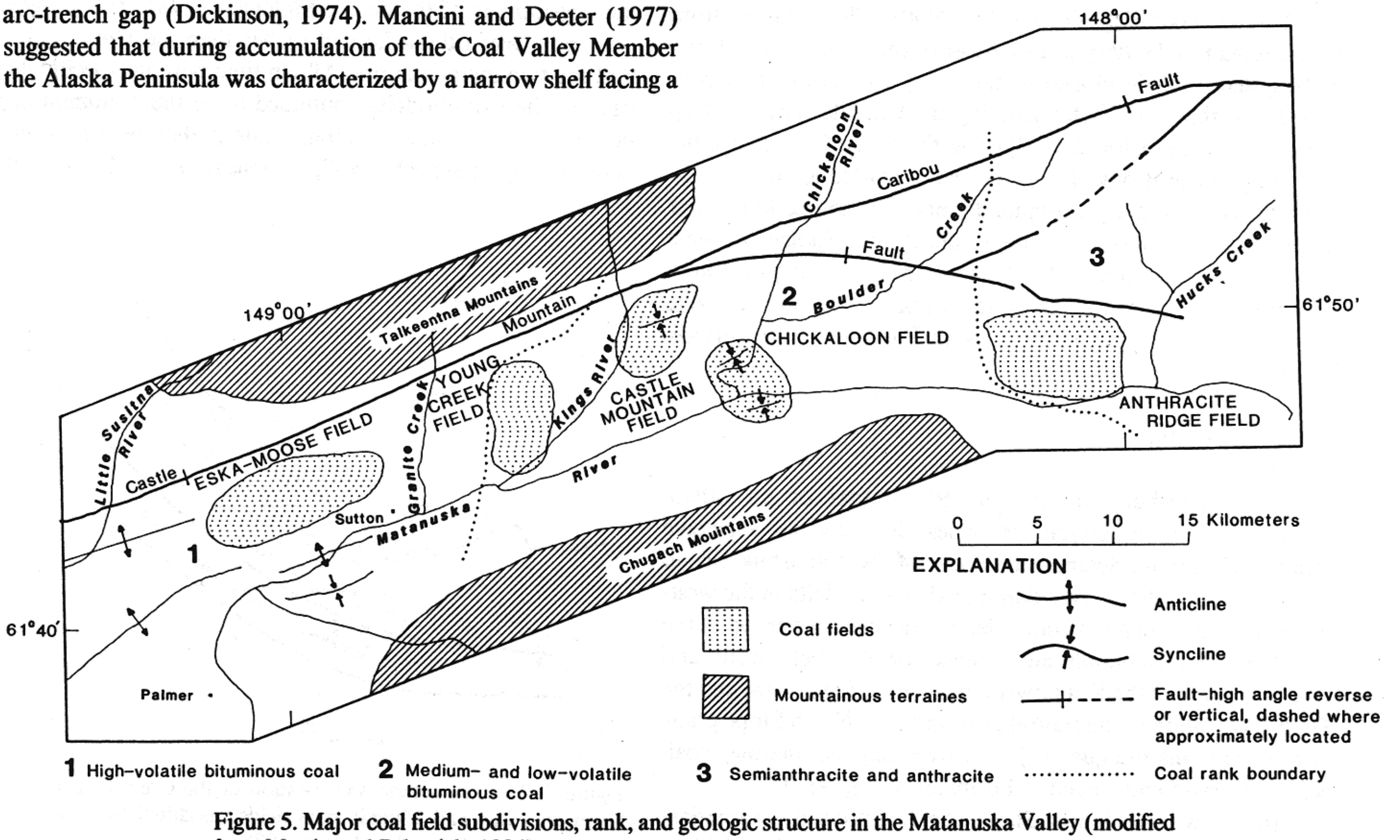

Figure 5. Major coal field subdivisions, rank, and geologic structure in the Matanuska Valley (modified from Merritt and Belowich, 1984).

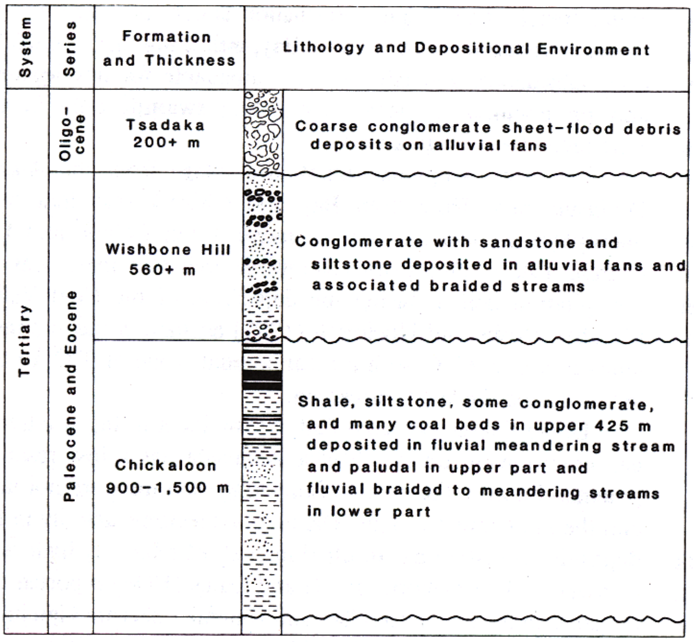

Figure 6. Stratigraphic nomenclature of the Tertiary rocks in the Matanuska Valley, Alaska (modified from Barnes and Payne, 1956; and Clardy, 1984).

NORTH SLOPE

Known coal deposits on the North Slope range from Mississippian to Tertiary in age. Most of this coal is related to a delta system that developed in the Early Cretaceous and continued into the early Tertiary, filling the Colville Basin, a deep assymetric basin or foredeep. During the Early Cretaceous, the beginning of the Brooks Range orogen recorded a shift in sediment dispersal from a predominantly northern source to a major southern and southwestern source: the Brooks Range orogenic belt. Coals accumulated in this delta system in the early Albian to Cenomanian Nanushuk Group, the Upper Cretaceous Colville Group, and the Upper Cretaceous to Pliocene Sagavanirktok Formation.

Nanushuk Group

The Nanushuk Group (Fig. 9) consists of an offlap, post-orogenic, molasse-type lithofacies, deposited on a passive continental margin. Sedimentary rocks of the Nanushuk Group are associated with the river-dominated Corwin delta in the western portion, and with the Umiat delta in the central portion of the North Slope (Ahlbrandt and others, 1979). Delta-front and shoreline strata of the Kukpowruk Formation in the west and the Tuktu Formation in the central portion of the North Slope grade upward and intertongue with the overlying nonmarine, coal-bearing Corwin and Chandler Formations (Fig. 9).

In the western North Slope, the Kukpowruk Formation, composed mainly of delta-front sandstones, ranges in thickness from 610 to 1,200 m in the outcrop belt in the northern foothills. The Corwin Formation consists of delta plain and alluvial plain shale, sandstone, conglomerate, and coal (Roehler and Stricker, 1979). This formation, while more than 3,450 m thick at Corwin Bluffs along the Arctic coast, thins eastward to zero in the subsurface near the Colville River.

In the central North Slope, the succession is more complex but, in general, nonmarine units overlie and intertongue with marine units. The marginal marine to marine Tuktu Formation intertongues with the delta-front and lower delta-plain Grandstand Formation (Fig. 9). The Grandstand Formation is overlain by and intertongued with the Killik Tongue of the Chandler Formation, a transitional or middle delta-plain sequence. Higher in the section, the Killik Tongue is overlain by a tongue of the Ninuluk Formation, which intertongues with the overlying Niakogon Tongue (Fig. 9). Molenaar (1985) indicated that the Seabee Formation, of the Colville Group, interfingers with both the Ninuluk Formation and Niakogon Tongue of the Chandler Formation.

Both deltas were river dominated, but the Umiat delta sediments reflect a higher degree of winnowing energy, as shown by a larger sand-to-mud ratio than the Colville delta (Ahlbrandt and others, 1979). The Umiat delta also apparently had lesser sediment volume and therefore a smaller source area than the Corwin delta. The area of demarcation between the two deltas is obscure; the Meade arch, extending southward from Point Barrow in Brookian time, probably did not play an active part in controlling the depocenters of the deltas. Molenaar (1981, 1985) suggested that the Corwin delta formed earlier than the Umiat delta and that the two merged during Albian time without specific demarcation. The Corwin delta continued to be the dominant depositional feature. Paleogeographic interpretations of Nanushuk deposition (Tetra Tech, 1982; Molenaar, 1981, 1985; Huffman

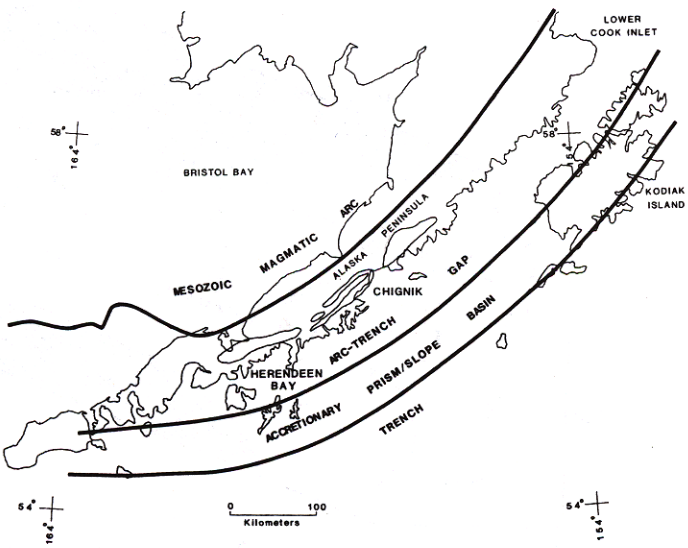

Figure 7. Tectonic setting and location of the Cretaceous coals of the Herendeen Bay and Chignik coal fields (modified from Mancini and others, 1978; and Wood and Bour, 1988).

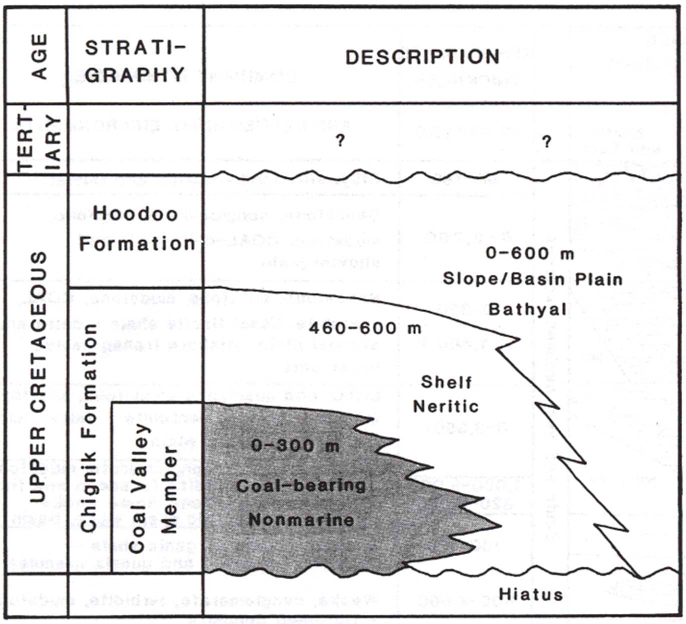

Figure 8. Generalized stratigraphic section of Cretaceous rocks in the Herendeen Bay and Chignik coal fields (modified from Mancini and others, 1978).

and others, 1984) stressed the dominant northeastward and eastward progradation of Nanushuk prodelta slope sediments. These studies also showed a strong northwestward concentration of sandstone in the upper part of the Nanushuk Group, from Umiat toward Point Barrow parallel to the paleoshoreline. This concentration may suggest that northwestward longshore currents moved sand from the Umiat delta along the active shelf of the Corwin delta front. This sand accumulation, interpreted to represent shoreline or offshore bar facies, may have been a controlling factor in restricting the development of the most prolific Nanushuk coal-generating delta environments to the western North Slope.

Spicer (1987) reported that the climate of the North Slope during Albian to Cenomanian time was cool with a mean annual temperature of 10 ± 3° C. Precipitation was sufficient to develop and accumulate thick peat deposits. Precipitation was also distributed throughout the year in a manner to preclude the oxidation and loss of organic material. Tree growth rings on the North Slope suggest a rapid change from summer to winter conditions during the Albian to Cenomanian (Spicer, 1987). This growth-ring pattern is consistent with the paleolatitude of approximately 80°N for the Colville Basin.

Sable and Stricker (1987), using all available data for the Nanushuk Group, estimated coal resources for the National Petroleum Reserve in Alaska portion of the North Slope. Using their methodology and all available data for the area of the known Nanushuk Group coal-bearing rocks, hypothetical coal resources for the Nanushuk Group on the North Slope are shown on Table 1. In summary, there are 1.3 trillion short tons of subbituminous and 1.9 trillion short tons of bituminous coal, for a total of 3.2 trillion short tons of hypothetical coal resources for the Nanushuk Group on the North Slope of Alaska.

TABLE 1. ESTIMATES OF HYPOTHETICAL COAL RESOURCES FOR THE NANUSHUK GROUP COAL IN THE NORTH SLOPE

Rank	Attitude	Overburden (m)	Resource Estimate*
Subbituminous	Dips generally 15° or less	0–150	1,149
		150–300	20
		300–600	10
		>600	1
		Total	1,180
	Dips generally 15° or more	0–150	101
		150–300	5
		300–600	5
		>600	1
		Total	112
	Subbituminous	Total (rounded)	1,290
Bituminous	Dips generally 15° or less	0–150	1,340
		150–300	0
		Total	1,340
	Dips generally 15° or more	0–150	571
		150–300	0
		Total	571
	Bituminous	Total (rounded)	1,910
	North Slope	Total (rounded)	3,200

*Reported in billions of short tons.

The Nanushuk Group coals of the North Slope range in apparent rank from Lignite A to high-volatile A bituminous coal with a mean of high-volatile C bituminous coal (Fig. 10). Total sulfur content ranges from 0.1 to 2.0 percent and has a mean of 0.3 percent, and the ash content has a mean of 11.0 percent (Affolter and Stricker, 1987a).

Colville Group

The Upper Cretaceous Colville Group (Fig. 9), a Brookian sequence younger than the Nanushuk Group, is best exposed along the lower part of the Colville River and its tributaries. Most of its areal extent is in northeastern Alaska (Fig. 10). Coals of the Colville Group and the younger Cretaceous and Tertiary Sagavanirktok Formation have been studied less than those of the Nanushuk Group because they have shown less economic potential. The Colville Group contains coal, but outcrop descriptions indicate that most coal beds are thinner and of lower rank than those in the Nanushuk Group. Many of these coals are described as lignites and "bony coals."

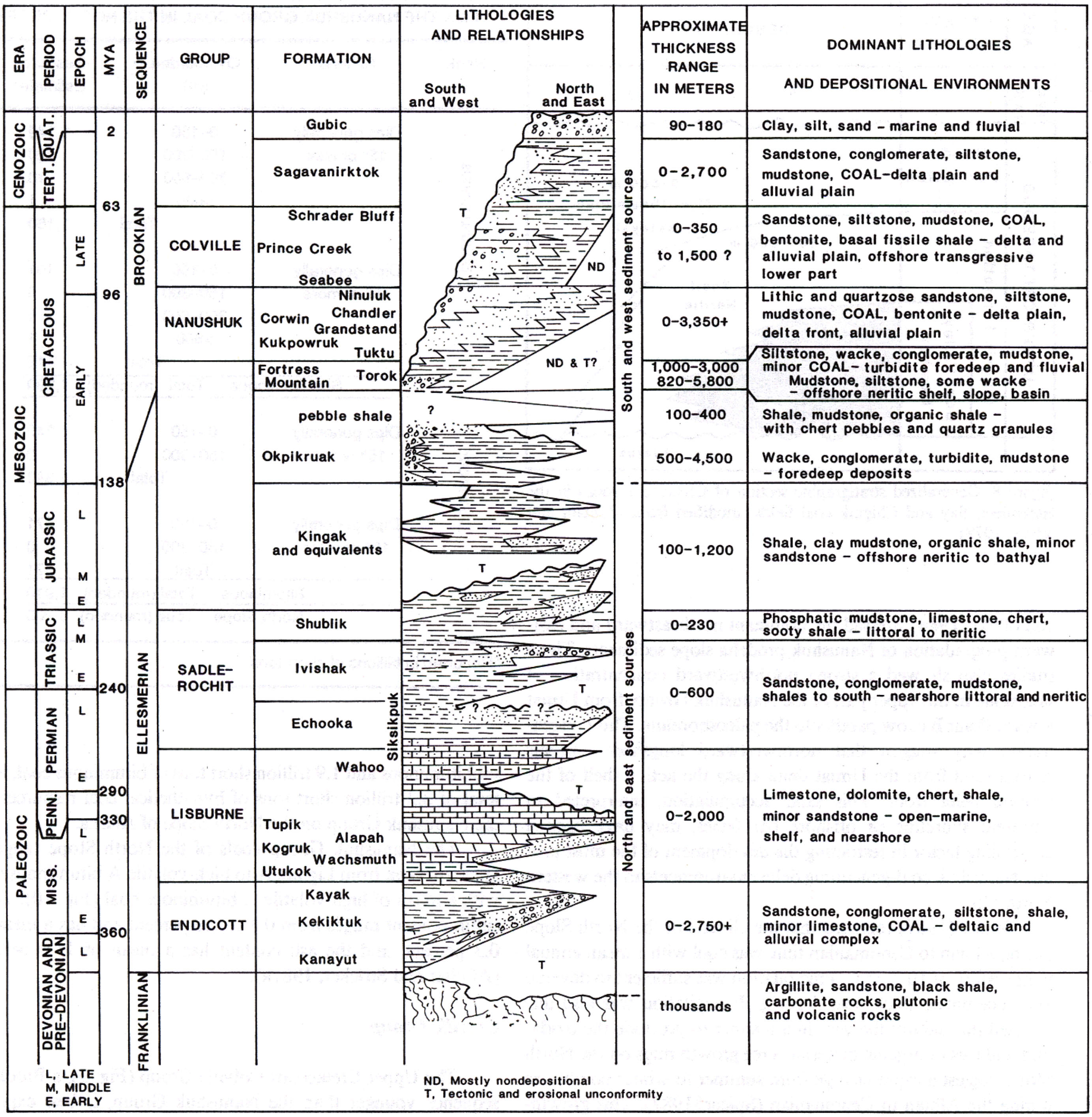

Figure 9. Generalized columnar section of rocks in the North Slope region (from Sable and Stricker, 1987).

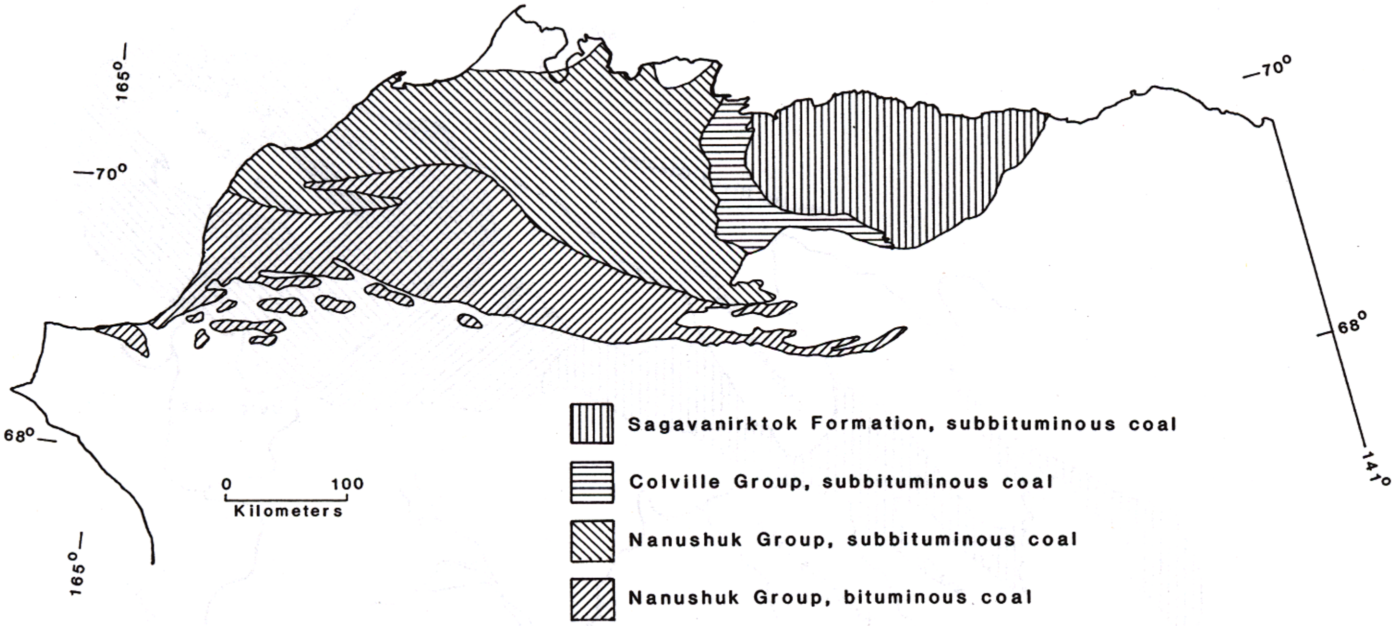

Figure 10. Distribution of coal rank in the North Slope region (modified from Sable and Stricker, 1987).

Sagavanirktok Formation

The Sagavanirktok Formation (Fig. 9), a thick sequence of sandstones, siltstones, mudstones, conglomerates, and coals, represents the final filling of the Colville Basin in the eastern North Slope during Late Cretaceous–early Tertiary time. Coal beds are distributed over an area of 15,000 km^2 (Fig. 10). West of the Sagavanirktok River the coal-bearing interval is as thick as 0.73 km. In the Prudhoe Bay area, the coal-bearing interval has been informally divided into an upper and lower coal zone (Roberts, 1991). The upper coal zone is as thick as 110 m and contains seven coal beds, and the lower coal zone is as thick as 260 m and contains 12 coal beds. The coals accumulated in alluvial and deltaic depositional environments. Apparent rank for these Sagavanirktok Formation coals range from lignite A to subbituminous B, with a mean of subbituminous C. Total sulfur content is low, with a mean of 0.37 percent (range of 0.08 to 2.02 percent) and a variable ash content of 1.16 to 46.72 percent (mean of 10.6 percent; Roberts and others, 1991).

Presently, no resource estimates are available for Tertiary coals in the eastern portion of the North Slope of Alaska. Affolter and Stricker (1987b) estimated the offshore hypothetical resources to be 300 billion short tons for the coal-bearing rocks in the Sagavanirktok Formation. My recent work indicates that the coal-bearing rocks of the Sagavanirktok Formation are thicker and of greater later extent onshore than offshore. Therefore, there should be at least as much hypothetical coal resource onshore as offshore in the eastern portion of the North Slope.

BERING RIVER COAL FIELD

The Bering River coal field contains low-volatile bituminous coal to meta-anthracite of unusually high rank (Fig. 11). The coals in the Kulthieth Formation (Fig. 12), of Eocene to Oligocene age (Plafker, 1967, 1987), crop out in a wedge-shaped area about 32 km east-west and from 3 to 8 km north-south. The Bering River coal field is located on the structurally complex Yakutat terrane (Plafker, 1983), near the subduction of the Pacific Plate beneath the North American Plate. The Yakutat terrane was several hundred kilometers south of its present position when these sediments were derived from upland areas of present-day British Columbia and southeastern Alaska.

The Kulthieth Formation is as thick as 2,800 m (Miller, 1957) and consists of cyclic fining- and coarsening-upward sequences. Turner and Whateley (1989) considered the lower part of the Kulthieth to consist of stacked, coarsening-upward, lower delta-plain deposits. The upper part of the Kulthieth is composed of fining-upward delta plain and lower alluvial plain sediments. Turner and Whateley (1989) noted that the thicker coals are found near the top of the fining-upward sequences.

Coals in the Bering River coal field are reported to be as thick as 9 m. However, the area is so extensively deformed that the term "pod" or "lens" is more applicable (Sanders, 1981). Sanders (1976) reported that the Bering River field may contain as much as 3.6 billion short tons of hypothetical coal resources.

The motion of the Yakutat terrane northward and docking and subduction of the terrane beneath the Chugach Mountains

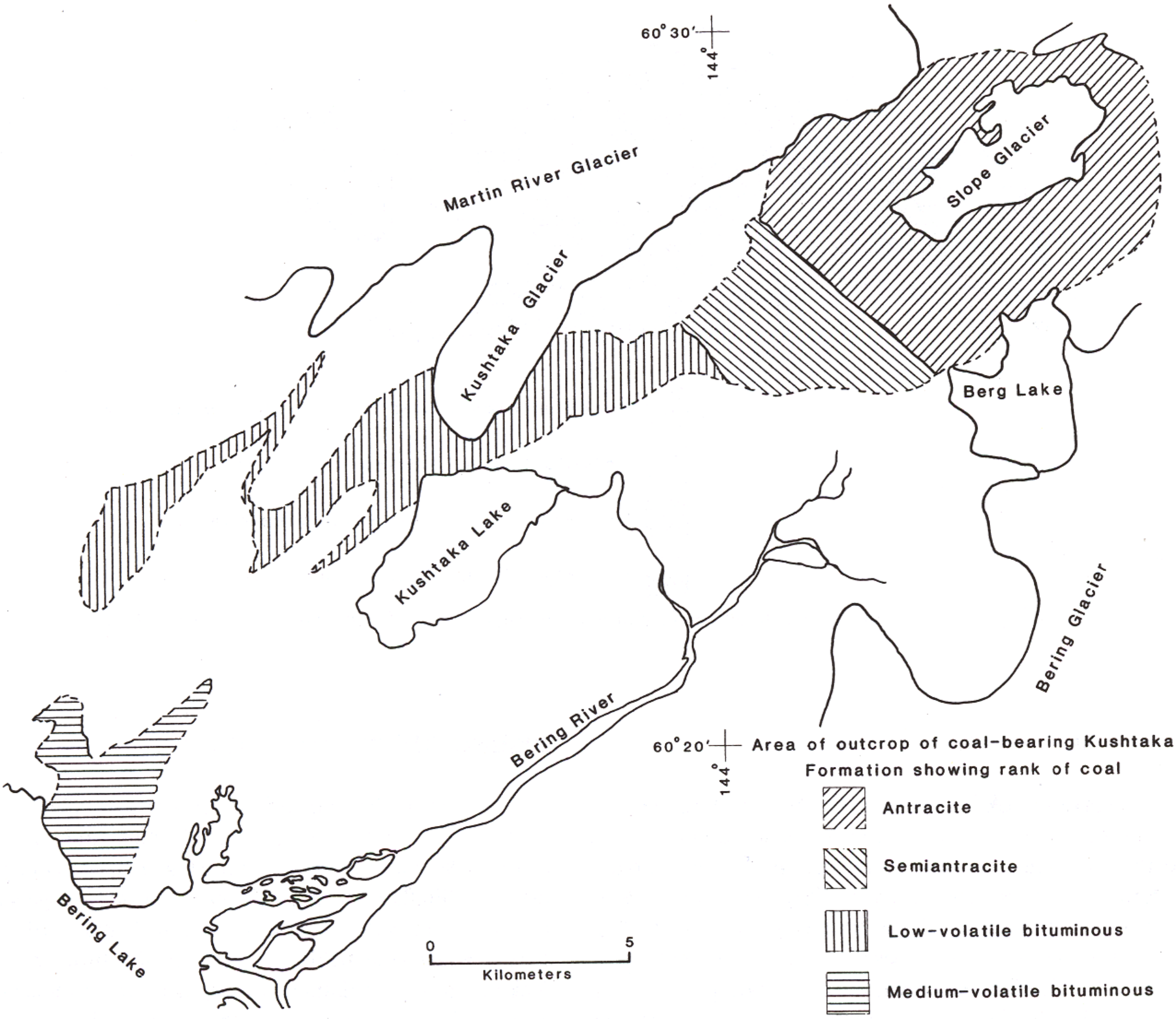

Figure 11. Distribution of coal rank in the Bering River coal field (modified from Barnes, 1951, 1967).

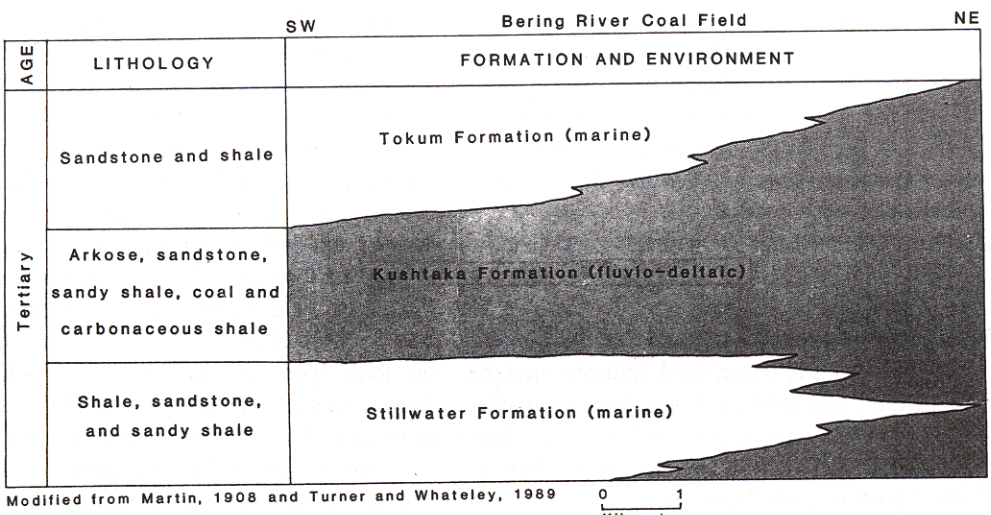

Figure 12. Generalized stratigraphic section of Tertiary rocks in the Bering River coal fields (modified from Martin, 1908; and Turner and Whateley, 1989).

intensely deformed the strata. Igneous intrusions at depth and numerous dikes and sills cut the coal-bearing sedimentary rocks and locally increased the rank of the coal. Bering River coals range in apparent rank from low-volatile bituminous coal at the west end of the field to meta-anthracite at the eastern end. Sulfur content ranges from 0.4 to 5.22 percent, with a mean of 1.2 percent.

SUMMARY

Coal in Alaska ranges in age from Mississippian to early Tertiary in age. Alaskan coals accumulated in many different environments of deposition. The coals with the greatest economic potential are found in the Tertiary Cook Inlet–Nenana regions, whereas most of Alaska's coal resources are in the Cretaceous strata on the North Slope. In general, the coals are bituminous to subbituminous in apparent rank and have the lowest sulfur contents of any United States coals. Merritt and Hawley (1986) have estimated that Alaska contains more than 170 billion short tons of identified and 5,600 billion short tons of hypothetical coal resources. With this large amount of coal, Alaska has the potential to play an important role in supplying the future energy needs of the United States.

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