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**2001 Guide to the petroleum, geology, and shallow gas
potential of the Kenai Peninsula, Alaska**

A Field Trip Guidebook

compiled by
T.A. Dallegge

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2001 Guide to the Petroleum, Geology, and Shallow Gas Potential of the Kenai Peninsula, Alaska

A Field Trip Guidebook Compiled by

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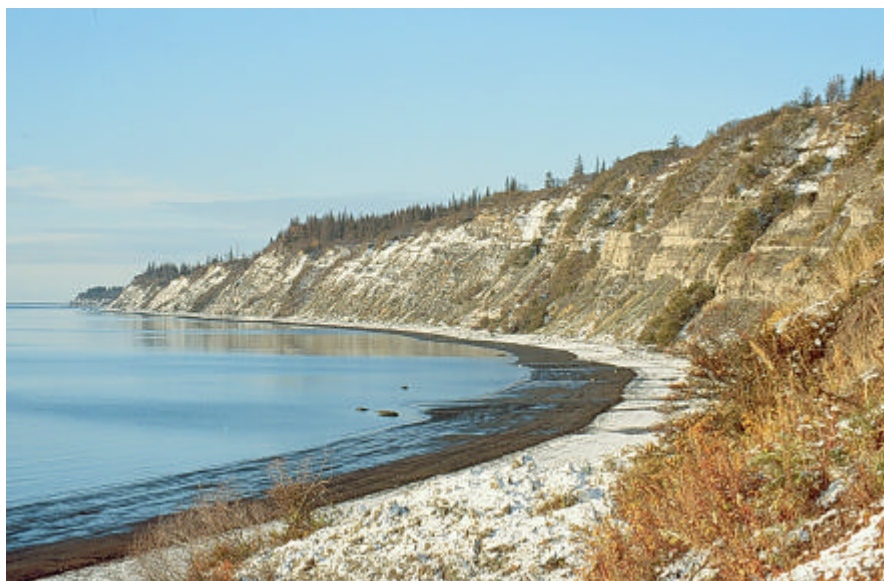


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Cover photo of Beluga and Sterling Formations west of McNeil Canyon, Kachemak Bay Alaska. Photo taken by T. Dallegge.

THE PENULTIMATE GREAT EARTHQUAKE IN SOUTHCENTRAL ALASKA: EVIDENCE FROM A BURIED FOREST NEAR GIRDWOOD

by
Rodney A. Combellick¹

INTRODUCTION

Determining the potential for future great earthquakes (Richter magnitude about 8 or 9) requires knowing how often they have occurred in the past. In the Anchorage, Alaska, region, only one great earthquake has occurred during historic time. This event, the great 1964 Alaska earthquake ($M_w=9.2$), was accompanied by tectonic uplift and subsidence that affected an area of more than 140,000 km² along 800 km of the Alaska-Aleutian subduction zone (fig. 1) (Plafker, 1969). Historic records and instrument monitoring show that no other great earthquake ruptured this segment, roughly between Kodiak and Cape Suckling, for at least 180 yr before the 1964 event (Sykes and others, 1980). However, there is no reason to doubt the inevitability of future earthquakes similar to the 1964 event. Adjacent areas of the Alaska-Aleutian arc have ruptured during at least one and, in some cases, during several great earthquakes throughout historic time. Considering that about 11 percent of the world's earthquakes have occurred in Alaska, including three of the ten largest events (Davies, 1984), the potential for future great earthquakes in the region is clearly high.

Given the limitations of instrument and historic records to resolve the recurrence times of great earthquakes, only geologic investigation can disclose the long-term record of sudden tectonic changes and earthquake effects. Recent geologic studies show that recurrence intervals for great earthquakes in this region range from about 400 to 1,300 yr (Plafker and others, 1992). My purpose in this paper is to present evidence from a coastal marsh near Girdwood that the penultimate, or second to last, great earthquake in the Anchorage region occurred between about 700 and 900 yr ago. This evidence comes from a layer of high-marsh peat² and rooted trees that were submerged by subsidence, probably killed by salt-water intake, and buried by postseismic deposition of intertidal silt and clay. I present preliminary evidence that subsid-

ence was substantial and sudden (coseismic), and suggest that this subsidence at Girdwood probably coincided with subsidence at Portage, Chickaloon Bay, Palmer Hay Flats, and Goose Bay and with uplift at Copper River Delta. If such a large area was deformed during a single event, it must have been a great earthquake similar to the 1964 event.

VERTICAL CHANGES DURING AND AFTER THE 1964 EARTHQUAKE

The 1964 earthquake released accumulated stresses on the Alaska-Aleutian subduction zone, where the North American and Pacific plates converge at about 6 cm/yr (DeMets and others, 1990). The associated pattern of uplift and subsidence (fig. 1) resulted from regional crustal warping and from displacements on subsurface portions of the northwest-dipping Aleutian megathrust and subsidiary reverse faults (Plafker, 1969). Downwarp of as much as 2 m occurred over an elongate region including Kodiak Island, Kenai Peninsula, most of Cook Inlet, and Copper River Basin. Uplift as much as 11.3 m occurred seaward of the subsidence zone in an elongate region including Middleton Island, Montague Island, most of Prince William Sound, and Copper River Delta. Superimposed on this pattern of coseismic deformation is regional interseismic subsidence (Plafker and others, 1992). The long-term net vertical displacement is the sum of coseismic and interseismic displacements. Therefore, some areas undergo coseismic and long-term subsidence (upper Cook Inlet), others coseismic and long-term uplift (Middleton Island), and still others coseismic uplift and long-term subsidence (Copper River Delta) or coseismic uplift and long-term stability (Montague Island).

Postearthquake changes have restored much of the subsided area of Turnagain Arm (fig. 2) to near pre-earthquake conditions. Subsidence totaled as much as 2.4 m at Portage, including about 1.6 m of regional tectonic subsidence and 0.8 m of local surficial compaction (McCulloch and Bonilla, 1970). During the decade following the earthquake, as much as 0.55 m of rebound occurred along Turnagain Arm (Brown and others, 1977). Additionally, intertidal silt deposition began in submerged areas immediately following the earthquake and by 1980 had nearly restored the tidal flats to pre-earthquake levels

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²In this paper, *high marsh* refers to the vegetated upper portion of the intertidal zone that is primarily influenced by terrestrial conditions (infrequently flooded by salt water). *Low marsh* refers to a topographically lower part of the intertidal zone that is primarily influenced by marine conditions (flooded at least daily by salt water).

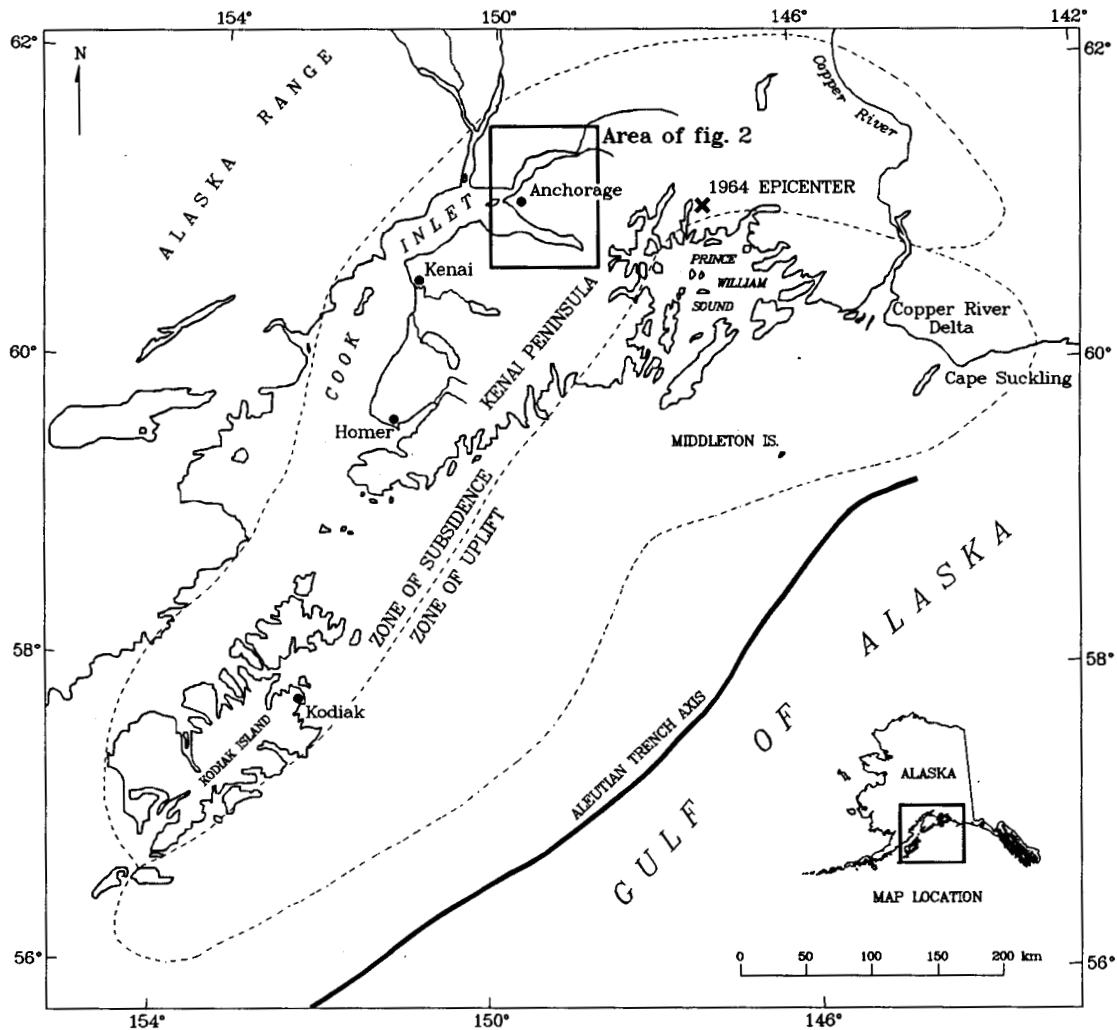


Figure 1. Region affected by vertical tectonic displacement during the great Alaska earthquake of 1964 (modified from Plafker, 1969, fig. 3).

(Bartsch-Winkler and Garrow, 1982). In the Portage area, Ovenshine and others (1976) mapped this deposit as the Placer River Silt. An equivalent but thinner deposit is present at Girdwood. This postearthquake silt overlies grasses, mosses, herbaceous plants, peat, and root systems of spruce and cottonwood trees on the high marsh that was submerged in the Portage and Girdwood areas during the earthquake.

PALEOSEISMOLOGY AND RADIOCARBON DATING

Determining the effects and timing of prehistoric earthquakes depends on (1) correct interpretation of the geologic evidence of earthquakes and (2) accurate dating of the affected rocks or sediments (Allen, 1986).

In the case of subduction-zone earthquakes like the 1964 Alaska event, the geologic evidence is usually related to sudden coastal uplift or subsidence (Plafker and Rubin, 1978; Lajoie, 1986) but may also be related to shaking effects, such as liquefaction (Obermeier and others, 1985).

Radiocarbon dating can provide a minimum or maximum age for an earthquake recorded in coastal sediments if organic material overlies or underlies the earthquake-related horizon. If organic material predating and postdating the horizon can be obtained, the age of the event can be bracketed. Alternatively, if it can be shown that the dated organisms died as a result of the earthquake, then the age of the youngest tissue approximates (very closely postdates) the age of the event.

Several sources of error make radiocarbon dating a relatively crude method for dating earthquakes and

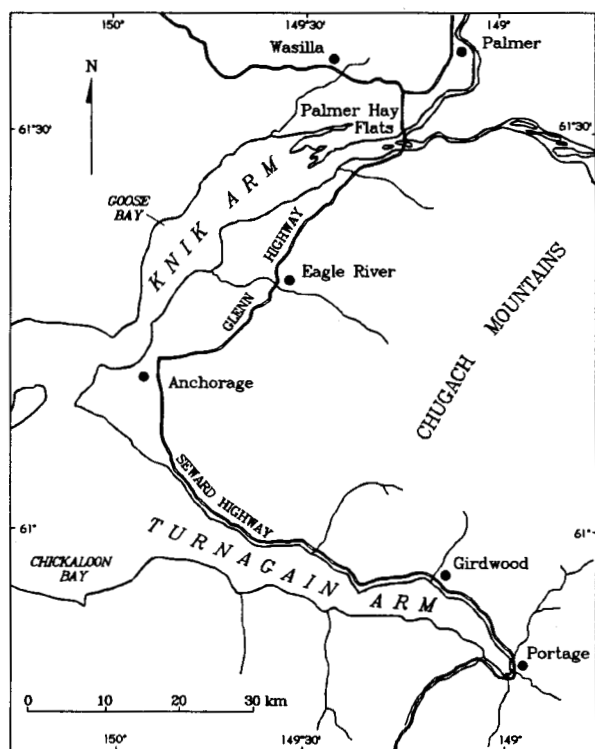


Figure 2. Anchorage region and portion of upper Cook Inlet, including study area in vicinity of Turnagain and Knik Arms (see fig. 1 for map location).

even less reliable for determining whether earthquake effects observed at different locations are attributable to a single event (Atwater and others, 1991). Bulk samples of organic material, such as peat, may predate or postdate the event by many years. Contamination by younger roots, detrital organic material, or bacterial decomposition can introduce significant error. Quoted laboratory errors on reported ages are normally at least several decades and may be understated because of unknown analytical errors (Scott and others, 1990). Different laboratories analyzing splits of the same or stratigraphically equivalent Holocene samples have reported ages that fail to overlap even at two standard deviations and may differ by up to 700 yr (Nelson, 1992). Finally, because of natural variation of ^{14}C content of atmospheric carbon through time, calibration to calendar years using dendrochronology is not linear and can result in a radiocarbon age yielding several possible calendar ages (Stuiver and Quay, 1980; Stuiver and Becker, 1986).

Despite these problems, conventional radiocarbon dating is a useful tool for determining approximate ages of earthquakes and their average recurrence interval. In some circumstances, high-precision radiocarbon dating of very carefully selected and prepared materials can

provide ages with quoted errors on the order of one or two decades (Atwater and others, 1991).

REGIONAL STUDIES

Numerous studies have documented repeated sudden vertical tectonic displacements in southcentral Alaska during the past 5,000 yr, or late Holocene (Plafker and Rubin, 1967, 1978; Plafker, 1969; Plafker and others, 1992; Combellick, 1986, 1991; Bartsch-Winkler and Schmoll, 1987, 1992). Although the timing of all events is not yet clear, the distribution of prehistoric uplift and subsidence appears consistent with the pattern of 1964 deformation.

Radiocarbon dating of submerged peat layers in estuarine sediments of upper Cook Inlet indicates that the area probably subsided coseismically six to eight times during the 4,700 yr prior to the 1964 event, implying recurrence times on the order of 600 to 800 yr (Combellick, 1991). Elevated terraces on Middleton Island record five pre-1964 uplifts during the past 4,300 radiocarbon yr (Plafker and Rubin, 1978), or 4,900 calendar yr. The most recent uplift preserved by Middleton Island terraces was about 1,300 yr ago. At Copper River Delta, which undergoes net long-term subsidence punctuated by coseismic uplift, buried peat and forest layers record four pre-1964 uplifts during the past 3,000 yr (Plafker and others, 1992). The most recent event represented in the Copper River Delta sequence was about 800 yr ago.

Karlstrom (1964) dated and briefly described a buried forest layer in tidal sediments at Girdwood and recognized that it recorded a period of lower relative sea level. He obtained an age of 700 ± 250 radiocarbon yr (510-920 calendar yr) for wood from a rooted stump at about 0.8 m below the pre-1964 surface and $2,800 \pm 180$ yr (2,759-3,207 calendar yr) for wood from a peat layer about 4 m lower in the section. Karlstrom, whose report was prepared prior to the 1964 earthquake, did not attribute burial of the forest layer to possible coseismic subsidence.

Plafker (1969) used Karlstrom's dates to infer a regional average subsidence rate of 2-30 cm per century between 700 and 2,800 radiocarbon yr ago. He also concluded that gradual tectonic submergence prevailed in Prince William Sound as much as 1,180 yr prior to the 1964 earthquake. Plafker and Rubin (1978) inferred that the lowest elevated terrace at Middleton Island (fig. 1), dated at 1,360 radiocarbon yr, represented the last coseismic uplift in the region prior to 1964. However, Plafker and others (1992), reported new evidence of widespread coseismic uplift with a calibrated age of 665-895 yr in the Copper River Delta.

BURIED FOREST LAYERS AT GIRDWOOD

Erosion by waves and tidal currents has exposed two peat layers with rooted tree stumps along coastal banks at Girdwood (fig. A3). Trees rooted in the uppermost layer were killed as a result of submergence during the 1964 earthquake, probably by saltwater intake. Many of these dead trees remain standing but their root systems are partially or completely buried beneath postearthquake silt (equivalent to Placer River Silt) up to several tens of cm thick. Patches of bark remain on above-ground portions of some of the trees and are commonly well preserved on buried portions of the trunks.

Stumps rooted in the lower layer are broken or eroded to heights of less than 1 m and encased in about 1 m of gray clayey silt between the upper and lower forest layers. None of the lower stumps protrude through the modern marsh surface. No bark remains on the specimens I observed from the lower layer except for very few small, loosely attached patches. The lower stumps are rooted in a layer of mossy and woody peat 10-15 cm thick, which has been partly removed by tidal and wave erosion where the stumps crop out at the base of the bank (fig. 3B). This lower layer of rooted stumps is probably the same layer that Karlstrom (1964) dated at 700 ± 250 radiocarbon yr.

Several lines of evidence indicate that the lower forest layer was submerged and buried as a result of sudden subsidence: (1) the contact between the peat layer and overlying mud is very sharp, indicating rapid burial, as with the 1964 layer; (2) outer growth rings of the buried stumps are continuous and as wide as or wider than inner rings, indicating healthy growth until death, comparable to that observed in coastal Washington by Atwater and Yamaguchi (1991); and (3) the lower part of the overlying mud layer contains below-ground stems of the halophytic plant *Triglochin maritimum*, indicating submergence to a lower level in the intertidal zone. In southwestern Washington, where diurnal tide range is about 3 m, *T. maritimum* is dominant only in low-marsh areas that are 0.5-2.0 m or more below the typical high-marsh surface (Atwater, 1987). In upper Cook Inlet, where diurnal tide range is about 10 m, *T. maritimum* may indicate greater than 2-m depth below the high-marsh elevation. The overlying mud layer shows a gradual upward increase in roots, grass stems, and other plant material and grades into the overlying peat, suggesting a gradual return to the high-marsh environment.

Although alternating layers of peat and intertidal mud can be produced by nonseismic processes (Nelson and Personius, in press), the sharp peat-mud contact, presence of *T. maritimum* in mud above the contact, apparent sudden death of rooted trees, and gradual mud-

peat transition are strong evidence of coseismic subsidence followed by gradual uplift or sedimentation that returned the tidal flat to high-marsh conditions. Still lacking, however, is convincing evidence of strong ground shaking in the form of liquefaction features associated with burial of the peat. This evidence may be very difficult to find; a 1991 reconnaissance of several km of tidal- and river-bank exposures in the Portage area, where liquefaction was extensive during the 1964 earthquake (McCulloch and Bonilla, 1970), revealed only a few sand dikes penetrating the 1964 soil (B. Atwater and R. Combellick, unpub. data, 1991). Locating similar evidence of ground shaking during previous events will be even more difficult because previous coseismic subsidence is interpreted mainly from borehole samples (Combellick, 1991).

RADIOCARBON AGES

My estimate for age of burial of the lower forest layer at Girdwood is based on radiocarbon dating of three wood samples and three peat samples. The wood samples were collected from the outermost 10 to 25 growth rings of three rooted tree stumps. Because bark was not present on the sampled stumps, these may not be the last growth rings added before death. However, the well-preserved condition of the stumps, nearly continuous outermost rings, and smoothness of the outer surface suggest that few or no growth rings have been lost to decomposition. Considering the potential sources of error in conventional radiocarbon dating, the exact position of the dated wood relative to the outermost ring at time of death is probably insignificant. If my assumption is correct that these trees were growing normally at the time of submergence and died quickly as a result of submergence, the average age of these outer rings should predate the time of the event by no more than a few years. The potential for contamination of wood samples with older or younger organic material is far less than for peat samples. Therefore, the wood samples should provide a more reliable age estimate for submergence.

Two of the peat samples were collected from the upper 2-3 cm of the peat layer exposed near the rooted stumps, immediately below the abrupt contact between the peat and overlying tidal mud. The third peat sample was collected from an equivalent stratigraphic position in a nearby borehole (Combellick, 1991, table 2, sample TA1-12.8). If the peat is composed primarily of plant material that was growing at or shortly before submergence, these samples should provide a closely limiting maximum age for the event. However, possible contamination by older plant matter or younger roots may introduce unknown errors.

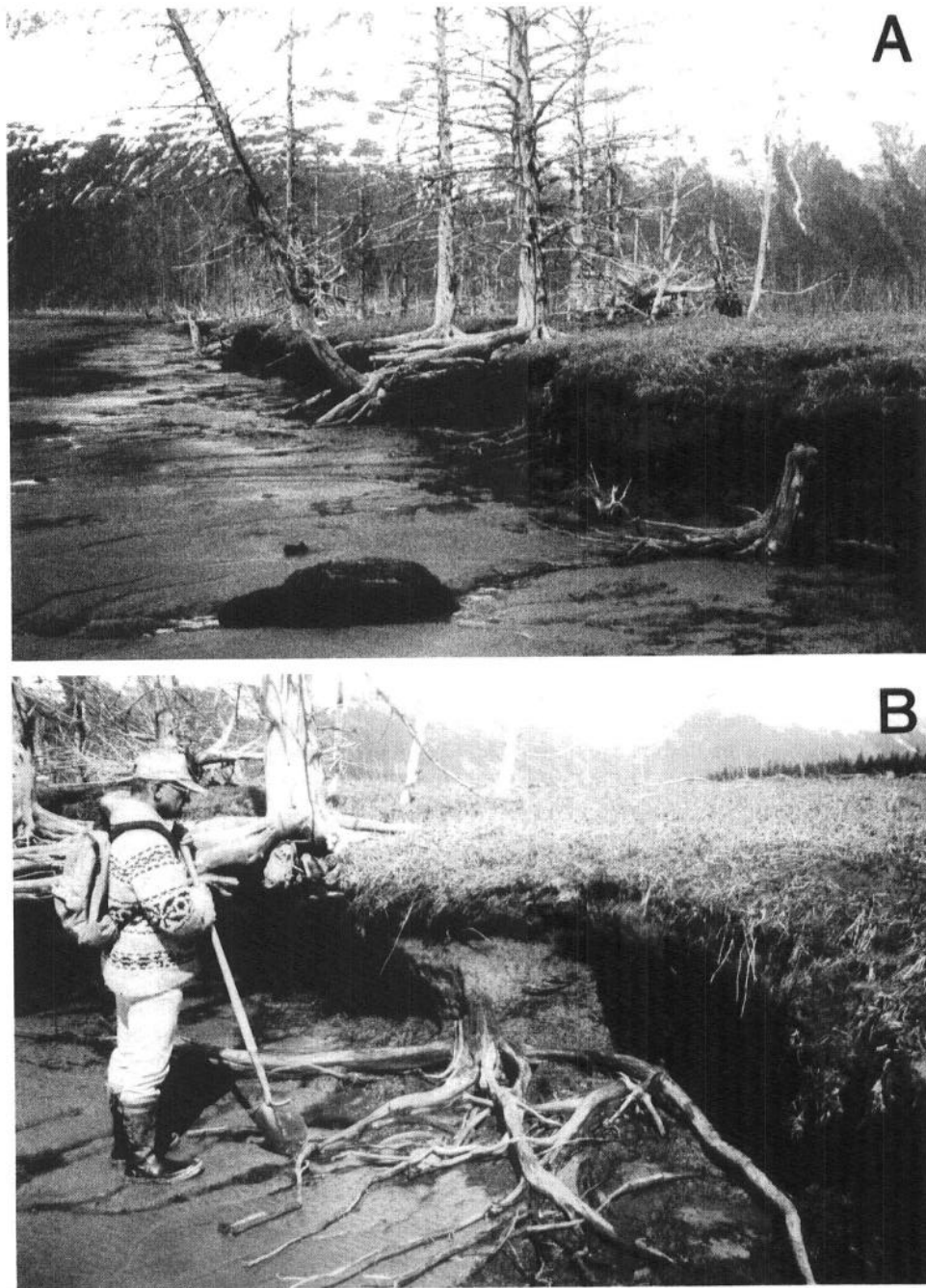


Figure 3. Erosion has exposed root systems of two generations of dead spruce trees in coastal banks along upper Turnagain Arm near Girdwood. (7A) View of standing trees that probably died from salt-water intake following submergence during the 1964 earthquake. The roots of these trees and other contemporaneous vegetation were buried by postearthquake deposition of intertidal silt. Stumps along the base of the bank are rooted in an older peat layer, which is buried beneath about 1 m of intertidal silt. (7B) Closeup of older rooted stump showing intertidal mud that buried the root system and associated peat layer (erosion has removed much of the peat). Death of these older trees and burial of the peat layer within which they are rooted probably resulted from subsidence during the previous great earthquake (1991 photographs).

Two commercial laboratories performed the radiocarbon dating using standard pretreatment and gas-proportional counting techniques. Reported radiocarbon ages (fig. 4) include a correction for natural $^{13}\text{C}/^{12}\text{C}$ isotopic fractionation and are referenced to A.D. 1950. Calibration to calendar years was based on tree-ring data of Stuiver and Becker (1986) and was performed using a computer program by Stuiver and Reimer (1986). The laboratories did not provide specific error multipliers to account for non-counting analytical errors, so I used a conservative value of 2 for all calibrated ages. Although this has the effect of doubling the quoted standard deviation, the probability that the true sample age is within the calibrated age range remains at 68 percent. This is because the quoted standard deviation may not be large enough to account for all sources of laboratory error (Stuiver and Pearson, 1986).

The weighted average age of the wood samples is 926 ± 35 radiocarbon yr, which gives possible calibrated ages of 799, 810, 830, 856, and 909 yr and an error range probably within the interval 744-946 yr B.P. at 68 percent confidence (fig. 4). The calibrated age range is greater than the uncalibrated range because of multiple intercepts in the calibration curve and greater rate of change of calibrated age versus radiocarbon age during this period (fig. 5).

Ages of the peat samples (fig. 4) are consistent with the wood ages but show greater variation, probably because of the longer period spanned by each peat sample and, in the case of sample 91-1-1, possible contamination by younger organic material.

REGIONAL CORRELATION AND DISCUSSION

Buried peat layers with characteristics similar to the lower Girdwood forest layer, but without observed rooted stumps, occupy an equivalent stratigraphic position in estuarine sediments at Portage and Palmer Hay Flats (Combellick, 1991) and at Chickaloon Bay and Goose Bay (this study) (fig. 2). Samples from the tops of the peat layers yielded ages that are consistent with the ages of wood and peat samples from the lower Girdwood forest layer (fig. 4). The reported 665-895-yr calibrated age for coseismic uplift in the Copper River Delta area (Plafker and others, 1992) is also consistent with the wood and peat ages in upper Cook Inlet.

These data do not prove that vertical displacement was coeval in all areas; if the dated deposits were produced by events separated by only a few years or decades, these events cannot be resolved by conventional radiocarbon dating. However, because the current body of paleoseismic

evidence indicates an average recurrence interval of 600-800 yr for great earthquakes in this region, it is reasonable to presume that the dated deposits represent a single event.

If vertical displacement was coeval, the minimum magnitude of this earthquake can be roughly estimated using an empirical relationship between magnitude of subduction-zone earthquakes and length of measurable deformation (West and McCrumb, 1988). Considering that deformation zones are elongated parallel to the trench axis, the deformation associated with the earthquake must have exceeded the 300-km distance between upper Cook Inlet and Copper River Delta because this line is roughly perpendicular to the trench axis. According to the graphic relationship of West and McCrumb (1988, fig. 1), the minimum earthquake magnitude for a 300-km-long zone of deformation is about 7.8.

High-precision dating involving much longer counting periods could provide radiocarbon ages with standard deviations on the order of one or two decades (Stuiver and Becker, 1986; Atwater and others, 1991). However, this technique may not improve resolution of the calendar age of the earthquake because of apparent wide variability of atmospheric ^{14}C between about 750 and 900 yr B.P. (A.D. 1050-1200). The resulting calibration curve (fig. 5) shows that radiocarbon ages between about 860 and 960 yr give multiple calibrated ages between 750 and 925 yr. As Atwater and others (1991) have demonstrated, it may be possible to precisely date older rings of rooted stumps, thereby obtaining radiocarbon ages on a steeper portion of the calibration curve (greater than 960 radiocarbon yr B.P.) where there are fewer multiple intercepts. Subtracting the number of growth rings between the sampled portion and the outer surface would then yield more precise calibrated ages for the samples. This method could help determine whether sudden vertical displacements in this region between 700 and 900 yr ago resulted from multiple great earthquakes.

SUMMARY AND CONCLUSIONS

The last great earthquake that caused tectonic deformation in the Anchorage region prior to 1964 probably occurred between 700 and 900 yr ago. This inferred earthquake caused vertical shoreline changes extending at least from upper Cook Inlet to the Copper River Delta. Evidence of these changes appears in tidewater banks at Girdwood, where a layer of peat and rooted tree stumps exposed about 1.7 m below the modern coastal high marsh is buried beneath intertidal mud. The abrupt upper contact of the peat, apparent sudden death of the trees, and presence of halophytic plant fossils in mud above the

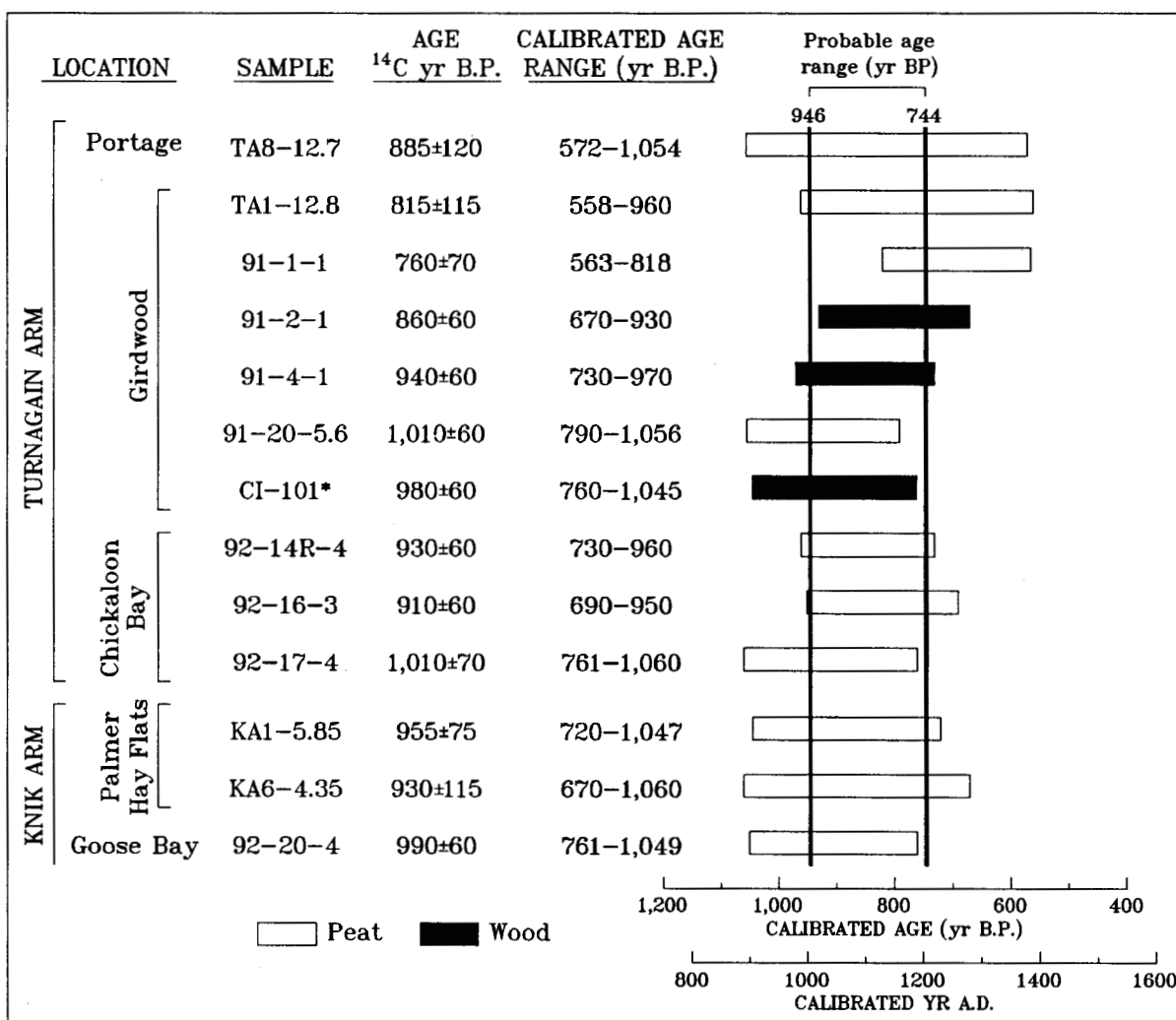


Figure 4. Radiocarbon ages of wood and peat samples used in this study. Wood samples were collected from the outer 10-25 growth rings of rooted stumps (*CI-101 age provided by Gordon Jacoby, written commun.). Peat samples were collected from the upper 2-3 cm of buried peat. Age in ¹⁴C yr B.P. is conventional radiocarbon age in years before A.D. 1950 with quoted counting error of one laboratory standard deviation. Calibrated age ranges at right are based on tree-ring data of Stuiver and Becker (1986) and incorporate an error multiplier of 2 to account for possible non-counting sources of laboratory error. Probable age range shown represents error limits of the average calibrated age of two wood samples at the Girdwood site, at 68 percent confidence (fig. 5).

contact indicate submergence into the low-marsh environment more rapidly than would be expected as a result of nontectonic rise of relative sea level. As intertidal silt deposition and possibly postseismic rebound restored the tidal flat to subaerial conditions, the mud above this forest layer became increasingly rich in plant matter and a new brackish-water high marsh developed. Subsidence during the 1964 earthquake submerged this marsh in a similar fashion and resulted in burial by intertidal silt.

Age control for this penultimate earthquake comes

from radiocarbon dates of outer growth rings from three rooted trees that were probably killed by salt water as a result of coseismic submergence. Mathematically combining these ages gives a calibrated age range probably within 744-946 calendar yr B.P. at 68 percent confidence. Peat samples from the top of the soil layer within which these stumps are rooted yield calibrated ages that are consistent with the wood ages but show greater variation. The wood and peat ages at Girdwood closely match ages obtained from similar buried peat layers at Portage,

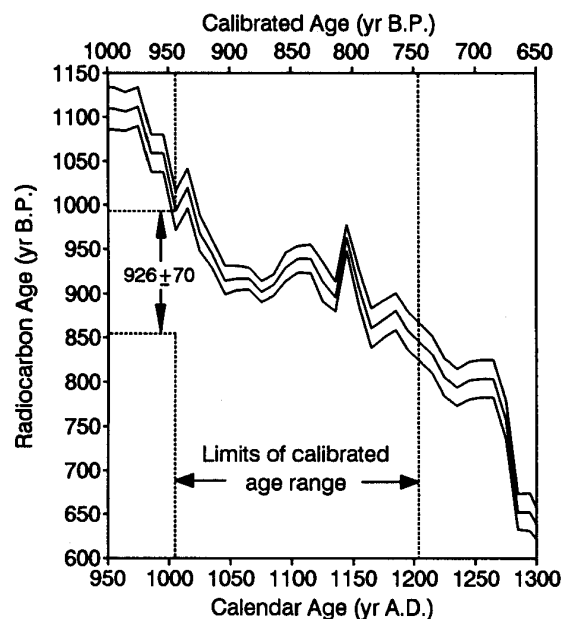


Figure 5. Portion of tree-ring calibration curve showing translation of average radiocarbon-age range for the two wood samples to calibrated probable range shown in figure 4. Prior to calibration, the error calculated from the laboratory standard deviations is increased by an error multiplier of 2. The center line is the calibration curve and the outer lines represent uncertainty of one standard deviation in the calibration data set; this standard deviation incorporates a laboratory error multiplier of 1.6 (modified from Stuiver and Becker, 1986, fig. 1B).

Chickaloon Bay, Palmer Hay Flats, and Goose Bay and from deposits formed by coseismic uplift at Copper River Delta. Although I presume that these vertical displacements occurred during a single great earthquake, multiple earthquakes may have affected each area separately within a period that was too brief to resolve with conventional radiocarbon dating. If the vertical displacements occurred during a single earthquake, its magnitude was probably 7.8 or larger.

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REFERENCES CITED

- Allen, C.R., 1986, Seismological and paleoseismological techniques of research in active tectonics, *in* Studies in geophysics: Active tectonics: Washington, D.C., National Academy Press, p. 148-154.
- Atwater, B.F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington State: *Science*, v. 236, p. 942-944.
- Atwater, B.F., and Yamaguchi, D.K., 1991, Sudden, probably coseismic submergence of Holocene trees and grass in coastal Washington State: *Geology*, v. 19, no. 7, p. 706-709.
- Atwater, B.F., Stuiver, Minze, and Yamaguchi, D.K., 1991, Radiocarbon test of earthquake magnitude at the Cascadia subduction zone: *Nature*, v. 353, p. 156-158.
- Bartsch-Winkler, S.R., and Garrow, H.C., 1982, Depositional system approaching maturity at Portage Flats, *in* Coonrad, W.L., ed., The U.S. Geological Survey in Alaska: Accomplishments during 1980: U.S. Geological Survey Circular 844, p. 115-117.
- Bartsch-Winkler, Susan, and Schmoll, H.R., 1987, Earthquake-caused sedimentary couplets in the upper Cook Inlet region, *in* Hamilton, T.D., and Galloway, J.P., eds., *Geologic Studies in Alaska by the U.S. Geological Survey during 1986: U.S. Geological Survey Circular 998*, p. 92-95.
- Bartsch-Winkler, Susan, and Schmoll, H.R., 1992, Utility of radiocarbon-dated stratigraphy in determining late Holocene earthquake recurrence intervals, upper Cook Inlet region, Alaska: *Geological Society of America Bulletin*, v. 104, no. 6, p. 684-694.
- Brown, L.D., Reilinger, R.E., Holdahl, S.R., and Balazs, E.I., 1977, Postseismic crustal uplift near Anchorage, Alaska: *Journal of Geophysical Research*, v. 82, no. 23, p. 3369-3378.
- Combellick, R.A., 1986, Chronology of late-Holocene earthquakes in southcentral Alaska: Evidence from buried organic soils in upper Turnagain Arm [abs.]: *Geological Society of America Abstracts with Programs*, v. 18, no. 6, p. 569.
- _____, 1991, Paleoseismicity of the Cook Inlet region, Alaska: Evidence from peat stratigraphy in Turnagain and Knik Arms: Alaska Division of Geological & Geophysical Surveys Professional Report 112, 52 p.

- Davies, J.N., 1984, Alaska's earthquakes: The Northern Engineer, v. 16, no. 4, p. 8-13.
- DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1990, Current plate motions: Geophysical Journal International, v. 101, no. 2, p. 425-478.
- Karlstrom, T.N.V., 1964, Quaternary geology of the Kenai lowland and glacial history of the Cook Inlet region, Alaska: U.S. Geological Survey Professional Paper 443, 69 p.
- Lajoie, K.R., 1986, Coastal tectonics, in Wallace, R.E., ed., Studies in geophysics: Active tectonics: Washington, D.C., National Academy Press, p. 95-124.
- McCulloch, D.S., and Bonilla, M.G., 1970, Effects of the earthquake of March 27, 1964, on the Alaska Railroad: U.S. Geological Survey Professional Paper 545-D, 161 p.
- Nelson, A.R., 1992, Discordant ^{14}C ages from buried tidal-marsh soils in the Cascadia subduction zone, southern Oregon coast: Quaternary Research, v. 38, no. 1, p. 74-90.
- Nelson, A.R., and Personius, S.F., in press, The potential for great earthquakes in Oregon and Washington: An overview of recent coastal geologic studies and their bearing on segmentation of Holocene ruptures, central Cascadia subduction zone, in Rogers, A.M., Kockelman, W.J., Priest, G., and Walsh, T.J., eds., Assessing and reducing earthquake hazards in the Pacific Northwest: U.S. Geological Survey Professional Paper 1560.
- Obermeier, S.F., Gohn, G.S., Weems, R.E., Gelinas, R.L., and Rubin, Meyer, 1985, Geologic evidence for recurrent moderate to large earthquakes near Charleston, South Carolina: Science, v. 227, p. 408-411.
- Ovenshine, A.T., Lawson, D.E., and Bartsch-Winkler, S.R., 1976, The Placer River Silt—An intertidal deposit caused by the 1964 Alaska earthquake: Journal of Research of the U.S. Geological Survey, v. 4, no. 2, p. 151-162.
- Plafker, George, 1969, Tectonics of the March 27, 1964, Alaska earthquake: U.S. Geological Survey Professional Paper 543-I, 74 p., 2 sheets, scales 1:2,000,000 and 1:500,000.
- Plafker, George, and Rubin, Meyer, 1967, Vertical tectonic displacements in south-central Alaska during and prior to the great 1964 earthquake: Journal of Geosciences, Osaka City University, v. 10, p. 53-66.
- _____, 1978, Uplift history and earthquake recurrence as deduced from marine terraces on Middleton Island, Alaska, in Proceedings of Conference VI, Methodology for Identifying Seismic Gaps and Soon-to-break Gaps, National Earthquake Hazards Reduction Program, 25-27 May, 1978: U.S. Geological Survey Open File Report 78-943, p. 687-721.
- Plafker, George, Lajoie, K.R., and Rubin, Meyer, 1992, Determining recurrence intervals of great subduction zone earthquakes in southern Alaska by radiocarbon dating, in Taylor, R.E., Long, Austin, and Kra, R.S., eds., Radiocarbon after four decades: An interdisciplinary perspective: New York, Springer-Verlag, p. 436-452.
- Scott, E.M., Aitchison, T.C., Harkness, D.D., Cook, G.T., and Baxter, M.S., 1990, An overview of all three stages of the international radiocarbon intercomparison: Radiocarbon, v. 32, no. 3, p. 309-319.
- Stuiver, M., and Becker, B., 1986, High-precision decadal calibration of the radiocarbon time scale, AD 1950-2500 BC: Radiocarbon, v. 28, p. 863-910.
- Stuiver, M., and Pearson, G.W., 1986, High-precision calibration of radiocarbon time scale, AD 1950-500 BC: Radiocarbon, v. 28, p. 805-838.
- Stuiver, Minze, and Quay, P.D., 1980, Changes in atmospheric carbon-14 attributed to a variable sun: Science, v. 207, p. 11-19.
- Stuiver, M., and Reimer, P.J., 1986, A computer program for radiocarbon age calibration: Radiocarbon, v. 28, p. 1022-1030.
- Sykes, L.R., Kisslinger, J.B., House, Leigh, Davies, J.N., and Jacob, K.H., 1980, Rupture zones of great earthquakes in the Alaska-Aleutian Arc, 1784 to 1980: Science, v. 210, no. 19, p. 1343-1345.
- West, D.O., and McCrumb, D.R., 1988, Coastal uplift in Oregon and Washington and the nature of Cascadia subduction-zone tectonics: Geology, v. 16, no. 2, p. 169-172.

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 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 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. 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 total 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.

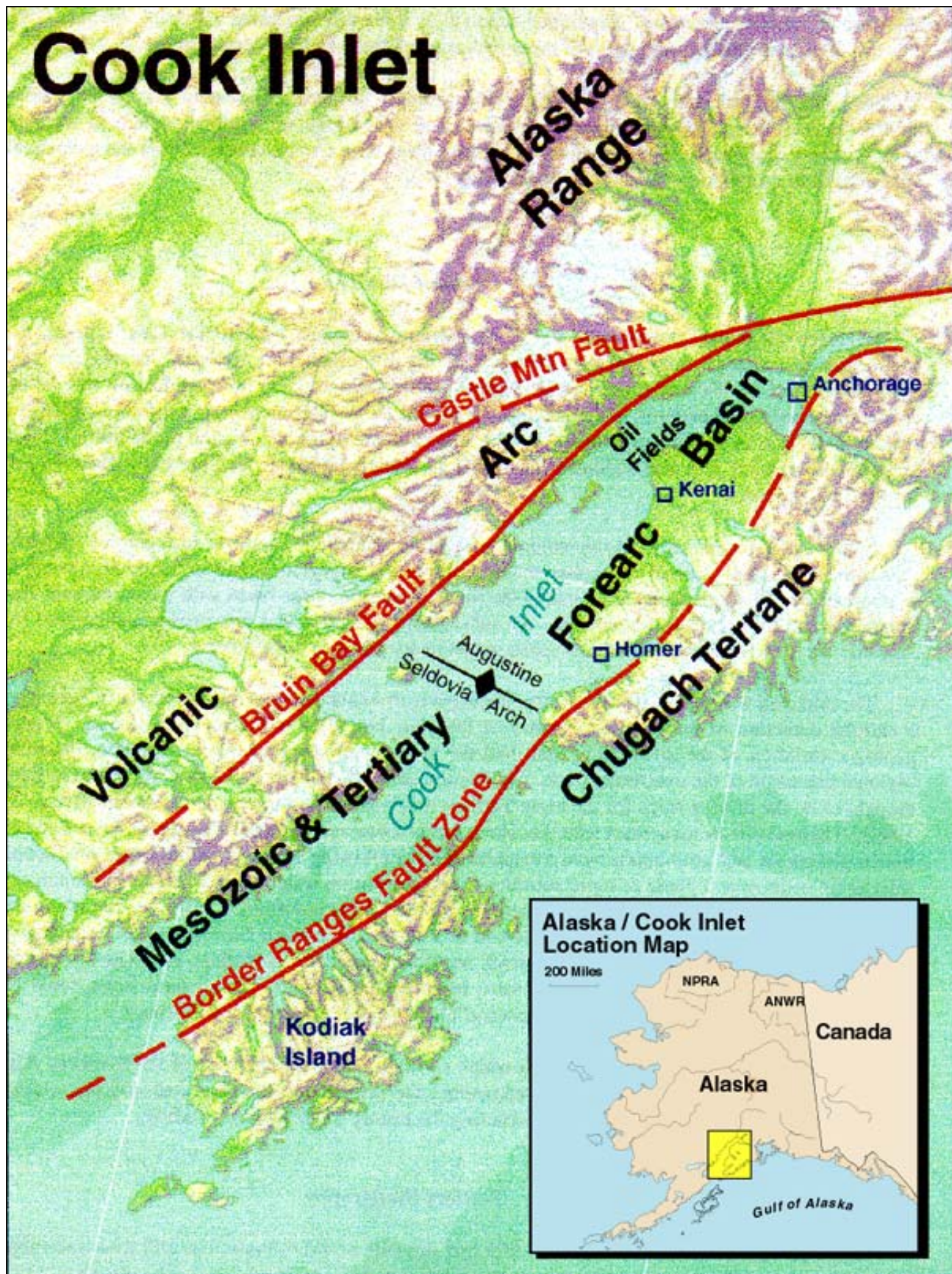


Figure 1. Present day Cook Inlet basin morphology and regional tectonic boundaries

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 obducted at the plate boundary. Continued subduction/obduction 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 to marginal 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 tectonism 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.

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 depositional 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.

Cook Inlet

Tectonic-Stratigraphic Correlation Chart

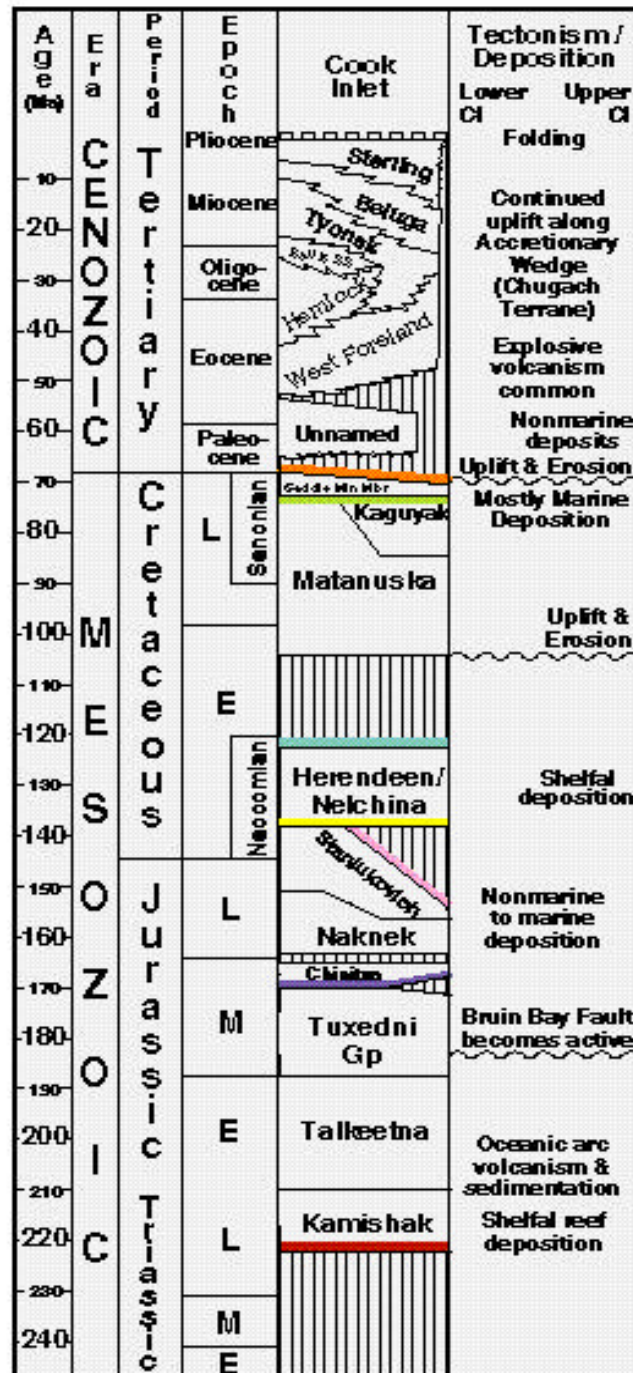


Figure 2. Tectonostratigraphic correlation chart for the Cook Inlet (from Currey et al., 1993).

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.

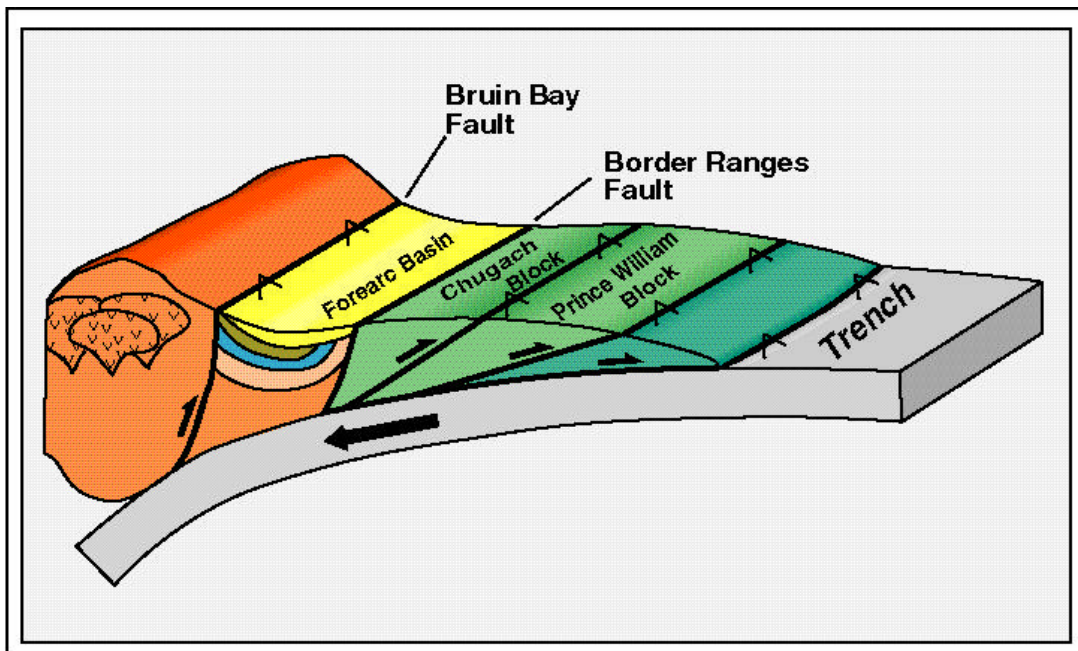


Figure 3: General tectonic configuration of Cook Inlet Basin and associated subduction zone (From Doherty, et al., 1994)

Tertiary Stratigraphy

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 depositional 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 regional unconformity (locally angular) at the base of the Tertiary section separates Mesozoic stratigraphy from overlying Paleocene/ Eocene volcanoclastic 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.

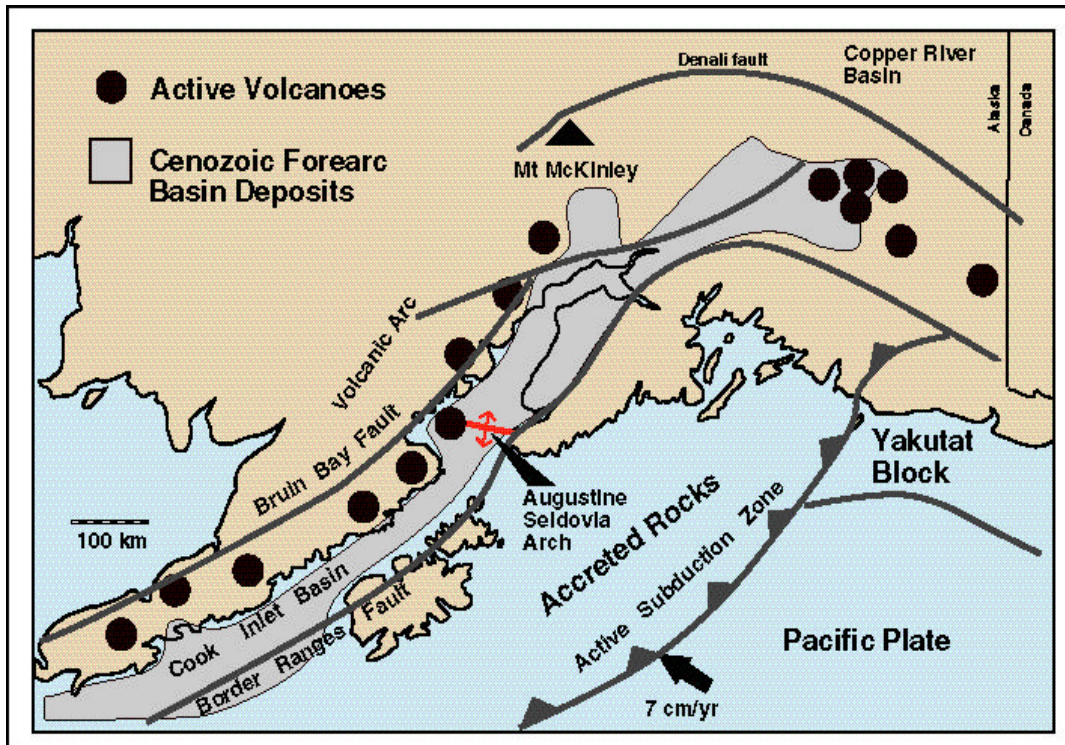


Figure 4: Present day tectonic framework and Cenozoic forearc basin deposits (from Doherty et al., 1994)

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 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.

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 unnamed in the basin-wide stratigraphic section.

The Eocene/Oligocene West Foreland Formation is tuffaceous sand and conglomerate that, with the exception of the localized 'unnamed' Paleocene unit, makes up the basal part of the inlet-wide Tertiary section. The dominant lithic component of the coarse facies is volcanoclastic 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.

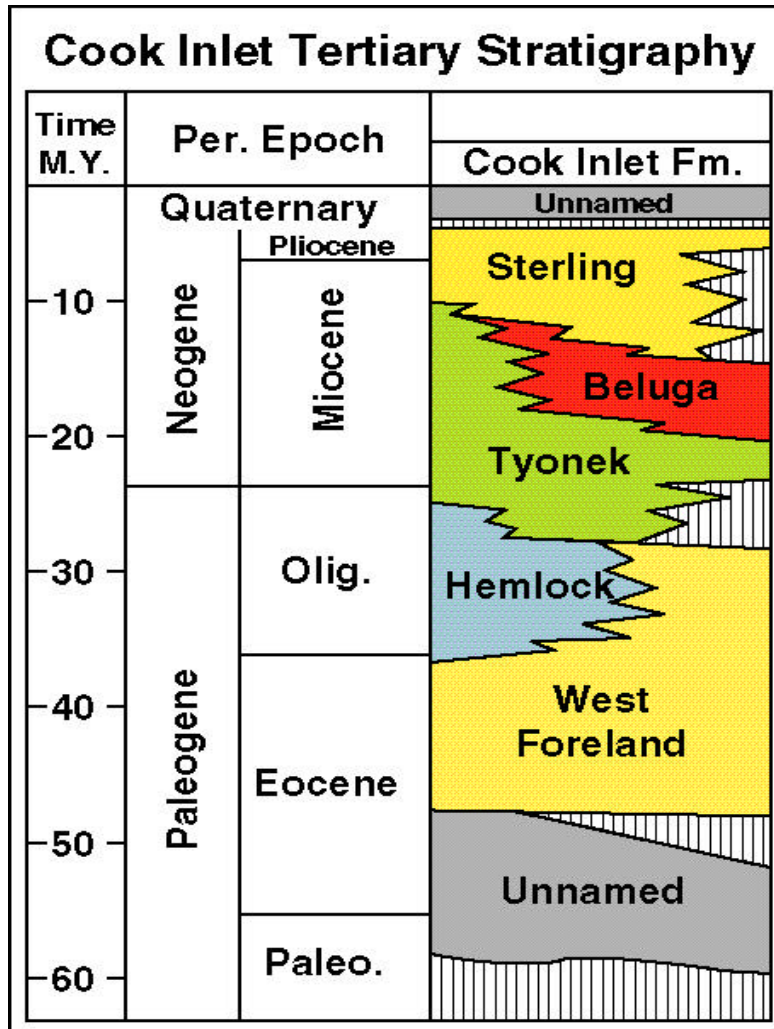


Figure 5: Generalized Cook Inlet Tertiary Stratigraphy

The Hemlock Conglomerate overlies the West Foreland and is an important oil reservoir in the basin. 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 over the volcanoclastic rich West Foreland. 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 beds.

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 volcanoclastics, 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.

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 clastic sediment 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 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 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.

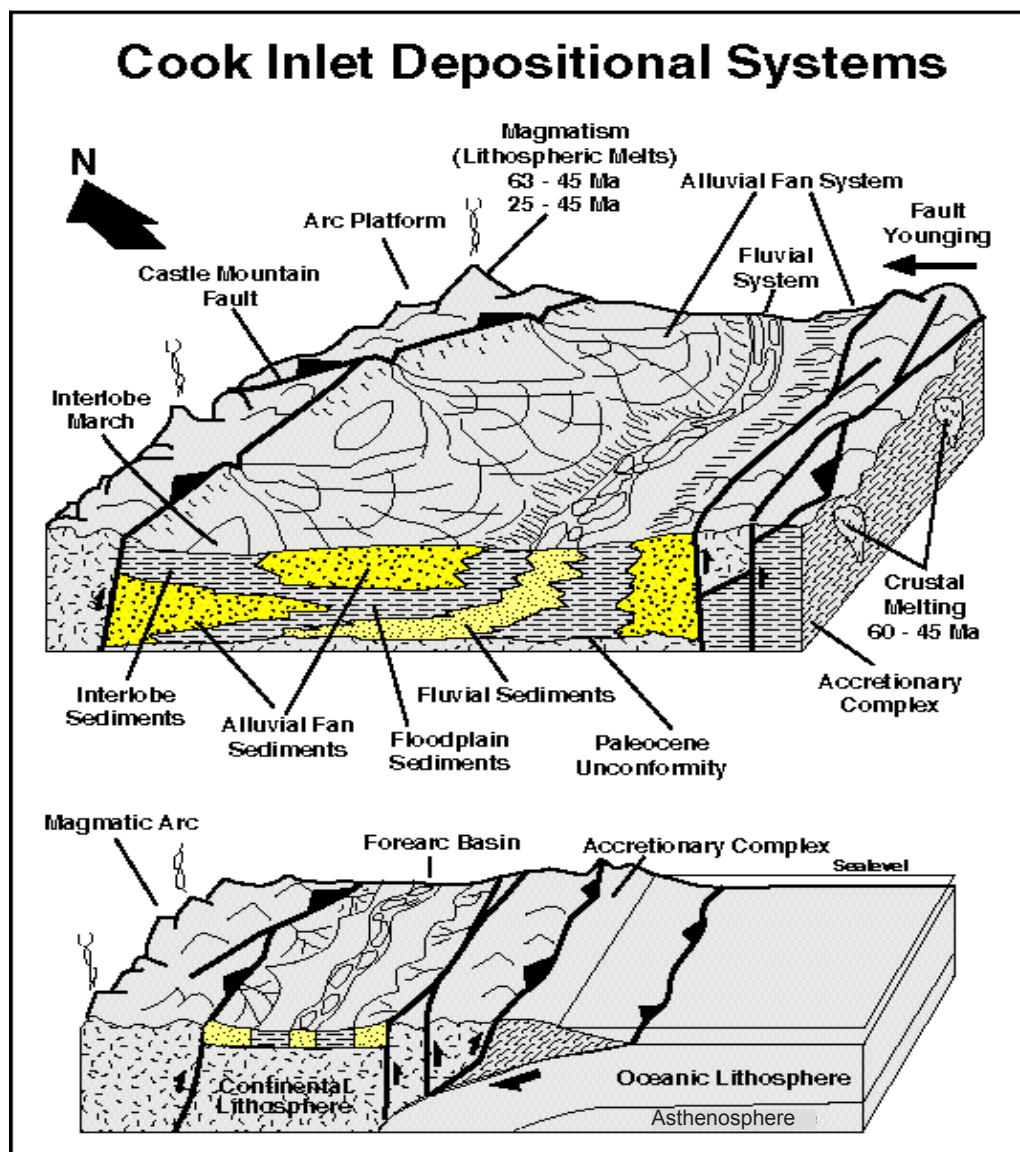


Figure 6. Cook Inlet Depositional systems model (From McGowen, et al., 1994)

Acknowledgments

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, Jef Corrigan, Ken Helmold and many others.

Reference List

- Dall, W. H., and Harris, G. D., 1892, Correlation Papers—Neocene: U.S. Geological Survey Bulletin 84, 349 p.
 Byrne, T., 1979, Late Paleocene demise of the Kula-Pacific spreading center: *Geology*, v. 7, p. 341-344.
 Calerwood, K. W., and Fackler, W. C., 1972, Proposed stratigraphic nomenclature for Kenai Group, Cook Inlet Basin, Alaska: *American Association of Petroleum Geologists Bulletin*, v. 56, no. 4, p. 739-754.

- Parkinson, L.J., 1962, One field, one giant-The story of the Swanson River: *Oil and Gas Journal*, v. 60 (13), p. 180-183.
- Plavis, T. L., 1982, Origin and age of the Border Ranges Fault of southern Alaska and its bearing on the Late Mesozoic tectonic evolution of Alaska: *Tectonics*, v. 1, no. 4, p. 343-368.
- Wang, J., Newton C. R., Dunne, L., 1988, Late Triassic transition from biogenic to arc sedimentation on the Peninsular terrane: Puale Bay, Alaska Peninsula; *Geological Society of America, Bulletin*, v. 100, p.1466-1478.

Internal ARCO Reports:

- Curry, et al., 1993
- Doherty, D. J., 1994
- McGowen, J. H., and Doherty, D. J., 1994

Additional References

- Adkison, W. L., Kelley, J. S., and Newman, K. R., 1975, Lithology and Palynology of the Beluga and Sterling Formations exposed near Homer, Kenai Peninsula, Alaska: U.S. Geological Survey Open-file Report 75-383, 239 p..
- Burk, C.A., 1965, Geology of the Alaska Peninsula-Island arc and continental margin: *Geological Society of America, Memoir* 99, p.19-78.
- Detterman, R. L., and Reed, B. L., 1980, Stratigraphy, structure, and economic geology of the Iliamna quadrangle, Alaska: U.S. Geological Survey Bulletin No. 1368-B, 86 p..
- Fisher, M. A., and Magoon, L. B., 1978, Geologic framework of lower Cook Inlet, Alaska: *American Association of Petroleum Geologists Bulletin*, v. 62, no. 3, p. 373-402.
- Hastings, D. S., Robinson, A. G., and Robinson, N. M., 1983, Stratigraphy, depositional history, and reservoir potential of Cretaceous and Early Tertiary rocks of lower Cook Inlet, Alaska, *American Association of Petroleum Geologists Bulletin*, v. 63, p. 480.
- Hite, D. M., 1976, Some sedimentary aspects of the Kenai Group, Cook Inlet, Alaska: *in* Miller, T. P., ed., Recent and ancient sedimentary environments in Alaska: Alaska Geological Society Symposium Proceedings, p. 11 - 123.
- Jones, D. L., and Silberling, N. J., 1979, The key to tectonic analysis of southern and central Alaska: U.S. Geological Survey Open File Report, 79-1200, p. 1-37.
- Kirschner, C. E., and Lyon, C. A., 1973, Stratigraphic and tectonic development of Cook Inlet petroleum province: *American Association of Petroleum Geologists Memoir* 19, p. 396-407
- Kremer, M. C., and Stadnick, G., 1985, Tertiary stratigraphy of the Kenai Peninsula-Cook Inlet Region: *in* Guide to the Geology of the Kenai Peninsula, Alaska: Alaska Geological Society Field Guide, p. 24-42.
- Magoon, L. B., and Claypool, G. E., 1979, Petroleum geology of Cook Inlet Basin, Alaska--An exploration model: U.S. Geological Survey Open-file Report 79-548, 23 p..
- Moore, J. C., and Connelly, W., 1979, Tectonic History of the continental margin of southwestern Alaska: Late Triassic to earliest Tertiary, *in* The relationship of plate tectonics to Alaskan geology and resources: Alaska Geological Society Symposium Proceedings, H1-H29.

Kenai Field, the Kenai Peninsula's Largest Gas Field

D.L. Brimberry¹, P.S. Gardner¹, M.L. McCullough¹, and S.E. Trudell¹
(REVISED April 2001)

History

In 1959, the Union Kenai Unit 14-6 well identified significant gas reserves in sandstones of the Tertiary Sterling, Beluga and Tyonek formations. The sandstones were deposited by streams that flowed through a broad valley which is mostly occupied by the Cook Inlet today. Kenai field owners (Unocal, Marathon Oil Company, SOCAL and CIRI) have sold natural gas to south-central Alaska for electricity production, heating and manufacturing since 1961. This prolific gas field and other Cook Inlet gas fields offered the opportunity to export natural gas to other markets in 1969. In 1993, Marathon assumed complete ownership and the operations of the field. The remaining reserve volume will continue to supply the utilities and the export markets past the year 2010. The following information identifies some specifics of the oil and gas geology for Kenai field.

Discovery

Well Name and Date: Union Kenai Unit 14-6 (API No. 50-133-10089-00), 1959
Reservoir Discovered: Tertiary Sterling Formation gas.
Total Depth: 15,047 feet measured depth.
Bottom Hole Formation: Tertiary West Foreland Formation.
Objective: Tertiary Hemlock Conglomerate oil.

PRODUCTION DATA (12/00)					
POOL NAME	TOP (SSTVD FT.)	INITIAL WELL NAME	YEAR	INITIAL PROD. (MMCF/D)	CUM. PROD (BCF)
Sterling	-3425	KU 14-6	1959	11	1774
Beluga	-4450	KBU 13-8	1977	10	158
Upper Tyonek	-7100	KDU 5	1978	5.2	7
Deep Tyonek	-8200	KDU 1	1967	11.5	31
TOTAL					2170

Reservoir Data

Total completions: 69 (Commingled flow, typically dual tubing strings).
Spacing: 160 to 1200 acres.
Drive: Gas expansion.
Structure: Simple anticline.
Gas Analysis: 99% Methane, 0.5% Nitrogen, 0.2% CO₂, 1008 BTU, 0.56 specific gravity

¹ Marathon Oil Co., P.O. Box 196168, Anchorage, AK 99519-6168

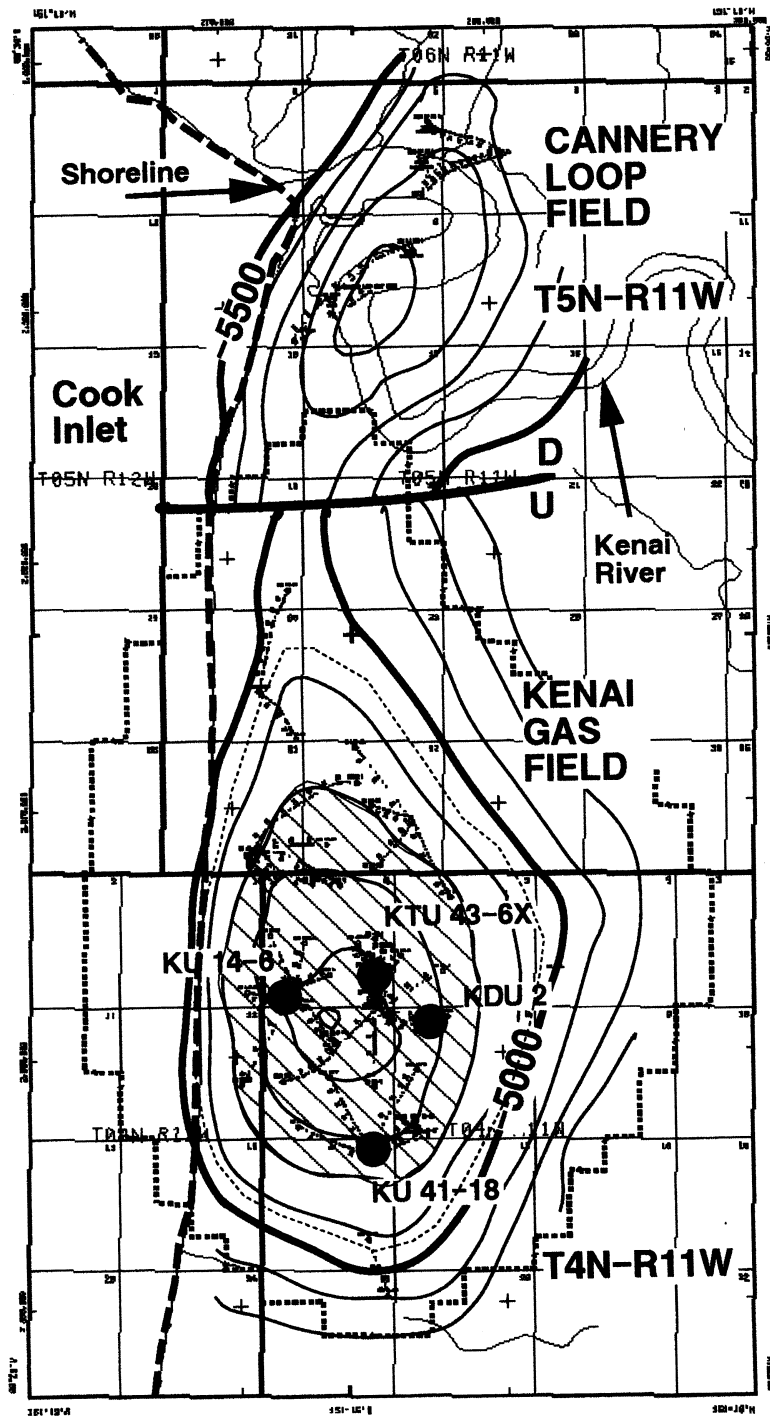


Figure 1. Structure map on the top of the Beluga Formation at Kenai field. Contour interval 100 feet. Sterling Formation accumulation area limit identified by dashed line. Approximate accumulation area for Beluga and Tyonek reservoirs identified by crosshatched area.

Structural Geology

The Kenai field structure (fig. 1) is a large simple anticline that stretches over 10 miles north-south (including the Cannery Loop field fault block) and 4 miles east-west. The only fault of significance to the structure is the large normal fault on the north end of the structure which segregates the Kenai field accumulation from the Cannery Loop field accumulation. Additional faulting is not recognizable with the well control but small NE-SW normal faults are seen on the seismic sections. Late Tertiary, local compression interrupted Sterling Formation deposition and created the structural feature for gas to migrate into.

Reservoir Description

The reservoirs for the Kenai field accumulation are sandstones in the Tertiary Kenai Group; Sterling, Beluga and Tyonek formations. Within the field the Tyonek is subdivided into two informal intervals referred to as the “upper Tyonek” and the “deep Tyonek”.

Sterling Formation (Plio-Pleistocene)

The gas reservoirs of the Sterling Formation (fig. 2) were deposited in large meandering streams which originated to the north/northwest. Productive sandstone sequences are typically 30-60 feet thick, some are more than 100 feet thick. The reservoirs are fine to coarse grained, moderately well sorted and angular to sub-rounded. Limited matrix material is evident in the sandstones. Composition of the sandstones varies from primarily quartz-rich feldspathic litharenites to sub-litharenites. Effective porosity ranges from 25 to 31 percent. Permeability of more than one darcy is common. The sandstones are semi-consolidated with slight cementation from calcite, authigenic smectite and kaolinite. Coals and silty shales separate the sandstones. These characteristics describe the most prolific reservoir at Kenai field. Sterling production extends along the northern nose of the Kenai field structure to cover the largest productive area of the productive intervals.

Beluga Formation (Late Miocene)

The approximately 2,600 feet of Beluga Formation section (fig. 3) represents a marked compositional difference from the underlying Tyonek Formation and the overlying Sterling Formation. The Beluga lithology is dominated with metasedimentary lithic fragments derived from the Chugach terrane to the east. The depositional sequence of the Beluga Formation at Kenai field grades from thin sandstones deposited on an outwash plain in the lower Beluga Formation to anastomosing streams in the upper Beluga Formation. Average bed thicknesses are 10-20 feet in the lower and middle Beluga Formation. Thicker, higher quality sandstones are in generally 20 foot sandstones beds in the upper Beluga Formation. The upper Beluga sandstones have effective porosity above 15 percent and permeability from five to more than 50 millidarcies. Middle and lower Beluga sandstones occasionally have these reservoir parameters; but, typically have 9-12% porosity and 0.1-10 millidarcies permeability. More than 85 percent of the gas reserves for the Beluga have flowed from the upper Beluga sandstones. The rock fabric is very fine to coarse grained, moderately sorted, sub-angular and moderately to well consolidated. Illite and smectite clays are present within the reservoir beds and serve with calcite as the cementing agents. Between the sandstone bodies, the Beluga section is dominated by silty shale with numerous thin, 1-2 foot thick coals. Beluga production does not

extend onto the northern nose of the Kenai structure, but is present on the small closure of Cannery Loop field to the north.

“Upper Tyonek” (Miocene)

The “upper Tyonek” sandstones (fig. 4) are the least productive units in Kenai field due to their thin nature and low reservoir quality. The sandstones were deposited by small tributaries of meandering and anastomosing streams which carried sand from the north-northwest. Overbank deposits are common and coals are considerably thicker in the Tyonek Formation (typically more than 10 feet thick) than in the overlying Beluga or Sterling Formations. The individual sandstones are very fine- to medium-grained. Fining upward to silt sequences or interlamination with silt is common in the sandstones. The cleaner, reservoir quality portions of the sandy intervals range from 20 - 40 feet thick. Sand composition varies laterally and vertically from poorly sorted feldspathic litharenites to moderately well sorted sub-litharenites. Grain angularity varies from angular to sub-rounded. Smectite clay dominates the matrix clay in the sandstone and serves as the consolidation agent. Effective porosity is 12 to 15 percent. Permeability ranges from 0.1 to 10 millidarcies. Fines migration and complexities associated with variability in the “upper Tyonek” reservoir sandstones are the primary deterrents to high flow rates and extensive reserves. Production from the “upper Tyonek” has also come only from the crestal portion of the field.

“Deep Tyonek” (Miocene)

The sandstone reservoirs of the “deep Tyonek” (fig. 5) are similar in composition to the “upper Tyonek”, quartz-rich feldspathic litharenites and sub-litharenites. The primary difference is that these deeper reservoirs represent larger meandering stream sands. Conglomeratic intervals are common in the thicker sandstones of the “deep Tyonek”. Grain size varies widely in the sandstone bodies from conglomerate to medium grained. Reservoir thicknesses exceed 40 feet in the blocky sandstone intervals. Effective porosity of around 12 percent and permeability of more than 50 millidarcies combined to yield initial gas flow rates in excess of 20 mmcfpd (million cubic feet per day) in the early “deep Tyonek” wells of the Kenai field. The sandstones are well consolidated with compaction, clay and calcite cement. Coal beds are thicker in the “deep Tyonek” than any unit above and are often located at the base of the reservoir bodies. “Deep Tyonek” production is limited to the crestal portion of the field and the small closure on the Cannery Loop feature to the north.

Hydrocarbons

The high methane content of the gas in the field and isotope markers indicate the gas reserves were generated by biogenic activity in the sediment. Abundant carbonaceous material in the form of coal and debris incorporated into the sediment is available for microbial consumption and methane generation. A very minor amount of condensate, approximately 1000 barrels per year, is produced with the gas from the “deep Tyonek” reservoirs. This may be related to the thermal cracking of the coals, but is not significant.

The oil seen in numerous other Cook Inlet fields is noticeably absent from the large Kenai structure. The two deep wells, Kenai Unit 14-6 and Kenai Unit 41-18, have minimal sample shows. The drill stem tests of the initial objective in the field, the Tertiary Hemlock Conglomerate, recovered connate water.

KTU43-6X

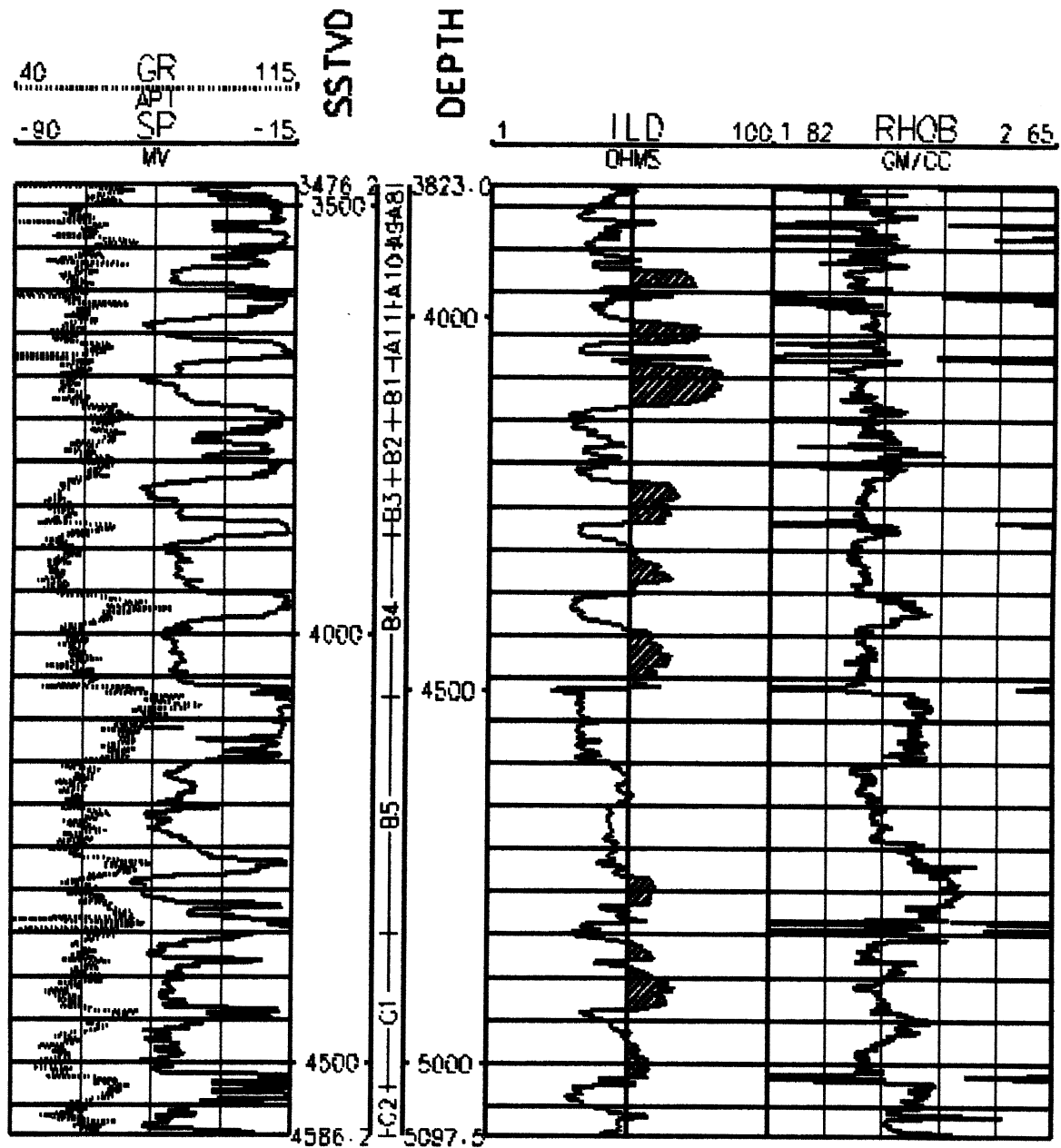


Figure 2. Log section for Sterling Formation in the Kenai Tyonek Unit 43-06X (API No. 50-133-20328-00) at Kenai field. Gas bearing zones identified by cross hatch on the resistivity log (logarithmic scale: 1 to 100 ohms). Gamma ray scale: 40 to 115 API. SP scale: -90 to -15 mv. Density (RHOB) scale: 50 to 0 percent.

KTU43-6X

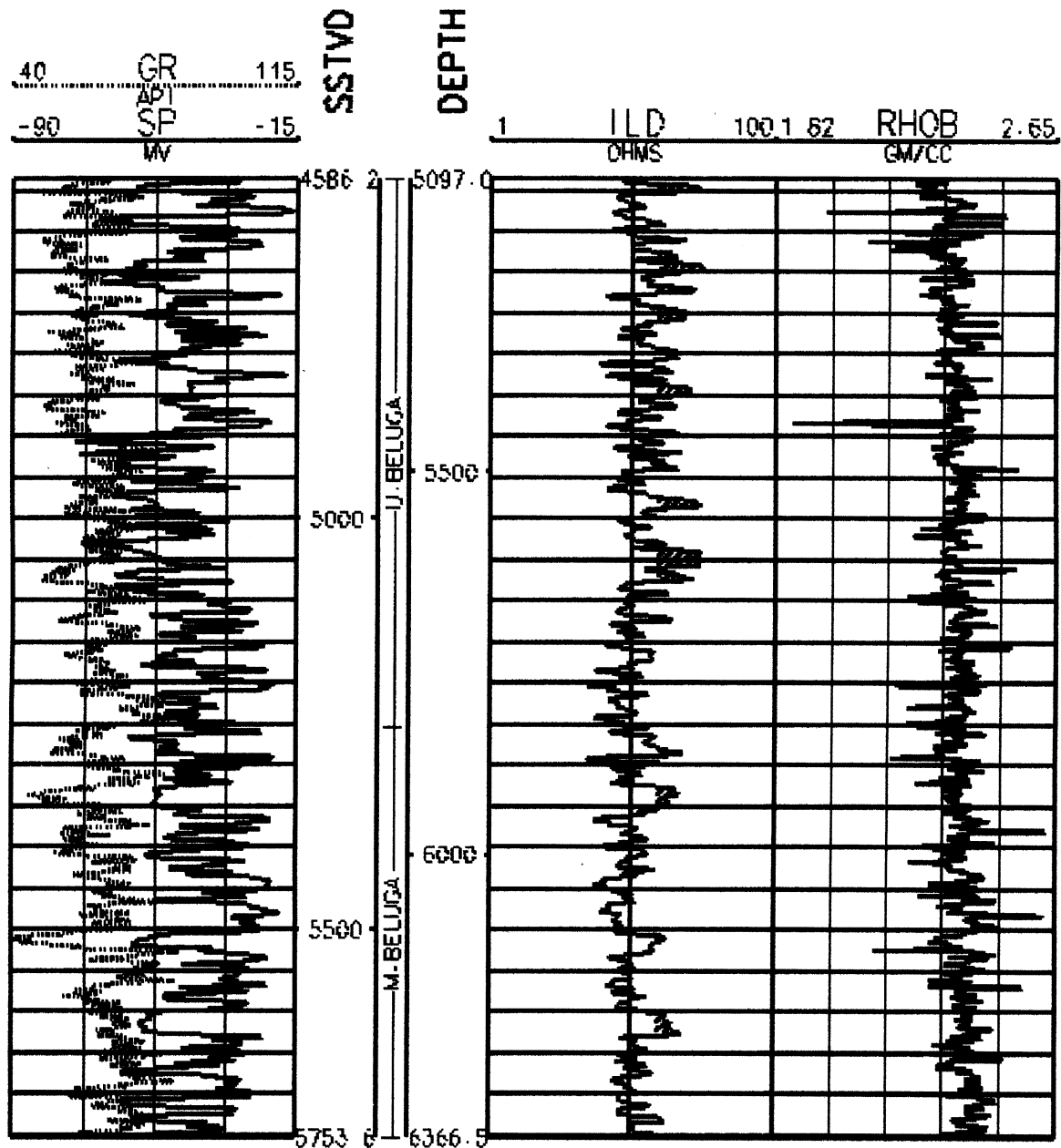


Figure 3. Partial log section for upper and middle Beluga Formation in the Kenai Tyonek Unit 43-06X (API No. 50-133-20328-00) at Kenai field. Gas bearing zones identified by cross hatch on the resistivity log (logarithmic scale: 1 to 100 ohms). Gamma ray scale: 40 to 115 API. SP scale: -90 to -15 mv. Density (RHOB) scale: 50 to 0 percent.

KDU-2

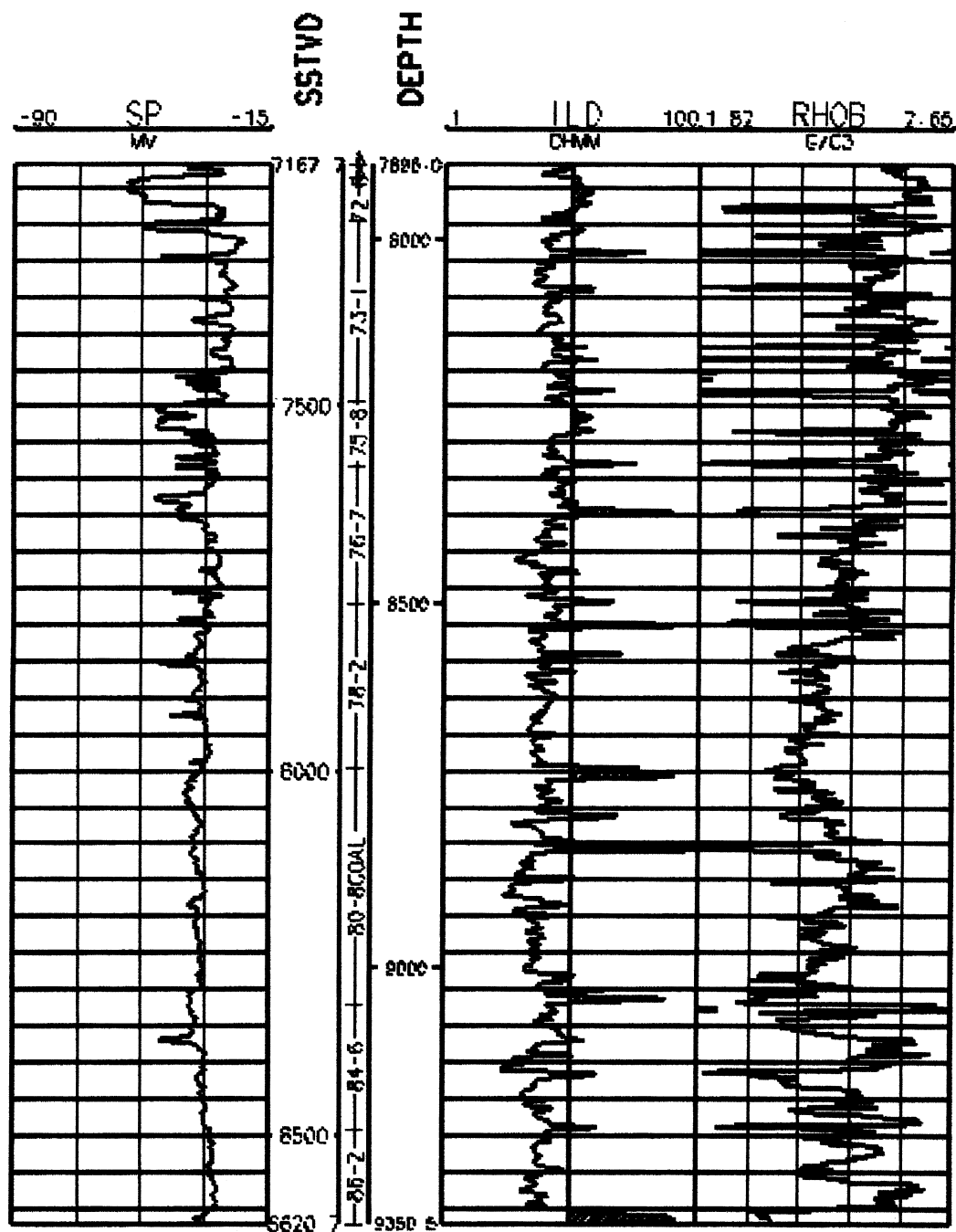


Figure 4. Log section for the “upper Tyonek” in the Kenai Deep Unit 2 (API No. 50-133-20121-00) at Kenai field. Gas bearing zones for the field are identified by sandy (SP response) intervals cross hatched on the resistivity log (logarithmic scale: 1 to 100 ohms). Gamma ray scale: 40 to 115 API. SP scale: -90 to -15 mv. Density (RHOB) scale: 50 to 0 percent.

KDU-2

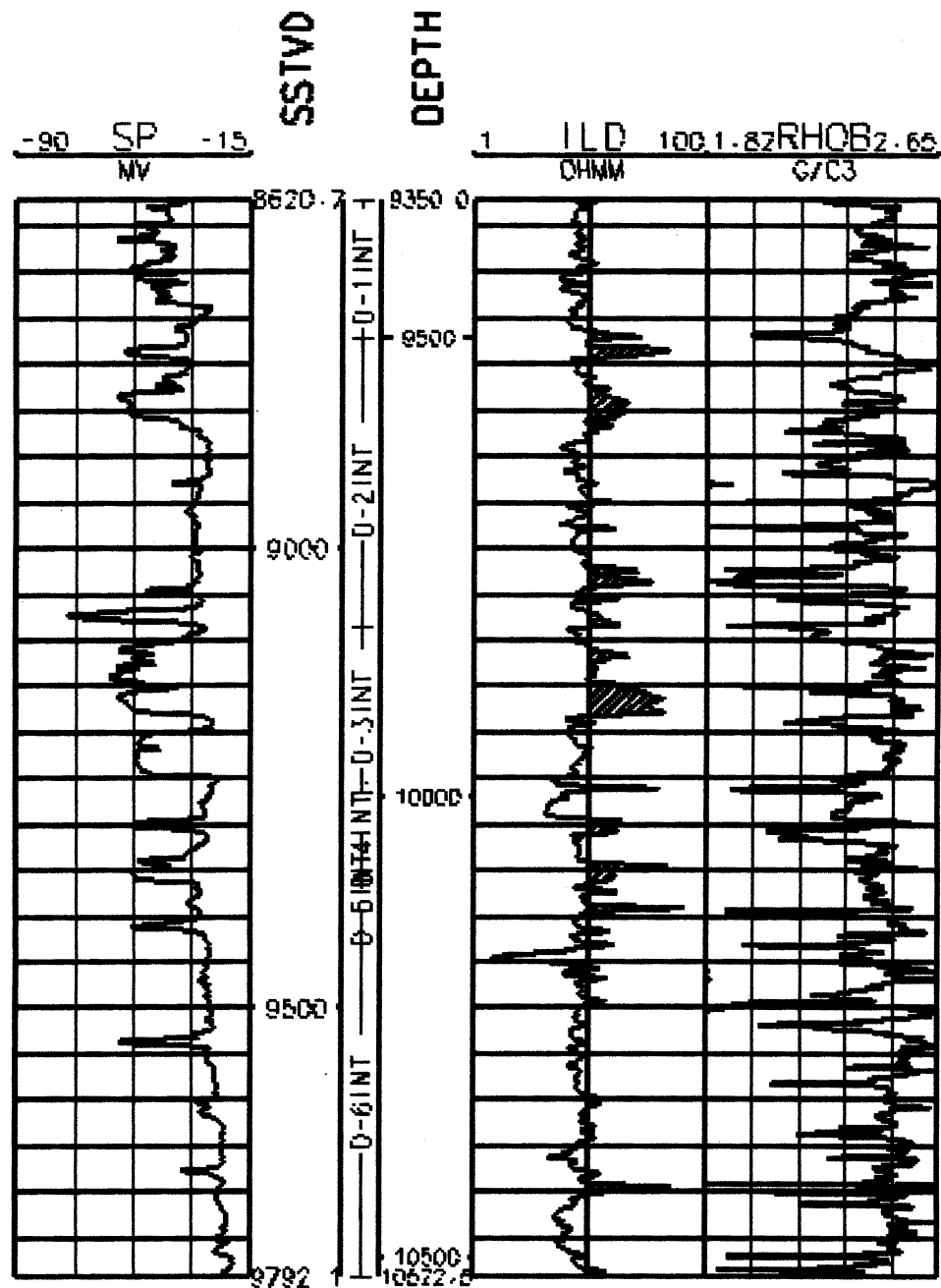


Figure 5. Log section for "deep Tyonek" in the Kenai Deep Unit 2 (API No. 50-133-20121-00) at Kenai field. Gas bearing zones for the field are identified by sandy (SP response) intervals cross hatched on the resistivity log (logarithmic scale: 1 to 100 ohms). Gamma ray scale: 40 to 115 API. SP scale: -90 to -15 mv. Density (RHOB) scale: 50 to 0 percent.

Summary

The prolific gas production from Kenai field has proven significant to the regional economy of the Kenai Peninsula. The production from the extremely high quality reservoirs in the Sterling Formation has been supported with additional production from the deeper Beluga and Tyonek formations. The simple anticlinal structure allows for very good recoveries from each well and efficient reservoir management. The field's production will continue to be a significant and reliable contributor to the resource base of the area.

High-resolution Chronostratigraphic Analyses of the Tertiary Kenai Group, South-central Alaska: Applications to Basin Analysis and Coal-bed Methane Assessment: An Update

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Introduction

This article first appeared in last year's Second Alaska Workshop on Coalbed Methane (Barker et al., 2000). The article is modified and includes an update section covering the current status of Dallegge's Ph.D. research. Some early material has cleared proprietary restrictions and is reported in Barker et al. this volume.

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 Tanai, 1972). Tertiary plant-bearing strata from Alaska, Pacific northwest and eastern Russia are correlated on the basis of these stages (Wolfe and Tanai, 1972; 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 coal-bed 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 coal-bed 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; Triplehorn 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 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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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 Stadnick, 1985; Reinink-Smith, 1987, 1989, 1990, 1995). Reinink-Smith (1987) has reported over 98 ash beds in coals from the Kenai 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 coal-bed 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.”

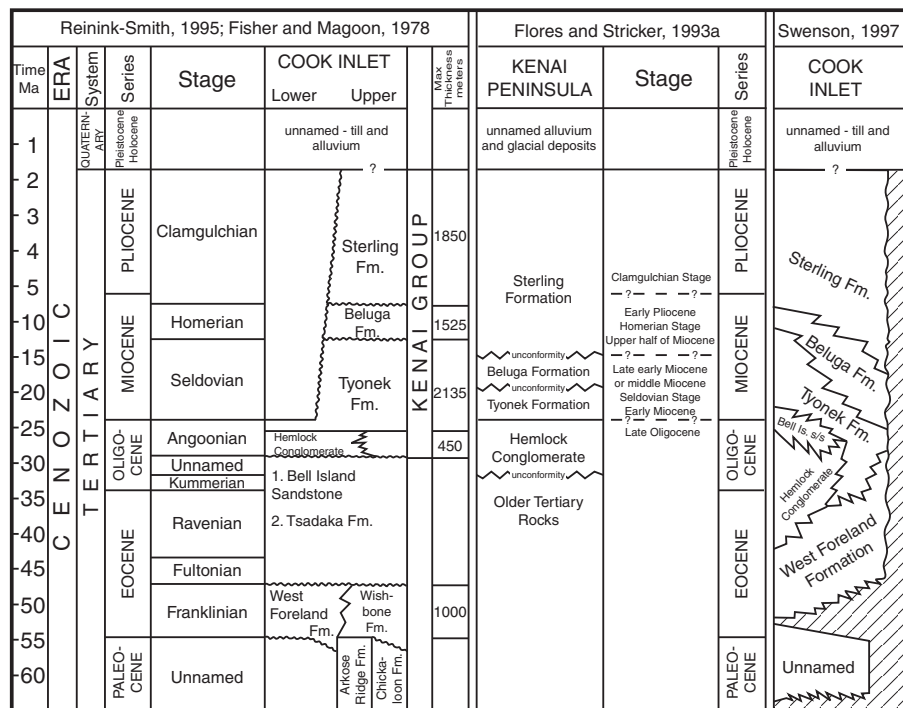


Figure 1. Time stratigraphic chart of Cenozoic units in Cook Inlet Basin showing three stratigraphic models. Note - Tertiary Series boundaries have been adjusted to 1999 Geological Society of America Time Scale; time chart is not to scale for the interval 0-5 Ma.

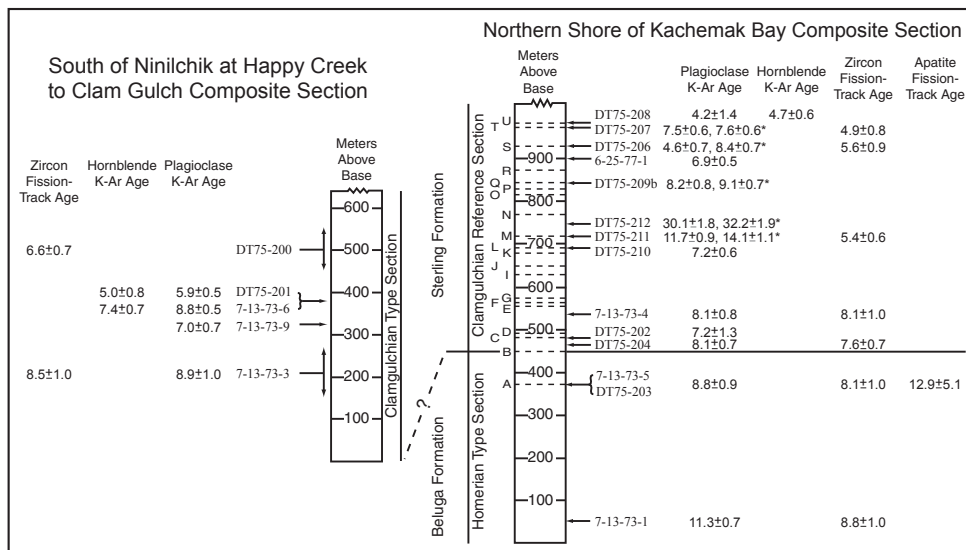


Figure 2. Comparison of all available absolute dates for the Beluga and Sterling Formations, Kenai Peninsula. Letters on Kachemak Bay section correspond to designated coal bed names of Barnes and Cobb (1959). Dates with asterisk (*) were attributed to apparent detrital contamination and not used in final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

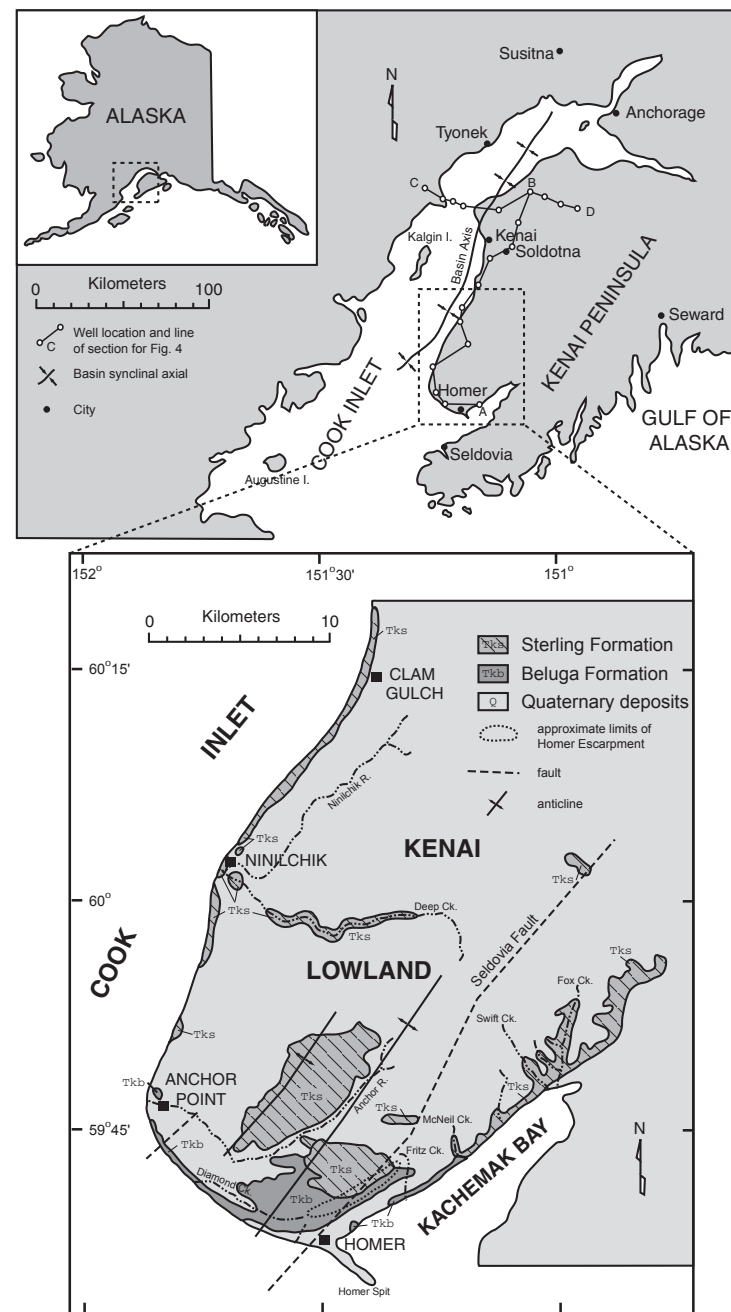


Figure 3. Regional and geologic maps of Cook Inlet area, south-central Alaska. Adapted and modified from Lueck et al., (1987); Reinink-Smith, (1990); Flores et al., (1997).

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 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 paleontological 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 stratigraphic 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)

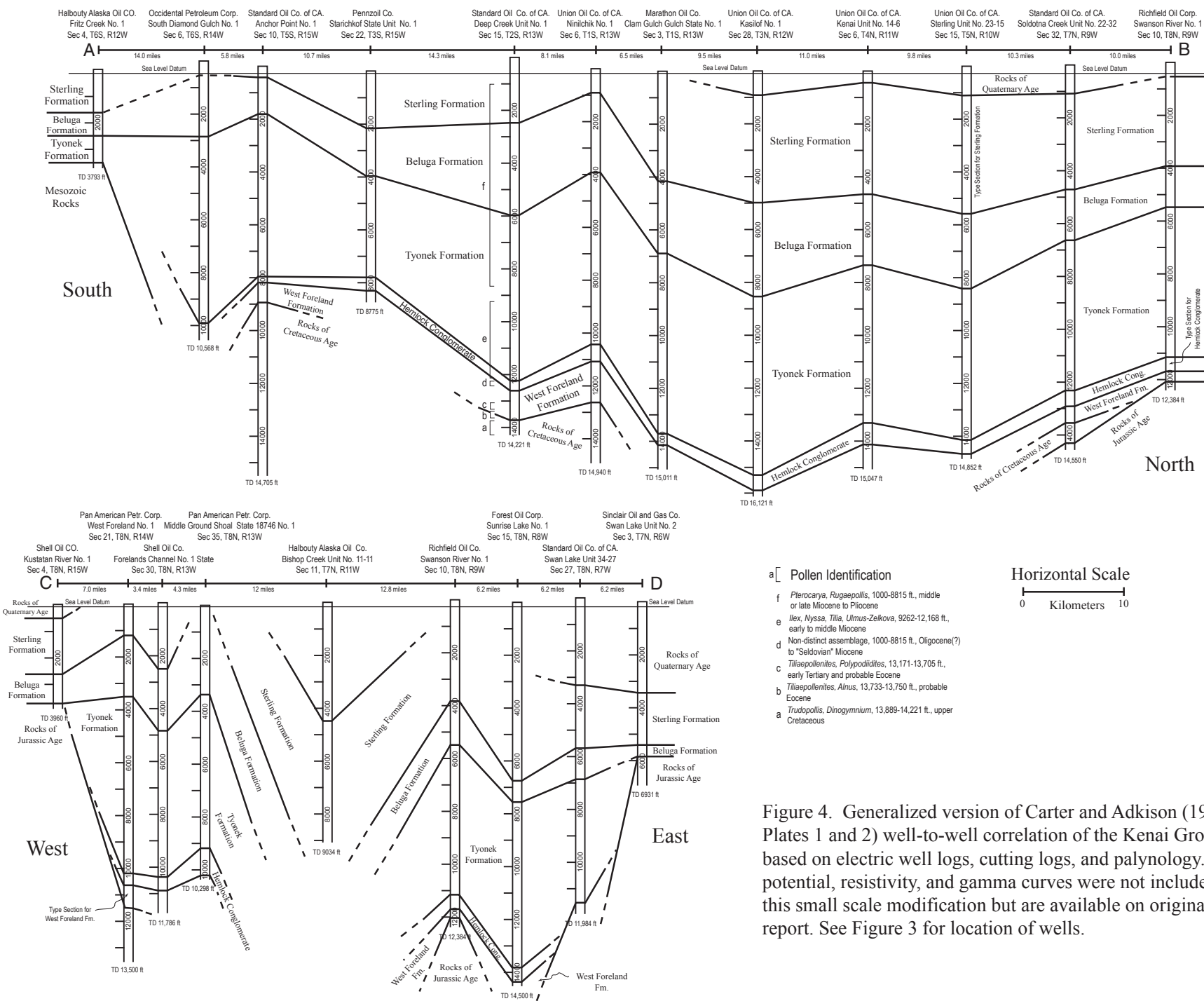


Figure 4. Generalized version of Carter and Adkison (1972, Plates 1 and 2) well-to-well correlation of the Kenai Group based on electric well logs, cutting logs, and palynology. Self-potential, resistivity, and gamma curves were not included on this small scale modification but are available on original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

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 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 identified by heavy mineral assemblages generally do not coincide with boundaries established by log correlations and palynological analyses (Hite, 1976).

Attempts to correlate coal beds locally and across the Kenai Peninsula (Barnes and Cobb, 1959; Adkison et al., 1975; Hite, 1976; Reinink-Smith, 1989, 1995) have shown that most coal beds 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 (Triplehorn, pers. comm, 1999). Thus, different aged coals can be placed in apparent stratigraphic continuity, and lateral correlation of coal beds 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 [SEM]) 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 difficult 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 Quaternary 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 (Hartman 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 ARCO 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 coal beds 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 coal beds. 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 coal beds have been reported from this section (Triplehorn et al., 1977; Turner et al., 1980; Reinink-Smith, 1987, 1990). By using precise $^{40}\text{Ar}/^{39}\text{Ar}$ 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 cores and cuttings housed at the Alaska Geological Materials Center in Eagle River, AK, the USGS Core Library in Denver, CO, and from the core libraries of several contributing oil companies (names withheld at this time due to proprietary agreements). 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.

$^{40}\text{Ar}/^{39}\text{Ar}$ 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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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 coal beds 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 coal-bed 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 coal-bed methane resource assessment.

Research update

Over the past year gas desorption analyses of coal cuttings, outcrop and core sampling, and $^{40}\text{Ar}/^{39}\text{Ar}$ sample preparation has begun. Coal cuttings were collected from several active exploration and production wells within the northern Cook Inlet basin and desorption and coal quality analyses are underway. Most of this data is still under proprietary agreement and can not be discussed at this time. Several weeks were spent sampling outcrop and core holdings for $^{40}\text{Ar}/^{39}\text{Ar}$ dateable material and vitrinite reflectance work. Several samples have been irradiated and are waiting their turn in the analytical line. Funding continues to be a limiting factor for the

project and much of last year was spent grant writing with limited success. This summer will see a return to field collection and continued radiometric dating preparation and analyses.

References Cited

- Adkison, W. L., Kelley, J. S., and Newman, K. R., 1975, Lithology and palynology of the Beluga and Sterling Formations exposed near Homer, Kenai Peninsula: U.S. Geological Survey Open-File Report 75-383, 239 p.
- Adkison, W. L., and Newman, K. R., 1973, Lithologic characteristics and palynology of Upper Cretaceous and Tertiary rocks in the Deep Creek Unit well, Kenai Peninsula, Alaska: U.S. Geological Survey Open-File report, 271 p.
- Barker, C. E., Dallegge, T.A. and Clough, J.C., 2000, Coalbed Methane Prospects of the Upper Cook Inlet: Field Trip Guidebook, Second Alaska Workshop on Coalbed Methane, Anchorage, AK, March 2,2000, Published as Alaska Division of Geological and Geophysical Surveys Miscellaneous Publications no. 41, 115 p.
- Barnes, F. F., and Cobb, E. H., 1959, Geology and coal resources of the Homer district, Kenai coal field, Alaska: U.S. Geological Survey Bulletin 1058-F, p. 217-260.
- Beikman, H. M., compiler, 1974, Preliminary geologic map of the southeast quadrant of Alaska: U.S. Geological Survey Map MF612.
- Berggren, W. A., Kent, D. V., Aubry, M. P., Hardenbol, J., eds., 1995, Geochronology, time Scales and global stratigraphic correlation: Society for Sedimentary Geology Special Paper No. 54, 386 p.
- Calderwood, K. W., and Fackler, W. C., 1972, Proposed stratigraphic nomenclature for the Kenai Group, Cook Inlet basin, Alaska: American Association of Petroleum Geologists Bulletin, v. 56, p. 739-754.
- Carter, R. D., and Adkison, W. L., 1972, Correlation of subsurface Tertiary rocks, Cook Inlet basin Alaska: U.S. Geological Survey Open-File Report 72-64, 8 p.
- Crick, R. W., 1971, Potential petroleum reserves, Cook Inlet, Alaska, *in* Cram, I. H., ed., Future petroleum provinces of the United States – their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 1, p. 109-119.
- Dall, W. H., and Harris, G. D., 1892, Correlation papers – Neogene: U.S. Geological Survey Bulletin 84, p. 234-238.
- Dallegge, T. A., 1999, Correlation and chronology of the Miocene-Pliocene Bidahochi Formation, Navajo and Hopi Nations, northeastern Arizona: Masters Thesis, Northern Arizona University, Flagstaff, Arizona, 304 p.
- Deino, A., Tauxe, L., Monaghan, M., Drake, R., 1990, $^{40}\text{Ar}/^{39}\text{Ar}$ age calibrations of the litho- and paleomagnetic stratigraphies of the Ngorora Formation, Kenya: *Journal of Geology*, V. 98, p. 567-587.
- Dorr, J. A., 1964, Tertiary non-marine vertebrates in Alaska – the lack thereof: American Association of Petroleum Geologists Bulletin, v. 48, p. 1198-1203.
- Fisher, M. A., and Magoon, L. B., 1978, Geologic framework of lower Cook inlet, Alaska: American Association of Petroleum Geologists Bulletin, v. 62, no. 3, p. 373-402.
- Flores, R. M., Myers, M. D., Stricker, G. D., and Houle, J. A., 1997, Core lithofacies analysis and fluvio-tidal environments in the AK 94 CBM-1 well, near Wasilla, Alaska, *in* Geological Studies in Alaska by the U.S. Geological Survey, 1997: U.S. Geological Survey Professional Paper 1614, p. 57-72.
- Flores, R. M., and Stricker, G. D., 1992, Some facies aspects of the upper part of the Kenai Group, southern Kenai Peninsula, Alaska, *in* Gradley, D. C., and Dusel-Bacon, C., eds., *Geologic studies in Alaska by the U.S. Geological Survey, 1991: U.S. Geological Survey Bulletin, 2041*, p. 160-170.
- Flores, R. M., and Stricker, G. D., 1993a, Interfluvial-channel facies models in the Miocene Beluga Formation near Homer, south Kenai Peninsula, Alaska, *in* Roa, P. D., and Walsh, D. E., eds., *Focus on Alaska's coal 1993: Mineral Industry Research Laboratory, University of Alaska, Fairbanks*, p. 140-166.
- Flores, R. M., and Stricker, G. D., 1993b, Reservoir framework architecture in the Clamgulchian (Pliocene) Sterling Formation, Kenai Peninsula, Alaska, *in* Dusel-Bacon, C., and Till, A. B., eds., *Geologic studies in Alaska by the U.S. Geological Survey, 1992: U.S. Geological Survey Bulletin 2068*, p. 118-129.
- Flores, R. M., Stricker, G. D., and Bader, L. R., 1997, Stratigraphic architecture of the Tertiary alluvial Beluga and Sterling Formations, Kenai Peninsula, Alaska, *in* Karl, S. M., Vaughn, N. R., and Ryherd, T. J., eds., 1997 guide to the geology of the Kenai Peninsula, Alaska: Anchorage, Geological Society of Alaska, p. 36-53.

- Fot'yanova, L. I., 1985, The Seldovian regional stage in Alaska and its analogs in the Soviet far east: *International Geology Review*, v. 27, no. 6, p. 669-677.
- Hartman, D. C., Pessel, G. H., and McGee, D. L., 1972, Preliminary report on stratigraphy of Kenai Group of upper Cook Inlet, Alaska: Alaska Division of Mines and Geology Special Report, v. 5, p. 1-4.
- Hayes, J. B., Harms, J. C., and Wilson, T. W., 1976, Contrasts between braided and meandering stream deposits, Beluga and Sterling Formations (Tertiary), Cook Inlet, Alaska, *in* Miller, T. P., ed., Recent and ancient sedimentary environments in Alaska: Alaska Geological Society Symposium, Proceedings, p. J1-J27.
- Hite, D. M., 1976, Some sedimentary aspects of the Kenai Group, Cook Inlet, Alaska, *in* Miller, T. P., ed., Recent and ancient sedimentary environments in Alaska: Alaska Geological Society Symposium, Proceedings, p. I1-I22.
- Hite, D. M., 1985, Some sedimentary aspects of the Kenai Group, Cook Inlet, Alaska, *in* Sisson, Alexandra, ed., Guide to the geology of the Kenai Peninsula: Anchorage, Alaska Geological Society, p. 3-19.
- Kelly, T. E., 1963, Geology and hydrocarbons in Cook Inlet Basin, Alaska, *in* Backbone of the Americas: American Association of Petroleum Geologist Memoir 2, p. 278-296.
- Kelly, T. E., 1985, Geological setting of the Kenai Peninsula and Cook Inlet Tertiary basin, south-central Alaska, *in* Sisson, Alexandra, ed., Guide to the geology of the Kenai Peninsula: Anchorage, Alaska Geological Society, p. 3-19.
- Kirschner, C. E., and Lyon, C. A., 1973, Stratigraphic and tectonic development of the Cook Inlet petroleum province, *in* Pitcher, M. G., ed., Arctic geology: American Association of Petroleum Geologist Memoir 19, p. 396-407.
- Kremer, M. C., and Stadnick, George, 1985, Tertiary stratigraphy of the Kenai Peninsula-Cook Inlet region, *in* Sisson, Alexandra, ed., Guide to the geology of the Kenai Peninsula: Anchorage, Alaska Geological Society, p. 24-42.
- Larson, E. E., and Evanoff, E., 1998, Tephrostratigraphy and source of the tuffs of the White River sequence, *in* Terry, D. T. LaGarry, H. E., Hunt, R. M., Jr., eds., Depositional environments, lithostratigraphy, and biostratigraphy of the White River and Arikaree Groups (late Eocene to early Miocene, North America): Geological Society of America Special Paper 325, p. 1-14.
- Leuck, L., Rawlinson, S. E., Belowich, M. A., Clough, J. G., and Goff, K. M., 1987, Kenai Coal assessment and mapping project, *in* Rao, P. D., ed., Focus on Alaska's Coal '86, proceedings of the conference held at Anchorage Alaska, October 27-30, 1986: Mineral Industry Research Laboratory, University of Alaska Fairbanks, p. 198-210.
- Magoon, L. B., and Anders, D. E., 1992, Oil-to-source-rock correlation using carbon-isotopic data and biological marker compounds, Cook Inlet-Alaska Peninsula, Alaska, *in* Moldowan, J. M., Albrecht, P., and Philp, R. P., eds., Biological Markers in Sediments and Petroleum; a Tribute to Wolfgang K. Seifert: Prentice Hall, New Jersey, p. 241-274.
- McClellan, P. H., and Giovannetti, D. M., 1981, New invertebrate fossils, but still no land vertebrates, from nonmarine Tertiary rocks of the Kenai Peninsula, Alaska, *in* Albert, N. R., and Hudson, T., eds., The United States Geological Survey in Alaska; accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. 84-86.
- Parkinson, L. J., 1962, One field, one giant – The story of Swanson River: *Oil and Gas Journal*, v. 60, no. 13, p. 180-183.
- Rawlinson, S. E., 1979, Paleoenvironment of deposition, paleocurrent directions, and the provenance of Tertiary deposits along Kachemak Bay, Kenai Peninsula, Alaska [M.S. thesis]: Fairbanks Alaska, University of Alaska-Fairbanks, 162 p.
- Rawlinson, S. E., 1984, Environments of deposition, paleocurrents, and provenance of Tertiary deposits along Kachemak Bay, Kenai Peninsula, Alaska: *Sedimentary Geology*, v. 38, p. 421-442.
- Reinink-Smith, L. M., 1987, The origin, mineralogy and geochemistry of inorganic partings in coal seams near Homer, Alaska, *in* Rao, P. D., ed., Focus on Alaska's Coal '86, proceedings of the conference held at Anchorage Alaska, October 27-30, 1986: Mineral Industry Research Laboratory, University of Alaska Fairbanks, p. 211-228.
- Reinink-Smith, L. M., 1989, Origin, character, application and correlation of tephra partings in Tertiary coal beds of the Kenai Peninsula, Alaska: Ph.D. Thesis, University of Alaska Fairbanks, Fairbanks, Alaska 131 p.

- Reinink-Smith, L. M., 1990, Relative frequency of Neogene volcanic events as recorded in coal partings from the Kenai lowland, Alaska: A comparison with deep-sea core data: *Geological Society of America Bulletin*, v. 102, p. 830-840.
- Reinink-Smith, L. M., 1995, Tephra layers as correlation tools of Neogene coal-bearing strata from the Kenai lowland, Alaska: *Geological Society of America Bulletin*, v. 107, no. 3, p. 340-353.
- Swenson, R. F., 1997, Introduction to Tertiary tectonics and sedimentation in the Cook Inlet Basin, *in* Karl, S. M., Vaughn, N. R., and Ryherd, T. J., eds., 1997 guide to the geology of the Kenai Peninsula, Alaska: Anchorage, Geological Society of Alaska, p. 18-27.
- Triplehorn, D. M., Turner, D. L., and Naeser, C. W., 1977, K-Ar and fission-track dating of ash partings in coal beds from the Kenai Peninsula, Alaska: A revised age for the Homeric Stage - Clamgulchian Stage boundary: *Geological Society of America Bulletin*, v. 88, p. 1156-1160.
- Turner, D. L., Triplehorn, D. M., Naeser, C. W., and Wolfe, J. A., 1980, Radiometric dating of ash partings in Alaskan coal beds and upper Tertiary paleobotanical stages: *Geology*, v. 8, p. 92-96.
- Wiggins, V. D., and Hill, J. M., 1987, Stratigraphy of Kenai Group, Cook Inlet, Alaska, and application of ecological shift plot: *American Association of Petroleum Geologists Bulletin*, v. 71, no. 5, p. 627.
- Wolfe, J. A., 1994, An analysis of Neogene climates in Beringia: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 108, p. 207-216.
- Wolfe, J. A., Hopkins, D. M., and Leopold, E. R., 1966, Tertiary stratigraphy and paleobotany of the Cook Inlet region, Alaska: *U.S. Geological Survey Professional Paper 398-A*, p. A1-A29.
- Wolfe, J. A., and Tanai, Toshimasa, 1972,

Ongoing Coalbed Desorption Studies, Cook Inlet Basin, Alaska

*by Charles E. Barker , Todd A. Dallegge (USGS, Denver and Fairbanks) and
Dan Seamount (Alaska Oil and Gas Conservation Commission)*

Abstract: Analysis of core and cuttings from nine wells around the northern edge of the Cook Inlet basin, Alaska, indicate 50 to 250 standard ft³ (SCF)/ton of biogenic and thermogenic coalbed methane (CBM). The apparent CBM potential is large: reports indicate up to 175 ft net coal thickness in portions of the basin buried at <6000 ft. deep.

The sub-bituminous coalbeds in the central and southern portions of the Cook Inlet basin contain, an average 60 scf/ton based on desorption of cuttings (dry ash-free basis, DAF). Reports suggest 750 billion tons of pure coal equivalent in these areas and simple calculation leads to a geologically indicated 45 trillion cubic feet (TCF) of gas in place (GIP). Adding a correction of 25% for cuttings gas content data to make it comparable to core data suggests about 60 TCF GIP. The higher rank coalbeds found in the Matanuska-Susitna (Mat-Su) Valley area contain about 350 billion tons with a gas content that averages 230 SCF/ton DAF based on desorption of core and cuttings data corrected to core equivalents. This geologically indicated resource is about 80 TCF GIP.

The indicated total Cook Inlet CBM resource estimate is about 140 TCF gas in place. If 10% of this resource is accessible for production and 50% of the accessible resource is recoverable, then the geologically indicated reserve is about 7 TCF. This is a 30 year supply to South-Central Alaska based on the current 220 BCF/yr consumption.

Slide: 1

Introduction

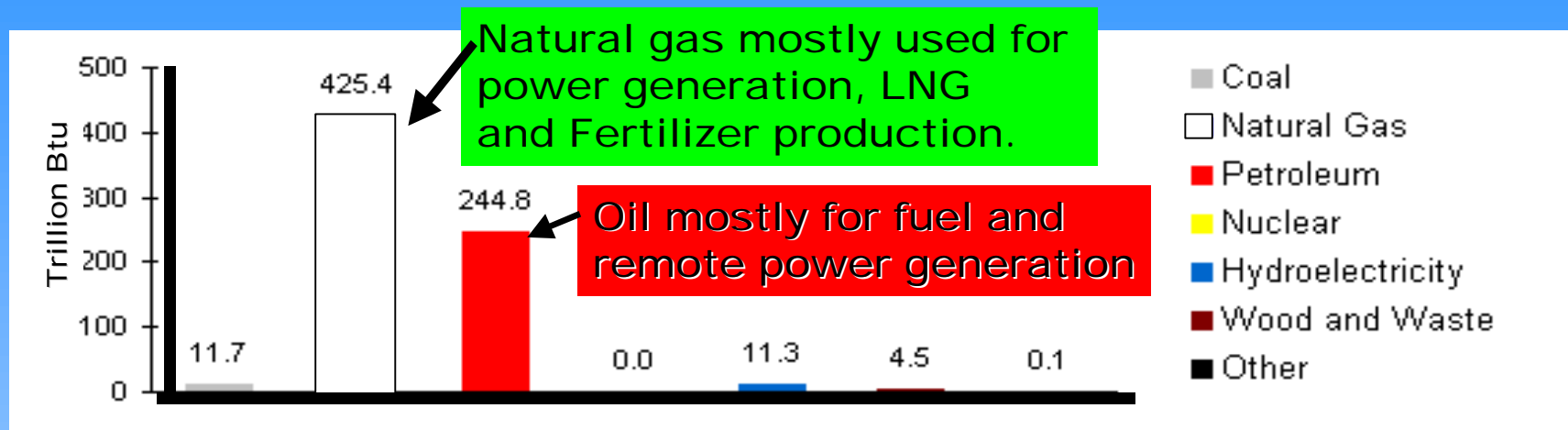
A major energy issue in the South-Central Alaska area is whether there is enough natural gas in coalbeds to justify development. South-Central Alaska is strongly dependent on natural gas for heating and electricity (slide 3) and faces energy shortages of natural gas (NG) due to declining production capacity and a lack of storage capacity. The NG supply problems are influenced by a lack of exploration incentive caused by the nation's lowest gas prices (slides 4 and 5). The low price is seemingly controlled by long term contracts and a relatively non-competitive marketing area limited to local area use, export as LNG, or as fertilizer made from natural gas. In 1998 there was some 2.15 to 2.95 trillion cubic feet (TCF) of producible conventional gas reserves. South-Central Alaska gas use is now about 220 BCF/ year. Thus, these 1998 reserves will apparently be depleted in 10 to 14 years (2008 to 2012) if new sources are not found (slide 6).

Although the reserves of natural gas in conventional traps is well known in the Cook Inlet, coalbed methane (CBM) reserves associated with the conventional gas fields are poorly known. Reports indicate Alaska contains widespread coal reserves, especially in the Cook Inlet and North Slope basins (slide 7), where a conventional oil and gas infrastructure is in place. Thus, CBM developed in the Cook Inlet basin could possibly use the existing infrastructure to rapidly develop and deliver new gas (slide 8).

Our project addresses the CBM reserve issue by measuring gas content in just-retrieved gas-bearing coal samples using canister desorption and the modified Bureau of Mines methods. We sampled coal cores and cuttings from wells drilled solely for CBM testing and also gleaned samples from oil and gas tests that drilled through shallow coalbeds (slide 8).

Slide: 2

Energy Sources, Alaska, 1997

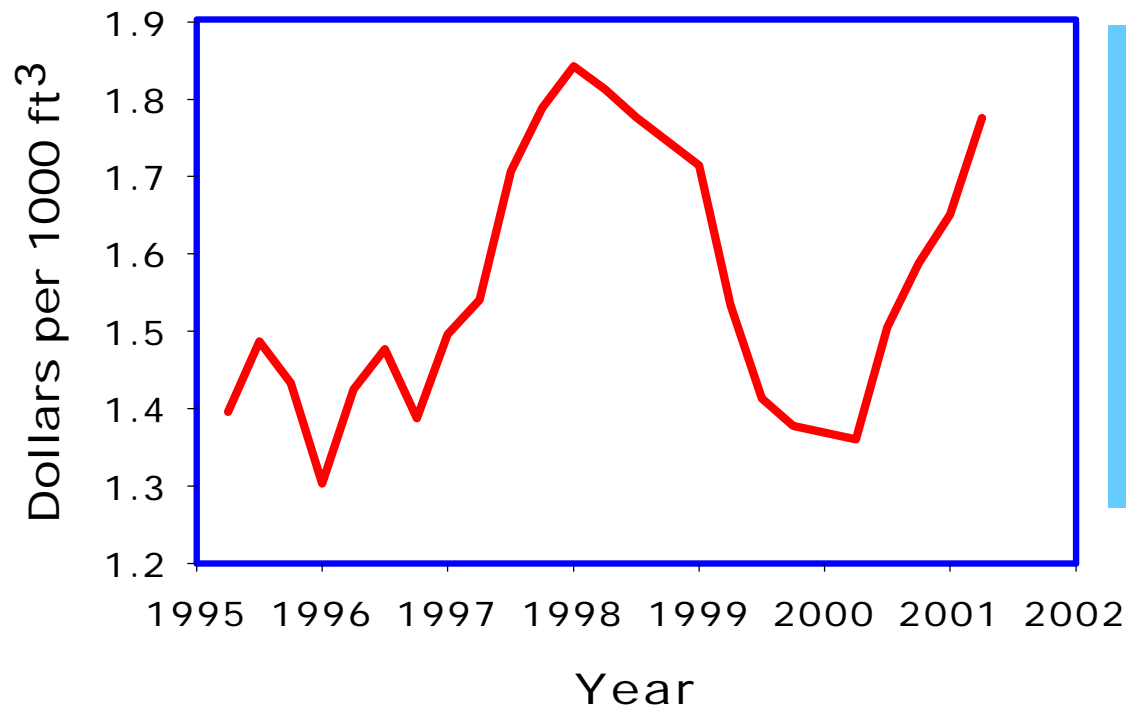


- At times of peak demand, spot gas shortages could occur by 2003 to 2005.
- Reports attribute initial shortages to a limited gas storage capacity
- In the future: shortages due to reduced production capacity

Slide: 3

Data Source: EIA (2001) <http://www.eia.doe.gov/emeu/sep/ak/>

Cook Inlet: Recent Gas Price History



- Delivered gas price approximately twice the City Gate price
- Long term contracts appear to control price
- Commercial users first to shut down during shortages

Data Source: AK Tax Revenue Division

Slide: 4

Alaska's Energy Prices & State Ranking (1997, in Dollars per Million Btu)

	Alaska	USA	Rank
All Energy	6.69	8.82	48
Gasoline	11.91	9.73	2
Petroleum	6.93	7.82	48
Natural Gas	2.07	4.62	51*
Coal	2.18	1.31	4
Electricity	29.57	20.15	8

* Includes Puerto Rico

Source: EIA (2001)

Slide: 5

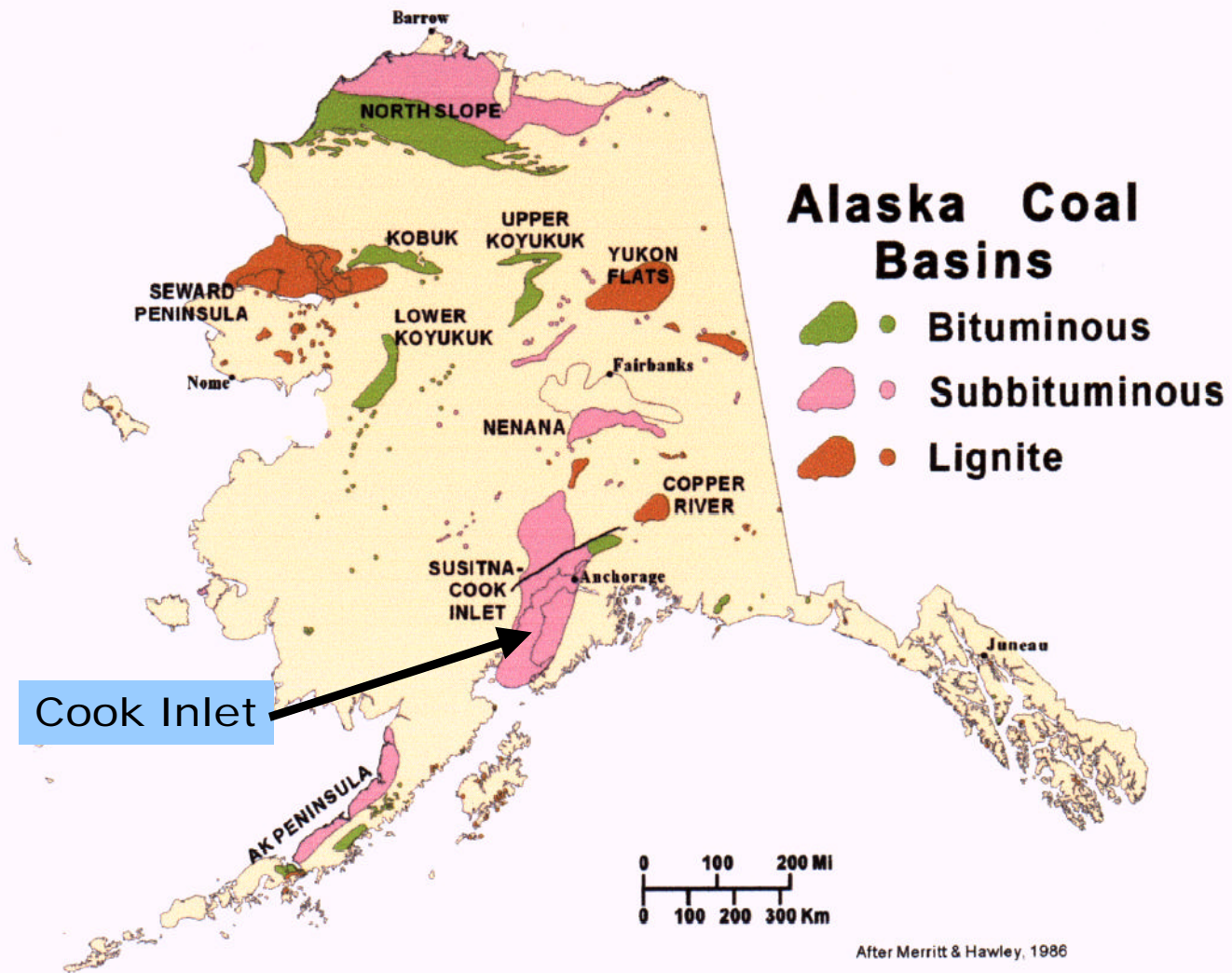
Cook Inlet Gas Proven Reserves 1998

Source	Developed (BCF)	Undeveloped (BCF)	Years to Depletion*
Phillips- Marathon	2494	85	11.3 (11.7)
AK DNR	2947	119	13.4 (13.9)
UNOCAL	2277	528	10.4 (12.7)
ENSTAR	2150	286	9.8 (11.1)

*at the current 220BCF/yr rate of consumption. Value in parentheses includes undeveloped reserves but no reserve growth or new discoveries

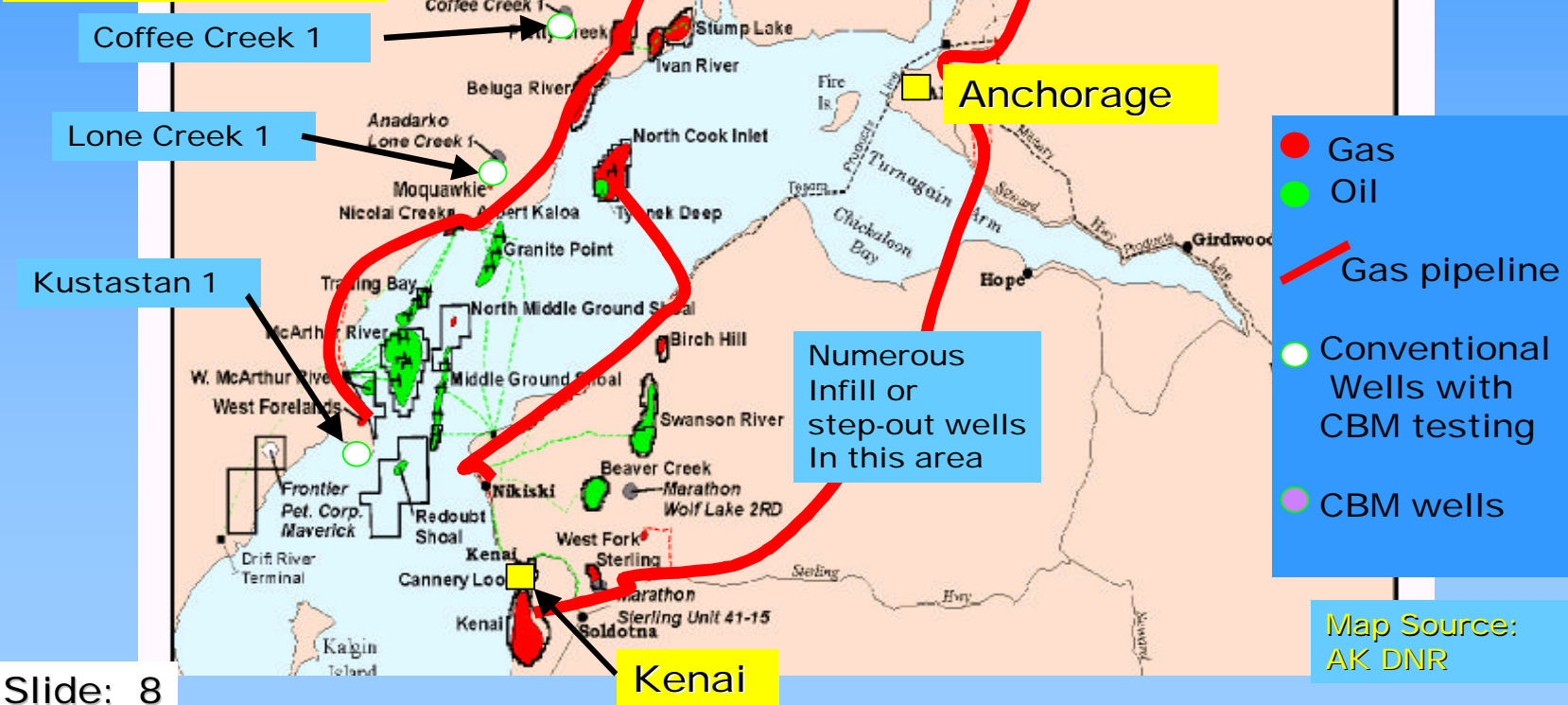
Data Source: DOE Opinion and Order no. 1473 (1999)

Slide: 6



Slide: 7

Recent Exploration In Cook Inlet



Desorption Methods

Cuttings: During drilling, potential coalbeds can be detected by monitoring drilling breaks and gas kicks on the geolograph or mud loggers gas detection equipment. The lag time is monitored so that coal cuttings can be captured at the shale shaker in a timely manner and the sampled depth can be calculated. The coal cuttings are washed in screens to remove fines and drilling mud and then immediately placed in pressure tight canisters. The gas content is measured over time using a modified Bureau of Mines method. The procedure now includes putting the canisters into temperature regulated water baths that match the drilling mud temperature. The gas desorbing from the coal cuttings is then periodically measured and totaled to determine the amount of gas in the coals. For the first 4 hours, often repeated measurements are required in order to define the lost gas curve. The lost gas curve determines a correction for the amount of gas lost as the cuttings are pumped up the well bore and before they are placed into the canisters. Because of the crushed nature of the cuttings, the amount of lost gas can be large. Thus, without this 'lost gas' correction, accurate measurements of gas contents in cuttings are not possible. We do not use a sink-float separation of non-coal materials to correct the gas content because we do not know how to separate the non-coal chips cut from the coal bed itself (partings) from the materials mixed in as the chips travel up the well bore.

The canisters used for cuttings can use a pressure plug that slides up inside the canister cylinder to the base of the cuttings sample (Slide 11). This feature minimizes headspace volume which can introduce errors in P-V-T gas calculations.

Slide: 9

Core: Coring operations were drilled next to existing wells and therefore the depth to the coal bed was known in advance. The procedure for measuring gas content on coal core is similar to coal cuttings, except the lost gas correction is computed from the time the core is lifted off the bottom. Lost gas corrections in conventional coring can also be large because of the long time required to retrieve the core. A lost gas correction is also required for accurate measurements of gas contents in core.

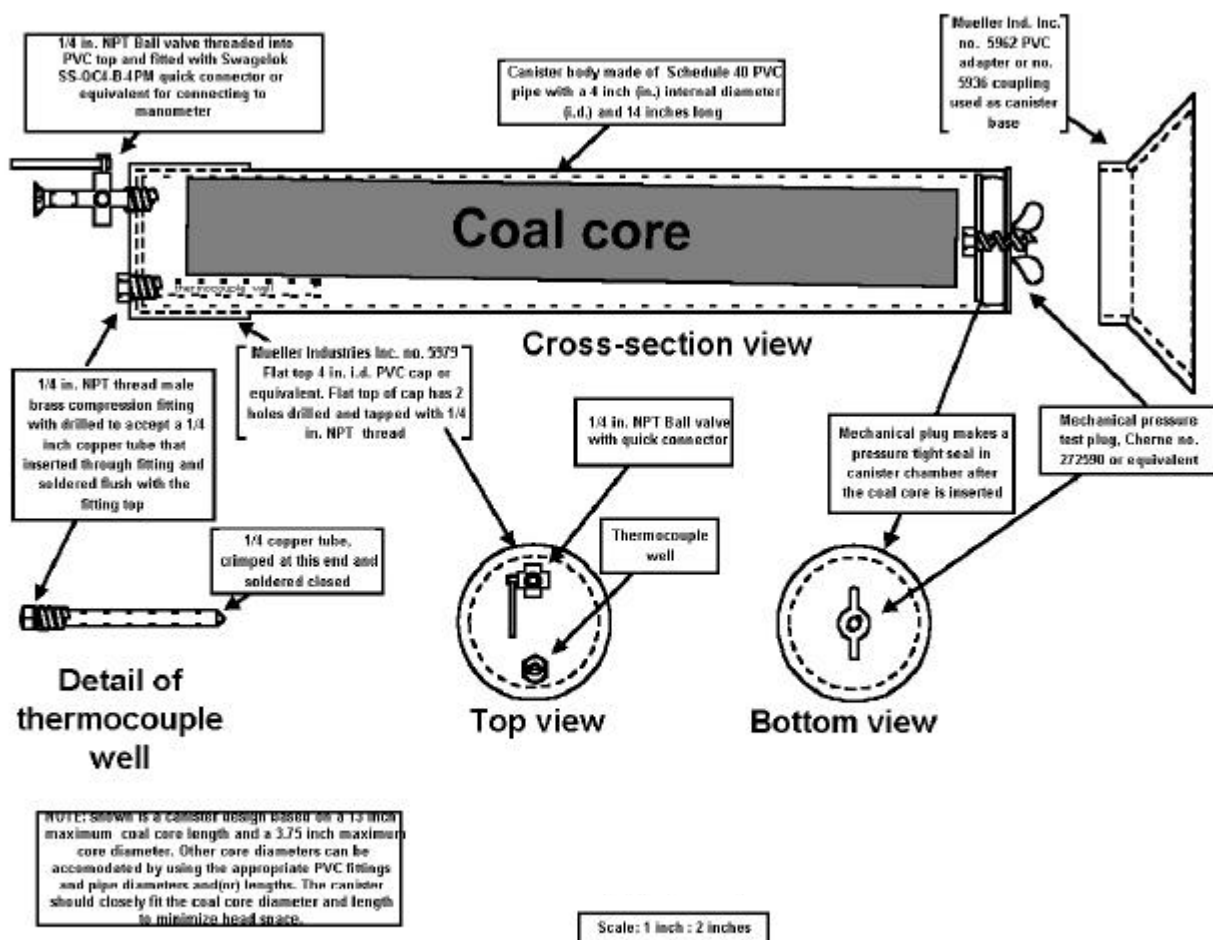
The canister for core is selected to fit the core diameter closely to minimize canister headspace that like in cuttings can introduce errors in P-V-T calculations.

Cuttings versus core: Samples of coal from core are better quality but relatively costly. Of course, the best sample for CBM analysis are pressure cores that capture the entire gas and fluid content along with the coal, making lost gas estimates unnecessary. We prefer core, but use cuttings as well, to make an estimate of gas in place in a realistic time frame. Studies of gas contents of related core and cuttings samples indicate that a gas content based on cuttings is generally 25 to 30% lower than a related core value (Nelson, 1999). However, values as high as 40 to 50% are reported. We conservatively apply only a 25% correction to gas content data to make them more comparable to core-based measurements.

Whether using cuttings or core samples, the canister headspace is measured after desorption. Headspace is calculated as volume of water required to fill the canister with the core or cuttings still filling it. A correction for headspace is made in our spreadsheet.

Slide: 10

The USGS Can -- a coal core desorption canister



Drafted by C.E. Barker October 4, 2000

Slide: 11

Coal Chemical Analysis

Coal chemical analysis is performed after canister desorption is completed. Completing desorption measurements may require 1 to 4 months for the Cook Inlet coals. Cuttings samples are coned and split into quarters for submission to various laboratory for analyses. Core samples are usually sliced with a saw to make composite or canister level samples for laboratory analyses.

We routinely run proximate chemistry (ash yield, moisture, fixed carbon, volatile matter and Btu content), methane adsorption isotherm, vitrinite reflectance and maceral petrography on composite samples of each coalbed. Selected coal samples from individual canisters that contain the lowest and highest gas content or most and least ash may also be analyzed at assess their effects on gas content.

We also characterize CH₄ and CO₂ samples taken during desorption using C, O, and H isotope analyses. Hydrocarbon composition in the natural gas is measured by gas chromatography analysis. These data are useful in interpreting a biogenic or thermogenic origin of the gas using tools like the Bernard diagram (see slide 23).

Slide: 12

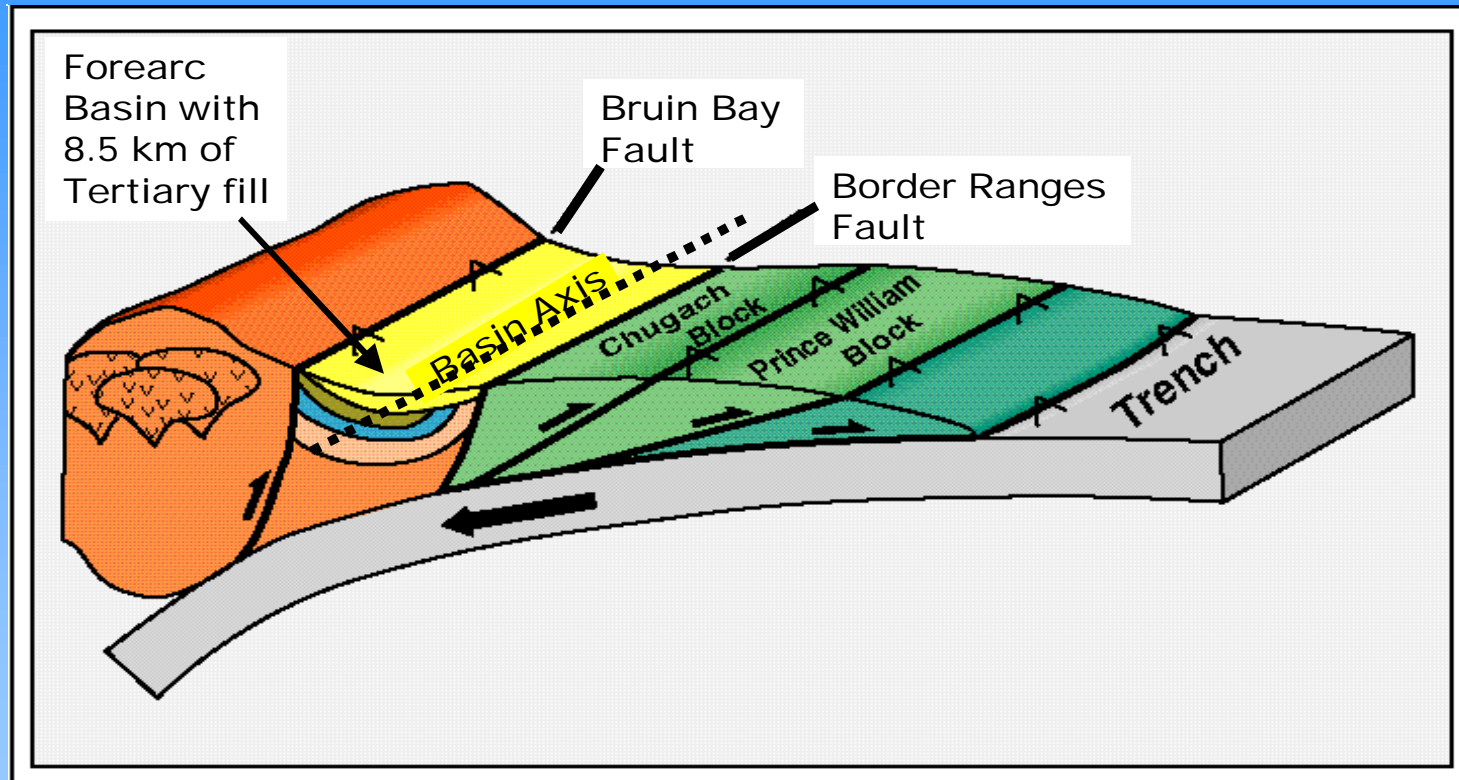
Cook Inlet Basin CBM Geology

The Cook Inlet Basin is an elongate, northeast-trending, fault-bounded forearc basin that contains 28,000 feet of Tertiary terrestrial sediment (Swenson, this volume; Slide 14). The basin is characterized by marginal alluvial fans feeding an axial fluvial depositional system. Rapid infilling of the basin is indicated by laterally discontinuous, interfingering beds of sandstone, siltstone, conglomerate, and coal (Slide 15). Coal bed methane production is strongly dependent upon the thermal maturity and depth to the coal bed. Optimal coal bed methane generation, maximum storage capacity occurs at a starting vitrinite reflectance value of 0.6 %Ro (Slide 16). Coalbeds, because of their plastic nature, tend to lose permeability and have non-economic production levels below a depth of about 6000 ft. These thermal maturity and depth to coalbed criteria suggest the most prospective areas of the Cook Inlet basin are to the north in the Mat-Su Valley area and to western and southern edge of the basin where coals are found at less than 6000 ft depth (Slide 16).

The Cook Inlet basin contains two basic types of CBM prospects: 1) thick immature coals of the Beluga and Tyonek Formations in the western and southern portions of the basin; and 2) thick mature coals of the Mat-Su valley area. So far we have identified only 1 ft to perhaps 15 ft thick, locally-discontinuous coals in the Sterling Formation. The generally immature Sterling coal, along with the deeply buried Tyonek coal onshore or offshore, and any coal remote to existing NG pipelines, are not thought prospective under current market conditions.

Slide: 13

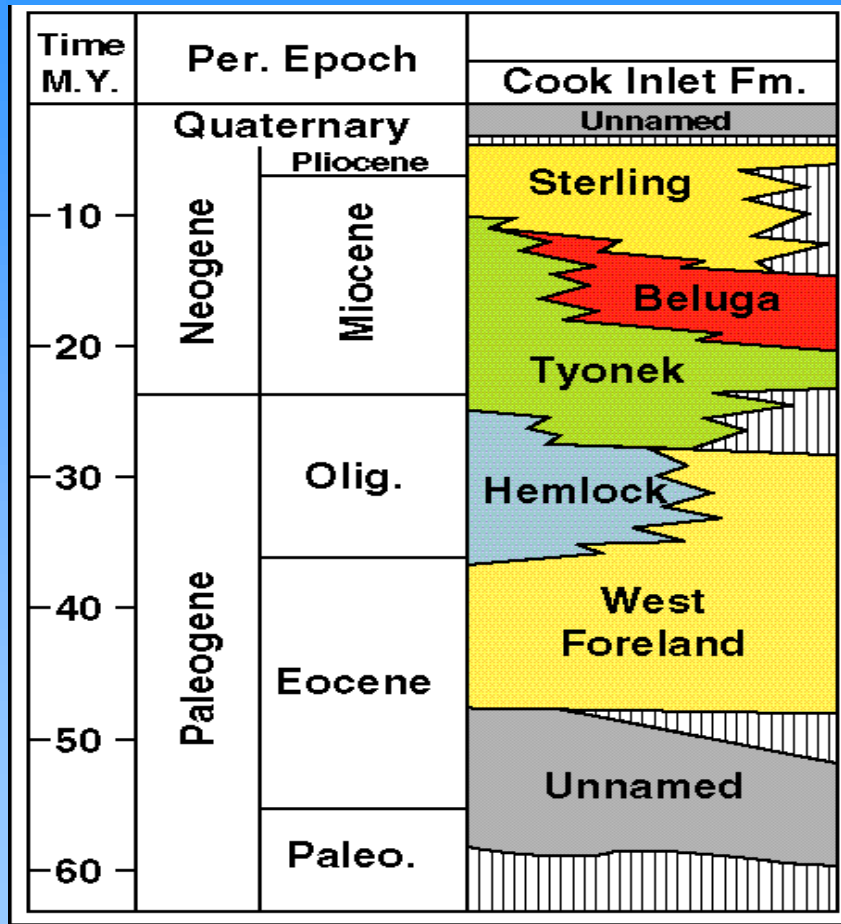
Tectonic Regime, Cook Inlet, Alaska



Modified from Doherty et al. (1994) and Swenson (2000)

Slide: 14

Cook Inlet Tertiary Stratigraphy



CBM Sources

← lignite, beds to 10 ft thick

← sb, beds to 40 ft thick

← sbC to hvBb,
beds >50 ft thick

SUMMARY:

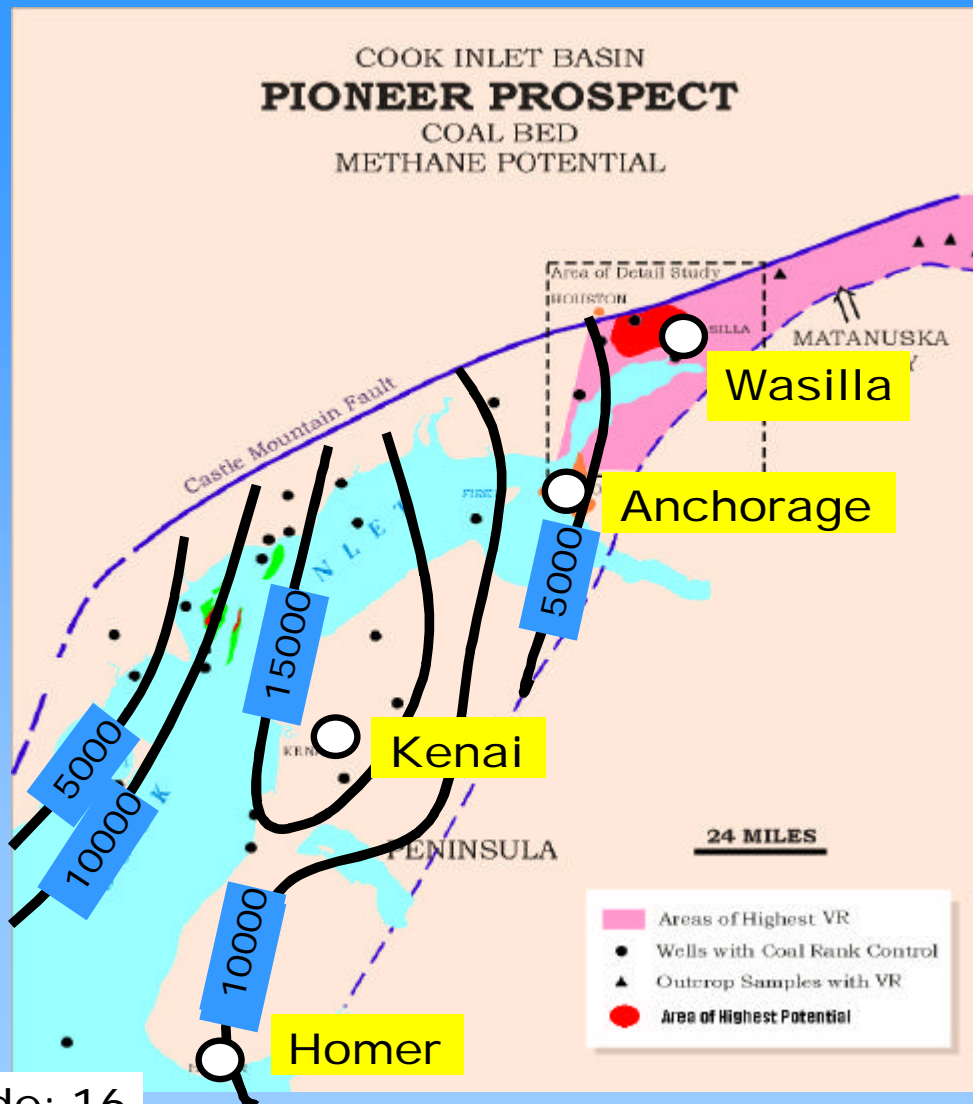
Two basic CBM plays:

1. Onshore immature coals
2. Onshore mature coals

← HvBb to A, beds to 34 ft.
Chickaloon Fm. (Mat-Su Valley)

Slide: 15

Modified From Swenson (2000), Smith (1995)



- **Only NE Cook Inlet has bituminous coals**
- **Depth to 0.6% Ro at less than 5000 ft depth**
- **Existing Gas Pipeline**
- **230 SCF/ton DAF Gas contents (incl. all Bit. coal data)**
- **Southern and Southwestern Cook Inlet may also be prospective**

~ Depth to 0.6% VR
(Smith 1995)

5000

Slide modified from Ocean Energy
& Unocal well permit presentations

Slide: 16

A Brief History of Cook Inlet CBM Exploration

The Alaska Department of Natural Resources AK-94 well, cored and desorbed in cooperation with the USGS, was the first CBM test well drilled in Alaska (Slide 18). Desorption tests of core from this well used USGS canisters and methods modified for improved temperature control. The results of this test indicating 40 net feet of coal at less than 1300 ft depth are averaging about 160 SCF /ton DAF (Slide 19). Documentation of gas-bearing coals in the Mat-Su valley was seminal in the subsequent CBM developments at Houston prospect and the Pioneer Unit. The location of these developments was controlled by apparently gas-bearing coal near the surface and a play area crossed by the major natural gas pipeline supplying South-Central Alaska (Slides 20 and 21). Analysis of isotherm and desorption data from Pioneer prospect core indicates that the Tyonek bituminous coal is saturated (Slide 22) with a mixed thermogenic and biogenic methane source (Slide 23).

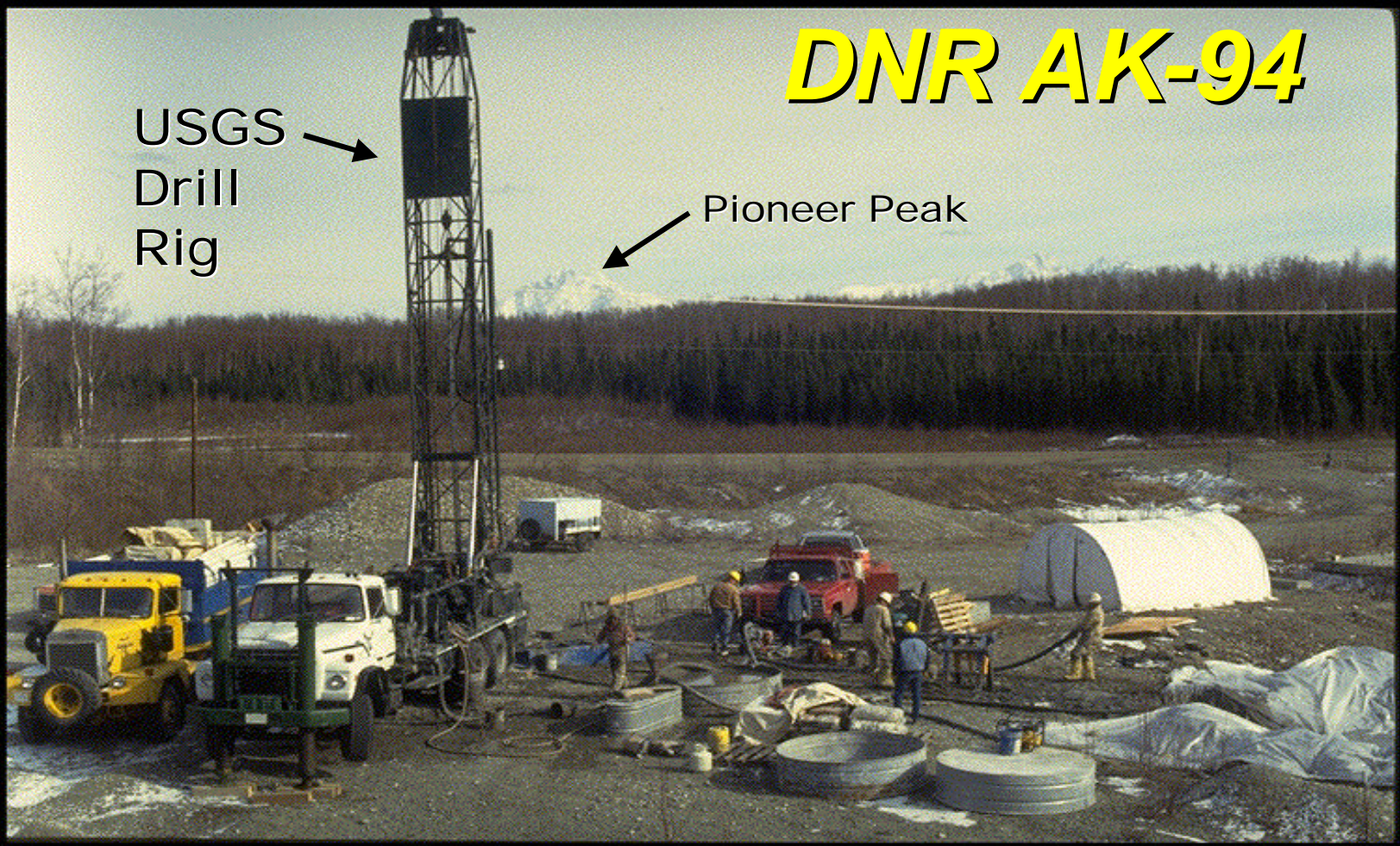
In 1997, measurements by the Forcenergy, UNOCAL and USGS of immature sub-bituminous CBM potential at the Coffee Creek 1 well indicate that the coals there may not be saturated (slide 24); possibly due to the effect of uplift and cooling (Slide 25) or to under-estimating gas content from cuttings. The CBM at Coffee Creek appears to have a biogenic origin (Slide 23). The concern is that under-saturated coals can require pumping large volumes of water to make the reservoir pressure decrease to the critical desorption point (Slide 25) for gas production. Water chemistry and disposal of the large amounts of produced water would be problematic (Slides 26 and 27).

Slide: 17

DNR AK-94

USGS
Drill
Rig

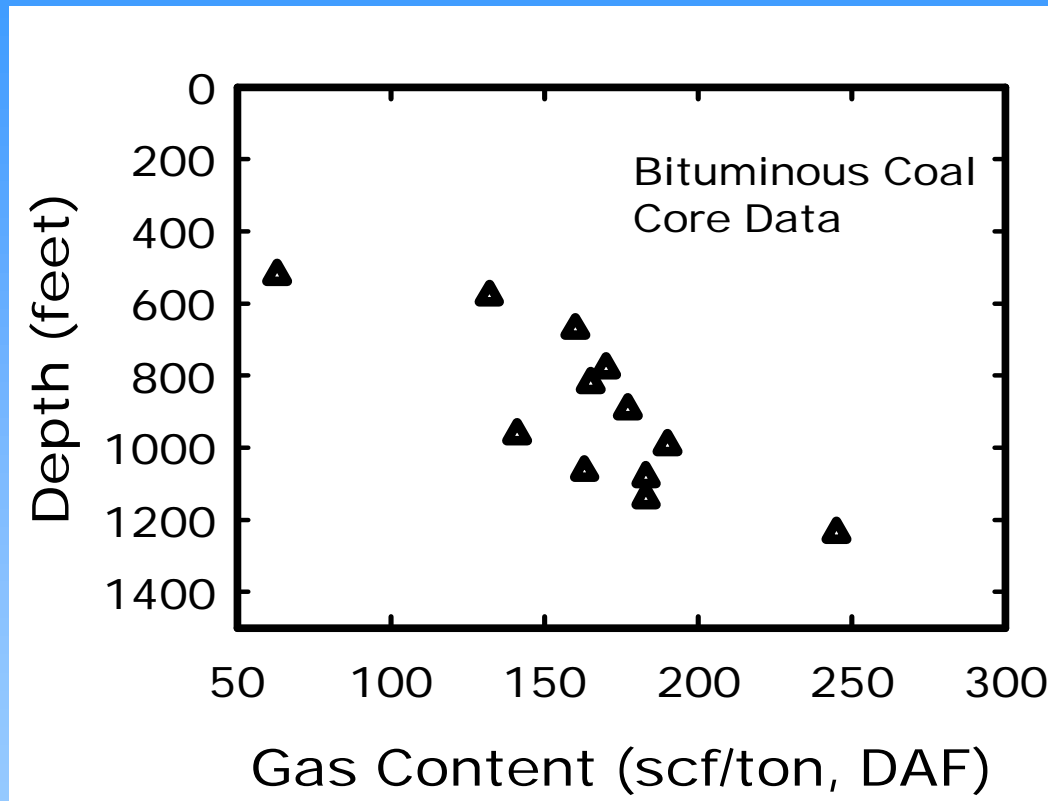
Pioneer Peak



Slide: 18

Photo by Smith, AK DNR, 1994

AK-94 Desorption Data



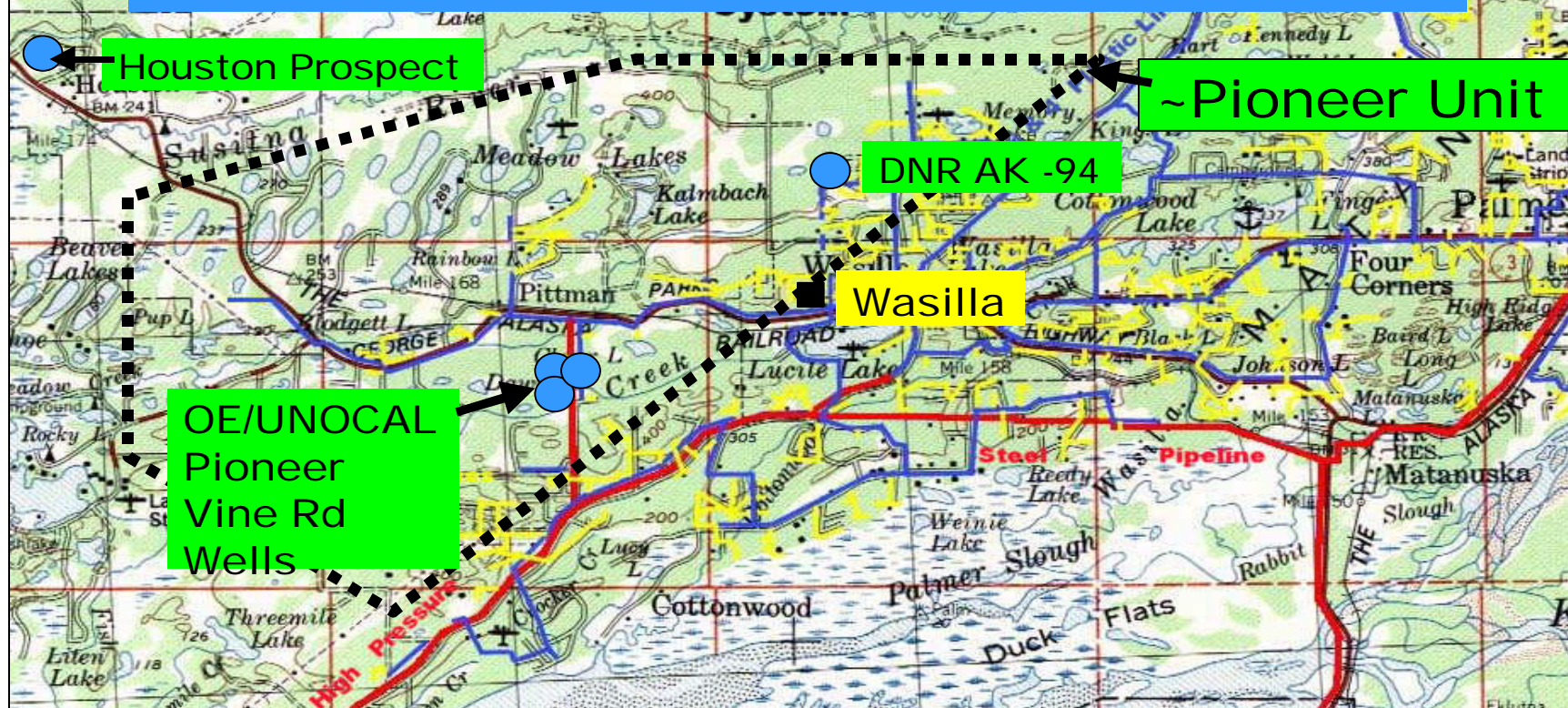
Data from Smith (1995) and AK Div. O&G files

Key Results:

- 40 net feet of coal
- < 1300 ft depth
- Mixed Biogenic and Thermogenic gas
- Averages about 160 SCF /ton DAF

Slide: 19

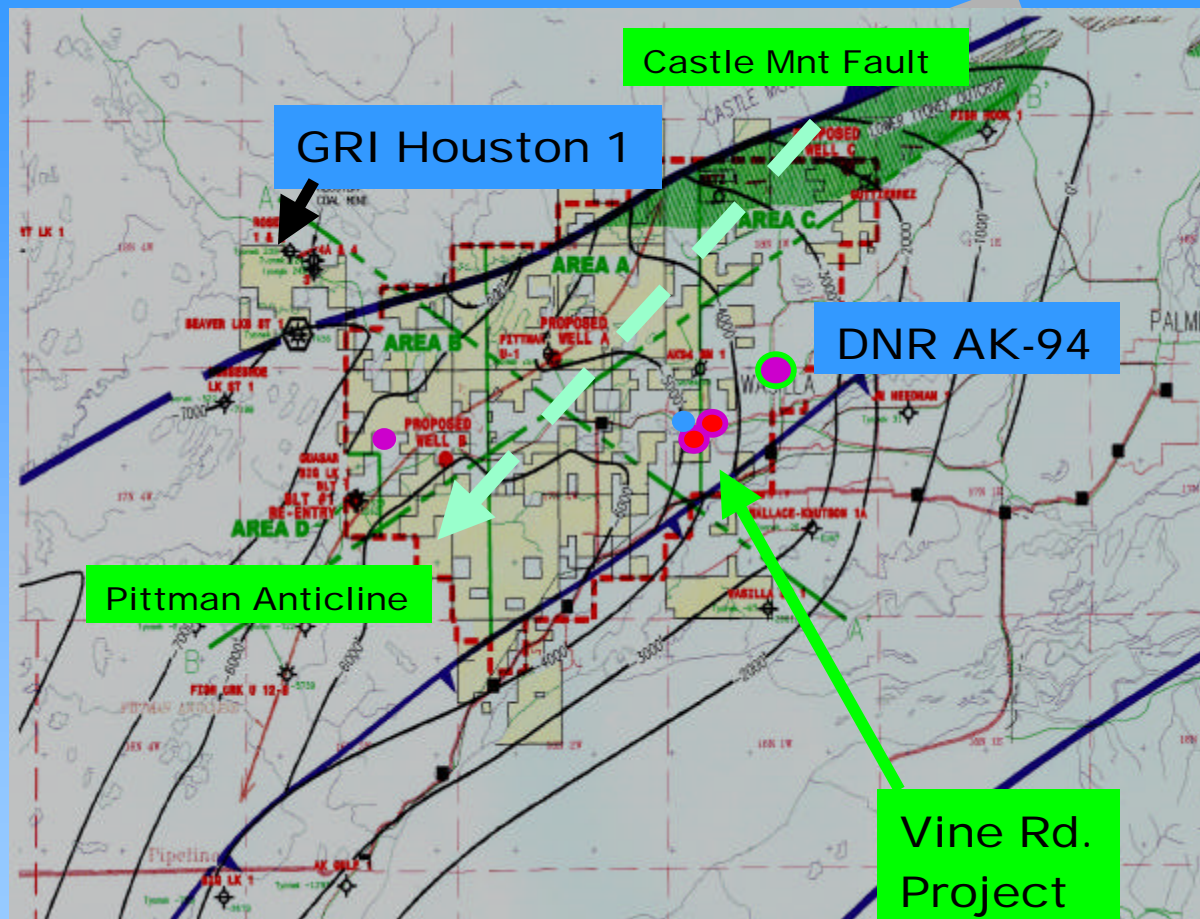
Enstar Gas Distribution System, Northern Cook Inlet



Slide: 20

Base pipeline map from Lapp Resources, Inc.

Structure at the Base of the Tyonek Formation

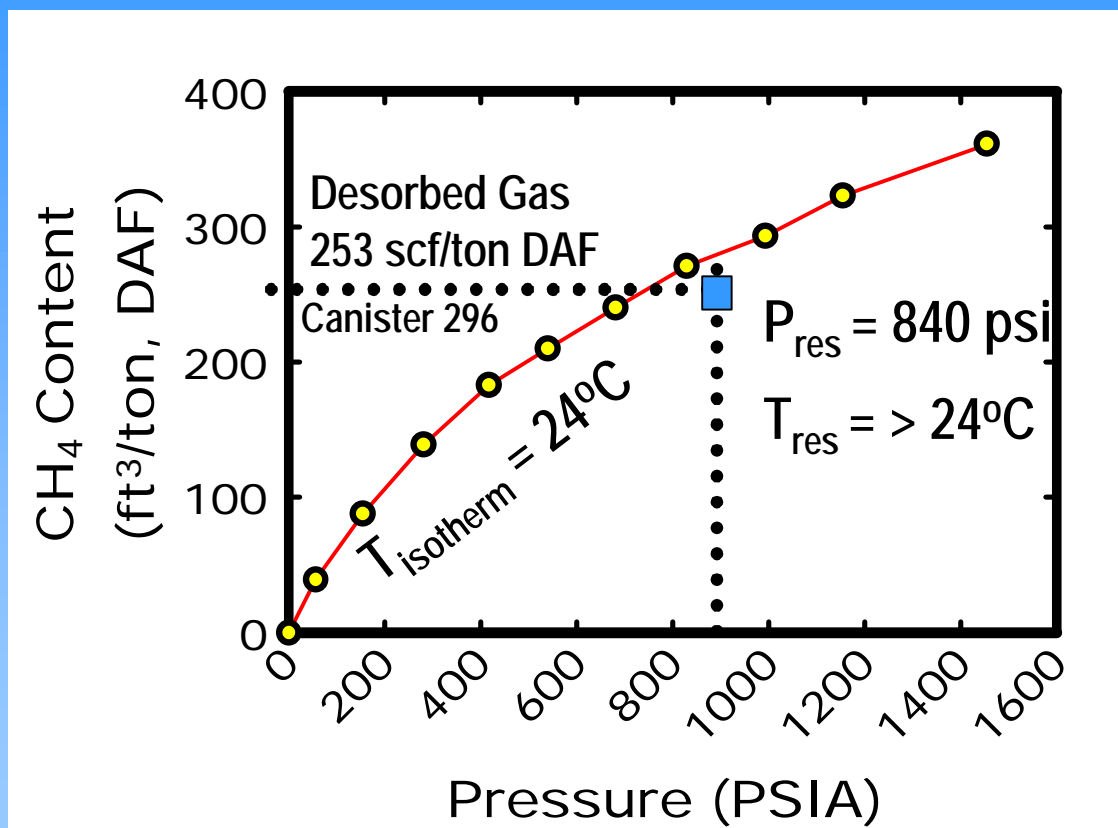


- *Bounded by two active reverse faults (seals?)*
- *Pittman Anticline bisects the unit (trap?)*
- *Exhumation of Bit. Coal to less than 5000 depth*

Slide modified from Ocean Energy & Unocal public well permit presentations

Slide: 21

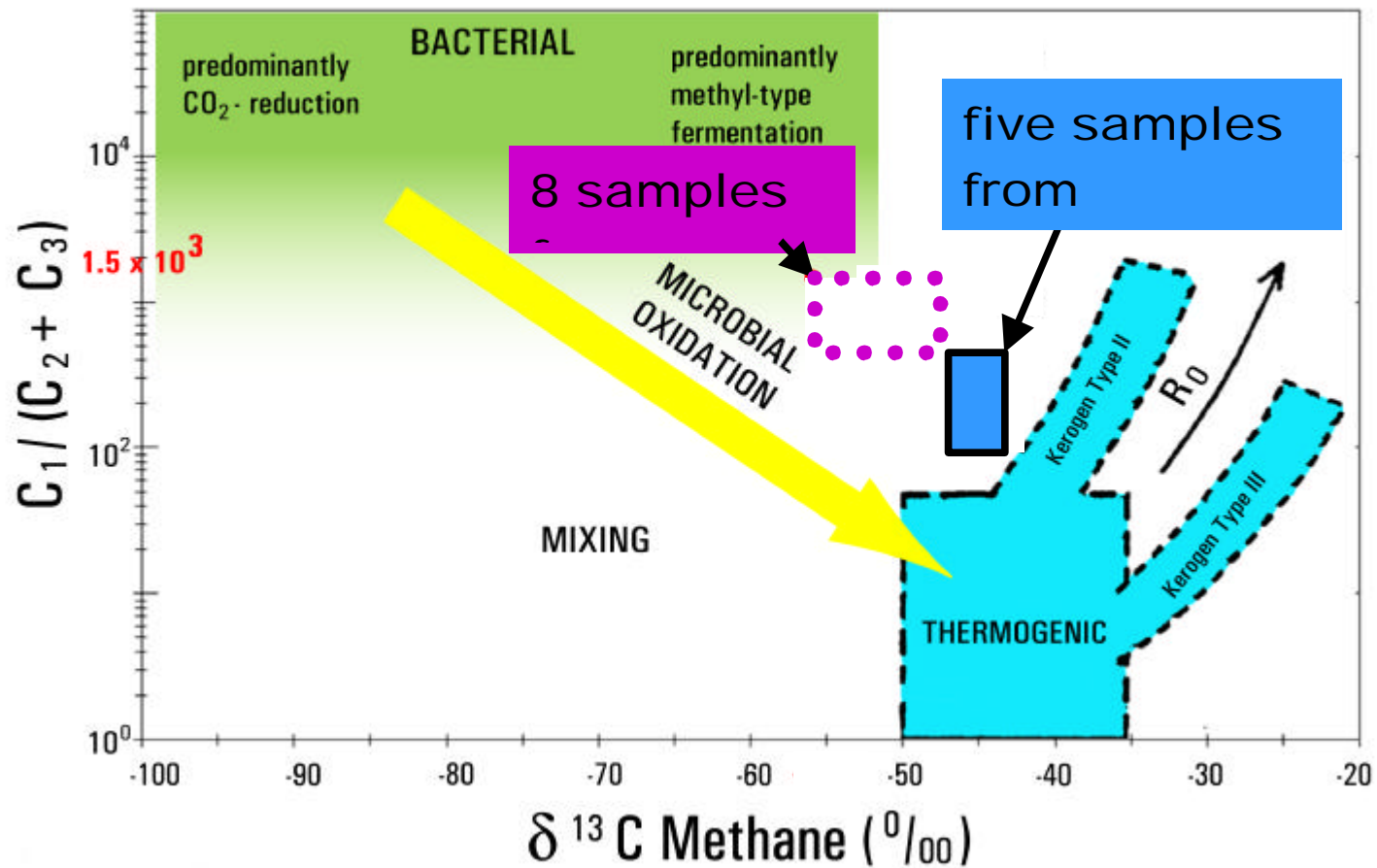
Pioneer Coal Saturation



Slide: 22

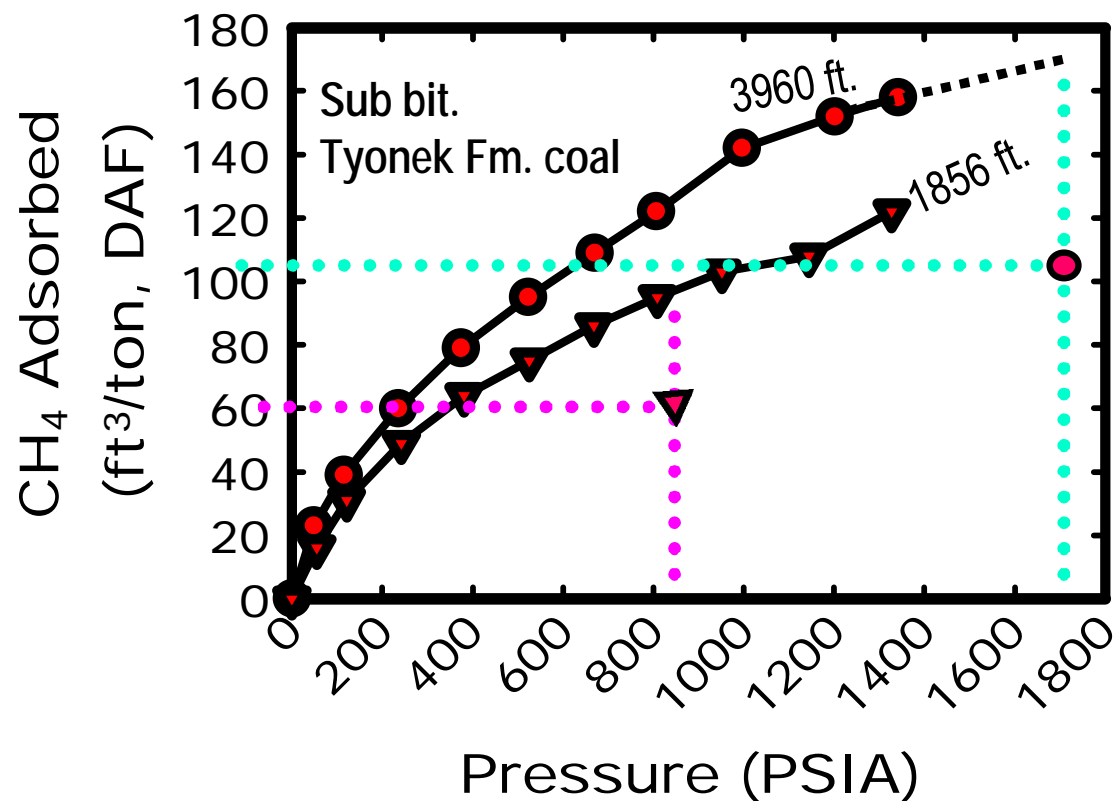
Coal sample and Isotherm data Courtesy of Ocean Energy and Unocal

Bernard Diagram



Slide: 23

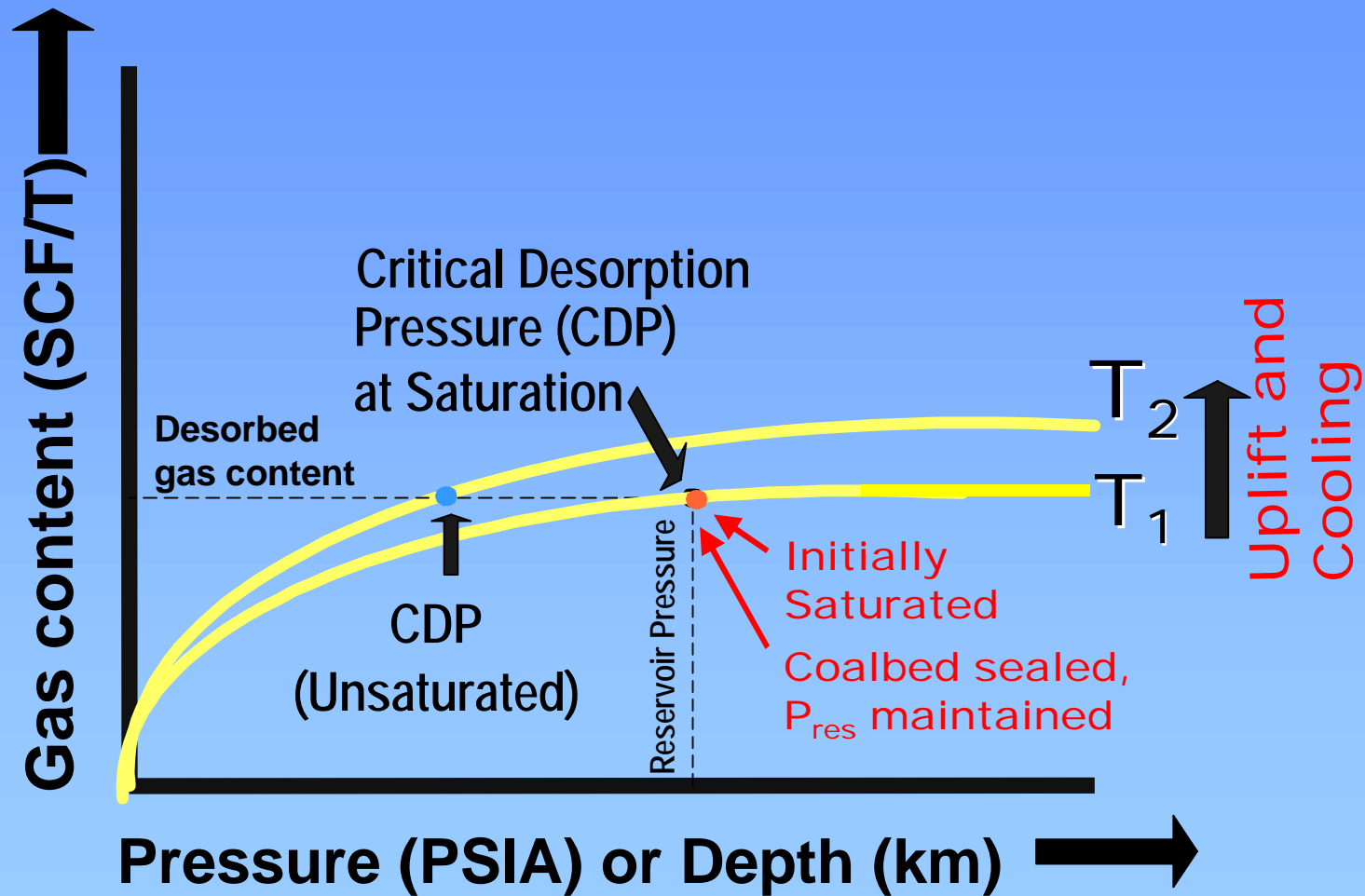
Coffee Creek 1 CBM Saturation



Slide: 24

Coal cuttings courtesy of Forcenergy and UNOCAL

Gas Contents of Saturated vs. Unsaturated Coals



Slide: 25

SUBSURFACE WATERS IN COOK Inlet, AK.

Tertiary strata:

Evolved meteoric Na-HCO₃ brine with 3,755 ppm TDS

Mesozoic strata:

Evolved seawater NA-Ca-Cl brine with 19,725 ppm TDS

<u>Reference Waters:</u>	<u>TDS ppm</u>
River water:	100
Max drinking water:	1500
Poor irrigation water:	3000
EPA limit, fresh water:	10000
Sea Water:	36000

Disposal Scenarios: Reinjection-likely

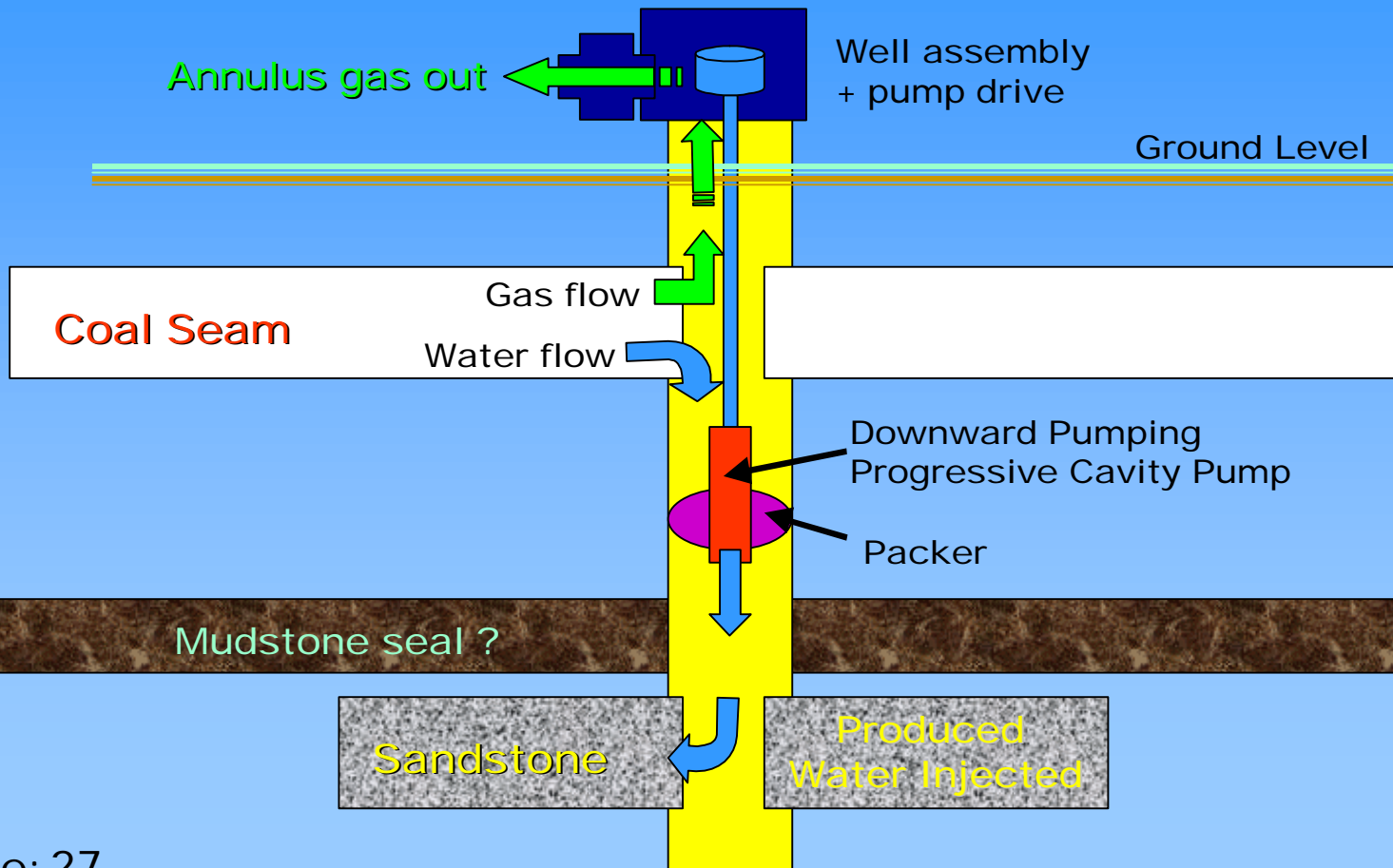
Reinjection into zones of < 3000 ppm not allowed by AK State.

Reinjection into zones of 3000 ppm to 10000 ppm by exemption.

Slide: 26

Water chemistry based on AGU poster now published as Bruhn and others (2000).
Reference waters mostly from Davis and DeWiest (1966)

GRI/Lappi Well Completion Concept



Slide: 27

Discussion:

Cuttings vs. Core to Estimate CBM Gas in Place?

Gas contents based on coal cuttings are typically (always?) low compared to values obtained from core or pressure core samples (Nelson, 1999; among others). The gas content appears to be lowered primarily because of sample contamination with drilling additives and admixture with caving materials as the cuttings are pumped up-hole. We also believe a major problem with cuttings is that the finer sizes of coal grains cut from the relevant seam are so small that complete gas diffusion is a rapid process and they lose all of their gas content while in the hole. These fine bits of now of dead coal (all gas lost on the trip up the well) plus the well contamination, when placed in the canister do not contribute gas; but they are included in the coal mass measured in the canister. Because gas content values are reported normalized to coal mass, those values that include dead coal or well contamination will be too low.

Unreleased data from Cook Inlet basin on gas contents from core with cuttings data that include a 25% correction show that the data fields overlap. The overlap suggests that the corrected cuttings data are comparable with the core data and apparently useful in estimating CBM gas content.

Slide: 28

Discussion: Comparison of CBM Basins

<i>Basin</i>	Gas in Place (TCF)	Avg. Prod. (Mcf/d/well)	Coal Rank	Typical Net Coal: Thickest bed (in ft)	Typical Desorption Time	Typical Gas Content (scf/ton)
San Juan	84	2000	hvb - Lvb	70:(50)	months	430
Raton	99	140	hvCb - mvb	40-70(<10)	weeks	2-500
Uinta	10	690	Sb - Hvb	24	weeks	400
Cherokee	6	100	Hvb	4	?	200
Black Warrior	20	100	Hvb - Lvb	25	?	350
Central Appalachian	5	120	Hvb - Lvb	11	?	250
Powder River	40	250	Sb	75	weeks	30
Cook Inlet (Bit.)	80	None (Yet)	Hvb - An	100's (30)	3 months (core)	230 bit.
Cook Inlet (Subbit)	115	None?	Sb	100's (30)	2 months (cuttings)	80 sb

Slide: 29

Base table from Nelson (1999); Cook Inlet data from unpublished sources

Cook Inlet CBM: Summary

- Gas contents and net coal thickness are similar to producing CBM basins
- However, some sb coal beds appear to be undersaturated
- 350 billion tons of pure bituminous coal so far averaging ~ 230 SCF/ton DAF of thermogenic gas = 80 TCF
(Note pure coal = in situ coal reserves minus an estimated mean 25% ash yield)
- 750 billion tons of pure subbituminous coal averaging ~60 SCF/ton DAF of biogenic gas = 45 TCF and corrected to core equivalents = 60 TCF
- Total geologically indicated CBM ~140 TCF gas in place
- Production and reinjection infrastructure in place
- In 1998, 2.15 to 2.95 TCF of conventional gas reserves.
- At 220 BCF/ year consumption, conventional gas reserves in south-central Alaska will apparently be depleted in 10 to 14 years (2008 to 2012).

Slide: 30

Acknowledgements

Government Collaborators

J. Clough (AK DNR-DGGS), R. Tingook (USGS) &
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Corporate Collaborators

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Unocal, Phillips, Marathon

Independent Geologists and Engineers

R. Downey, N. Waechter, D. Lappi and M. Belowicz

Slide: 31

References

- Bruhn, R.L., Parry, W.T., and Bunds, M.P., 2000, Tectonics and fluid pressure distribution in a deformed forearc basin, Cook Inlet, Alaska. *Geol. Soc. Amer. Bull.*, V. 112, no. 4, p. 550-563.
- Davis, S.N. and DeWiest, R.J.M., *Hydrogeology*: J. Wiley and Sons, New York, 463 p.
- Doherty, D.J., 1994, Internal ARCO Report referenced in Swenson, 2000 (see below).
- Merritt, R.D. and Hawley, C.C. 1986, Map of Alaska's Coal Resources: Alaska Department Of Natural Resources, Special Report 37. 1 Sheet.
- Nelson, C.R., 1999, Advances in Coalbed Reservoir Gas-In-Place Analysis: *Gas Tips*, V. 5, p.
- Smith, T.N., 1995, Coalbed methane potential for Alaska and drilling results for the upper Cook Inlet basin: *Intergas '95, Proceedings of Symposium*, May 15-19, 1995, Tuscaloosa, Alabama, 21 p.
- Swenson, R. F., 2000, Introduction to Tertiary tectonics and sedimentation in the Cook Inlet Basin, *in* Barker, C. E., Dallegge, T.A. and J.C. Clough, 2000, Coalbed Methane Prospects of the Upper Cook Inlet: Field Trip Guidebook, Second Alaska Workshop on Coalbed Methane, Anchorage, AK, March 2, 2000. Published as Alaska Division of Geological and Geophysical Surveys Miscellaneous Publications no. 41, 115 p.

Slide: 32

Road Log for the 2001 Alaska Coalbed and Shallow Gas Resources Field Trip to the Kenai Peninsula, Cook Inlet Alaska

by

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Introduction

This field trip covers geologic and economic features related to oil and gas production in Cook Inlet and on the Kenai Peninsula. We have emphasized new discoveries or insights into the potential for shallow gas exploration of these areas. Previous field guides contain considerable additional geologic information that is not reprinted here (Clark, 1981; Winkler et al., 1984; Triplehorn et al., 1985; Karl et al., 1997). For additional stops and geologic details, we suggest the 1997 AGS road log (Karl et al., 1997) as a supplement to this guide.

This log is not the traditional mileage marker road log based on odometer readings. Constant road construction and inconsistencies in vehicle odometers has limited the usefulness and accuracy of previous logs. We are trying a new technology approach due to the increased availability and accuracy of the Global Positioning Satellite (GPS) system. This GPS road log gives waypoint information at all points of interest and intersections on the trip. We hope that future expeditions to the area can upload these waypoints into their GPS equipment and thus have a very accurate system to follow this guide. Many features from the 1997 AGS guide have been cited with GPS information so correlation with this log can be accomplished.

The Kenai Peninsula is a popular recreational getaway for many Alaskans and is a key tourist destination. Other than great geologic exposures of late Tertiary rocks, the Kenai Peninsula offers abundant fishing, hiking, boating, and site-seeing activities. Rubber boats and tide charts are recommended for the beach outcrops and several stops on this trip. Most of the stops are on state or federal lands but access to some areas off the road right-away are on private land and permission should be acquired prior to access. Weather in Alaska can be unpredictable and one should be prepared for freezing conditions and/or wet weather, especially in the early spring and late summer months (April-May, August-September).

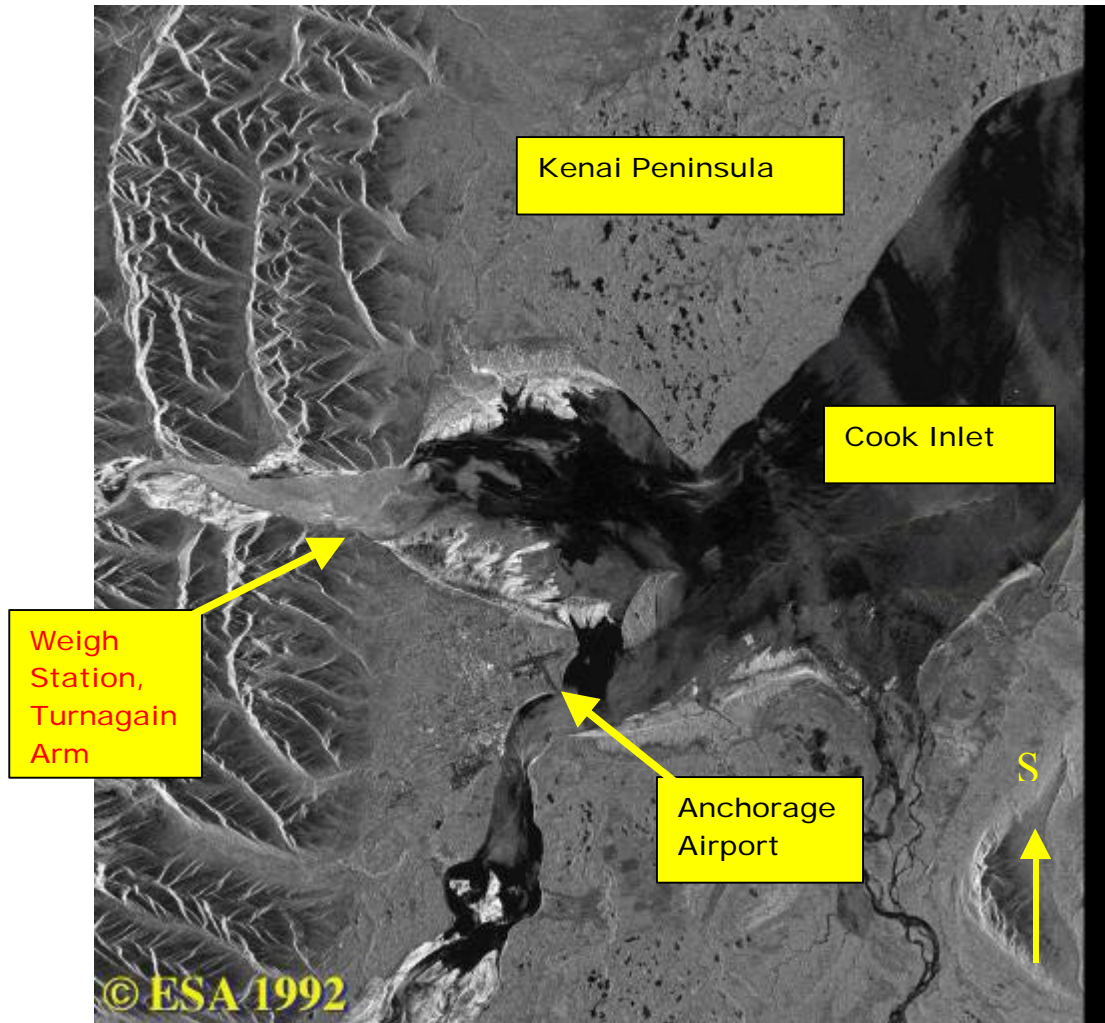
Road Log

This field trip starts from the Anchorage Marriot Downtown Hotel but road log information does not start until the commercial weigh station on the Seward Highway in Turnagain Arm. Most roads leading south will eventually intersect this Seward Highway. We suggest following the New Seward Highway out of Anchorage by any of the multiple east-west roads that intersect this major north-south thoroughfare. The New Seward Highway will merge with the Seward Highway.

Day1

From the Anchorage Marriot Downtown take 6th Avenue eastbound (towards the Chugach Mountains) to Gambell Street. Turn right (south) on Gambell. The road merges with the New Seward Highway, continue south to the Seward Highway and beginning of road log.

Waypoint 1 Weigh-station on Seward Highway in Turnagain Arm: N61.03641° W149.77579°



Modified Scene acquired on August 8, 1992 with permission from European Space Agency. Use approved only for educational purposes.

Waypoint 2 Beluga Point: N61.00726° W149.69180°, There is a easily accessible roadside pullout on the south side of the highway with an information kiosk. Across the highway the road cut exposes a boulder conglomerate of the McHugh Complex, part of the Mesozoic accretionary wedge. Clasts in the conglomerate consist of greenstone, argillite, chert, limestone, siltstone, and gabbro (Karl et al., 1997). Limited age control for the McHugh Complex has been reported from nearby locales that include a plutonic clast K-Ar age of 146 ± 7 Ma (M.A. Lanphere, quoted in Clark, 1981) and limestone clast conodont age of

Meramecian to Morrowan (Late Mississippian to Early Pennsylvanian; Nelson et al., 1986). About 4.6 miles east of here we cross a low angle thrust and enter the Valdez Group in the footwall of the thrust (Karl et al., 1997). The Valdez Group is composed of well-bedded, slightly deformed, Late Cretaceous turbidites. We will be in outcrops of the Valdez Group for the next ~100 miles. See Bradley et al. (1997) for more detail.

Waypoint 3 Bird Creek: N60.97364° W149.46521°, A popular salmon fishing area during the summer run.

Stop 1

Waypoint 4 Girdwood Tidal Marsh, AK: N60. 92943° W149.14708°, Nearly all of the trees visible on this marsh were killed by saltwater intake as a result of subsidence during the great 1964 earthquake. Most of the 1964-era buildings in the part of Girdwood near the present intersection of Seward Highway and Alyeska Road were inundated, and many were subsequently moved to higher ground up Alyeska Road.

The most extensive tidal flooding occurred about two weeks after the earthquake during the next high spring tides. During the following two decades, repeated tidal flooding resulted in deposition of several tens of centimeters of silt, restoring the flats to near pre-earthquake levels. Salt-tolerant grasses now dominate the vegetation on Girdwood flats, and the marsh surface is flooded by seawater only at extreme high tides.

Visible in tidal-bank exposures at the edge of the marsh is a stratigraphic record of the 1964 event, where postearthquake marine silt overlies peat containing freshwater plants that were killed by saltwater flooding. The peat is 10-15 cm thick and contains the roots of dead trees, many of which are still standing. Also visible about 1 m below the 1964 peat layer is a second layer of stumps rooted in peat, yielding radiocarbon ages with an average age range of 730-900 cal yr B.P. This forest layer was probably buried as a result of the previous 1964-style great earthquake. Depending on exposure and accessibility, an older buried peat layer is visible 1-2 m beneath the 730-900-yr layer in the western part of the marsh. This older layer has a radiocarbon age of 1,170-1,360 yr B.P. and probably records another previous coseismic-submergence event. Still older peat layers, ranging to a maximum age of about 4,000 B.P. are visible at low tide in various portions of the marsh and in samples from a 19-m-deep borehole. Evidence of as many as five pre-1964 great earthquakes appears in the tidal-marsh stratigraphy at Girdwood and roughly correlate with the ages of uplift associated with these prehistoric earthquakes along the Gulf of Alaska margin.

PORTAGE TOWNSITE (no stop)

The abandoned townsite marks the location of the main route through the mountains to Prince William Sound used by native Alaskans and developed by miners in 1902. The Alaska Central Railway surveyed the route in 1904. The buildings west of the road were destroyed by high water resulting from subsidence during the 1964 earthquake and partially buried by tidal silt during the following two decades. The dead trees and remaining old buildings are protected artifacts of the earthquake.

Stop 2

Waypoint 5 Portage Creek stop: N60.82734° W148.97679°, At this location, near the axis of maximum subsidence during the 1964 earthquake, the postearthquake Placer River Silt is up to 2 m thick. Numerous abandoned buildings in the vicinity are partially filled with silt and, as at Girdwood, most of the trees on Portage flats were killed by saltwater intake during high tides following the earthquake. The pre-1964 ground surface, associated peat layer, and numerous artifacts such as milled wood, cables, and pallets are visible in the bank exposures downstream from the bridge. Also visible are clastic dikes of sand and gravel that erupted to the former ground surface as a result of earthquake-induced liquefaction. Postearthquake tidal flooding eroded most of these dikes to a depth of about 0.5 m below the 1964 ground surface and replaced the eroded portion with silt. Consequently, few sand boils were preserved. However, nearly every dike is associated with a break in the peat that does not extend into the overlying silt, indicating that the sand erupted after the peat formed but before the silt was deposited. These stratigraphic relationships effectively place the dike formation at the time of the 1964 earthquake and serve as an excellent analog in the search for paleoseismic evidence in other areas of the world.

No evidence of pre-1964 coseismic subsidence is visible in the tidal banks at Portage because any remaining older peat layers are buried under modern tidal-channel deposits. Additionally, most boreholes drilled in the vicinity of Portage show that tidal sediments have been eroded by streams and replaced with alluvium over much of the area. However, continuous core samples from one borehole in unworked tidal deposits south of Portage show evidence of as many as seven pre-1964 events during the past 5,000 yr. The stratigraphic record at Portage, Girdwood, and other tidal marshes along upper Cook Inlet suggests that 1964-style (Mw 8-9) earthquakes have occurred in the region an average of every 600-800 yr. This generally agrees with the record of uplift events preserved at Copper River Delta and Middleton Island along the Gulf of Alaska coast.

Waypoint 6 Portage Glacier Access Road Intersection: N60.81966° W149.46521°, Continue past this intersection staying on the Seward Highway. The Portage Glacier road headed east (left) leads to Begich, Boggs Visitor Center maintained by the Forest Service. Portage Lake and Portage Glacier are popular tourist destinations.

Waypoint 7 Turnagain Pass: N60.78807° W149.21002°, The pass enters a broad glacial valley that has numerous visible landforms from the late Wisconsin and early Holocene glaciation of the area, including terminal moraines, lateral moraines, kame terraces, proglacial-lake basins, and ice-marginal channels and benches (Comebelick, 1984).

Waypoint 8 Hope Junction: N60.78062° W149.43183°, This junction leads to the small community of Hope, AK. Continue past this intersection remaining on the Seward Highway.

Waypoint 9 Sterling Highway/Seward Highway Junction: N60.54189° W149.56228°, Take exit to the right for the Sterling highway. This intersection has changed considerably in the last two years. The return point is not the same as the exit and comes out a few tenths of a mile further south of this exit.

Waypoint 10 Cooper Landing: N60.49052° W149.82383°, This waypoint is located at the Tesoro gas station on the north side of the road (right) in this small community.

Waypoint 11 Kenai-Russian River Ferry Access: N60.48790° W150.00058°, This is another popular fishing destination. A Forest Service campground is located near here and there are several cultural and historical sites in this area.

Waypoint 12 Sterling, AK: N60.53783° W150.77445°, Waypoint located at the weigh station. This community expanded after the discovery of oil and gas at Swanson River north of the highway. This was the first economic discovery in Alaska with production from this and surrounding plays continuing today.

Waypoint 13 Sterling Highway/Kenai Spur Road intersection, Soldotna, AK: N60.48717° W151.05488°, Turn right (north) on Kenai Spur Road. Follow out of town towards Kenai, AK.

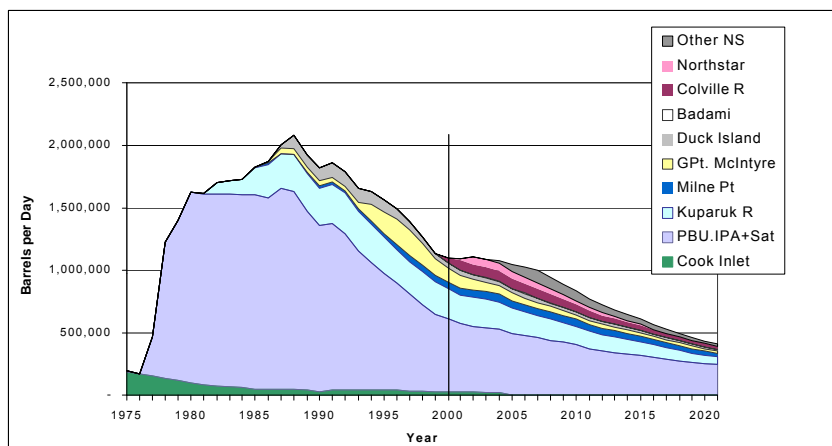
Waypoint 14 Kenai Spur Road/Warren Ames Bridge Access Road, Kenai, AK: N60.55834° W151.23941°, Continue through on the Kenai Spur Road through town and head north towards Nikiski.

Waypoint 15 Agrium Agriculture Fertilizer Plant: N60.67393° W151.37236°, This plant is a major consumer of natural gas from Cook Inlet.

- Of the roughly 8.3 TCF of gas that has been discovered in the Inlet, over 90 % was discovered prior to 1968 (the year Prudhoe Bay was discovered).
- All of the major fields, which account for over 90 % of the original reserves, were discovered while drilling for deeper oil objectives.
- Present recoverable reserves (behind pipe) are around 2.7 TCF.
- Present consumption is around 215 bcf/yr.
- Major consumers include: Utilities @ 60 bcf/yr (Enstar, Chugach Electric, ML&P), Urea Plant @ 54 bcf/yr, LNG plant @ 78 bcf/yr, Field operations and other @ 23 bcf/yr.
- Present contracts call for interruption in industrial supply to satisfy deliverability to local consumers if the need arises. Enstar's requirements follow a distinct seasonal swing (obviously based on the weather).

Waypoint 16 Tesoro Road: N60.68679° W151.38211°, This road leads to the main production facility for the Tesoro Alaskan Refinery. Cook Inlet production supplies most of the oil refined by Tesoro (72,000 bbls/day total production capacity). A small portion of oil is tankered in from Valdez. Cook Inlet's contribution to the total volume of throughput should improve with production from Forrest's Osprey Platform.

Historical and Projected Alaska Oil Production 1975 - 2021



From AK DNR

Waypoint 17 Salamatof Road Junction: N60.68437° W151.38061°, We won't be taking this route on this field due to lack of bus turnaround space. This ~0.5 mile drive west (left) leads to the shores of Cook Inlet and a view of the offloading docks where oil and LNG are loaded on tankers. The end of the road is at N60.68329° W151.39096°.

Waypoint 18 Nikiski Beach Road: N60.73100° W151.29943°, Turn left (west) onto Nikiski Beach Road.

Stop 3

Waypoint 19 Nikiski Docks overlook: N60.74162° W151.30343°, At this location we get a fine view (weather permitting) of Cook Inlet. On the other side of the inlet, the Bruin Bay Fault bounds the northwestern edge of this forearc basin. Several active arc-volcanoes line this side of the Cook Inlet. On a good day, over a dozen offshore platforms can be seen in the inlet. North of Redoubt Volcano, onshore exploration and production are occurring at the West McArthur River Unit by Forcenergy and Unocal. The sea cliff exposures here are mapped as Quaternary surficial deposits (Magoon et al., 1976) mostly of glacial origin (Reger et al., 1995; Reger and Pinney, 1996). Age control is limited to a few radiocarbon dates of peat at the very top of the section and organic material from an estuarine silt near the mouth of the Kenai River (Combelick and Reger, 1994; Reger et al., 1996).

Phillips operates several fields in Cook Inlet, North Cook Inlet Gas Field, Beluga Gas Field, and Lone Creek/Moquawkie Field. The Tyonek platform taps the North Cook Inlet Gas Field with the entire feed going to the Kenai LNG plant. In July 2000, the Beluga Gas Field produced 21 net mmcf/d for customers in south central Alaska. Based on the Lone Creek gas discovery well, Phillips and a co-venturer completed an offset delineation well near the existing Beluga field on the west side of Cook Inlet. This well was determined to

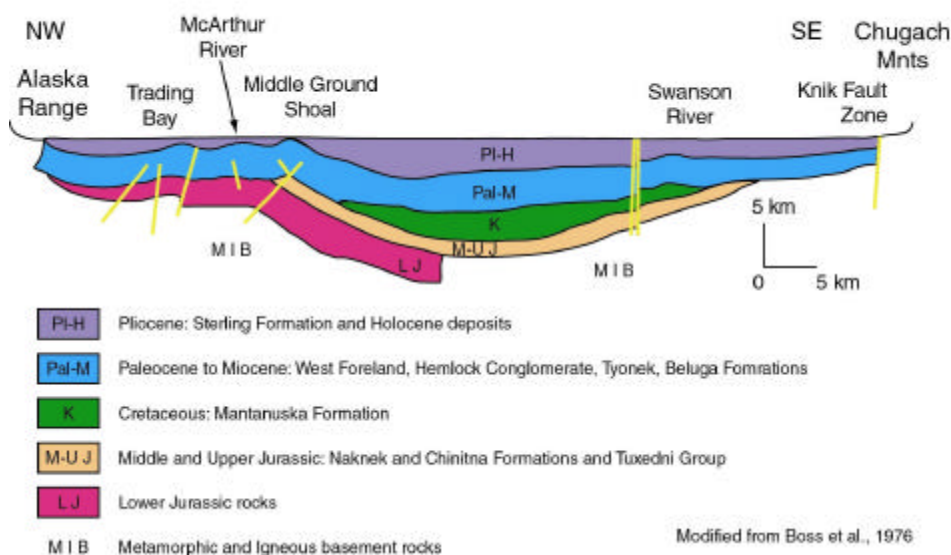
be non-commercial, however gas sales from the Lone Creek discovery well are planned for January 2002. Recent area-wide lease sales by the state of Alaska have allowed Phillips to increase its undeveloped exploration acreage in the Cook Inlet area by 41,800 acres to a total of 48,800 acres. Information in the previous paragraph is from the web page:

(<http://www.phillips66.com/newsroom/operations/alaska.html#Alaska>, 4-17-01)

Cook Inlet Oil Fields



Central Cook Inlet Cross Section



Return to waypoint 18 and turn right (south) onto Kenai Spur Highway.

Stop 4

Waypoint 20 Phillips/Marathon LNG Plant: N60.67842° W151.37575°, For this field trip we will be given a short tour of this research facility. Phillips and Marathon are 70/30 partners in the LNG facility. Both companies provide gas to the plant. Phillips' supplies gas exclusively from the Tyonek Platform for this project and operates the plant while Marathon runs the tankers that deliver LNG to markets in Japan. The facility has operated since 1969 with over 1000 tanker loads delivered to date. Tankers make the round trip voyage every 20 days. The facility processes 1.5 million tons per year of liquefied natural gas.



**Photo from <http://www.phillips66.com/photolibrary/images/93-57-31.gif>
Polar Eagle tanker loading at Kenai Plant**

Continue south on Kenai Spur Highway back towards Kenai, AK.

Waypoint 21 Kenai Spur Road/Warren Ames Bridge Access Road, Kenai, AK: same waypoint as 18, N60.55834° W151.23941°, Turn right (south) onto Warren Ames Bridge Access Road and cross the Kenai River.

Waypoint 22 Warren Ames Bridge Access Road/Kalifornski Beach Road intersection: N60.51840° W151.20237°, Turn right (west) onto Kalifornski Beach Road.

Waypoint 23 Kenai Gas Field, intersection into production/office area: N60.47534° W151.27695° Marathon began operating the Kenai Gas Field in 1993. Gas from Sterling,

Beluga and Tyonek reservoirs flows to local gas markets and the LNG facility. The field has produced since 1961 and still has a solid future. Marathon is currently drilling additional development wells within the field to develop new reserves identified in recent years. The Glacier Rig #1 (owned by Marathon and operated by Inlet Drilling) has been active in the field since May 2000. The made for purpose rig is truck mounted, has a significantly reduced foot print and takes far fewer loads to move between locations. The rig has already exceeded operational expectations. Drilling projects in its brief history have included horizontal and extended reach wells at Kenai Gas Field and other Marathon projects.



Photo by T. Dallegge of Rig setup at Beaver Creek

Waypoint 24 Kalifornski Beach Road/Sterling Highway intersection: N60.32429° W151.25511°, Turn right (west) onto the Sterling Highway towards Homer, AK.

Waypoint 25 Clam Gulch State Recreation Area intersection: N60.23351° W151.38572°, Beach access available here as well as a nice state campground. We will visit this location on Day 2.

Waypoint 26 Corea Creek: N60.17211° W151.44353°, At the mouth of Corea Creek in the beach cliffs a fault is noticeable near the creek.

Stop 5

Waypoint 27 Photo stop: N60.15427° W151.49661°, Nice overlook of Cook Inlet and volcanoes Redoubt and Illiamna.

Waypoint 28 Crossing of Ninilchik River: N60.05564° W151.64885°

Waypoint 29 Crossing of Deep Creek: N60.03029° W151.68116°

Waypoint 30 Anchor Point community: N59.78439° W151.83179°

Waypoint 31 Diamond Gulch Bridge over Diamond Creek: N59.66973° W151.66712°, Over 550 meters of Beluga Formation is exposed in the beach cliffs at the mouth of Diamond Creek. Rocks north of the creek dip to the southwest while rocks south of creek are nearly horizontal. A concealed fault with unknown displacement has been reported here (Karl et al., 1997). Composite sections of the Beluga Formation in these beach cliffs make up the Homerian paleobotanical stage designated by Wolfe et al. (1966). Other than a few reported fish fossils, leaves and pollen are the only paleontological evidence ever reported for the Kenai Group.

Stop 6

Waypoint 32 Homer overlook: N59.65500° W151.62584°, This is a popular photo stop overlooking Kachemak Bay and the Kenai Mountains. Kachemak Bay is a deep fiord that is 40 kilometers long and 39 kilometers wide at the mouth. At the end of the Bay is the commercially developed Homer Spit. Most boating activity, including large commercial barging comes and goes from the docks on the Homer Spit. This spit formed as a submarine end-moraine complex by the partial grounding of a tidewater glacier that once occupied Kachemak Bay (Karl et al., 1997). Icefields and alpine glaciers cover the Kenai Mountains across the bay. These mountains are part of the same accretionary wedge that we drove past in Turnagain Arm and Cooper Landing area. The Border Ranges Fault runs along the edge of the mountains and Kachemak Bay separating the accretionary wedge from the forearc basin that accumulated the Tertiary Kenai Group. The Beluga Formation is exposed in the cliffs below and is predominately composed of large sandstone beds with minor mudstone and subbituminous coal. We will visit these outcrops the following day. On a clear day the symmetrical cone of Augustine Volcano can be seen at the southern limits of Cook Inlet some 100 kilometers to the southwest. Across the bay on the southern shores near Seldovia, AK and continuing further to the west, are limited exposures of the Tyonek Formation. These deposits are thin and discontinuous and are juxtaposed up against the Border Ranges Fault system. Fossil plant specimens from these locations were used to define the Seldovian paleobotanical stage (Wolfe et al., 1966).

Waypoint 33 Homer Business District junction: N59.64297° W151.52283°, Continue straight through the intersection, the road changes names to Homer Spit Road. A left turn would put you in the business district of Homer. Follow Homer Spit Road to the “lands end.”

Waypoint 34 Lands End Resort: N59.60130° W151.40797°, This is our destination for the first day. We will be staying at this resort and enjoying the lovely views of Kachemak Bay and the Kenai Mountains.

Day 2

From the northeastern edge of the resort we have a view of the hills above Homer and can see beach cliffs extending up the northern shores of Kachemak Bay. In the hills above Homer, outcrops of Sterling Formation are visible in stream and road cuts. At beach level the outcrops toward the mouth of Kachemak Bay are composed of Beluga Formation deposits. The boundary between the Beluga and Sterling Formations has been proposed near the mouth of McNeil Canyon up the northeast end of the bay based on projections from the subsurface (Adkisson et al, 1972). The boundary between the Homerian and Clamgulchian paleobotanical stage was coincidentally placed near this location (Wolfe et al., 1966) at the B coal of Barnes and Cobb (1959). Triplehorn et al. (1977) recorded several K-Ar ages from volcanic ash partings in coal above and below the B coal. They assigned an average age of 8 Ma for the boundary between the two paleobotanical stages. The depositional environment for the Homerian age rocks were interpreted as braided-meandering fluvial systems while the Clamgulchian age rocks were considered meandering fluvial systems (Rawlinson, 1984). Rawlinson (1979, 1984) determined from provenance and paleocurrent studies that the source area for the Beluga and Sterling Formations in Kachemak Bay was from the Kenai Mountains.

Proceed back up Homer Spit Road past waypoint 33 through Homer staying on the Sterling Highway.

Stop 7

Waypoint 35 Ocean Shores Hotel/Alaska National Wildlife Refuge Visitor Center: N59.64271° W151.55337°, We will be taking a short walk down the beach to look at the Beluga Formation and the Cooper coalbed. Access to this beach is across private property owned by the Ocean Shores Motel, permission is required. Checking a local tide table is advised prior to attempting this trek. Walk ~0.5 km (25 minutes) down the beach to the west to at least N59.64218 W151.57886.

The Beluga Formation at this location consists primarily of thick (4.5-25 m), stacked (3-5 individual units), sharp based, laterally extensive, lenticular sandstone packages that are interbedded with thin fine-grained units consisting of coal and carbonaceous shale (Flores et al., 1997). Formation of these sandstone packages is interpreted as deposition from channelized flows of a composite braided and low-sinuosity meandering stream system (Flores and Stricker, 1992, 1993a, 1993b).

From this location, several coal horizons can be seen interbedded within the large channel sandstone complexes of the upper Beluga Formation. The 1.2-1.5 meter thick coal in the cliffs above is the Cooper coal bed of Barnes and Cobb (1959). This coal bed extends around to the west toward the Bluff Point-Diamond Gulch areas (Barnes and Cobb, 1959; Flores et al., 1997). Laterally extensive thick coals such as the Cooper coal bed would make good shallow coalbed methane targets on the Kenai Peninsula.

Recently the state of Alaska has opened areas across the state for shallow gas exploration. The requirements for these leases are not as restricted and expense as conventional leases thus allow for smaller companies to get involved in the search for coalbed methane (CBM) and other shallow gas resources.

Alaska State Shallow Gas Leases

Non-competitive leases for natural gas and CBM within 3000 feet of the surface

No bonus, only application fee of \$500 and annual rental of \$0.50 per acre

The royalty is set at 6.25%

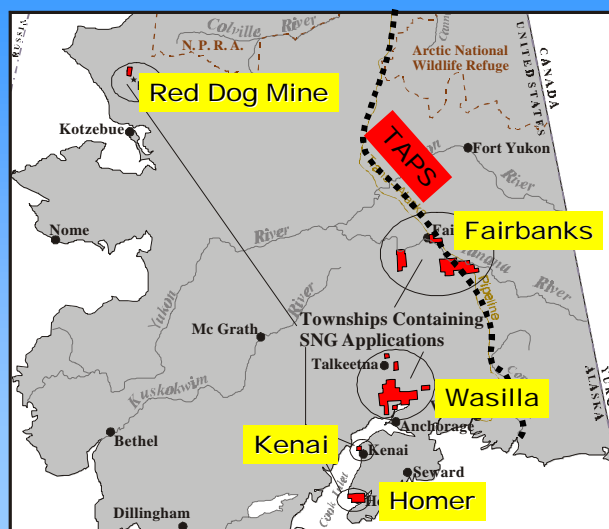
The term of the lease is limited to 3 years

Lease is renewable with production

A shallow gas lease may consist of up to 5,760 acres

A lessee may not hold more than 46,080 acres (two townships) within this program

Applications for Shallow Natural Gas Leases:



Base Map From Alaska DNR (2001)

Update on Coalbed and Conventional Shallow Gas Exploration – Homer Area,

(Reference: modified from <http://home.gci.net/~lapres/>, 4-17-01)

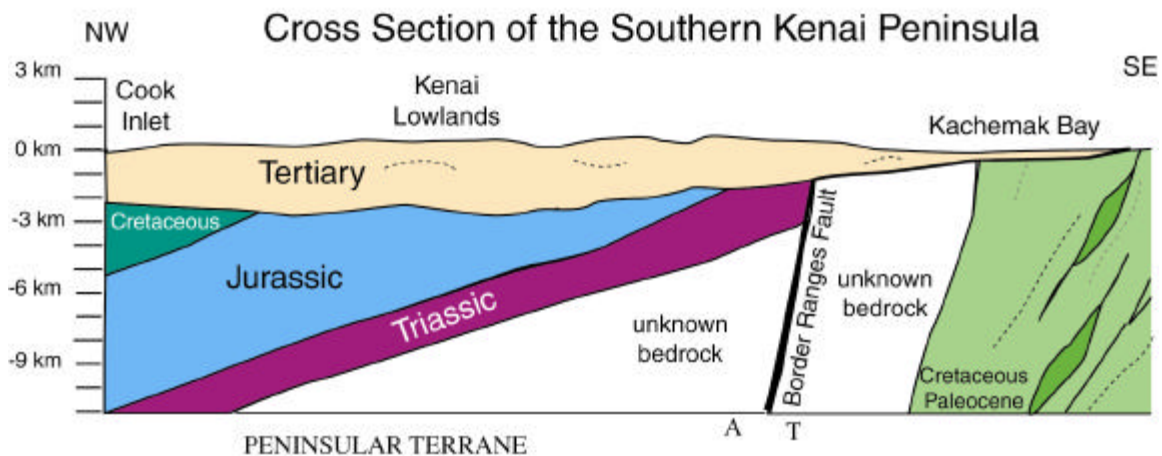
...LAPP Resources, Inc., among others, recently applied for Alaska State Shallow Natural Gas leases to explore for CBM and natural gas in the Homer area. Homer is not currently supplied with natural gas and local residents use a variety of fuels including beach coal, wood, propane, oil, and electricity to provide space heating. The Homer area is not on a gas pipeline system and the area's 10,000 residents are not thought to be a large enough economic market to extend the existing gas pipeline system from the Kenai area. If successful in finding producible gas in shallow wells, it will be possible to provide a cleaner low-cost energy source for the community. This development plan has the advantage of not requiring a costly pipeline to the community from the gas fields to the north. Rather, the gas will be supplied from under or near the town and supply the local market only.

Return to Ocean Shores Hotel

Waypoint 36 Go north on the Sterling Highway to Diamond Ridge Road: N59.67442° W151.67464°, Turn right (east) on Diamond Ridge Road and follow it to waypoint 37.

Waypoint 37 Skyline Road junction: N59.66471° W151.56973°, Turn left (north) at the stop sign on Skyline Road and follow it to waypoint 38.

Waypoint 38 Sterling quarry: N59.66943° W151.56236°, The quarry is located on private property, permission is advised. This quarry cuts a sandstone-dominated section of the middle to upper Sterling Formation. The sandstone ranges from volcanoclastic to arkosic with abundant wood clasts, leaf imprints, and mudstone rip-up clasts noted (Karl et al., 1997). Net to gross ratios in the Sterling are 60 to 70% with porosity and permeability in Sterling sands that can get as high as 28% porosity and 2 Darcies of permeability.



Modified from Bradley et al., 1999

Retrace path back through waypoint 37 to waypoint 36 at the junction of the Sterling Highway and Diamond Ridge Road. Go north (right) on the Sterling Highway headed back toward Seldotna, AK to waypoint 25 (mile 117.8) at the Clam Gulch Recreational Area. Turn left (west) at the brown park state sign and follow road to the campground and waypoint 39.

Stop 8

Waypoint 39 Clam Gulch Campground: N60.23918° W151.39433°, take the right into the campground area, the road continues down to the beach but is narrow and has little area to turnaround in on the sandy beach. Four-wheel drive is recommended for beach access. During the off-season, the campground is unattended and we will pull around the loop and park in the extra parking area near the exit. There is an additional overflow parking area along the road if needed. Walk down the road to the beach (N60.23990 W151.39909).

Prominently lying in the intertidal zone are several large boulders of igneous rocks deposited as glacial dropstones probably derived from Alaska-Aleutian Range on the west

side of Cook Inlet (Reger and Pinney, 1997). Extending north and south from this location we can see beach cliff outcrops of the lower Sterling Formation. The Sterling here is composed of ~70% sandstone, 25% siltstone, and 5% coal-shale (Flores et al., 1997) that has been interpreted to represent meandering stream deposits (Hayes et al., 1976; Flores et al., 1997).

Wolfe et al. (1966) designated this locality the type section for the Clamgulchian stage. K-Ar dating of volcanic ash from the coals here places imprecise ages between 9 and 5 Ma with several ages out of stratigraphic continuity (see Figure 2, Dallegge and Barker, this volume). Using the more precise $^{40}\text{Ar}/^{39}\text{Ar}$ method at the University of Alaska Fairbanks, T. A. Dallegge hopes to better define the age and lateral and vertical relations of the Kenai Group stratigraphy within Cook Inlet Basin. Several volcanic ash beds have been collected from this locality and dateable materials are currently awaiting analysis.

To the south where the beach cliffs bend back toward the west, a black band can be noted near the beach level. This black band is two coal seams separated by an altered volcanic ash bed. The strata containing the coal beds are slightly folded into a synclinal form. The coal beds are ~0.5 meter in total thickness and continue some distance laterally before they disappear beneath the recent colluvium and vegetation cover along the beach. Further to the south, near the mouth of Corea Creek (just around the point), fisherman have mentioned that at extreme low tides, extensive coal beds are exposed by the waves offshore and large volumes of coal can be ripped up by storms and strewn along the beach. This area apparently has fairly extensive beds of coal and may be a potential area for exploring for shallow coalbed methane.

Return to the parking area and proceed back to the junction with the Sterling Highway. Go north and follow the Sterling Highway past waypoint 24 and on into Soldotna. On the other side of Soldotna, you will go through the junction at waypoint 13. Continue on the Sterling Highway back to the Seward Highway and on to Anchorage.

References Cited

- Adkison, W. L., Kelley, J. S., and Newman, K. R., 1975, Lithology and palynology of the Beluga and Sterling Formations exposed near Homer, Kenai Peninsula: U.S. Geological Survey Open-File Report 75-383, 239 p.
- Barnes, F. F., and Cobb, E. H., 1959, Geology and coal resources of the Homer district, Kenai coal field, Alaska: U.S. Geological Survey Bulletin 1058-F, p. 217-260.
- Bradley, D.C., Kusky, T.M., Karl, S.M., Haeussler, P.J., 1997, Field Guide to the Mesozoic accretionary complex along Turnagain Arm and Kachemak Bay, south-central Alaska, *in*: Karl, S.M., Ryherd, T.J., and Vaughn, N.R., eds., 1997 Guide to the geology of the Kenai Peninsula, Alaska: Alaska Geological Society, Field Trip Guidebook May 8-10, Anchorage Alaska, p. 1-12.
- Bradley, D.C., Kusky, T.M., Haeussler, P.J., Karl, S.M. and Donley, D.T., 1999, Geologic map of the Seldovia quadrangle, south-central Alaska: U.S. Geological Survey Open-File Report 99-18, map 1:250,000.
- Clark, S.H.B., 1981, Guide to bedrock geology along the Seward Highway north of Turnagain Arm: Alaska Geological Society, Publication no. 1, 36 p.
- Comebellick, R.A., 1984, Surficial-geologic map of the Seward D-6 quadrangle, Alaska: Alaska Division of Geological and Geophysical Surveys Report of Investigations 84-15, scale 1:63,360.

- Combellick, R.A., and Reger, R.D., 1994, Sedimentological and radiocarbon-age data for tidal marshes along eastern and upper Cook Inlet, Alaska: Alaska Division of Geological and Geophysical Surveys Report of Investigations 94-6, 60 p.
- Flores, R. M., and Stricker, G. D., 1992, Some facies aspects of the upper part of the Kenai Group, southern Kenai Peninsula, Alaska, *in*: Gradley, D. C., and Dusel-Bacon, C., eds., *Geologic studies in Alaska by the U.S. Geological Survey, 1991: U.S. Geological Survey Bulletin, 2041*, p. 160-170.
- Flores, R. M., and Stricker, G. D., 1993a, Interfluvial-channel facies models in the Miocene Beluga Formation near Homer, south Kenai Peninsula, Alaska, *in*: Roa, P. D., and Walsh, D. E., eds., *Focus on Alaska's coal 1993: Mineral Industry Research Laboratory, University of Alaska, Fairbanks*, p. 140-166.
- Flores, R. M., and Stricker, G. D., 1993b, Reservoir framework architecture in the Clamgulchian (Pliocene) Sterling Formation, Kenai Peninsula, Alaska, *in*: Dusel-Bacon, C., and Till, A. B., eds., *Geologic studies in Alaska by the U.S. Geological Survey, 1992: U.S. Geological Survey Bulletin 2068*, p. 118-129.
- Flores, R.M., Stricker, G.D., and Bader, L.R., 1997, Stratigraphic architecture of the Tertiary alluvial Beluga and Sterling Formations, Kenai Peninsula, Alaska, *in*: Karl, S.M., Ryherd, T.J., and Vaughn, N.R., eds., 1997 *Guide to the geology of the Kenai Peninsula, Alaska: Alaska Geological Society, Field Trip Guidebook May 8-10, Anchorage Alaska*, p. 36-53.
- Hayes, J. B., Harms, J. C., and Wilson, T. W., 1976, Contrasts between braided and meandering stream deposits, Beluga and Sterling Formations (Tertiary), Cook Inlet, Alaska, *in*: Miller, T. P., ed., *Recent and ancient sedimentary environments in Alaska: Alaska Geological Society Symposium, Proceedings*, p. J1-J27.
- Karl, S.M., Ryherd, T.J., and Vaughn, N.R., 1997, 1997 *Guide to the geology of the Kenai Peninsula, Alaska: Alaska Geological Society, Field Trip Guidebook May 8-10, Anchorage Alaska*, 128 p.
- Nelson, S.W., Blome, C.D., Harris, A.G., Reed, K.M., and Wilson, F.H., 1986, Late Paleozoic and Early Jurassic fossil ages from the McHugh Complex, *in*: Bartsch-Winkler, S., and Reed, K.M., eds., *Geologic Studies in Alaska by the U.S. Geological Survey during 1985: U.S. Geological Survey Circular 978*, p. 60-64.
- Rawlinson, S. E., 1979, Paleoenvironment of deposition, paleocurrent directions, and the provenance of Tertiary deposits along Kachemak Bay, Kenai Peninsula, Alaska [M.S. thesis]: Fairbanks Alaska, University of Alaska-Fairbanks, 162 p.
- Rawlinson, S. E., 1984, Environments of deposition, paleocurrents, and provenance of Tertiary deposits along Kachemak Bay, Kenai Peninsula, Alaska: *Sedimentary Geology*, v. 38, p. 421-442.
- Reger, R.D., Combellick, R.A., and Brigham-Crette, J., 1995, Update of latest Wisconsin events in the upper Cook Inlet region, southcentral Alaska, *in*: Combellick, R.A., and Tannian, F., eds., *Short notes on Alaska geology 1995: Alaska Division of Geological and Geophysical Surveys Professional Report 117*, p. 33-45.
- Reger, R.D., and Pinney, D.D., 1996, Late Wisconsin glaciation of the Cook Inlet region with emphasis on Kenai Lowland and implications for early peopling, *in*: Davis, N.Y., and Davis, W.E., eds., *Adventures through time: Readings in the anthropology of Cook Inlet, Alaska: Anchorage, Cook Inlet Historical Society*, p. 15-35.
- Reger, R.D., and Pinney, D.D., 1997, Last major glaciation of Kenai Lowland, *in*: Karl, S.M., Ryherd, T.J., and Vaughn, N.R., eds., 1997 *Guide to the geology of the Kenai Peninsula, Alaska: Alaska Geological Society, Field Trip Guidebook May 8-10, Anchorage Alaska*, p. 54-67.
- Wolfe, J. A., Hopkins, D. M., and Leopold, E. R., 1966, Tertiary stratigraphy and paleobotany of the Cook Inlet region, Alaska: U.S. Geological Survey Professional Paper 398-A, p. A1-A29.