Geologic Model and Assessment of Potential Unconventional (Tight) Gas Resources in Upper Cook Inlet Basin, South-Central Alaska

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By Christopher J. Schenk and Philip H. Nelson

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Assessment of Unconventional (Tight) Gas Resources in Upper Cook Inlet Basin, South-Central Alaska

Compiled by C.J. Schenk

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Geologic Model and Assessment of Potential Unconventional (Tight) Gas Resources in Upper Cook Inlet Basin, South-Central Alaska

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Abstract

A geologic model was developed for the assessment of potential Mesozoic tight-gas resources in the deep, central part of upper Cook Inlet Basin, south-central Alaska. The basic premise of the geologic model is that organic-bearing marine shales of the Middle Jurassic Tuxedni Group achieved adequate thermal maturity for oil and gas generation in the central part of the basin largely due to several kilometers of Paleogene and Neogene burial. In this model, hydrocarbons generated in Tuxedni source rocks resulted in overpressure, causing fracturing and local migration of oil and possibly gas into low-permeability sandstone and siltstone reservoirs in the Jurassic Tuxedni Group and Chinitna and Naknek Formations. Oil that was generated either remained in the source rock and subsequently was cracked to gas which then migrated into low-permeability reservoirs, or oil initially migrated into adjacent low-permeability reservoirs, where it subsequently cracked to gas as adequate thermal maturation was reached in the central part of the basin. Geologic uncertainty exists on the (1) presence of adequate marine source rocks, (2) degree and timing of thermal maturation, generation, and expulsion, (3) migration of hydrocarbons into low-permeability reservoirs, and (4) preservation of this petroleum system. Given these uncertainties and using known U.S. tight gas reservoirs as geologic and production analogs, a mean volume of 0.64 trillion cubic feet of gas was assessed in the basin-center tight-gas system that is postulated to exist in Mesozoic rocks of the upper Cook Inlet Basin. This assessment of Mesozoic basin-center tight gas does not include potential gas accumulations in Cenozoic low-permeability reservoirs.

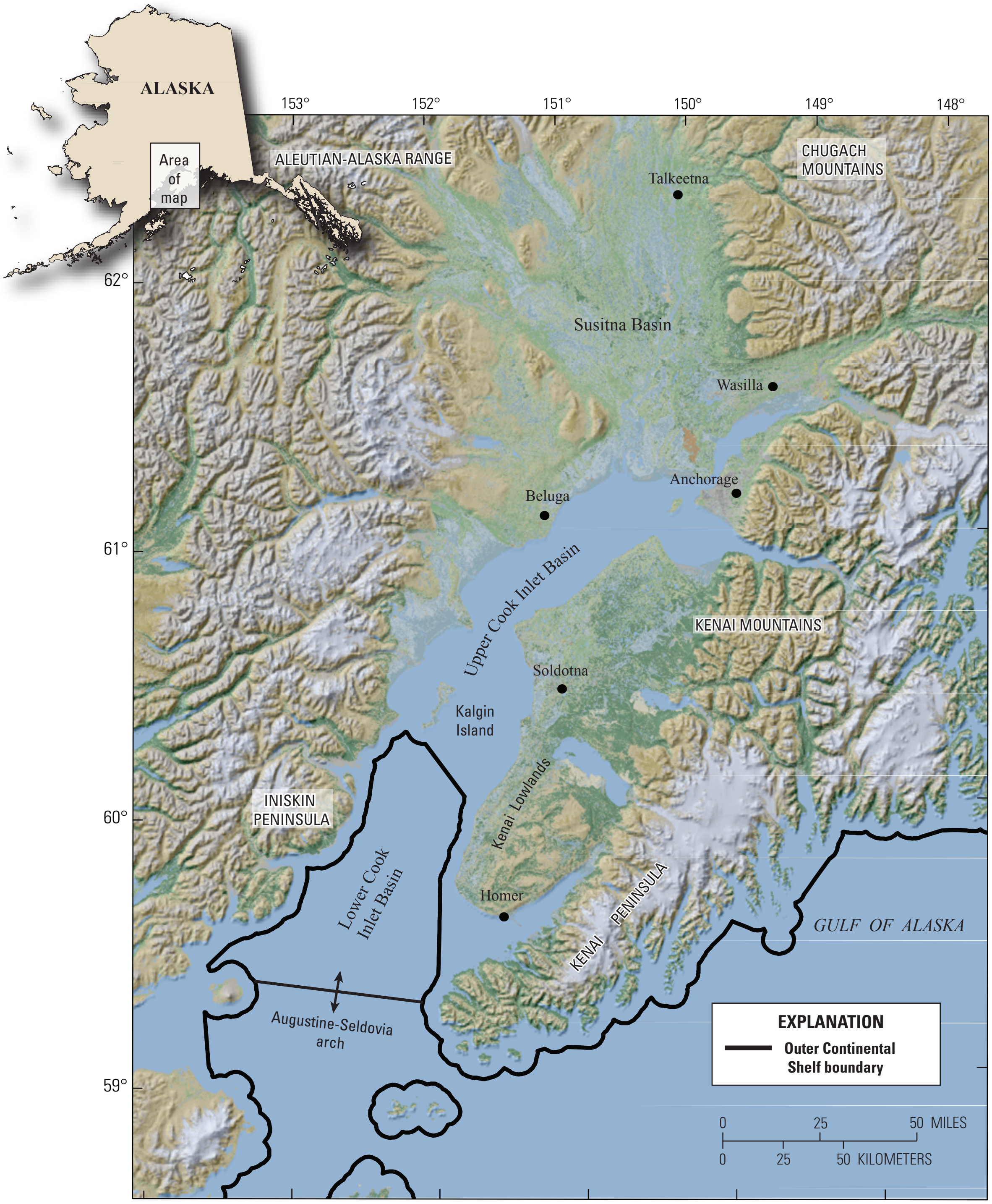
Introduction

A core function of the Energy Resources Program of the U.S. Geological Survey (USGS) is the assessment of undiscovered, technically recoverable conventional and unconventional (continuous) oil and gas resources in U.S. basins. As part of the assessment effort, the upper Cook Inlet Basin of south-central Alaska (fig. 1) was recently assessed for both conventional and unconventional resources (Stanley and others, 2011). Since the first oil and gas discoveries at Swanson River Field in 1957 and at Kenai Gas Field in 1959, more than 30 conventional fields have been discovered in upper Cook Inlet Basin with cumulative production (as of 2010) of 1.3 billion barrels of oil and 7.4 trillion cubic feet of gas. Geochemical analysis of oil and gas in these conventional fields demonstrates the presence of a Mesozoic thermogenic marine oil and gas system and a Cenozoic biogenic gas system (Claypool and others, 1980). The presence of a thermogenic petroleum system suggests that unconventional resources might be possible, such as shale-oil, tight-oil, shale-gas, or tight-gas. These types of resources have not been previously assessed in the upper Cook Inlet Basin.

This paper presents a geologic model developed as the basis for a quantitative assessment of potential thermogenic tight-gas resources in Mesozoic rocks in the central part of upper Cook Inlet Basin (fig. 1). Coalbed gas resources of the Cook Inlet–Susitna Basins were assessed (fig. 1; Rouse and Houseknecht, 2012), and potential shale-gas, tight-oil, and shale-oil resources were evaluated, but not quantitatively assessed (Stanley and others, 2011).

The focus of this study is the Mesozoic section in upper Cook Inlet Basin as potential marine source rocks and associated unconventional, low-permeability reservoirs are postulated to be in Jurassic rocks. Low-permeability Cenozoic sandstones are known to exist in upper Cook Inlet Basin (Hickey and others, 2007; Helmold and others, 2011), but these sandstones are not included in this assessment of the Mesozoic section in the deep, central part of the basin. The well-known Cenozoic nonmarine section in upper Cook Inlet Basin is important for the thickness of overburden that served to seal and mature potential Jurassic marine source rocks (Magoon, 1994a).

Following a brief review of resource definitions, the tectonic history, stratigraphy, reservoirs, thermal maturation, and overpressure are reviewed as background for the development of a geologic model used in the assessment of the central part of upper Cook Inlet Basin.



Base credit: US National Park Service

Figure 1. Location map showing Cook Inlet Basin in south-central Alaska. The Outer Continental Shelf (OCS) boundary is shown by black line. Kalgin Island separates the informal lower from upper Cook Inlet Basin.

Definition of Conventional and Unconventional Resources

For assessment purposes, the USGS recognizes conventional and unconventional oil and gas resources (fig. 2). Briefly, conventional oil and gas accumulations: (1) are buoyant upon a water column, (2) have well-defined areal extents called "fields," (3) are outlined by dry holes, (4) have good reservoir properties, (5) can have water production increasing with time relative to oil or gas, (6) have well-defined traps and seals, and (7) have high recovery factors. Conventional resources span the spectrum from structurally to stratigraphically trapped oil or gas accumulations. Exploration in upper Cook Inlet Basin has focused on structurally trapped conventional accumulations, and potential remains for undiscovered stratigraphically trapped oil and gas (Thomas and others, 2004).

Unconventional (continuous) oil and gas accumulations differ from conventional in several aspects (fig. 2). In general, unconventional oil and gas accumulations: (1) are regional in extent, (2) have few truly dry holes, (3) have only local to no migration of hydrocarbons (source rocks are reservoirs or in close proximity to reservoirs), (4) have low permeability and porosity, (5) have variable water production, (6) are generally not buoyant upon water, (7) have no well-defined trap or seal, (8) have Estimated Ultimate Recoveries (EUR) generally lower than conventional wells, (9) have abnormal pressures, and (10) require artificial stimulation for primary production, most commonly by hydraulic fracturing.

These general guidelines reflect the definition of end-member accumulations. With unconventional resources, the focus is on the source rock-reservoir rock system, as generally they are one and the same (shale oil, shale gas, coalbed gas) or are in close proximity (tight oil, tight gas) forming stratigraphically constrained systems.

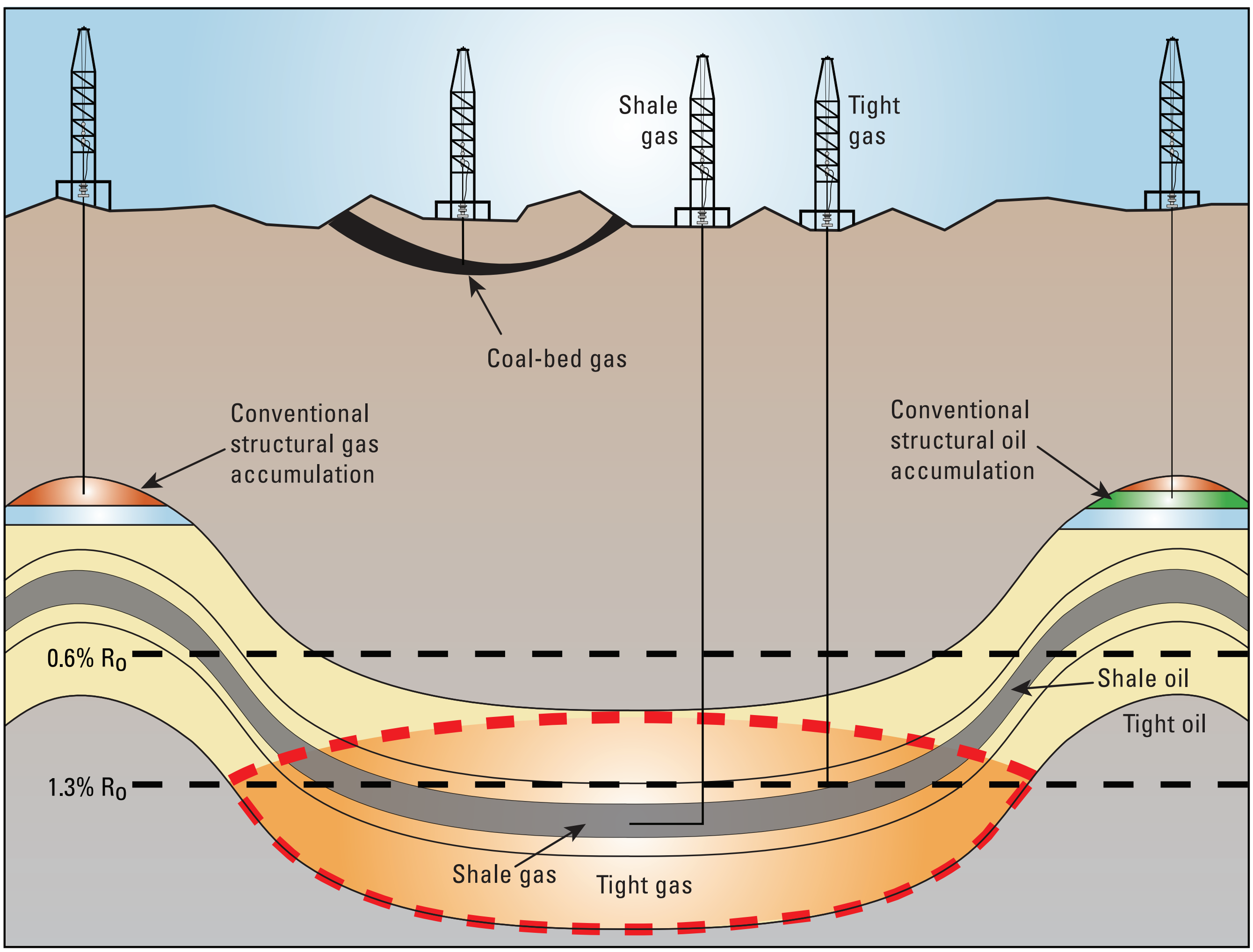


Figure 2. Schematic diagram illustrating conventional and unconventional oil and gas accumulations as used in assessments by the U.S. Geological Survey. Shale gas, shale oil, tight gas, tight oil, and coalbed gas are unconventional accumulations. (R_o, vitrinite reflectance)

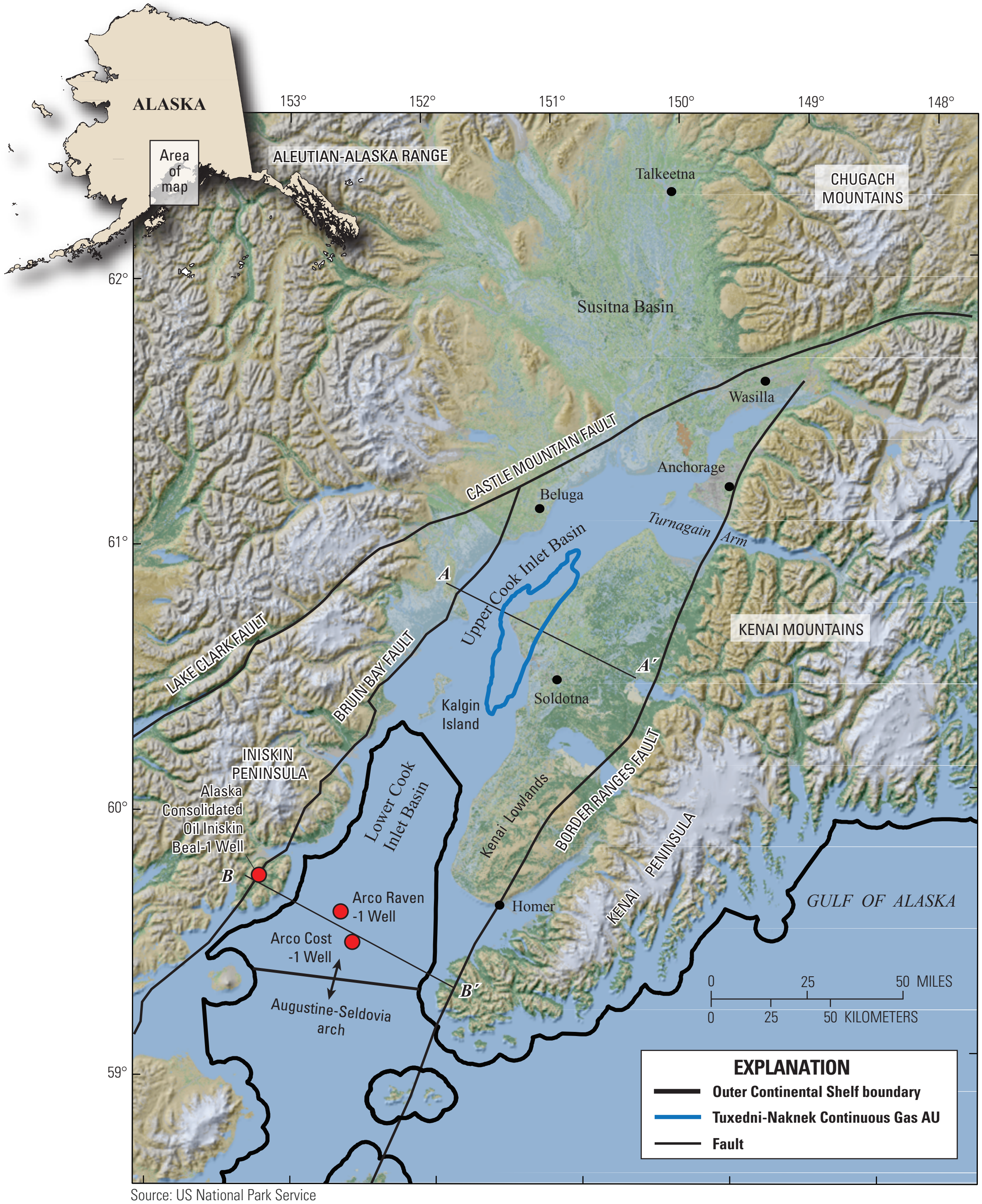


Figure 3. Map of Cook Inlet Basin showing boundaries defined by Border Ranges fault, Castle Mountain fault, Bruin Bay fault, and Augustine-Seldovia arch. Kalgin Island provides an informal distinction between upper and lower Cook Inlet Basin. Lines of cross section are shown in figure 6. Shown are locations of the ARCO COST–1 well, ARCO Raven–1 well, and the Alaska Consolidated Oil Iniskin Beal–1 well. The Chugach accretionary complex includes the Chugach Mountains, Kenai Mountains, and Kenai Peninsula south of the Border Ranges fault. Faults are from Haeussler and others (2000).

Mainly for tax purposes, tight gas was defined in the United States for many years as potential reservoir rock with a permeability of 0.1 millidarcy (mD)or less. With time, this definition has been relaxed to include reservoirs that are generally near this threshold of permeability but are known to have a requirement of stimulation to enhance or initiate production (Holditch, 2006). For most tight-gas reservoirs, production is achieved by hydraulic fracturing of stacked, low-permeability reservoirs utilizing closely spaced vertical wells that intersect as many lenticular, gas-charged sandstone bodies as possible. In contrast, recent production from shale-gas and shale-oil reservoirs is mainly from the horizontal drilling segments of a well with multiple stages of stimulation and completion.

Location of Cook Inlet Basin

Cook Inlet Basin is located in south-central Alaska, and includes the city of Anchorage, Alaska's largest metropolitan area (figs. 1 and 3). For several decades, Anchorage has relied heavily on natural gas from Cook Inlet Basin for electrical generation and commercial purposes. Cook Inlet Basin is bounded to the north by the Castle Mountain fault and to the northwest by the Bruin Bay fault, which largely separate fore arc rocks from Alaska and Aleutian Range arc and related rocks (fig. 3). To the east and southeast, the Border Ranges fault separates Cook Inlet fore arc rocks from the partly coeval Chugach accretionary complex (Pavlis, 1982), which forms the Chugach and Kenai Mountains (Plafker and others, 1994; Gasser and others, 2012; Scharman and Pavlis, 2012). For this paper, the southwestern limit of the basin is defined by the northwest-southeast trending Augustine-Seldovia arch (fig. 3). Cook Inlet Basin is informally divided into an upper Cook Inlet Basin and a lower Cook Inlet Basin, with the dividing line at or about the location of Kalgin Island (fig. 1). For oil and gas assessments, the USGS is responsible for the U.S. onshore and state-waters area, and the Bureau of Ocean Energy Management (formerly Minerals Management Service) is responsible for the Outer Continental Shelf (OCS). The focus of this assessment is on upper Cook Inlet, as much of the lower Cook Inlet Basin resides in the OCS (fig. 1). Current oil and gas production is only from upper Cook Inlet Basin, as wells drilled and tested in lower Cook Inlet Basin have not been commercially successful.

Mesozoic and Cenozoic rocks crop out in proximity to the major basin-bounding faults and have provided much relevant information on Cook Inlet petroleum geology (Detterman and Hartsock, 1966; Blasko, 1976; Fisher and Magoon, 1978; LePain and others, 2011). Oil and gas exploration in lower Cook Inlet (fig. 3) dates back at least 100 years, and exploration was focused in this area due to numerous oil seeps and oil-stained outcrops. Early studies by the USGS were driven by the need to qualitatively assess the oil and gas potential of this area in the postwar years (Kirschner and Minard, 1949; Detterman and Hartsock, 1966). These studies documented the stratigraphy and depositional environments of the Jurassic stratigraphic units in particular, and are therefore relevant to this study.

Today, Cook Inlet Basin represents part of the forearc to the Aleutian subduction zone (Haeussler and others, 2000). The Kenai and Chugach Mountains represent the accretionary complexes that formed outboard of the forearc since the Cretaceous (fig. 3). The Border Ranges fault zone represents a paleo-subduction thrust that is now a dextral strike-slip fault separating the fore arc from rocks within the accretionary complex. The greater Cook Inlet area is perhaps one of the most studied arc-related terranes in the world, and the following is a brief summary of the tectonic history with selected references to enable us to place the Mesozoic section within the tectonic evolution of this complex continental margin.

Tectonic Evolution of Cook Inlet Basin

Mesozoic and Cenozoic rock units of the southern Alaska continental margin record a complex tectonic evolution that includes multiple episodes of subduction, terrane accretion, accretionary complex formation, arc- and non-arc related magmatism, deformation and exhumation, metamorphism, and basin-formation processes (Plafker and Berg, 1994; Plafker and others, 1994; Farris and others, 2006; Madsen and others, 2006; Trop and Ridgway, 2007; Trop, 2008). Cook Inlet Basin resides within the Peninsular terrane of the Wrangellia composite terrane (Nokleberg and others, 1994; Plafker and Berg, 1994; Clift and others, 2005a, b; Greene and others, 2010; Koons and others, 2010). This composite terrane is an amalgamation of at least three terranes (Peninsular, Alexander, and Wrangellia) that docked with each other and terminally with the North American continent between Late Jurassic to mid-Cretaceous time (Hillhouse, 1987; Nokleberg and others, 1994; Plafker and others, 1994). Major tectonic events that affected the Cook Inlet area include the evolution of the intra-oceanic Talkeetna arc system (Reed and others, 1983; Clift and others, 2005a, b), collision of Wrangellia composite terrane with North America (fig. 4), subduction of the Kula spreading ridge (Madsen and others, 2006; Scharman and Pavlis, 2012), and the late Neogene collision of the Yakutat terrane (Plafker and Berg, 1994; Pavlis and others, 2004; Koons and others, 2010). For the following tectonic summary, a three-part temporal division considers rock units deposited prior to (Pre-Collision), during (Syn-Collision), and post-accretion of (Post-Collision) the Wrangellia composite terrane, following the scheme of Trop and Ridgway (2007).

Pre-Collision Rock Units

Prior to collision with each other and with the North American plate, the Wrangellia, Peninsular, and Alexander terranes largely included south-facing intra-oceanic arc systems conveyed from more equatorial positions across

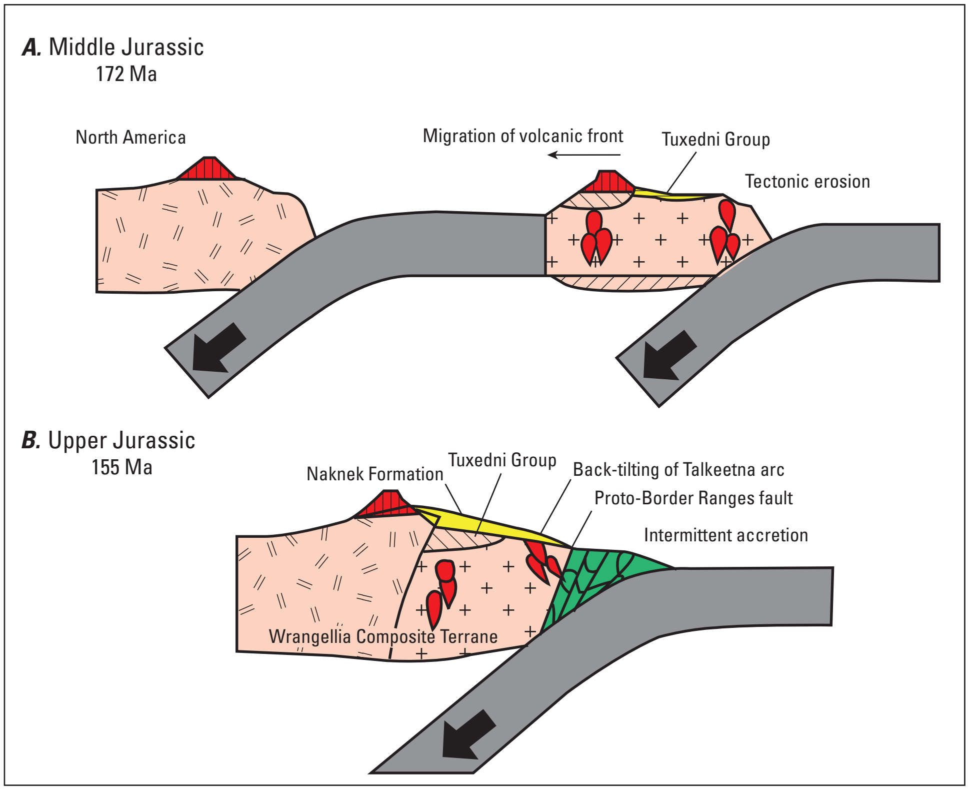


Figure 4. Schematic diagram illustrating Jurassic northeast dipping subduction as related to the Mesozoic stratigraphy of Cook Inlet Basin (modified from Clift and others, 2005b). *A*, Middle Jurassic fore arc and back arc marine facies of the Tuxedni Group (including potential source rocks and reservoir rocks) were deposited on the intra-oceanic Talkeetna arc platform. *B*, Initial collision of Talkeetna arc with North America in Late Jurassic led to synorogenic clastic deposition of the Naknek Formation, a potential tight-gas reservoir with the source being the Tuxedni Group. (Ma, million years ago; gray, oceanic crust; pink, continental crust; red, plutonic rocks; green, accretionary prism; yellow, clastic rocks)

the northern Pacific Basin by northeast-dipping subduction. Basement in these terranes is generally deformed and includes metamorphosed Paleozoic rocks. The focus of this paper is on the Talkeetna arc and the Peninsular terrane units that encompass the Cook Inlet area (Magoon, 1994a). The Upper Triassic Kamishak Formation (fig. 5), a sequence of marine-shelf carbonates and coeval deeper-water organic-bearing mudstones, represents the first sedimentary rocks above a prominent unconformity on deformed Permian rocks recognized in lower Cook Inlet Basin (Wang and others, 1988; Whalen and Beatty, 2008).

The marine carbonate environment of the Kamishak was succeeded in Early Jurassic time by deposition of up to 7 kilometers (km) of volcaniclastics, breccias, agglomerates, tuffs, and lava flows of the Talkeetna Formation (fig. 5), representing volcanic activity within the intra-oceanic Talkeetna volcanic arc (Clift and others, 2005a). By Middle Jurassic time, fore arc and back arc settings were firmly established on the intra-oceanic Talkeetna arc platform. Following volcanic sedimentation represented by the Talkeetna Formation, more than 3 km of near-shore marine sandstones, siltstones, and mudstones of the Middle Jurassic Tuxedni Group (fig. 5) onlapped the volcanic edifice of the Talkeetna Formation (LePain and others, 2011). Organic-bearing marine mudstones of the Tuxedni Group are postulated to be the principal petroleum source rocks for thermogenic oil and gas in the Cook Inlet Basin (Kelly, 1963; Osment and others, 1967; Fisher and Magoon, 1978; Magoon, 1994a, b; Peters and others, 2006; Lillis and Stanley, 2011). Conformably overlying the Tuxedni Group is a sequence of siltstones, minor conglomerates, and turbiditic sandstones of the Chinitna Formation (fig. 5), representing fine-grained deposition following a rise in sea level and the establishment of deep-marine environments.

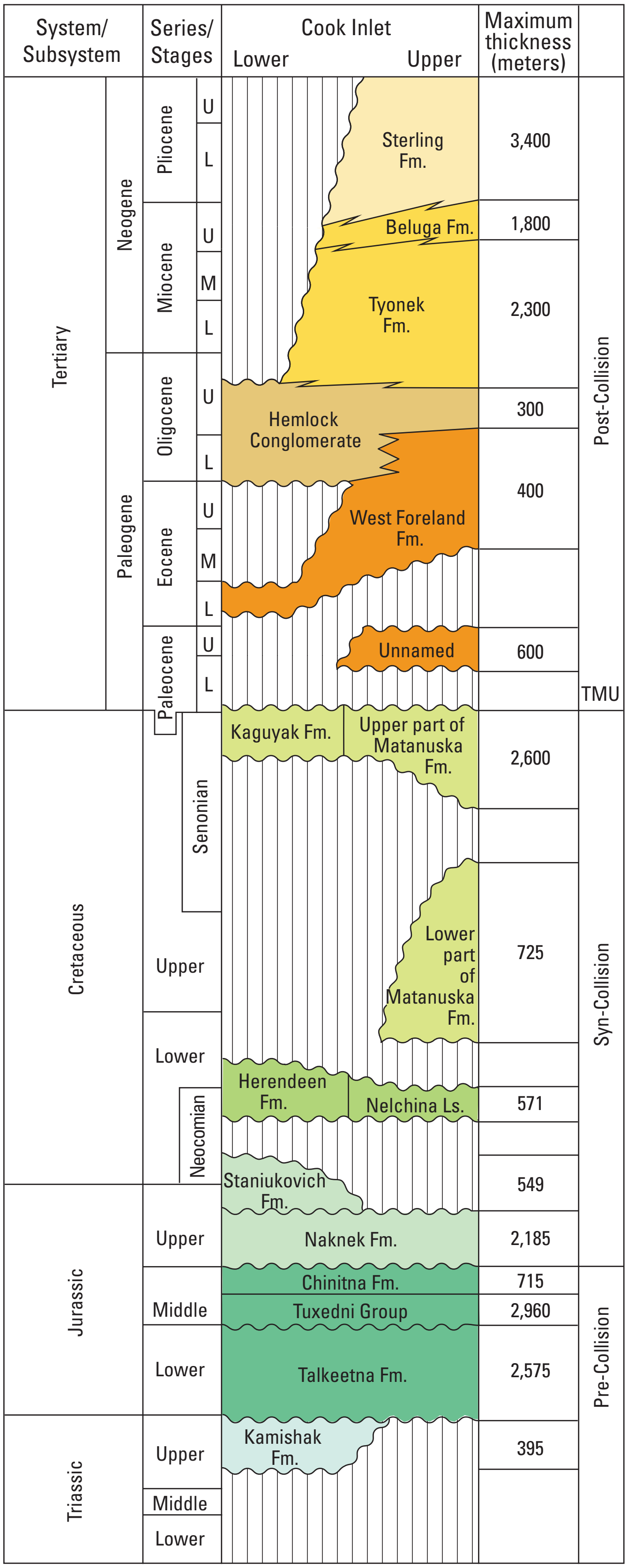


Figure 5. Generalized stratigraphy of Cook Inlet Basin, south-central Alaska. The Middle Jurassic Tuxedni Group includes potential petroleum source rocks; the Upper Jurassic contains potential reservoir rocks. The Cretaceous section illustrates unconformities and limited deposition as the Wrangellia composite terrane diachronously collided with North America. Subduction in the Paleogene of more buoyant Kula spreading ridge led to uplift and erosion manifest in the "Top Mesozoic Unconformity" (TMU). Subsidence following Kula subduction resulted in deposition of several kilometers of Tertiary nonmarine sediments, all of which serve as overburden to thermally mature Middle Jurassic source rocks. The Tertiary section is meant to schematically illustrate the intercalated nature of the stratigraphic units in upper Cook Inlet Basin. Modified from Fisher and Magoon (1978), Magoon and Claypool (1981), Magoon (1986), and Swenson (2003).

Syn-Collision Rock Units

In Late Jurassic time, the Wrangellia composite terrane began to progressively collide from southeast to northwest with the northwest-trending margin of North America (Ridgway and others, 2002). Uplift and erosion associated with collision resulted in deposition of the synorogenic Upper Jurassic Naknek Formation, a sequence of more than 3 km of conglomerates, sandstones, and siltstones deposited in Talkeetna fore arc and back arc settings (fig. 5). The Naknek Formation was deposited in environments ranging from fluvial-alluvial and shallow-marine to deep-marine slope and submarine-fan systems (Fisher and Magoon, 1978; Magoon and Egbert, 1986; Trop and others, 2005).

In lower Cook Inlet Basin, the Upper Jurassic to Lower Cretaceous Staniukovich Formation comprises a series of deep-marine sandstones and siltstones overlying the Naknek Formation. The Herendeen Formation (Nelchina Limestone in upper Cook Inlet Basin) unconformably overlies the Staniukovich Formation in lower Cook Inlet and Naknek Formation in upper Cook Inlet and consists of a thick sequence of siltstones and minor sandstones with thin beds of *Inoceramus* fragments, which were possibly deposited as sediment-gravity flows in a deep-marine fore arc environment.

By Late Cretaceous time, the Wrangellia composite terrane was terminally docked with the Alaskan margin of North America (Plafker and others, 1994). This phase of collision resulted in the overall synclinal form of lower Cook Inlet Basin and presumably upper Cook Inlet Basin (Fisher and others, 1987) and erosion of Mesozoic stratigraphic units along the basin margins. Uplift and erosion led to deposition of the upper part of the Matanuska Formation (fig. 5; Kaguyak Formation in lower Cook Inlet), which unconformably overlies the Herendeen Formation and the lower part of the Matanuska Formation in upper Cook Inlet Basin. This deposition records environments ranging from fluvial-alluvial to shallow marine and deep marine (Nokleberg and others, 1994).

Post-Collision Rock Units

Paleogene rocks in Cook Inlet Basin include the Wishbone, Chickaloon, and Arkose Ridge Formations that are well known from the adjacent Matanuska Valley coal fields (Triplehorn and others, 1984), but these rocks have a limited distribution (Swenson, 2003), and are not shown in figure 5. These stratigraphic units are well known from the coal fields in the adjacent Matanuska Valley (Triplehorn and others, 1984). Depositional environments range from fluvial to shallow marine. The Paleogene was also a time of significant dextral motion along bounding faults in Cook Inlet Basin (Haeussler and others, 2003; Trop and Ridgway, 2007; Trop, 2008; Scharman and Pavlis, 2012).

In late Paleogene time, possibly due to low-angle northeast-dipping subduction of a more buoyant and topographically higher-standing Kula spreading ridge (Bradley and others, 1993; Haeussler and others, 2003), the Wrangellia composite terrane was subject to widespread uplift and erosion. This formed a regional unconformity recognized on seismic sections in the Cook Inlet Basin as the "Top Mesozoic Unconformity" (TMU, fig. 5; Shellenbaum and others, 2010). Subduction of the Kula oceanic spreading ridge, with associated regional uplift and erosion, led to deposition of the West Foreland Formation (fig. 5), a sequence of non-marine sandstones and siltstones. As less-buoyant crust was subducted, subsequent thermal relaxation led to extension and rapid subsidence (Bradley and others, 1993), which was more pronounced in upper Cook Inlet Basin than in lower Cook Inlet Basin. Subsidence was far more effective in upper Cook Inlet Basin compared to lower Cook Inlet Basin (fig. 6; cross section *B–B′*); upper Cook Inlet has about 7 km of Paleogene and Neogene sediment (cross section *A–A′*) compared to less than 2 km preserved in lower Cook Inlet Basin.

Subsidence following ridge subduction eventually resulted in accommodation space for 7 km of Paleogene and Neogene deposition in upper Cook Inlet Basin (Wilson and others, 2012). The initial clastic wedge was conglomerate, sandstone, and coal of the Hemlock Conglomerate, representing deposition in alluvial and fluvial environments. The Hemlock Conglomerate was succeeded by the Tyonek Formation, a 2.5-km-thick sequence of non-marine fluvial rocks (fig. 5). The Tyonek Formation is overlain by the Beluga Formation, a sequence of fluvial and alluvial rocks. Overall, the Neogene section in upper Cook Inlet Basin is a complexly interfingering sequence of fluvial, alluvial, and coal deposits (Swenson, 2003).

In late Neogene time, the collision of the Yakutat terrane, a fragment of more buoyant oceanic crust, with the margin of southern Alaska had significant far-field effects

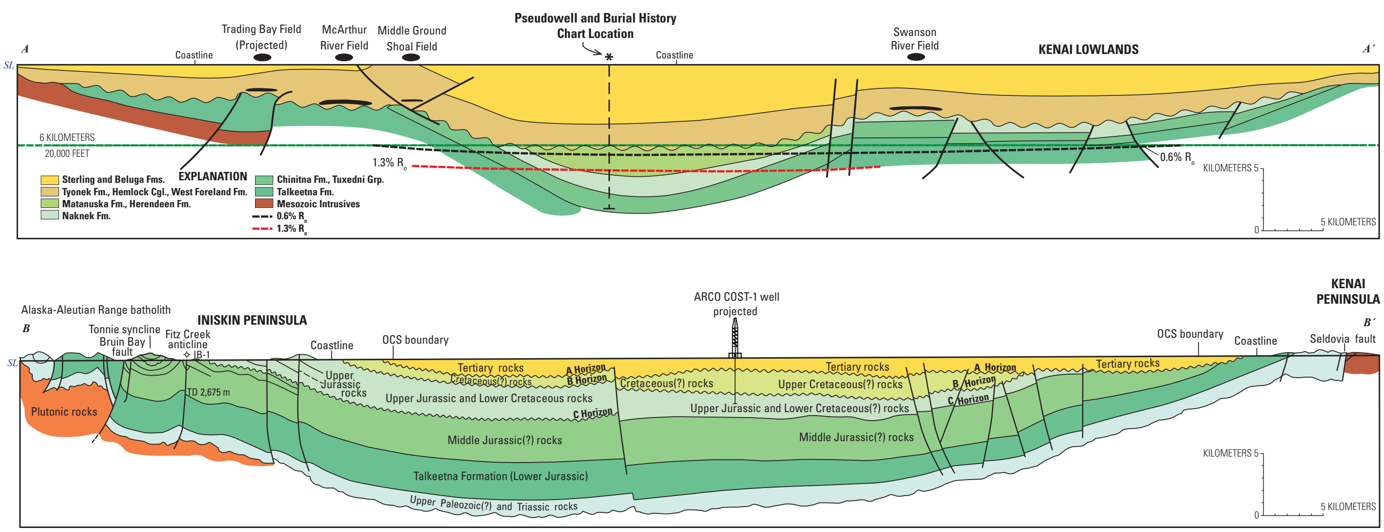


Figure 6. Geologic cross sections through Cook Inlet Basin, south-central Alaska. *A*, Cross section *A–A′* in upper Cook Inlet Basin showing the Jurassic section (Talkeetna Formation, Tuxedni Group, Chinitna, and Naknek Formations), limited Cretaceous section (Herendeen and Matanuska Formations), and thick Tertiary section (West Foreland Formation, Hemlock Conglomerate, and Tyonek, Beluga, and Sterling Formations). Thermal-maturity boundaries (Magoon, 1994b) indicate that the Tuxedni Group, Chinitna, and Naknek Formations are probably within the generation window for thermogenic gas. Line of cross-section is shown in figure 3. Location of burial-history model from Magoon (1994a), Peters and others (2006) and Lillis and Stanley (2011). Cross section from Boss and others (1976). *B*, Cross section *B–B′* through lower Cook Inlet Basin illustrating the thick Mesozoic section and thin (less than 2 kilometers) Tertiary section compared to the upper Cook Inlet Basin. Location of ARCO COST–1 well and Alaska Consolidated Oil Iniskin Beal–1 well (IB-1) are shown on section. Line of cross section is shown in figure 3. From Magoon (1986). (R_o, vitrinite reflectance; TD, total depth; m, meters; km, kilometers) (Click here to open full-size, high resolution image.)

on Cook Inlet Basin (Plafker and others, 1994; Haeussler and others, 2000; Bruhn and Haeussler, 2006; Koons and others, 2010). The Yakutat collision served to compress the southern Alaska margin, leading to uplift, causing the Wrangellia composite terrane to “escape” to the southwest by dextral-fault motion. Transpression associated with dextral fault movement in upper Cook Inlet Basin formed tight, asymmetric, north-south trending fault-cored anticlines that form the structural traps for conventional oil and gas fields (Haeussler and others, 2000).

In summary, the accretion of Mesozoic intra-oceanic volcanic arcs and related terranes to the margin of North America brought potential hydrocarbon reservoirs and source rocks of Jurassic age within the margin of North America. Paleogene subduction of buoyant ridge rocks and then less-buoyant oceanic crust led to subsidence in upper Cook Inlet Basin, and this accommodation space was eventually filled with several kilometers of Paleogene and Neogene sediments, which resulted in thermal maturation of Mesozoic source rocks. Mesozoic source rocks would have been largely thermally immature until Neogene burial, indicating that the petroleum system would only have to be preserved for several million years rather than tens of millions of years.

Cook Inlet Basin Stratigraphy

The Mesozoic and Cenozoic stratigraphy reflects the tectonic evolution of Cook Inlet Basin (fig. 5). The Upper Triassic Kamishak Formation is known principally from lower Cook Inlet Basin, and has not been recognized in upper Cook Inlet Basin. The presence or absence of Kamishak is important, as organic-bearing Kamishak mudstones might be viable petroleum source rocks. Since the Kamishak is not known in upper Cook Inlet Basin, volcanic rocks of the Lower Jurassic Talkeetna Formation (fig. 5) are generally considered to be economic basement (Fisher and Magoon, 1978). The Middle Jurassic Tuxedni Group is known mainly from exposures in lower Cook Inlet (Detterman and Hartsock, 1966; LePain and others, 2011; 2012), where it is up to 3 km thick, and divided into six formations representing three major transgressive-regressive cycles deposited along the fore arc and back arc marine environment of the intra-oceanic Talkeetna arc system.

The Tuxedni Group in the lower Cook Inlet area contains organic-bearing black shales that are the most likely hydrocarbon source rocks. Overlying the Tuxedni Group is the Chinitna Formation, which consists of two siltstone members totaling about 715 meters (m) thick. The Chinitna is not known to contain potential source rocks or reservoir rocks, but Chinitna reservoirs remain a possibility as siltstones within shale sequences are commonly tight reservoirs in several Rocky Mountain basins (Hettinger and Roberts, 2005). The Chinitna is also important because the upper siltstone member contains the first petrographic evidence of plutonic-lithic grains; this provides evidence of significant unroofing of the Talkeetna arc. The plutonic lithics contain feldspars that are susceptible to dissolution forming secondary porosity.

The Chinitna Formation is unconformably overlain by coarse clastics of the synorogenic Upper Jurassic Naknek Formation (fig. 5) deposited in fore arc and back arc basins as collision began between North American plate and Wrangellia composite terrane. We postulate that the Naknek Formation is one of the main reservoirs for potential tight-gas resources in the central part of upper Cook Inlet Basin.

The Naknek Formation is unconformably overlain by the Nelchina Limestone, a fine-grained unit deposited in a deep-marine setting, possibly largely as sediment-gravity flows. Like the Chinitna Formation, the Nelchina is not known to have source-rock potential. The Nelchina Limestone is unconformably overlain by clastics of the Lower and Upper Cretaceous Matanuska Formation (fig. 5), a sequence of sandstones and mudstones deposited as uplift and erosion occurred following terminal collision of Wrangellia with North America.

Following terminal suturing of the Wrangellia composite terrain with North America, the Cook Inlet Basin area was part of a larger fore arc to the newly reorganized volcanic arc and subduction of oceanic crust beneath the expanded continental margin. Eocene subduction of the more-buoyant Kula spreading ridge resulted in uplift and widespread erosion, formed the regional TMU, and deposition of clastic units of the West Foreland Formation. Subduction of less-buoyant oceanic crust in the Oligocene resulted in extension and rapid subsidence within upper Cook Inlet Basin. The resulting accommodation space was filled with several kilometers of largely non-marine clastics and coal, represented by the Hemlock Conglomerate and the Tyonek and Beluga Formations (fig. 5), all of which served as overburden to thermally mature the Middle Jurassic source rocks and cause loss of porosity and permeability in potential Tuxedni Group and Naknek Formation reservoirs. The Hemlock, Tyonek, and Beluga Formations exhibit intercalating relationships (Swenson, 2003).

In latest Oligocene time, collision began between the Yakutat terrane and North America; this eventually resulted in the development of northeast-southwest trending compressional structures in Cook Inlet Basin (Haeussler and others, 2000), many of which contain oil and gas reservoirs. Collision of the Yakutat terrane and concomitant uplift resulted in erosion and subsequent deposition of the Late Neogene Sterling Formation.

Tuxedni-Naknek Petroleum System

Thermogenic oil and gas and biogenic gas accumulations are known to exist within upper Cook Inlet Basin (fig. 1). For this report, we are interested in the origin of thermogenic oil and gas, as those would be part of a deep basin-centered tight-reservoir system. The most likely source for thermogenic gas (and oil) in upper Cook Inlet Basin is organic-bearing mudstones of the Middle Jurassic Tuxedni Group (fig. 5; Kelley, 1963; Osment and others, 1967; Claypool and others, 1980; Magoon and Claypool, 1981; Magoon and Anders, 1992; Magoon, 1994a, b; Peters and others, 2006; Lillis and Stanley, 2011). Little direct information is available on the Tuxedni Group rocks from upper Cook Inlet Basin, whereas Tuxedni core and outcrop samples have been analyzed in lower Cook Inlet Basin (Claypool and others, 1980). Analyses of isotopic and biomarker data from these rock samples suggest that oils are similar to oils taken from upper Cook Inlet Basin reservoirs.

Geochemical data from organic-bearing mudstones from the Tuxedni suggest an oil-source rock with Type II marine organic matter. Total organic carbon (TOC) is moderate, with values ranging from 0.8 to 2.1 weight percent organic carbon.

For conventional oil and thermogenic gas accumulations in upper Cook Inlet Basin, oil and gas generated in Middle Jurassic mudstones migrated out of the mudstones, along faults, and into Cenozoic reservoirs within structural traps, such as the source-reservoir plumbing system interpreted at North Middle Ground Shoal Field (fig. 7). Oil and gas traps are composed of a series of northeast-southwest trending tight asymmetric fault-cored anticlines formed in late Neogene time. Petroleum generation is modeled to have begun in the Neogene (Magoon, 1994a; Peters and others, 2006; Lillis and Stanley, 2011).

In the ARCO COST–1 well in lower Cook Inlet Basin (fig. 3), several oil shows in Upper Jurassic Naknek sandstones were attributed to an underlying Middle Jurassic Tuxedni marine source (Magoon, 1986). The oil shows were observed over several thousand feet of Naknek section. This observation is critical, as it demonstrates that oil migrated up-section from Tuxedni mudstones into low-permeability Naknek sandstones. Naknek sandstones with oil shows in the ARCO COST–1 well are partially cemented by laumontite and calcite.

Oil and gas shows were also reported from the Red Glacier Formation of the Tuxedni Group in the Alaska Consolidated Oil Iniskin Beal–1 well in lower Cook Inlet (fig. 3), at depths between about 700 and 2,300 m (Fisher and Magoon, 1978, their fig. 18). One oil show and two gas shows (biogenic gas?) were reported from the Tuxedni interval, again providing strong evidence that hydrocarbons were generated from Tuxedni mudstones. In this example, hydrocarbons remain in the source rocks. This suggests a potential unconventional source-reservoir system in lower Cook Inlet Basin, although this system was not part of the current study. Vitrinite reflectance data from a sample at 2,987 m in this well is about 0.65 percent, which is near the threshold for oil generation; gas shows must be biogenic or were generated thermally and migrated from Kamishak mudstones underlying the Talkeetna and Tuxedni interval.

In lower Cook Inlet Basin, the Upper Triassic Kamishak Formation (fig. 5) might also be a viable source for hydrocarbons (Blodgett and Sralla, 2006). The presence of Kamishak source rocks is not known in upper Cook Inlet Basin, and Kamishak source rocks are not considered to be a source in upper Cook Inlet Basin based on detailed analyses of reservoir oils (Peters and others, 2006; Lillis and Stanley, 2011).

The Tuxedni-Naknek petroleum system is identified as the most likely source for hydrocarbons that might be in tight-gas reservoirs of the Tuxedni Group, and Chinitna and Naknek Formations in the deep central part of the upper Cook Inlet Basin. Generation of significant volumes of thermogenic gas is less likely as gas-oil ratios (GOR) in Cook Inlet fields indicate that gas is not pervasive (Magoon, 1994a) and that oils are probably undersaturated with gas (Stokes and others, 2010). The GOR data are in the range of 200–500 cubic feet of gas per barrel (cfg/bbl), which are low compared to average U.S. GOR data.

Thermal Maturity

Thermal maturity of postulated Tuxedni source rocks in the deep, central part of upper Cook Inlet Basin remains the most significant source of geologic uncertainty in this assessment and is unknown due to the lack of drilling and sampling in an area (as much as 8 km deep) where source rocks of the Tuxedni Group might exist (figs. 5, 6). Thermal maturity is extrapolated from wells drilled to shallower horizons. Generalized thermal maturity thresholds, which correspond to vitrinite reflectance (R_o) values of 0.6 percent and 1.3 percent R_o, were shown on a cross section of upper Cook Inlet Basin by Magoon (1994a). The thermal thresholds are schematic and uncertain, but they suggest that the threshold for oil generation (0.6 percent R_o) in the central part of the basin is at about 6.5 km depth, and the threshold for thermal gas (1.3 percent R_o) is at about 8 km depth (fig. 6*A*).

Burial-history modeling in upper Cook Inlet Basin implies that the basin is thermally cool, with geothermal gradients of 19 to 27 degrees Celsius per kilometer (°C/km; Lillis and Stanley, 2011). Low heat-flow is partially attributed to: (1) location of the fore arc Cook Inlet Basin over the subduction zone, (2) low thermal conductivity of numerous coal beds, and (3) Neogene deposition causing suppression of thermal contours. Several burial-history models were developed from wells with calibration data, and were used as a basis to model a deep pseudowell in the central part ("kitchen") of the basin, within the area being assessed in this study for tight gas (Lillis and Stanley, 2011). Lillis and Stanley concluded that, using the average heat-flow from wells in this proximity calibrated with vitrinite reflectance data, peak-oil generation (0.9 percent R_o) occurred at about 15 million years ago (Ma) in the center of the basin, coinciding with a kerogen-transformation ratio of about 50 percent.

The model also implied that the beginning of gas generation (1.3 percent R_o) was in late Miocene to Pliocene, and that present day values of thermal maturity (1.8 percent R_o) are at the highest levels ever reached. This modeling implies that, late in the burial history, oil generated from Tuxedni marine source rocks could have migrated short distances into Tuxedni, Chinitna, and Naknek low-permeability reservoirs. The thermal-maturity model also indicates that conditions are adequate for oil to crack to gas. Earlier modeling in the same deep-basin location by Peters

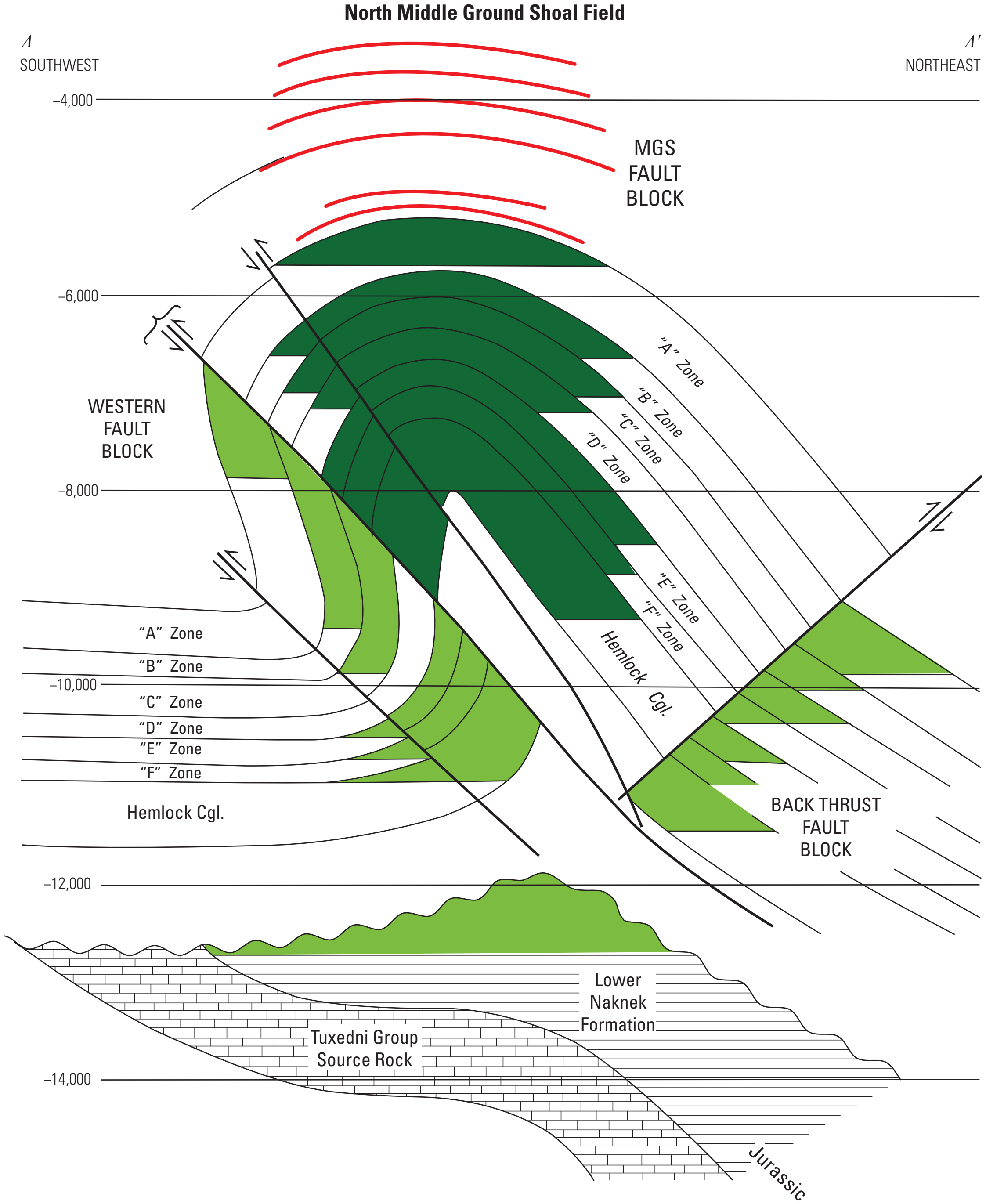


Figure 7. Schematic cross section of North Middle Ground Shoal field, upper Cook Inlet Basin, Alaska. This field illustrates how Jurassic source rocks are interpreted to provide hydrocarbons to structurally trapped reservoirs in an asymmetric, faulted anticline. Zones "A" through "F" are in the lower part of the Tyonek Formation. From Gregerson and Shellenbaum (2010). (MGS, Middle Ground Shoal)

and others (2006) implied that Tuxedni source rocks achieved thermal maturity for oil generation at about 22 Ma (early Miocene) and reached the gas generation threshold by 9 Ma (late Miocene). Peters and others (2006) concluded that the mean value for present day R_o of Tuxedni source rock at a depth of 27,100 feet (ft) is 2.9 plus or minus 0.6 percent, which suggests that Tuxedni source rocks are well within the thermal gas-generation window in the center of the basin.

Overpressure

A few authors have discussed overpressure in Cook Inlet Basin. In a summary using three graphs, Powley (2008) outlined a large area of overpressure that covered most of the upper Cook Inlet, extending onshore to the west, onto a portion of the Kenai Peninsula to the east, and with a narrow southward unknown extension into lower Cook Inlet (fig. 1). Based on pressure data from the West Foreland, Middle Ground Shoal, Granite Point, and other Cook Inlet fields (fig. 8), the base of normal pressure was placed at an elevation of –10,600 ft. A thick seal with a high local-pressure gradient extended from –10,600 to –13,800 ft where the extrapolated pressure is 12,450 pounds per square inch (psi), and an overpressured zone extended from –13,800 ft to the deepest pressure measurement of 13,650 psi at –16,300 ft (a pressure-depth ratio of 0.84 psi/ft). A sonic log from a well in the West Foreland field exhibited a travel time (velocity) reversal from –10,600 to –13,600 ft, thereby corroborating the pressure measurements. Powley's graphs, based on data in Amoco Oil Company files, were originally available as unpublished lecture notes for an American Association of Petroleum Geologist's exploration school in 1980 and have since appeared in Hunt (1990) and Powley (2008). Powley and Hunt proposed a model of a thick flat-topped seal separating the shallow, normally pressured section from a deeper, overpressured section. Subsequent drilling and testing in upper Cook Inlet has revealed a more complex picture as shown by Bruhn and others (2000) and by our own inspection of mud weight and test data.

Bruhn and others (2000) tabulated 42 pressure measurements in 17 wells, mostly from upper Cook Inlet, based on initial reservoir pressures, drill-stem tests, and repeat formation tests from publicly available files. Of these 42 measurements, 13 were from depths greater than –11,000 ft and 9 of these had pressure-depth ratios greater than 0.57 psi/ft (mud weight of 11 pounds per gallon, ppg). Bruhn and others noted that overpressure occurs sporadically in discrete intervals of varying thickness in lower Tertiary rocks and, based on a sonic log and pressure measurements in the Swanson River field (fig. 8), speculated that high fluid-pressure could be even more extensive in older rocks. To explain the sporadic pressure occurrences in Tertiary rocks, Bruhn and others proposed that brine and hydrocarbons from a deep Mesozoic source migrated upwards along faults to strata where seals were created by secondary zeolite and carbonate minerals that were deposited as brines cooled and mixed.

Indicators of overpressure examined for this study were: (1) deflections from normal-compaction trends in sonic and resistivity logs, (2) indirect measures of pressure from mud weight, and (3) direct measurements of pressure from drillstem tests. These three indicators were examined on a well-by-well basis for 31 wells in Cook Inlet Basin, using well logs available from the State of Alaska and drill-stem tests and mud weights from a database leased from IHS Energy Group (2011). Mud weight is expressed in pounds per gallon. Pressure, which is expressed in pounds per square inch, is divided by depth to obtain a pressure-depth ratio in psi/ft. A mud weight can be converted to a pressure-depth ratio by multiplying ppg by 0.052. For example, values for fresh water are 8.33 ppg and 0.433 psi/ft.

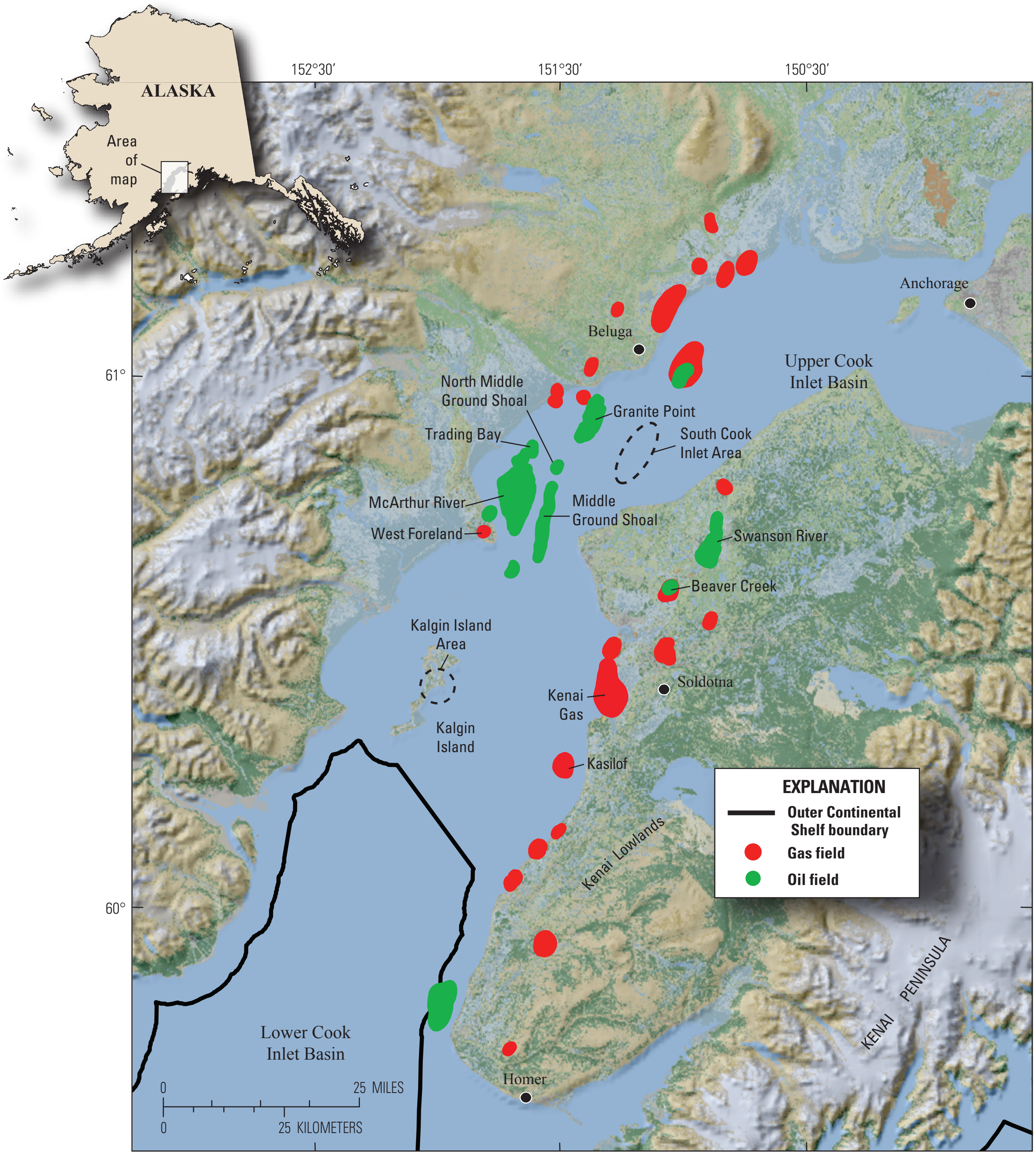
The sonic log in the Kalgin Island–1 well (fig. 9*A*) shows a good compaction trend (decreasing transit time or increasing velocity) from top of the log to a depth of –12,400 ft. A disruption in the compaction trend in the West Foreland Formation is attributed to lithology rather than to a pore-pressure increase, because two drill-stem tests at –13,500 ft recorded pressure-depth ratios that were normal and slightly below normal. The gamma-ray geophysical log in the Tyonek Formation shows a sand-shale ratio of greater than 50 percent. The low sonic velocity and low density (leftward) spikes in the sonic and density logs are attributed to coal beds.

In the North Foreland State–1 well (fig. 9*B*), mud weights were gradually increased from 9 ppg at –3,000 ft to 17 ppg at –17,770 ft in the Naknek Formation. Resistivity, sonic velocity, and density geophysical logs are all high in the Matanuska and Naknek Formations; there is no evidence that high pore pressure, as indicated by high mud weights, is affecting the petrophysical properties.

The Wolf Lake–1 well (fig. 9*C*) penetrates the Naknek Formation at –13,600 ft. Geophysical well logs show no reversal indicating overpressure—the reductions in resistivity and sonic transit time in the West Foreland Formation are attributed to lithology, based on the character observed in the Kalgin Island–1 well (fig. 9*A*). Mud weights in the upper part of the well were 10 ppg, increasing to 13.1 ppg at a total depth of –14,000 ft.

The geophysical well logs in the Soldotna Creek Unit 33–33 well (fig. 9*D*) show prominent reversals in the resistivity and sonic logs. Sonic transit time values below a depth of –13,700 ft are markedly higher than a trend extended from values above that depth, and resistivity values are 1 to 5 ohm-m in Chinitna Formation and Tuxedni Group, well below the resistivity values recorded in the three other wells of figure 9. Some portion of these reversals could be attributed to the enlarged borehole from –14,700 to –17,100 ft recorded on the caliper log; however, the reversals occur above and below the washout zone, so the reversals are regarded as valid measurements. Note that this well is on the same structure as the Wolf Lake–1 well (fig. 9*C*), showing that its well-log character appears to be a localized feature.

In summary, the well logs exhibit no reversals that are diagnostic of overpressure, with the exception of well



Base credit: US National Park Service

Figure 8. Map showing the location of upper Cook Inlet oil and gas fields, field names, and field areas mentioned in the text. South Cook Inlet and Kalgin Island Areas are denoted by dashed lines. Field outlines are from Shellenbaum and others (2010).

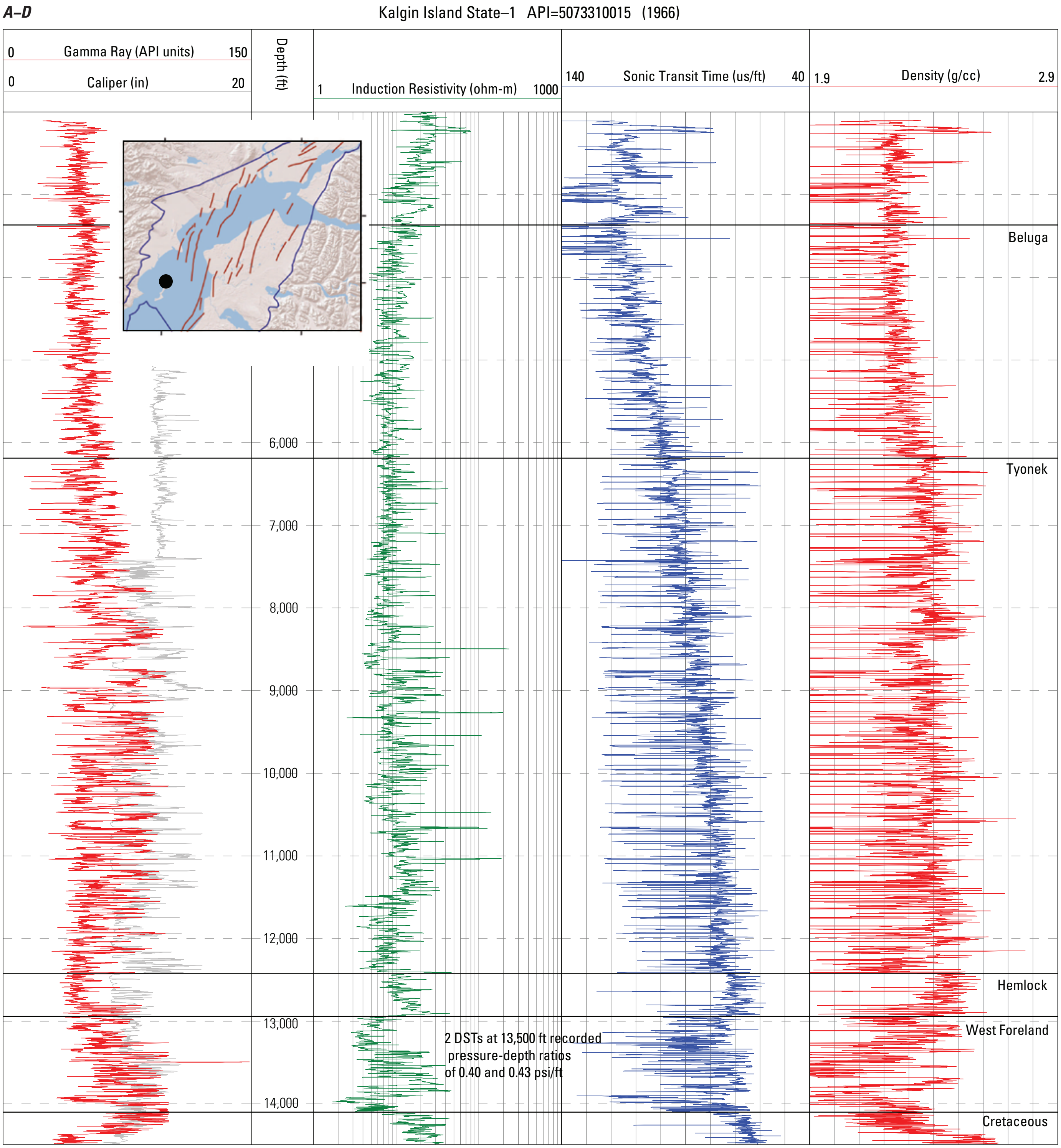
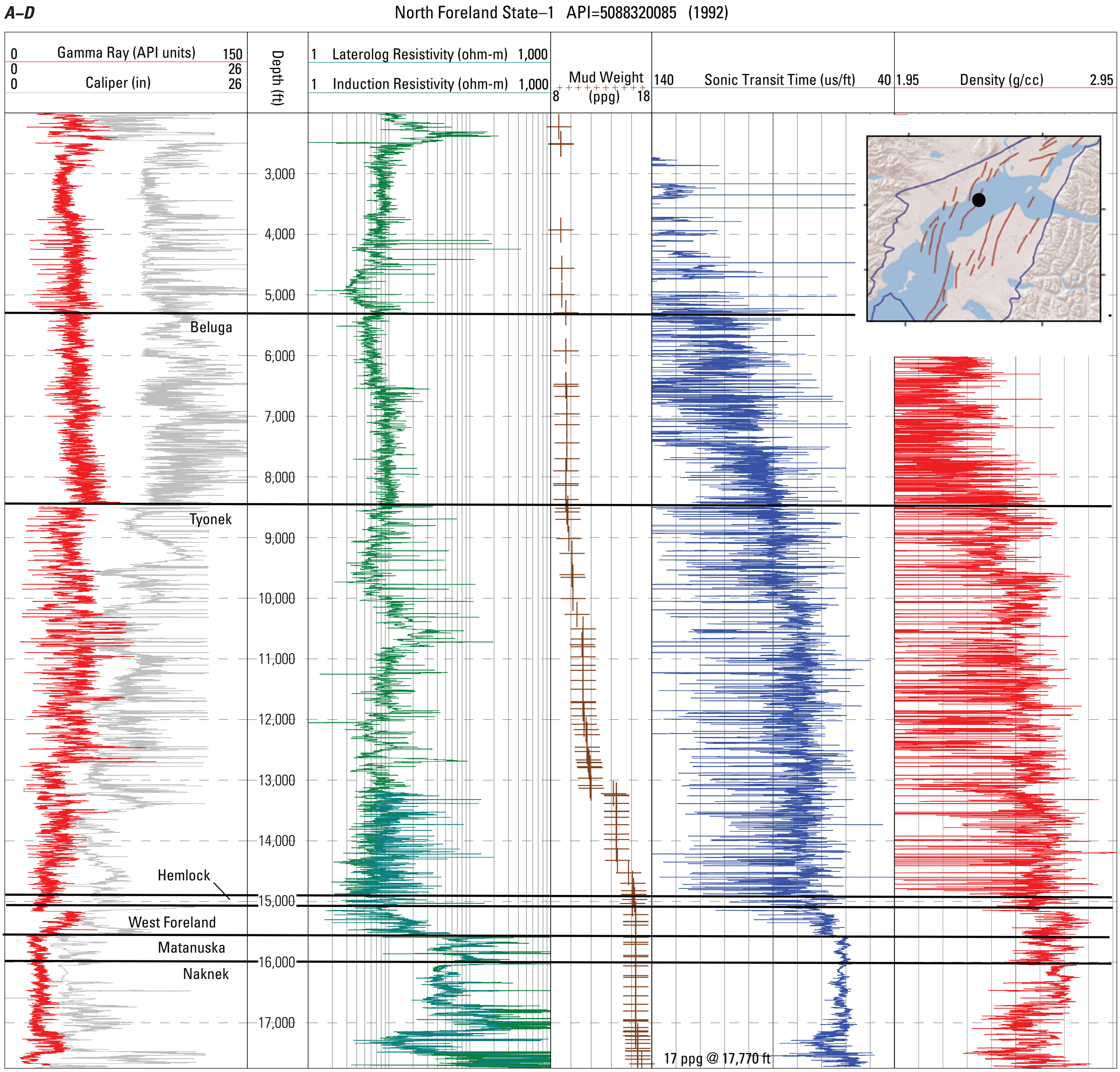


Figure 9. Well logs and other well-based information related to discussion of overpressure. *A*, Kalgin Island State–1 well. *B*, North Foreland State–1 well. *C*, Wolf Lake–1 well. *D*, Soldotna Creek Unit 33–33 well. Inset maps show well locations. (API, define here; in, inches; ft, feet; ohm-m, ohm-meters; µs/ft, microseconds per foot; g/cc, grams per cubic centimeter; ppg, pounds per gallon)



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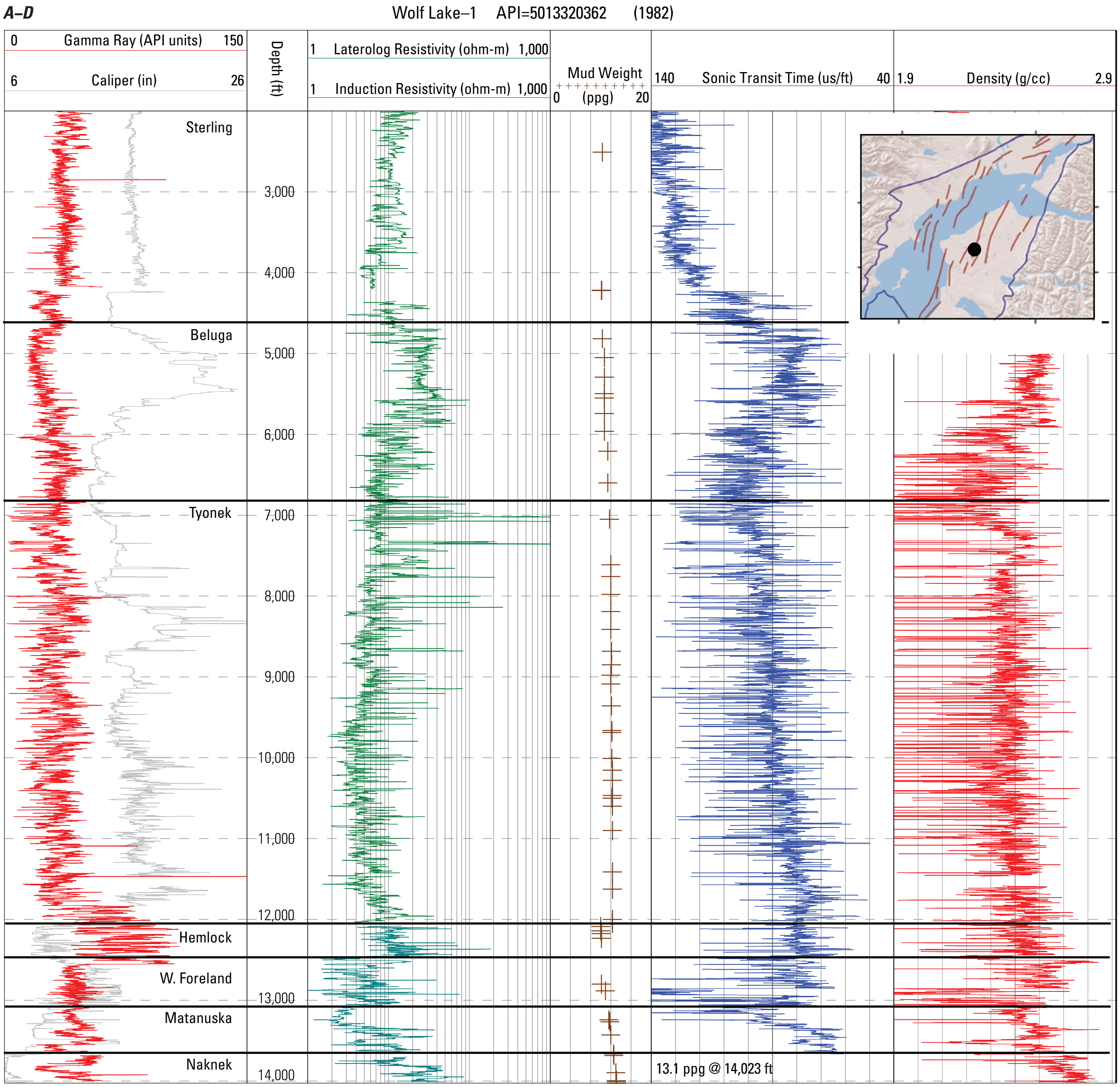
A–D



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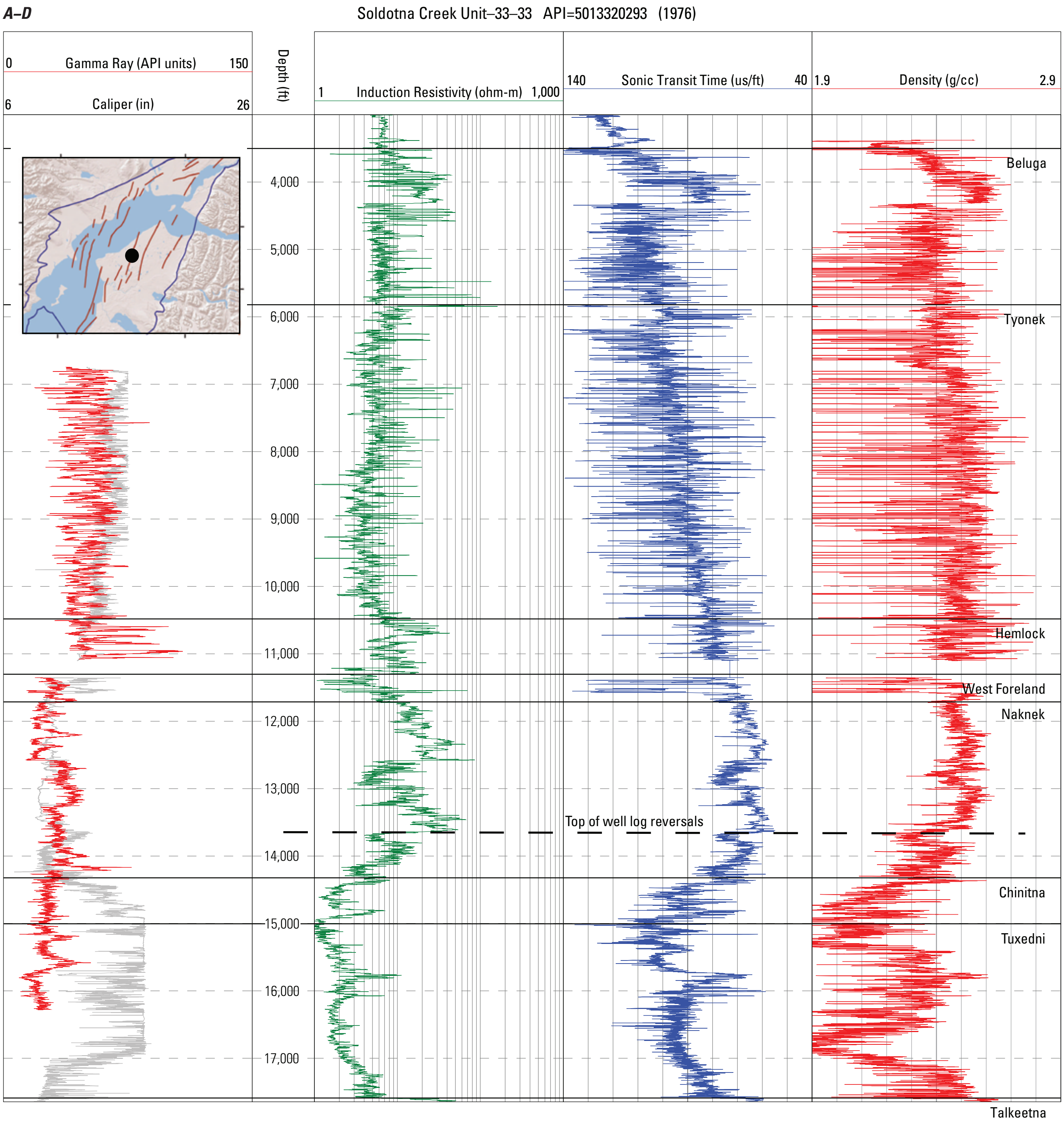

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Soldotna Creek Unit 33–33. However, both drill-stem tests and mud-weight data show that overpressure exists at depths greater than –10,000 ft. As the mud-weight data are less plentiful than the drill-stem tests and also tend to corroborate the drill-stem tests, the mud-weight data presented herein are restricted to figures 9*B* and 9*C*. The drill-stem tests provide the best documentation of overpressure.

Pressures from drill-stem tests are plotted as a function of elevation (fig. 10*A*); data are from oil and gas fields (fig. 10*B*). Normal pressure is represented by points falling on or near the hydrostatic gradient of 0.45 psi/ft. Data from wells in the Kalgin Island area and Kasilof field (fig. 8) are normally pressured regardless of depth, establishing a southern boundary to the overpressured area. A few tests show overpressure at approximately –9,000 ft, but most overpressure data fall in the depth range of –10,500 to –16,000 ft. The overpressure trend from Powley (2008) coincides with an increase in pressure commencing at –11,250 ft, supported mainly by tests from the Granite Point and North Cook Inlet fields, and wells in the South Cook Inlet area (fig. 8). Although these three fields demonstrate a fairly consistent trend of pressure increasing with depth, other fields display a mix of normal pressure and overpressure at elevations below –13,000 ft. For example, of the four tests from Beaver Creek field (fig. 8) plotted at elevations ranging from –14,776 to –15,846 ft, three are slightly overpressured and only one is clearly overpressured with a pressure-depth ration of 0.62 psi/ft. The data show that some fields are largely normally pressured, some show consistent increase of overpressure with depth, and some show a mix of normal pressure and overpressure. These data do not support the model of a fixed top of overpressure as proposed by Powley (2008), but instead show an erratic lateral and vertical spatial dependence of overpressure with the upper Cook Inlet, consistent with the observations of Bruhn and others (2000).

In many basins, overpressure can be attributed to a combination of disequilibrium compaction (retention of pore-space fluids during burial) and hydrocarbon generation (production of petroleum liquids and gases that occupy more pore space than the source kerogen). However, in the case of the Tertiary strata of the Cook Inlet, disequilibrium compaction is precluded by the high sand content of the Tyonek Formation (figs. 9*A*–*D*). Consequently, we attribute the presence of overpressure in the Cook Inlet to the generation of hydrocarbons driven by rapid burial in Neogene time, a process that continues today. Late-stage faulting is the likely cause of both the distribution of hydrocarbon reservoirs in Tertiary rocks and the spatially erratic distribution of overpressure.

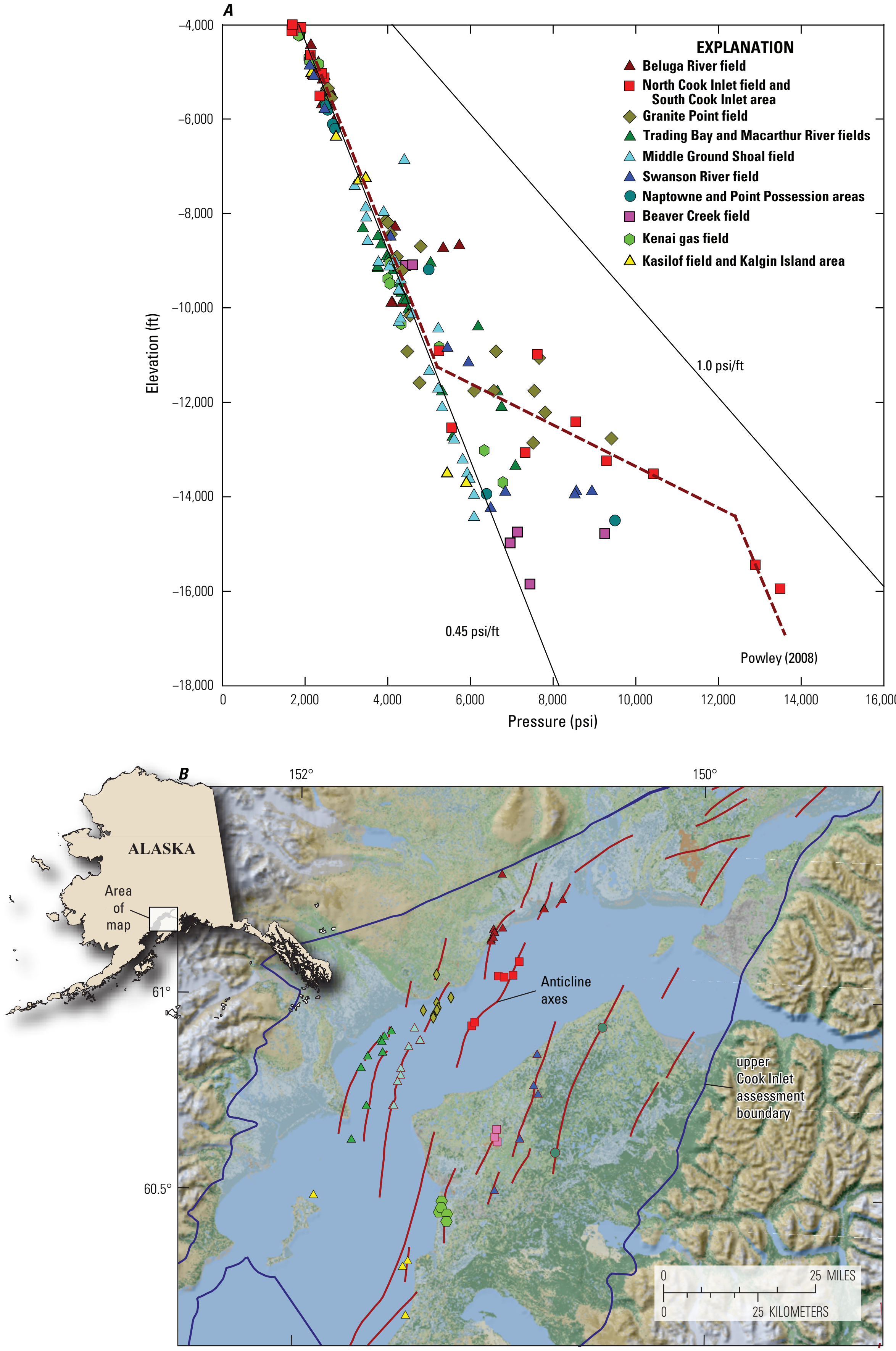
Reservoirs and Reservoir Quality

Unlike conventional reservoirs in which adequate porosity and permeability is required for fluid recovery, unconventional reservoirs by definition do not exhibit conventional ranges of porosity and permeability. Permeability in some unconventional reservoirs is measured in microdarcies to nanodarcies, and effective porosity can be less than 10 percent. Stimulation is required for fluid recovery.

Sandstone and siltstone reservoirs lose permeability and porosity through burial compaction and diagenesis. In the evolution of porosity and permeability, initial framework-grain composition and pore-fluid chemistry are important, as initial compositions of the rock framework and fluids can dictate the types of diagenetic and thermal changes in a rock with time. The complex tectonic and burial history of rocks in Cook Inlet Basin imparted considerable variation on initial-framework compositions (Magoon and Egbert, 1986). Variation in framework composition resides in the percentages of volcanic and plutonic lithic grains. Rocks resulting from eroded arc terranes generally have more volcanic lithic grains (Tuxedni Group), and those from plutonic rocks have more feldspar and plutonic lithic grains (upper member of Chinitna Formation and Naknek Formation). Volcanic lithic grains are known to be mechanically and chemically labile and can significantly reduce permeability on compaction and diagenesis. Feldspars can be altered chemically, which leads to dissolution and replacement. Secondary cements such as clays and zeolites (such as laumontite and heulandite) can form following feldspar dissolution. The Chinitna and Naknek Formations are interpreted here to provide better (tight) reservoir potential.

Porosity and permeability data integrate the effects of framework composition, compaction, and diagenesis. Hickey and others (2007) and Helmold and others (2011) provide critical data on the composition, diagenesis, and petrophysical properties of the major rock units in upper Cook Inlet Basin. Their summaries of outcrop porosity and permeability from Cook Inlet Basin show that Middle Jurassic Tuxedni and Naknek sandstones are partially within the informal definition for tight reservoirs (permeability less than 0.1 millidarcy) (fig. 11), whereas Cenozoic rocks are generally in the more conventional realm of porosity and permeability ranges. However, their compilation of more-extensive subsurface data illustrates that, in addition to the Naknek and Tuxedni, Cenozoic units such as the Hemlock Conglomerate, the Tyonek Formation, and the West Foreland Formation have

Figure 10. Data related to studies of overpressure. *A*, Plot of pressure vs. elevation with symbols showing well locations on different structures on map in part *B*. A single well in map *B* has one or more drillstem test measurements in part *A*. Thin solid lines show the hydrostatic (0.45 psi/ft) and lithostatic (1.0 psi/ft) gradients. Dashed line shows pressure-elevation relation from Powley (2008) for four fields. *B*, Map of upper Cook Inlet showing structural fold axes where oil and gas fields have been discovered and locations of wells with drillstem tests plotted in part *A*. Assessment area of the upper Cook Inlet Basin is from Stanley and others (2011). Locations of anticlines are from Wilson and others (2012). (ft, feet; psi, pounds per square inch; psi/ft, pounds per square inch per foot)—Following page.



Base credit: US National Park Service

many samples that fall within the informal definition for tight-gas sandstones (fig. 11). This study does not assess the potential for resources in these Cenozoic sandstones.

Potential reservoirs for tight-gas accumulations include sandstones and siltstones of the Tuxedni Group, siltstones of the Chinitna Formation, and sandstones and siltstones of the Naknek Formation, as these rocks are interpreted to be in the thermal gas generation window. Given the uncertainty in the magnitude of thermal maturation, sandstones of the lower Matanuska Formation are also possible low-permeability reservoirs. Sandstones and siltstones of the Tuxedni Group are generally high in volcanic lithics, and loss of porosity and permeability could result from compaction, including formation of pseudomatrix, and intergranular cementation. Siltstones of the Chinitna Formation are also potential tight reservoirs, similar to siltstones of the Lewis Shale in the Greater Green River Basin (Hettinger and Roberts, 2005).

Sandstones of the Naknek Formation potentially represent the most viable low-permeability reservoirs. Naknek sandstones contain higher percentages of plutonic lithic framework grains compared to Tuxedni sandstones (fig. 12). This results in less pseudomatrix with compaction. Cementation is more important than compaction for porosity-loss in potential Naknek sandstone reservoirs. Laumontite is the most common cement as it replaces plagioclase and volcanic glass and fills fractures and intergranular porosity. Calcite is the second most important cement.

Sandstones cemented by zeolites (such as laumontite) were considered for many years to be removed from the reservoir realm due to near complete loss of porosity and permeability. However, fluids with high carbon dioxide percentages that precede hydrocarbon migration have been shown to dissolve laumontite, forming secondary porosity (Crossey and others, 1984). Naknek sandstones cemented by laumontite could have undergone such a partial removal of cement prior to hydrocarbon migration.

In the ARCO COST–1 well in lower Cook Inlet (fig. 3), several reported shows of oil are in partially laumontite-cemented Naknek sandstones (Magoon, 1986). The oil shows occur over several thousand feet of section. This might be an example where such carbon-dioxide rich fluids were introduced into laumontite-cemented Naknek sandstones, forming partial secondary porosity, which was then occupied by oil. The same process could have occurred in Tuxedni and Chinitna rocks in the central part of the basin.

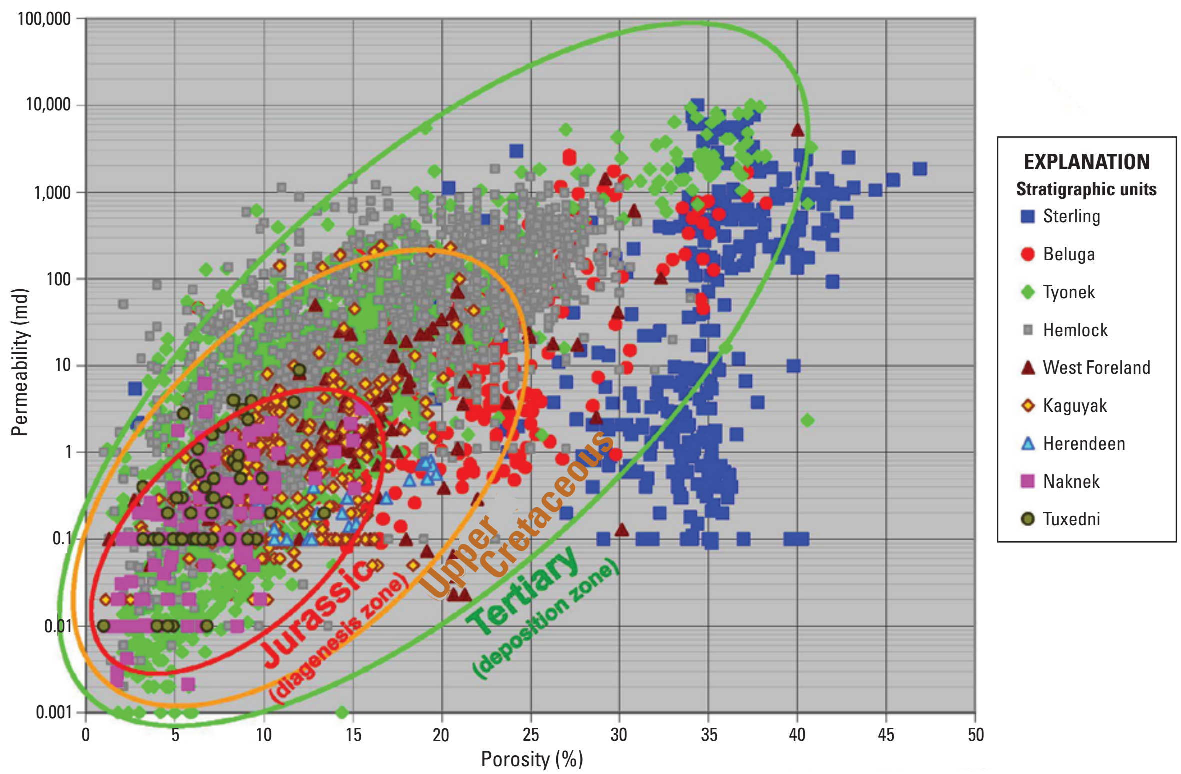


Figure 11. Porosity and permeability of samples from Mesozoic and Tertiary rocks in upper Cook Inlet Basin. Subsurface data showing several stratigraphic units are within the informal definition of tight reservoirs (less than 0.1 mD permeability), including Naknek Formation, Tuxedni Group, and some Tertiary rocks including West Foreland Formation, Hemlock Conglomerate, and Tyonek Formation. From Helmold and others (2011). (mD, millidarcy; %, percent)

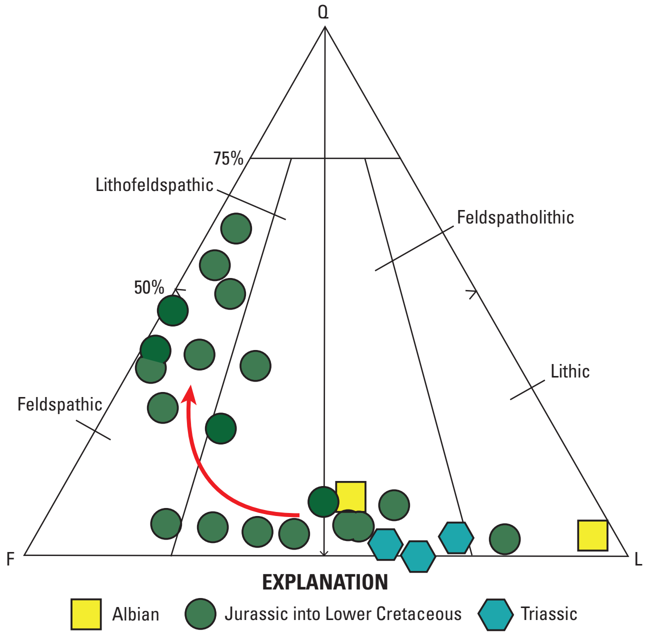


Figure 12. Quartz-Feldspar-Lithics plot (Q-F-L) of sandstones from the lower Cook Inlet area. Sandstone compositions evolve (red arrow) from volcanic lithic-rich Triassic and Jurassic and Lower Cretaceous rocks (Talkeetna Formation, Tuxedni Group) to feldspathic-rich sandstones (Chinitna and Naknek Formations), as samples record progressive unroofing of plutonic rocks of the Talkeetna arc. From Magoon and Egbert (1986).

Geologic Model for Assessment

Several geologic conditions, most of which are uncertain, would have to be coincident in the burial history of the Tuxedni source-rock system for an unconventional gas accumulation to form in the central part of upper Cook Inlet Basin. The geologic model is as follows: first, a pod of Middle Jurassic Tuxedni Group marine source rock with adequate total organic carbon would be required in the central part of the basin. Second, burial by several kilometers of Paleogene and Neogene sediment would have placed Tuxedni source rocks across the thermal thresholds for oil or gas generation. Third, hydrocarbon generation would have been sufficient to develop an overpressure situation, allow migration of oil or gas into adjacent sandstones and siltstones of the Tuxedni Group and Chinitna and Naknek Formations, and possibly drive water out of the system. Fourth, if oil migrated into the sandstones and siltstones, then thermal conditions for cracking to gas were required in the central part of the basin. Fifth, progressive compaction and diagenesis of sandstones in the Middle Jurassic Tuxedni Group and Chinitna Formation and Upper Jurassic Naknek Formations would have resulted in loss of porosity and permeability and development of low-permeability sandstones and siltstones. Finally, the system would have to be preserved with minimal loss of overpressure. A schematic summary of the model is presented in figure 13.

Geologic uncertainty is manifest in most of these model parameters. The presence of adequate Tuxedni source rocks is inferred from the geochemistry of oils in Cenozoic reservoirs in upper Cook Inlet fields. The extent and thickness of Tuxedni source rocks is unknown. Thermal maturation of the source rock is another uncertain parameter, as modeling suggests that sufficient thermal exposure has occurred in the central part of the basin. The development of overpressure is known from wells in the basin, but we do not know if the condition exists solely in the basin center, or if overpressure is more widely distributed. Cracking of oil to gas is hypothetical, assuming that oil migrated and that thermal conditions permitted cracking to occur. The petrophysical properties are perhaps best predicted from known data from both the lower and upper Cook Inlet Basin. Preservation of the system is unknown, but since the system is hypothesized to be late Neogene in development, preservation is less of an issue than with older systems.

Assessment Unit Description

The postulated areal extent of the geologic model is termed an “assessment unit” (AU) by the USGS. The Tuxedni-Naknek AU is defined in this study to encompass the area in the central part of upper Cook Inlet Basin within which we hypothesize thermogenic gas is present in low-permeability pore systems of Tuxedni, Chinitna, and Naknek sandstones and siltstones (figs. 14, 15).

We chose the –23,000 foot (ft) depth contour to the top of the TMU (Shellenbaum and others, 2010) as the central tendency (most likely) of the AU area, and the maximum area chosen at the –20,000 ft contour. This would perhaps place the Tuxedni Group at about 8 km depth, which is the depth at which the Tuxedni would be thermally mature for gas.

The AU map illustrates that the maximum boundary of the proposed tight-gas accumulation is in the center of the basin (fig. 15). Updip from this area are the existing oil and gas fields, most of which are sourced by the Middle Jurassic Tuxedni Group. The map also shows that the AU is both onshore and offshore.

Assessment Input Data

The geologic model provides a probabilistic basis for the possibility of a tight-gas accumulation in the central part of the basin, with the realization of the magnitude of geologic uncertainties. Given the model, and the fact that no wells have been drilled in the AU, the assessment leverages what we understand of the geology and production of tight-gas reservoirs in several basins in the lower 48 states.

Geologic and engineering information required for the tight-gas assessment is summarized in table 1. The data in table 1 are extracted from an in-house input form used

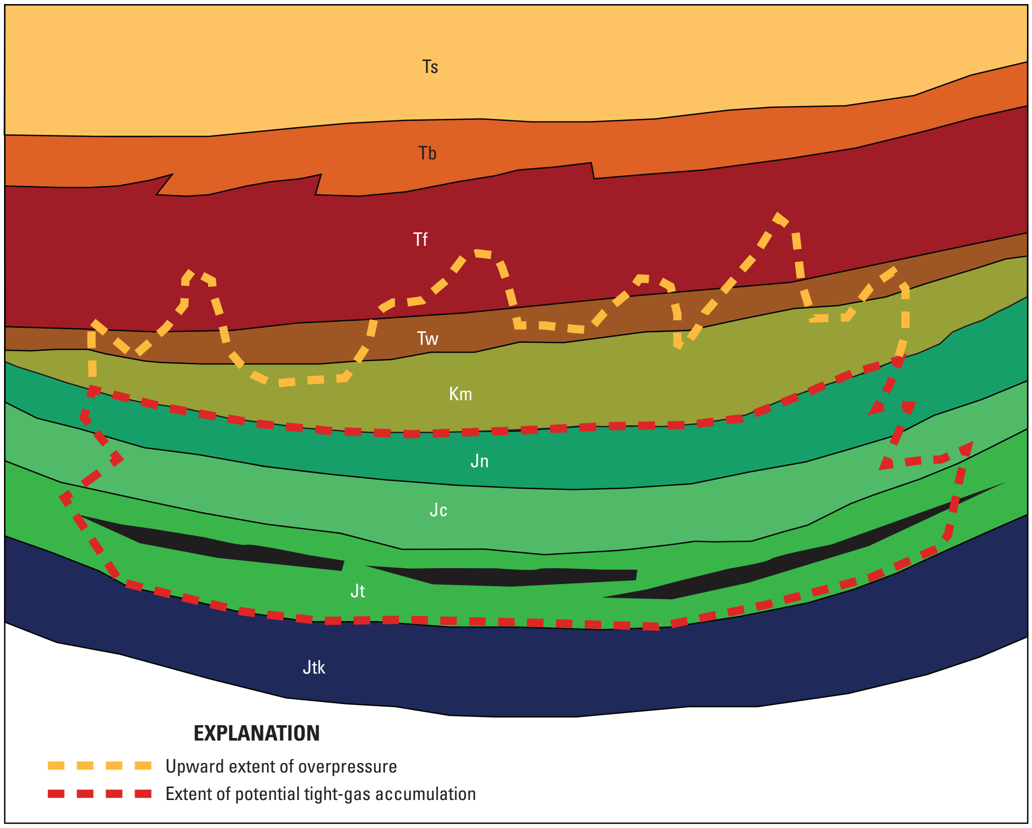
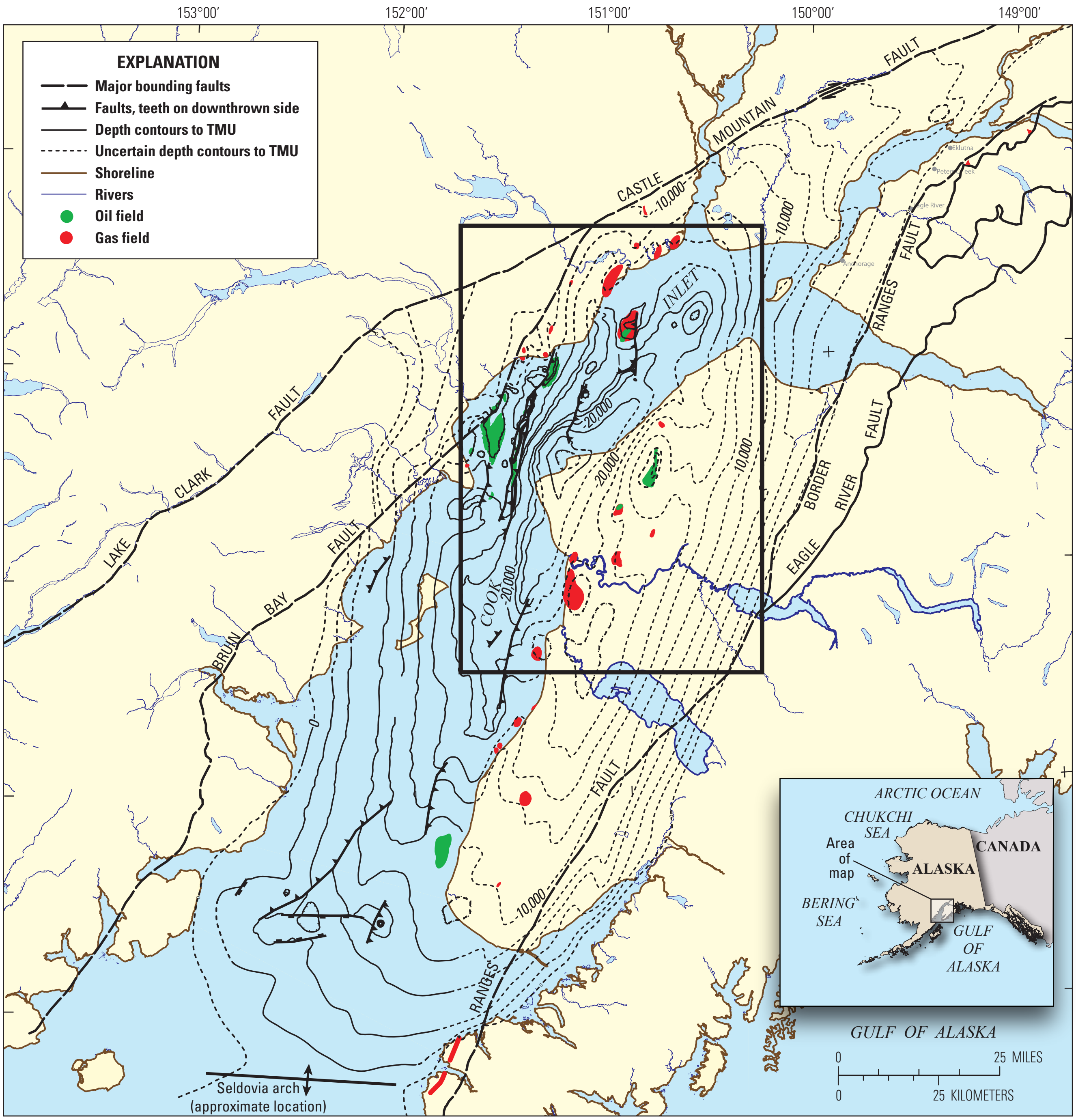


Figure 13. Schematic diagram of the geologic model developed for this assessment. Oil and gas generated in organic-rich black shales of the Tuxedni Group migrated into low-permeability reservoirs in the Tuxedni Group and Chinitna and Naknek Formations, which are overpressured. The overpressured zone is interpreted to extend upward into younger strata along faults and fracture zones. (Jtk, Talkeetna Formation; Jt, Tuxedni Group; Jc, Chinitna Formation; Jn, Naknek Formation; Km, Kaguyak Formation; Tw, West Foreland Formation, Tf, Tyonek Formation; Tb, Beluga Formation; Ts, Sterling Formation)

Table 1. Key assessment input data for the Tuxedni-Naknek Continuous Gas Assessment Unit (AU).

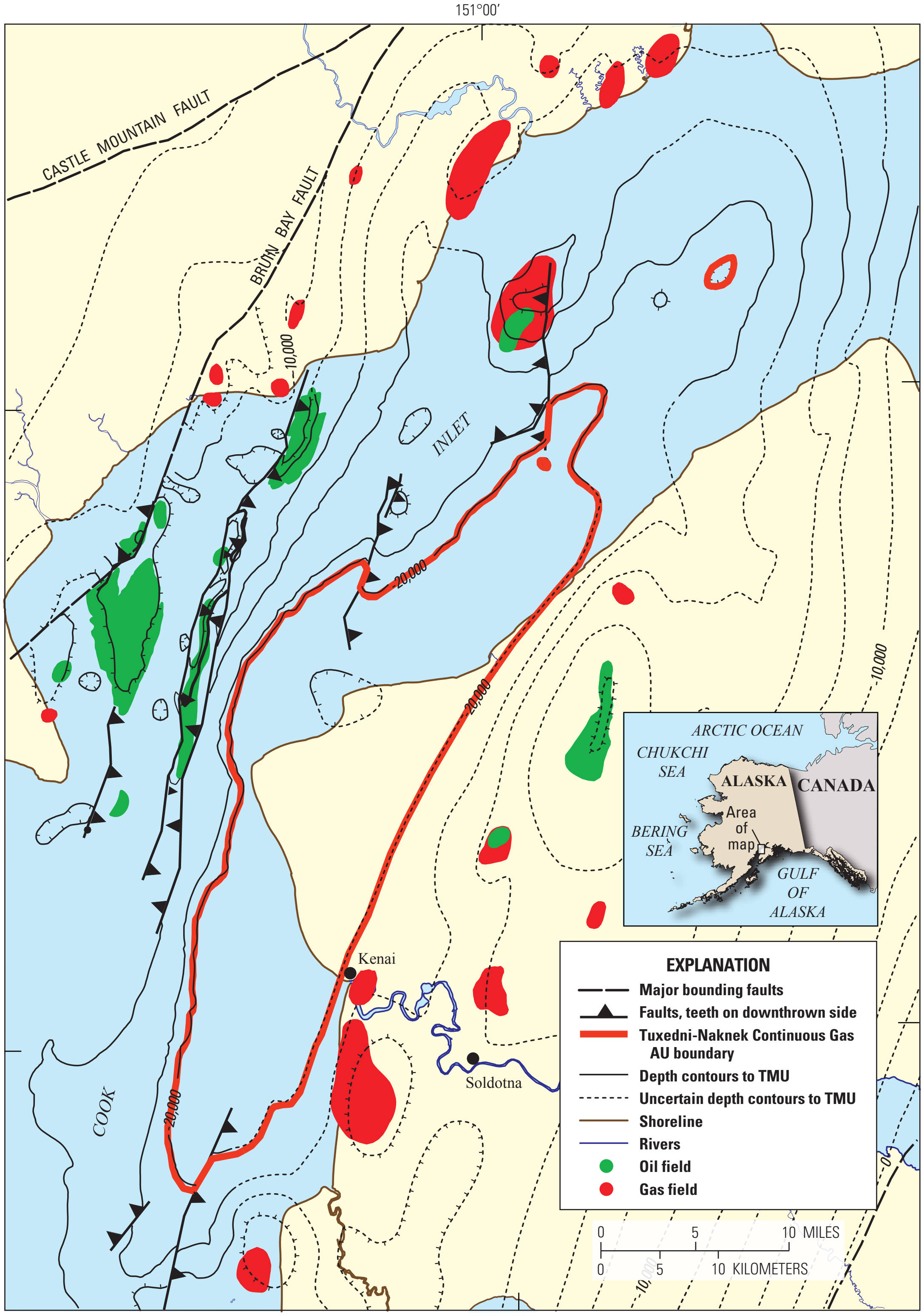
[Estimated Ultimate Recovery (EUR), well-drainage areas, and success ratios are from U.S. tight-gas analogs. MMBO, million barrels of oil, BCFG, billion cubic feet of gas; AU, assessment unit; %, percent. The average EUR input uses median rather than mode.]

Assessment input data	Tuxedni-Naknek Shale Gas AU			
	Minimum	Mode	Maximum	Calculated mean
Potential production area of AU (acres)	201,600	224,000	246,000	224,000
Average drainage area of wells (acres)	80	140	320	180
Percent of AU untested	0.5	24	95	39.8
Success ratios (%)	0.02	0.6	30	1.29
Average EUR (MMBO, oil; BCFG, gas)	75	90	95	86.7



Base map from State of Alaska, Department of Natural Resources,
Alaska Statewide Core GIS database

Figure 14. Map of Cook Inlet Basin showing depth contours to the "Top Mesozoic Unconformity." Contour interval is 2,000 feet. From Shellenbaum and others (2010). Inset area shown in figure 15.



Base map from State of Alaska, Department of Natural Resources, Alaska Statewide Core GIS database

Figure 15. Map showing boundary of the Tuxedni-Naknek Continuous Gas Assessment Unit (AU) encompassing the maximum area of a potential tight-gas accumulation in upper Cook Inlet Basin. As drawn, the AU boundary (red line) approximates the -20,000-foot contour on the “Top Mesozoic Unconformity” as defined by Shellenbaum and others (2010). The AU is drawn to encompass a hypothetical area with thermal maturity postulated to be greater than about 1.3 percent vitrinite reflectance. Oil (green) and gas (red) fields shown in relation to structure. Contour interval is 2,000 feet.

in the assessment. The input form is a shorthand method standardized to record all information relevant to complete a quantitative assessment, keeping the geologic model as a basis for the input. The input demonstrates that probability distributions are used rather than point values for most input data. The following sections contain explanations for the various categories of input data.

Assessment Unit Probabilities

Given the minimum total recovery per cell of 0.02 billion cubic feet of gas (BCFG; used in all USGS assessments), the chance for 1 well in the AU area have an EUR greater than 0.02 BCFG was interpreted to be 100 percent, or no geologic risk on adequate charge, timing, and presence of low-permeability reservoir rocks for a well of minimum size.

Assessment Unit Area

The area of an AU is one of the primary inputs to the quantitative assessment. The area of the Tuxedni-Naknek AU is defined on the basis of the postulated extent of Tuxedni Group marine source rocks, the thermal maturity of the source rocks, and the extent of overpressure. As limited thermal maturation data are available in this part of the basin, and using Magoon's (1994a) interpretation of the thermal-gas window in the central part of the basin, we used the –20,000 ft depth to TMU contour to define the maximum extent of possible tight-gas saturation in Tuxedni, Chinitna, and Naknek sandstones and siltstones (figs. 14, 15). There is considerable uncertainty on this contour line, as discussed by Schellenbaum and others (2010). The –20,000 foot contour encompasses a maximum AU area of about 224,000 acres. Given the uncertainty of this boundary, a 10-percent uncertainty was included, giving a minimum AU area of 201,600 acres, a mode of 224,000 acres, and a maximum of 246,000 acres.

Area per Cell of Untested Cells

In the assessment methodology drainage areas of wells are defined as areas within which potential wells in the assessment unit will drain a reservoir, but are interpreted to not interfere with adjacent wells during production given current technology for stimulation and completion. For the Tuxedni, Chinitna, and Naknek reservoirs, there are no wells in the AU that would constrain the range of cell sizes. For this reason, we used the summary of cell-size distributions for all low-permeability reservoirs assessed in the United States. These summary distributions represent thousands of tight-gas wells and are used here as analogs for drainage areas for potential Jurassic reservoirs. The distribution of drainage areas was chosen to be 80 acres at the minimum, 140 acres at the mode, and 320 acres at the maximum, with a calculated mean of 180 acres. The choice of 320 and 140 acres reflects the idea that marine sandstones of the Tuxedni Group and Chinitna Formation are generally more continuous than Naknek Formation fluvial sandstones. Horizontal wells might be the preferred method of recovery over vertical wells, but vertical wells would be more reasonable in the Naknek. This distribution reflects the uncertainty in determining drainage areas of wells in low-permeability reservoirs.

Percent of AU that is Untested

No wells penetrate the Jurassic section in the central part of the upper Cook Inlet Basin, so 100 percent of the AU area is untested.

Percent of AU with Resource Potential

The area of the AU that is untested and has the geologic characteristics to potentially be successful is informally called a "sweet spot" for production. At the central tendency, we chose the –23,000 foot contour as the area that would most likely have the proper thermal maturity, low-permeability reservoirs, and overpressure to potentially have gas in the tight-pore system of the Tuxedni, Chinitna, and Naknek. The –23,000 foot contour encompasses about 60,761 acres, or about 27 percent of the total AU area. Applying the mean success ratio (0.867 percent) against this area yields an area of 24 percent, or about 52,418 acres, representing about 24 percent of the total AU area (table 1). The maximum area was chosen to be encompassed by the –20,000 foot contour, which represents about 224,000 acres. Applying a success ratio of 95 percent gives an area of 212,800 acres, or 95 percent of the total AU area. The minimum was chosen to be a scenario in which virtually the entire AU potential failed, with only a handful of successful wells, or about 1,120 acres (76 cells of 180 acres each), representing about 0.5 percent of the total AU area. The area distribution, 0.5, 24, and 95 percent illustrates the considerable geologic uncertainty associated with thermal maturity, hydrocarbon charge and migration, and timing of events such as gas emplacement.

Total Gas Recovery per Cell

Since no wells in this AU penetrate the Jurassic stratigraphic section, the choice of EUR distribution was guided by analog EUR distributions developed from other low-permeability reservoirs in the United States (U.S. Geological Survey Oil and Gas Assessment Team, 2012). The "family" of EUR distributions for U.S. tight-gas reservoirs is shown in figure 16. For potential Tuxedni, Chinitna, and Naknek reservoirs, we chose a median EUR of 0.6 BCFG, which is in the middle of the cloud of EUR curves for tight gas. The minimum EUR is 0.02 BCFG by default, and is used as a minimum in all USGS assessments of low-permeability reservoirs. The maximum EUR was chosen to be 30 BCFG, which is a large EUR with a low probability in these types of reservoirs. The mode of the distribution is 0.6 BCFG, and the calculated mean is

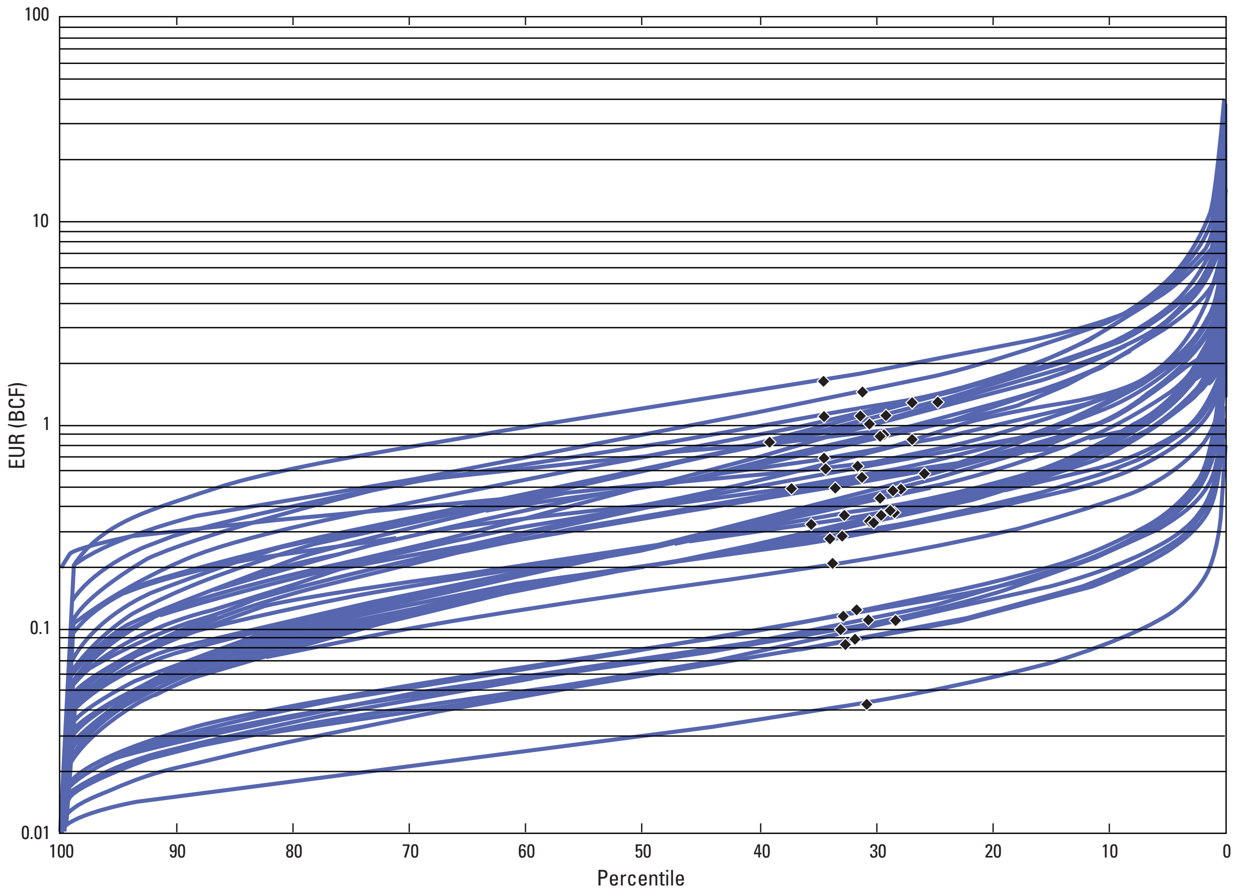


Figure 16. Diagram showing the "family" of curves for Estimated Ultimate Recovery (EUR) distributions from assessed tight-gas units in the lower 48 states. Mean values are shown by the black diamonds on each curve. From U.S. Geological Survey Oil and Gas Assessment Team (2012). (BCF, billion cubic feet of gas)

1.29 BCFG. This distribution again illustrates the geologic uncertainty in this AU for presence of source, charge, and timing of petroleum system events.

Average Co-Product Ratio

The co-product ratio, in this case the liquids-to-gas ratio in a gas reservoir, is used in the assessment to calculate potential volumes of liquids associated with this hypothetical tight-gas accumulation. Using analogs from other assessments of similar source-reservoirs rock systems in the United States, we chose a distribution of 7 barrels of liquid per million cubic feet of gas (BLIQ/MMCFG) at the minimum, 15 BLIQ/MMCFG at the mode, and 22 BLIQ/MMCFG at the maximum.

Success Ratios

In all low-permeability AUs assessed in the United States, we pay careful attention to the reported final well classifications that impact the calculation of the historic success ratio. For these reservoirs, another family of curves from the U.S. accumulations was used as analogs. We used a minimum success ratio of 75 percent, a mode of 90 percent, and a maximum of 95 percent, with a calculated mean of 86.7 percent for a well of minimum EUR. This distribution is typical for U.S. tight-gas accumulations, and shows that these reservoirs generally have high percentage of successful wells. However, this does not imply that the wells are economic.

Drilling Depths

Potential drilling depths were estimated to range from a minimum of 6,000 m, a mode of 7,000 m, and a maximum of 10,000 m. Again, this distribution does not imply that wells drilled to these depths would be economic.

Assessment Results

The USGS estimates that the mean volume of technically recoverable basin-center tight gas might be 637 billion cubic feet of gas, with an F95 fractile of 257 BCFG and a F5

Table 2. Tuxedni-Naknek Continuous Gas Assessment Unit assessment results.

[BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas accumulations, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under assumption of perfect positive correlation.]

Total Petroleum Systems (TPS) and Assessment Units (AU)	AU Probability	Field Type	Total Undiscovered Resources							
			Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean
Tuxedni-Naknek Continuous Gas Total Petroleum System										
Tuxedni-Naknek Continuous Gas AU	1.0	Gas	257	568	1,254	637	3	8	19	9
Total unconventional resources			257	568	1,254	637	3	8	19	9

fractile of 1,254 BCFG (table 2). This estimate is only for potential basin-center tight gas in upper Cook Inlet Basin and does not include any potential Cenozoic tight-gas reservoirs. The range of estimates illustrates the considerable geologic uncertainty with the geologic model for this assessment unit. The co-product ratio resulted in a calculated mean of 9 million barrels of natural gas liquids (MMBNGL), with a F95 of 3 MMBNGL and an F5 of 19 MMBNGL (table 2).

Discussion

The USGS assessment of conventional and unconventional resources of upper Cook Inlet Basin indicates that undiscovered resources are predominantly conventional gas (mean of 13.7 trillion cubic feet of gas, TCFG), with potential for undiscovered resources in structural and stratigraphic traps (Stanley and others, 2011). Coalbed gas resources in the Cook Inlet and Susitna Basins have a mean of 4.7 TCFG. Although the mean resource estimate for basin-center tight gas is 0.64 TCFG, we agreed that it was important to include this potential resource in the assessment of upper Cook Inlet Basin given what is currently known of tight-gas systems in the United States. The possibility for shale-oil and shale-gas resources was evaluated in Tuxedni Group source rocks (D.W. Houseknecht, oral commun., September 12, 2012) but was not quantitatively assessed, as there were no data on potential recoverable oil or gas remaining in the source-rock reservoir system. Evidence for generation and migration of oil from the Tuxedni is manifest in oil fields of upper Cook Inlet Basin, but retention of oil in the source rock is not manifest.

Tight sandstones are known to be present in several Cenozoic stratigraphic units in upper Cook Inlet Basin, including the West Foreland Formation, Hemlock Conglomerate, and Tyonek Formation (Hickey and others, 2007; Helmold and others, 2011). The extent and distribution of these tight sandstones were not mapped as part of this study. These sandstones might be reservoirs for gas generated from adjacent coals; this source-reservoir situation is common to many tight-gas systems in Rocky Mountain basins (Cumella and Scheeval, 2005).

Economics were not part of this assessment, as the estimates presented here are for technically recoverable resources and not economically recoverable resources. A certain percentage of the Tuxedni-Naknek Continuous Gas AU is offshore, which is today largely outside of the economic threshold of unconventional oil and gas accumulations, even for the lower 48 states.

In the course of this study, we speculated on the possibility that the Middle Jurassic Tuxedni Group might contain unconventional oil or gas in the lower Cook Inlet Basin. Oil and gas shows reported in the Alaska Consolidated Oil Iniskin Beal–1 well, the ARCO COST–1 well, and the ARCO Raven–1 well demonstrate that oil and possibly biogenic gas was generated within organic-bearing shales of the Red Glacier Formation. We suggest that the Tuxedni Group and possibly the Naknek Formation in lower Cook Inlet could host tight oil or tight gas.

Summary

A geologic model was developed to advance the hypothesis that a tight-gas accumulation is possible in the deep, central part of upper Cook Inlet Basin. The model relies on organic-bearing marine source rocks in the Middle Jurassic Tuxedni Group to have generated oil, gas, and overpressure. The model also assumes that limited, short-distance migration occurred to admit gas (or oil initially) into low-permeability sandstone and siltstone reservoirs in Middle Jurassic Tuxedni Group and Chinitna Formation, and Upper Jurassic Naknek Formation. Geologic uncertainty centers on the existence of adequate source rocks, thermal maturation, generation, expulsion, and limited migration, and on retention in low-permeability rocks. The quantitative assessment of a potential basin-centered tight-gas accumulation relied heavily on geologic analogs from other U.S. tight-gas accumulations, which provided data on EURs, drainage areas, and success ratios.

References Cited

Blasko, D.P., 1976, Oil and gas exploration on the Iniskin Peninsula, Alaska: U.S. Bureau of Mines Open-File Report 76–69, 19 p.

Blodgett, R.B., and Sralla, Bryan, 2006, A major unconformity between Permian and Triassic strata at Cape Kekurnoi, Alaska Peninsula—Old and new observations on stratigraphy and hydrocarbon potential: Studies by the U.S. Geological Survey in Alaska, 2006—U.S. Geological Survey Professional Paper 1739–E, 13 p.

Boss, R.F., Lennon, R.B., and Wilson, B.W., 1976, Middle Ground Shoal Oil Field, Alaska, *in* Braunstein, Jules, ed., North American Oil and Gas Fields: American Association of Petroleum Geologists Memoir No. 24, p. 1–22.

Bradley, D.C., Haeussler, P.J., and Kusky, T.M., 1993, Timing of Early Tertiary ridge subduction in southern Alaska, *in* Dusel-Bacon, Cynthia, and Till, A.B., eds., Geologic Studies in Alaska by the U.S. Geological Survey, 1992: U.S. Geological Survey Bulletin 2068, p. 163–177.

Bruhn, R.L., and Haeussler, P.J., 2006, Deformation driven by subduction and microplate collision—Geodynamics of Cook Inlet Basin, Alaska: Geological Society of America Bulletin, v. 118, no. 3, p. 289–303.

Bruhn, R.L., Parry, W.T., and Bunds, M.P., 2000, Tectonics, fluid migration, and fluid pressure in a deformed forearc basin, Cook Inlet, Alaska: Geological Society of America Bulletin, v. 112, no. 4, p. 550–563.

Claypool, G.E., Threlkeld, C.N., and Magoon, L.B. III, 1980, Biogenic and thermogenic origins of natural gas in Cook Inlet Basin, Alaska: American Association of Petroleum Geologists Bulletin, v. 64, no. 8, p. 1131–1139.

Clift, P.D., Draut, A.E., Kelemen, P.B., Blusztajn, Jerzy, and Greene, Andrew, 2005a, Stratigraphic and geochemical evolution of an oceanic upper crustal section: The Jurassic Talkeetna volcanic Formation, south-central Alaska: Geological Society of America Bulletin, v. 117, no. 7–8, p. 902–925.

Clift, P.D., Pavlis, Terry, DeBari, S.M., Draut, A.E., Rioux, Matthew, and Kelemen, P.B., 2005b, Subduction erosion of the Jurassic Talkeetna-Bonanza arc and the Mesozoic accretionary tectonics of western North America: Geology, v. 33, no. 11, p. 881–884.

Crossey, L.J, Frost, B.R., and Surdam, R.C., 1984, Secondary porosity in laumontite-bearing sandstones, *in* McDonald, D.A., and Surdam, R.C., eds., Clastic Diagenesis: American Association of Petroleum Geologists Memoir No. 37, p. 225–237.

Cumella, S.P., and Scheevel, Jay, 2008, The influence of stratigraphy and rock mechanics on Mesaverde gas distribution, Piceance Basin, Colorado, *in* Cumella, S.P., Shanley, K.W., and Camp, W.K., eds., Understanding, exploring, and developing tight-gas sands: American Association of Petroleum Geologists Hedberg Series, No. 3, p. 137–155.

Detterman, R.L., and Hartsock, J.K., 1966, Geology of the Iniskin-Tuxedni region, Alaska: U.S. Geological Survey Professional Paper 512, 78 p.

Farris, D.W., Haeussler, Peter, Friedman, Richard, Paterson, S.R., Saltus, R.W., and Ayuso, Robert, 2006, Emplacement of the Kodiak batholiths and slab window migration: Geological Society of America Bulletin, v. 118, no. 11–12, p. 1360–1376.

Fisher, M.A. and Magoon, L.B. III, 1978, Geologic framework of Lower Cook Inlet, Alaska: American Association of Petroleum Geologists Bulletin, v. 62, no. 3, p. 373–402.

Fisher, M.A., Detterman, R.L., and Magoon, L.B. III, 1987, Tectonics and petroleum geology of the Cook Inlet–Shelikof Basin, southern Alaska, *in* Geology and resource potential of the western North America and adjacent ocean basins-Beaufort Sea to Baja California: Circum-Pacific Council for Energy and Mineral Resources, v. 6, Chapter 10, p. 213–229.

Gasser, Deta, Rubatto, Daniela, Bruand, Emilie, and Stuwe, Kurt, 2012, Large-scale, short-lived metamorphism, deformation, and magmatism in the Chugach metamorphic complex, southern Alaska: A SHRIMP U-Pb study of zircons: Geological Society of America Bulletin, v. 124, no. 5–6, p. 886–905.

Greene, A.R., Scoates, J.S., Wels, Dominique, Katvala, E.C., Israel, Steve, and Nixon, G.T., 2010, The architecture of oceanic plateaus revealed by the volcanic stratigraphy of the accreted Wrangellia oceanic plateau: Geosphere, v. 6, no. 1, p. 47–73.

Gregersen, L.S, and Shellenbaum, D.P., 2010, PowerPoint presentation at U.S. Geological Survey Cook Inlet Geology Review: Anchorage, Alaska, September 12, 2010, unpublished.

Haeussler, P.J., Bradley, D.C., Wells, R.E., and Miller, M.L., 2003, Life and death of the Resurrection plate—Evidence for its existence and subduction in the northeastern Pacific in Paleocene-Eocene time: Geological Society of America Bulletin, v. 115, no. 7, p. 867–880.

Haeussler, P.J., Bruhn, R.L., and Pratt, T.L., 2000, Potential seismic hazards and tectonics of the upper Cook Inlet Basin, Alaska, based on analysis of Pliocene and younger deformation: Geological Society of America Bulletin, v. 112, no. 9, p. 1414–1429.

Helmold, K.P., LePain, D.L., Wartes, M.A., Stanley, R.G., Gillis, R.J., Petersen, C.S., and Herriott, T.M., 2011, Reservoir potential of Tertiary and Mesozoic sandstones, Cook Inlet, Alaska: PowerPoint presentation at U.S. Geological Survey Cook Inlet Geology Review: Anchorage, Alaska, September 12, 2010, unpublished.

Hettinger, R.D., and Roberts, L.N.R., 2005, Lewis Total Petroleum System of the Southwestern Wyoming Province, Wyoming, Colorado, and Utah, chap. 9 *of* U.S. Geological Survey Southwestern Wyoming Province Assessment Team, Petroleum systems and geologic assessment of oil and gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS–69–D, 43 p.

Hickey, J.J., Wilson, M.D., and Reifenstuhl, R.R., 2007, Petrographic study of 50 samples from Tertiary sandstones of Cook Inlet, Alaska—Potential tight gas reservoirs: Alaska Division of Geophysical and Geological Surveys Report of Investigations 2007–2, 69 p.

Hillhouse, J.W., 1987, Accretion of southern Alaska: Tectonophysics, v. 139, p. 107–122.

Holditch, S.A., 2006, Tight gas sands: Journal of Petroleum Technology, p. 84–90. [June, 2006, Society of Petroleum Engineers Paper 103356]

Hunt, J.M., 1990, Generation and migration of petroleum from abnormally pressured fluid compartments: American Association of Petroleum Geologists Bulletin, v. 74, no. 1, p. 1–12.

IHS Energy Group, 2011, PI/Dwights Plus U.S. Production Data: IHS Energy Group; database available from IHS Energy Group, 15 inverness Way East, D205, Englewood, Colo., 80112, U.S.A.

Kelly, T.E., 1963, Geology and hydrocarbons in Cook Inlet Basin, Alaska, *in* Childs, O.E., and Beebe, B.W., eds., Backbone of the Americas—Tectonic history from pole to pole: American Association of Petroleum Geologists Memoir no. 2, p. 278–296.

Kirschner, C.E., and Minard, D.L., 1949, Geology of the Iniskin Peninsula, Alaska: U.S. Geological Survey Oil and Gas Investigations Map 95, 1 sheet.

Koons, P.O., Hooks, B.P., Pavlis, T., Upton, P., and Barker, A.D., 2010, Three-dimensional mechanics of Yakutat convergence in the southern Alaskan plate corner: Tectonics, v. 29, TC4008, 17 p.

LePain, D.L., Lillis, P.G., Helmold, K.P., and Stanley, R.G., 2012, Migrated hydrocarbons in exposure of Maastrichtian nonmarine strata near Saddle Mountain, Lower Cook Inlet, Alaska: Alaska Division of Geological and Geophysical Surveys Report of Investigations 2012–1, 19 p.

LePain, D.L., Stanley, R.G., Gillis, R.J., Helmold, K.P., Peterson, C.S., and Wartes, M.A., 2011, Deposition of the Middle Jurassic Tuxedni Group, Lower Cook Inlet, Alaska—Initial exhumation of an Early Jurassic island arc and incipient motion on the Bruin Bay Fault Zone [abs.]: American Association of Petroleum Geologists Search and Discovery Abstract No. 90125.

Lillis, P.G., and Stanley, S.G., 2011, Petroleum generation modeling for Cook Inlet Basin, Alaska [abs.]: American Association of Petroleum Geologists Pacific Section Meeting Abstract, Anchorage, Alaska, May 8–11, 2011, Proceedings: American Association of Petroleum Geologists.

Madsen, J.K., Thorkelson, D.J., Friedman, R.M., and Marshall, D.D., 2006, Cenozoic to Recent plate configurations in the Pacific Basin: Ridge subduction and slab window magmatism in western North America: Geosphere, v. 2, no. 1, p. 11–34.

Magoon, L.B. III, 1994a, Tuxedni-Hemlock(!) petroleum system in Cook Inlet, Alaska, U.S.A., *in* Magoon, L.B. III, and Dow, W.G., eds., chap. 20 *of* The petroleum system—From source to trap: American Association of Petroleum Geologists Memoir No. 60, p. 359–370.

Magoon, L.B. III, 1994b, Petroleum resources in Alaska, *in* Plafker, George, and Berg, H.G., eds., The Geology of Alaska: Boulder, Colo., Geological Society of America, Geology of North America, v. G-1, p. 905–936.

Magoon, L.B. III, and Anders, D.E., 1992, Oil-to-source-rock correlations using carbon-isotopic data and biological marker compounds, Cook Inlet–Alaska Peninsula, Alaska, chap. 13 *of* Moldowan, J.M., Albrecht, Pierre, and Philp, R.P., eds., Biological markers in sediments and petroleum: Prentice Hall, New Jersey, p. 241–274.

Magoon, L.B. III, and Claypool, G.E., 1981, Petroleum geology of Cook Inlet Basin—An exploration model: American Association of Petroleum Geologists Bulletin, v. 65, no. 3, p. 1043–1061.

Magoon, L.B. III, 1986, Stratigraphic units of the COST No. 1 well, *in* Magoon, L.B. III, ed., Geologic studies of the Lower Cook Inlet COST No. 1 well, Alaska Outer Continental Shelf: U.S Geological Survey Bulletin 1596, p. 17–22.

Magoon, L.B. III, and Egbert, R.M., 1986, Framework geology and sandstone composition, *in* Magoon, L.B. III, ed., Geologic studies of the Lower Cook Inlet COST No. 1 well, Alaska Outer Continental Shelf: U.S Geological Survey Bulletin 1596, p. 65–90.

Nokleberg, W.J., Plafker, G., and Wilson, F.H., 1994, Geology of south-central Alaska, *in* Plafker, George, and Berg, H.G., eds., The Geology of Alaska: Boulder, Colo., Geological Society of America, Geology of North America, v. G–1, p. 311–366.

Osment, F.C., Morrow, R.M., and Craig, R.W., 1967, Petroleum geology and development of the Cook Inlet Basin of Alaska, *in* Proceedings of the 7th World Petroleum Congress, Mexico, 1967: Elsevier Publishing Co., Amsterdam, v. 2, p. 141–150.

Pavlis, 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, p. 343–368.

Pavlis, G.L., Picornell, C., Serpa, L., Bruhn, R.L., Plafker, G., 2004, Tectonic processes during oblique collision—Insights from the St. Elias orogen, southern North American Cordillera: Tectonics, v. 23, TC3001, 14p.

Peters, K.E., Magoon, L.B. III, and Hudson, Travis, 2006, Origin and generation timing of Cook Inlet petroleum—Circum-Arctic chemometrics and 1-D geohistory modeling [abs.], *in* Geological Society of America, 102nd Cordilleran Section Meeting, May 8–10, 2006, Anchorage, Alaska: Geological Society of America , Abstracts with Programs, v. 38, no. 5, p. 71.

Plafker, George, and Berg, H.C., 1994, Overview of the geology and tectonic evolution of Alaska, *in* Plafker, George, and Berg, H.G., eds., The geology of Alaska: Boulder, Colo., Geological Society of America, Geology of North America, v. G-1, p. 989–1021.

Plafker, George, Moore, J.C., and Winkler, G.R., 1994, Geology of the southern Alaska margin, *in* Plafker, George, and Berg, H.G., eds., The Geology of Alaska: Boulder, Colo., Geological Society of America, Geology of North America, v. G-1, p. 389–450.

Powley, D.E., 2008, Selected occurrences of abnormal pressures in Alaska: American Association of Petroleum Geologists, Search and Discovery Article No. 60011. [slides from undated earlier work at Amoco Production Company by D.E. Powley]

Reed, B.L., Miesch, A.T., and Lanphere, M.A., 1983, Plutonic rocks of Jurassic age in the Alaska-Aleutian Range batholiths—Chemical variations and polarity: Geological Society of America Bulletin, v. 94, p. 1232–1240.

Ridgway, K.D., Trop, J.M., Nokleberg, W.J., Davidson, C.M., and Eastham, K.R., 2002, Mesozoic and Cenozoic tectonics of the eastern and central Alaska Range—Progressive basin development and deformation in a suture zone: Geological Society of America Bulletin, v. 114, no. 12, p.1480–1504.

Rouse, W.A., and Houseknecht, D.W., 2012, Assessment of the coal-bed gas total petroleum system in the Cook Inlet–Susitna region, south-Central Alaska: U.S. Geological Survey Scientific Investigations Report 2012–5145, 19 p.

Scharman, M.R., and Pavlis, T.L., 2012, Kinematics of the Chugach metamorphic complex, southern Alaska—Plate geometry in the north Pacific margin during the Late Cretaceous to Eocene: Tectonics, v. 31, 14 p.

Shellenbaum, D.P., Gregersen, L.S., and Delaney, P.R., 2010, Top Mesozoic unconformity depth map of the Cook Inlet Basin, Alaska: Alaska Division of Geological and Geophysical Surveys, Report of Investigations 2010-2, 1 sheet.

Stanley, R.G., Charpentier, R.R., Cook, T.A., Houseknecht, D.W., Klett, T.R., Lewis, K.A., Lillis, P.G., Nelson, P.H., Phillips, J.D., Pollastro, R.M., Potter, C.J., Rouse, W.A., Saltus, R.W., Schenk, C.J., Shah, A.K., and Valin, Z.C., 2011, Assessment of undiscovered oil and gas resources of the Cook Inlet region, south-central Alaska, 2011: U.S. Geological Survey Fact Sheet 2011–3068, 2 p.

Stokes, P.J., Grether, William, and Walsh, T.P., 2010, Cook Inlet gas study: an analysis for meeting the natural gas needs of Cook Inlet utility customers: Petrotechnical Resources Alaska, 133 p.

Swenson, R.F., 2003, Introduction to Tertiary tectonics and sedimentation in the Cook Inlet Basins, *in* Dallegge, T.A., comp., 2001 guide to the petroleum geology of and shallow gas potential of the Kenai Peninsula, Alaska: Alaska Division of Geological and Geophysical Surveys, Miscellaneous Publication 128, p. 10–19.

Thomas, C.P., Doughty, T.C., Faulder, D.D., and Hite, D.M., 2004, South-Central Alaska natural gas study: National Energy Technology Laboratory, Arctic Energy Office, U.S. Department of Energy Final Report, Contract DE–AM26–99FT40575, 207 p.

Triplehorn, D.M., Turner, D.L., and Naeser, C.W., 1984, Radiometric age of the Chickaloon Formation of south-central Alaska—Location of the Paleocene-Eocene boundary: Geological Society of America Bulletin, v. 95, p. 740–742.

Trop, J.M, 2008, Latest Cretaceous forearc basin development along an accretionary convergent margin—South-central Alaska: Geological Society of America Bulletin, v. 120, no. 1–2, p. 207–224.

Trop, J.M., and Ridgway, K.D., 2007, Mesozoic and Cenozoic tectonic growth of southern Alaska—A sedimentary basin perspective, *in* Ridgway, K.D., Trop, J.M., Glen, J.M.G., and O’Neill, J.M., eds., Tectonic growth of a collisional continental margin: Crustal evolution of southern Alaska: Geological Society of America Special Paper No. 431, p. 55–94.

Trop, J.M., Szuch, D.A., Rioux, Matthew, and Blodgett, R.B., 2005, Sedimentology and provenance of the Upper Jurassic Naknek Formation, Talkeetna Mountains, Alaska—Bearings on the accretionary tectonic history of the Wrangellia composite terrane: Geological Society of America Bulletin, v. 117, no. 5–6, p. 570–588.

U.S. Geological Survey Oil and Gas Assessment Team, 2012, Variability of distributions of well-scale Estimated Ultimate Recovery for continuous (unconventional) oil and gas resources in the United States: U.S. Geological Survey Open–File Report 2012–1118, 18 p., http://pubs.usgs.gov/of/2012/1118/.

Wang, Jason, Newton, C.R., and Dunne, Lorie, 1988, Late Triassic transition from biogenic to arc sedimentation on the Peninsula terrane, Puale Bay, Alaska Peninsula: Geological Society of America Bulletin, v. 100, p. 1466–1478.

Whalen, M.T., and Beatty, T.W., 2008, Kamishak Formation, Puale Bay, *in* Bristol Bay–Alaskan Peninsula region, overview of 2004–2007 geologic research: Alaska Division of Geological and Geophysical Surveys, Report of Investigations 2008–IG, p. 105–129.

Wilson, F.H., Hults, C.P., Schmoll, H.R., Haeussler, P.J., Schmidt, J.M., Yehle, L.A., and Labay, K.A., 2012, Geologic map of the Cook Inlet Region, Alaska: U.S. Geological Survey Scientific Investigations Map 3153, 1:250,000 scale, 2 sheets.

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