Appendix A: Additional Geological Information for the Alaska Peninsula

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A. Description of Stratigraphic Units

Formations known or expected to underlie the State lease sale area are described below in stratigraphic order. The amount of detail provided here is in proportion with the amount of new work conducted beyond the detailed stratigraphic descriptions provided in Detterman and others (1996) and Wilson and others (1999). The discussion of the Cottonwood Bay Greenstone is from Detterman and others (1996). The discussion of the Kamishak Formation and reservoir and petroleum systems properties are based on the work of Whalen and Beatty (2008). The discussion of source rock potential is based on the work of Decker (2008). The description of potential hydrocarbon seals is based on the work of Bolger and Reifenstuhl (2008). Results of petrographic analyses by Helmold and others (2005, 2008) and Finzel and others (2005) are included within the formation descriptions. Additional information about the hydrocarbon reservoir and source rock potential of the lease sale area for the Bear Lake and Milky River formations is based on the work of Finzel and others (2005).

References in text reference citations are listed at the end of Chapter 6.

1. Mesozoic Units

Mesozoic sedimentary rocks of the Chignik subterrane form most of the exposed portion, or upland outcrop belt, along the Alaska Peninsula. The Mesozoic strata (layers) range in age from Late Triassic to Late Cretaceous with a maximum combined thickness of about 8,500 m (Detterman et al. 1996). The Mesozoic units known or expected to underlie the proposed lease sale area ascend in layers or stratigraphic order (sequence of deposition) beginning with the Kamishak Formation from the Upper Triassic period. The other formations and ages include the Talkeetna Formation (Lower Jurassic), Kialagvik Formation (Middle Jurassic), Shelikof Formation (Middle Jurassic), Naknek Formation (Upper Jurassic), Staniukovich Formation (Lower Cretaceous), Herendeen Formation (Lower Cretaceous), Chignik Formation (Upper Cretaceous), and the Hoodoo Formation (Upper Cretaceous). Unconformities are numerous among these stratigraphic units, representing episodes of erosion and/or non-deposition during portions of Early Jurassic, early Late Jurassic, and mid- to Late Cretaceous time (USGS 1996).

Where the base of the Mesozoic succession is exposed at Cape Kekurnoi near Puale Bay, limestones of the Upper Triassic Kamishak Formation inconsistently overlie an unnamed Permian agglomerate, volcaniclastic sandstone, and fossiliferous limestone unit (Blodgett and Sralla 2008). The Kamishak limestones were deposited under tropical conditions (Blodgett and Sralla, 2008), and contain exceptionally rich oil-source potential (Wang 1987; Decker 2008). The remainder of the Mesozoic sedimentary succession consists primarily of clastic rocks rich in volcanic and plutonic framework components deposited adjacent to an island arc (Detterman et al. 1996).

The Mesozoic sedimentary rocks are predominantly marine in origin. In the lower part of the section, the Lower to Middle Jurassic formations (Talkeetna, Kialagvik and Shelikof) consist primarily or significantly of volcanic components. In the upper part of the section, most of the Upper Jurassic through Upper Cretaceous formations (Naknek, Staniukovich, Herendeen and Chignik) consist of feldspathic to arkosic sandstones. The provenance (source area) for the clastic (fragmental) sediments was originally an early Mesozoic volcanic arc. The provenance then shifted with time to the Alaska-Aleutian Range batholith (Middle Jurassic) and included some recycled older sediments (Detterman et al. 1996).

a. Cottonwood Bay Greenstone: Late Triassic (Norian)

The Cottonwood Bay Greenstone is composed of dark green to gray metavolcanicrocks along the south shore near Cottonwood Bay on the western side of Lower Cook Inlet. It appears a similar sequence of metavolcanic rocks is exposed near the northeast end of the Alaska Peninsula. These rocks are suggestive of greenschist facies, (epidote-albite-actinolite) and probably metamorphosed from porphyritic basalt. These rocks are interpreted to be preserved roof pendants in the Alaska-Aleutian Range batholith just west of the Bruin Bay fault. The Cottonwood Bay Greenstone is associated with the basal member of the overlying Kamishak Formation suggesting its age is probably Norian (Detterman et al. 1996).

b. Kamishak Formation: Late Triassic (Norian)

The Kamishak Formation is the oldest sedimentary Mesozoic unit on the Alaska Peninsula at about 800 meters thick (Detterman et al. 1996).

i. Lithology

Detterman and others (1996) subdivided the Kamishak formation into three members consisting of limestone, chert, and volcanic rocks. Whalen and Beatty (2008) described the Kamishak Formation in the Paule Bay area as four distinct units (from oldest to youngest): biostromal; nodular limestone and conglomerate; rhythmically bedded limestone; and siliceous limestone units. The upper portion of the Kamishak Formation contains basalts and volcaniclastic rocks that are interbedded with the carbonate sediments. The two subsurface penetrations of the Kamishak Formation were in the ARCO Wide Bay Unit 1 well east of State acreage and the Amoco Cathedral River Unit 1 well located in the southwest corner of the State sale area.

ii. Lower Contact

Contact relations with other stratigraphic units are obscure. The base of the Kamishak Formation is commonly a fault contact (Wang et al. 1988; Detterman et al. 1996) but locally the unit appears to onlap an angular unconformity atop the underlying greenish volcaniclastic unit (Hanson 1957; Blodgett and Sralla 2008; Whalen and Beatty 2008, page 126). Greenish clasts identified in the deformed interval at the base of the nodular limestone and conglomerate unit and greenish sands within the siliceous limestone unit indicate that the volcaniclastics were locally exposed to erosion during deposition of much of the Kamishak Formation (Whalen and Beatty 2008, page 128).

iii. Upper Contact

There is a gradational contact with the overlying Talkeetna Formation (Detterman et al. 1996; Decker 2008).

iv. Depositional Environment

It appears to be a shallow water carbonate shelfal environment with localized reef and biohermal buildups. Rhythmically bedded biostromal layers are interpreted as deposition below wave base. Siliceous limestone units are interpreted as deposition above wave base on a carbonate ramp with localized areas of syndepositional folded and mass wasted carbonate sediments deposited at the edges of the steepened ramp slope. Synsedimentary folds and deformed limestones are present indicating active tectonic deformation during deposition of the Kamishak Formation (Whalen and Beatty 2008, page126).

v. Petrography

Whalen and Beatty (2008) describe a variety of carbonate facies containing lime mudstone, wackestone, packstone, grainstone, and rudite fabrics. Some units contain skeletal fragments, pelloids, and volcaniclastic sandstone.

vi. Reservoir Quality

Reservoir quality appears generally poor from outcrop samples taken at the time of the study. The carbonate facies present are pervasively cemented with calcite; the more clastic facies contain both calcite and quartz cement. The only facies present in the Puale Bay area with some macroscopic porosity are contained in the conglomerate and coarse grained rudstone beds within the nodular limestone and conglomerate unit. Secondary porosity could exist in the subsurface, with solution enhancement of fractures or as a result of dolomitization in the biostromal unit (Whalen and Beatty 2008).

vii. Hydrocarbon Generating Potential

The Kamishak formation contains good to very good source rock potential. Organic geochemical analysis consisting of total organic carbon (TOC) and Rock-Eval pyrolysis suggest that the best source rock potential lies in the siliceous limestone and rhythmically bedded units. TOC analysis yielded Type I, II, and III results; average values were predominantly in the Type II oil-prone range. Rock Eval data analyses indicate the source rocks range in the boundary between immature and mature (Whalen and Beatty 2008). Decker (2008) discusses and compares outcrop samples analyzed for source rock characteristics from Puale Bay collected by DO&G and DGGS with previous work. Based on total organic carbon, rock-eval pyrolysis, kerogen petrography, and vitrinite reflectance data from Puale Bay outcrop samples, Decker (2008) concludes that the Kamishak Formation present at Puale Bay is highly oil-prone.

viii. Seal Potential

Four samples from crystalline limestones within the Kamishak formation were analyzed and classified as Sneider Type A (best quality seal potential) in the study area (Bolger and Reifenstuhl 2008).

c. Talkeetna Formation: Early Jurassic (HEttangian – Sinemurian)

i. Lithology

The Talkeetna Formation consists of clastic sedimentary and volcanic rocks. Tuffaceous sandstone and tuff are exposed in the Puale and Alinchak Bays; volcanic conglomerate and sandstones are present northeast of Becharof Lake. In the southwestern part of the Alaska Peninsula, the unit consists of a sequence of tuffaceous siltstone, sandstone, and limestone (based on the AMOCO Cathedral River #1 well) that is similar to the rocks exposed at Puale Bay (Detterman et al. 1996). The ARCO Wide Bay #1 well is the only other Alaska Peninsula area well that penetrated the Talkeetna Formation (Finzel et al. 2005).

ii. Lower Contact

There is a gradational contact with the underlying Kamishak Formation (Detterman et al. 1996).

iii. Upper Contact

The Talkeetna formation is generally conformable with the overlying Kialagvik Formation. It is disconformable in places where section is missing due to nondeposition or erosion (Detterman et al. 1996).

iv. Depositional Environment

The depositional environment is considered open shelf due to the presence of ammonites in places (Detterman et al. 1996).

v. Reservoir Potential

Reservoir potential is low due to the abundance of volcanic ash, tuffs and other volcanic rocks interspersed with conglomerates, sandstones, and shales.

d. Kialagvik Formation: Middle Jurassic (Late Toarcian – Early Callovian)

i. Lithology

The lower part of the formation consists of cross-bedded sandstone, lenses of conglomerate, shale, and in places bivalves, abundant wood and carbonaceous debris exposed along Wide Bay. The upper part of the formation contains rhythmically bedded thin gray siltstone and sandstone sequences; locally containing limestone nodules and lenses. At Puale Bay the section is approximately 790 meters thick. It is composed of deep water turbidite assemblages consisting of rhythmically bedded thin gray siltstones and tan sandstones and conglomerates. In places these are channelized massive (Bouma C sequences), and in other places disorganized (debris flow) deposits. The Bear Creek well (located between Wide Bay and Puale Bay) encountered around 1,000 meters of siltstone and shale assigned to the Kialagvik Formation. The Cathedral River #1 well, located on the southern end of the Alaska Peninsula contained about 530 meters of the Kialagvik Formation (Detterman et al. 1996; Decker 2008).

ii. Lower Contact

Contact with the underlying Talkeetna Formation at Puale Bay is an unconformity (Detterman et al. 1996).

iii. Upper Contact

The upper contact is unconformable with the overlying Shelikof Formation (Detterman et al. 1996).

iv. Depositional Environment

The lower part of the unit is nearshore and contains thick-shelled bivalves indicating a high energy shallow-water environment. The upper unit contains features which represent deposition due to a deeper water turbidite environment. The Kialagvik Formation is only present in outcrop on State acreage at Wide and Paule Bays (Detterman et al. 1996).

v. Reservoir Potential

Reservoir potential is low. Overall the formation’s depth of burial has likely physically compacted the interbedded finer grained layers and ductile grains, as well as chemically unstable lithics, within the sandstone bodies. This would greatly reduce the original porosity. Helmold and Brizzolara (2005) reported permeabilities of 0.005 to 0.7 md for a small set of outcrop samples from the formation.

vi. Hydrocarbon Generating Potential

Hydrocarbon generating potential for this formation is considered good. The Kialagvik Formation is correlated with the middle Jurassic Tuxedni Group along the west side of Cook Inlet that is considered the source rock for most of the oil produced in Cook Inlet (Magoon and Anders 1992). Decker (2008) concluded that the Kialagvik Formation present at Puale Bay is highly oil-prone based on Puale Bay outcrop samples analyzed for the following source rock characteristics: total organic carbon, rock-eval pyrolysis, kerogen petrography, and vitrinite reflectance data.

vii. Seal Potential

Depending on the geometry of the rhythmically bedded thin gray siltstone and sandstone sequences there is seal potential. No samples were studied for seal potential.

e. <u>Shelikof Formation: Middle Jurassic (Callovian)</u>

i. Lower Contact

It is believed the contact between the Shlikof and underlying Kialagvik Formation is conformable (Detterman et al. 1996).

ii. Upper Contact

The upper contact is unconformable with the overlying Naknek Formation (Detterman et al. 1996).

iii. Lithology

Detterman (1996) hypothesized the Shelikof Formation underlies the entire Alaska Peninsula. The formation contains abundant coarse volcanic debris and attains up to 1,402 meters in thickness. The lower part of the formation consists of thick-bedded to massive, dusky-yellowish-green graywacke and conglomerate that is dominated by volcanic clasts. The upper part of the formation consists mainly of brownish-gray siltstone containing limestone nodules (Detterman et al. 1996). In the subsurface the Shelikof Formation is recognized in the Cathedral River 1 and Painter Creek 1 wells.

iv. Depositional Environment

The Shelikof Formation consists of abrupt lateral facies changes that indicate deep to shallow water deposition (Detterman et al. 1996). From the rock descriptions, the formation appears to represent turbidite sequences consisting of channelized conglomerate (Bouma A) sequences fining (grain size decreasing) upward into variations of Bouma ABDE sequences. The presence of ammonites locally in the upper part of the formation suggests an open marine environment throughout deposition of the Shelikof Formation.

v. Reservoir Quality

Reservoir quality is low. This is indicated by samples of Shelikof Formation sandstones scatter plotted by Helmold and others (2005).They plot as low porosity/low permeability. The presence of abundant volcanic rock fragments and the relatively deep burial would suggest the loss of porosity is due to alteration of the volcanic lithics through both diagenesis and compaction. This is a result of burial deep enough to compact ductile grains and matrix.

vi. Seal Potential

Depending on the geometry of the brownish-gray siltstone containing limestone nodules (Detterman et al. 1996), there appears to be some seal potential, although no samples were collected. The diagenesis and compaction of the volcanic lithic grains degrading reservoir quality could also aid in forming a hydrocarbon barrier or seal.

f. <u>Naknek Formation: Late Jurassic (Oxfordian – Tithonian)</u>

The uplifting Alaska-Aleutian Range batholith was the main provenance (origin) for the Naknek Formation. It is believed the batholith was uplifted and eroded shortly after it solidified (Detterman et al. 1996).

i. Lower Contact

Regionally, where it is exposed in the Alaska Peninsula, the Naknek formation is disconformable with the Middle Jurassic Shelikof Formation (Detterman et al. 1996).

ii. Upper Contact

The upper contact of the Naknek formation is conformable with the overlying Staniukovich Formation (Detterman et al. 1996).

iii. Lithology

Detterman and others (1996) subdivided the Naknek formation into five members. The formation attains a maximum thickness of approximately 3,205 meters in the Alaska Peninsula and averages approximately 1,700 to 2,000 meters (Detterman et al. 1996). Only two members were recognized and described in the State study area (Decker et al. 2008a):

1) The Indecision Creek Sandstone Member (Tithonian – Kimmeridgian): medium gray fine- to medium-grained arkosic sandstone and siltstone. Although not a large percentage of the framework grain composition, the member was recognized by unaltered biotite and hornblende; and
2) Northeast Creek Sandstone Member (Oxfordian): light gray arkosic sandstone, cross-bedded in places, and locally containing magnetite laminae and thin beds of conglomerate.

In the subsurface the Naknek Formation is recognized in the Cathedral River 1 and Painter Creek 1 wells (Finzel et al. 2005).

iv. Depositional Environment

The depositional environment consists of shelf sequences ranging from shoreface to starved deep basin and fan delta environments. Rapid facies changes are due to the rapid uplift and erosion of the Alaska-Aleutian Range batholith (Detterman et al. 1996, page 19).

v. Petrography

The Naknek Formation contains clean well sorted sandstones, conglomerates, lithic sandstones and ammonites, and the bivalve *Buchia* (Detterman et al. 1996).

vi. Reservoir Quality

The reservoir quality shows as having low potential as conventional oil or gas reservoirs, and moderate potential as tight gas sandstones. Porosity and permeability analysis of several Naknek outcrop samples show low porosity and low permeability attributable to extensive zeolite alteration in most areas, indicating lower reservoir quality (Helmold and Brizzolara 2005). The presence of unaltered biotite and hornblende grains suggests that perhaps the depth of burial of the Naknek may not have adversely affected the overall diagenesis and compaction of individual sandstone and conglomerate sequences. Thus, there may be areas in the subsurface where porosity is preserved locally (Detterman et al. 1996),

g. Staniukovick Formation: (Early Cretaceous (Berriasian – Valanginian)

The Staniukovich formation conformably overlies the Naknek and underlines the Herendeen Formation. The type section described by Detterman and others (1996) consists of a light olive gray siltstone containing two light olive-brown sandstone intervals that are overlain by shaly olive-gray siltstone which contains numerous calcareous nodules and concretions. However, only the upper siltstone interval that weathers to form distinctive red-brown slopes is present in the study area (Decker et al. 2008a). The Staniukovich Formation is present in the David River 1A, Hoodoo Lake 2, and Painter Creek 1 wells.

i. Reservoir Potential

Although not studied in detail by DNR, the sandstone intervals are genetically similar to those in the underlying Naknek Formation and are expected to have low potential as conventional oil or gas reservoirs (Bolger and Reifenstuhl 2008; Decker et al. 2008).

ii. Seal Potential

Four samples were analyzed for seal potential. Their lithology ranged from siltstones, sandstones, and argillaceous sandstones. Two of the samples plotted as Sneider Type B and two plotted as Sneider Type C seals, suggesting that the Staniukovich formation has moderate to marginal sealing potential (Bolger and Reifenstuhl 2008).

h. Herendeen Formation: Early Cretaceous (Hautervian – Barremian)

The Herendeen Formation forms a conformable contact with the underlying Staniukovich Formation and forms an unconformable contact with the overlying Chignik Formation. The Herendeen formation consists of thin beds of uniformly medium grained yellow to light brownish yellow calcareous sandstone that contains abundant *Inoceramus* fragments that weathers to light gray platy surfaces with a distinct petroliferous, sulfur odor (Decker et al. 2008a). Samples of the formation studied to date yield little evidence of reservoir quality (Helmold et al. 2005), though the high calcite content could develop secondary porosity under the proper subsurface conditions. In the subsurface, the formation is present in the David River 1A and Hoodoo Lake 2 wells.

i. Chignik Formation: Late Cretaceous (Campanian to Maastrichtian)

The Chignik Formation described in the Staniukovich-Herendeen Area is subdivided by Decker and others (2008a) into the marine Chignik Formation with the non-marine coal bearing Coal Valley Member. In the subsurface, the Chignik Formation is identified in the David River 1A, Hoodoo Lake 2, and Painter Creek 1 wells.

i. Lower Contact

The Chignik Formation's lower contact is unconformable to the underlying Herendeen, Staniukovich, and Naknek Formations (Detterman et al. 1996).

ii. Upper Contact

In some areas the Chignik Formation forms an unconformable upper contact with the overlying Tolstoi Formation. In others, the Chignik appears to conformably underlie the Hoodoo Formation (Detterman et al. 1996).

iii. Lithology

The dominant lithology consists of interbedded siltstones, sandstones, and conglomerates composed of chert, quartz, granitic, and minor volcanic clasts (Decker et al. 2008a).

iv. Depositional Environment

The Chignik formation consists of cyclic tidal flat, floodplain, and fluvial sequences. The interbedded non-marine coal bearing Coal Valley Member represents fluvial and floodplain deposits. In the State area, the Chignik Formation is a shallow water facies equivalent to the deep water turbidite depositional sequence represented by the Hoodoo Formation (Decker et al. 2008a).

v. Reservoir Potential

The formation was not studied in detail but some samples appear to have nominal oil or gas reservoir potential. In the subsurface, the formation is present in the David River, Hoodoo Lake, and Painter Creek wells.

vi. Source Rock Potential

The coals within the Coal Valley Member could potentially be a source of either thermogenic or biogenic gas (Finzel et al. 2005).

j. Hoodoo Formation: Late Cretaceous (Campanian to Maastrichtian)

The Hoodoo Formation has an unconformable contact with the underlying Herendeen Formation and a disconformable contact with the overlying Tolstoi Formation. In the Staniukovich – Herendeen area the Hoodoo formation is time equivalent to and interfingers with both the Chignik Formation and the Coal Valley member. Generally the formation represents an overall coarsening upward lower slope turbidite succession. It consists of thin bedded splintery dark gray to black shale, siltstone, and fine-grained sandstone that shallows upward to a shelfal succession. The shelfal succession consists of coarser grained sandstones and conglomerates containing ammonites, and clasts of plutonic, volcanic, chert, and quartz clasts in areas of channel development (Detterman et al. 1996; Decker et al. 2008a). The formation has not been studied in detail by DNR geologists, but appears to have minimal oil or gas reservoir potential where encountered in the course of geologic mapping south of Herendeen Bay. The formation was not formerly identified in the subsurface due to its interfingering relationship with the Chignik Formation.

2. Tertiary Units

The Tertiary succession is somewhat thinner than the Mesozoic with a maximum combined thickness of about 5,400 m (17,700 ft.), but a great deal thinner at many other areas due to non-deposition or post-depositional erosion (Detterman et al.1996). The Tertiary units known or expected to underlie the proposed lease sale area ascend in layers or stratigraphic order beginning with the Tolstoi Formation from the Upper Paleocene – Middle Eocene time. The other units and ages include the Meshik Volcanics (Upper Eocene – Middle Oligocene), which interfinger with the volcaniclastic Stepovak Formation of the same age; the Bear Lake Formation (Middle to Upper Miocene); and the Milky River Formation (Pliocene). Many of the stratigraphic relationships are inconsistent. The inconsistencies in rocks separating the Bear Lake and Milky River formations vary greatly between offshore and onshore locations. The offshore seismic data show a more subtle unconformity, but the upland outcrop belt onshore shows a profound angular unconformity (Decker et al. 2005).

The Tertiary rocks are predominantly non-marine and contain a considerable amount of volcanic and intrusive igneous rocks, volcanic debris, and volcanic units lying between different rock beds or strata. The provenance for sediments of the Tertiary formations was volcanic deposits from the same time period and recycled Mesozoic sedimentary and plutonic rocks of the Alaska Peninsula. It appears the Mesozoic sedimentary rocks are the main source for the Tolstoi and Bear Lake Formations. The Stepovak and Milky River Formations consist of lightly reworked volcanic fragments associated with two major pulses of concurrent volcanic arc activity. The first began during the Eocene (48 Ma) and continued into the early Miocene (22 Ma), and is referred to as the Meshik arc (Wilson 1985). Most of the rocks from this prolonged episode of eruptive activity are included within the Meshik volcanics. The second pulse of volcanic activity started during the late Miocene and is continuing at present as the Aleutian arc. Intrusive bodies ranging in size from small stocks and plugs to large batholiths were emplaced throughout the Tertiary (Detterman et al. 1996).

a. Tolstoi Formation: Late Paleocene to Middle Eocene

i. Lower Contact

Throughout most of the Alaska Peninsula, the lower contact of the Tolstoi Formation shows a major unconformity as it overlies the Chignik, Hoodoo, Staniukovich, or Naknek Formations (Detterman et al. 1996).

ii. Upper Contact

Where the Tolstoi Formation is overlain by the Meshik Volcanics, the contact is an unconformity (Detterman et al. 1996).

Regionally, where exposed in the Alaska Peninsula is disconformable with the Middle Jurassic Shelikof Formation.

iii. Lithology

Clast content of the sandstones and conglomerates are predominantly granitic and arkosic. The granitic and arkosic rock fragments and up to 30% of the lithic conglomerate clasts are weathered volcanics, suggestive of a Mesozoic source as opposed to the younger magmatic material that dominates the composition of the other Tertiary formations (Detterman et al. 1996; Decker 2008a). The formation contains a significant amount of carbonaceous mudstone (Detterman et al. 1996; Decker 2008). The Tolstoi Formation was encountered in the Sandy River 1, David River 1A, Hoodoo Lake 2, and North Aleutians Cost wells.

iv. Depositional Environment

The Tolstoi formation onlaps the underlying Mesozoic rocks. Detterman (1996) interpreted Pavlof Bay as a shallow water marine environment. To the northeast toward Chignik Bay the formation progressively becomes more non-marine, consisting of overall coarsening upward shallow marine deltaic sequences that grade into non-marine delta plain, braided fluvial, and flood plain deposits (Detterman et al. 1996; Decker 2008).

v. Reservoir Quality

Reservoir potential is good in the channelized sandstone and conglomerates depending on the degree of degradation and diagenesis of the volcanic lithics. Although the formation contains stable granitic and arkosic clasts, up to 30% of the volcanic clasts present are weathered. Because of this, reservoir quality may be degraded by the chemical alteration and subsequent compaction of unstable volcanic lithic clasts (Detterman et al. 1996). Depending on the amount of diagenesis that has occurred and the depth of burial, the Tolstoi could be a potential reservoir in the more marine sandstone sections as well as the braided stream channels. In the Cook Inlet Basin, the Tolstoi formation is a time equivalent of the Chickaloon and West Foreland formations. Helmold and others' (2008) scatter plotted porosity verses permeability for many outcrop samples. They illustrate that some of the samples have low porosity and permeability, thus poor reservoir properties, but good potential as seals. Many of the outcrop samples demonstrate good porosity and permeability values suggesting good reservoir potential (Helmold et al. 2008).

vi. Hydrocarbon Generating Potential

The presence of carbonaceous mudstones within the Tolstoi Formation indicates that depending on the depth of burial there is potential for the generation of petroleum liquids. However, high matrix adsorption effects would likely limit expulsion efficiency, minimizing the likelihood of a significant Tertiary-sourced oil accumulation within the Alaska Peninsula state acreage (Decker 2008).

vii. Seal Potential

Five samples from the Tolstoi formation were analyzed for seal potential. Three claystone samples analyzed were Sneider Seal Type A, suggesting excellent seal potential. The fourth sample analyzed, sandstone with a compacted matrix, was classified as a Sneider Seal Type C. The fifth sample, an organic-rich, coaly claystone was classified as a Sneider Type D. The variety of Sneider Seal type quality suggests that the Tolstoi Formation may be a good sealing rock in some areas, but not everywhere.

b. <u>Meshik Volcanics: Late Eocene to Early Oligocene</u>

The lower contact of the Meshik Volcanics to the overlying Tolstoi is interpreted as an angular unconformity. Volcanic rock types include andesites, basalts, and dacites. In places the Meshik is interbedded with reworked volcaniclastic rocks of the Stepovak Formation. The Meshik Volcanics are identified in the Port Heiden 1 and Ugashik 1 wells (Detterman et al. 1996).

c. Stepovak Formation: Late Eocene to Early Oligocene

i. Contacts

The Stepovak Formation is structurally conformable, but stratigraphically it is disconformable with the underlying Tolstoi. Similarly it is disconformable with the overlying Unga Formations. Locally, the Meshik Volcanics are interbedded with reworked volcaniclastic rocks of the Stepovak Formation (Detterman et al. 1996).

ii. Lithology

The formation is subdivided into a lower and upper member. The lower member consists of coarsening upward sequences of laminated dark brown laminated shale, siltstone, and sandstone containing graded bedding and rip-up clasts. The upper member contains abundant unaltered volcanic rocks deposited in a shallow water (30 – 50 meters) shelfal environment (Detterman et al. 1996). On the Staniukovich Peninsula the upper member contains vesicular lava flows and flow breccias that grade upward into volcaniclastic sandstone and conglomerate that are locally burrowed and contain bivalves and carbonate concretions. The Stepovak Formation is identified in the Sandy River Fed 1, Port Heiden 1, David River 1A, Hoodoo Lake 1 and 2, Great Basins 1, Becharof 1, and the North Aleutian Shelf COST 1 wells (Helmold and Brizzolara 2005).

iii. Reservoir Quality

The Stepovak is moderately sorted. Numerous samples identified as Stepovak Formation from the offshore North Aleutian Shelf COST 1 well have porosity ranging from 17% to 33% and permeability ranging from 1 to more than 1000 md (Helmold and Brizzolara 2005; Helmold et al. 2008). Reservoir quality measurements from outcrop and the onshore Becharof 1 well indicate significantly lower overall reservoir quality in the formation (Helmold et al. 2008). The formation contains a high percentage of volcanic rock fragments. The presence of Meshik volcanics within the Stepovak formation would generate heat and areas of contact metamorphism that would destroy reservoir quality. Away from the Meshik Volcanics the diagenetic alteration of the unstable volcanic rock fragments, coupled with compaction due to burial, would significantly reduce primary porosity and permeability.

iv. Seal Potential

Two samples were analyzed and plotted as Sneider C seals, suggesting a marginal seal capacity for the Stepovak Formation. One was argillaceous sandstone and the other compacted sandstone (Bolger and Reifenstuhl 2008).

d. Bear Lake Formation: Miocene

i. Lower Contact

The Bear Lake formation overlies the Meshik Volcanics and Stepovak and Tolstoi formations. Most contacts are disconformities and a few are angular conformities. The maximum thickness of the Bear Lake formation is estimated to be about 1,000 meters (Detterman et al. 1996).

ii. Upper Contact

The Milky River Formation overlies the Bear Lake formation at some localities by volcanic and volcaniclastic rocks. Most of the contacts are disconformities and a few are angular unconformities (Detterman et al. 1995).

iii. Lithology

The distinguishing characteristics of the Bear Lake Formation are a greater abundance of nonvolcanic debris; abundant fossils (primarily pelecypods, gastropods, and echinoids); and the sand grains are moderately well sorted and rounded and compared to the underlying Stepovak and Tolstoi formations. The Bear Lake Formation is considerably better sorted, contains a higher percentage of chert and quartz, and a significantly smaller percentage of volcanic detritus than the other Tertiary sandstones in the State acreage area. The provenance of the Bear Creek sandstones appears to be the older Mesozoic sedimentary strata, possibly the Alaska-Aleutian Range batholith (Detterman et al. 1996, page 55). The Bear Lake Formation is present in the subsurface in the Sandy River Fed 1, Port Heiden 1, Great Basins 1 and 2, Becharof 1, Ugashik 1, David River 1/1A/1ARD, Hoodoo Lake 1 and 2, and the OCS North Aleutian 1 well.

iv. Depositional Environment

The Bear Lake formation consists of marine shelfal (up to @ 100 meters), tidal, and non-marine deposits. The area of thickest deposition for the Bear Lake sediments appears to have been isolated from the volcanic-rich sediments deposited of the southeast side of the Alaska Peninsula (Detterman et al. 1996).

v. Reservoir Quality

The Bear Lake subsurface samples vary considerably in framework grain size and sorting due to the varying amount of clay and detrital silt in a given sample. They are enriched in sedimentary grains, chert, monocrystalline quartz, and plagioclase. Some of the Bear Lake samples contain abundant clay minerals that are present as individual laminae or are dispersed as matrix in the rock fabric. The clay laminae are composed of illite and mixed-layer illite/smectite swelling clays, which could adversely affect reservoir quality when exposed to fresh water. Cementation does not appear to be a significant component of these sandstones. The formation contains distinct well sorted sandstone layers. Its framework grain composition is dominated by quartz, chert, and plagioclase, and was not buried too deeply to compact the ductile clay components. Because of this, the Bear Lake formation is a potential reservoir rock (Helmold et al. 2008).

vi. Source Rock Potential

Analysis by Decker (2008) indicates that some of the coals within the Bear Lake formation may possess marginal capacity to generate petroleum liquids. However, high matrix adsorption effects would likely limit expulsion efficiency, minimizing the likelihood of a significant Tertiary-sourced oil accumulation within the Alaska Peninsula state acreage.

vii. Seal Quality

Eleven outcrop samples containing distinctly laminated fabrics from the Bear Lake Formation were analyzed for Sneider Seal type by Bolger and Reifenstuhl (2008). Four of the samples analyzed were classified as Sneider Type A, three as Sneider Type C, two as Sneider Type D, one as Sneider Type E, and one that is not considered a seal, but rather a reservoir rock. The samples suggest that the Bear Lake formation could be both an effective reservoir and seal (Bolger and Reifenstuhl 2008).

e. Milky River Formation: Pliocene

The Milky River Formation was named by Galloway (1974) to describe volcanic and sedimentary rocks along the Milky River overlying the Bear Lake Formation. Detterman and others (1981) officially defined the formation; it varies in thickness from 465 meters thick at its type locality onshore up to 1000 meters in offshore boreholes (Detterman et al. 1996; Finzel et al. 2005).

i. Lower Contact

The lower contacts show disconformities and unconformities with the underlying Bear Lake Formation. In places the unconformity is angular (Detterman et al. 1996; Decker 2008).

ii. Upper Contact

The Milky Formation has unconformable contact with younger volcanic flows and surficial deposits (Detterman et al. 1996).

iii. Lithology

The formation consists of volcanogenic, non-marine sedimentary rocks and interlayered volcanic flows and intrusive sills. The lower part of the unit consists of dark gray to brown poorly indurated coarse-grained cross-bedded sandstone with abundant magnetite and poorly sorted pebble-cobble-boulder conglomerates composed of volcanogenic debris. The upper part of the formation consists of abundant volcanogenic lithics that are interlayered with volcanic flows and intrusive sills (Detterman et al. 1996) and contains abundant clay laminae (Helmold et al. 2008). The Milky River contains the most volcanic detritus of all the Tertiary sandstones in the study area (Detterman et al. 1996). In the subsurface, the Milky River Formation is present in the following wells: Sandy River Fed 1, Port Heiden 1, Great Basins 1 and 2, Becharof 1, Ugashik1, David River 1/1A/, Hoodoo Lake 1 and 2, Painter Creek 1, and the OCS North Aleutian 1 well.

iv. Depositional Environment

The depositional environment consists of a non-marine fluvial system with locally thick pebble to boulder filled braided fluvial channels in the basal part of the unit consisting of cobble-boulder conglomerates. The upper part of the formation fines upward and contains channelized cross-bedded sandstones composed of fluvial volcanic sandstones.

v. Petrography

The Milky River sandstones are predominantly composed of coarse-grained volcanic rock fragments (up to 65% in some samples) plagioclase, quartz, heavy minerals, some detrital matrix (up to 10%) and good porosity (in the range of 15-33%) (Helmold and Brizzolara 2005; Helmold et al. 2008).

vi. Reservoir Potential

Porosity and Permeability cross plot from the subsurface samples for the Milky River Formation demonstrate very high porosity and permeability values (@ 100 md and 35% - 40% porosity). The presence of a high percentage of volcanic rock fragments and heavy minerals as major framework components indicates a chemically and mechanically immature reservoir rock (Helmold et al. 2008). Primary porosity could be preserved due to the relatively low depth of burial that would inhibit the diagenesis of unstable volcanics and prevent the compaction of ductile grains. The Milky River is a potential gas-bearing reservoir rock because it is possible that the coals from the underlying Bear Lake formation could have generate biogenic gas and migrated into the reservoir (Fenzel et al. 2005).

vii. Hydrocarbon Generating Potential

The formation contains little organic material (Helmold et al. 2008).

viii. Seal Potential

Seal potential for the Milky River Formation is considered poor (Finzel et al. 2005). No samples were analyzed for seal potential. The unit does not contain appreciable continuous shale or siltstone layers. The overlying Quaternary deposits could possibly effectively seal potential gas reservoirs within the Milky River formation.

B. Additional Oil and Gas Potential Information

1. Oil and Gas Potential

a. Overview of the Petroleum Systems Approach

Kerogens derived primarily from land plants, which are common in coal-bearing nonmarine rocks and deltaic sequences, are lean in hydrogen relative to carbon, and primarily generate methane (CH_4), or dry natural gas, the simplest of all hydrocarbon molecules. Kerogens made up of algae and other marine microorganisms contain a higher fraction of hydrogen relative to carbon, and when subjected to the proper level of thermal maturity, will form oils (long-chain hydrocarbon molecules) of various complexities, which are more enriched in hydrogen.

Framework grains form the lattice that creates porosity (void spaces) and permeability (connections that allow fluid to flow through adjoining pore spaces). The composition of the framework grains is important in determining whether sandstone is a suitable reservoir. Unstable sand grains that are subject to chemical altering due to interaction with subsurface fluids upon burial recrystallize to form cements in a pore-clogging process called diagenesis that clogs the pore spaces and degrades reservoir potential. The amount of clay, mud, and ductile framework grains, and matrix within a given rock will decrease its overall porosity and permeability as it is buried and compacted, much like squeezing a tube of toothpaste into a jar of marbles.

Depth of burial is an important component to consider for the compaction of ductile grains and the chemical alteration of unstable grains. Chemical alteration of igneous rock fragments commonly forms clays and zeolite minerals that degrade reservoir quality.

Structural traps are much easier to identify on seismic data, especially if only 2-D surveys are available. Stratigraphic traps are more difficult to identify, requiring detailed knowledge of the subsurface gained either from 3-D seismic or numerous previous well penetrations.

2. Source Rock Potential

Based on total organic carbon, RockEval pyrolysis (controlled heating experiments), kerogen typing, and vitrinite reflectance measurements, the Triassic Kamishak and Jurassic Kialagvik formations present in outcrops at Puale Bay are highly oil-prone. The vitrinite reflectance data confirms that these Mesozoic formations lie in the immature to early oil-window thermal maturity previously indicated only by pyrolysis data (Decker 2008). Previous work reaches the same conclusion that potential Mesozoic source rocks contain dominantly oil-prone marine organic matter (Wang et al. 1988; Magoon and Anders 1992; Finzel et al. 2005).

In contrast, the Tertiary backarc basin fill formations encountered in the North Aleutian Shelf COST #1 well are dominated by terrestrially-sourced coaly kerogen and are thus most likely to generate mostly natural gas (Dow 1983; Turner et al. 1988; Sherwood et al. 2006; Finzel et al. 2005). Some carbonaceous mudstones of the Tolstoi Formation yield pyrolysis results that suggest they may be marginally capable of generating light oil or condensate in addition to natural gas (Decker 2008).

3. Reservoir Potential

Mesozoic deposition occurred on the flanks of a magmatic arc, resulting in mostly clastic sediments containing abundant volcanic and plutonic rock fragments (Sherwood et al. 2006). Upon burial, the volcanic rock fragments easily degraded into laumontite, heulandite, and other zeolite minerals that fully blocked the porosity between grains. Other digenetic effects include the formation of cements such as chlorite/smectite, and carbonate (Dutrow 1982). In addition, deep burial of most of the

Mesozoic units resulted in mechanical compaction of ductile grains to form pore-blocking pseudo-matrix. Most of the Mesozoic clastic units are thus unlikely reservoir candidates.

The limestones of the Triassic Kamishak Formation and the carbonate-rich sandstones of the Lower Cretaceous Herendeen Formation could host secondary porosity created by chemical leaching of carbonate components. At or near the top of the Mesozoic succession, the Upper Cretaceous Chignik Formation has some potential for maintaining primary porosity and permeability due to shallower depth of burial.

The younger Mesozoic sediments contain a smaller percentage of volcanic rock and likely contain more stable framework grains. Depending on the timing of hydrocarbon generation and migration relative to pore-filling chemical alteration, it is conceivable that some oil reservoirs may have escaped diagenetic degradation due to sufficient oil saturation to prevent cement formation. However, Magoon (1994) assumes that oil generation within Middle Jurassic source beds occurred mostly during Tertiary time after potential Mesozoic reservoirs underwent compaction and diagenesis that degraded and blocked original porosity, likely excluding them as viable reservoirs.

Compaction and diagenetic alteration of potential Tertiary rocks is more promising due to shallower depth of burial and/or the presence of more stable clastic grain types. In a general way, the Tertiary backarc basin succession may mirror the Tertiary clastic section in the Cook Inlet forearc basin, consisting of the Hemlock, Tyonek, Beluga, and Sterling Formations. In those formations, primary porosity was preserved because of shallower depth of burial and favorable diagenetic history, in which some oil accumulated in porous Hemlock and lower Tyonek sandstones.

The Miocene Bear Lake and Unga Formations and the Eocene-Oligocene Stepovak Formation contain the highest percentage of stable rigid framework grains in the Tertiary section. Numerous samples from these formations yield good to excellent porosity and permeability, marking them as the best candidate reservoirs. The Pliocene Milky River Formation contains the highest amount of unstable volcanic rock fragments, but has been so shallowly buried that nearly all samples yield excellent reservoir quality. However, the same shallow burial makes it unlikely to be overlain by effective seals.

4. Trap Potential

a. Structural – Stratigraphic Complexities

The geology of the Alaska Peninsula includes multiple episodes of tectonic and magmatic activity, resulting in a geologic record punctuated by numerous erosional unconformities (Decker 2008). Many of these surfaces are expressed by angular discordance and contrasts in rock type that may set up trapping configurations in the lease sale area. In addition, both extensional and compressional structures are commonly observed in outcrop and interpreted in the limited seismic data available. The overall tectonic framework and structural style suggests that much of the deformation may be transpressional and transtensional in origin, hybrids resulting from oblique motion of the Pacific Plate relative to the North American Plate (Alaskan block).

Significant variations in structural style and complexity occur along the length of the Alaska Peninsula (Decker et al. 2008a). For example, an area just west of Herendeen Bay referred to as the Sapsuk domain contains a single broad uplift cored by a major thrust or reverse fault with few crosscutting faults. In contrast, just to the east between Herendeen Bay and Port Moller, the Staniukovich domain contains a complicated faulted network of both longitudinal (lengthwise) and transverse (crosswise) faults that form a doubly-plunging, rhomboid-shaped uplift that is broken up into numerous structural compartments, as well as narrower fault-bounded folds to the south.

The prominence of both stratigraphic and structural complexity makes it very likely that trapping configurations are common in the sale area. Additional regional seismic data will be needed to map the location and size of potential structural and stratigraphic traps in the subsurface prior to exploration drilling.

b. Seal Capacity

Bolger and Reifenstuhl (2008) analyzed the seal capacity of 26 samples from the Alaska Peninsula using mercury injection capillary pressure measurements and classified the results according to the Sneider Seal Classification (Sneider 1997). Of the samples classified, 40% are Sneider Type A, the best seal quality seals, capable of holding oil columns of 3,200 feet or gas columns of 2,400 feet. Type A seals are present in the Bear Lake, Kamishak, and Tolstoi Formations. Type A seals consist of claystone (Tolstoi Formation), limestone (Kamishak Formation), and argillaceous (clay-rich) siltstone and sandstone samples with a distinctly thin, laminar fabric (Bear Lake Formation). The porosity in the Type A seals ranges from 1.2% (Kamishak limestone) to 20.2% (Bear Lake argillaceous siltstone). In all cases, Type A seals have a fine scale pore structure that supports high capillary pressures (Bolger and Reifenstuhl 2008).

Type C seals are the next most common, accounting for approximately 30%of the samples, capable of trapping oil columns of 400 feet or gas columns of 300 feet. For the most part, they are moderately argillaceous to argillaceous siltstones. Type C seals were found in the Stepovak and Bear Lake Formations (Bolger and Reifenstuhl 2008). A majority of the Type C seal rocks have a bimodal pore structure and the seal capacity is generally limited by the presence of the larger pores. Where the Type C seals have a laminated fabric that creates the bimodality, the seal quality may be higher if the laminations are oriented perpendicular, or at a high angle, to the hydrocarbon migration direction. In the Type C samples, porosity ranges from 4.8% (Stepovak Formation) to 18.2% (Bear Lake Formation).

Four samples analyzed were classified as Type D (Tolstoi and Bear Lake Formations) and E seals (Bear Lake Formation), with relatively ineffective sealing characteristics. Porosity in these samples ranged from 17.3% to 37% and permeability ranged from 0.285 to 1.3 md. These samples have grain supported fabrics with some porosity between grains, and in some cases are more effective as reservoir rocks than as seals. However, if the laminations are perpendicular to the hydrocarbon migration direction these rocks could function as seals, although perhaps ‘leaky’ ones (Bolger and Reifenstuhl 2008).

5. Resource Potential Summary

- The proposed Alaska Peninsula Areawide lease sale area remains dramatically underexplored. Very little seismic data is available over state acreage. Surveys that do exist consist mainly of low-quality 2-D lines that are inadequate for prospect-level analysis or the rigorous assessment of undiscovered resources.

- The Triassic Kamishak Formation and the Jurassic Kialagvik Formation (age equivalent to the Tuxedni Formation source rock in Cook Inlet) are potentially oil-generative source rocks, though their distribution in the subsurface of the lease sale is uncertain. Further work is required to determine if there is a viable migration pathway from these potential Mesozoic source rocks to potential Tertiary reservoirs.

- Coals within the Tertiary formations may likely generate biogenic gas that could have migrated into adjacent reservoir rocks, similar to the Tyonek, Beluga, and Sterling reservoirs of Cook Inlet.

- Geochemical analyses and inferences regarding subsurface distribution of the various source rock and potential reservoir formations suggest that potential hydrocarbon accumulations on State acreage are more likely to be gas rather than oil reservoirs.

- The Mesozoic clastic formations are reservoir challenged due to chemical alteration of unstable grains and compaction of ductile lithics and matrix. These characteristics stem in large part from the magmatic provenance control on petrology, the history of volcanic and plutonic activity in the area, and the associated diagenesis.

- Tertiary formations contain enough preserved porosity and permeability to function as potential conventional oil and gas reservoirs.

- Given the complex tectonic, structural, and stratigraphic history of the area, it is likely that many potential traps exist, though in places they may be small or compartmentalized. Modern 2-D and/or 3-D seismic will be necessary to define drillable prospects in most areas.

- Reservoir seal capacity studies on outcrop samples indicate that several formations are potential good sealing rocks.

- Field work, subsurface data, and lab analysis indicate that the Ugashik sub-basin, in the vicinity of the Great Basins wells, is a fault-bounded feature that contains a thick sequence of preserved Tertiary strata that appears prospective for a hydrocarbon accumulation.