INTRODUCTION

by
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Abstract

From 2004 through 2007, the Alaska Division of Geological & Geophysical Surveys led four partial field seasons dedicated to petroleum systems research in the Port Moller, Chignik, Ugashik Lakes, and Puale Bay areas of the Bristol Bay—Alaska Peninsula region. A collaborative effort with the Alaska Division of Oil and Gas and researchers from other organizations, this project has yielded significant new geologic field data, laboratory analyses, and interpretations integrated with subsurface and geophysical data. Our findings document fundamental characteristics of the region's source rocks, reservoir units, seal facies, and structural styles, which collectively determine the oil and gas endowment of the onshore portion of the Bristol Bay – North Aleutian basin. This volume represents the final series of new interpretive reports associated with this four-year project. Some of these chapters contain additional data or observations that supplement or supersede previous findings, but most of the topics covered in previous publications are not included here.

Twenty-eight wells have been drilled since oil and gas exploration began on the Alaska Peninsula over a century ago. The establishment of the Alaska Peninsula areawide oil and gas lease sale in 2005 offered the first access for energy exploration in the region in over two decades. The sale area encompasses 23,470 km^2 (5.8 million ac), mostly in the Bristol Bay lowlands on the northwest side of the Alaska Peninsula. Only eleven wells, all drilled between 1959 and 1985, have tested prospects on State lands available for exploration in the areawide sale. Quantitative assessment of the oil and gas resource endowment for the areawide sale is outside the scope of this study. Limited by a critical lack of subsurface data, the 1995 U.S. Geological Survey resource assessment assigned modest oil and gas potential to the onshore Alaska Peninsula. Potential may be greater offshore in federal waters of the North Aleutian basin, where a 2006 resource assessments by the U.S. Minerals Management Service yield mean, technically recoverable resource estimates of 753 million barrels of oil and natural gas liquids, and 244 million m^3 (8.6 trillion ft^3 [TCF]) of natural gas.

Though past exploration has not yielded commercial production, there are indications that the necessary components of active petroleum systems may be present in both Mesozoic and Cenozoic successions. Source presence and effectiveness are demonstrated by the presence of significant oil and thermogenic gas seeps in Mesozoic units, and by subsurface thermogenic and biogenic gas shows in Tertiary units in wells. Mesozoic sandstones are degraded by zeolites, but may function as tight-gas reservoirs, particularly in the presence of favorable fracture systems, and the carbonates of the Triassic Kamishak Formation may locally develop reservoir quality. Reservoir presence and effectiveness is much more promising in Tertiary formations, in particular the Miocene Bear Lake Formation, as confirmed by petrographic and porosity-permeability analyses of outcrop and well samples. The area's complex stratigraphic and structural history suggests that structural and unconformity-related stratigraphic trapping configurations are likely present. Seal capacity studies demonstrate that both Mesozoic and Cenozoic formations could contain significant hydrocarbon columns.

PETROLEUM SYSTEMS OVERVIEW

This volume contains previously unpublished findings from field, office, and laboratory research conducted between 2004 and 2007, focused on petroleum system studies of the Alaska Peninsula. The study area extends from Cathedral River, Pavlov Bay, and Port Moller on the southwest to the Ugashik Lakes and Puale Bay on the northeast (fig. 1). The topical papers presented here have undergone outside peer review, and this entire volume is publicly available on the Division of Geological & Geophysical Surveys' website (www.dggs.dnr.state.ak.us). The DGGS website has a searchable publications database from which all project reports may be downloaded (no charge) or purchased as paper copies. Information in this report is particularly relevant to hydrocarbon resources and exploration models on lands offered for oil and gas leasing in the Alaska Peninsula areawide lease sale. More information pertinent to this areawide lease sale, including maps and posters illustrating geopolitical, geological, and geophysical data, biostratigraphic interpretations, and other data is available for free download from the Alaska Division of Oil and Gas (DOG) website (http://www.dog.dnr.state.ak.us/oil/products/publications/akpeninsula/ak_peninsula.htm).

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The State of Alaska reopened the frontier Bristol Bay basin (also known as the North Aleutian basin) for oil and gas leasing on State acreage after a two-decade hiatus in 2005. The new areawide sale encompasses some 23,470 km^2 (5.8 million ac), mostly in the Bristol Bay lowlands on the northwest side of the Alaska Peninsula. Two State-administered Alaska Peninsula areawide oil and gas lease sales have been held to date (October 2005 and February 2007), but at the time of this writing, there are no announced plans for seismic data acquisition or exploratory drilling on State-issued leases in the region. Of the 28 previously-drilled exploration wells and sidetrack holes on the Alaska Peninsula, eleven are within the limits of the areawide sale, all drilled between 1959 and 1985 (fig. 2). Drilling on the Alaska Peninsula began in 1903 with the Costello-1 well (222 m [728 ft] total depth). The most recent well drilled onshore was the Becharof-1, completed in 1985 (2,750 m [9,023 ft] total depth). The offshore North Aleutian Shelf COST-1 well was drilled in 1982-83 (5,229 m [17,155 ft] total depth), bottoming in Eocene-age Tolstoi Formation (Sherwood and others, 2006).

Oil or gas shows were reported in the majority of Alaska Peninsula wells, but no oil or gas has been commercially produced. Citing a critical lack of subsurface information, Magoon and others (1996) estimated that Cenozoic and Mesozoic plays in onshore areas of the Alaska Peninsula have only modest oil and gas endowment. Historically, oil has been the focus of exploration, and little drilling has been devoted to gas, for which potential may be greatest in the Miocene-age Bear Lake Formation (Hite, 2004). Offshore, in federally managed waters of the North Aleutian basin, Sherwood and others (2006, p. 84) estimated mean, undiscovered, technically recoverable nonassociated gas resources in the Bear Lake Formation–Stepovak Formation (Miocene–Oligocene) gas play at 5.473 trillion ft^3 (TCF). This represents the most prospective play assessed in the basin, where the total mean, undiscovered, technically recoverable resource for all plays in federal waters is estimated at 753 million barrels of oil and natural gas liquids, and 8.6 trillion ft^3 gas (Sherwood and others, 2006, p. 84).

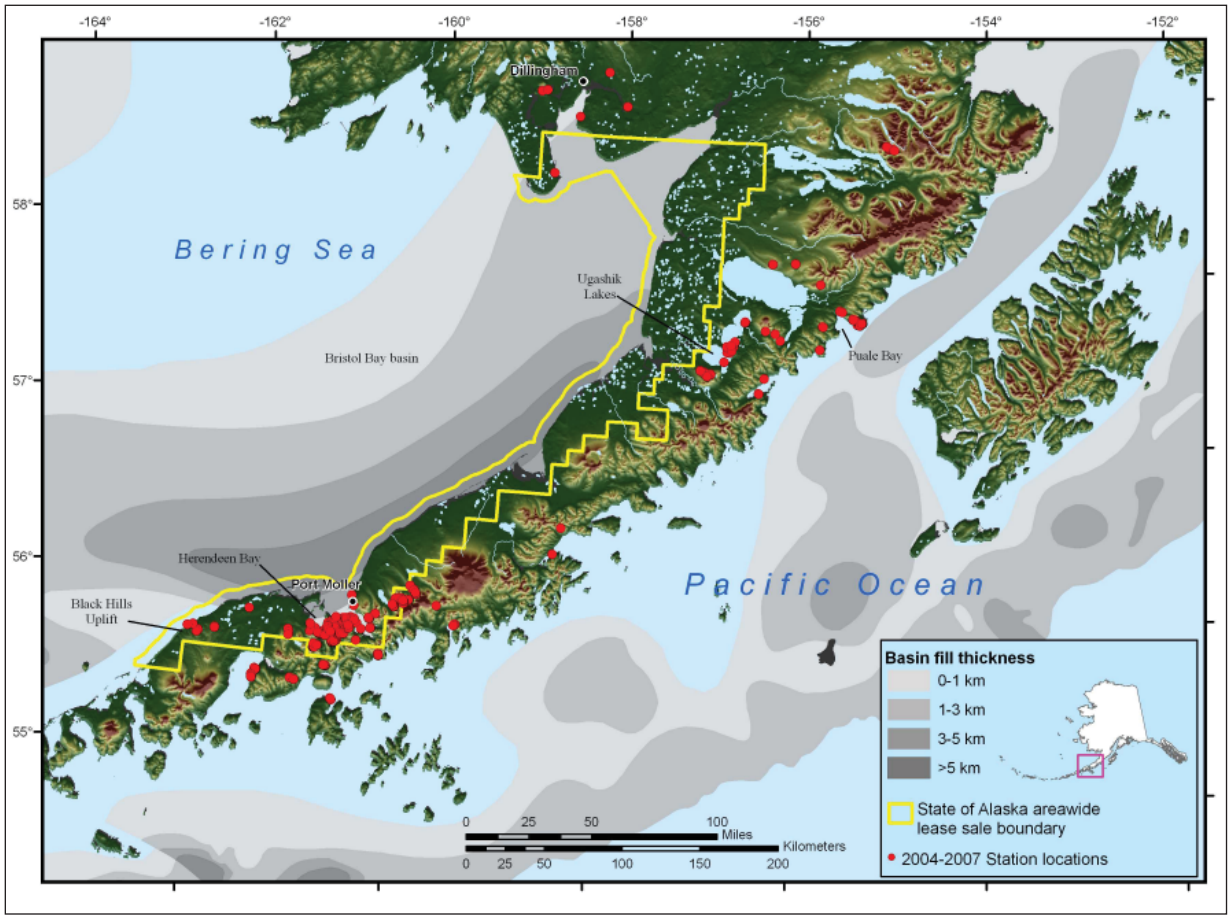

Figure 1. Location map of Alaska Peninsula, State Division of Oil and Gas Areawide Lease Sale, and general location of field stations and samples.

Most of the research conducted over the course of this project, including several of the studies published in this volume, addressed the geology of State lands on the northwestern side of the Alaska Peninsula, near the thicker, southern edge of the asymmetric Bristol Bay back-arc basin. Cenozoic basin-fill thicknesses range from greater than 4,500 m (>15,000 ft) below state waters to zero in nearby uplifts (fig. 1). The presence of Mesozoic rocks at oil-window maturity at the surface on the Black Hills uplift 40 km (25 mi) southwest of Port Moller, and in the Staniukovich peninsula area, 8 km (5 mi) southwest of Port Moller, indicate substantial local uplift adjacent to the basin's southern margin. A complex subsidence and uplift history introduces elements of both prospectivity and exploration risk to structural and stratigraphic plays in Mesozoic and Cenozoic units along the basin's southern margin (Finzel and others, 2005; Decker, this report).

While neither Mesozoic nor Cenozoic petroleum systems have been proven by significant oil or gas discoveries, there is substantial evidence that all their necessary components exist at various places within the region. Triassic and/or Jurassic source rocks generate oil and gas seeps on the southeastern Alaska Peninsula in the Wide Bay and Oil Creek areas (Magoon and Anders, 1992). One of these seeps flows 18 degree API gravity oil at an estimated rate of one-half barrel per day, along with a small amount of combustible gas. Over time, this flowing seep has created a large asphaltic mat overgrown by surface vegetation (Reifenstuhl and others, 2004; Finzel and others, 2005). Nearby at Puale Bay, Triassic Kamishak Formation limestones and Jurassic Kialagvik Formation mudstones contain excellent oil-prone source rocks, with total organic carbon values of up to 5.3 percent and 3.5 percent, respectively, and hydrogen indices as high as 756 mg/g and 680 mg/g, respectively (Decker, this volume). These Mesozoic units are the likely source of thermogenic methane that seeps vigorously from the Lower Cretaceous Herendeen Formation near the axis of a major surface anticline in the sale area (Port Moller hot spring, northeastern Staniukovich peninsula; Decker and others, 2005; Decker and others, this report). Reservoir potential in Jurassic sandstones appears to be regionally degraded by zeolite mineralization (Helmold, Brizzolara, and Reifenstuhl, this volume). Under the most favorable conditions, these low porosity and permeability units

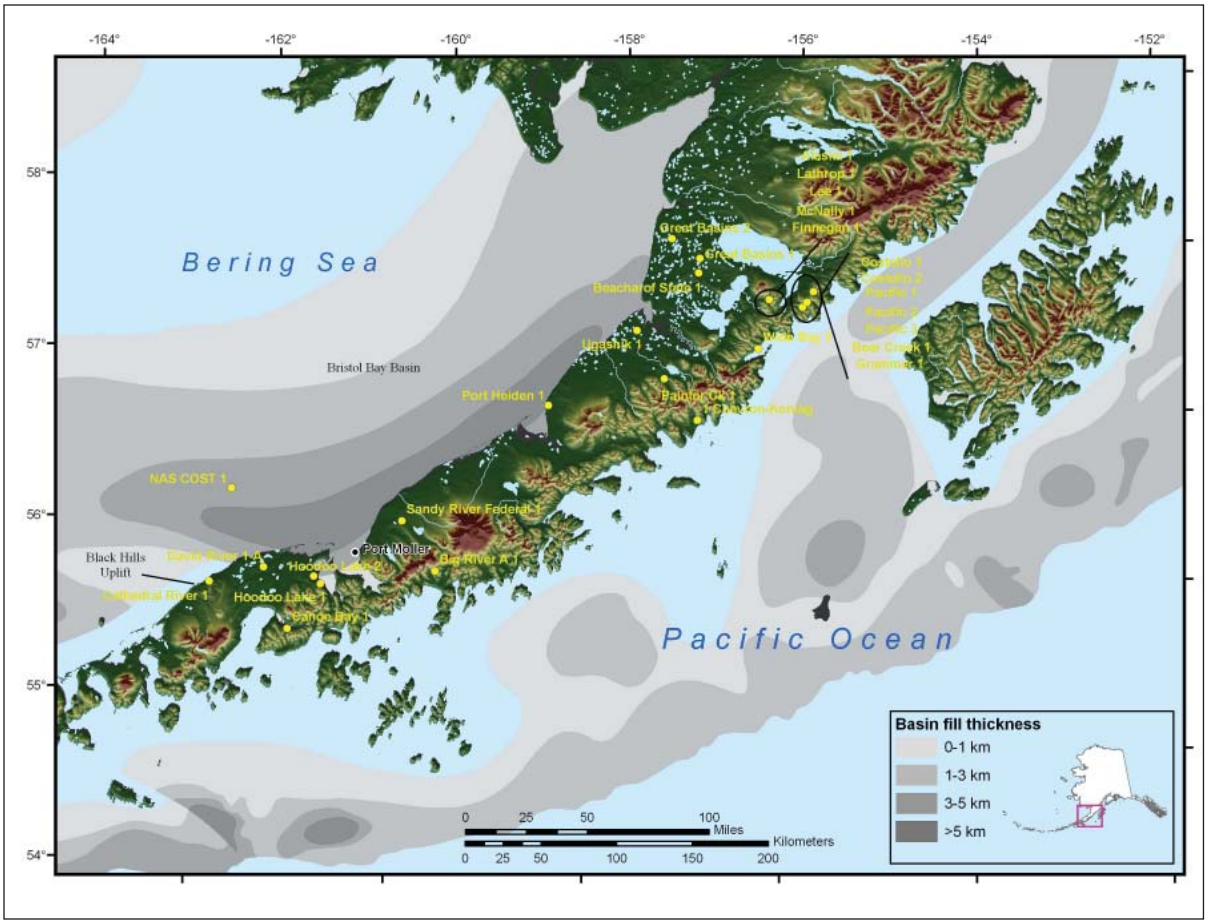

Figure 2. Alaska Peninsula, generalized basin thickness, and wells.

may constitute gas reservoirs, particularly where highly fractured. Magoon and others (1996), Sralla and Blodgett (2007), and Blodgett and Sralla (2008) speculate that reefoid or biostromal facies of the Kamishak Formation may locally possess reservoir quality in the subsurface. Finally, deformation and erosional events associated with multiple stages tectonism in the region are likely to have generated structural and/or unconformity-related traps. Mesozoic reservoirs may be sealed by marine mudstones of the Lower Cretaceous Staniukovich Formation, which have been shown locally to have good seal capacity (Strauch and others, 2006; Loveland and others, 2007; Helmold, Brizzolara, and Reifenstuhl, this volume; Bolger and Reifenstuhl, this volume).

Source characteristics of the potential Cenozoic petroleum system indicate that the succession filling the back-arc basin is mainly prospective for natural gas. Depending on thermal maturity, Upper Cretaceous to Tertiary coals and carbonaceous mudstones of the Chignik, Tolstoi, Stepovak, and Bear Lake Formations should be excellent sources for either thermogenic or biogenic gas. Rock-Eval and kerogen analyses suggest that Paleogene coals and carbonaceous shales of the Tolstoi Formation may have marginal capacity to generate light oil or condensate, and isotopic- and gas-wetness data support a liquids-associated thermogenic origin for some gas shows encountered in Tertiary sandstones, but their effectiveness as sources of petroleum liquids is probably severely limited by low expulsion efficiency (Decker and others, 2006; Decker, this volume). Several Tertiary sandstones have fair to excellent potential as oil or gas reservoirs, particularly the Miocene Bear Lake Formation and equivalents (Helmold, Brizzolara, and Reifenstuhl, this volume). Nonmarine to marginal marine mudstones interbedded with reservoir sands locally indicate good seal capacity (Bolger and Reifenstuhl, this volume), similar to those in the partially analogous Tertiary system of Cook Inlet.

REVIEW OF PREVIOUS WORK

As summarized in detail by Detterman and others (1996), the first systematic geologic investigations in the Alaska Peninsula – Bristol Bay region began shortly after the purchase of Alaska from Russia in 1867. Two phases of U.S. Geological Survey explorations are recorded in more than 20 early reports by W.H. Dall, J.E. Spurr, R.W. Stone, W.W. Atwood, S.R. Capps, R.S. Knappen, G.C. Martin, K.P. Mather, S. Paige, W.R. Smith and others published between 1870 and 1930. Those studies focused on coal, minerals, and petroleum resource potential, but made important inroads toward defining the regional stratigraphic framework. As petroleum exploration progressed, industry geologists documented their field and subsurface geologic observations in internal reports, some of which are now in the public domain. For example, Hanna and others (1937) reviewed the petroleum geology of the Bear Creek anticline southwest of Puale Bay in a report to the three-company partnership they represented.

Burk (1965) published a detailed monograph accompanied by and maps and measured sections describing the geologic history, stratigraphy, and structure of the Alaska Peninsula southwest of Wide Bay. His report remains one of the most wide-ranging and thorough references for the region. Wisehart (1971) studied the paleo-environment of the upper and middle Miocene-age Bear Lake Formation, followed by Lyle and others (1979), who provided detailed information on the petroleum-reservoir and source-rock potential of Tertiary and Mesozoic rocks on the Alaska Peninsula area. Lower and Middle Jurassic stratigraphic details in the Puale Bay area were defined by Imlay and Detterman (1977).

Wilson and others (1985) recognized the pronounced structural and thermal differences across the Bruin Bay fault, which runs along the center of the northern Peninsula terrane (Silberling and others, 1985). Wilson and others (1985) defined the exposures on the west side of the Alaska Peninsula as the Iliamna subterrane, rocks structurally complex and overmature in terms of oil and gas potential. In contrast, rocks of the Chignik subterrane lie east of the Bruin Bay fault and are only weakly to moderately folded and are well within the thermal range of oil and gas generation (for example, at Puale Bay). Supporting geologic data included geochronology and whole-rock geochemistry (Wilson and others, 1981; 1992; 1994), mapping (Detterman and others, 1981a; 1987; Wilson and others, 1995), and megafossil identifications (Detterman and others, 1981b). Detterman and others (1996) integrated stratigraphic findings from these and other studies, and erected a detailed yet regional stratigraphic framework of the Alaska Peninsula constraining the geologic and depositional history of the Alaska Peninsula. Geologic mapping and regional geology culminated in the compilation of a regional digital geologic map of the Alaska Peninsula at 1:500,000 scale (Wilson and others, 1999). C.M. Molenaar led the Alaska Peninsula portion of the southern Alaska province oil and gas assessment by Magoon and others (1996) as part of a nationwide assessment by the U.S. Geological Survey. Citing a critical lack of subsurface information, that assessment estimated modest oil and gas potential in Tertiary and Mesozoic plays in onshore areas of the Alaska Peninsula.

Kirschner (1988) compiled a map of Alaska's oil and gas basins, including seismic cross sections, two of which depict the North Aleutian and St. George basins. The regional tectonic history of the Bering Sea and Tertiary basins of the Bering shelf was treated in significant detail by Worrall (1991) in a Geological Society of America Special Paper. The tectonic evolution

of Bristol Bay, in particular, was interpreted by Walker and others (2003).

The North Aleutian Shelf Co-Owned Stratigraphic Test well #1 (NAS COST#1) was completed to 3,833 m (17,155 ft) in 1983, and Turner and others (1988) compiled a geological and operational summary. Later, Sherwood and others (2006) produced an updated oil and resource assessment for the Mineral Management Service's North Aleutian planning area. Their report included numerous findings regarding the NAS COST #1 well as applied to their assessment including all the downhole sampling and tests.

In preparation for the renewal of onshore leasing Alaska Peninsula areawide sale, the Alaska Division of Oil and Gas released a digital compilation that summarized data availability and presents publicly available digital well logs and seismic data (Meyer and others, 2004). The Bristol Bay Native Corporation underwrote and distributed a comprehensive review of the region's exploration history, data availability, stratigraphic and structural framework, petroleum geology, oil and gas potential, and land ownership (Hite, 2004).

The Alaska Division of Geological & Geophysical Surveys and the Alaska Division of Oil and Gas began field studies in 2004 in the Puale Bay and Wide Bay regions (Reifenstuhl and others, 2004a, 2004b; Reifenstuhl and others, 2005). Field, office, and laboratory studies expanded during 2005, 2006, and 2007 to include the rest of the study area described in this report, as well as both formal and informal collaborations with academic researchers, consultants, and corporate petroleum geologists. Since 2005, this collaboration has directly or indirectly spawned numerous publications other than those included in this volume.

- Finzel and others (2005) reported on the sedimentology, stratigraphy, and hydrocarbon reservoir source rock potential of Tertiary and Mesozoic strata (fig. 3) from outcrop and subsurface samples and offered a detailed interpretation of the Bear Lake Formation based on several measured sections
- Mickey and others (2005) provided a biostratigraphy study of the northwestern Alaska Peninsula and Bristol Bay based on 11 wells including the NAS COST #1 well
- Blodgett and Clautice (2005) gave an historic account of the oil and gas seeps of the northern Alaska Peninsula
- Decker and others (2005) presented a wide-ranging report covering details of eight measured sections of the Bear Lake, Stepovak, and Tolstoi Formations, the character of the Miocene–Pliocene unconformity, outcrop structure of the Naknek Formation in the Black Hills uplift, and the Bear Lake Formation in Herendeen Bay, organic geochemistry and coal evaluation, isotope geochemistry of thermogenic gas seep in Herendeen Bay, and geochemistry disproving the existence of the historically-reported oil seeps in the greater Dillingham area
- Strauch and others (2006) and Loveland and others (2007) reported reservoir- and seal-quality analyses from outcrop samples based on porosity and permeability and mercury injection capillary pressure data, which indicated good reservoirs within the Bear Lake Formation and good seals locally in Tertiary and Cretaceous rocks
- Decker and others (2006) summarized supporting evidence for potentially functional Mesozoic and Cenozoic petroleum systems on the Alaska Peninsula, and discussed play concepts for reopening the basin to exploration
- Gillis and others (2007) presented preliminary results of petroleum system field studies in the Port Moller area
- Sralla (2007) presented an interpretation of hydrocarbon exploration potential in the Herendeen Bay region
- Sralla and Blodgett (2007) addressed the reservoir potential of the Triassic Kamishak Formation in the Puale Bay area
- Blodgett and Sralla (2008) reviewed and interpret the Permian/Triassic unconformity and hydrocarbon potential in the Puale Bay region
- Blodgett and others (2008) reported and interpreted a suite of Jurassic–Pliocene megafossils
- Gillis and others (2008) outlined implications of new apatite and zircon fission-track thermochronology for Mesozoic and Tertiary basin margin exhumation on the Alaska Peninsula; and
- Finzel and others (in press) detail their observations, interpretations, and implications of the stratigraphic framework, depositional environment, and reservoir characteristics of the Bear Lake Formation in a frontier, gas-prone basin.

KEY FINDINGS, THIS VOLUME

The following nine chapters represent stand-alone, peer-reviewed treatments of various topics addressed over the course of this project. The final part of this volume is an extended bibliography for the geologic literature of the Bristol Bay—Alaska Peninsula region.

Chapter B (Decker, this volume) presents new outcrop geochemical data for the Triassic Kamishak and Jurassic Kialagvik Formations at Puale Bay alongside pre-existing data for Tertiary units encountered in the North Aleutian Shelf COST #1 well. The accompanying analysis characterizes each formation in terms of total organic carbon content, kerogen composition, thermal maturity, and potential for generating and expelling oil and gas. The new data confirm previous descriptions of

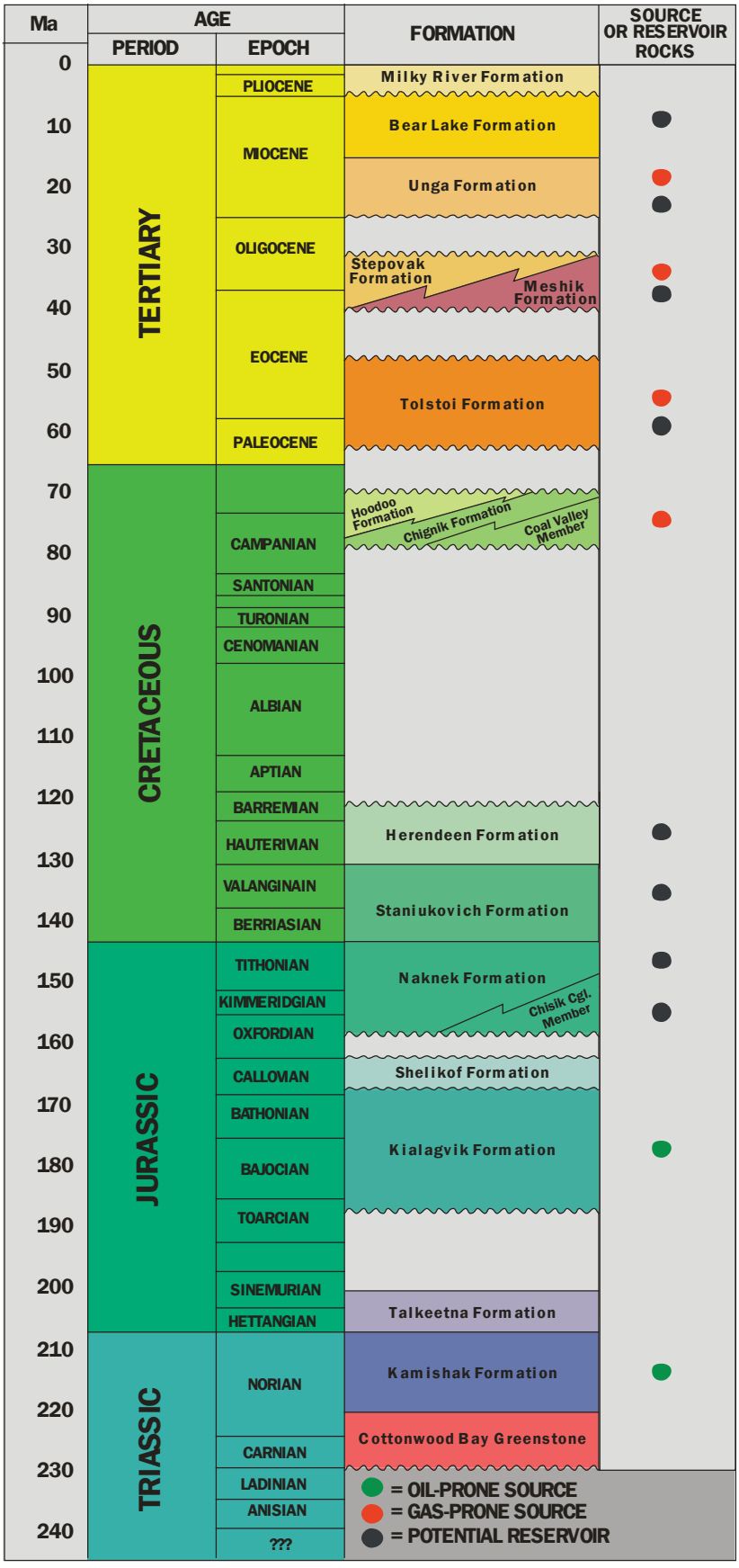

Figure 3. Stratigraphic column for the Alaska Peninsula showing rock formations with generally favorable hydrocarbon source potential (oil prone: green dots; gas prone: red dots) and hydrocarbon reservoir potential (black dots) (modified from Hite, 2004).

the Mesozoic source rock units as highly oil prone and are the first to confirm the section's immature to early oil-window thermal maturity previously indicated only by pyrolysis data. The Cenozoic backarc basin fill is dominated by terrestrially-sourced coaly kerogen, and is prospective for natural gas sourced from mature horizons in fault-bounded structural lows.

Chapter C (Helmold, Brizzolara, and Reifenstuhl, this volume) describes the reservoir quality and underlying petrographic characteristics of Alaska Peninsula formations, with particular emphasis on Tertiary sandstones sampled in core from five wells. Data from these samples are augmented by analyses of outcrop samples from a variety of Tertiary and Mesozoic units collected over the course of the project, and from publicly available data collected by industry field programs. Bear Lake and Stepovak Formation sandstones represent the most likely high-quality petroleum reservoirs.

Chapter D (Bolger and Reifenstuhl, this volume) characterizes the seal capacity that can be expected within Mesozoic and Cenozoic petroleum systems of the region, as defined by mercury injection capillary pressure analyses. Of 26 six outcrop samples from the Kamishak, Staniukovich, Tolstoi, Stepovak, and Bear Lake Formations, twelve are shown to be capable of supporting a gas column in excess of 300m (1000 ft) of gas, or an oil column of at least 400 m (1300 ft), assuming "standard" reservoir fluid properties. Four of these samples are argillaceous siltstones within the Bear Lake Formation, representing a facies commonly interbedded with high quality potential reservoir sandstones. These are important and encouraging findings, given that seal capacity was identified early in the project as a key uncertainty, particularly for the Cenozoic petroleum system on the Alaska Peninsula.

Chapter E (Hartbauer, this volume) briefly demonstrates the use of microprobe techniques in assessing variations in composition and alteration of sandstones from the Bear Lake Formation. Applied so far to samples from outcrops near the type section, these techniques show promise for investigating the provenance and diagenetic history of Alaska Peninsula sandstones on a more regional scale.

Chapter F (Decker, Reifenstuhl and Gillis, this volume) integrates outcrop, well, seismic, and magnetic data to recognize and define several new major tectonic elements in the Ugashik-Becharof Lakes region near the northeastern end of the North Aleutian basin, and interpret how they may have interacted during Cenozoic time. This report provides evidence that the largely Neogene fill of the Ugashik sub-basin was deposited on the formerly upthrown block of the Bruin Bay fault. This occurred as a response to transtensional subsidence made possible by linkage of the Ugashik Lakes fault system with cross faults of the Becharof discontinuity.

Chapter G (Whalen and Beatty, this volume) and Chapter H (Blodgett, this volume) both describe aspects of the Upper Triassic Kamishak Formation revealed in outcrops near the mouth of Puale Bay. The former describes and interprets lithofacies observed in detailed measured section analyses conducted during 2007. It also includes a brief overview of a subset of the outcrop geochemical data presented in Chapter B (Decker, this volume). Blodgett (this volume) emphasizes paleontological details of the formation gleaned from previously published literature, unpublished U.S. Geological Survey internal reports, and new collections made by the author during field investigations in 2007. Among other findings, both of these papers assert the significance of a probable basal angular unconformity separating the Kamishak Formation from underlying agglomerate, volcaniclastic sandstone, and limestone strata believed to be of Permian age.

Chapter I (Decker, Reifenstuhl, Gillis, and Loveland, this volume) provides a preliminary geologic map and structural model for the Staniukovich peninsula-Herendeen Bay area south of Port Moller. This mapping covers much of the best exposures within the boundaries of the areawide lease sale, including most of the onshore acreage that received bids in the two sales since 2005. This study resolves major inconsistencies between previous geologic maps and structural interpretations of the area, and provides new understanding of the local geologic framework as it affects oil and gas potential. These results are relevant not only to these tracts and immediately adjacent areas, but also to evaluating regional structural models.

Chapter J (Bergman, Murphy, and Kelley, this volume) reports the results of zircon and apatite fission track geochronology analyses conducted on Eocene to Miocene core samples from the North Aleutian Shelf COST #1 well. The authors conclude that this part of the back-arc basin has probably witnessed a simple Tertiary subsidence history with paleo-heat flow akin to the present regime, with a mean geothermal gradient of 31 °C/km. In addition, patterns of uranium content versus depth suggest the progressive unroofing of an evolving magmatic arc; deeper samples represent more primitive (uranium-depleted) igneous rocks, and shallower samples represent a more evolved (uranium-enriched) igneous suite.

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