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## **The Relationship between the Timing of Hydrocarbon Generation Between the Bristol Bay Depositional Basin and the Port Moller Area and Southern Portion of the Bristol Bay Basin of the Alaska Peninsula**

Claire Rochelle Jones

*Louisiana State University and Agricultural and Mechanical College*

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THE RELATIONSHIP BETWEEN THE TIMING OF HYDROCARBON GENERATION  
BETWEEN THE BRISTOL BAY DEPOSITIONAL BASIN AND THE PORT MOLLER  
AREA AND SOUTHERN PORTION OF THE BRISTOL BAY BASIN OF THE ALASKA  
PENINSULA

A Thesis

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in

The Department of Geology and Geophysics

by

Claire Rochelle Jones

B.S., Southern Methodist University, 2013

B.A., Southern Methodist University, 2013

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## TABLE OF CONTENTS

ACKNOWLEDGEMENTS.....	ii
ABSTRACT.....	v
CHAPTER	
1 INTRODUCTION .....	1
1.1 Previous Studies.....	3
2 GEOMORPHOLOGICAL SUMMARY .....	9
2.1 Overview .....	9
2.2 Stratigraphic History .....	10
2.3 Structural and Tectonic History .....	11
3 STRATIGRAPHY .....	15
3.1 Overview .....	15
3.2 Kamishak Formation (Upper Triassic, Ladinian–Norian; 235–208.5 Ma).....	15
3.3 Talkeetna Formation (Lower Jurassic, Hettangian–Sinemurian; 201.3–182.7 Ma) .....	18
3.4 Kialagvik Formation (Middle Jurassic, Bajocian–Bathonian; 170.3–166.1 Ma) .....	19
3.5 Shelikof Formation (Middle Jurassic, Callovian; 166.1–163.5 Ma) .....	20
3.6 Naknek Formation (Upper Jurassic, Oxfordian–Tithonian; 165–145 Ma).....	21
3.7 Staniukovick Formation (Lower Cretaceous, Berriasian; 145–139.8 Ma) .....	23
3.8 Herendeen Formation (Lower Cretaceous, Valanginian–Hauterivian; 139.8–125 Ma) .	24
3.9 Chignik Formation (Upper Cretaceous, Campanian–Maastrichtian; 83.6–66 Ma) .....	24
3.10 Hoodoo Formation (Upper Cretaceous, Campanian–Maastrichtian; 83.6–66 Ma).....	25
3.11 Tolstoi Formation (Lower Tertiary, Eocene; 59.2–23.03 Ma) .....	26
3.12 Stepovak Formation (Lower Tertiary, Oligocene; 38–23.03 Ma) .....	28
3.13 Unga Formation (Upper Tertiary, Miocene; 23.1–11.62 Ma) .....	29
3.14 Bear Lake Formation (Upper Tertiary, Miocene; 11.6–5.3 Ma) .....	29
3.15 Milky River Formation (Upper Tertiary, Pliocene; 5.3–1.81 Ma) .....	31
4 EXPLORATION WELLS .....	33
4.1 Overview .....	33
4.2 Cathedral River 1 .....	33
4.3 Canoe Bay 1 .....	35
4.4 Big River 1A .....	36
4.5 David River 1/1A .....	37
4.6 Sandy River 1 .....	37
4.7 Hoodoo Lake 1 .....	38
4.8 Hoodoo Lake 2 .....	39

5	METHODOLOGY .....	40
5.1	Stratigraphic Framework .....	40
5.2	Thermal Modeling .....	41
5.3	Subsidence Analysis .....	53
5.4	Hydrocarbon Generation.....	54
5.5	Organic Geochemistry .....	57
6	RESULTS .....	62
6.1	Source and Generation Potential.....	62
6.2	Estimating Inversion .....	63
7	DISCUSSION.....	65
7.1	Petroleum Geology .....	65
7.2	Source Rocks .....	66
7.3	Mesozoic Source Rocks.....	67
7.4	Cenozoic Source Rocks .....	68
7.5	Reservoir Rocks .....	69
7.6	Migration.....	70
7.7	Potential Traps .....	70
7.8	Seals .....	71
7.9	Potential Plays.....	72
8	CORRELATION BETWEEN THE PETROLEUM SYSTEMS .....	75
9	CONCLUSION.....	77
	REFERENCES .....	78
	VITA.....	86

## **ABSTRACT**

The Alaska Peninsula has been the target of oil and gas exploration throughout much of the 20<sup>th</sup> century. Although most exploration efforts have focused on the Cook Inlet area, the geological setting of the Alaskan Peninsula suggests that economically viable resources may be located further south on the northern side bordering Bristol Bay (Port Moller area). This study investigates the relation of petroleum system elements between the northern and southern section of the Alaskan Peninsula with a particular focus on the potential for petroleum accumulation on the southern section close to Herendeen Bay. The analysis included the integration of a variety of geological and geophysical data from well logs, cores, and seismic profiles. I reconstructed the accumulation of sediment in the basin north of the peninsula and used backstripping subsidence analysis to identify periods of accelerated basement subsidence linked to regional tectonic extension. This analysis was then used to predict thermal history that was compared with thermal indicators from the wells. Basin inversion up to ~900 m since the Pliocene was predicted along the southern edge of the basin, resulting in peak temperatures being reached before the present day.

## CHAPTER 1 INTRODUCTION

Worldwide, hydrocarbons have been found in many different types of sedimentary basins. Tectonic and thermal models have been used to explain the generation of oil and gas; however, many of these models are rather simplistic (Sherwood *et al.*, 2006) and have best been applied in regions where there are only one or two phases of tectonic activity. In reality, commercial accumulations of oil and gas are found in locations that have been subjected to many phases of tectonic activity. And Alaska is a world-famous province for oil and gas exploration despite the fact that it has been subjected to repeated phases of tectonic and magmatic activity resulting in complex thermal and depositional histories that are not easily handled by simplistic models (Decker *et al.*, 2007; Detterman, 1990). In general, active margins often have long lived histories of tectonic activity that can affect the generation and accumulation of commercially viable amounts of hydrocarbons.

In this project I have analyzed a sedimentary basin on the north side of the Alaska Peninsula in order to isolate the key processes responsible for the generation of oil and gas and have constrained which of those key processes are most important in the establishment of a viable hydrocarbon system that has been affected by multiple stages of tectonic activity with resultant faulting. Before further expensive exploration efforts can be undertaken it makes sense to examine the data that are available in order to assess whether a viable hydrocarbon system might have been developed in this area.

A petroleum systems model representing the southern Alaska Peninsula has never been generated. I created such a model for the Port Moller area (Figs. 1 and 2) and then compared that new model to the existing petroleum system models for the northern Alaska Peninsula offshore

in Bristol Bay in order to determine whether or not the models are the same or if the models differ. The similarities and differences are important to define if we are to tell if the knowledge used to discover plays from the northern areas are easily transferred and applied to those regions to the south. Alternatively if the models differ, then the approach to petroleum exploration and extraction would be quite different. The main data was obtained from well logs from three wells: David River 1/1A, Hoodoo Lake 2, and Big River 1A (Fig. 2). These wells contain more complete sections, whereas there is limited stratigraphy recovered at the other drill sites: Cathedral River 1, Sandy River 1, Hoodoo Lake 1 and Canoe Bay 1. In all but one well, Cathedral River 1, drilling did not reach the crystalline basement. Four wells were used to help correlate and build a larger more representative model of the area. I used a combination of wells in order to build a composite stratigraphy in order to get a more comprehensive understanding of the deep evolution of the sedimentary basin below the levels drilled in any one single well.

Publically available data includes well log data, total organic carbon (T.O.C.) contents, thermal maturation data, vitrinite reflectance/visual kerogen, rock-eval parameters, organic yield, thin section petrography, and mineralogy determined by x-ray diffraction.

In general, the Alaska Peninsula has been considered to have a low potential for oil accumulations. However, the southern region of the peninsula (Port Moller region) has the highest prospectively for oil (Barth, 1956). According to Detterman *et al.*, (1985), the data obtained from the wells drilled in the Port Moller region show that sandstone in that area is porous and often have good permeability, characteristics of a viable petroleum system. In addition, data from the wells in the south indicate that stratigraphic sequence contains less volcanic debris in two sections; the Tertiary and Mesozoic segments (Detterman *et al.*, 1985;



Hite, 2004). This study's results provide data analysis to establish a petroleum systems model to examine whether the Port Moller region does in fact have good potential for oil or gas exploration and to establish if there is a relationship between the timing of hydrocarbons between that of the north and the south depositional basins along the Alaska Peninsula.

## **1.1 Previous Studies**

The Alaska Peninsula extends approximately 800 km southwest from the mainland of Alaska separating Bristol Bay from the Pacific Ocean (Fig. 1). Thick sequences of sedimentary rocks and oil seeps found throughout the Peninsula have attracted the attention of geologists and thus has resulted in gas and oil exploration throughout the twentieth century. Despite the occurrence of oil seeps and oil/gas shows in most drilled wells, an economically viable quantity of hydrocarbon resources has yet to be discovered (Detterman, 1990).

Various investigations have been completed on the exposed strata in the Alaska Peninsula (Smith and Baker, 1924; Martin, 1904, 1905; Dall, 1896; Hudson, 1986). The US Geological Survey conducted a survey between 1977 and 1988, which provided a wealth of paleontological and lithological data for the Alaska Peninsula (Turner, 1988). More recently Sherwood *et al.*, (2006) studied the petroleum systems and their theorized systems are shown in Fig. 3, with the cross section located out in the middle of the Bristol Bay Basin near North Aleutian COST 1 well. Largely, Sherwood *et al.*, (2006) hypothesized the traps to be charged by gas, oil, and condensate originating from deeply buried, gas-prone source rocks of Cenozoic age. For the southwest part of the Bristol Bay Basin, closer to my study area, where oil-prone Mesozoic rocks possibly underlay, traps in Mesozoic sandstones are hypothesized to be charged by original oil

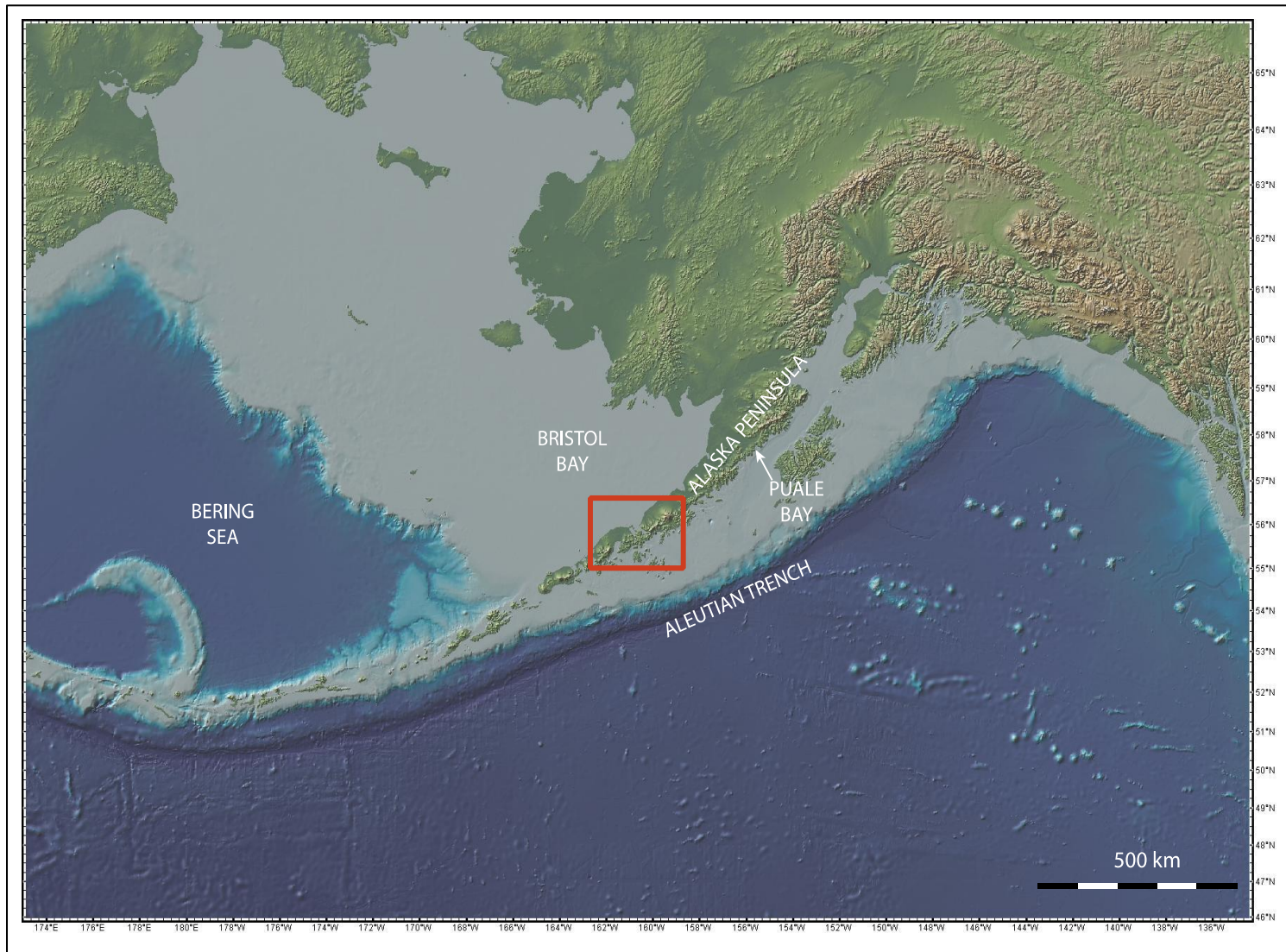


Figure 1 Shaded bathymetric map of the Alaska, showing study area located within the red box. Major structures are noted. Data from GeoMapApp.



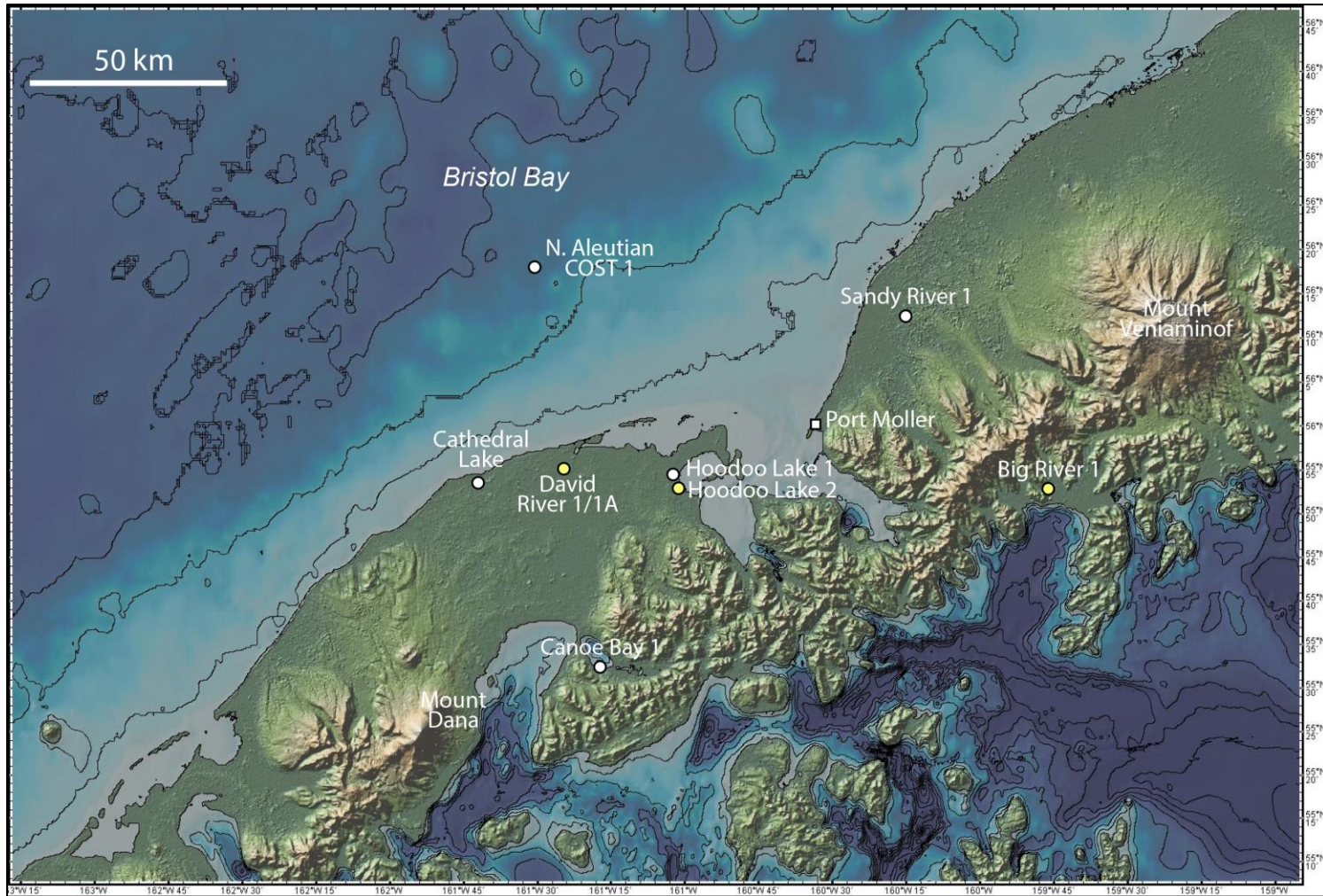


Figure 2: Shaded bathymetric map of the study area showing the location of the primary drilling sites considered in our analysis together with the major topographic features of the region especially the two volcanoes on either side of the study area. Bathymetric consults are in 25 m intervals. Yellow dots represent those wells subject to detailed subsidence analysis. Data from GeoMapApp.

migration from Mesozoic oil source rocks, within my study area. Traps in Cenozoic sandstones overlying oil-prone Mesozoic rocks are hypothesized to be charged by re-migration of oil out of disrupted Mesozoic reservoirs (Sherwood *et al.*, 2006).

The hypothetical petroleum system responsible for the majority of potential undiscovered oil and gas resources located in the center of the Bristol Bay Basin (Fig. 3) are located within the sandstone reservoirs (Bear Lake-Stepovak play sequence) within the domes draped over basement uplifts that are charged by petroleum generated in Tertiary rocks (Tolstoi play sequence) that are deeply buried in grabens flanking the uplifts. Faults in the immediate area may provide the critical pathways of migration between the deep oil and gas generation centers adjoining basement uplifts and the shallow traps that overlie the uplifts.

The hypothetical petroleum system responsible for a minority fraction of undiscovered oil resources in the Planning Area, land open for leasing along the Alaska Peninsula for oil and gas drilling and exploration, is illustrated on the left side of Figure 3a. Mesozoic rocks beneath the Black Hills uplift reached thermal maturity sufficient for oil generation prior to Eocene time and may contain oil pools that formed in Mesozoic, or probably Cretaceous time. Cenozoic-age faulting may have disrupted some of these oil pools and provided avenues for re-migration into traps in overlying Oligocene-Miocene reservoir sandstones of the Bear Lake-Stepovak play sequence. Traps in Tertiary reservoirs on the Black Hills uplift may also be charged by gas and condensate migrating out of deeply buried Tertiary strata in North Aleutian basin. However, this would require 50+ miles of lateral migration through the highly faulted southwest part of the North Aleutian basin, with great risk of diversion of migrating petroleum up faults and loss to surface seeps.

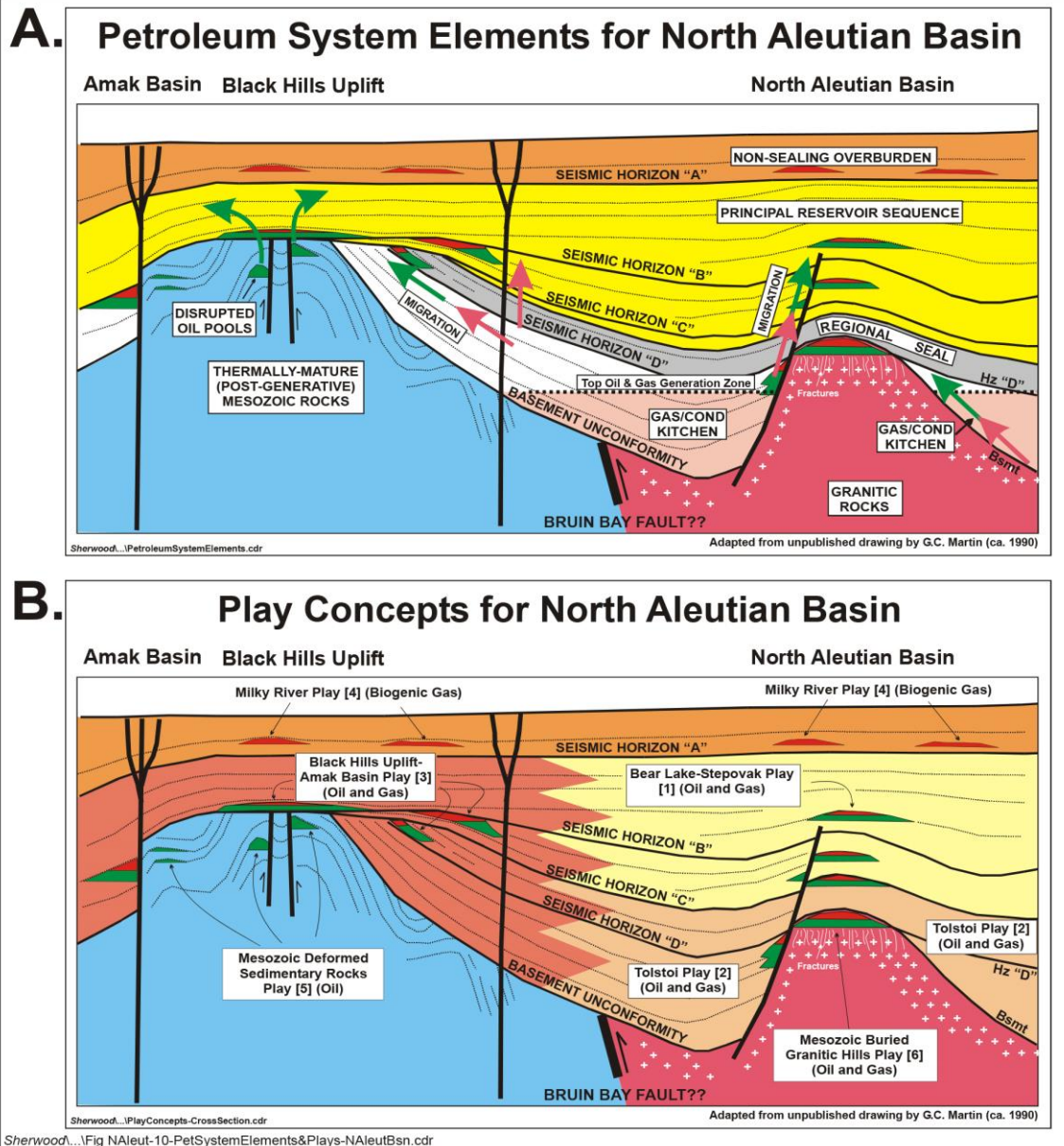


Figure 3: Schematic cross sections illustrating petroleum system elements and play concepts for North Aleutian Basin OCS Planning Area (Sherwood *et al.*, 2006). A) Petroleum system elements, including regional reservoir sequence floored by a regional seal and underlain by deep gas/condensate “kitchens” in grabens flanking uplifts. Petroleum generated in “kitchens” migrates to traps in shallow reservoir formations draped over basement uplifts via faults that pierce the regional seal. The Black Hills uplift may be reached by long-distance lateral migration of petroleum across highly faulted areas. Fault disruption of Mesozoic oil pools beneath the Black Hills uplift may release oil into overlying strata. Arrows show hypothetical migration paths for gas (red) and oil (green). B) Six oil and gas plays defined for North Aleutian Basin OCS Planning Area, separated on the basis of reservoir character, structural style, and access to petroleum sources.

My objective is to test to see if these offshore models are applicable to the nearby onshore of the Alaska Peninsula.



## CHAPTER 2 GEOMORPHOLOGICAL SUMMARY

### 2.1 Overview

The Alaska Peninsula is part of an active continental margin, with the Bristol Bay basin forming a back arc extensional basin (Figs.4 and 5). Subduction has proceeded since the Talkeetna oceanic arc accreted to North America (Yukon Composite Terrane) during the Jurassic (Detterman *et al.*, 1969). This location's rich geological history since the Paleozoic resulted in accumulation of a thick sequence of sediment as shown in the stratigraphic column (Fig. 8). The strata I consider here are composed of late Paleozoic to Quaternary sedimentary, igneous, and minor metamorphic rocks that record the history of a number of magmatic arcs and their accretion to form modern Alaska (Burk, 1965; Hatten, 1971; McLean, 1977).

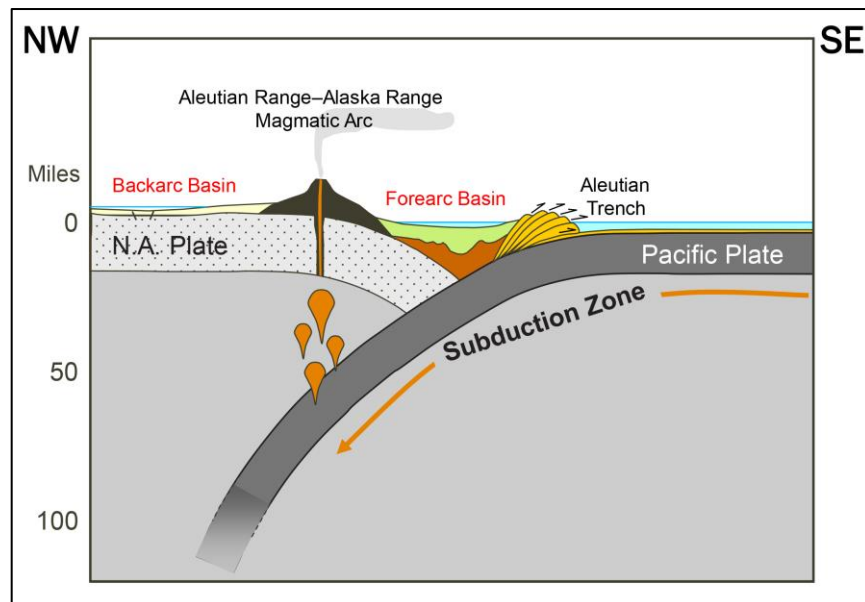


Figure 4: Cartoon showing the subduction of the Pacific Plate under the North American Plate, forming the Aleutian Trench, forearc basin, the Magmatic Arc (Aleutian Range) and the backarc basin (Bristol Bay) Modified from Tornqvist (2005).

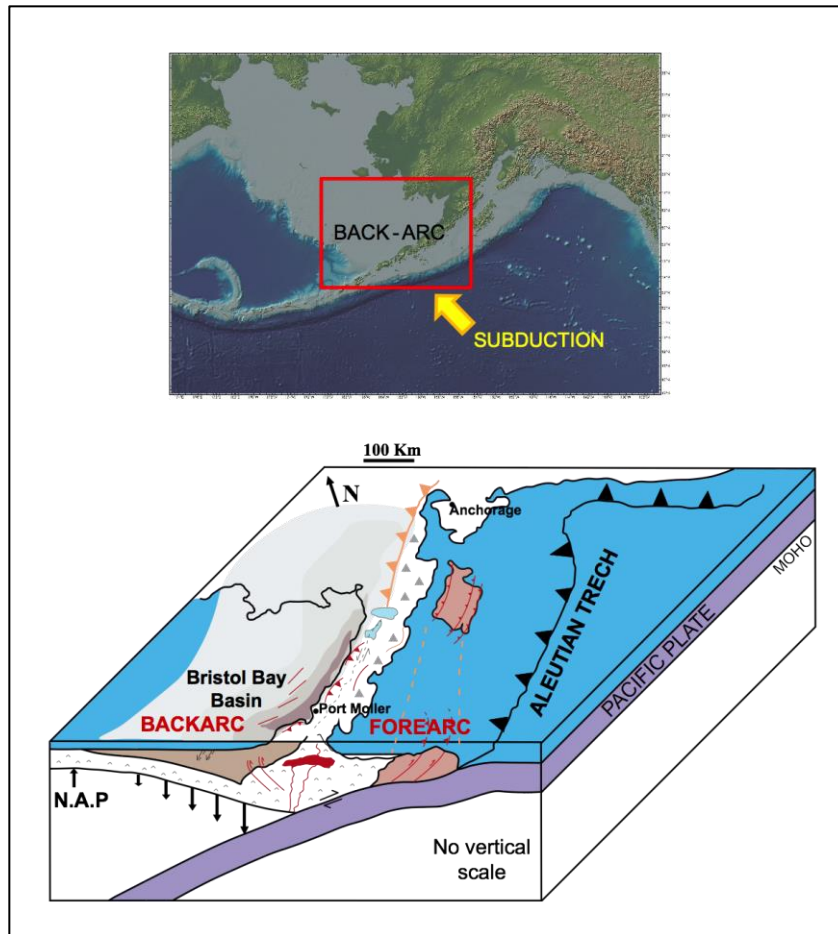


Figure 5: Cartoon showing the subduction of the Pacific Plate under the North American Plate, forming the Aleutian Trench. Resulting in the backarc basin known as Bristol Bay.

## 2.2 Stratigraphic History

During the Early Jurassic an intrusion of granitic plutons, as part of the Talkeetna Arc, initiated the formation of what is now the Alaska Peninsula. The granites were intruded into a sequence of volcanic and marine sedimentary rocks of Permian to Early Jurassic age (Bascle *et al.*, 1987; Finzel *et al.*, 2005). Uplift initiated along faults along the southeastern edge of the Bristol Bay Basin, following pluton emplacement (Marlow *et al.*, 1994). This uplift event triggered erosion of sedimentary rocks and their redeposition as Middle Jurassic strata (i.e., the



Kialagvik and Shelikof Formations). Detritus from these plutons chiefly comprises the thick Upper Jurassic and Lower Cretaceous arkosic sequences (Burk, 1965). During the majority of Cretaceous time deformation and uplift was moderate along the peninsula (Marlow *et al.*, 1994), with a major erosion event late in the Cretaceous prior to deposition of the Chignik Formation and its southern equivalent the Hoodoo Formation.

Throughout the Early Tertiary marine and non-marine volcanic material and sediments accumulated in great thickness, forming a disconformity with the underlying Cretaceous (Burk, 1965; Comer *et al.*, 1987; Finzel *et al.*, 2005). Paleocene and Eocene deposits were widespread, and volcanism seems to have been ubiquitous (Burk, 1965). Eocene sediments were deposited in greater thickness in the outer Alaska Peninsula than to the northeast. As subsidence continued into the Miocene, new volcanic materials, as well as sediments eroded from older rocks accumulated all throughout the Alaska Peninsula due to uplift linked to ongoing subduction accretion. Volcanism was restricted generally to the present Pacific coastal area (Burk, 1965).

## **2.3 Structural and Tectonic History**

All the prominent structural features (Figs. 6 and 7) of the Alaska Peninsula were formed by post-Miocene deformation. Presently, the region continues to experience uplift (Burk, 1965; Sherwood *et al.*, 2006). There were five periods of deformation that occurred within the Alaska Peninsula, three of which were associated with plutonic intrusion, with minor structural warping occurring in the Early Jurassic, Early Tertiary and Mid-Tertiary (Burk, 1965).

The Bristol Bay basin represents an extensional backarc area related to the ongoing subduction to the South now lying north of the active volcanoes along the Alaska Peninsula (Figs. 4 and 5).

Seismic profiling shows that this area has largely been characterized by normal faulting related to regional extension with more recent compressional deformation along the southern edge, as manifested by a series of northward propagating thrusts and anticlinal folds largely located along the coast of the Alaska Peninsula and dating from the latter part of the Neogene. The history of the basin can thus be divided into an earlier extensional setting and the latter compressional environment with subsidence driven by flexure due to loading by the thrust sheets.

The southeast edge of the Bristol Bay Basin has been deformed into three faulted anticlinal complexes (including the Black Hills Uplift; Fig. 7) along the coast of the Alaska Peninsula due to thrusting from the south (Burk, 1965; Finzel *et al.*, 2005). Sediment thicknesses are greater offshore to the northwest where deformation is less. The fundamental structure both on and offshore is characterized by deep faults bounding wedges of uplifted crustal rocks, especially to the south (Burk, 1965).

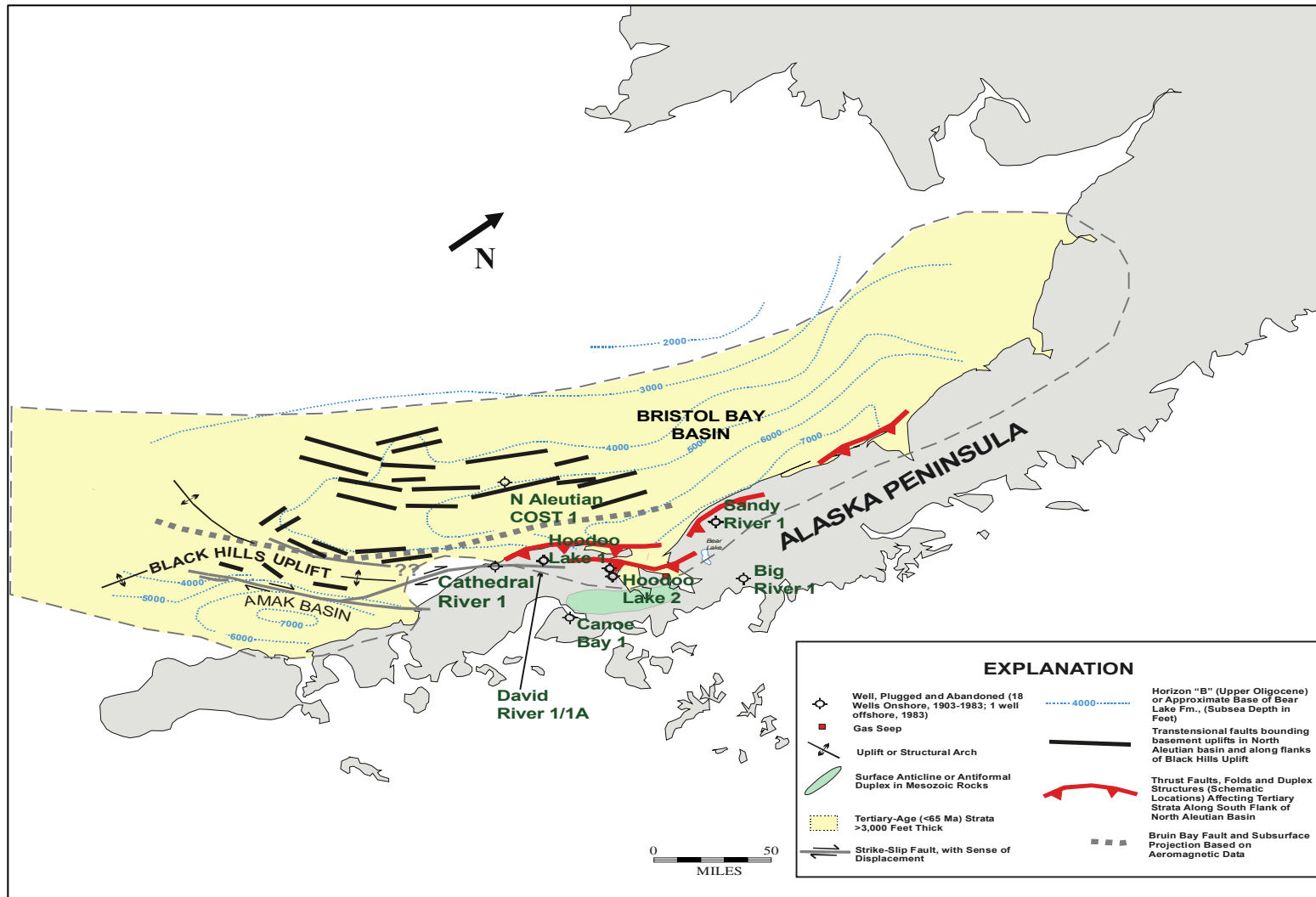


Figure 6: Principle geologic structures of the North Aleutian-Bristol Bay basin and contiguous areas, including: 1) transtensional faults and basement uplifts in western parts of the basin; 2) wrench fault system of the Black Hills uplift; 3) fold/thrust belts along the southeast margin of the basin. Along with primary drilling sites (modified from Sherwood *et al.*, 2006).

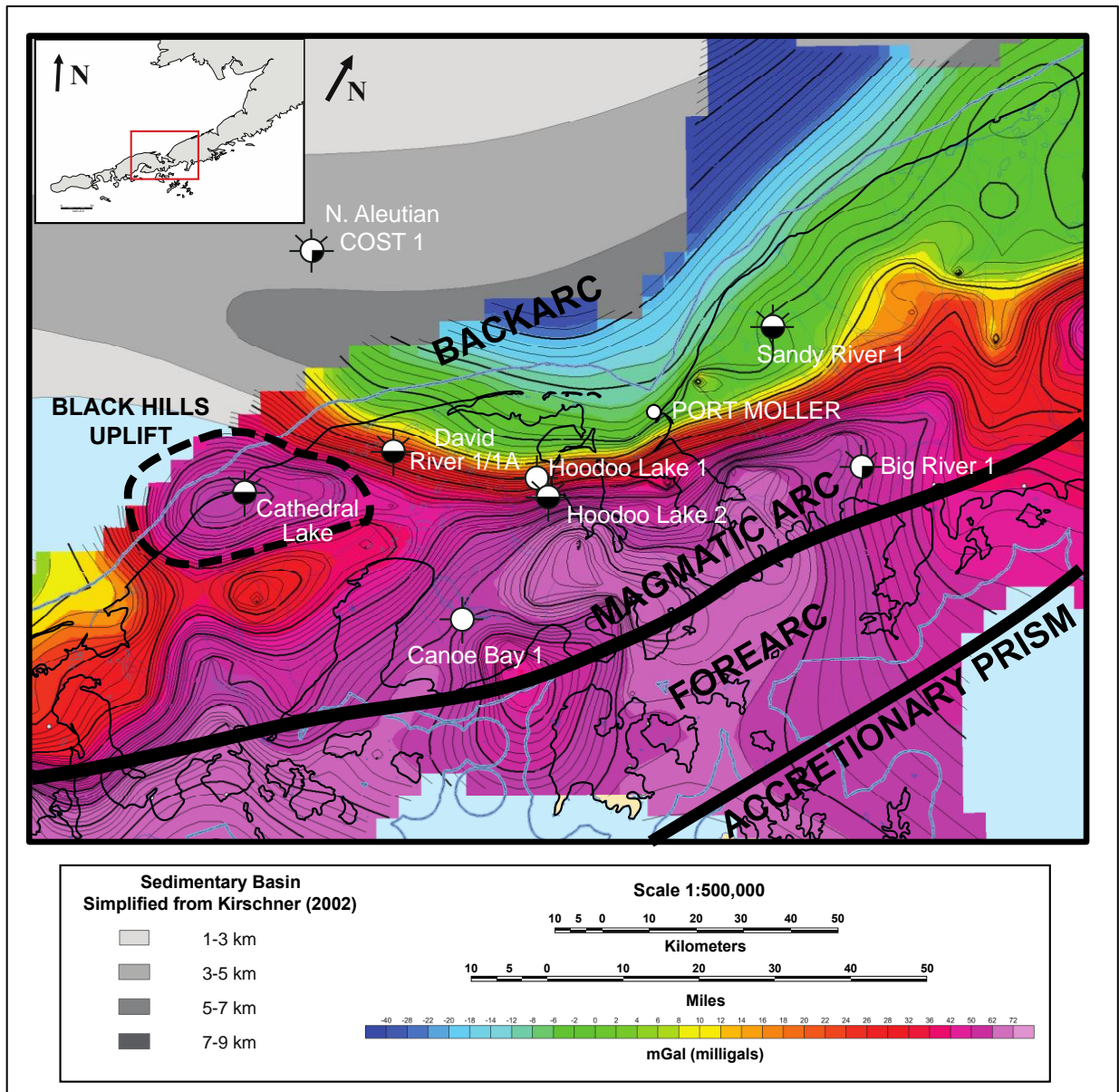


Figure 7: Bouguer Gravity map of study location displaying the location of the primary drilling sites along with the tectonic framework formed from the subduction of the Pacific Plate under the North American Plate. Sedimentary Basin fill is modified from Kirschner (2002).

## CHAPTER 3 STRATIGRAPHY

### 3.1 Overview

The Alaska Peninsula is primarily composed of Mesozoic and Cenozoic sedimentary rocks heavily influenced by volcanic and plutonic activity (Bascle *et al.*, 1987; Fig. 8). A number of formations are recognized and I here summarize their overall character and age that I then used to undertake subsidence analysis of the Bristol Bay Basin in order to understand the potential for active hydrocarbon systems.

### 3.2 Kamishak Formation (Upper Triassic, Ladinian–Norian; 235–208.5 Ma)

The Kamishak is the oldest Mesozoic formation found within my study area. The lower contact, not observed in this study, of the Kamishak Formation base is an angular unconformity, which underlies the greenish volcanoclastic unit (Whalen & Beatty 2008). Clasts indicate that the volcanoclastics had been exposed locally to erosion during the Kamishak Formation deposition. The upper contact is gradational with the overlying Talkeetna Formation (Detterman *et al.*, 1996).

The Kamishak is subdivided in three members, including limestone, volcanic rocks, and chert. Detterman and Reed (1980) divided unit into three members, in descending order, Ursus Member, middle member, and Bruin Limestone Member. An interval of brecciated and calcite-recemented basalt occurs near top of section, as does a volcanic breccia interval in lower part of the section.

The Kamishak Formation was deposited in a shallow water carbonate shelfal environment along with a high-energy environment, below the wave base. Reef and biohermal buildups are localized. The rhythmically bedded biostromal layers are referred to be depositions below the wave base (Detterman *et al.*, 1996). While the siliceous limestone units are usually referred to be deposition above the wave base, located on the carbonate ramp, localized with syn-depositional folded carbonate sediments and mass wasted carbonate sediments that are deposited on the edges of steepened ramp slope. The presence of the deformed limestone's and synsedimentary folds indicates active tectonic deformation during deposition (Whalen & Beatty 2008).

The Kamishak Formation reservoir quality is poor, as indicated by the outcrop samples (ANDR, 2014). The carbonate facies that are present are pervasively cemented by calcite, which means that the most clastic facies have both the quartz and calcite cement (Detterman *et al.*, 1996). It is also possible for the secondary porosity to exist in the subsurface containing solution enhancement fractures or sometimes resulting from the dolomitization that occur in the biostromal unit (Wilson *et al.*, 2015).

The Kamishak Formation has variedly good source rock potential. According to the organic geochemical analysis that consist of the TOC and pyrolysis shows that the most suitable source rock is the siliceous limestone and the rhythmically bedded units. Thus, the TOC analysis resulted in different types of rock potential which include type I, II and III (Decker *et al.*, 2007). In the analysis the results, taken at Puale Bay by Bolger & Reifenhuth (2008) showed that the average values were more dominant in the type II oil prone range. This is not observed within the Port Moller area where analysis showed that the Kamishak Formation is more over gas prone

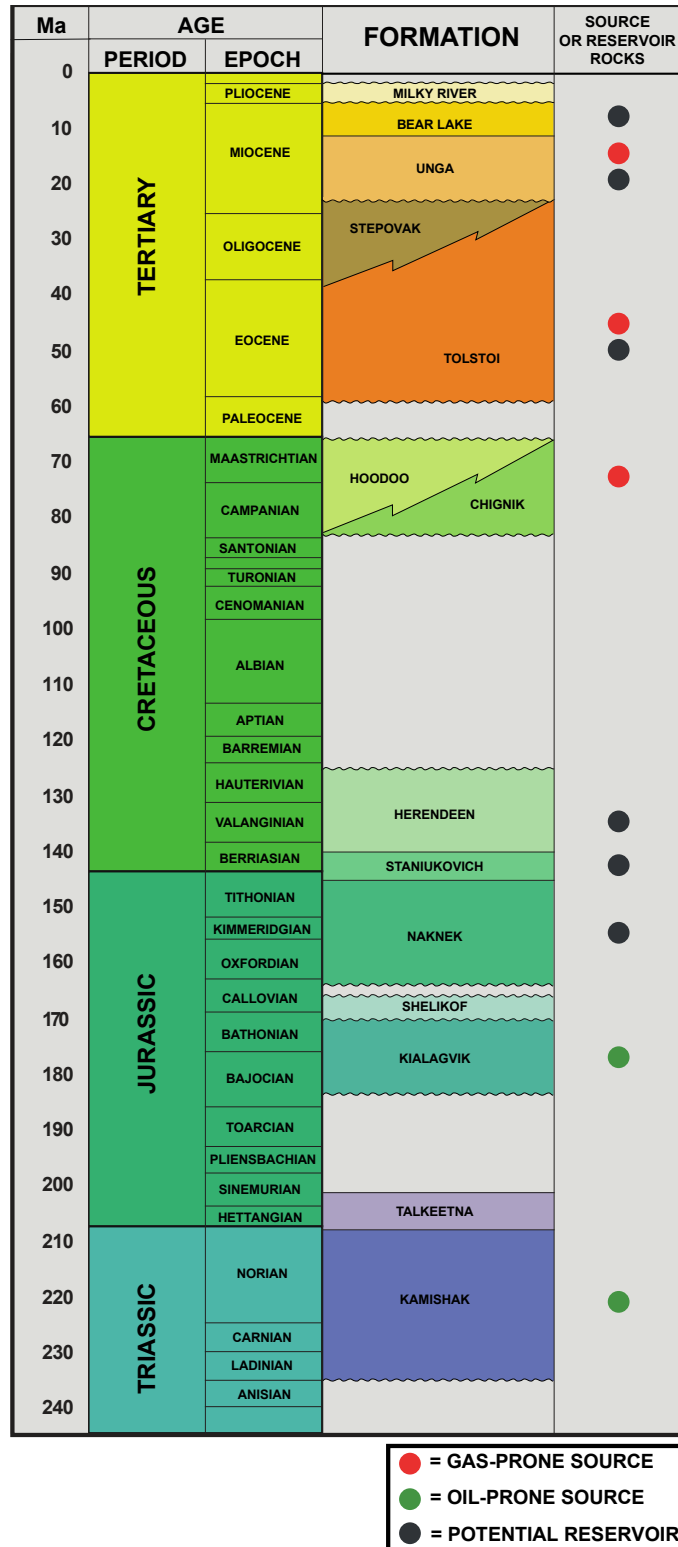


Figure 8: Stratigraphic column for the Alaska Peninsula, with regards to formations only encountered through analysis of the six wells, showing rock formations with generally favorable hydrocarbon source potential (oil prone: green dots; gas prone: red dots) and hydrocarbon reservoir potential (black dots) (modified from Hite, 2004).

(Fig. 8). As for a seal, Bolger & Reifenstuhl (2008) sampled four locations of the Kamishak and were classified as a Snider Type A seal, which is the best quality for seal potential.

### **3.3 Talkeetna Formation (Lower Jurassic, Hettangian–Sinemurian; 201.3–182.7 Ma)**

The Talkeetna Formation comprises of extrusive volcanic and volcanoclastic sedimentary rocks derived from an arc complex. Lithologically, it consists of volcanic flows, breccia, tuff, and agglomerate that is locally interbedded minor sandstone and shale, all being somewhat altered or metamorphosed (Detterman & Hartsock (1966); Detterman & Reed, 1980). The unit also consists of andesitic flows, flow breccia, tuff, and agglomerate and includes subordinate interbeds of sandstone, siltstone, and limestone (based off of Cathedral River 1 well) in a dominantly shallow marine sequence (Csejtey *et al.*, 1978)

The Lower contact between the Talkeetna Formation and Kamishak Formation is considered to be a gradational contact (Detterman *et al.*, 1996). The upper contact is conformable with the Kialagvik Formation. It is also disconformable in the areas where some sections are missing because of the non-deposition or as a result of erosion (Detterman *et al.*, 1996).

The Talkeetna Formation depositional environment is said to be an open shelf because it contains ammonites in some horizons. The Talkeetna Formation reservoir potential is regarded to be low because of the high presence of volcanic tuffs, ash and other volcanic rocks that are interspersed with the shales, sandstones and conglomerates. The Talkeetna Formation has low seal potential because of the abundance of tuff and ash (Helmold *et al.*, 2008).



### **3.4 Kialagvik Formation (Middle Jurassic, Bajocian–Bathonian; 170.3–166.1 Ma)**

The Kialagvik Formation consists of fossiliferous sandstone, siltstone, and minor conglomerate, grading upward into fossiliferous siltstone, mudstone, and rare limestone, seen at Wide Bay near Puale Bay, may not be present in my study area. The lower part of the formation was deposited in near-shore, shallow-water environment. This is known because the sandstone is crossbedded and contains lenses of conglomerate and fossils indicative of high-energy environment (Wilson *et al.*, 2015). The upper part of the unit displays characteristics of deeper water deposition including thin, rhythmically bedded siltstone and sandstone packages and limestone nodules and lenses (Wilson *et al.*, 2015). The Cathedral River 1 well is observed to have up to 530 meters of the formation (Helmold *et al.*, 2008).

Contact of the Kialagvik Formation with the overlying Shelikof Formation is unconformable (McLean, 1977). The lower contact with the Talkeetna Formation is disconformable.

The overall Kialagvik Formation reservoir potential is very low. This formation within its sandstone bodies, are the chemically unstable lithics, interbedded finer grains layers and ductile grains. This reduces the porosity of the formation to permeability of about 0.005 to 0.7 md for the outcrops analyzed from the formation (Detterman *et al.*, 1996). Source and seal potential for the Kialagvik formation is that the hydrocarbon generation potential is considered to be good. This is verified within my study area, where observed in the Cathedral River 1 well, the Kialagvik Formation ranges from fair to good and can generate both oil and gas. This is because it correlates accurately with the middle Jurassic Tuxedni group located at the west side of Cook Inlet, which is considered to be the source rock for the oil produced in Cook Inlet. According to

Decker (2008), the Kialagvik Formation that is found at the Herendeen Bay is highly oil prone. This is based on the total organic carbon, kerogen petrography, rock eval pyrolysis and vitrinite reflectance data. The Kialagvik Formation seal potential depends on the geometry of the rhythmically bedded sandstone and thin gray siltstone sequences. However, there were not samples that were analyzed for the seal potential.

### **3.5 Shelikof Formation (Middle Jurassic, Callovian; 166.1–163.5 Ma)**

From the USGS (YEAR), the lithology of the Shelikof Formation varies from the lower part of the formation where it is mainly thick-bedded to massive, dusky-yellowish-green graywacke and conglomerate, and minor amounts of siltstone, whereas in the upper portion of the Shelikof Formation is mainly volcanic sandstone interbedded with massive and laminated brownish-gray siltstone containing calcareous sandstone clasts. Many lithic intervals are present within the upper part of the unit, have a fining-upward sequence from conglomerate to sandstone or sandstone to siltstone (Allaway *et al.*, 1984).

The lower contact of the Shelikof Formation is conformable with the underlying Kialagvik Formation according to Detterman *et al.*, (1996). As for the overlying, upper contact, it is unconformable with the Naknek Formation (Decker, 2008).

According to Detterman *et al.*, (1996) the Shelikof Formation underlies the whole of the Alaska Peninsula. The depositional environment for the Shelikof Formation is made of abrupt lateral facies changes indicating a deep to shallow water deposition. The presence of the ammonites locally in the upper part of the Shelikof formation indicates that there is an open marine environment throughout the formation (Detterman *et al.*, 1996). The Shelikof formation

is recognized in the subsurface of the Cathedral River 1 well along with the Painter Creek 1 well (not considered in this study; Finzel *et al.*, 2005).

The Shelikof Formation reservoir quality is overall low. This is indicated by the samples from the formation from Helmold *et al.*, (2005) that indicated low porosity and low permeability. In addition, the presence of abundant volcanic rocks fragments and the relatively deep burial are indications that there is loss of porosity as a result of alteration of volcanic lithics through the compaction and diagenesis. The result of the burial deep is high for compact matrix and ductile grains (Wilson *et al.*, 2015).

There appears to be seal potential in the Shelikof formation because of the limestone nodules on the geometry of the brownish gray siltstone. The compaction and the diagenesis of the volcanic lithic grains degrading reservoir quality may also be helping the hydrocarbon barrier or seal (Wilson *et al.*, 2015).

### **3.6 Naknek Formation (Upper Jurassic, Oxfordian–Tithonian; 165–145 Ma)**

The Naknek is conformable with the overlying Staniukovich Formation and unconformably overlies the Shelikof Formation (Decker, 2008). The Jurassic age Alaska-Aleutian Range batholith was the main source of sedimentary debris for the Naknek Formation. From faunal evidence, USGS, the Naknek Formation ranges in age from about 163.5 to 145 Ma; hence, uplift and erosion of batholith occurred during and shortly after emplacement.

On lithology, the Naknek Formation is divided into five sub-members; this subdivision was not applied in the assessment of this formation within this study. The formation attains thickness that is approximated to be about 3,205 meters in Alaska Peninsula. Some of the

members include is the Indecision Creek Sandstone Member which is a medium gray fine or arkosic sandstone and siltstone. This member was found by unaltered biotite and hornblende. The other member is the Northern Creek Sandstone. It consists of light gray arkosic sandstone that is cross-bedded in certain localities and it contains magnetite laminae and other thin beds of conglomerate locally. The surface of Naknek Formation is usually recognized in the Painter Creek 1 well and Cathedral River 1 well (Finzel *et al.*, 2005).

The depositional environment of the Naknek Formation is made up of the shelf sequences that range from the shore face to the starved deep basin and fan delta environments. The Naknek Formation rapid facies changes are caused by the rapid uplift and erosion that occur from the Alaska-Aleutian Range batholith.

The Naknek Formation reservoir quality is low within conventional oil and gas reservoirs, but having a moderate quality within its tight gas sandstones. This is seen in the permeability and porosity analysis of many Naknek Formation outcrops samples that indicate that they have low porosity and permeability (Helmold & Brizzolara 2005). Which is caused by the extensive zeolite alteration in majority of the areas thus indicating a lower reservoir quality (Helmold *et al.*, 2008).

Naknek Formation seal potential is indicated by the availability of the unaltered biotite and hornblende grains, which show that the burial of the formation may have been greatly affected by the diagenesis and compaction of the individual conglomerate and sandstone sequences. This indicates that there are different areas that show that porosity is locally preserved (Finzel *et al.*, 2005).

### **3.7 Staniukovick Formation (Lower Cretaceous, Berriasian; 145–139.8 Ma)**

The contacts between the Staniukovick Formation surrounding units has only the upper siltstone interval that is prone to weathering to form distinctive red-brown slopes found in the Bays. The Staniukovick formation is found in David River 1A and Hoodoo Lake 2 wells (Finzel *et al.*, 2005).

Lithologically, the Staniukovick Formation is conformable to the Naknek Formation as well as conformable with its underlying Herendeen Formation. This section consists of a light gray olive siltstone containing two sandstone intervals that are overlain by a siltstone that is made up of various calcareous nodules and other concretions (Detterman *et al.*, 1996).

The Staniukovick Formation depositional environment indicates that the sandstone intervals are genetically similar to those that are found in the underlying Naknek Formation. Reservoir potential for Staniukovick Formation has lower potential because they are similar to that of the Naknek Formation (Wilson *et al.*, 2015).

Bolger & Reifenhohl (2008) analyzed four samples for the seal potential. The results indicated that the lithology ranged significantly from siltstone, sandstone and argillaceous sandstones, and indicates that two of them had a Sneider Type B and two had Sneider type C seals. This suggested that the Staniukovick Formation is made of moderate marginal sealing potential (McLean, 1977).

### **3.8 Herendeen Formation (Lower Cretaceous, Valanginian–Hauterivian; 139.8-125 Ma)**

The contacts between Herendeen Formation surrounding units has a conformable contact with the underlying Staniukovich Formation and an unconformable contact with the overlying Chignik Formation. The Herendeen Formation, formerly known as the Herendeen limestone because of its exposure in the Herendeen Bay, it is actually an unusually uniform calcarenaceous sandstone. This formation is found within hot springs southwest of Port Moller, as well as, found within the David River 1 and the Hoodoo Lake 2 wells (Wilson *et al.*, 2015).

The lithology for the Herendeen Formation indicates that it is made of the thin beds of uniformly grained medium grained calcareous sandstones that are made up of *Inoceramus* fragments (Decker *et al.*, 2008). The Herendeen Formation depositional environment is within a shallow marine. There is little evidence of the reservoir quality within the samples collected and studied by Helmold *et al.*, (2005). However, it is possible to develop secondary porosity due to the high calcite content. The Herendeen Formation is made of moderate marginal sealing potential (Finzel *et al.*, 2005).

### **3.9 Chignik Formation (Upper Cretaceous, Campanian–Maastrichtian; 83.6–66 Ma)**

The Chignik Formation unconformably overlies the Herendeen Formation, in some places as well as the Staniukovich and Naknek Formation (Detterman *et al.*, 1996). It conformably interfingers and underlies the Hoodoo Formation. Where it does not interfinger it is unconformable with the overlying Tolstoi Formation. This is because, even though they are time-equivalents, the two units (Chignik and Hoodoo Formations) are in contact, the Hoodoo

Formation conformably overlies the Chignik Formation, with indicates a generally transgressive sequence (Detterman *et al.*, 1996).

The dominant lithology of Chignik Formation consists of the interbedded sandstones, siltstones and conglomerates that contain chert, granitic, minor volcanic clasts and quartz (Detterman *et al.*, 1996). The depositional environment contains cyclic, nearshore-marine, tidal-flat and nonmarine floodplain and fluvial deposits. There is also Chignik Formation equivalent non-marine coal beds, Coal Valley Member, around 2 m thick that are located within Herendeen Bay area. The Chignik Formation is ultimately made of shallow water facies that are equivalent to the deep-water turbidite depositional sequence that is found in Hoodoo Formation (McLean, 1977).

Reservoir potential for the Chignik Formation is noted to have nominal gas and oil reservoir potential, but none were observed in this study. The formation is found within David River and Hoodoo Lake 2 wells. The source and seal potential for the Chignik Formation has coals within the Coal Valley Members that could be potentially be a great source of the thermogenic or biogenic gas (Wilson *et al.*, 2015), this however is not supported by this study because no coals of the Coal Valley Member were encountered.

### **3.10 Hoodoo Formation (Upper Cretaceous, Campanian-Maastrichtian; 83.6–66 Ma)**

This formation was named by Burk (1965) for its exposures southeast of Hoodoo Mountain between Herendeen and Pavlof Bay. The upper contact between the Hoodoo Formation and the Tolstoi Formation is disconformable, although it is known to be to be structurally conformable in various areas. The lower contact is unconformable to the underlying

Herendeen Formation. Within the Port Moller and Herendeen Bay area the Hoodoo and Chignik Formations are observed to interfinger each other, along with the Coal Valley Member.

The Hoodoo Formation lithology, is made of the thin bedded splintery shale, fine grained sandstone and siltstone all found in the upward shelfal succession. This indicates a coarsening upward lower slope turbidite succession (Detterman *et al.*, 1996). Ergo, the depositional environment shallows from a lower slope into a shelfal succession.

The formation appears to have a minimum oil and gas reservoir potential as seen through outcropping near Herendeen Bay. No information of reservoir or seal has been analyzed.

### **3.11 Tolstoi Formation (Lower Tertiary, Eocene; 59.2–23.03 Ma)**

The lower contact of the Tolstoi Formation is that of a major unconformity with the Naknek, Staniukovich, Chignik and Hoodoo Formations throughout most of the Alaska Peninsula (Detterman *et al.*, 1996). The upper contact is disconformable with overlying units.

In the Tolstoi Formation the lithology comprises mainly of sandstone that is grading upwards. Sandstone intervals tend to be massive or thick bedded, medium grained while, siltstone section are thin bedded. The clast content of the conglomerates and sandstones are highly granitic and arkosic, being of weathered volcanics. This suggests a Mesozoic source comprising the formation. The Tolstoi Formation also contains a significant amount of carbonaceous mudstone. It is found in the Sandy River 1, Hoodoo Lake 2 and David River 1A wells (Finzel *et al.*, 2005).

The depositional environment for the Tolstoi Formation onlaps the underlying Mesozoic rocks, suggesting a shallow water marine environment. To the northern part of the Chignik Bay



the formation is a non-marine environment that consist of the coarsening upwards through the shallow marines deltaic sequences which also grades into the non-marine braided fluvial, flood plan deposits, and delta plain (Wessel & Kroenke, 2008).

The Tolstoi Formation reservoir potential is observed to be good within the channelized sandstone and conglomerates within the formation; however, the reservoir potential is dependent of the extent of degradation and the diagenesis of the volcanic lithics present. The Tolstoi Formation contains higher quantities of arkosic and granitic clasts than has been observed within the other formations present amongst the Alaska Peninsula formations (Wessel & Kroenke, 2008). However, the quality of these higher-level quantities of sandstone and granitic clasts depends on the amount of the diagenesis that has taken place in the depth of the burial. Hence, the Tolstoi Formation is a potential reservoir within the sections that contain marine sandstone and braided stream channels as opposed to sections that do not contain those characteristics. According to the Helmold *et al.*, (2008), poor reservoir quality is indicated. However, the samples also indicated the Tolstoi Formation to be a good seal. The fact that the Tolstoi Formation contains carbonaceous mudstones could indicate that there is potential for oil. Within my study area the Tolstoi Formation shows a generation potential from fair to good and will generate both oil and gas.

As for the seal potential, five samples collected from the Tolstoi formation were taken through a seal potential analysis by the ANDR (2014). From the five samples, the three claystones were found to have Sneider Seal type A this indicates that it has a great seal potential. The fourth sample was classified as the Sneider type D and the last one was organic rich classified as Sneider type D. The existence of a large variety of Sneider is an indication that the Tolstoi formation may be a good sealing rock in several areas (Bolger & Reifenstuhel, 2008).

### 3.12 Stepovak Formation (Lower Tertiary, Oligocene; 38–23.03 Ma)

The contact between the Stepovak Formation and its overlying Unga Formation is disconformable, while its lower contact is structurally conformable with the Tolstoi Formation, but when it comes to stratigraphically; it is disconformable. The Meshik Volcanics, not observed in this study area, is interbedded and contains reworked volcanoclastic rocks within the Stepovak Formation (Detterman *et al.*, 1996).

The lithology for Stepovak Formation has been subdivided into the lower and the upper members. The lower member is made up of the coarsening upward sequences that are of the laminated shale, siltstone, and sandstone, having graded bedding and rip-up clasts (Bolger & Reifentstahl, 2008). The upper member is made up of the abundant unaltered volcanic rocks that are found on the shallow-water marine environment (30- 50 meters) regarded as shelfal. The Stepovak Formation is found in the Sandy River 1, Hoodoo Lake 1 and 2 (Wilson *et al.*, 2015).

Reservoir quality for the Stepovak Formation is usually moderately sorted, but over all it is considered to be poor. This is know from samples taken from the North Aleutian Shelf COST 1 well that show a porosity range from 17% to 33% and a permeability of more than 1000 md (Helmold *et al.*, 2008). The Stepovak Formation is known to have a high abundance of volcanic rock fragmentation. The existence of the Meshik Volcanics within various horizons of the Stepovak Formation would have caused areas of heat and contact metamorphism where the two formations met. Where the Stepovak and the Meshik do not meet, diagenetic alteration of the volcanic rock fragments present within the Stepovak Formation along with compaction as a result of burial, would reduce the primary porosity and permeability of the unit (Manuszak *et al.*, 2007). The seal potential for the Stepovak Formation with two samples analyzed and plotted as

Sneider C seals, indicating the Stepovak functions as a good seal, potentially for the underlying Tolstoi Formation (Bolger & Reifenhuth, 2008).

### **3.13 Unga Formation (Upper Tertiary, Miocene; 23.1–11.62 Ma)**

The contacts of the Unga Formation according to Detterman *et al.*, 1996 are not well defined, neither the top nor base of the formation are exposed, and, therefore, its relation to other units is not clear-cut. However, because Unga Formation has similar structural features as the underlying and overlying units, it can be discerned that the Unga Formation disconformably overlies the Stepovak Formation and is disconformable in most localities, but also conformably overlain by the Bear Lake Formation.

The Unga Formation is composed of  $\geq 25\%$  volcanic rocks. These include tuff, lahar deposits and debris-flow deposits. Volcanic rocks are dominant in the upper part, whereas carbonaceous shale and coal are restricted to the lower part of the unit; sandstone and conglomerate throughout unit are composed of poorly sorted and typically loosely consolidated volcanic debris. The formation was deposited within a shallow-marine to non-marine, siliciclastic environment. The Unga Formation contains substantial thicknesses of good reservoir sandstones and conglomerates. No regional seals have been identified to date.

### **3.14 Bear Lake Formation (Upper Tertiary, Miocene; 11.6–5.3 Ma)**

The lower contact of the Bear Lake Formation is either overlying the Meshik Volcanic and the Tolstoi and Stepovak Formations, with the majority of the contacts being disconformities

and very few have angular unconformities. As for the upper contact, the Bear Lake Formation is overlain by the Milky River Formation with a disconformable contact and can, in some localities be an angular unconformity (Bolger & Reifenhuth, 2008).

The pronounced lack of volcanic debris and abundance of fossils distinguish the Bear Lake Formation lithology. In addition, the sand grains are also moderately sorted and properly rounded compared to those in the underlying Tolstoi and Stepovak Formations. This means that the Bear Lake Formation has a greater percentage of quartz and chert, comparatively to the other formations observed within the Alaska Peninsula.

Depositional environment for the Bear Lake Formation consist of inner-neritic marine shelfal and non-marine, along with tidal deposits (Helmold *et al.*, 2008). The reservoir quality for the Bear Lake Formation is considered to be good but it varies with grain size and sorting of the varying amount of detrital silt and clay. The grains are highly enriched by the sedimentary grains, monocrystalline quartz, plagioclase, and chert. There are areas of the Bear Lake Formation that contain clay minerals that are present as individual laminae or it is dispersed within the rocks fabric. There is no significant cementation of the sandstones and the formation is made up of distinct and well-sorted layers of sandstones. This results in the Bear Lake Formation being a good potential reservoir rock (Wessel & Kroenke, 2008).

Source and seal potential for Bear Lake Formation is described by Decker (2008) and in his analysis he discovered that there are coals found within the Bear Lake Formation that may have a marginal capacity to generate oil. However, the formation contains a high matrix adsorption, this would limit the expulsion efficiency thus reducing its significance as a tertiary source oil accumulation for the Alaska Peninsula (Finzel *et al.*, 2005). There were eleven outcrops samples collected by Bolger & Reifenhuth (2008) that contained distinct laminated

fabrics. In the analysis four samples were found to have Sneider Type A, three had Sneider Type C, another two has Sneider Type D, and one Sneider Type E and another which was not considered to be a seal, but a reservoir rock. The outcomes of the analysis of the samples indicated that the Bear Lake Formation is an effective seal as well as a reservoir (Bolger & Reifentstahl, 2008).

### **3.15 Milky River Formation (Upper Tertiary, Pliocene; 5.3–1.81 Ma)**

The Milky River Formation unconformably overlies Bear Lake Formation, with some contact shows of disconformities and angular unconformities (Decker, 2008). The overlying younger volcanic flows and surficial deposits form an unconformable contact.

The Milky River Formation is of variable thickness (but about 600 m at thickest) and consists of volcanogenic, nonmarine sedimentary rocks and interlayered flows and sills; volcanic rocks are thicker and more abundant stratigraphically upward within the formation (Detterman *et al.*, 1996). The lower part of formation contains coarse, highly crossbedded and channeled, fluvial volcanoclastic sandstones and cobble-boulder conglomerates. Rocks within the formation are poorly indurated and have clasts composed almost entirely of volcanic debris. Within the upper part of the formation numerous porphyritic andesite flows, lahar deposits, and tuff beds are present and are interlayered with sedimentary rocks. Volcanic rock clasts in lahar deposits are observed to be  $\geq 2$  meters in diameter.

Depositional environment for the Milky River Formation is made of the non-marine fluvial system that has thick pebble to boulder sizes that has filled the braided fluvial channels. The upper section of the Milky River Formation fines upwards and has channelized crossbedded

sandstones that are made of the fluvial volcanic sandstones (Bolger & Reifenhuth, 2008). The sandstones are predominantly made of the coarse-grained volcanic rocks debris including plagioclase, heavy mineral, and quartz and detrital matrix. It overall has good porosity (Helmold *et al.*, 2008).

Reservoir potential for the Milky River Formation has both high porosity (35%-40%) and permeability (100 md). The presence of abundant volcanic rock fragments and other heavy minerals make it an immature reservoir rock (Helmold *et al.*, 2008). The Milky River Formation may be a reservoir for biogenic gas generated within the underlying Bear Lake Formation that has migrated into the Milky River Formation.

Overall the Milky River Formation has very little organic material, making it a poor source rock (Bolger & Reifenhuth, 2008). The seal potential for the Milky River Formation is considered to be significantly poor (Finzel *et al.*, 2005). No samples have been analyzed to confirm this. But its lack of seal is because the formation does not have a continuous siltstone or shale layers. On the other hand, the overlying deposits may not be possible to become seal potential for gas reservoirs in the Milky River Formation (Helmold *et al.*, 2008).

## **CHAPTER 4 EXPLORATION WELLS**

### **4.1 Overview**

In effort to investigate the petroleum systems that are located within the Alaska Peninsula, twenty-seven exploratory wells were drilled and wireline data were acquired from these locations. This study uses data from seven wells located within the Port Moller area (Fig. 2). These wells were chosen because little to no evaluation has been conducted from the data acquired, although they were among some of the most promising wells within the peninsula (Table 1).

### **4.2 Cathedral River 1**

The exploration well Cathedral River 1 is located 0.6 mile (1 km) from the coast of Bristol Bay and drilling started on June 20<sup>th</sup> 1973 and was completed one year later on 13<sup>th</sup> August 1974 (Burk, 1965). The well was drilled to a depth of 14,301 feet (4,358.9 m) on the northwestern slope of Black Hills Uplift and was drilled to a depth of 14, 301 feet (4,358.9 m) penetrating the thick Mesozoic sequence in the region.

Despite the fact that the Black Hills Uplift contains the outcrops of the southern Naknek Formation and that there is a possibility this well being included in a larger fault block, these possibilities cannot be proven due to the fact that the well was drilled from the middle of the Naknek Formation (Detterman *et al.*, 1985) downward.

Similarly, from the research and experiments carried out by McLean (1977) indicate that the sandstone found in the upper section of the Cathedral River 1 well 8,500 feet (2590 m)

Table 1: Table showing what well log data is available for wells. Well top and bottom depths for each well.

Well Log Data	Canoe Bay Unit 1	Sandy River Federal 1	David River 1/1A	Hoodoo Lake Unit 1	Hoodoo Lake Unit 2	Cathedral River Unit 1	Big River A-1
Top Depth	121 ft	255 ft	70 ft	141 ft	345 ft	178 ft	312.5 ft
Bottom Depth	6,642 ft	13,068 ft	13,769 ft	8,041 ft	11,243 ft	14,301 ft	11,370 ft
Gamma Ray							
Induction Electrical							
Dual Induction							
Microlog							
Sonic Log							
Mudlog							
Dipmeter							
Formation Density							
Neutron Porosity							
Directional							
Synthetic Seismogram							
Shale Density							
Geochemical Gas							



contain oil stains. According to Detterman (1990), this signifies oil presence in the region. Further, Turner (1988) indicated that the organic carbon content is low, averaging 0.20 percent, from test he carried out. However, samples taken at a deeper depth (>8,500 feet) show a higher percentage of organic carbon content. The percentage was found to be 0.68 despite the samples being contaminated with mud.

From the data obtained in the well, it is clear that diagenetic alterations to the pore space in the mineral grains have been significantly reduced (Mullen, 1987). Consequently, this reduces the formation of oil deposits in the source rock. On the contrary, the northeast side of Naknek Formation, within the sandstones, indicates that the rock formation in the region has not undergone major diagenetic alteration. Thus, the region is considered by Burk (1965) to be prospective for the production of oil as it contains thick, well-sorted, clean sandstones.

#### **4.3 Canoe Bay 1**

The drilling of Canoe Bay 1 well commenced in August 26<sup>th</sup> 1961. However, the well was later abandoned in October 26<sup>th</sup> 1963 at a depth of 6,642 feet (2,024.5 m). The well is located 1 mile (0.6 km) south of Canoe Bay. According to Reineck & Wunderlich (1968), within the Alaska Peninsula it is the only well drilled within entirely one formation. From the records, it was found that the lithology on which the well was drilled was the Hoodoo Formation. Nevertheless, the depth of the well drilled does not reflect the thickness of the formation.

According to Reineck & Wunderlich (1968), the well was drilled in a location that contained beds that were dipping steeply with the occurrence of some repetition of bed sections. From the well, the data collected indicated that some sections in the formation had six thick sand

bodies (Smith & Baker, 1924). Therefore, the well was not positioned in a geologically sound location (Mullen, 1987). Additionally, there were no significant data that were obtained from the well samples since the Hoodoo Formation contained highly fracture and steep dipping siltstone (Reineck & Wunderlich, 1968). The fracture siltstone could not form a sufficient location for accumulation of organic matter thus, reducing the chances of having oil deposits in the location.

#### **4.4 Big River 1A**

Drilling of Big River 1A well was initiated on September 21<sup>st</sup> 1976 and completed on March 25<sup>th</sup> 1977 reaching a total depth of 11,371 feet (3,466 m). The lithologies of the formations recovered from the well site contain various different sections according with depth. At 390 feet (119 m), the main material found was alluvium (Detterman *et al.*, 1985). Below that thick layers of tuff and also volcanic breccia were present characteristic of the Stepovak Formation, with possible interfingering of the Meshik Volcanics.

In addition, data from the well also indicated that Tolstoi Formation was underlying the Stepovak Formation. However, the samples from the log extracted from the well indicated that there was a presence of more tuff than normally observed in the formation (Burk, 1965). It should be noted that the presence of tuff is linked to coal hence suggesting that the underlying beds are clay, rather than tuff.

#### **4.5 David River 1/1A**

Drilling started on November 6<sup>th</sup> 1968 and was completed on July 31<sup>st</sup> 1969. The well is located on a glacial moraine, 5 miles (8 km) inland from Bristol Bay and 2.5 miles (4 km) north of David River. Drilling reached a depth of 13,769 feet (4,197 m). There are several interpretations of this well (Brockway *et al.*, 1975; McLean, 1977). Detterman (1990) identified a low-angle thrust fault at 12,575 feet (3,832 m), possibly calling for some repeated sections.

David River 1/1A is located on the glacial moraine of the Brooks Lake Glaciation, extending 650 feet (198 m) and form an unconformity over the Milky River Formation. The Milky River Formation then also forms an unconformity on top of the Bear Lake Formation at 1,375 feet (419 m). Both the Milky River and Bear Lake Formations are poorly indurated and no oil residue was noted.

#### **4.6 Sandy River 1**

The Sandy River 1 well was drilled 1.5 miles (2.4 km) on the south side of Sandy River and 8 miles (12.8 km) from the Bristol Bay coast. The drilling commenced on September 4<sup>th</sup> in 1962 and was completed by on December 3<sup>rd</sup> 1963. The formation on which the well was drilled was found to be a thick section of the Bear Lake Formation with a series of thin marine and non-marine clastic rocks (Hite, 2004). In addition, there is also an occurrence of duplication in the landform on the upper coal section from 4,450 feet (1356 m) and the lower section from 9,325 feet (2,842 m)(Barth, 1956). However, there is not enough evidence that shows the presence of duplication thus, it is considered as just a thick section.

A total of nineteen samples were taken from the well and tested by Hudson (1986). Porosity test showed that the sandstone from the well had porosity between 23.7% and 36.6%. In addition, permeability was found to range between 0.1 and 1,268 mD (Detterman *et al.*, 1985). However, from the samples below 10,000 feet (3048 m) it was found that there was oil stains present (Hudson, 1986). Hence, this alluded to the possibility of oil deposits present in the area. Further, the data from the well showed that rock characteristics below 10,625 feet (3129 m) were different. The rocks at this depth were found to be more mature and had a substantial amount of volcanic debris. Consequently, from the data collected on rock characteristics and formations showed that there was a chance of existence of oil deposit in the area.

#### **4.7 Hoodoo Lake 1**

Drilling started on Pan American Hoodoo Lake 1 on December 17<sup>th</sup> of 1969 and was completed on January 9<sup>th</sup> of 1970, drilling to a total depth of 8,049 feet (2,453 m). The well is located on a glacial moraine, due to this the upper 235 feet (72 m) of section was not logged, because it was presumed to be part of the glacial moraine. The first formation encountered was thin sequences of conglomerate sandstone, consistent with the Milky River Formation. Underlying is an abnormally thick sequence of the Bear Lake Formation, with no indication of formation repetition. Present are thick units of quartz-rich sandstone predominately containing conglomerates. Siltstone, shale, carbonaceous shale, and coal are interbedded with the sandstone. Fossils, marine mollusks, found within the formation tell that the Bear Lake Formation was deposited in a near shore -shore face and back-beach swamp environment. Around 7,000 feet

(2,133 m) the well encounters the Stepovak Formation, this is known from the volcanic-rich siltstone and shale that are encountered.

Hoodoo Lake 1 well shows no indication of oil generation, one of only two within the study area. Because of this the rocks are considered immature.

#### **4.8 Hoodoo Lake 2**

The Hoodoo Lake 2 well was spudded on February 13<sup>th</sup> 1970 and was completed on April 28<sup>th</sup> 1970, reaching a total depth of 11,243 feet (3,427 m). This well was drilled about 2.5 miles (4 km) northwest of the mountain front west of Herendeen Bay. These mountains are part of a major low-angle thrust fault block. Evidence of these faults is encountered at the bottom of the well, around 10,000 feet (3,048 m). This strongly suggests that the structure at the south end of the Alaska Peninsula is considerably more complex than farther north along the peninsula where open folds are prevalent. The recognition of this complex structure has major implications for petroleum exploration both onshore and in offshore areas.

The drill site sits on top of a glacial moraine, making up the first 350 feet (107 m) of sediment encountered within Hoodoo Lake 2. McLean (1977) has published a considerable amount of organic geochemistry data for the Hoodoo Lake 2 well. Most of the organic carbon is either woody or carbonaceous material that is more likely to produce gas rather than oil. Amorphous carbon is the main foundation for petroleum is not present in great quantity in the rocks within the Hoodoo Lake 2 well. The maturation index and vitrinite reflectance data indicate that only rocks of the Stepovak and older formations have reached the stage of oil generation (McLean, 1977).

## CHAPTER 5 METHODOLOGY

### 5.1 Stratigraphic Framework

In order to examine the stratigraphic framework of my study area, I used Petrel G & G software. I loaded the well data including well headers, deviations, and logs, into Petrel. Although there is no seismic collected in my study area (Fig. 9), there are seismic data that were collected in the region and that were used developing a basin evolution and stratigraphic framework. After the well log data were loaded, I focused on gamma ray (GR), spontaneous potential (SP), resistivity (ILD) and sonic (DT) logs as these logs were present in all the seven wells. Based on those logs, I picked out stratigraphic units, well tops, and horizons that are representative of the stratigraphic units in the area (Fig. 10). Seismic data was then used along with the well tops to correlate and generate a cross section.

Successful petroleum exploration relies on detailed analysis of the petroleum system, identification of potential source rocks, their maturity and kinetic parameters, and their regional distribution. This is best accomplished by using the Rock-Eval pyrolysis data. TOC measures the total carbon present, along with inorganic carbon. Combining both types of data provides information on the kerogen type, sedimentary environment, effective source rock identification, and thermal maturity. To use this data I graphed these parameters against each other within the wells for those from which I had data to do so (Figs. 11, 12, 13 and 14). 1) TOC (wt. %) versus depth to establish generation potential, using the parameters of the TOC values between: 0 – 0.5 (poor), 0.5 – 1 (fair), 1 – 2 (good) and 2-3 (very good). 2) Hydrocarbon Index (HI) (mg S<sub>2</sub>/g TOC) versus depth to establish the hydrocarbon type, using the parameters of HI values between:

0 – 150 (gas source), 150 – 300 (gas and oil source) and 300 – 500 (oil source) 3) TOC versus HI to give a more detailed analysis of expected hydrocarbon products and reflect other characteristics such as kerogen type, lithology, depositional environment, and maturity (Figs.15 and 16).

## 5.2 Thermal Modeling

In order to predict the thermal history at each of the drill sites I undertook a subsidence analysis backstripping exercise using the well data from each of those locations (Fig.17).

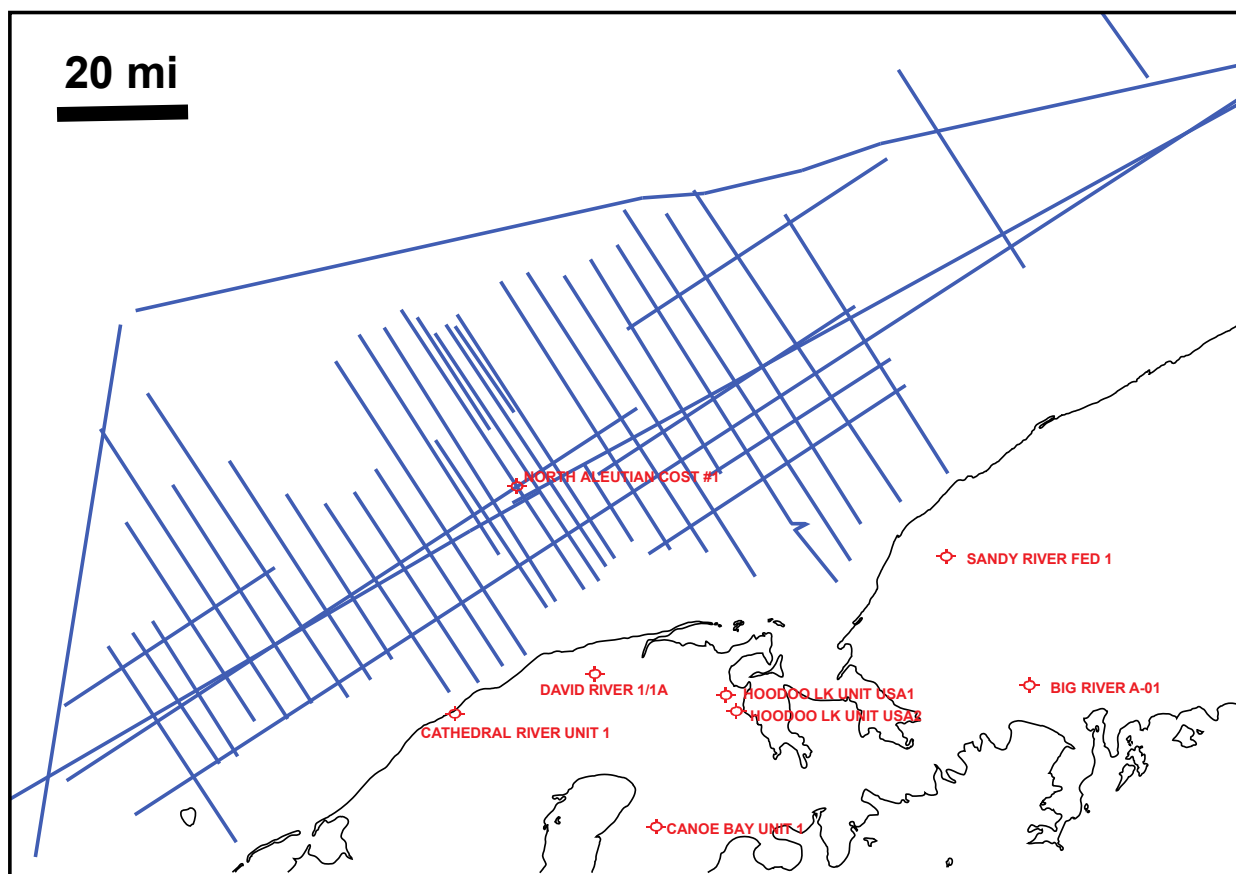


Figure 9: Publically available seismic datasets used in this study, converted to SEG-Y format by DOG as on component of digital data compilation and released (DOG, 2004).

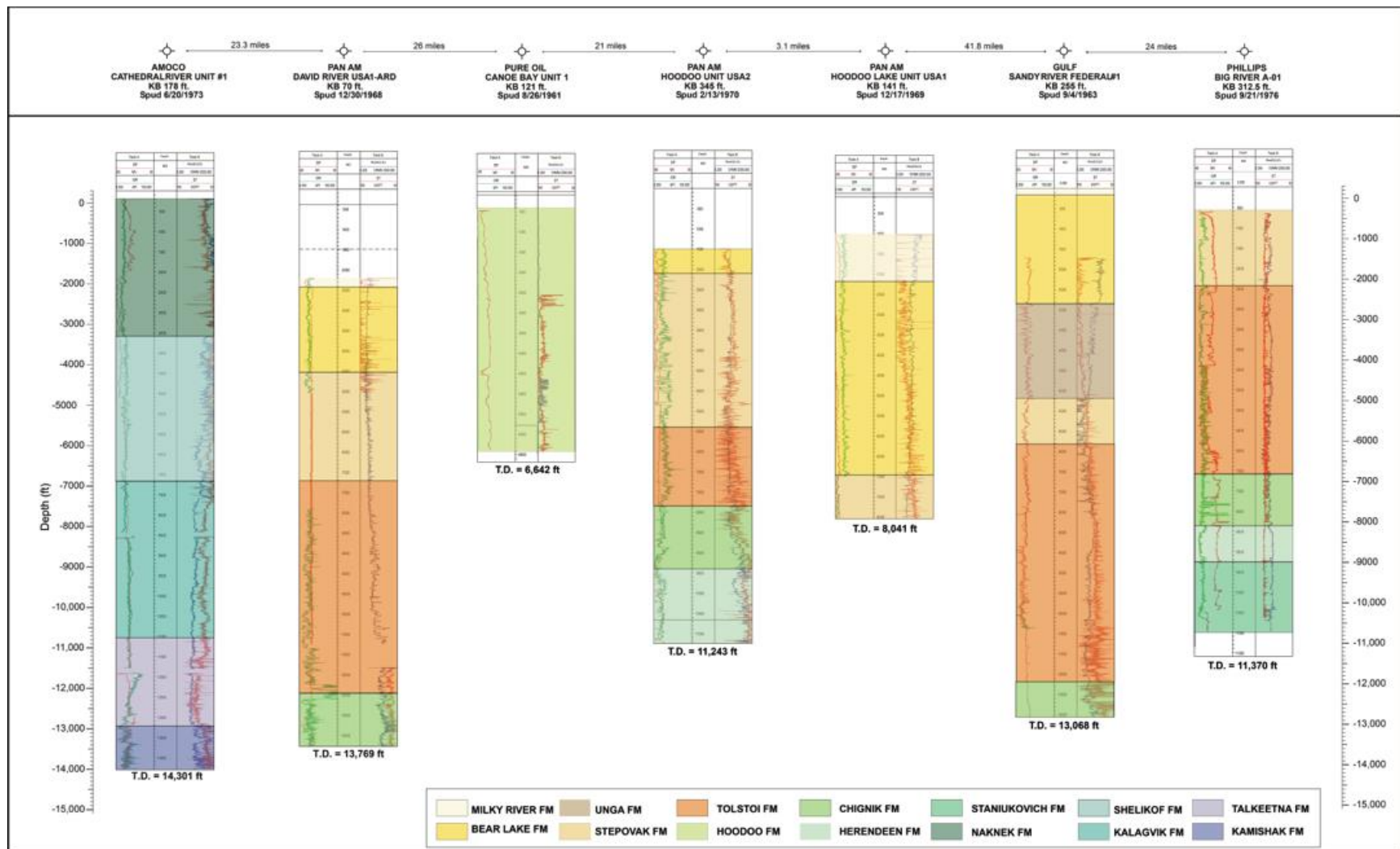


Figure 10: Spontaneous potential (SP), gamma ray (GR), resistivity (ILD) and sonic (DT) logs at each of the studied drill sites, together with the interpretation shown as color coding as indicated by the legend at the base of the figure.



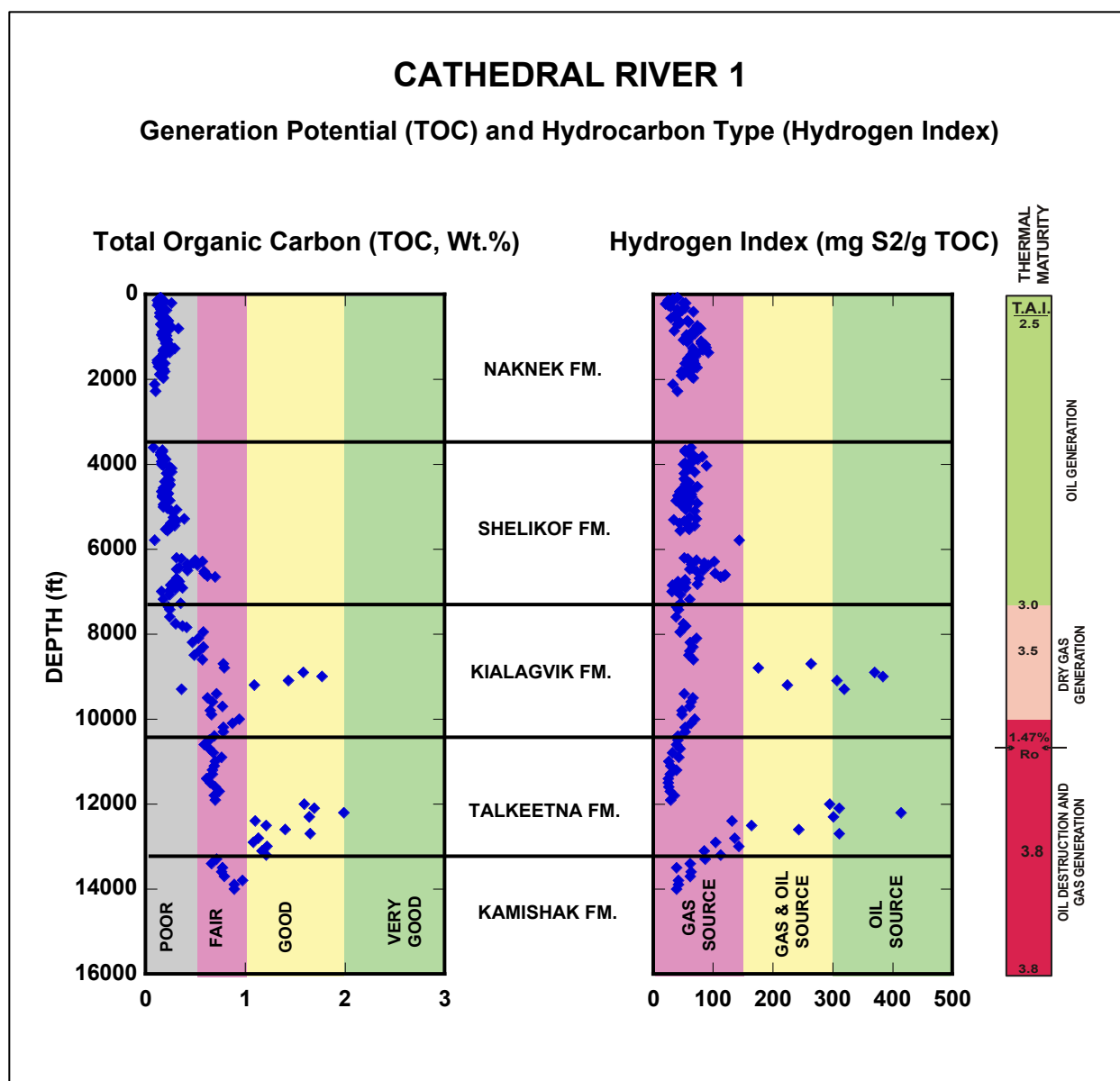


Figure 11: Generation potential (total organic carbon) and hydrocarbon type (hydrogen index) indicators for Mesozoic rocks in the Cathedral River 1 well. T.A.I. (thermal alteration index) data from Anderson *et al.*, 1977. Vitrinite reflectance data point at 10,650 feet bkb from Robertson Research (1982).

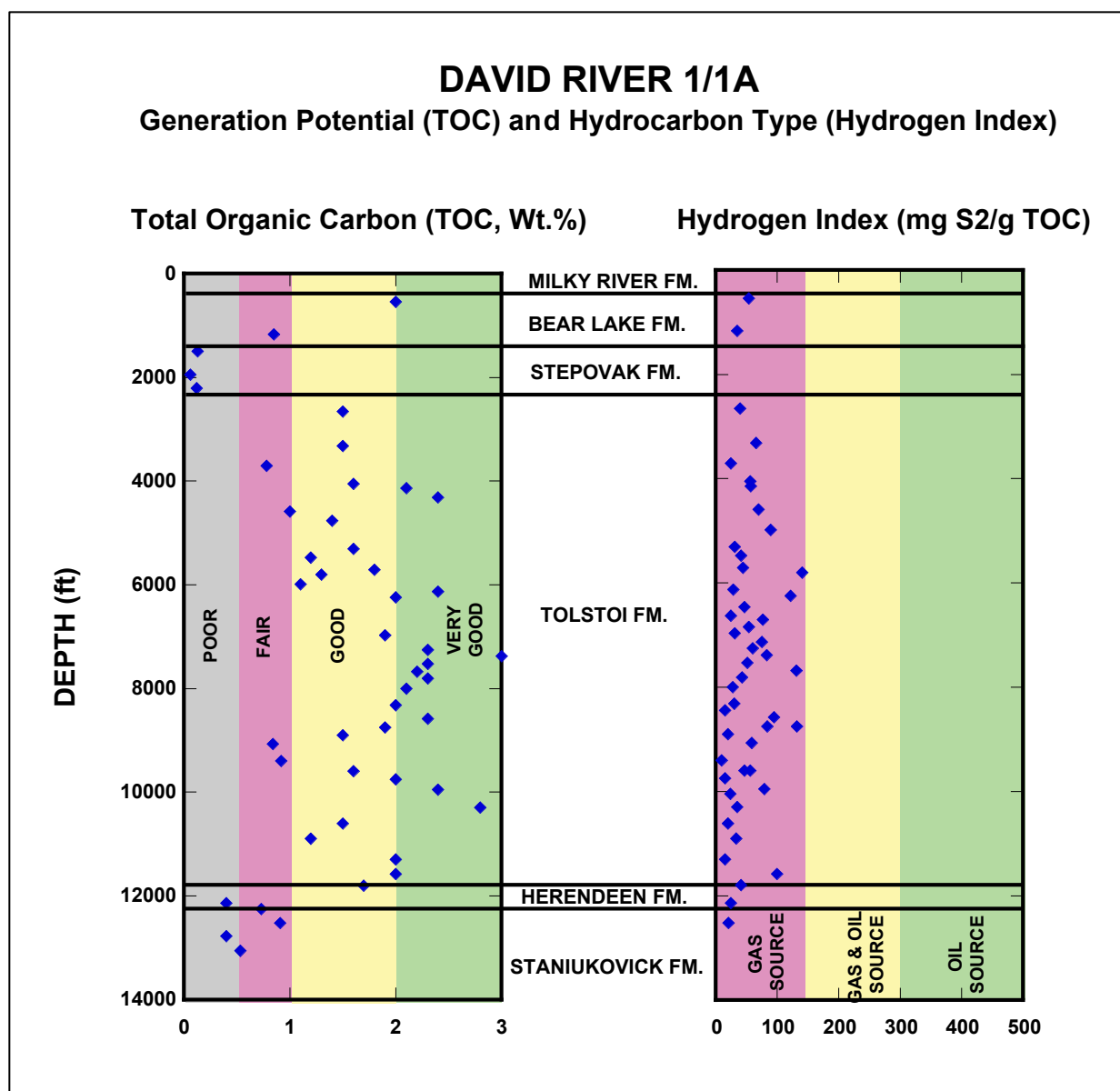


Figure 12: Generation potential (total organic carbon) and hydrocarbon type (hydrogen index) indicators for Mesozoic/Cenozoic rocks in the David River 1/1A well.

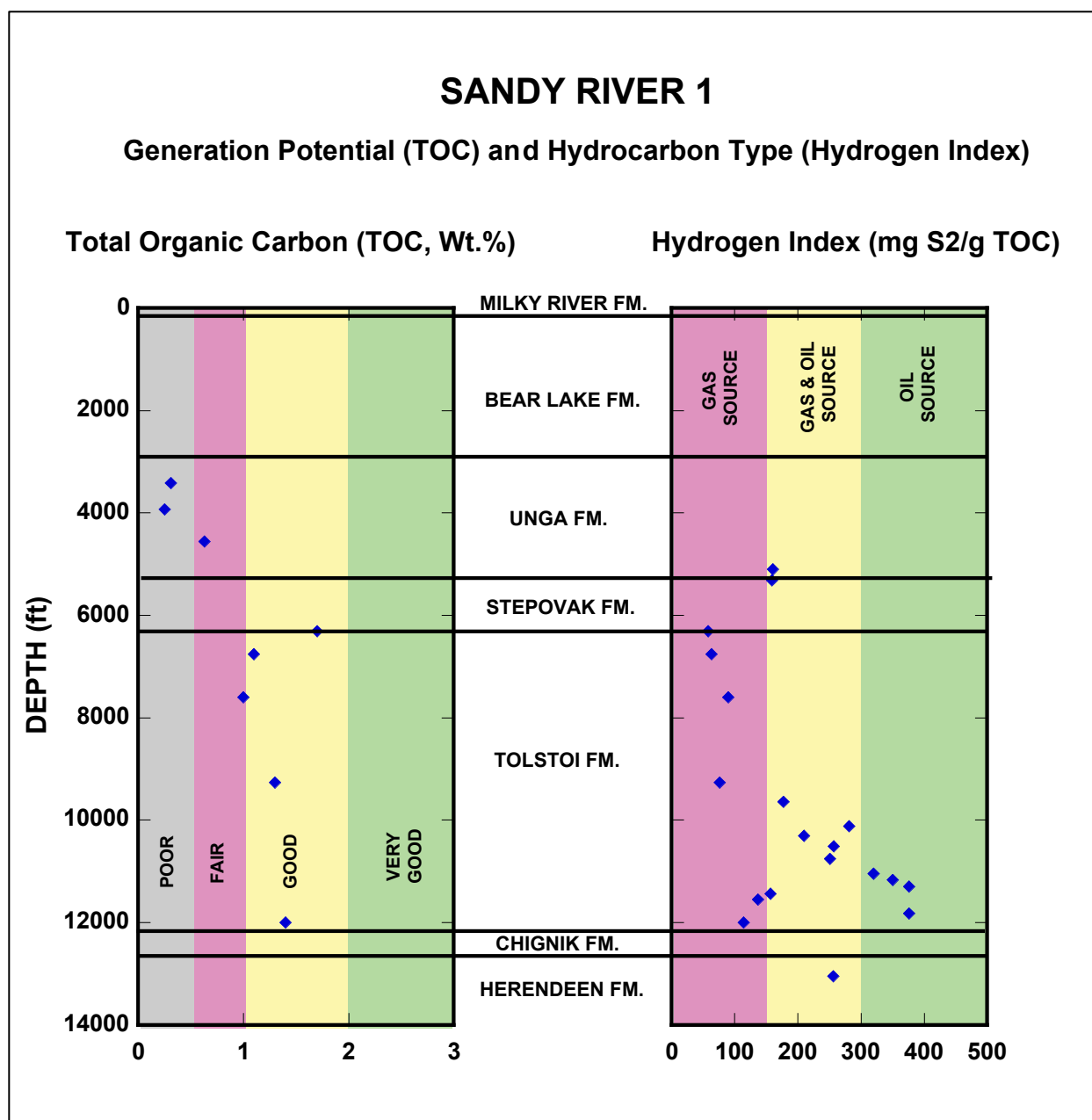


Figure 13: Generation potential (total organic carbon) and hydrocarbon type (hydrogen index) indicators for Mesozoic/Cenozoic rocks in the Sandy River 1 well.

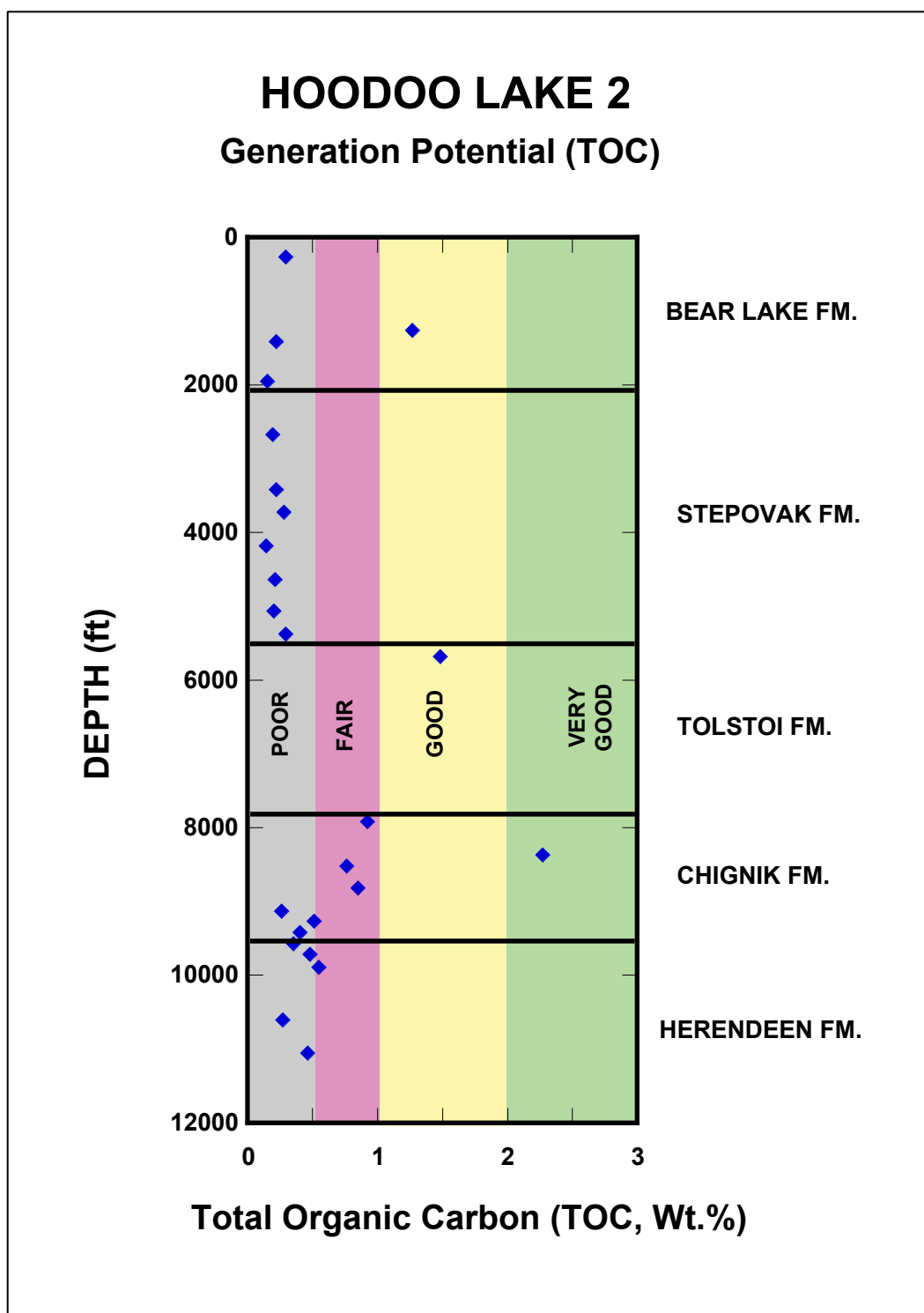


Figure 14: Generation potential (total organic carbon) indicators for Mesozoic/Cenozoic rocks in the Hoodoo Lake 2 well.

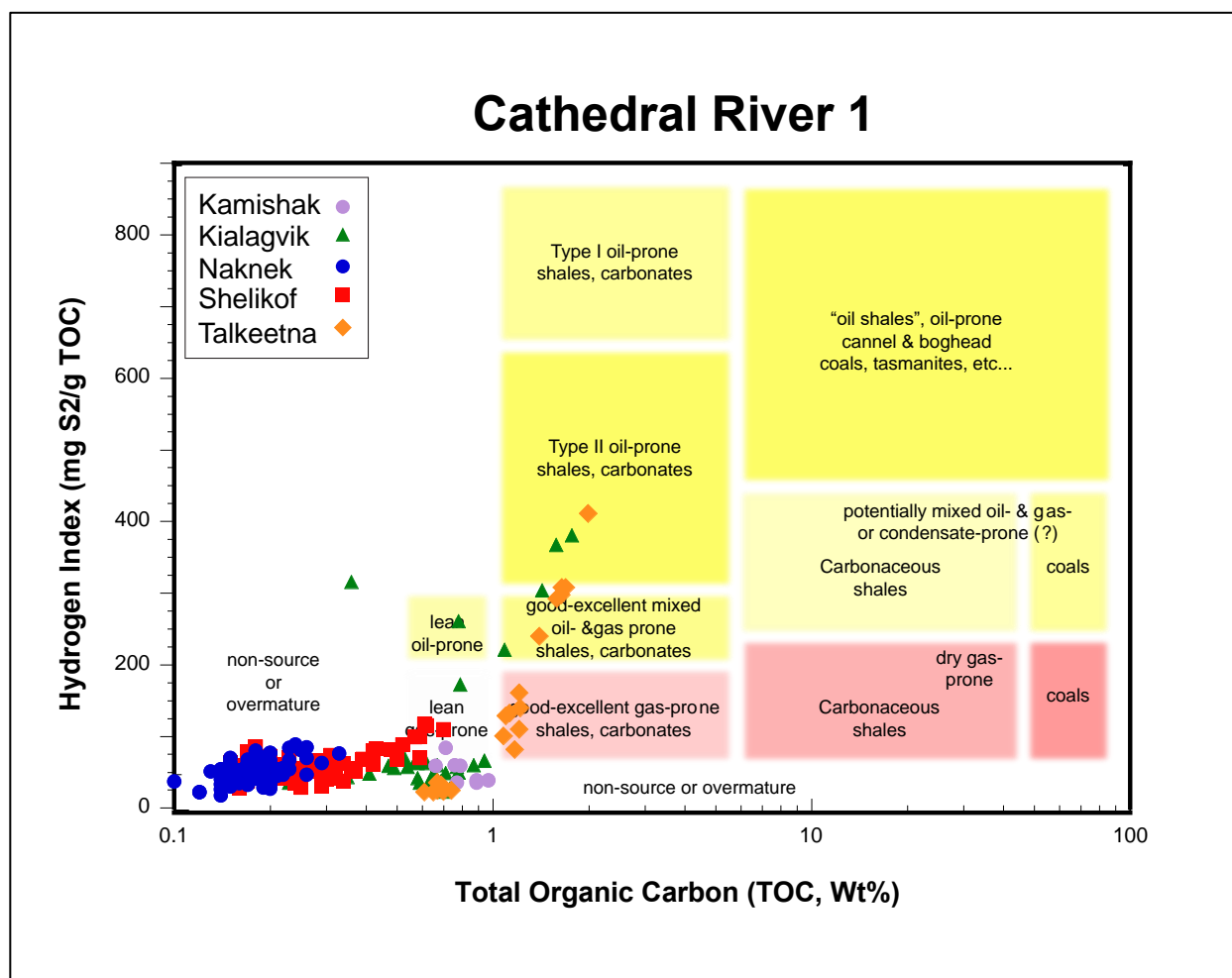


Figure 15: Both the quantity and type of organic matter are readily apparent in a plot of hydrogen index (HI) versus total organic carbon (TOC) for Cathedral River 1. Samples are plotted on loosely defined fields that suggest expected hydrocarbon products and reflect other characteristics such as kerogen type, lithology, depositional environment, and maturity. These fields are non-unique, and should be considered in light of other available information, particularly in the case of coals and other rocks containing coaly kerogens.

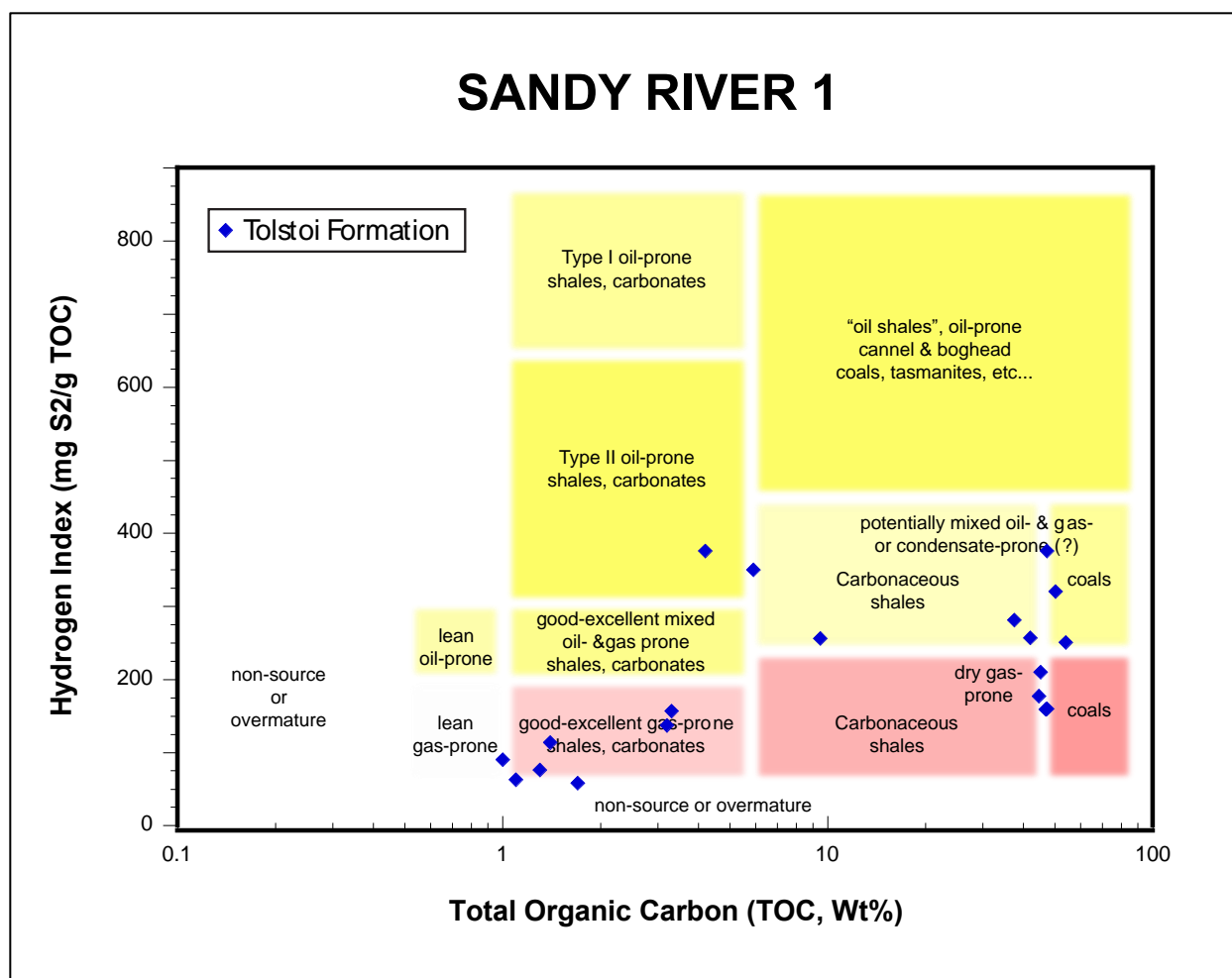


Figure 16: Both the quantity and type of organic matter are readily apparent in a plot of hydrogen index (HI) versus total organic carbon (TOC) for Sandy River 1. Samples are plotted on loosely defined fields that suggest expected hydrocarbon products and reflect other characteristics such as kerogen type, lithology, depositional environment, and maturity. These fields are non-unique, and should be considered in light of other available information, particularly in the case of coals and other rocks containing coaly kerogens.

Standard backstripping techniques were used, following the methodology of Sclater and Christie (1980) in order to separate sediment loading, water depth variations, sea level variability and tectonic substance the basement into the different components (Table 2 and 3). Because drilling in each location never reached the crystalline basement I extended the drilled section to basement by assuming that the underlying strata were the same as those drilled at the nearest well that did penetrate deep into the section, particularly Cathedral River 1, which encountered

the most complete section of Naknek and underlying formations. I treated the Triassic and older as essentially crystalline basement meaning that I did not have to consider the compaction of these units during the analysis of the section which is the focus of this study. It was important to account for these older formations because they have a considerable thickness, which would require a large amount of extension at the beginning of the basin's development during the Jurassic. Ignoring this earlier subsidence would have significantly reduced the predicted heat flow and led to large under prediction of the geothermal gradient.

Although the Bristol Bay area has recently been one in which compressional tectonics has dominated, resulting in the tilting and uplift of the stratigraphy on the south side of the basin, for much of its history this was a dominantly extensional basin as revealed by seismic reflection data. As a result I undertook a subsidence analysis of the basin assuming that extensional deformation alone was accounting for the subsidence observed to start around 170 Ma, Mid Jurassic. In order to undertake the subsidence analysis I used lithology, paleo-water depth and age data derived from a USGS report, which compiled drilling information from the different drill sites spread around the Bristol Bay area (ADNR, 2014). These lithology types were used to estimate compaction factors based on the values provided by Sclater and Christie (1980). When a given formation contained a mixture of different sediment types, I estimated an average value by pro-rating the percentage of each sediment type within the overall formation. No correction was made for eustatic sea level variation over the time of the basin's development, because this is poorly known and was of relatively small magnitude compared to the overall subsidence so that little uncertainty was introduced (Haq *et al.*, 1987).

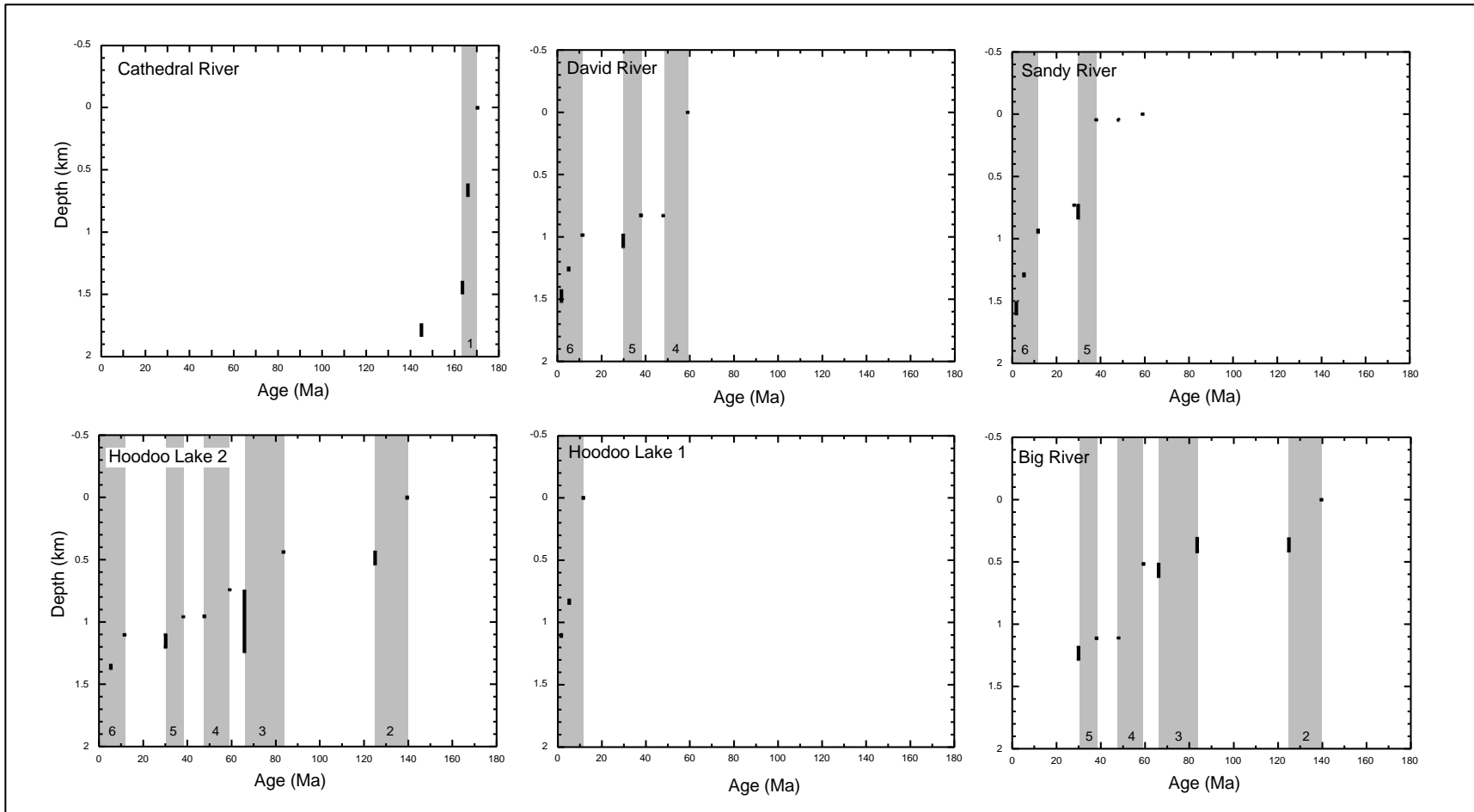


Figure 17: Results of backstripping analysis from drilling data at the six wells considered as part of this study. Vertical bars indicate uncertainties in paleo-water depth. The depth indicated the sediment unloaded depth to basement. No attempt was made to correct for sea level variation. Vertical gray shaded bars indicate periods of rapid subsidence associated with tectonic events numbered 1 to 6. Events 1 to 4 are associated with extensional deformation with the youngest was linked to periods of subsidence driven by thrusting within the Peninsula.



Table 2: Methodology of Sclater and Christie (1980) in order to separate sediment loading, water depth variations, sea level variability within each formation. Each formation is broken down into its composition percentages.

Top	Age of Surface	Age of Base	Conglomerate	Sandstone	Siltstone	Mudstone	Limestone	Volcanic	C	Phi	Water Depth Max	Water Depth Min
Milky River	1.8	5.3	15	50		5		30	0.176	28.5	100	0
Bear Lake	5.3	11.6	10	90					0.253	45.0	20	0
Unga	11.6	28.1	5	35	35	5		20	0.262	42.0	20	0
Stepovak	30	38	15	20	15			50	0.128	19.0	100	0
Tolstoi	48	59.2	10	40	45			5	0.294	47.0	0	-100
Hoodoo	66	83.6		10	40	45		5	0.413	60.5	500	10
Chignik	66	83.6	5	55	30	5		5	0.296	49.0	100	0
Herendeen	125	139.5					100		0.710	60.0	100	0
Stanlukovich	139.5	145		80	20				0.294	52.0	100	0
Naknek	145	163.5		35	30	35			0.390	60.0	100	10
Shelikof	163.5	166.1		15	15	50		20	0.354	51.5	100	0
Kialagvik	166.1	170.3		5	90		5		0.400	59.5	100	0
Basement	170.3											

Table 3: Each well's depth in meters where the following formations were encountered.

Top	Cathedral River Unit 1	Hoodoo Lake Unit 2	David River 1/1A	Sandy River Federal 1	Hoodoo Lake Unit 1	Canoe Bay Unit 1	Big River A-1
Milky River			0	49	0		
Bear Lake		0	741	890	666		
Unga				1587			
Stepovak		640	1341	1920	2123		119
Tolstoi		1770	2207	3762		0	747
Hoodoo		2400	3444	3813		1448	
Chignik							2175
Herendeen		2870					2574
Stanlukovich		3290					2850
Naknek	0						
Shelikof	1160						
Kialagvik	3050						
Basement	3660						

### 5.3 Subsidence Analysis

The results of the backstripping at the six drilling sites are shown in Figure 17 where the sediment unloaded depth to basement is shown. Six major subsidence events were reconstructed on the basis of this analysis of which the youngest two were interpreted to be the result of compressional deformation and thrusting, driving flexure of the foreland north of the peninsula. Seismic profiles show propagation of compressional thrust sheets northward into the basin at those times (i.e., 30–38 Ma and 11 Ma to the present) (Fig. 18). However, earlier subsidence events were attributed to extensional tectonics. In order to calculate the amount of extension and predict heatflow following each of the extensional events I assumed local isostatic equilibrium and applied the uniform pure shear extensional model of McKenzie (1978). Because each extensional event was less than 20 million years in duration I was able to satisfy the assumption of instantaneous extension implied by this model (Jarvis and McKenzie, 1980). For each subsidence event I measured the total amount of sediment unloaded subsidence during that extensional event and then applied this to the McKenzie model in order to estimate the total amount of extension, assuming equal amounts of crustal and mantle lithosphere extension ( $\beta$ ) (beta), where  $\beta$  was used to predict the thermal history using the same model.

I assumed that there was no significant extension, or other excessive heatflow, prior to the first extensional event starting at 170 Ma (Fig. 17). In order to calculate how each successive extensional event impacted the thermal history I calculated the additional amount of heatflow that would be derived as a result of the extra extension that occurred during each of the four tectonic events, essentially adding together the extra heatflow from each one in turn and allowing an exponential decay to occur following the cessation of extension. In doing so I follow the

normal procedure outlined by McKenzie (1978). This meant that every time there was an extensional event there was a sharp increase in the amount of heatflow, followed by an exponential decay until the next event. I assumed that this exponential decay continued during the compressional phase of activity, with no extra heatflow as a result of the flexural subsidence that began at 38 Ma.

After calculating the heatflow in milliwatts per meter squared ( $\text{mW/m}^2$ ) I assumed a thermal conductivity of 1.4 watts per meter-kelvin ( $\text{W}/(\text{m}\cdot\text{K})$ ) to convert the heatflow to a predicted geothermal gradient and in turn use this to calculate the depths to critical temperature windows in hydrocarbon generation. In particular, I estimated the 100 to 150°C window associated with oil maturation and 150–220°C associated with peak natural gas production.

## **5.4 Hydrocarbon Generation**

In order to estimate whether potential source rocks had ever reached maturation, or whether they had reached peak temperatures in the past, rather than the present day as normally assumed, I constructed a “Geohistory” diagram from the backstripping calculations to reconstruct how the thickness of the basin fill had evolved through time, including a compaction adjustment, and then superimposed the predicted depths to the 100°, 150° and 220°C isotherms on top of that. The Geohistory diagram was not used to try and look at vertical tectonics but simply at the accumulation history in the basin. I was able to check the accuracy of the predicted thermal model by comparing the present day temperature at the base of the well, as measured by downhole logging with that predicted from the calculations described above.

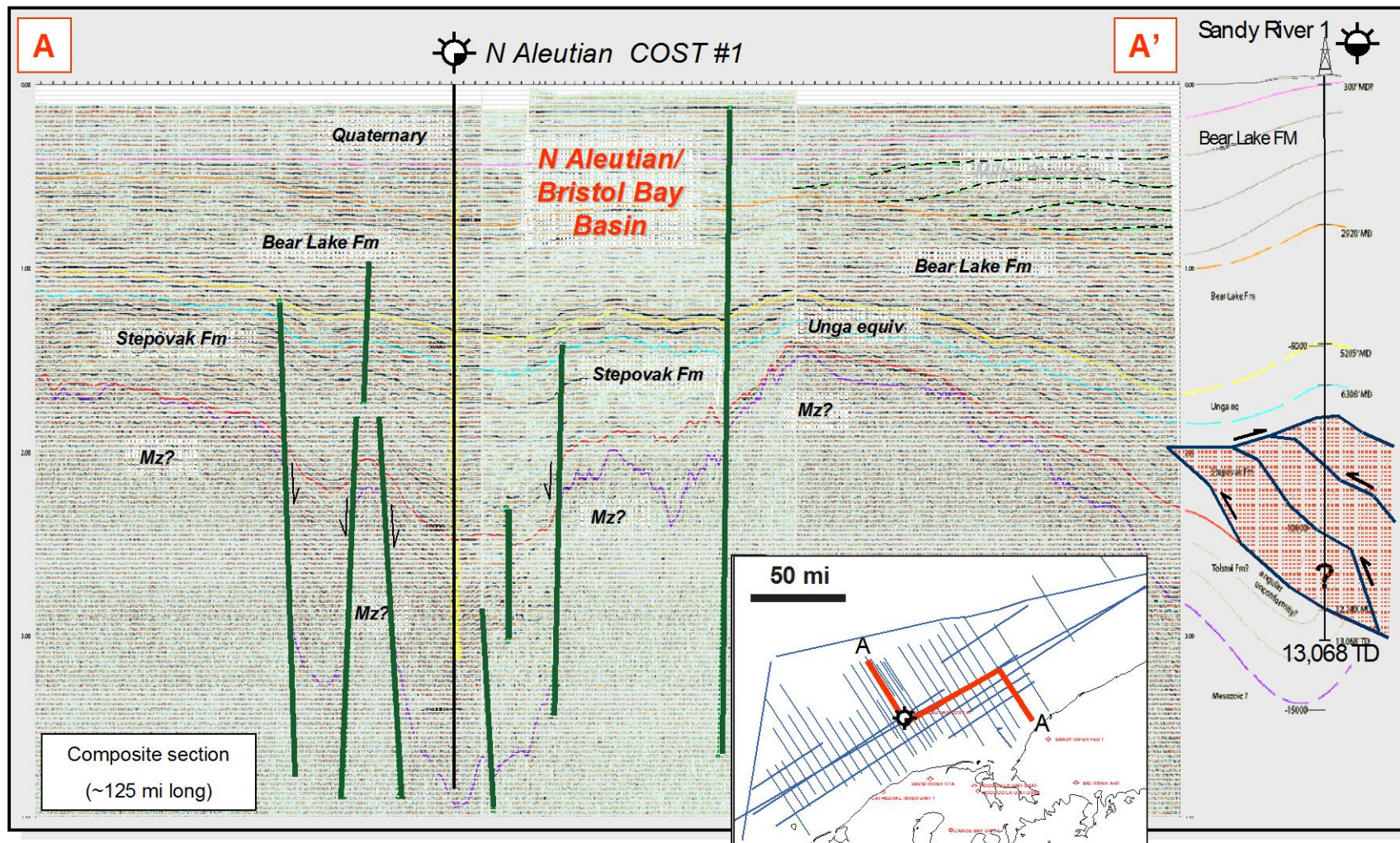


Figure 18: Representative seismic lines cutting through the Bristol Bay Basin on A-A' trends northwest-southeast through the North Aleutian Shelf COST 1 well to interpreted section to onshore Sandy River 1 well. Shows truncation of the Milky River Formation into the underlying Bear Lake Formation, reflecting prograding of the Milky River Formation. Modified from Decker (2009).

I focused my modeling efforts on three of the more complete sections spread across the Bristol Bay-Port Moller, i.e., at Hoodoo Lake 2, David River 1 and Big River 1A. The more limited stratigraphy recovered at the other drill sites to which I had access made them less useful for the prediction of the vertical tectonics and the development of the hydrocarbon system. In the case of these three targeted well sites my prediction was generally accurate within  $\pm 5^{\circ}\text{C}$ , giving me confidence that the assumptions that I had made were generally robust, at least within the overall uncertainties of the approach. Batir *et al.*, 2013 measure modern day well temperature values were used during this analysis as well to show accuracy within my predictions.

In the reconstructed Geohistory diagrams (Figs .19, 20 and 21) presented I removed the assumed lack of subsidence during the unconformity periods (shown in grey) that mark much of the geological history within the basin, because in practice it is not possible to say what the vertical tectonics were like during those times since no sediment was deposited that would allow motions to be tracked during those time periods. This was particularly important especially during the youngest two unconformities because it is during the last of these, between 30 and 11 Ma that the modern stratigraphy appears to have been buried and then re-exhumed, so that much of the section drilled reached peak temperatures during that time period. The present day temperatures at the base of the wells are mostly slightly cooler than those predicted on the basis of the vitrinite reflectance data collected from those wells. This suggests moderate amounts of basin inversion. I was able to estimate the amount of that inversion based on the scale of that mismatch between modern-day and maximum temperatures and assuming the geothermal gradient now measured in each of those wells.

An important exception to this approach had to be used at Big River where modern downhole logging records peak temperature of around  $220^{\circ}\text{C}$  at the base of the well (Batir *et al.*,

2013). This value is hard to accept because vitrinite data from the base of the well indicates a peak temperature of around 135–140°C. It is not possible for the modern temperature to be higher than the maximum temperature, otherwise the vitrinite should be reset to values of 220°C, which it is not. This very high value at the base of the well is moreover surprising because it is much greater than any values encountered in any of the other wells in this area. The highest geothermal gradient is otherwise 40°C/km at Canoe Bay, which is also on the south side of the peninsula. While that is not impossible it does imply extremely high geothermal gradients (64°C/km) in this one particular well (Batir *et al.*, 2013), although the setting is not especially unusual compared to the others, sitting along the southern edge of the Bristol Bay basin and not especially close to the active volcanoes. It is the mismatch between vitrinite and the modern well temperature data that suggests that this value is in error, or at least is not representative of the basin evolution over longer periods of time. In order to be more realistic I use a geothermal gradient of 35°C/km in making my predictions with the understanding that this might be in error should the elevated temperatures be substantiated by further research. However, in the current context these very high values are inconsistent with the other information I have from that area.

## **5.5 Organic Geochemistry**

Type I kerogen is hydrogen rich (atomic H/C of 1.4 to 1.6: HI of > 700) and is derived predominantly from zooplankton, phytoplankton, micro-organisms (mainly bacteria), and lipid rich components of higher plants (H/C ratio 1.7 to 1.9). Type II

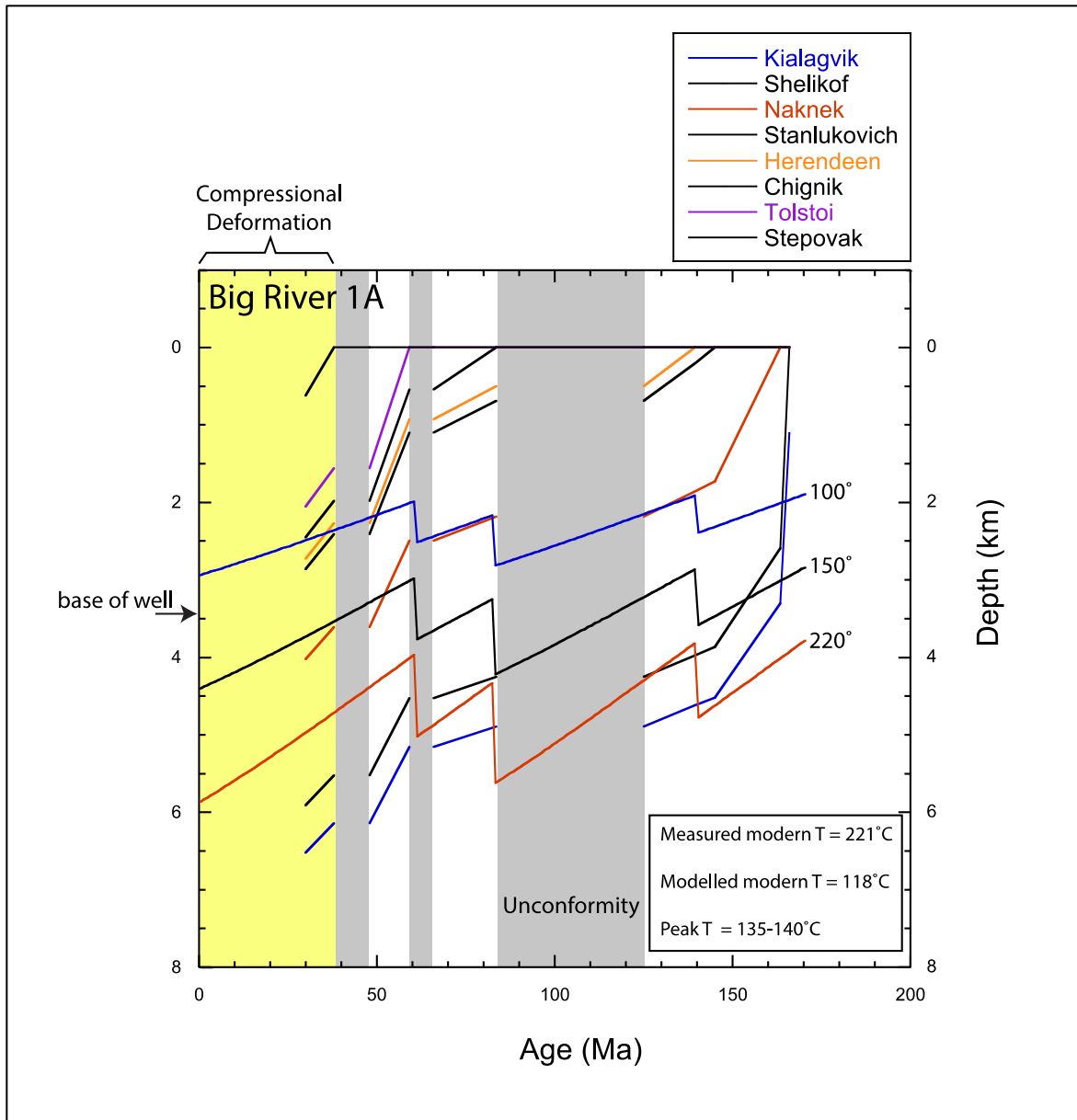


Figure 19: Geohistory diagram for the Big River 1A drilling site showing the depths to the tops of the different formations encountered in this well, along with the extrapolated underlying sequences derived from nearby locations. Isotherms are provided for the 100°C, 150°C and 220°C in order to define the rough limits of the oil and gas generating zone. Gray vertical bars indicate times of unconformity linked to times of uplift and erosion. The yellow shaded area on the left of the figure shows the time of compressional deformation linked northward thrusting along the coast of the Alaska Peninsula. An arrow along the Y-axis shows the depth of the drill site within the Stanlukovich Formation.



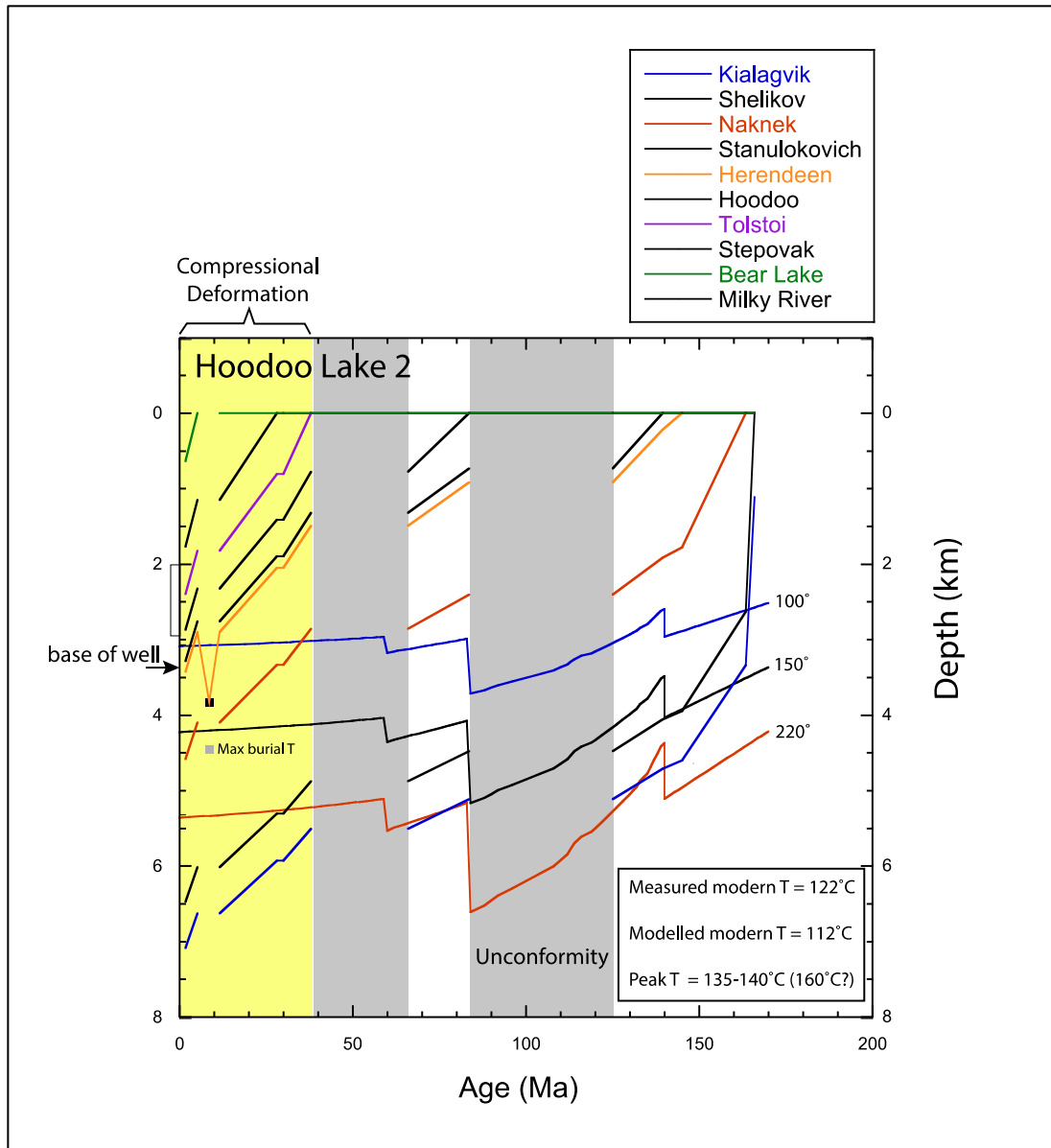


Figure 20: Geohistory diagram for the Hoodoo Lake 2 showing the depths to the tops of the different formations encountered in this well, along with the extrapolated underlying sequences derived from nearby locations. Isotherms are provided for the 100°C, 150°C and 220°C in order to define the rough limits of the oil and gas generating zone. Gray vertical bars indicate times of unconformity linked to times of uplift and erosion. The yellow shaded area on the left of the figure shows the time of compressional deformation linked northward thrusting along the coast of the Alaska Peninsula. An arrow along the Y-axis shows the depth of the drill site within the Herendeen Formation. Note the predicted deeper burial of the Herendeen during the Neogene and prior to more recent inversion when peak burial temperatures are predicted based on vitrinite reflectance data from the well.

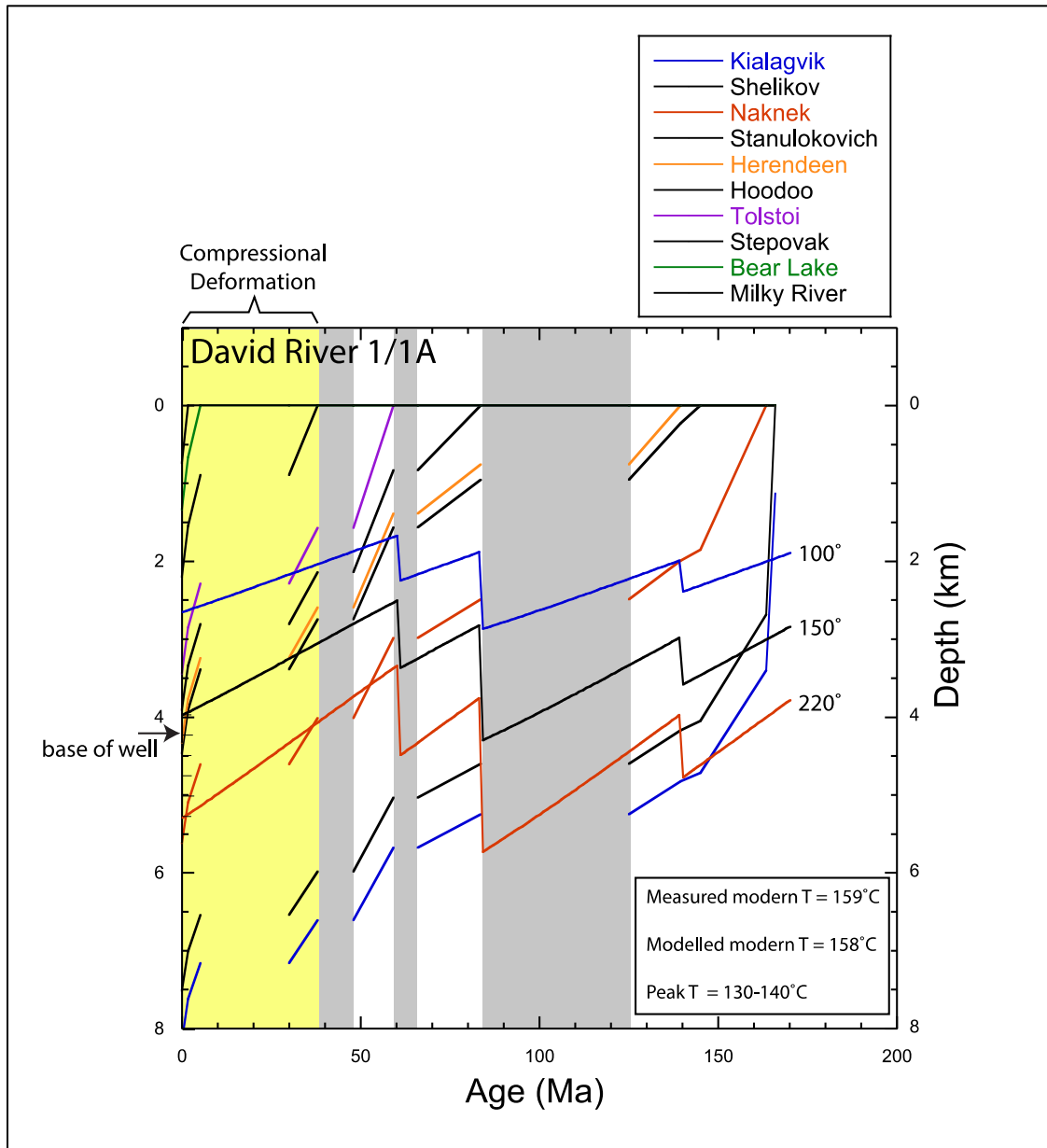


Figure 21: Geohistory diagram for the David River 1/1A showing the depths to the tops of the different formations encountered in this well, along with the extrapolated underlying sequences derived from nearby locations. Isotherms are provided for the 100°C, 150°C and 220°C in order to define the rough limits of the oil and gas generating zone. Gray vertical bars indicate times of unconformity linked to times of uplift and erosion. The yellow shaded area on the left of the figure shows the time of compressional deformation linked northward thrusting along the coast of the Alaska Peninsula. An arrow along the Y-axis shows the depth of the drill site within the Hoodoo/Chignik Formation. Note the predicted and measured temperature at the base of the well are in good agreement but contrast with the cooler temperatures derived from vitrinite reflectance data, but which cannot be considered reliable. No evidence for significant inversion is inferred.

kerogen is intermediate in composition ( $H/C \approx 1.2$ ;  $HI \approx 600$ ) and derived from mixtures of highly degraded and partly oxidized remnants of higher plants or marine phytoplankton. Type III kerogen is hydrogen poor ( $H/C$  ratio 1.3 to 1.5) and oxygen rich and is mainly derived from cellulose and lignin derived from higher plants. Type IV kerogen is hydrogen poor and oxygen rich and essentially inert. This organic matter is mainly derived from charcoal and fungal bodies. Type IV kerogen is not always distinguished but is grouped with Type III.

## CHAPTER 6 RESULTS

### 6.1 Source and Generation Potential

In analyzing the Cathedral River well by graphing the TOC versus depth along with HI versus depth. For the majority of the Mesozoic sequence within the Cathedral River 1 well, the rocks are rated as poor to fair sources (TOC) for gas (Hydrogen Index). However, there are two significant anomalies are observed in Figure 21. Shales and tuffaceous limestones, the Kialagvik Formation, (8,700 to 9,300 feet) appear to rate as “good” potential sources for oil and wet gas. Cherty shales and marlstones, the Talkeetna Formation, (12,000 to 12,700 feet) also appear to form “good” sources for oil and wet gas. These anomalies are somewhat suspect because the elevated thermal maturity ( $>3.0$  T.A.I., or greater than approximately 1.0% vitrinite reflectance below 7,300 ft bkb) of much of the Cathedral River 1 sequence indicates that most of the original oil generation potential of the Mesozoic rocks has been depleted (T.A.I. (thermal alteration index) data from Anderson *et al.*, (1977). Vitrinite reflectance data point at 10,650 feet bkb from Robertson Research (1982). A single vitrinite reflectance analysis (6 measurements) at 10,650 feet yielded a mean value of 1.47%, well past the 1.35% vitrinite reflectance isograd marking exhaustion of all oil generation potential. The top of the prominent geochemical anomaly within the Talkeetna Formation lies at 12,000 ft bkb, 1,350 feet below the lone vitrinite reflectance measurement. However, the Cathedral River 1 well data are at least permissive of the potential existence of oil sources within the Mesozoic sedimentary rocks beneath the Black Hills uplift. That some oil source rocks once existed within the Mesozoic sequence beneath the Black Hills uplift is supported by the observation of oil shows throughout the Cathedral River 1 well.

Evaluating the wells encountered the Cenozoic; David River 1A, Sandy River 1 and Hoodoo Lake 2, showed that within David River 1A and Sandy River the Tolstoi Formation had the best shows, while within the Hoodoo Lake 2 well, the Chignik Formation was within the fair (1-2) range for generation potential.

In David River 1A and Sandy River 1, the total organic carbon (TOC) data suggest that source potential ranges from “fair” to “very good.” Hydrogen index (HI) values suggest mostly gas sources, HI>100 in David River 1A, in Sandy River 1 hydrogen index (HI) values with HI>400 that might be capable of generating oil. Sample descriptions reveal that most samples with TOC values exceeding 1.0% include coal, as either discrete fragments in cuttings or coaly laminations in core samples. The key question then is whether or not these high-HI coals, or possibly non-coal lithologies mixed with coal material in samples, are legitimately capable of generating oil.

## **6.2 Estimating Inversion**

I estimate basin inversion of around 900 m at Hoodoo Lake 2 based on the difference between past peak temperature and the modern. At the base of David River 1A vitrinite values in the Cretaceous sedimentary rocks indicate peak temperatures likely no more than around 140°C, which has a discrepancy with the modern measured and modeled temperatures, which are both close to 160°C. Since both these facts are not really consistent this suggests that the vitrinite is underpredicting the peak temperature and may be a function of a poor correction for the supposed Cretaceous age of the organic matter. It's not clear how I can correct for this uncertainty except by assuming that the amount of inversion that is occurred at David River 1A

is not particularly high. Seismic imaging from the northern edge of the peninsula shows a clear inversion after sedimentation of the Bear Lake Formation, decreasing to the north. I would anticipate less inversion at Sandy River 1 compared with Hoodoo Lake 2. The seismic line modified from Decker (2008) (Fig. 18) indicates ~300 m of uplift under Sandy River as a result of the northward thrust propagation. Furthermore, further north offshore inversion falls to zero values so that the modern temperature would be likely the peak temperature, such as at the N Aleutian COST #1 well. Inversion plays a much greater role in governing basin thermal history along the range front, along the northern coast.

## CHAPTER 7 DISCUSSION

### 7.1 Petroleum Geology

The Bristol Bay Basin is comprised of sedimentary and volcaniclastic rocks that range in age from Jurassic to Holocene (Hite, 2005). However, the thickest portion of the stratigraphy, which is of interest to those exploring onshore, is the thick Tertiary section and portions of the Cretaceous, as well as some Mesozoic formations (Sherwood *et al.*, 2006). Important Cretaceous and Cenozoic formations, i.e. those that have yielded oil and gas shows, include the Milky River, Bear Lake, Stepovak, Tolstoi, and Chignik Formations (Decker *et al.*, 2006). Source rock units in these formations show an appropriate thermal maturity to generate petroleum resources. The greatest unknown factor is the effect that clays, derived from altered volcanic rocks, may have played in limiting the large-scale migration of oil to suitable traps (Decker *et al.*, 2006; Hite, 2005; Finzel *et al.*, 2005; Bascle *et al.*, 1987).

There are several oil seeps in the southern Alaska Peninsula, such as in Herendeen Bay and the Port Moller area. The different wells in and around this region have shown oil and gas. There have been no tests of the oil but the gas tests have been flowed at economic rates. The many gas and oil seeps found in the region occur near the outcrop of the Chignik Formation exposure. Those that have been geochemically typed come from the Upper Triassic Kamishak Formation and the Jurassic Kialagvik Formation (Wilson *et al.*, 2015). The origin of the kerogens is in plants, which are usually found in coal-bearing non-marine rocks and deltaic sequences. These have little hydrogen compared to the amount of carbon present, so that majority end up generating methane gas or sometimes dry natural gas of the simplest hydrogen

molecule (Bolger & Reifenhuth, 2008). Therefore, kerogens that are made of algae and other marine organisms with a higher hydrogen ratio relative to carbon can undergo thermal maturity to form oils of different complexities that are highly enriched with hydrogen. The framework grains form a lattice generating significant porosity and permeability. As a result, the composition of the framework grains is critical in the determination of suitability of any given sandstone to be a reservoir (Helmold *et al.*, 2008).

## **7.2 Source Rocks**

Source rocks contain kerogen, a natural material that is dominantly made out of carbon and hydrogen, the fundamental elements in oil and gas. To produce oil or gas, a source rock must be buried both deep enough and long enough within a basin “kitchen” to convert kerogen into hydrocarbons. Formation of oil or gas in a source rock causes migration of hydrocarbons out of the source rock. Subsequently the lower density of hydrocarbons forces them to move upwards along the course of highest permeability, as a result of the fact that their density is lighter than and they are immiscible in water found in the pore spaces of the encompassing sedimentary rock.

There are two recognized potential source rocks in the North Aleutian Basin: 1) Mesozoic sedimentary rocks that underlie the southwest part of the North Aleutian Basin and the Black Hills uplift; and 2) Cenozoic rocks that comprise the North Aleutian Basin fill. This study focuses on the burial history and thermal evolution of both the Mesozoic and Cenozoic source rocks.



### 7.3 Mesozoic Source Rocks

Much of the Mesozoic sequence of the Alaska Peninsula contains marine shale and mudstone (McLean, 1988). Black shale is especially abundant in the Hoodoo Formation of Late Cretaceous age, which crops out in the southwestern part of the Peninsula (Wang *et al.*, 1988). The Triassic limestone and chert section at Puale Bay is thermally mature and according to pyrolysis data of Wang *et al.*, 1988 lies within the oil-generating window (i.e. 100–150°C). Oil seeps near Puale Bay are presumed to emanate from Middle Jurassic shale and mudstone (Decker, 2008). In summary, the Mesozoic sequence in some parts of the Alaska Peninsula contains source rocks that lie within the window for oil and gas generation, suggesting that it is feasible for the same to be true in the Port Moller region.

The principal point of control for the source rock potential in Mesozoic strata in the study area is the Cathedral River 1 well (Fig. 1). Some indicators for source rock potential in the Mesozoic of this well are illustrated by (Figs. 9 and 13), where critical intervals have relatively high total organic carbon and elevated hydrogen indices, more than 1% by weight in the former and greater than 150 mg.s<sup>2</sup>/g in the latter (Sherwood *et al.*, 2006).

For most of the Mesozoic sequence penetrated by the Cathedral River 1 well, the rocks are rated as poor to fair sources for gas. However, shales and tuffaceous limestones in the interval from 8,700 to 9,300 feet (2650–2834 m) in the Kialagvik Formation appear to rate as “good” potential sources for oil and wet gas. In addition, cherty shales and marlstones in the interval from 12,000 to 12,700 feet (3,657–3,870 m) in the Talkeetna Formation also appear to form “good” sources for oil and wet gas (Fig. 9). Unfortunately, the pyrolysis data are

inconclusive because the well samples may have been contaminated by drilling mud additives (Peters, 1986; Sherwood *et al.*, 2006).

Thermal maturity data indicate that the rocks in the Cathedral River 1 well were previously more deeply buried than in the present day (Fig. 13) (Sherwood *et al.*, 2006). Because the well is located on the Black Hills uplift, where Mesozoic strata are unconformably overlain by Eocene rocks (north flank), it appears that peak thermal maturation occurred during a Mesozoic cycle of deep burial, at least in that area. The Mesozoic oil sources in this area may have generated and expelled their oil long before the deposition of Tertiary-age reservoir sandstones, or the formation of drape anticlines in Oligocene-Miocene strata atop the Black Hills Uplift. Whether the same is true along the southern margin of the basin along the edge of the peninsula, which has experienced more recent inversion is the subject of this study.

#### **7.4 Cenozoic Source Rocks<sup>[1]</sup>**

The North Aleutian Shelf COST 1 well, positioned further offshore towards the north in the central part of the Bristol Bay basin, is the principal point of control for source rock potential in Tertiary-aged fill in the North Aleutian Basin. Total organic carbon (TOC) data suggest that source potential ranges from “poor” to “very good” for the whole stratigraphic column. Hydrogen index (HI) values suggest mostly gas sources with some intervals where HI>300 that might be capable of generating oil (Sherwood *et al.*, 2006). Sherwood *et al.*, (2006), Robertson Research (1983) and Turner *et al.*, (1988) unanimously conclude that the Tertiary sequence penetrated by the North Aleutian Shelf COST 1 well contains primarily Type III organic matter. This gas-prone organic matter occurs in coal beds or is dispersed as finely divided material in

clastic sedimentary rocks and forms poor to very good sources for gas, with minor potential for condensates and light oil (Sherwood *et al.*, 2006).

## **7.5 Reservoir Rocks**

A reservoir rock is any rock with interconnected pore space, capable of holding commercial quantities of liquid or gaseous hydrocarbons. In the Alaska Peninsula sandstones and limestones are more likely to be considered as possible reservoir rocks than shales, slates, or igneous rocks (Bascle *et al.*, 1987). For rocks deposited during the Mesozoic: the Talkeetna, Naknek, Staniukovich, Herendeen and Hoodoo (or equivalent Chignik) Formations comprise at least partly sandstones and conglomerates that might form good potential reservoirs, depending on whether or not the right combination of a structural or stratigraphic trap and porosity is present (Sherwood *et al.*, 2006; Bascle *et al.*, 1987). Because these Mesozoic formations were deposited adjacent to a volcanic arc, most of the clastic sediments contain high amounts of feldspar, volcanic and plutonic rock fragments, degrading sandstone as a potential reservoir because of the tendency for these components to break down into clays during diagenesis (Sherwood *et al.*, 2006). During diagenesis clays clog pore spaces through applied pressure; they can deform around more rigid grains and squeeze pores out of existence (Bascle *et al.*, 1987; Burk, 1965). Younger formations contain less volcanic debris and have been less deeply buried, and thus presumably suffered less from compaction and diagenesis (Sherwood *et al.*, 2006). For these reasons the Staniukovich and the Naknek Formations and younger Cretaceous units form the best candidates as promising Mesozoic reservoirs (Sherwood *et al.*, 2006). The early migration of hydrocarbons into a sandstone can preserve the primary porosity of that sandstone

(Bascle *et al.*, 2006). Diagenesis may create secondary porosity that can be filled and preserved by later formed hydrocarbons (Decker *et al.*, 2006). Given the right set of circumstances and quantity of sandstone, it is possible that significant reservoirs could exist on the peninsula, or in the sedimentary rocks along the southern edge of the Bristol Bay basin (Bascle *et al.*, 2006).

## **7.6 Migration**

For the Mesozoic sequence plays, Burk (1965) recommends that the greater part of the expansive open folds on the Peninsula were formed in Pliocene time, which may clarify why the significant structures tested by drilling have been dry because source rock maturity may have been achieved rather earlier and the structures though potentially good for trapping are too young to have been effective at the critical moment (McLean, 1988). By Pliocene time, Mesozoic rocks would have been subjected to significant diagenesis connected with late Tertiary volcanism and plutonism, which made potential supplies of hydrocarbons difficult because potential migration pathways would have been hard and tight (Bascle *et al.*, 2006; Sherwood *et al.*, 2006).

## **7.7 Potential Traps**

Most mapped prospects in the North Aleutian Basin are simple domes overlying fault-bounded basement uplifts. Because these uplifts are related to the rifting of the basin they are potentially of significantly greater age than younger folding related to northward thrusting along the northern edge of the Peninsula in Pliocene. These domes range up to 93,000 acres (376 km<sup>2</sup>) in closure area. In the central part of the North Aleutian Basin 65 miles northwest of Port Moller,

these domes are surrounded by deep parts of the basin where the lowermost strata have been heated to temperatures sufficient for conversion of organic matter to oil and gas,  $>100^{\circ}\text{C}$  (Sherwood *et al.*, 2006). Oil and gas generated in these basin depths might be expected to have migrated upward into the domes over the basement uplifts (Finzel *et al.*, 2005).

A dominant trap on the edge of the North Aleutian Basin is the Black Hills Uplift. Over the Black Hills Uplift, the Tertiary sequence is thin (2,000 to 5,000 ft) and thermally immature. However, Mesozoic rocks that might form a source for oil underlie the area. On the Black Hills Uplift, broad domes of Tertiary strata range up to 133,000 acres in area ( $538\text{ km}^2$ ; Sherwood *et al.*, 2006).

## 7.8 Seals

No regionally extensive seals have been found. Local, intraformational seals probably exist in Cenozoic formations: The lower silty part of the Stepovak Formation could provide a regional seal for the underlying Tolstoi Formation reservoirs. Interbedded thin non-marine to shallow marine siltstones and shales could provide the intraformational seals for the Stepovak-Unga-Bear Lake Formation reservoirs. Fault related seals are expected in some of the structural traps (Finzel *et al.*, 2005).

Lower parts of the Milky River Formation characterized by minor mudstones just above the Miocene-Pliocene unconformity could provide a top seal for Bear Lake Formation reservoirs (Sherwood *et al.*, 2006). The same formation could act as the regional top seal for a Tertiary petroleum system; however, its integrity and lateral continuity is questionable due to its poorly consolidated nature (Finzel *et al.*, 2005).

## 7.9 Potential Plays

The basic elements of a functional petroleum system are effective sources, reservoirs, and traps. The presence of these three elements by themselves does not ensure that a viable hydrocarbon system will be present. The elements must also interact with each other properly and at the right time to create oil or gas accumulations.

The URS considers the Alaska Peninsula Mesozoic play to be exceptionally theoretical, constrained for the most part by the absence of good reservoir rock. The URS rates oil and gas plays in view of the likelihood of all three characteristics: source, supply, and trap. The Mesozoic play has singular appraisals of 0.9 for source rock, 0.3 for reservoir rock, and 0.9 for structural traps; with a combined likelihood of 0.24 (or 24%) (URS, 2006). The USGS's evaluation of unfamiliar assets for this play midpoints at 52.1 million barrels of oil (MMBO), taking into account estimations of the size and number of unfamiliar gatherings, gas-to-oil ratios, oil gravity, and depth. The USGS describes the Tertiary Play as being hypothetical for both oil and gas stored in Tertiary shallow marine and nonmarine sandstones occurring in broad open folds that underlie alluvium of the Bristol Bay lowlands (URS, 2006).

The URS gives the Alaska Peninsula Tertiary play a combined probability of occurrence of 0.32, based on individual probabilities of 0.5 for source rock, 0.8 for reservoir rock, and 0.8 for structural traps (URS, 2006). Their estimates of undiscovered resources for this play average 1.3 MMBO for oil and 5.0 MMBO equivalent for natural gas (Molenaar, 1996). Based on my findings throughout this study my potential plays are shown here in Figure 22 and my Events Chart in Figure 23.

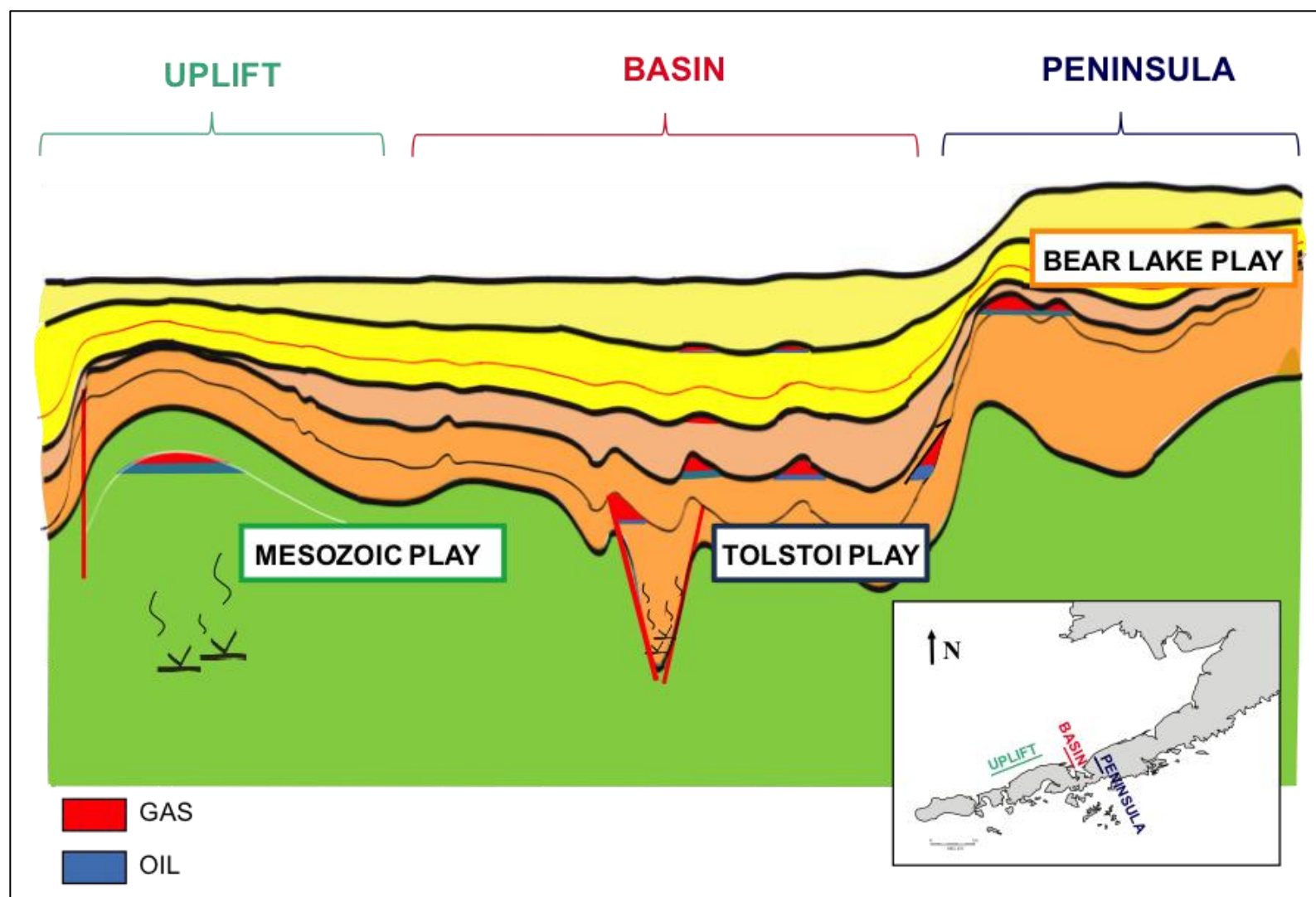


Figure 22: Schematic cross sections illustrating play concepts Three oil and gas plays defined for my study area, separated on the basis of reservoir character, structural style, and access to petroleum sources.

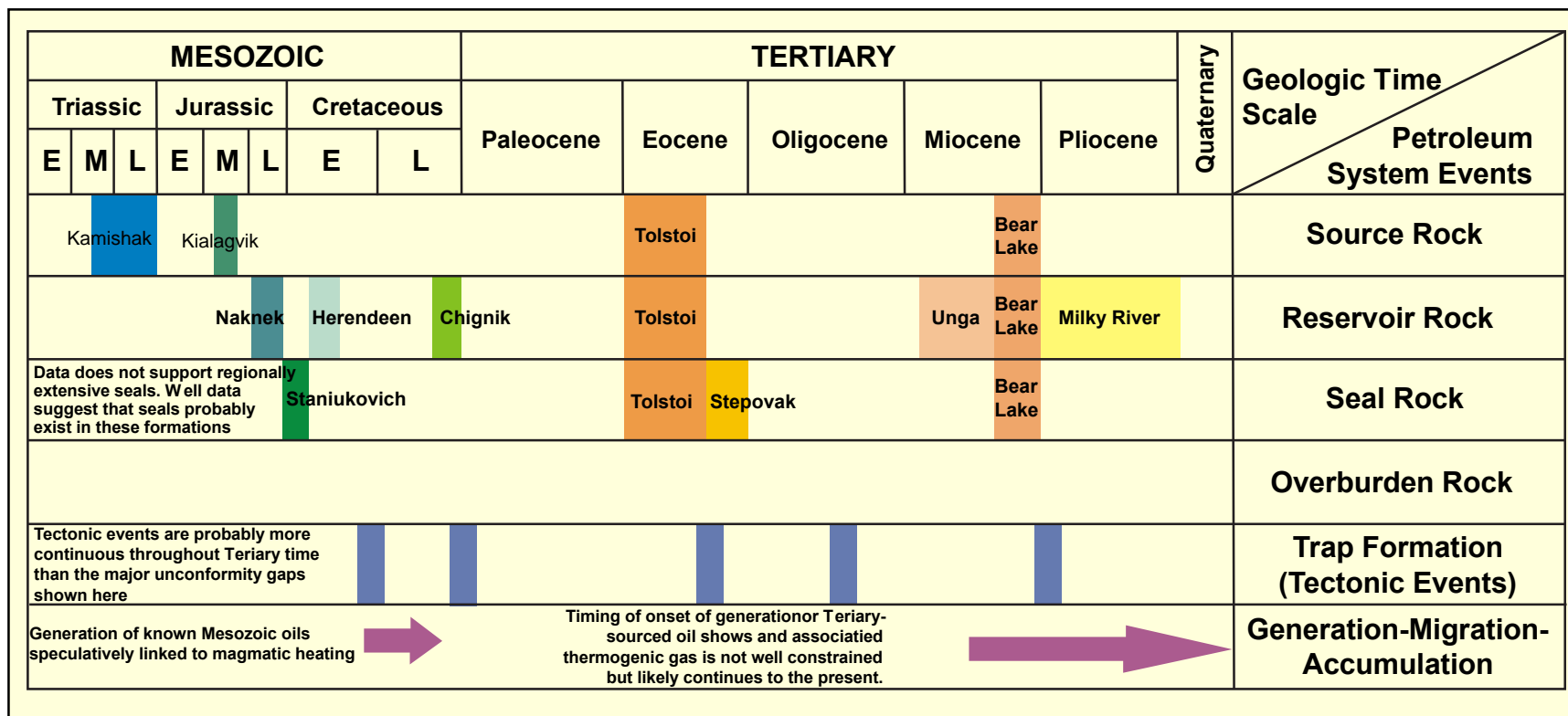


Figure 23: Events chart summarizing the geologic ages and timing relationships of the critical components of the Bristol Bay petroleum system.



## CHAPTER 8 CORRELATION BETWEEN THE PETROLEUM SYSTEMS

In general, the Alaska Peninsula has been considered to have a low potential for economic oil accumulations. However, the southern region of the Peninsula has the highest probability of having commercial oil reservoirs, and is the focus of this study (Barth, 1956). According to Detterman *et al.*, (1985) the data obtained from the wells drilled in the southern study region show that Tolstoi and Stepovak Formation sandstones in the Port Moller area are porous and have good permeability. These are characteristics of a viable petroleum system (Detterman *et al.*, 1985). In addition, data from the wells in this study area indicate that these stratigraphic sequences do not contain much volcanic debris in the Tertiary and Mesozoic sections (Detterman *et al.*, 1985). Detterman *et al.*, (1985) stated that the rock formations found in the southern region also extended to the western region of the peninsula. Hence, the sedimentary formations in both southern and western parts of Bristol Bay are both complimentary for oil accumulation (Mullen, 1987). However, some regions in the south indicate an absence of a petroleum system (Detterman *et al.*, 1985). The Canoe Bay 1 well penetrated highly fractured rocks with steep dips. Consequently, the probability of having economic volumes of oil accumulate in this location is low. However, in general the southern region of the peninsula has rock formations with characteristics that allow hydrocarbon generation and preservation to occur.

In contrast, data from the northern region of the study area indicate that the rock formations in that region also have characteristics that favor formation of a viable petroleum system (Hudson, 1986) (Fig. 13). From the data obtained and analyzed from the northernmost well, Sandy River 1, it was evident that the rock formations in this region allow accumulation of

oil (Burk, 1965). This is because, as data analysis indicated, the porosity of sandstone in the location of the well was recorded to be up to 36.6%, with permeability of up to 1,268 millidarcys (Hudson, 1986). This is a favorable condition for the accumulation of petroleum, assuming it is being generated at depth elsewhere in the basin. Additionally, data from Sandy River 1 also indicated that below 10,000 feet, the rocks have a thermal maturity with significant amounts of volcanic debris in the presence of oil stains (Detterman *et al.*, 1985). It is evident that the petroleum systems in the southern and northern side of the Alaska Peninsula are generally similar and encouraging for future prospects.

## CHAPTER 9 CONCLUSION

From the study, it is evident that the petroleum systems along the southern edge of the Bristol Bay Basin and north coast of the Alaska Peninsula, in the Port Moller area, and the middle of the Bristol Bay Basin are in different ways similar. This shows that, the Alaska Peninsula is viable for future petroleum exploration. Data from the wells show the presence of oil stains and also characteristics of rocks that allow accumulation of petroleum. My modeling of the thermal evolution of the basin along the southern edge shows good source rocks, such as the Tolstoi Formation are now predicted to be in oil window (e.g.,  $\sim 120^{\circ}\text{C}$  at David River 1/1A well) and because the source has only entered thermal maturity since  $\sim 30$  Ma there is a good chance that this is still active and producing. I estimate  $\sim 900$  m of basin inversion during the Neogene at Hoodoo Lake 2,  $\sim 300$  m at Big River 1 and a poorly defined by likely low amount of inversion at David River 1/1A. This implies that the sources here are no longer at peak burial temperature but could have been  $\sim 30^{\circ}\text{C}$  hotter in the Miocene. Some loss of source quality must have occurred at this time. However, the inversion related to thrusting from the south is also responsible for forming some of the traps seen as anticlines along the southern edge of the basin and which are also critical for a viable petroleum system. I further note that suitable source rocks (i.e. the Tolstoi Formation) are still present offshore further north in the vicinity of the North Aleutian Formation COST-1 well at productive temperatures and that these could be supplying trap structures along the Port Moller coast region driven by lateral migration into the structural highs. More studies on samples from the existing wells and drilling of more wells needs to continue if we are to improve our understanding of basin evolution and its impact on hydrocarbon generation and accumulation.

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## **VITA**

Claire Rochelle Jones, born in Denver, Colorado, but spent most of her life in Houston, Texas, received her bachelor's in both the science and the arts from Southern Methodist University in 2013. Thereafter, she attended graduate school within the department of Geology and Geophysics at Louisiana State University. She plans to receive her master's degree in August 2017.