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Seismic Analysis of the Ikpikpuk-Umiat Basin, NPRA, North Slope, Alaska

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DEDICATION

This work is dedicated to my twin brother Aaron Fulk:

May the competition live forever…
ABSTRACT OF THE THESIS

Seismic Analysis of the Ikpikpuk-Umiat Basin, NPRA, North Slope, Alaska
by
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San Diego State University, 2010

The Ikpikpuk-Umiat basin of Alaska’s North Slope accumulated ~ 30,000’ of clastic and carbonate strata during regional extension or transtension from the Late Devonian-Permian. However, this investigation confirms that low-intensity compressional shortening formed east-west trending fault propagation folds in addition to north-south trending flower structures recorded during upper Endicott Group and Lower Lisburne Group deposition. Mapping biostratigraphically age constrained horizons on reprocessed 2D NPRA seismic profiles provide a method for dating the deformation. This research reveals that the Ikpikpuk-Umiat basin experienced a local stress field inversion from 349-299 Ma prior to Triassic drifting. Observations from this work suggest that this synrift localized inversion propagated through the basin from east to west. Either a rotation in the direction of extension/transtension (causing strain partitioning), or a two stage basin formation (extension followed by a shear propagating through the basin) resulted in low-intensity thrusting recorded from the late Mississippian through the Pennsylvanian.
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ACKNOWLEDGEMENTS

The completion of this work is the result of many people’s influence on my life. It was made possible by the support of my parents, brother and family. I would like to thank them for always impressing upon me the importance of becoming the best possible version of myself.

Additionally, I would like to thank my undergraduate professors for the passion and enthusiasm they invigorate in their classes. Dr. Chris Connors, Dr. Lisa Greer, Dr. Dave Harbor, and Dr. Jeff Rahl’s love of geology is contagious. Without their guidance I would still be searching for my vocation.

I would like to thank Dr. Dave Houseknecht for presenting the initial questions, which were the beginning of this project. I would also like to thank him for providing me the privileged opportunity of working under his guidance at the EERT. I would like to acknowledge Dr. Gary Girty for his patience despite seemingly never having time to sleep he always found time to address my concerns. Most Importantly, I would like to thank Dr. Rob Mellors for agreeing to be my lead advisor and having the ability to always summon additional effort from me.
CHAPTER 1

INTRODUCTION

The Ikpikpuk-Umiat basin extends 7,000 km² beneath the eastern section of the National Petroleum Reserve in Alaska (NPRA) (Bird, 1981). The NPRA is bound to the west and north by the Chukchi and Beaufort Seas and to the east and south by the Colville River and the Brooks Range, respectively (Figure 1). The NPRA is comprised of Arctic Alaska Basin sediments largely deposited in the foreland basin of the Brooks Range, the Colville Trough (Figure 2).

![Figure 1. Location map of National Petroleum Reserve Alaska (NPRA), Trans-Alaska Pipeline (TAPS), ANWR and native lands (colored in orange). Additionally, the Pt. Barrow, Alpine, Prudhoe Bay, and Pt. Thomson commercial accumulations are labeled. Regional seismic profiles used in interpretations are the red lines and the two wells used to tie the seismic data and date events are black circles. The basins with the thickest Ellesmerian Sequence are colored green (Meade and Ikpikpuk-Umiat). Figure is edited from Bird, K.J., and Houseknecht, D.W., 2002, U.S. Geological Survey 2002 Petroleum Resource Assessment of the National Petroleum Reserve in Alaska (NPRA), U.S. Geological Survey Fact Sheet 045-02, www.pubs.usgs.gov/fs045-02, accessed June 2009.](image)

Underlying Cretaceous strata of the Colville Trough in the NPRA are Late Devonian-Triassic sediments, sourced from a northern tectonic high, and deposited on a rifted passive margin that extended from present day Arctic Alaska and northwest Canada offshore to the
Chukchi and Beaufort Seas (Bird, 1981). The thickest successions of Late Devonian-Triassic strata in the NPRA accumulated in the Meade and Ikpikpuk-Umiat basins which subsided due to Late Paleozoic rifting and extension (Gryc, 1988). Stratigraphic correlation between these sub-basins and the Hanna Trough, which lies beneath the Chukchi Sea west of NPRA, suggest that the Hanna Trough, the Meade sub-basin, and the Ikpikpuk-Umiat sub-basin subsided concurrently and may be systematically related (Sherwood et al., 2002).

The Ikpikpuk-Umiat basin is bound in the subsurface to the west by the Meade Arch, the north by the Barrow Arch, the east by the Colville High, and the south by the Umiat Platform- a ramp for the front of the Brooks Range (Figure 3). The Ikpikpuk-Umiat basin is a sub-basin of the Colville Trough. Across Arctic Alaska three mega sequences were deposited over metamorphosed basement (Franklinian): the Ellesmerian (Carboniferous-Jurassic), the Beaufortian (Jurassic-Cretaceous) and the Brookian (Cretaceous to Cenozoic) (Hubbard et al., 1987).

The stratigraphy of Ellesmerian, Beaufortian, and Brookian strata is well-established on the North Slope (Bird, 1981; Bird, 1988; Gryc, 1988; Houseknecht, 2001). The
Ellesmerian mega-sequence may be subdivided into three sequences: the Lower (synorogenic fill which crops out in the Brooks Range), the Middle (Endicott and Lisburne Groups), and the Upper (Sadlerochit Group and drift sequence). The Middle Ellesmerian sequence is regionally well-defined in previous work as a broad succession of passive-margin strata that is laterally extensive across Arctic Alaska (Hubbard et al., 1987). In the Ikpikpuk-Umiat basin, graben-filling successions enigmatically record Carboniferous compressional
deformation identified in previous publications (Bird, 1981; Mauch, 1987). Prior work suggests that faults observed in 2D seismic profile likely inverted along previously existing normal faults due to northerly compression (Figure 4) (Mauch, 1987). Additionally, Mauch (1987) notes that, “thrusts were cut by numerous tear faults having only a few miles of displacement” (p. 168). Previous workers were unable to describe the features in more detail due to the low resolution of original NPRA seismic profiles. As a result, the age and mode of pre-Cretaceous deformation observed in the Ikpikpuk-Umiat basin is still undetermined. Additionally, most pre-Jurassic deformation in central and southern NPRA has been overprinted by Cretaceous-Tertiary Brookian deformation.

![Figure 4. Regional line R-8 displaying the top of basement (green), the top of the Endicott Group (purple), the top of the Lisburne Group (pink), the top of the Shublik Formation (purple), and the Lower Cretaceous Unconformity (cyan). Basin faults are outlined in red. The fault propagation folds with associated thinning of beds in the Lisburne Group are suggestive of a local compressional stress field.](image)

However, the Ikpikpuk-Umiat basin is ideal for this study because it was not tectonically overprinted, due to southern basement highs, which ramped Brooks Range deformation above Late Paleozoic strata. Reprocessed 2D seismic profiles provide higher resolution imaging of the basin subsurface and confirm the presence of local compressional features (reverse faults, tear faults, fault propagation folds, and synkinematic thinning of
beds). While there is little evidence for a Late Paleozoic regional stress field inversion on the North Slope, the features observed in Middle Ellesmerian strata of the Ikpikpuk-Umiat basin do confirm that a local stress field inversion occurred.

Recent literature on Paleozoic Arctic tectonics (Colpron and Nelson, 2009; Lane, 2007; Nokleberg et al., 2000) limits the regional settings that may have existed during the formation of the Ikpikpuk-Umiat basin. Basin subsidence in the region is proposed to have commenced as an Early – Mid Devonian orogeny concluded (Hubbard et al., 1987; Sherwood et al., 2002). Mauch (1987) suggested a two stage basin evolution: early rifting in the Lower Paleozoic basement with subsequent Endicott Group deposition, followed by a brief episode of northward compression. A local stress field inversion derived from distal tectonics is supported by recent work describing a Carboniferous deformational event in the Richardson Mountains and Mackenzie Delta east of NPRA (Lane, 2007). Hubbard et al. (1987) advocated a pull-apart or transtensional evolution for the Meade and Ikpikpuk-Umiat basins. While a persistent extensional or transtensional regional setting containing local compressional features seems paradoxical, field work in other areas and recent kinematic modeling may provide a solution (Allmendinger, 1998; De Paola et al., 2005).

This investigation integrates North Slope regional studies (Hubbard et al., 1987; Moore et al., 1994), well log data (Gryc, 1988; Miller et al., 2000), and well core reports (Haywood, 1983; Houseknecht, 2001; Mickey et al., 2006) with interpretations from this work derived from reprocessed 2D NPRA seismic profiles (Miller et al., 2000), in order to describe the mode of deformation for the compressional features observed in the Ikpikpuk-Umiat basin. Biostratigraphic studies are correlated with seismic stratigraphic analysis of reprocessed 2D NPRA seismic profiles to constrain the age of inversion related deformation. 2D restorations of selected seismic profiles document the style and age of deformation.
CHAPTER 2

PRE-BROOKIAN TECTONIC SETTING

The NPRA is underlain by the North Slope subterrane of the Arctic Alaska-Chukotka micro plate (Moore et al., 1994). This micro plate is a composite block of Alaskan subterranes that did not evolve until the opening of the Canadian Basin in the Jurassic, however in this work crust that eventually evolved into the Arctic Alaska-Chukotka micro plate is termed the “proto Arctic Alaska micro plate” (Macdonald et al., 2009). Crustal basement underlying the “proto-Arctic Alaska micro plate” was derived from several polygenetic sources (Nokleberg et al., 2000).

The Paleozoic tectonic history of the Arctic is a complex series of events involving a number of terranes (Colpron and Nelson, 2009; Smith, 1985). These terranes were accreted to the northwest margin of Laurentia during the early and middle Paleozoic (Nokleberg et al., 2000). Colpron and Nelson (2009) proposed that a NW propagating, narrow, Scotia-style, subduction system termed the “Paleozoic NW Passage,” was active from the Silurian-Permian. The system of sinistral strike slip faults which constitute the southern boundary of the “Paleozoic NW Passage” are inferred to have translated several subterranes (Pearya, Alexander, Wrangel) westward from Siberia and Baltica. However, details of plate tectonic settings prior to the mid-Paleozoic are speculative, because extensive Cretaceous and Tertiary deformation has overprinted important successions of strata from the available geologic record (Hubbard et al., 1987).

Deformation in Arctic Alaska basement records the onset of an early Devonian orogeny followed by a younger Late Devonian-Carboniferous orogenic event (Moore et al., 1994). Both of these events in the past have been grouped together and referred to as the Ellesmerian Orogeny. However, Lane (2007) identified the earlier event recorded in Arctic Alaska as a distinctly different orogeny entirely and terms it the Romanzof Orogeny. It is recorded in the Northeast Brooks Range, the Mackenzie Delta, and the eastern North Slope (Lane, 2007). The well constrained Early – Middle Devonian Romanzof Orogeny is interpreted as the accretion of the proto Arctic Alaska microplate to the northwest Laurentian
margin. Romanzof related deformation is characterized by tight isoclinal folds, north-directed thrust faults, and post tectonic intrusions (Lane, 2007).

Felsic magmatic intrusions were a result of post-Romanzof rifting and are present in the North Slope sub-surface and to the south in the Hammond and Coldfoot subterranees (Colpron and Nelson, 2009). Lane (2007) proposed that post-Romanzof rifting produced the south-facing continental margin on the North Slope by Late Devonian time. Additionally, regional work supports that the North Slope was oriented along strike of a rift axis and experienced extension from the Late Devonian-Triassic (Sherwood et al., 2002). This regional work corroborates that Late Paleozoic sub-basins on the proto Arctic Alaska micro plate initially formed as the offshore rift axis propagated across a paleo continental margin as the Romanzof Orogeny concluded. Vitrinite reflectance data reveals a high heat flow during early basin formation which subsequently cooled at a steady rate between 300 and 100 Ma (Lerche et al., 1984). Crustal cooling provided accommodation space for the rapidly subsided basins.

In the Late Devonian, the Ellesmerian Orogeny initiated as Laurentia translated north-northwest and deformed rocks in the Canadian Arctic Islands and adjacent northern Greenland (Lane, 2007) (Figure 5). Late Devonian-Early Carboniferous, low-intensity, contractional faults and folds extend from Yukon as far west as the Richardson Mountains (Lane, 2007). Additionally, age constrained deformation recorded in the Richardson Mountains and the Mackenzie Delta suggest that deformation progressed approximately from north or northwest to south or southeast (Lane, 2007). The age and low-intensity thrusting style of deformation suggests that Carboniferous Ellesmerian-related deformation may have caused the compressional features in the Ilpikpuk-Umiat basin being investigated in this work. However, the nearest confirmed Ellesmerian deformation, in the Richardson Mountains, is 350 miles southeast of the Ilpikpuk-Umiat basin.

Synchronous with - and perhaps systematically related to the Ellesmerian Orogeny recorded on the northwest margin of Laurentia - ocean floor of the Angayucham and Panthalassa (ancestral Pacific Oceans) plates was subducted eastward beneath the western Laurentian continental margin (Nokleberg et al., 2000). This subduction zone persisted from the Devonian – Carboniferous and may have influenced the deformational event recorded in eastern Arctic Alaska at the same time.
It’s inferred from northward onlapping that Middle Ellesmerian sediments in the North Slope sub-surface was sourced from a persistent, northern, tectonic high (Bird, 1981). During initiation of Middle Ellesmerian deposition the proto Arctic Alaska micro plate may have been juxtaposed with the western margin of the Lomonosov Ridge/Barents Shelf terrane (Hubbard et al., 1987). The Lomonosov Ridge, a submarine basement high composed of sialic continental crust, could be a remnant of the northern clastic source for the Middle Ellesmerian Sequence. Colpron and Nelson (2009) suggested that the Middle Ellesmerian northern sediment source is a northern terrane that no longer exists termed “Crocker Land.” Towards the end of the Ellesmerian Orogeny, in the early Mississippian, regional extension is observed across Arctic Alaska and northwest Canada possibly due to Panthalassa/Anguyacham slab roll back (Colpron and Nelson, 2009).
During Upper Ellesmerian Sequence deposition it is generally accepted that the North Slope drifted away from the persistent northern tectonic high that sourced the Endicott Group of the Middle Ellesmerian Sequence. This continued until the opening of the Canadian Basin, a sub-basin of the Amerasian Basin. The manner in which the Canadian Basin opened is debated. Traditionally it is believed that the Arctic Alaska micro plate rotated counterclockwise away from the Canadian Arctic Islands (Moore et al., 1994). More recent work suggests that the North Slope sub terrane was not simply connected to the Canadian Arctic Islands and that the Canadian Basin opened along a pre existing suture between Laurentia and the North Slope (Macdonald et al., 2009). This episode of drift was followed by the Brookian Orogeny (Late Jurassic-Tertiary). The Brookian Orogeny resulted from southward subduction of oceanic lithosphere beneath northern Alaska (Moore et al., 1994).
CHAPTER 3

NPRA BASEMENT GEOLOGY

The architectural evolution of a basin is largely influenced by existing structural features in basement and here a brief review of NPRA basement geology is provided.

The basement complex is the informal term used to refer to all rocks in the subsurface beneath the North Slope of Alaska that are older than the Late Devonian-Mississippian Endicott Group (Bird, 1988). The basement complex is variably deformed, weakly metamorphosed to unmetamorphosed, and is composed of a variety of lithologies. The subsurface boundaries of the Ikpikpuk-Umiat basin are the Meade Arch to the west, the Umiat platform to the south, and the Barrow Arch to the north (Figure 3, p. 3). The Barrow Arch represents the currently high-standing part of the rift shoulder that formed during opening of the Amerasia basin. The other arches and platforms are believed to be tectonized early Paleozoic sediments that were intruded by Middle Devonian granites (Kelley and Brosgé, 1995), probably during the Romanzof Orogeny (Lane, 2007). The basement complex lies beneath more than 30,000’ of overlying strata in the center of the Ikpikpuk-Umiat basin, but rises to within ~7,500’ of the surface along the axis of the Barrow Arch (Dumoulin, 2001). Wells offshore and onshore northern NPRA confirm the basement is largely composed of fine grained, steeply inclined argillite, slate phyllite, or minor quartzites termed tectonized siliciclastics (Sherwood et al., 2002).

Dumoulin (2001) subdivided the NPRA basement into six groups based on composition and age: varicolored argillites, organic-rich siliceous argillite and chert, gray argillite with interbedded siltstone to sandstone, chert dominated conglomerate and sandstone, Devonian granite penetrated by the East Teshekpuk well, and the extensively brecciated, hydrothermally altered quartz-veined rock of the Ikpikpuk-Umiat basin penetrated by the Ikpikpuk 1 well.

The interval cored at the Ikpikpuk 1 well was assigned to the basement complex (Bird, 1988). Cores recovered at the base of the well are composed of almost 100% quartz and “quartzite.” These cores were interpreted as cataclastic metasedimentary rock
Core 16 (15,463-67’) shows cross-cutting, fine-to very coarse grained, quartz veins. Only a few veinlets of coarse sparry carbonate were also noted, otherwise the remaining mineral content was entirely quartz (Brockway, 1983). Core 14 (15,420-21’) consists of similar quartz veins along with angular fragments of polycrystalline quartz in a fine grained matrix (Dumoulin, 2001). The matrix (wilkeite) also contained rare fragments of possible protolith material resembling chert and fine-grained volcanic rock (Dumoulin, 2001). The Ikpikpuk 1 well was drilled to a basement high and a fault is noted at the location of the well. It is interpreted that the faulting occurred during the formation of the Ikpikpuk basin in Devonian or Mississippian time. Dumoulin (2001) suggests that the quartzite breccia at the base of the well formed in the fault zone. The wilkeite matrix is a rare mineral often associated with contact metamorphism (Haywood, 1983), but it possibly was formed here due to hydrothermal alteration associated with the faulting (Dumoulin, 2001).

It is interpreted from the diversity of composition within the Franklinian basement that it was derived from several exotic terranes shedding sediments to the area from the Early to Middle Paleozoic (Nokleberg et al., 2000; Sherwood et al., 2002). The polygenetic source of the basement is undetermined but it may have been a series of terranes that traveled along the sinistral strike-slip system mentioned by Colpron and Nelson (2009).

Wells penetrating North Slope basement are restricted to the north NPRA. Therefore, geophysical studies are used to gain a more detailed understanding of its composition across the rest of the NPRA. Saltus, Hudson, and Connard (1999) utilized gravity, magnetic, seismic, and borehole data to map the North Slope basement. North Slope gravity and aeromagnetic data reveal a bimodal basement, bisected by a deep magnetic high that strikes NW-SE, and transects the Umiat basin (Saltus et al., 2002). Northeast of this magnetic high the basement produces gravity anomalies consistent with normal sialic crustal densities (i.e. the brecciated quartzite penetrated by the Ikpikpuk 1 well). Southwest of the magnetic high, gravity anomalies are consistent with a denser, more mafic composition (Saltus et al., 2001). Saltus et al. (2002) concludes through analysis of anomaly wavelengths that most of the magnetic anomaly variations in NPRA are sourced in basement (long-wave), but in a few cases shorter-wavelength features suggest that mafic material may lay within lower Ellesmerian strata.
The center of the Umiat basin is identified as a probable area for mafic intrusions based on the presence of short-wavelength anomalies (Saltus et al., 2002). However, mafic material near the base of the Ellesmerian Sequence is unconfirmed by well data as none of the legacy wells penetrates the base of the Ellesmerian Sequence south of seismic profile R-14 – where the geophysical data indicates intrusions. These intrusions may be due to the initiation of extension or transtension in previously weakened “leaky” crust (Garfunkel, 1981).

The bimodal nature of North Slope basement is characteristic of an oceanic-continental transition (OCT) in the crust. Anomalous crust was emplaced during a paleo rift in either the Neoproterozoic, or more likely during Middle Paleozoic post-Romanzof extension. Herman and Zerwick (1994) speculate that a gravity anomaly in the Hanna Trough is indicative of a mafic mass in the lower crust (>20 km depth). It is interpreted that this mafic body was emplaced during the Middle Devonian rifting of the Hanna Trough and may be related to the mafic body underlying the Umiat basin and defined by Saltus et al. (2002). Based in part on these observations, Sherwood et al. (2002) suggested that the Hanna Trough in the Chukchi Sea may be related to the NPRA Paleozoic sub-basins.

Additionally, Saltus et al. (2002) presented gravity and aeromagnetic data that show basement fault trends north of the OCT from NW-SE and W-E south of the anomalies. The trends converge east of the basin bounding faults to a W-E trend. Aeromagnetic data also displays conjugate NE-SW basement trends in northeast NPRA and some N-S trends in the southern foothills of central NPRA (Saltus et al., 1999).

Increased heat flow within the upper crust (evidenced by mafic intrusions), crustal thinning with associated normal faults, and the juxtaposition of a mafic magmatic body with sialic basement along strike of a rift axis all agree with regional detrital-zircon isotopic studies that suggests the proto North Slope sub-terrane was formed via oblique extension or transtension along a regional transform-fault system (McClelland, 1997). The geologic record of this regional transform fault was largely overprinted, but may be intact in the Hanna Trough and the Meade and Ikpikpuk-Umiat basins.
CHAPTER 4

MIDDLE ELLESMERIAN STRATIGRAPHY

Hubbard et al. (1987) generally defines the Middle Ellesmerian Megasequence as a northern-sourced transgressive-regressive succession. This megasequence unconformably overlies Franklinian Basement and in the Ikpikpuk-Umiat basin is ~20,000’ thick. Hubbard et al. (1987) suggests that the unconformity surface separating Franklinian basement complex and Ellesmerian strata may be as old as early Mississippian (335 Ma) in the Ikpikpuk-Umiat basin center while biostratigraphic work suggests a Late Devonian age at the Inigok 1 well (355 Ma). The Middle Ellesmerian Megasequence is composed of three lithostratigraphic units, which represent approximately 220 m.y. of deposition from the Late Devonian to the Late Jurassic (Figure 6). These include the Endicott Group (nonmarine and marine clastic rocks), the Lisburne Group (marine carbonate rocks), and the Sadlerochit Group (marine carbonate and sedimentary rocks). Northward stratigraphic onlap, convergence, truncation, increasing grain size, and marine to nonmarine facies changes indicate that the paleo-continental margin lay near the present day coast but an open sea to the south persisted (Bird, 1981). The sequence records a general northward transgression of the sea (from Kekiktuk Conglomerate in the Endicott Group to Lisburne Carbonates) followed by a regression (Sadlerochit Group Kavik Shale).

Each group contains several formations and the following sections are a summary of the group’s geologic setting followed by its description through well cores described in the Inigok 1 well report (Haywood, 1983). The Inigok 1 well is near the deepest part of the basin and records transitional events that are not seen in the condensed and structurally higher section cored and logged in the Ikpikpuk 1 and other NPRA wells. It is important to note that both wells display episodes of faulting in the Endicott and Lisburne Groups. The strata penetrated in these wells suggest that during deposition of the Endicott, Lisburne, and Sadlerochit Groups the basin was rifted, moderately extended, and perhaps experienced sagging. The depositional setting progressed from a continental margin to a restricted epeiric sea which opened into a broadly developed shallow sea (Moore et al., 1994).
Figure 6. Interpreted stratigraphic column from Inigok 1 well with sequence and formation names. The synthetic seismogram created from unpublished velocity models of the USGS is displayed to the right of the composite Gamma Ray log. Biostratigraphic zones are from Figure 30.1 of Gryc, G., ed., 1988, Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, Washington, DC, United States Government Printing Office, p. 940. The absolute age correlation is inferred from Figure 3 of Mickey, M., Haga, H., and Bird, K. J., 2006, Micropaleontology of selected wells and seismic shot holes, northern Alaska; USGS Open File Report 2006-1055, CD-ROM. A fault propagation fold is interpreted in red.

ENDICOTT GROUP

Regionally, the Endicott Group is characterized by nonmarine and shallow marine clastic rocks (Moore et al., 1994). It grades upward from nonmarine clastics, coal-bearing sandstone, shale, and conglomerate (Kekiktuk Conglomerate) to shallow marine black shale (Kayak Shale) and/or red and green shale (Itkilyariak Formation) as an overall transgressive
sequence (Wilson et al., 2001). The Kekiktuk Formation unconformably overlies the Franklinian sequence basement complex.

A fan delta system or braid delta producing low-gradient, high-sand, braided streams are proposed as the depositional setting for the lower Kekiktuk Formation (Wilson et al., 2001). In the deepest parts of the Umiat-Ikpikpuk basin some volcanic clasts may be present at the base of the Lower Kekiktuk Formation (Saltus et al., 2002). The Kekiktuk Formation (19,550-19,372’) contains medium to very coarse grained, quartzitic sandstone with interbedded layers of conglomerate, shale, and anthracitic coal. A sandstone from 19,367.2-19,370’ is dark gray and appeared highly shattered and slickensided. Lower Kekiktuk Conglomerate in the Ikpikpuk 1 Well (15,320’-15,470’) is indicative of cataclastic metasediments (Haywood, 1983). Massive sand beds from 80-100’ lie above these lower conglomerates and grade stratigraphically upward into successively thinner sandstone, shale, and siltstone units less than 20’ thick.

The Kayak Formation, which consists of interbedded limestone, shale, and siltstone overlie the Kekiktuk conglomerate. The Kayak Formation is interpreted as subtidal shale and limestone. The Kayak Formation is more laterally extensive than the Kekiktuk Conglomerate which supports progressive onlap as the basin filled or during an episode of transgression. The intraformational limestones are dark gray and fossiliferous. In the Ikpikpuk 1 well, the correlative Itkilyariak Formation is observed, which consists of interbedded sandstone, siltstone, and shale. The presence of more coarse grained clastics in the Itkilyariak Formation (Ikpikpuk 1 well) is likely due to closer proximity to the sediment source (northern tectonic high).

The Endicott Group was deposited on an irregular topographic surface. The massive sand beds and cross bedding within the sands of the Kekiktuk Formation suggests a rapidly deposited trough-fill depositional setting while the interbedded shales signify flood basin deposits (Wilson et al., 2001). The shale and coal record a low energy depositional environment probably indicative of a swamp. The inferred depositional environment for the Kekiktuk Formation is confirmed by laterally discontinuous facies changes in well cores common on a deltaic flood plain, or marginal marine environment (Wilson et al., 2001). The generally finer grained Kayak Formation may signify a lacustrine or shallow-depth brackish seaway depositional environment. The thick stacking of similar facies in both the Kekiktuk
and Kayak Formations indicates that sedimentation was equal to subsidence during Endicott Group deposition.

**Lisburne Group**

The Endicott Group grades upward into shallow-marine carbonate rocks of the Lisburne Group (Bird, 1981), which change facies southward into phosphate rich distal muds. It was deposited on an irregular topographic surface with substantial relief (Dumoulin and Bird, 2001). The carbonate platform of the Lisburne Group is discontinuously present from the Chukchi Sea to Cape Lisburne across Arctic Alaska to the northern Yukon in western Canada. It confirms that a regional shallow water carbonate platform was prevalent across the region from the Carboniferous to the Permian. The Lisburne Group is largely undeformed on the North Slope and is an important reservoir rock for the Prudhoe Bay field (Dumoulin and Bird, 2001). The sequence is interpreted as having formed on a south-facing, slowly subsiding, passive continental margin and either onlaps or is truncated laterally across approximately the present day shoreline (Dumoulin and Bird, 2001). It represents several northward transgressions but in the NPRA has a critical westward component towards the Hanna Trough as well. The basal Lisburne Group strata in the Izipikpuk-Umiat basin is Mississippian, but across several of the basement highs (Fish Creek Platform) it may be as young as Middle Pennsylvanian (Dumoulin and Bird, 2001). In this work the classification scheme sub dividing the Lisburne Group into Mississippian and Pennsylvanian strata from Dumoulin and Bird (2001) is implemented.

**Mississippian Strata**

Dumoulin and Bird (2001) divide Mississippian strata of the Izipikpuk-Umiat basin into three informal units: a lower limestone, a middle dolostone, and an upper limestone. The lower Lisburne Group at the Inigok 1 well is interbedded Kayak Shale and limestone and is a transition between siliclastic and carbonate deposition. The lower limestone unit overlies this transition and is largely comprised of bryozoans-pelmatozoan packstones and wackestones. It is also scattered with thin interbedded shales, gray dolomites, and occasional siltstones, which increase in shale content below 16,850’. The lower limestone unit is 1,410’ thick and foraminifers indicate an Osagean-Chesterian age. The Osagean strata are mainly dark gray to black limestone with some interbedded dolomitic and cherty limestone
(Dumoulin and Bird 2001). The upper Chesterian succession is light to dark-gray limestone, lesser dolostone. Argillaceous material is common throughout the lower limestone unit.

The lower limestone unit is overlain at the Inigok and Ikpikpuk wells by a ~250’ thick dolomite. At the Ikpikpuk 1 and Inigok 1 wells the dolostone grades into bioclastic packstones and also contains interbedded dark argillaceous material as well (Dumoulin and Bird, 2001). The unit, outside of the bioclastic packstones, does not contain many fossils but it is stratigraphically constrained to be Chesterian in age (Dumoulin and Bird, 2001).

The dolostone unit is overlain by a laterally extensive upper limestone unit that is also believed to be Chesterian in age (Dumoulin and Bird, 2001). At the Inigok 1 well the unit is 480’ thick and comprised of white to gray limestone, darker gray dolostone, and minor gray silty shale (Haywood, 1983). At the Inigok 1 well the unit thins to 290’ thick and is comprised of buff to tan limestone with less abundant dolostone but substantially more abundant siltstones to fine-grained sandstones (Dumoulin and Bird, 2001). Mississippian aged Lisburne Group strata likely formed in a chiefly shallow-water setting that increases in lateral extent stratigraphically upwards. In the Ikpikpuk-Umiat basin lime-mud-rich lithologies are the most prevalent and the lower limestone and dolomite units are interpreted as having accumulated below the wave base (Dumoulin and Bird, 2001). However, grainstones present in the upper limestone unit may indicate increased wave energy and deposition in a shallower aquatic environment. Siliclastic detritus present at the Ikpikpuk 1 well suggests that it was exposed to an even shallower depositional environment closer to the northern terrigenous source of the sediments (Dumoulin and Bird, 2001).

**Pennsylvanian Strata**

Pennsylvanian aged strata of the Lisburne Group are present in well cores across the NPRA. The unit is thickest at the Inigok 1 well (~1,500’) where Pennsylvanian strata is comprised of medium to dark-gray limestone and dolomitic limestone overlain by brown to gray limestones interbedded with dark gray shales and siltstones (Haywood, 1983). There are 10-50’ thick shallowing-upward cycles present in Pennsylvanian aged Lisburne Group strata across the NPRA. These cycles are generally marked by dark-gray or gray-green shale and bioturbated bryozoan wackestone/packstone and grade upward into ooid and bioclastic grainstone. This is interpreted as an open marine, sub-wave base setting followed by a
regression to a nearshore shoal depositional setting (Dumoulin and Bird, 2001). This may be related to glacioeustatic sea level fluctuations. There is some debate as to the age of the uppermost limestone unit unerlying the Lisburne Group – Sadlerochit Group transition unit. Most prior work dates these units as Permian but a shortage of fossil assemblages in these strata limits the confidence of this age (Dumoulin and Bird, 2001).

Overlying the Pennsylvanian limestone unit is a transition zone (13,980-14,474’) unique to the Inigok 1 well. This transition is early Permian in age and records a northward transgression as interbedded light to dark gray, chalky to very fine crystalline limestones grade upward into dark gray to tan, fossiliferous, slightly dolomitic to calcareous silts. The transition zone is 60% limestone and 27% siltstone ranging in unit thickness from 3-30’.

Cores of the siltstone reveal the presence of brachiopods, pelecypods and crinoids. At a depth of 14,051.7’ in the Inigok 1 well a highly slickensided fracture is present and indicates a possible small fault. 9’ of limestone underlying the siltstone was “highly fractured” with indications of slickensides, calcite cement, and vertical hairline fractures. The transition unit records the end of carbonate accumulation due to an influx of siliclastic detritus. It may also signify a shift to a deeper and (or) colder water environment which did not promote carbonate accumulation (Dumoulin and Bird, 2001).

**Sadlerochit Group**

The Sadlerochit Group is composed of the Echooka Formation (13,656-13,980), the Kavik shale, the Ivishak Formation (12,640-13,656’), and the Fire Creek Formation. The Sadlerochit Group converges and onlaps the Lisburne Group over the Barrow Arch. The Group is a generally coarsening upward sequence from shale to mudstone to sandstone and conglomerate. This is largely attributed to a southward progradation of fluvio-deltaic systems. This coarsening upwards trend is terminated or transgressed by the Fire Creek Siltstone (Wilson et al., 2001).

The Echooka formation is a fossiliferous, fine to very fine grained, silty sandstone (Wilson et al., 2001). The siltstones are very dark to medium gray, carbonaceous, slightly glauconitic, partly pyritic, shaly, and siliceous, but become slightly dolomitic to very calcareous near the top of the Lisburne Group. The sandstones are fine to very fine grained, subangular, siliceous and slightly carbonaceous. The beds are thin with the maximum
thickness being 15’ (13,675-13,690’). This largely silty sandstone is interpreted to have a shelfal to prodelta depositional environment (Wilson et al., 2001).

The Kavik Shale grades upward from very dark gray shales to medium to dark grey siltstones (13,314-13,464’). The shales consist of dark gray parallel laminated mudstone and are interbedded with thin parallel laminated and ripple cross laminated siltstones and a 35’ sand (Wilson et al., 2001) (13,590-13,625’). The siltstones are slightly siliceous, argillaceous to shaly, slightly carbonaceous and pyritic. The Kavik Shale is interpreted as having accumulated in a shelf or distal delta front depositional environment. In the Ikpikpuk 1 well plant fragments are present near the top of the section suggesting a more deltaic influence in depositional setting (Haywood, 1983). The Kavik Shale is unconformably overlain by the Ivishak Formation.

The Ivishak Formation thickens to the south and west from the Barrow Arch. It is dominated by distal fine grained siltstones with interbedded shales in the lower section and sandstones interbedded with thin shales in the upper section. In the Ikpikpuk 1 well the lower section (10,732-11,098’) is characterized by red to pink silty shales and siltstones interbedded with carbonaceous sandstone beds interpreted to be marginal marine settings transitioning to bar, or distributary channel deposits. The upper section of the Ivishak (12,640-13,314’) is buff to very light gray, very fine to fine grained, subangular to subrounded, medium to well sorted, siliceous, to quartzitic, and barren of fossils. Core from the upper Ivishak (12,705-12,735’) had very fine grained sandstones with thin interbedded shales displaying numerous sedimentary structures, small-scale ripple laminations, rip-up clasts, bioturbation, and possible high-angle cross beds. These features are indicative of a high energy, near-shore depositional environment. It is a generally regressive sequence and is overlain by the transgressive Fire Creek Siltstone (Wilson et al., 2001).

The Fire Creek Siltstone is comprised of siltstone, mudstone, and minor sandstones. Ripples are present in the siltstone and interbedded sands while parallel laminations are present in the interbedded mudstones. Therefore, the sandstone was deposited at the toe of a delta while the finer grained mudstone was likely deposited via suspension at a distal toe front (Wilson et al., 2001). The Shublik Formation overlies the Fire Creek Siltstone and is the prominent source rock in Prudhoe Bay.
The Shublik Formation is an organic-, phosphate-, and glauconitic-rich, fossiliferous, sandstone and limestone. It grades upwards from fine grained sandstone to siltstone and limestone (Haywood, 1983). Recent work suggests that the high density of organic matter within the Shublik Formation is because the Formation was recorded at a well-developed upwelling zone (Parrish et al., 2002). At the Inigok 1 well the Shublik Formation is dominated by organic-rich limestone and becomes more influenced by siliciclastic deposition northward (Parrish et al., 2002).

**UNDEFORMED ELLESMERIAN STRATA**

Overlying the Sadlerochit Group, but still considered the Middle Ellesmerian Sequence, is the Sag River Sandstone (12,170-12,220’) and Kingak Formation (10,260-12,170’). Due to the gentle northward dip of beds in conjunction with parallel northward thickening of units it is interpreted that the paleo-epeiric sea opened and that true passive margin conditions existed from the Middle Triassic through the Jurassic.
CHAPTER 5

SEISMIC DATA AND INTERPRETATION

The seismic data used in this study is reprocessed 2-D regional seismic profiles across the NPRA (Miller et al., 2000). There are 22 lines, totaling 3,470 line-miles in the data set. Miller et al. (2000) applies the following techniques in reprocessing: post stack amplitude scaling, frequency filtering, noise burst editing, spiking deconvolution, datum statics, NMO (utilizing velocity analysis), and residual static corrections. All of these applications should improve the resolution of the seismic data. Data quality is still considered moderate to poor, especially in the deeper sections. However, the clarity of the enigmatic compressional features in the Lower Ellesmerian Sequence of the Umiat-Ikpikpuk basin is much improved. Poor data quality is likely due to surface topography, permafrost and shallow gas hydrate velocity anomalies, or an inability to shoot directly along the planned line due to extreme weather or sensitive wildlife. Depth converted sections and velocity models were used to create synthetics in order to tie seismic data to well logs (Figure 6, p. 14). For this study lines R-6, R-7, R-8, R-9, R-13, R-14, and R-15 were interpreted in Kingdom Suite (see Figure 1 (p. 1) for locations).

A critical aspect of this study was the ability to identify isochronous horizons in the seismic reflection profiles that could be dated with paleontological data. This was accomplished by tying the biostratigraphic data from the Inigok 1 well report (Haywood, 1983) to the seismic data via synthetic seismograms (Figure 7) and with comparison to Mickey et al. (2006). The Inigok 1 well was chosen due to the completeness of its recorded strata and the extensive work previously completed on its biostratigraphy (Gryc, 1988; Mickey et al., 2006) and burial history (Lerche et al., 1984). Absolute age dates for the time horizons (described below) were inferred from Mickey et al. (2006), which correlated the Mamet and Fusulinid stratal zones to chronostratigraphic zones with absolute ages.

Time horizons were chosen as either unconformities (evidenced by upper boundary onlapping and lower boundary truncation), depositional hiatuses (upper boundary concordance and lower boundary truncation or onlap), or maximum flooding surfaces (basin
A wide transgressive sequence with lower boundary onlap and upper boundary concordance) as seen in Figure 8. Seismic stratigraphic principles were used to map the horizons across all appropriate profiles so that they were representative of an isochronous event (Vail et al., 1977). Several of these horizons did not span the entire basin, but onlapped stratigraphically lower horizons or were truncated by stratigraphically higher horizons instead. The following sections are a summary of the interpreted profiles (Figures 9 and 10).

Basin wide time horizons were picked in the seismic data at the Inigok 1 well based on well core data and prior work on the data set (Bird, 1981; Mauch, 1987; Kulander et al., 2005). The seismic character of North Slope sequence boundaries is well documented in Kulander et al. (2005) and have been assigned absolute age ranges (Mickey et al., 2006). The top of the Endicott Group, top of the Lisburne Group, and top of the Sadlerochit (top of the Shublik Formation) were picked first then tied from the Inigok 1 well to lines R-8 and R-14. Horizons were mapped to seismic profiles R-13 and R-15 at their intersection with R-8 and then the seismic character of the reflections were used to map the horizons across the rest of the profile. Similarly these horizons at seismic profiles R-6, R-7, and R-9 were tied from their intersections with profile R-14. The picked horizons were then quality checked by tying them to the well log and well core information from the Ikpikpuk 1 well (Figure 7, p. 22). Once the formation top horizons were mapped, intrasequence isochronous horizons (Figure 6, p. 14) were then picked using the same workflow.
Figure 8. Displaying seismic stratigraphic relationships between different time horizons on seismic profile R-8 at the location of the Inigok 1 well. Cc- Concordance; Di- Divergence; Dp-Downlap; Hm- Hummocky Strata; On- Onlap. Thrust fault offsetting basement is red.
Figure 9. Interpreted north-south seismic profiles from reprocessed 2D NPRA seismic data. Displayed seismic profiles are boxed on the inset map. Note the difference in scale for each profile.
Figure 10. Interpreted east-west seismic profiles from reprocessed 2D NPRA seismic data. Displayed seismic profiles are boxed on inset map. Note the difference in scale for each profile.
R-6

Seismic profile R-6 is the lowest quality of all the regional profiles. It contains several areas with poor data (i.e. shotpoint 6300-6600). The structural features (faults and fault-related folds) and multi-depocenter geometry common in the other N-S profiles are absent in profile R-6. The basin center also lies farther north in this profile (shotpoint 7200) than in the rest of the dataset (shotpoint 3000-5000). Profile R-6 displays two pronounced depositional hiatuses. This is attributed to the profile transecting structurally high basement, a north-south trending basement high, known as the Meade Arch (Figure 2, p. 2). Kekiktuk Conglomerate is completely absent and Kayak Shale is the first recorded strata. This part of the basin undergoes another depositional hiatus as Mississippian Lisburne Group is also absent until 318 Ma. The mapped Lisburne Group of this profile is significantly thinner than in the rest of the basin. However, the Sadlerochit Group and Shublik Formation almost reach their maximum thicknesses in the north section of this line (shotpoint 6000-8000). Observed thin draping of pre-Sadlerochit Group horizons suggests that this was the western basin margin prior to Sadlerochit Group deposition.

The southern section of the profile displays Brookian Orogeny deformation within the Endicott Group. This is because profile R-6 lies west of the Umiat Platform and its Endicott Group sediments were deposited at more shallow depths. Thrusting of several sections of Lisburne Group carbonates into thick sequences between shotpoint 2500 and 5000 occurred during the Brookian Orogeny (Kulander et al., 2005).

R-7

Profile R-7 displays two basin center faults (shotpoint 4100 and 4300) and two, basin margin, south dipping, faults (shotpoint 5800 and 5400). Deposition does not begin along this profile until ~ 349 Ma. The thick section of Kayak Shale between shotpoint 4500 and 5500 may indicate the basin opened asymmetrically between 3495-345 Ma. Lower Lisburne Group deposition is also absent in this profile and carbonate deposition does not begin until ~333 Ma. North of shotpoint 4400, the Lisburne Group maintains apparent thickness. However, in the basin center, the beds thin over the southward dipping structure at shotpoint 4300 before thickening again between shotpoint 2300 and 3250. This indicates syndepositional uplift of the structure located at shotpoint 4300. Additionally, the apparent
divergence of reflectors in the Lisburne Group along the structure at shotpoint 4050 signifies active growth of reflectors in the hanging wall from 333 to 318 Ma. Data quality is insufficient to resolve the exact fault structure but these faults may form a flower structure, which would indicate a component of strike-slip motion. This structure must have become dormant around 250 Ma as the Sadlerochit Group maintains laterally consistent apparent thickness and appears to have been deposited under quiet tectonic conditions. The thickening of Lisburne Group carbonates between shotpoint 2300-3250 suggests that the basin had both a northern and southern depocenter during Lisburne Group deposition.

The fault at shotpoint 5400, that was normal during Kayak Shale deposition, appears to have inverted briefly during deposition of Lisburne Group carbonates at ~318 Ma. This is inferred from the thinning of apparent thickness between the top of the Endicott Group and the Lower Lisburne Group horizon (336 Ma). The fault at shotpoint 5800 is normal and appears to have been active between 318-299 Ma. This is the western extent of the most northern en echelon, basin margin normal faults. The fault experiences low-magnitude offset and results in divergence of Lisburne Group strata between the 318 and 299 Ma horizons. The NPRA subsided uniformly after Lisburne Group deposition. This is inferred from the consistent apparent thickness of the Sadlerochit Group over both Lisburne Group depocenters. The Shublik Formation onlaps the Fire Creek Siltstone while the Sag River Sandstone onlaps the Shublik Formation at shotpoint 3000 and shotpoint 4200, respectively.

R-8

Profile R-8 displays pre-existing, basin margin, south dipping, en-echelon normal faults and flatten at the Endicott Group-basement contact at shotpoints 4400, 4900, and 5350. The southern end of the profile displays a north dipping, listric, normal fault (shotpoint 2250) that may flatten along the Endicott Group-basement contact but is not well imaged at that point. Additionally, the profile displays high-angle faults that may form a wide flower structure. Folding is associated with the upper termination of the faults (shotpoint 2900, 3250, and 3600). The positive uplift clearly shows that a locally, compressional stress field existed within the basin center during early parts of the basin’s formation. This system of basin center faults may represent the along-strike continuation of the tightly spaced faults at shotpoint 4100 and 4300 of profile R-7. If these faults are related, then this would indicate a
NW-SE trending fault system. These faults are similar to the faults imaged on R-7 and dip to the south. The Inigok 1 well crosses a fault surface at shotpoint 3650 (Haywood, 1983).

This profile displays the most complete stratigraphic sequence within the data set. The basin’s initial depocenter was between shotpoint 2300 – 3000. Kekiktuk Conglomerate rapidly filled ~3,000’ of accommodation space prior to Kayak Shale deposition, which began to accumulate over a northward migrating depocenter. The faults at shotpoints 2900, 3250, and 3600 were likely normal between 352 and 345 Ma, as shown by southward apparent thickening at those locations. However, between 345 and 342 Ma, it is inferred from horizon thinning over the crest of the ramp anticline that motion on the fault at shotpoint 3600 showed thrust motion and formed the anticline.

Several other faults on the profile also show indications of structural inversion but the reversal in motion does not appear to occur simultaneously but rather occurred progressively from east to west. For example, the fault at shotpoint 2900 shows thinning strata that are thickening at shotpoint 3250. The timing appears to begin immediately after the Endicott Group deposition. By 299 and 318 Ma the structures at shotpoint 2900 and 3250 both displayed uplift as shown by thinned strata. Deposition continued between these structures at 318 and 336 Ma.

During Lower Lisburne Group deposition the normal faults at shotpoints 4450, 4900, and 5250 were episodically active providing accommodation space in the north. The carbonates generally are not faulted but instead reflections diverge or converge across the basin center structures based on the compaction and throw being accommodated in the Endicott Group. Between 333 and 318 Ma Pennsylvanian aged strata of the Lisburne Group increased in apparent thickness at both basin depocenters (shotpoints 2300-2900 and 3250-3600). Accommodation space may have been created by compaction of underlying Endicott Group sediments.

By 299 Ma the basin appears to be tectonically inactive as evidenced by lower accumulation rates and an absence of compressional features (thinner strata thickness). A slight northward increase in apparent thickness and lack of faulting in Sadlerochit Group strata suggests that the basin is in a passive margin setting. The upward parabolic reflector at shotpoint 2900 (depth ~3.25 seconds) in the Upper Lisburne Group and Sadlerochit Group strata is either a narrow graben or an artifact of processing. Similar to profile R-7 there is a
northward convergence of the Sag River Sandstone and it onlaps the Shublik Formation at shotpoint 3250.

**R-9**

Profile R-9 displays two, basin margin, south dipping, normal faults in its northern section (shotpoints 4400 and 4600) that flatten at the Endicott Group-basement contact. Additionally, there is another south dipping, basement normal fault at shotpoint 3800. A system of basin center faults, related to those observed in profiles R-8 and R-7 are located at shotpoints 3650, 3400, 3000, and 2600. Similar to profile R-8 the basin subsided asymmetrically. Two north dipping, normal faults (shotpoint 2600 and 3000) and three, south dipping, faults (shotpoints 3400, 3650, and 3800) were normal sense during this time. The basin records Kekituk Conglomerate deposition but there is a depositional hiatus between 352-345 Ma as the two middle Endicott horizons are absent. This depositional hiatus may be indicative of a low relief erosional surface that dips westward towards the basin center. It may also be due to the fluvio-deltaic depositional environment of the lower Endicott Group (Wilson et al., 2001). The channel sourcing the eastern part of the basin may have been starved of sediments during this time, or the channel may have migrated westward towards the deepest part of the basin.

Sometime between 342 and 336 Ma the faults at shotpoints 3400 and 3600 record a local inversion. The thickening of the Lower Lisburne Group between shotpoints 4500 and 3750 suggests that the fault at shotpoint 3800 was active during this time and that the Endicott sediments were likely undergoing compaction. The thinning of the 336 Ma horizon across the faults at shotpoints 3400 and 3650 suggest that the faults were actively thrusting between 342 and 336 Ma. Similar to profile R-8, this local positive uplift (shotpoint 3600) forms two depocenters within the basin. However, this phenomenon is not as pronounced here as it is in profile R-8. The eastern basin records a passive margin setting between 333 and 318 Ma, evidenced by Pennsylvanian aged strata of the Lisburne Group and Permian aged strata of the Sadlerochit Group displaying slight southward thickening, low angle dips (<5°) and are absent of structures. Also similar to profiles R-7 and R-8, the northward thickening of the Shublik Formation, the onlap of the Shublik Formation, and the onlap of
the Sag River Sandstone at shotpoint 3900 support a northward sea level transgression during their deposition.

**R-13**

Profile R-13 displays three north-south trending normal faults (shotpoints 5600, 4350, and 4300. The profile does not record Lower Endicott Group deposition, but begins sedimentation of two depocenters (shotpoints 3500-4250 and 4500-5500) around 345 Ma. These depocenters are separated by the Meade Arch. During Endicott Group deposition the west dipping faults at shotpoint 4050 and 5600, and the graben bounding faults at 4300 and 4350, are active and offset basement, as well as Kayak Shale. Mississippian aged strata of the Lisburne Group are absent and carbonate deposition does not begin until approximately 318 Ma.

The thickening of the Lower Lisburne Group horizon (336 Ma), between shotpoint 4500 and 5250, suggests that the basin subsided more rapidly to the east between 342 and 336 Ma. Conversely, the pronounced thickening of the next stratigraphic horizon within the Lisburne Group (333 Ma) between shotpoints 3500 and 4500, suggests that accommodation space was limited in the east and that subsidence was focused in the western depocenter between 336 and 332 Ma. Additionally the thickening of this horizon over the graben at the crest of the basement high (shotpoint 4300) indicates that the graben bounding faults (shotpoints 4300-4350) reactivated during this time interval. The near vertical, west dipping, strike slip fault at shotpoint 4000 begins displacing Lower Lisburne Group strata during this time. This is the only profile that records this fault and so offset direction is difficult to ascertain. The consistent apparent thickness of strata between 299 and 318 Ma suggests that passive margin conditions existed. The Sadlerochit Group reaches its maximum thickness at shotpoint 3900 and thins to the east. This supports that the western depocenter is more pronounced to the north (Ilpikpuk basin) while the eastern depocenter reaches its maximum thickness to the south (the Umiat basin-also seen in profile R-15). The Sag River Sandstone onlaps at shotpoint 4000 confirming that its deposition is confined to the east of the Meade Arch.
Profile R-14 displays one system of faults- a flower structure- with four eastward dipping splay faults (shotpoints 9800, 10050, 10200, 10250) and one westward dipping fault also flattening at the same decollement surface (shotpoint 10750). This system of faults also contains two antithetic, east dipping faults: one near the 345 Ma horizon (shotpoint 10450) and another near the 352 Ma horizon within the Kekiktuk Conglomerate (shotpoint 10600). An eastward dipping normal fault (shotpoint 11000) near the 345 Ma horizon. This system of faults is recorded on profile R-15 and the horizons it offsets (Lower Endicott Group) suggest that it is related and synchronous with the basin center structures from the north-south profiles. The profile records initial basin subsidence at a depocenter between shotpoint 9500 where a thin lens of Kekiktuk Conglomerate was deposited. The subsequent Endicott Group horizons thicken at the same depocenter and drape onto the Meade Arch to the west. The basin center flower structure maintains normal dip slip during Endicott Group deposition providing accommodation space for sedimentation. The upper Endicott Group (Kayak Shale) thickens in the far west section of the line (shotpoint 8000). The Lower Lisburne Group (horizons 336 and 333 Ma) accumulates in a western basin depocenter (shotpoint 11000-11500) and thins over the faults until onlapping the Meade Arch at shotpoints 9600 and 9400. This suggests that the flower structure experienced a local inversion during this time, which corroborates with the evidence for inversion in the other profiles.

A dramatic shift in the basin’s evolution occurs between 333 and 318 Ma. As seen in profiles R-8 and R-9 the basin center begins to subside at two depocenters (shotpoints 9500-10200 and 11000-11500). The thinning of the strata over the basin center structure may be a result of the inversion between 336 and 333 Ma, or it may suggest that the structure is still experiencing uplift at this time. It is likely that one or two of the fault splays are active but it is difficult to determine because the carbonates do not fault, but converge or diverge due to underlying fault activity. Also making it difficult to determine which fault splays are active, and the time period the inversion ends, is the low resolution of data and the hummocky seismic character across the flower structure within the Lisburne Group (shotpoint 10250-11000). It is clear that between 318-299 Ma the basin center has become tectonically inactive as evidenced by laterally consistent apparent thickness in Pennsylvanian aged strata of the
Lisburne Group and the Permo-Triassic Sadlerochit Group. Sag River Sandstone onlaps the Shublik Formation in the east section of the profile at shotpoint 11500.

**R-15**

Profile R-15 displays graben bounding faults (shotpoint 9600 and 9750), a low angle, west dipping, basin margin, normal fault (shotpoint 10150), two east dipping, basin margin, normal faults (shotpoint 11750 and 12000) with one associated, west dipping, antithetic normal fault (shotpoint 12100), and a basin center flower structure with three west dipping fault splays (shotpoint 10550, 10600,10650) and two east dipping fault splays (shotpoint 11050). The basin records lower Kekiktuk Conglomerate deposition across a symmetric basin (shotpoint 10500-12500), where it reaches its maximum thickness within the data set. However, the basin undergoes a depositional hiatus between 352 and 345 Ma. This suggests that the basin originally subsided at a southern depocenter, with its deepest part transected by profile R-15 (where Kekiktuk Conglomerate reaches maximum thickness), and then subsided further north (as evidenced on profiles R-8 and R-14) before continuing to subside more homogenously across the entire basin. During deposition of Kekiktuk Conglomerate in this southern depocenter (seen in profile R-8 as well) the graben near the crest of the Meade Arch is actively subsiding, as are several of the basin center faults and the pair of eastern basin margin, west dipping, normal faults. Kayak Shale unconformably overlies the Kekiktuk Conglomerate and onlaps the same basement high in the east (shotpoint 12600) and the Meade Arch in the West (shotpoint 9400). During Kayak Shale deposition (345-342 Ma) the west dipping normal fault of the eastern basin margin becomes active and episodically displaces Ellesmerian Sequence strata until approximately 299 Ma. Also during this time the antithetic, east dipping, normal fault of the western basin margin becomes active as evidenced by the local thickening of the Kayak shale overlying it and the divergent seismic character of its reflectors (shotpoint 12100).

Mississippian aged strata of the Lisburne Group (horizons 336 and 333 Ma) is thickest in the basin center (shotpoint 11000-11750), but thins over the western fault splays of the basin center flower structure. As observed in profile R-14, this suggests that these western, east dipping, fault splays experience a local inversion of stress field between 336-
333 Ma. The basin center flower structure in profile R-15 lies directly south of the basin center flower structure in profile R-14 indicating a north-south axis.

The synchronous timing of the inversion along a linear north-south axis suggests that this inversion occurred during one episode as part of a basin wide stress field inversion also observed in profiles R-7, R-8, and R-9. By 318 Ma the basin displays homogenous apparent thickness from east to west indicating a tectonically quiet setting. This setting persists through the rest of Ellesmerian Sequence deposition (299-250 Ma). Sag River Sandstone Formation is not recorded this far south in the basin and must onlap to the north somewhere between profiles R-14 and R-15 (as observed at shotpoint 3250 of profile R-8).

**Compressional Features from Profile R-8**

The clearest example of a compressional feature occurs on line R-8 and is referred to as structure 1(Figure 11). Structure 1 is a high angle fault that offsets basement and ramps up into sedimentary fill. Horizons in the hanging wall create an open asymmetric anticline. The interlimb angle of the anticline increases stratigraphically upward. Horizons on the back limb display long, gentle, back limb dips which are less than the ramp dip but increase with distance from the fault surface. The basal layer (basement complex) is offset by the fault and the hanging wall displays horizontal shortening and thickening (bulges in the anticline core). The fault of structure 1 becomes more steeply inclined as it propagates through Kayak Shale sediment (349 and 345 Ma horizons). The more steeply dipping fault ramp results in a synclinal fault propagation fold as evidenced by thinner horizons over the crest of the ramp anticline and thickening of those horizons in the synclinal fault propagation fold (Allmendinger, 1998). It is difficult to ascertain the pre-thrust architecture of the structure. However, apparent thinning of the 342 and 336 Ma horizons over the crest of the anticline suggests that the fault was actively propagating through the underlying sediments during this time. It should be noted that a flower structure is present in profile R-14 at its intersection with R-8. However, the relationship between the north-south trending flower structure (profiles R-14 and R-15) and the fault propagation folds of profile R-8 is still unclear.

Structures 2 and 3 from Figure 11 overlay two south dipping faults (at depth ~ 4 seconds), which display low-magnitude offsets. These faults flatten with depth and while the horizons they cut show little discrete offset they do display low-magnitude decreasing
Figure 11. Uninterpreted and interpreted screen capture of seismic profile R-8 with observed fault bend fold (structure 1) and fault propagation folds (structures 2 and 3).

apparent thickness over the faults (349 and 345 Ma horizons). It should be noted that offset is difficult to quantify due to the low-intensity of compression (<5% shortening) and loss of seismic character across the interpreted fault planes. The south dipping ramps underlying structures 2 and 3 may be an expression of simple shear propagating north through the hanging wall of the ramp from structure 1. These ramps may have been unable to accommodate progressive, albeit low-intensity, compression in the basin and the higher angle overlying faults may have resulted.

The fault at depth 3.5 seconds underlying structure 3 is synthetic to the more shallow dipping fault at a depth of ~4 seconds and fractures Mississippian aged Lisburne Group
carbonates at the crest of the fold. Horizons overlying structure 3 form a symmetric, gentle fold. The stratigraphically higher fault at structure 2 is a high angle antithetic fault at a depth of 3.5 seconds. This fault exhibits undeterminable displacement. However, reflectors crossing the fault are highly fractured and lose seismic character. This may suggest a strike slip fault oriented oblique to the seismic profile. Deformation across structure 2 is more heterogenous with asymmetric gentle folds in the Endicott Group horizons and more symmetric open folds in Lisburne Group carbonates.

The broad draping and gentle fold tightness of these structures support a fault-propagation mechanism. Fold geometry caused by fault propagation is largely influenced by the ratio between fault propagation and slip along the fault (Allmendinger, 1998). Low magnitude displacement along the fault, the gentle interlimb angle of the folds and low-magnitude apparent thickness changes across the faults all support that for structures 2 and 3 fault propagation was approximately equal to fault displacement (Allmendinger, 1998). Faults underlying structures 2 and 3 appear to have little or no net offset but have created folds. As faults that invert from normal to reverse sense displacement approach zero net offset, deformation will increase upward creating anticlinal folds (Allmendinger, 1998).

Intense fracturing across faults and fault propagation folds confirm that the stress regime of the Ikpikpuk-Umiat basin was compressional from 345 Ma - 299 Ma. Synkinematic accumulation of Kayak Shale and Lisburne Group carbonates was recorded during this time. Loss of seismic character across interpreted fault surfaces with little or no dip slip displacement suggest that faults may obliquely transect profile R-8. Additionally, a multitude of small-scale thrusts cutting 2-3 reflectors across the crests of the folds may be tear faults, as suggested by Mauch (1985), which would suggest wrench deformation caused the low-intensity compression. The presence of flower structures on profiles R-14 and R-15 along strike of profile R-8 also support wrench dominated deformation.
CHAPTER 6

VISUALIZATION

In order to visualize the evolution of these structures the isochronous horizons were flattened within the SMT seismic interpretation software. While flattening on picked horizons provides an approximate visualization of the basin’s evolution, it is not representative of the true genesis of the Ikpikpuk-Umiat basin because this basin did not begin as a flat surface. Rather, a series of actively rifted grabens floored the basin, similar to the Hanna Trough (Sherwood et al., 2002). Therefore, restorations of the N-S seismic profiles (R-7, R-8, R-9) were completed in Midland Valley’s kinematic software suite, Move 2D (Figure 12). Line restoration was used to confirm the age range for localized inversion. The mapped horizons were exported from SMT’s seismic interpretation suite to a kinematic modeling program (Midland Valley’s Move software). In this modeling software suite decompaction analysis was completed for the Endicott Group based on the Inigok 1 and Ikpikpuk 1 well log data. The decompacted horizons were then restored from their current geometry to an inferred slope surface. 2D restoration from stratigraphically higher horizons to lower horizons maintains basement integrity. However, the complex 3D nature of deformation across the faults was unable to be replicated or restored due to a lack of 3D data. Therefore, displacement direction in 2D is inferred from stratigraphic relationships and the geometry of the folds observed. The three north-south seismic profiles provide insight into the evolution of the Umiat basin’s western margin (R-7), basin centre (R-8), and eastern margin (R-9).

The restoration of the western basin margin (R-7), the basin center (R-8), and the eastern basin margin (R-9) all confirm the above interpretations. Most importantly, extension dominates the structures bounding the basin’s depocenter as it subsided asymmetrically. The only difference between the interpretations from the seismic profiles and the restorations is that basin inversion may have occurred as early as 349-345 Ma within the basin center as evidenced in the restoration of profile R-8. Inversion related thrusting continues in the basin center until 333 Ma creating fault propagation folds during early to middle Lisburne Group.
Figure 12. Restorations of western basin margin (R-7), basin center (R-8), and eastern basin margin (R-9) completed in Midland Valley’s 2D Move software suite.
deposition. It should be mentioned that this could be due to the decompaction algorithm performed on the horizons. However, while the decompaction function within the software may have created anomalous artifacts and this may be an example, one would suspect that the decompaction would create more space between horizons subsequently minimizing horizon thinning over inverted structures. Therefore, it is assumed that the relationships observed are accurate. Additionally, it is suggested that the inverted stress field propagated westward as line R-7 experiences basin center thrusting after profiles R-8 and R-9 from 342-299 Ma. It is difficult to determine when profile R-9 records inversion as it experiences a depositional hiatus between 352 and 345 Ma. It may be inferred though that its structures were inverted during that time as thrusting is evident when sediments begin to accumulate again and inversion is observed in the profile from 342-336 Ma.

Profile R-9 is the first profile to record tectonically inactive conditions at 333 Ma while profiles R-8 and R-7 follow, at 299 and 250 Ma, respectively. This progressive shut off of inversion also corroborates with a westward propagating stress field inversion. These restorations suggest that the basin experienced localized synrift inversion from 352 Ma to approximately 299 Ma. It was determined from the restoration of profile R-8, using the line length tool in 2D Move, that compression experienced by the 333 and 318 Ma horizons resulted in approximately 3% shortening. However, because the bed was deposited on an irregular surface it is difficult to determine the geometry of the original depositional surface. Therefore, this calculation simply confirms that compression was low-intensity (<5% shortening).

In order to visualize the basin fault architecture in 3D the interpreted fault surfaces from each 2D profile were interpolated into 3D surfaces within the Move 3D modeling software (Figure 13). This 3D visualization displays the interpreted structure of the basin (Figure 13). Several west-east, northwest-southeast trending basin margin structures and all but one north-south trending structure appear on only one seismic profile and are therefore not imaged. The visualization displays three northwest-southeast trending, en echelon, normal faults in the north part of the basin. There is one northwest-southeast trending extension dominated, basin bounding normal fault to the south. This fault is listric and flattens with depth across profiles R-7 and R-8. Additional normal faults may have existed to the south but may be either sub-seismic, occur on only one profile, or were overwritten.
Figure 13. 3D visualization of Umiat-Ikpikpuk subbasin. Basin bounding extension dominated faults are colored different shades of red. Wrench dominated, basin center structures are colored different shades of blue. The flower structure observed in profiles R-8, R-14, and R-15 is colored green.
As a way to investigate the inversion interpretation, three northwest-southeast basin center faults which may have experienced inversion are visualized. The most northern basin center fault is the first in the basin to experience inversion. The one furthest south only transects profiles R-9 and R-8 and from the restorations it is inferred that this was the second structure in the basin to invert (342 Ma). It experiences episodic reverse dip slip displacement from 345 to 336 Ma. The middle basin center fault inverted initially at 342 Ma and then inversion propagated westward. These two northern basin center faults diverge westward across profiles R-7 and R-8 and then converge east of R-6. Additionally, the faults observed on profiles R-8, R-14, R-15 are imaged and include five main fault splays whose displacement was variable over its life. This structure intersects the two basin center faults.
CHAPTER 7

DISCUSSION

The preceding interpretation demonstrates that the Ikpikpuk-Umiat basin includes high-angle faults with compressional features embedded in the basin. Indications of possible strike-slip movement are also observed, which might explain changes in throw along strike and over time. In the following discussion these features are explained in terms of the regional tectonics and in particular, the Hanna Trough and onshore propagation onto continental affinity crust.

Shortly after the initiation of the Early-Mid Devonian Romanzof Orogeny, several subbasins began to subside on and offshore the Arctic Alaska Terrane (Lane, 2007). The Hanna Trough initiated rifting just prior to the Ikpikpuk-Umiat subbasin and forms a classic rift graben which records Middle Devonian-Permian rift phase subsidence composed of Ellesmerian Sequence strata. The Hanna Trough is divided into two rift segments; a north segment 100 km west of the southern segment connected by a dextral transform fault (Sherwood et al., 2002). As the southern (direction based on current orientation) rift axis approaches onshore Arctic Alaska it rotates counter-clockwise, from N-S to a NW-SE trend and partitions stress across divergent fault splays and previously weakened structures (Figure 2, p. 2).

As rift axis approach continental margins they vary in deformational style (Benes and Scott, 1996). The ocean-continent transition (OCT) is weaker than both the mafic and sialic crusts and is unable to support large shear stresses. Geophysical studies provide evidence for a possible lithospheric boundary underlying the center of the Ikpikpuk-Umiat basin but the existence of a relict OCT is not confirmed as basement has not yet been breached by drilling south of the Inigok 1 well. Offshore, northwest from the NPRA, the rift was accommodated along a single longitudinal ridge (Hanna Trough). However, as rifts approach continental margins, the zone of extension may splay and widen into a number of basement grabens and uplifts (horsts, platforms, arches) forming complex indentations into the margin (Benes and Scott, 1996). The irregular basement surface during Endicott Group deposition in addition to
the high relief experienced during Lisburne Group accumulation supports that the Ikpikpuk-Umiat basin opened as a continental-margin parallel rift propagated across the North Slope in the Mid-Late Devonian. The rapid subsidence of the basin, geophysical anomalies in basement and steep walls of the basin early in the Ikpikpuk-Umiat basin’s genesis suggest that dynamic topography, due to a mantle anomaly, may have influenced the Devonian formation of the Arctic Alaska subterrane.

Seismic analysis from this investigation of enigmatic compressional features observed on 2D NP

RA seismic profiles support that localized compression, or possible wrench-faulting occurred during the Carboniferous, synchronous with deposition of Kayak shale and Mississippian aged Lisburne Group strata. Horizon length analysis in Midland Valley’s 2D Move reveals that compression was low intensity and resulted in <5% shortening of the 333 and 318 Ma horizons. Possible mechanisms which may have caused low intensity compression are differential compaction of underlying sediments, strike-slip faulting, or that the Ellesmerian Orogeny propagated further west than previously thought.

It remains to be seen if differential compaction created the features observed in this investigation as Bird (1981) proposed. The presence of laterally heterogenous delta deposits along with confirmed tight sands in the Endicott Group, fractured limestones in the Lisburne Group, and minimal displacement along the interpreted faults all make this a viable mechanism for some of the draping folds observed in seismic profile R-8 (structures 2 and 3). However, it does not account for the flower structures evident in the basin center, or the intense fracturing in the crests of some of the folds.

Lane (2007) proposed that the Ellesmerian Orogeny was two separate orogenic events. The later Ellesmerian Orogeny deformed rocks in eastern Arctic Alaska and adjacent British Columbia from the Late Devonian through the Carboniferous (Lane, 2007). The Ellesmerian Orogeny produced low-intensity, north vergent thrusting in the Richardson Mountains east of the NPRA (Lane 2007). While the precise orientation of the paleo-North Slope relative to the Richardson Mountains (Yukon terrane) is still debated it may be inferred that Ellesmerian related compression in the Ikpikpuk-Umiat basin would have likely resulted in a north-northwest convergence (Figure 4, p. 4). Northward convergence may have caused the features observed in seismic profiles R-7 and R-8 (fault propagation folds), but it seems
like an unlikely mechanism for the basin center flower structures and the Ikpikpuk-Umiat basin is ~350 miles away from the nearest known Ellesmerian-related deformation.

Oblique extension propagating from the west may have resulted in dextral shear across the Late Paleozoic North Slope (Figure 6, p. 14). Hubbard et al. (1987) was the first to suggest a strike slip/transtensional basin setting for the Ikpikpuk-Umiat basin. A shear zone may have sourced the structures observed in the Ikpikpuk-Umiat basin through either restraining bends, or strain partitioned transtension.

The flower structure underlying the intersection of profiles R-8 and R-14 may be indicative of a restraining bend along the proposed shear zone. While the imaged faults appear to display a slight right step in geometry near these structures (which would be a releasing bend in a dextral system) the dataset is sparse and does not provide enough evidence to support or rule out this mechanism. A restraining bend mechanism suggests a two stage basin formation comprised of an extensional basin origin followed by propagation of a shear system through the basin resulting in localized inversions. This hypothesis does support variable offsets and a progressive propagation of a stress field through the basin. De Paola et al. (2005) suggests that when the primary displacement direction of basin bounding blocks is at a low angle (< 20°) to basin bounding normal faults transtensional stress may spatially partition. Partitioning results in an extension dominated zone at the basin margins (as observed in the northern and southern part of the Ikpikpuk-Umiat basin) and a wrench dominated zone at the basin center. Oblique extension in the extension dominated zone is accommodated along pre-existing, basin bounding, normal faults while wrench related stress in the wrench dominated zone is accommodated along strike slip faults at the basin center. Previously weakened crust in basement, such as the potential OCT that exists in the Ikpikpuk-Umiat basin, has proven to be critical in the formation of transtensional basins as shown by recent analogue modelling (Wu et al., 2009). As displacement increases across the basin center shear, the finite axis of shortening (Z') inverts and swaps with the mediate finite axis (Y') within the wrench dominated zone (De Paola et al., 2005). This swap of the finite axis of shortening and the mediate finite axis results in horizontal shortening within the wrench dominated zone, or inversion. This hypothesis is supported by the similarity in basin margin and basin center faults with those in the analogue modelling of Wu et al. (2009). Additionally, the length to width to depth ratio (2: 1 : .5) of transtensional basin models from
Wu et al. (2009) is strikingly close to that of the Ikpikpuk-Umiat basin (22:12:.7) (Figure 14). This mechanism suggests the basin opened under a transtensional setting and experienced localized inversion as it developed. However, this mechanism has not yet been presented in seismic data and the magnitude of horizontal shortening experienced by the wrench dominated zone is variable.

Figure 14. Isopach Map from the top of the Lisburne Group to the basement. These are interpreted to be the strata deposited during deposition. The depth is in meters. The basin displays a length of 228 km and a length of 124 km. The ratio of dimensions for this basin are similar those modeled in Wu, J. W., McClay, K., Whitehouse, P., and Dooley, T., 2009, 4D analogue modeling of transtensional pull-apart basins: Marine and Petroleum Geology, v. 26, p. 1608-1623.

It is difficult to constrain strike slip shear without 3D seismic data and hence establishing piercing points, the direction of offset, or the magnitude of offset in the NPRA dataset is speculative. It is clear though that a shear system is the best explanation for the features observed in the Ikpikpuk-Umiat basin. To determine whether the structures are a result of a basin-wide change in stress field orientation (extension followed by shear), or merely a local inversion of stress field during continuous transtension (strain partitioning) would require a more detailed understanding of how these events impacted the entire North Slope.
CHAPTER 8

CONCLUSIONS

Biostratigraphically age-constrained horizons mapped on 2D NPRA seismic profiles reveal that the Ikpikpuk-Umiat basin experienced extension followed by a local stress field inversion as evidenced by compressional deformation from 345-299 Ma. The age and mode of deformation described in this investigation suggest that northeast-southwest extension/transtension, in addition to the crustal cooling substantiated in prior work, initiated Ikpikpuk-Umiat basin subsidence in the Late Devonian. Basin bounding normal faults terminating in basement and a system of north-south trending flower structures likely evolved during this time. Either a two stage basin formation of extension followed by a shear propagating through the basin, or rotation in direction of extension/transtension causing strain partitioning resulted in low intensity thrusting. At the onset of the Permian (299 Ma) horizontal compression was not recorded in the Ikpikpuk-Umiat basin and the basin appears to have entered a drift phase. Previously, it was believed that the entire Ellesmerian Sequence recorded passive margin deposition from the Late Devonian through the Triassic (Bird, 1981; Kulander et al., 2005). Detailed analysis from this work confirms that the sequence records a mild inversion during the Carboniferous caused by either a transtensional basin origin, or a shear propagating through an extensional basin.
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