Oil & Natural Gas Technology

DOE Award No.: DE-FC26-06NT41248

Final Report

Unraveling the Timing of Fluid Migration and Trap Formation in the Brooks Range Foothills: A Key to Discovering Hydrocarbons

Submitted by:

Catherine L. Hanks

Dept. of Petroleum Engineering and Geophysical Institute,
University of Alaska
Fairbanks, Alaska 99775
chanks@gi.alaska.edu

Prepared for:

United States Department of Energy
National Energy Technology Laboratory

December 31, 2008

Office of Fossil Energy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ABSTRACT

Naturally occurring fractures can play a key role in the evolution and producibility of a hydrocarbon accumulation. Understanding the evolution of fractures in the Brooks Range/Colville basin system of northern Alaska is critical to developing a better working model of the hydrocarbon potential of the region. This study addressed this problem by collecting detailed and regional data on fracture distribution and character, structural geometry, temperature, the timing of deformation along the Brooks Range range front and adjacent parts of the Colville basin, and the in situ stress distribution within the Colville basin. This new and existing data then were used to develop a model of how fractures evolved in northern Alaska, both spatially and temporally.

The results of the study indicate that fractures formed episodically throughout the evolution of northern Alaska, due to a variety of mechanisms. Four distinct fracture sets were observed. The earliest fractures formed in deep parts of the Colville basin and in the underlying Ellesmerian sequence rocks as these rocks experienced compression associated with the growing Brooks Range fold-and-thrust belt. The orientation of these deep basin fractures was controlled by the maximum in situ horizontal stress in the basin at the time of their formation, which was perpendicular to the active Brooks Range thrust front. This orientation stayed consistently NS-striking for most of the early history of the Brooks Range and Colville basin, but changed to NW-striking with the development of the northeastern Brooks Range during the early Tertiary. Subsequent incorporation of these rocks into the fold-and-thrust belt resulted in overprinting of these deep basin fractures by fractures caused by thrusting and related folding. The youngest fractures developed as rocks were uplifted and exposed.

While this general order of fracturing remains consistent across the Brooks Range and adjacent Colville basin, the absolute age at any one location varies. Fracturing started in the southwest deep in the stratigraphic section during the Late Jurassic and Early Cretaceous, moving northeastward and upsection as the Colville basin filled from the west. Active fracturing is occurring today in the northeastern parts of the Colville basin, north of the northeastern Brooks thrust front.

Across northern Alaska, the early deep basin fractures were probably synchronous with hydrocarbon generation. Initially, these early fractures would have been good migration pathways, but would have been destroyed where subsequently overridden by the advancing Brooks Range fold-and-thrust belt. However, at these locations younger fracture sets related to folding and thrusting could have enhanced reservoir permeability and/or served as vertical migration pathways to overlying structural traps

TABLE OF CONTENTS

DISCLAIMER	i
ABSTRACT	ii
TABLE OF CONTENTS	iii
 CHAPTER 1: <i>Unraveling the timing of fluid migration and trap formation in the Brooks Range foothills: a key to discovering hydrocarbons</i>	
Introduction	1-1
Executive Summary	1-2
Experimental Approach	1-6
Chapter 1 References	1-6
Chapter 1 Figures.....	1-10
 CHAPTER 2: <i>Mechanical stratigraphy and the structural geometry and evolution of the central and eastern foothills of the Brooks Range, Northern Alaska</i>	
Introduction	2-1
Mechanical stratigraphy & structure of Central Brooks Range foothills	2-2
Mechanical stratigraphy & structure of Eastern Brooks Range foothills	2-9
Chapter 2 References	2-15
Chapter 2 Figures.....	2-20
 CHAPTER 3: <i>Structural character, fracture distribution, thermal and uplift history of a transect across the western foothills of the northeastern Brooks Range (eastern transect)</i>	
Introduction	3-1
Surface Observations	3-1
Subsurface Observations.....	3-6
Integration of surface and subsurface data	3-8
Fracture Distribution and Character	3-9
Thermal constraints on faulting, folding, and fracturing	3-13
Geochronologic constraints on deformation.....	3-16
Discussion.....	3-17
Chapter 3 References	3-22
Chapter 3 Figures.....	3-33

Chapter 4: <i>Fracture distribution, thermal history and structural evolution of the central Brooks Range foothills, Alaska</i>	4-1
Abstract	4-1
Introduction	4-2
Regional Geology	4-2
Methods	4-5
Observations	4-6
Reconstructions.....	4-11
Discussion.....	4-13
Conclusions.....	4-15
Chapter 4 References	4-17
Chapter 4 Figures.....	4-24
 CHAPTER 5: <i>Present-day in situ stress distribution in the Colville Basin, northern Alaska and implications for fracture development</i>	5-1
Introduction	5-1
Geologic Setting.....	5-1
Measurement of <i>In Situ</i> Stress	5-2
Results.....	5-4
Discussion.....	5-5
Chapter 5 References	5-6
Chapter 5 Figures.....	5-10
 CHAPTER 6: <i>Integration & Conclusions</i>	6-1
Introduction	6-1
Key Observations.....	6-1
Integration into a regional model	6-2
Implications for hydrocarbon migration and reservoir enhancement	6-5
Conclusions.....	6-5
Chapter 6 References	6-7
Chapter 6 Figures.....	6-8
 BIBLIOGRAPHY	B-1

CHAPTER 1

Introduction:

Unraveling the timing of fluid migration and trap formation in the Brooks Range foothills: A key to discovering hydrocarbons

By

Catherine L. Hanks

Dept. of Petroleum Engineering and Geophysical Institute, University of Alaska
Fairbanks, Alaska 99775 chanks@gi.alaska.edu

The purpose of this study was to develop a model for how fractures evolved in the Colville basin in order to better predict hydrocarbon migration pathways, the timing of hydrocarbon migration, and the timing of trap formation in northern Alaska. This chapter serves as an overview to the whole study. Chapters 2, 3, 4, and 5 detail topical studies conducted as part of this project and the results of those studies. Chapter 6 integrates the findings of these topical studies and draws conclusions that address the project as a whole.

Introduction

Seventy-five percent of Alaska's operating budget comes from hydrocarbon production, and a large part of the state's non-governmental economy is related to hydrocarbon exploration, production and transportation. The vast majority of this production is from the North Slope, a well-established petroleum-producing province with a cumulative production of over 9.9 billion barrels of oil (BBO) and condensate and defined reserves of 6.1 BBO and 26.5 trillion cubic feet of gas. However, the producing and most intensely explored area of the North Slope is limited to the geologically simplest northern margin of the Colville basin. As the established oil fields in the Prudhoe Bay area age, additional hydrocarbon resources need to be discovered in order to keep Alaska's economy healthy. The undeveloped southern Colville basin and adjacent Brooks Range foothills have abundant untapped natural gas potential, but the timing of hydrocarbon generation and migration with respect to trap formation and/or reservoir development is complex and poorly understood.

Understanding the evolution of fractures in the Colville basin hydrocarbon system is critical to developing a better working model of the hydrocarbon potential of the region. Naturally occurring fractures can play a key role in the evolution and producibility of a hydrocarbon accumulation. Fractures can both provide pathways for hydrocarbon migration into a reservoir and enhance permeability within a reservoir. Fractures are also dynamic, and can be damaged or destroyed during drilling and production. Many of the prolific hydrocarbon fields in the Middle East are controlled by fractures, as are some fields in the Canadian foothills, the along-strike equivalent of the Brooks Range foothills. On the North Slope, Lisburne field is a recognized as a naturally fractured reservoir where fractures play a key role in hydrocarbon production (Missman and Jameson, 1991).

Fractures develop at different times during the evolution of a hydrocarbon system, under a variety of conditions and due to a variety of causes. Fracture formation is commonly intimately related to the structural history of the host rocks and is difficult to predict. This study focused on the distribution, conditions and timing of fracture formation in the Colville basin and adjacent Brooks Range foothills of northern Alaska. The goal of the study was to develop a clear picture of when and where fractures developed in the Colville basin in order to better predict oil and gas migration pathways, timing of hydrocarbon migration, and timing of trap formation.

Executive Summary

The purpose of this study was to develop a model for how fractures evolved in the Colville basin in order to better predict hydrocarbon migration pathways, the timing of hydrocarbon migration, and the timing of trap formation in northern Alaska. In order to accomplish this goal, the project had to:

- establish the fracture history of the Brooks Range foothills and adjacent Colville basin
- put that fracture history in a structural/stratigraphic/thermal/geochronologic framework
- determine the current in situ stress state of the Colville basin to establish present-day probable fracture orientations and depth of fracturing
- develop a series of paleogeographic reconstructions showing the orientation and location of fractures

In order to accomplish these goals, detailed structural, thermal and geochronologic data were collected along two surface-to-subsurface transects. A regional in situ stress study of the Colville basin established the present day stress orientations within the basin. This information was then integrated into a model of fracture development in northern Alaska through time.

The major results of the project are:

- The structural style of the Brooks Range range front varies along strike. In the central Brooks Range, the range front is a complex frontal duplex/triangle zone; in the northeastern Brooks Range, the range front consists of a simpler passive roof duplex.
- Despite this variation in structural style, both transects have similar fracture sets. The four fracture sets identified in both areas are:
 - an early filled fracture set related to regional stresses prior to folding and thrusting;
 - a later, filled fracture set that formed during thrusting;
 - two younger, unfilled fracture sets that are related to late folding and/or uplift and unroofing.
- All four fracture sets do not occur throughout the stratigraphic column exposed at the surface. Older, filled fracture sets are restricted to Triassic and older rocks Ellesmerian sequence rocks; for the most part Brookian Jurassic and younger rocks filling the Colville basin exhibit only unfilled fractures related to late folding and/or uplift. This suggests that filled fractures develop at depth.

- Apatite fission track ages suggest that deformation and uplift have been episodic during the late Cretaceous and early Tertiary, with different parts of each transect active at any one time. Uplift in the northeastern Brooks Range is significantly younger than that in the central Brooks Range.
- Thermal data from fracture fill suggest that the early fractures that formed in the foreland basin prior to incorporation in the Brooks Range fold-and-thrust belt initially formed at temperatures in or exceeding the oil generation window, but were subsequently overprinted by higher temperature structures. This implies that these early fractures might have been good migration pathways at one time, but were destroyed by later deformation and would not be good exploration targets. However, fractures that have formed under similar conditions in the Colville basin but have not yet been subject to fold-and-thrust deformation could still act as migration pathways.
- Borehole breakout analysis of wells in the Colville basin indicates that present-day maximum horizontal in situ stress within the Colville basin is oriented NNW. The highest number and greatest length of breakouts occur at $S_v > 80$ Mpa, which corresponds to a depth of ~10,000 feet. This is interpreted as the top of the zone of active fracturing or the ‘fracture window.’
- Paleogeographic reconstructions illustrate how the three sets of deformation-related fractures formed diachronously across the Brooks Range and adjacent Colville basin. The earliest deep basin fractures would have formed during Early Cretaceous time in the southwestern part of the Colville basin where Cretaceous sediment thickness exceeded 10,000 feet. These early fractures were oriented north-south, orthogonal to the Brooks Range thrust front. As the Colville basin filled from the west, more of the basin and underlying passive margin was buried to depths >10,000 feet, and the zone of deep basinal fracturing grew to the northeast. Deep basin fracture orientations remained north-south in orientation until development of the northeastern Brooks Range in Tertiary time, when in situ stress orientations switched to northwest-southeast. This orientation of active fracturing is continuing at depth today.

These results suggest that early deep basin fractures may have served as initial hydrocarbon migration pathways out of the deep basin to accumulations on the Barrow Arch, but probably were not significant migration pathways for later structural traps that formed as the Brooks Range fold-and-thrust belt progressively incorporated the Colville basin sediments. However, fold and fault-related fracturing could have provided vertical migration pathways in these areas as well as enhanced reservoir permeability.

Geologic Setting

The Colville basin lies between the Brooks Range to the south, and the North Slope to the north in a region that has had a long and complex geologic history (Fig. 1.1; Moore and others, 1994). The Colville basin is a foreland basin built on a south-facing late Paleozoic to early Mesozoic passive continental margin. The Brooks Range began to form in Middle Jurassic time with the

collapse of an oceanic basin between an intraoceanic arc to the south and the passive continental margin of northern Alaska. During latest Jurassic and earliest Cretaceous time, collision of the intraoceanic arc with the passive continental margin led to detachment and hundreds of kilometers of northward displacement of oceanic and continental-margin rocks.

Despite the large magnitude of shortening, little sub-aerial topography formed and the Colville basin began as a deep-water foreland basin (e.g., Mayfield and others, 1988; Bird and Molenaar, 1992; Moore and others, 1994). Syndeformational sediments from the Brooks Range were of insufficient volume to fill the basin from the south. Relatively slow deposition continued on the north flank of the basin. Shortly after the main phase of compressional collapse of the continental margin, rifting led to formation of the oceanic Canada basin to the north (present geographic coordinates) in Early Cretaceous time (Grantz and May, 1983; Moore and others, 1994). This resulted in a fundamental change in the northern boundary of the North Slope from a continental interior to a passive continental margin. A major influx of sediment into the Colville basin occurred in mid-Cretaceous time, filling the basin from west to east (e.g., Mull, 1985; Huffman and others, 1988; Molenaar and others, 1988). However, contraction in the Brooks Range continued episodically throughout the Cenozoic to the present, and has resulted in northward progradation of fold-and-thrust deformation into the Colville basin and, in the northeastern Brooks Range, locally across the Cretaceous rifted margin (Grantz and others, 1990; Hanks and others, 1994).

This complex geologic history is reflected in the stratigraphy of the region. The stratigraphy of the northeastern Brooks Range, Colville basin and North Slope can be divided into four distinct depositional sequences (Fig. 1.2; Reiser, 1970; Mull, 1982). The oldest rocks are slightly metamorphosed, deformed Proterozoic to Devonian sedimentary and volcanic rocks. These are overlain by northerly-derived, Mississippian to Lower Cretaceous passive margin sedimentary rocks of the Ellesmerian sequence (Reiser, 1970; Reiser and others, 1980; Lane, 1991; Moore and others, 1994). Jurassic and Lower Cretaceous clastic rocks of the Beaufortian sequence record initial rifting that ultimately led to the formation of the present-day northern Alaska continental margin (Hubbard and others, 1987). These sedimentary rocks are in turn overlain by Lower Cretaceous to recent clastic rocks of the Brookian sequence that are derived from the Brooks Range to the south (Bird and Molenaar, 1992) and fill the Colville basin.

All four sequences contain potential reservoir horizons and the Ellesmerian, Beaufortian and Brookian sequences provide source intervals. Overall, seven petroleum systems have been identified in northern Alaska, ranging from Paleozoic sources and reservoirs to Cenozoic sources and reservoirs (Magoon and others, 2003). Potential traps vary from structural traps in the Brooks Range foothills to structural/stratigraphic and stratigraphic traps along the Barrow arch and within the Colville basin (Bird, 1996).

This multiplicity of potential sources, reservoirs and traps highlights the importance of understanding the timing of hydrocarbon generation and migration within each petroleum system. However, because of the size of the region and the sparsity of the data, efforts of modeling hydrocarbon generation and migration have focused on numerical models based

primarily on the regional distribution and character of source rocks, and the amount of regional sedimentary and/or structural overburden (Lampe and others, 2003; Magoon and others, 2003). These models do not include the influence of fractures either as migration pathways or as a means of enhancing or creating reservoirs.

Previous fracture studies in northern Alaska

Natural fractures can form in a variety of ways under a variety of conditions. Fractures can develop at depth in a basin that is under regional compression in what appear to be undeformed, flat-lying rocks (e.g., Lorenz and others, 1991). Fractures can develop as a response to folding of the same layered rocks (e.g., Stearns and Friedman, 1969; Cooper, 1992). Fractures can also form as the rocks are uplifted as a result of removal of overburden during unroofing (e.g., Hancock and Engelder, 1989)

Because folding incorporates rocks that were originally flat-lying but under compression, fracturing likely occurs repeatedly in a continuum with other structures as rocks in a foreland basin are incorporated into a fold-and-thrust belt (Hanks and others, 2006). In addition, as the understanding of thrust-related folding improves, it becomes increasingly clear that thrust-related folds can develop in a variety of ways, leading to a variety of possible fracture patterns (e.g., Cooper, 1992; Jamison, 1997; Hanks and others, 2004, 2006; Hayes and Hanks, 2008). Thus, the history of fracture development in a fold-and-thrust belt like the Brooks Range and adjacent Colville basin can involve a complex interplay of lithology, mechanical stratigraphy, burial depth, fold type, and uplift history.

Previous detailed fracture studies in the northeastern Brooks Range support this hypothesis (Hanks and others, 1997; Hanks and others, 2002; Hanks and others, 2004, 2006; Hayes and Hanks, 2008). Four fracture sets are observed throughout the range, but not necessarily in every stratigraphic interval or of the same origin (Fig. 1.3). The earliest fractures observed probably formed north of and orthogonal to the fold-and-thrust belt at moderate depths in basinal sediments. These fractures were probably open during hydrocarbon generation and migration. These early fractures are overprinted by fractures and other structures that are related to folding of the rocks when they were incorporated into the fold-and-thrust belt. This deformation and associated fracturing happened at elevated temperatures, reflecting either greater depths of burial or a higher geothermal gradient. In either case, temperatures exceeded the oil and gas generation window. The latest fractures are probably related to compression as the rocks were uplifted and/or stress release as overburden was removed during uplift. These youngest fractures formed at lower temperatures, when hydrocarbons would once again be stable.

Correctly interpreting the multiple generations of fractures and penetrative structures can thus yield important clues to the sequence, conditions, and mechanisms of deformation, which in turn can have profound implications for the timing of hydrocarbon migration and trap development. However, each fold-and-thrust belt is unique, and commonly varies in the timing and character of deformation along its length. Consequently, the timing and conditions of fracture

development can vary both between fold-and-thrust belts and within a single fold-and-thrust belt and its associated basin.

Approach used in this project/Experimental procedure

This project involved three separate tasks that were done as student masters theses: two subsurface-to-surface transects and a regional subsurface study of the Colville basin (Figure 1.1). Detailed summaries of these projects are included in this report as Chapters 3, 4 and 5. Regional structural analysis provided a context for this detailed work and is summarized in Chapter 2.

For the two transects, detailed structural, thermal and geochronologic data were collected across the Brooks Range foothills/Colville basin transition. Surface data were collected on foot from helicopter-placed spike camps; existing seismic data were reinterpreted for the subsurface parts of each transect. Apatite fission track analyses and modeling were done by P. O'Sullivan (AtoZinc); M. Parris (PetroFluid Solutions) conducted microthermometry on fracture fill. Organic-rich samples were analyzed for thermal maturity by the U.S. Geological Survey laboratories, courtesy of D. Houseknecht.

This new and existing surface and subsurface structural, thermal and geochronologic data were integrated into balanced cross sections of each transect. *LithoTect* (Geo-Logic Systems) was used for some of the balancing and restorations.

The regional study of the in-situ stress distribution throughout the Colville basin and North Slope subsurface used primarily borehole breakout analysis of existing wells. This study constrained the type, orientation and depth at which open fractures are currently forming today (Ch. 5).

The detailed work in these topical studies was then integrated with existing regional analyses into a series of paleogeographic reconstructions showing possible past distribution of open fracture networks within the Colville basin and thus the orientation of basin-scale fluid flow through time (Ch. 6).

References*

(*references for each subsequent chapter are included at the end of that chapter)

- Bird, K., 1996, Region 1: Alaska: *in* Gautier, D.L., Dolton, G.L., K.I. Takahashi, K.I., and K.L. Varnes, K.L., eds., 1995 National assessment of United States Oil and Gas Resources—Results, Methodology, and Supporting Data, U.S. Geological Survey Digital Data Series DDS-30, Release 2.
- Bird, K.J., and Molenaar, C.M., 1992, The North Slope foreland basin, *in* Macqueen, R.W., and Leckie, D.A., eds., Foreland basins and foldbelts: American Association of Petroleum Geologists Memoir 55, p. 363-393.

- Cooper, M., 1992, The analysis of fracture systems in surface thrust structures from the foothills of the Canadian Rockies, *in* McClay, K., ed., Thrust Tectonics, Chapman & Hall, London, p. 391-405.
- Grantz, A., and May, S.D., 1983, Rifting history and structural development of the continental margin north of Alaska, *in* Watkins, J.S., and Drake, C.L., eds., Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 77-100.
- Grantz, A., May, S.D., and Hart, P.E., 1990, Geology of the Arctic continental margin of Alaska, *in* Grantz, A., Johnson, L., and Sweeney, J.F., eds, The Arctic Ocean region: Geological Society of America, Boulder, Colorado, The Geology of North America, v. L., p. 257-288.
- Hancock, P.J., and Engelder, T., 1989, Neotectonic joints: Geological Society of America Bulletin, v. 101, p. 197-1208.
- Hanks, C.L., Lorenz, J., Teufel, L. and Krumhardt, A.P., 1997. Lithologic and structural controls on natural fracture distribution and behavior within the Lisburne Group, northeastern Brooks Range and North Slope subsurface, Alaska. American Association of Petroleum Geologists Bulletin 81, 1700-1720.
- Hanks, C.L., Wallace, W.K., Lorenz, J., Atkinson, P.K., Brinton, J., and Shackleton, J.R., 2002, Timing and character of mesoscopic structures in detachment folds and implications for fold development--an example from the northeastern Brooks Range, Alaska, *in* Wallace, W.K., and others, The influence of fold and fracture development on reservoir behavior of the Lisburne Group of northern Alaska: Fourth semiannual report, Department of Energy, award DE-AC26-98BC15102, p. E1-E24.
- Hanks, C. L., Parris, T. and Wallace, W.K., 2006, Fracture paragenesis & microthermometry in Lisburne Group detachment folds: implications for the thermal and structural evolution of the northeastern Brooks Range, Alaska: AAPG Bulletin, vol. 90, no. 1, p. 1-20.
- Hanks, C.L., Wallace, W.K., Atkinson, P.K., Brinton, J., Bui, T., Jensen, J., Lorenz, J., 2004, Character, relative age and implications of fractures and other mesoscopic structures associated with detachment folds: an example from the Lisburne Group of the northeastern Brooks Range, Alaska: Bulletin of the Canadian Society of Petroleum Geologists. vol. 52, no. 2 (June, 2004), p. 121-138.
- Hanks, C.L., Wallace, W.K., and O'Sullivan, P., 1994, The Cenozoic structural evolution of the northeastern Brooks Range, Alaska, *in* Thurston, D., and Fujita, K., eds., 1992 Proceedings International Conference on Arctic Margins, U.S. Minerals Management Service Outer Continental Shelf Study 94-0040, p. 263-268.

- Hayes, M. and Hanks, C.L., 2008, Evolving mechanical stratigraphy during detachment folding: *Journal of Structural Geology*, vol. 30, pp. 548-564.
- Houseknecht, D.W., and Bird, K.J., 2006, Oil and gas resources of the Arctic Alaska petroleum province: U.S. Geological Survey Professional Paper 1732-A, 11 p., available online at: <http://pubs.usgs.gov/pp/pp1732a/>
- Hubbard, R. J., Edrich, S. P., and Rattey, R. P., 1987, Geologic evolution and hydrocarbon habitat of the "Arctic Alaska Microplate": *Marine and Petroleum Geology*, vol. 4, no. 1, p. 2-34.
- Huffman, A.C., Jr., Ahlbrandt, T.S., and Bartsch-Winkler, S., 1988, Sedimentology of the Nanushuk Group, North Slope, *in* Gryc, G., ed., 1988, *Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982*: U.S. Geological Survey Professional Paper 1399, p. 281-298.
- Jamison, W.R., 1997, Quantitative evaluation of fractures on Monkshood anticline, a detachment fold in the foothills of western Canada: *American Association of Petroleum Geologists Bulletin*, v. 81, no. 7, p. 1110-1132.
- Lampe, C., Peters, K.E., Magoon, L.B., Bird, K.J., and Lillis, P.G., 2003, The Shublik's petroleum systems of the Alaskan North Slope—a numerical journey from source to trap: *American Association of Petroleum Geologists Abstracts with Programs*, p. A98.
- Lane, L.S., 1991, The pre-Mississippian "Nerukpuk Formation," northeastern Alaska and northwestern Yukon: review and new regional correlation: *Canadian Journal of Earth Sciences*, v. 28, p. 1521-1533.
- Lorenz, J. C., Teufel, L. W., and Warpinski, N. R., 1991, Regional fractures 1: A mechanism for the formation of regional fractures at depth in flat-lying reservoirs: *American Association of Petroleum Geologists Bulletin*, v. 75, no. 11, p. 1714-1737.
- Magoon, L.B., Lillis, P.G., Bird, K.J., Lampe, C., and Peters, K.E., 2003, Alaskan North Slope petroleum systems: *American Association of Petroleum Geologists Abstracts with Programs*, p. A111.
- Mayfield, C.F., Tailleux, I.L., and Ellersieck, I., 1988, Stratigraphy, structure, and palinspastic synthesis of the western Brooks Range, northwestern Alaska, *in* Gryc, G., ed., *Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982*: U.S. Geological Survey Professional Paper 1399, p. 143-186.
- Missman, R. A., and J. Jameson, 1991, An evolving description of a fractured carbonate reservoir: the Lisburne field, Prudhoe Bay, Alaska, *in* R. Sneider, W. Massell, R. Mathis, D. Loren, and P. Wichmann, eds., *The integration of geology, geophysics, petrophysics,*

- and petroleum engineering in reservoir delineation, description, and management: First AAPG–SPE–SPWLA Archie Conference, Houston, Texas, October 22–25, 1990, p. 204–224.
- Molenaar, C.M., Egbert, R.M., and Krystinik, L.F., 1988, Depositional facies, petrography, and reservoir potential of the Fortress Mountain Formation (Lower Cretaceous), central North Slope, Alaska, *in* Gryc, G., ed., 1988, Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 257-280.
- Moore, T.E., Wallace, W.K., Bird, K.J., Karl, S.M., Mull, C.G., and Dillon, J.T., 1994, Chapter 3: Geology of northern Alaska, *in* Plafker, G., and Berg, H.C., eds., The geology of Alaska: Geological Society of America, Boulder, Colorado, The Geology of North America, v. G1, p. 49-140.
- Mull, C.G., 1982, Tectonic evolution and structural style of the Brooks Range, Alaska: an illustrated summary, *in* Powers, R.B., Ed., Geologic studies of the Cordilleran thrust belt: Rocky Mountain Association of Geologists, Denver, Colorado, v.1, p.1-45.
- Mull, C.G., 1985, Cretaceous tectonics, depositional cycles, and the Nanushuk Group, Brooks Range and Arctic Slope, Alaska, *in* Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 7-36.
- Reiser, H.N., 1970, Northeastern Brooks Range--a surface expression of the Prudhoe Bay section, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: American Association of Petroleum Geologists Pacific Section, p. K1-K13.
- Reiser, H.N., Brosgé, W.P., Dutro, J.T., Jr., and Detterman, R.L., 1980, Geologic map of the Demarcation Point quadrangle, Alaska: U. S. Geological Survey Miscellaneous Investigations Series Map I-1133, scale 1:250,000, 1 sheet.
- Stearns, D., and Friedman, M., 1969, Reservoirs in fractured rock in stratigraphic oil and gas fields: Classification, exploration methods, and case histories: American Association of Petroleum Geologists Memoir 16, p. 82-106.

Figure 1.1.

A. Map of the North Slope and northern Brooks Range showing National Petroleum Reserve of Alaska (NPRA) and the Arctic National Wildlife Refuge (ANWR) boundaries and the area of petroleum production around Prudhoe Bay.

B. Generalized geologic map of the North Slope and northern Brooks Range showing major tectonic elements and the areas of study summarized in this report. Modified from Moore and others, 1994.

Figure 1.2. Generalized stratigraphic column for the Arctic Alaska Petroleum Province showing known and potential reservoir and source rocks. Modified from Houseknecht and Bird (2005).

Figure 1.3. Time-Temperature-Depth chart showing tectonic environments of fracture formation and possible burial and uplift paths of the Lisburne Group and Permian to Triassic Echooka Formation in the northeastern Brooks Range (curves i, ii and iii). Schematic cross sections A-E illustrate the proposed structural conditions during the development of different fracture sets, with fracturing occurring at the ☆. See Hanks et al, 2006 for complete discussion.

CHAPTER 2

Mechanical stratigraphy and the structural geometry and evolution of the central and eastern foothills of the Brooks Range, northern Alaska

By

Wesley K. Wallace

Geophysical Institute and Department of Geology and Geophysics, University of Alaska, Fairbanks, Alaska 99775, wallace@gi.alaska.edu.

In collaboration with (in alphabetical order):

Paul L. Decker, Alec S. Duncan, Emily S. Finzel, Robert J. Gillis, Ellie E. Harris, Andrea M. Loveland, C. Gil Mull, Paul B. O'Sullivan, Paige R. Peapples, Rocky R. Reifensuhl, Robert F. Swenson, and Marwan A. Wartes.

Introduction

This chapter provides an overview of the structural framework and evolution of the central and eastern Brooks Range foothills. While numerous sources of information are available on specific areas and aspects of this region, the study and understanding of the region remain in relative infancy, and very little work specifically addresses the structural geology of the region. The objective of this chapter is to provide a coherent overview and understanding of the structural geometry and evolution of the region that is difficult to obtain from the existing published literature.

This overview is based on the understanding I have developed of the northern Brooks Range and its foothills during the course of fieldwork since 1983. The synthesis presented here is my own, although the observations and concepts are supported by work published by many authors. The observations and interpretations of Gil Mull have been especially helpful in establishing a framework for understanding the structural geometry and evolution of the foothills. Parts of the region are covered by U.S. Geological Survey 1:250,000 scale geologic maps (Brosge et al., 1979; Bader and Bird, 1986 (and the sources thereof); Kelley, 1990), but a more recent program of 1:63,360 mapping in the foothills by the Alaska Division of Geological and Geophysical Surveys has been particularly helpful in defining and documenting foothills structure. This overview relies especially on observations from two map areas each in the central foothills (Siksikpuk River: Peapples et al., 2007; Cobblestone Creek: Mull et al., in press) and in the eastern foothills (Shaviovik River: Reifensuhl et al., 2000; Kavik River: Wartes et al., in prep.). Master's theses done by Alec Duncan (2007) and Andrea Loveland (in prep.) as part of the project covered by this report also documented important aspects of the structure of the area. I have independently reached a number of conclusions similar to those presented by Moore et al. (2004) based on their work farther to the west, although our interpretations differ in some details.

A variety of new observations and concepts developed over the past decade or so allows a synthesis that was not previously possible. In particular, the orogenic wedge concept provides a framework to explain how the foothills have evolved and why structures such as duplexes, triangle zones, and breaching thrusts formed where they did. The orogenic wedge concept also led to a new model for the geometry and evolution of foreland basins that is directly applicable to the Brooks Range foothills. It has long been recognized that the Brooks Range formed during multiple phases of deformation, but extensive fission-track thermochronology has provided new insight into the absolute age and areal distribution of deformational events.

This overview addresses the part of the foothills from the Killik River on the west to the Canning River on the east. The central foothills (Killik River to Ribdon and Sagavanirktok Rivers and the eastern foothills (Ribdon and Sagavanirktok Rivers to Canning River) are presented separately because they represent two different stages of evolution in which different structures formed in different stratigraphy. Structures in the central foothills formed first, during the two major phases of evolution of the main axis of the Brooks Range, and those in the eastern foothills formed during the later evolution of the northeastern Brooks Range. The mechanical stratigraphy played a fundamental role in the types of structures that formed in both areas, so that is the starting point for discussion of each area.

Mechanical stratigraphy and structure of the central Brooks Range foothills

The foothills of the central Brooks Range consist of far-travelled allochthons of the Brooks Range orogen to the south, near the mountain front, and deformed foreland basin deposits to the north (Figure 2.1). Interpretations of the complex stratigraphy and structure of the boundary between these two elements are controversial and continue to evolve (e.g., Mull, 1982, 1985; Moore et al., 1994, 2004; Mull et al., 2003). The results presented in this report support the interpretation that the southern part of the foothills is underlain by the tip of a northward-tapered allochthonous wedge that was emplaced during the initial Middle Jurassic to Early Cretaceous large-displacement (several hundred kilometers) phase of evolution of the orogen. This was succeeded by uplift and erosion in mid-Cretaceous time that provided sediments to the foreland basin to the north, which filled from the west and south. The onset of this uplift and erosion coincided with large-scale extension in the southern Brooks Range. Small-displacement and probably local contraction in the northern Brooks Range and southern foothills may have accompanied and/or post-dated extension and was followed by relative tectonic quiescence during the Late Cretaceous. A major orogenic event in Paleocene time deformed both the previously emplaced allochthons and the foreland basin deposits in the southern foothills. This event created the present topographic Brooks Range and the conspicuous structures in the foreland basin deposits, but involved only relatively small displacement (several tens of kilometers).

This section summarizes the major mechanical-stratigraphic and structural elements of the central Brooks Range foothills. The summary includes the following parts: the mechanical stratigraphy and structural geometry of the allochthons, the mechanical

stratigraphy of the foreland basin deposits, the geometry and kinematics of structures formed during mid-Cretaceous to Paleocene time, and the sequence of events in the structural evolution of the foothills.

Mechanical stratigraphy and structural geometry of the allochthons

Major displacement in Middle Jurassic to Early Cretaceous time resulted in the structural stacking of seven stratigraphically distinct allochthons in the Brooks Range (Mayfield et al., 1988; Moore et al., 1994) (Figure 2.2). The two uppermost allochthons were derived from the intra-oceanic arc and ocean that lay to the south of Arctic Alaska, and the five lower allochthons represent the detached and displaced stratigraphic cover of the late Paleozoic to early Mesozoic south-facing passive continental margin of Arctic Alaska. These allochthons are stacked from top to bottom in the order in which they were emplaced from south to north. The allochthons are not laterally continuous single sheets, but instead are structurally duplicated in some places or absent in others. The five sedimentary allochthons represent a complex paleogeography of basins and platforms. Only the lowest and most extensive of the allochthons, the Endicott Mountains allochthon (EMA), is extensively present in the area of this study, so it is the only one that will be described.

The EMA in the central Brooks Range foothills consists of two thick competent mechanical-stratigraphic intervals that are bounded above and below by incompetent intervals that serve as detachments for folds and thrust faults (Wallace et al., 1997) (Figures 2.3 and 2.4). The lower competent interval is the Upper Devonian to Lower Mississippian Kanayut Conglomerate, which consists of conglomerate, sandstone, and interbedded shale and mudstone. Folds and thrust faults in the Kanayut Conglomerate are rooted in the underlying thick Upper Devonian Hunt Fork Shale. The Lower Mississippian Kayak Shale separates the Kanayut Conglomerate from overlying competent carbonates of the Mississippian Lisburne Group. Folds and thrust faults in the Lisburne Group typically are rooted in the Kayak Shale. Thin-bedded mudrock, siliceous mudstone, and argillaceous limestone of the Pennsylvanian Siksikpuk and Triassic Otuk Formations form a thick, relatively incompetent interval above the Lisburne Group. This interval forms an upper detachment above the Lisburne Group as well as being shortened internally by complex folds and thrust faults.

The uppermost element of the EMA is the Lower Cretaceous (Berriasian to Valanginian) Okpikruak Formation, which consists of turbidites, broken formation, and *mélange* (Mull, 1985, 1997; Crane, 1987; Molenaar, 1988; Peapples et al., 2007) (Figure 2.4). The turbidites display complex folds and thrust faults. The broken formation consists of structurally disrupted beds of graywacke sandstone in a scaly argillite matrix. The *mélange* is broken formation that also includes internally deformed lenses and tabular blocks of different rock units, the largest of which extend laterally up to several kilometers. The lenses and blocks in the *mélange* are most commonly chert from the Picnic Creek or Iqnavik River allochthons, but also include basalt, diabase, and carbonate from these and other allochthons, including EMA itself. This unit was previously interpreted to represent the thin leading edge of the Picnic Creek or Iqnavik River

allochthons (e.g., Mull et al., 1997), but is interpreted here to be turbidites and olistostromes that were deposited on the leading edge of the EMA during its emplacement (Crane, 1987; Peapples et al., 2007). The Okpikruak probably formed a veneer on the north-dipping front edge of the allochthon and a depositional wedge that accumulated in the bottom of the basin ahead of the allochthon. Thus, the Okpikruak is the highest and farthest forward element of the allochthon. The broken formation and *mélange* are interpreted to have originated during syn-tectonic olistostrome deposition, but these incompetent rocks have been overprinted everywhere to varying degrees by later tectonic deformation. The unit generally has deformed incompetently because it is dominantly fine-grained and thin-bedded.

Mechanical stratigraphy of the foreland basin deposits

The stratigraphically lowest rock units deposited after emplacement of the EMA include the Fortress Mountain Formation (Figures 2.3 and 2.4) and the related Cobblestone Sandstone and “Eo-Fortress Mountain formation” (Mull, 1982, 1985; Molenaar, 1988; Mull et al., 1997, in press; Peapples et al., 2007). The Fortress Mountain Formation consists of interbedded sandstone, conglomerate, and mudrock. The lower part of the unit typically consists of a fine-grained and thin-bedded interval, whereas the much more competent upper part is much coarser-grained and thicker-bedded. The unit is generally proximal with a high percentage of coarse-grained rocks, but it varies greatly over short distances in thickness, grain size, and bed thickness. The age of the unit is not known with precision, but it is generally interpreted to be Aptian to Albian, and locally possibly as old as Hauterivian (Peapples et al., 2007). The unit overlies the Okpikruak Formation and older rocks of EMA on a regionally important angular unconformity that is interpreted to indicate that EMA was emplaced prior to deposition of the Fortress Mountain (Mull, 1982; Mull et al., 1997; Moore et al., 2004). The interlayering of fine- and coarse-grained intervals and the well-defined bedding of the unit favor formation of rounded folds whose size and character correspond with the local thickness and competency of the unit.

Locally in the southern foothills, a texturally and compositionally more immature unit, informally known as the “Eo-Fortress Mountain formation” (Peapples et al., 2007), appears to occupy a stratigraphic position between the Okpikruak Formation and the Fortress Mountain proper. No fossils are known from the unit, but it is presumed to be bracketed between Valanginian and Aptian. This unit is dominantly coarser-grained, thicker-bedded, and more poorly organized than the Fortress Mountain and so forms folds that are more variable in geometry.

The Cobblestone Sandstone is interpreted to be a distal member of the Fortress Mountain Formation that may be older than most of the rest of the unit (Harris et al., 2002; Mull et al., in press). It consists dominantly of thin-bedded sandstone that has been deformed into imbricate thrust faults or folds that are generally tighter and of shorter wavelength than in the rest of the unit.

In the subsurface of the Colville basin to the north, the distal equivalent of the Fortress Mountain Formation is finer-grained and thinner-bedded than the more proximal Fortress Mountain exposed near the range front. It consists of basin-bottom turbidites that were covered by progradation of slope clinoforms in the overlying Torok Formation. This interval is identified either as Fortress Mountain or lower Torok in the subsurface (Molenaar, 1988; Bird and Molenaar, 1992; Kumar et al., 2002), but it is referred to here as “distal Fortress Mountain” to distinguish it from the very different proximal Fortress Mountain and from overlying Torok that displays different reflector character and structural behavior. The structure of distal Fortress Mountain is typically poorly resolved in seismic reflection data, but it locally displays complex short-wavelength folds and minor thrust faults.

The Torok Formation is a thick succession dominated by monotonous shale to mudstone that overlies the Fortress Mountain Formation (Molenaar, 1988; Bird and Molenaar, 1992; Houseknecht and Schenk, 2001) (Figures 2.3 and 2.4). The Torok is a regionally important detachment interval that separates the complex structures in the older units exposed near the range front from the rhythmic map-scale folds in younger units that typify most of the foothills to the north. The Torok typically displays sub-map-scale chevron folds and local minor thrust faults.

The Nanushuk Formation gradationally overlies the Torok Formation and thickens and coarsens upward (Huffman, 1985; Mull, 1985; Huffman et al., 1988; Mull et al., 2003) (Figures 2.3 and 2.4). The lower part is dominantly thin-bedded fine-grained sandstone and the upper part consists of medium-grained sandstone to conglomerate in thick beds separated by shale intervals. The upward increase in thickness and grain-size of competent intervals and their separation by incompetent intervals results in the formation of map-scale flat-bottomed synclines and rounded to cusped anticlines.

In summary, the depositional character and geometry of the foreland basin deposits played a significant role in the structural architecture of the southern foothills (Figure 2.4). The proximal Eo-Fortress Mountain and Fortress Mountain formed a mechanically competent but highly variable interval restricted to a narrow wedgetop position immediately north of the present range front. More distal equivalents of the Fortress Mountain, including the Cobblestone Member, formed a less competent interval that is present locally along the range front but is laterally extensive into the foreland basin, where it was deposited on the autochthon. The Torok Formation serves as a laterally extensive detachment interval that separates distinct structural styles in the distal Fortress Mountain below and the Nanushuk Formation above.

Structural architecture of the southern foothills

Two new concepts help to provide a new and clearer understanding of the structural architecture of the southern foothills. The first concept is that orogens evolve as wedges that structurally thicken internally until they are strong enough to move above a basal detachment (e.g., Dahlen and Suppe, 1988; Willett et al., 1993). They grow and move into their foreland through a complex interplay among internal thickening, basal

displacement, incorporation of new material at the base and front of the wedge, and removal of material by erosion and extension at the top of the wedge. The second concept applies the first to the geometry and evolution of foreland basins (DeCelles and Giles, 1996). The traditional model is that fold-and-thrust belts are displaced over the adjacent foreland basin on a thrust fault (Figure 2.5A). DeCelles and Giles (1996) proposed a new model in which proximal foreland basin sediments are deposited on the leading edge of the orogenic wedge (Figure 2.5B). As the orogenic wedge deforms internally and moves into the foreland, it incorporates both the wedge-top deposits and deposits accumulated in the foredeep ahead of the previous wedge tip.

The structural architecture of the southern foothills can be subdivided into several elements that reflect their position relative to the allochthonous wedge and within the mechanical stratigraphy. These elements are systematically arranged and exposed stratigraphically and structurally up-section from south to north (Figures 2.6 and 2.7).

This structural style displayed by the Endicott Mountains allochthon was described and named a multistory duplex wedge by Wallace et al. (1997) (Figure 2.8). The allochthon forms a northward-tapered structural wedge in which duplexes of thrust-truncated folds in the Kanayut, Lisburne, and Siksikpuk/Otuk and structures in the Okpikruak formed separately between their bounding detachments (Figures 2.6 and 2.8). The basal detachment of the allochthon cuts up section to the north, so the wedge thins and the strata at its base become progressively younger northward. The detachments within the wedge typically define a gentle regional north dip as a consequence of displacement and thickening of the wedge, but the north-vergent thrust-faults in the duplexes between detachments generally dip to the south.

The Kanayut and Lisburne form boxy, asymmetrical overturned map-scale folds that are cut and displaced northward by thrust faults (Wallace et al., 1997; Peapples et al., 2007) (Figure 2.6). The thinner Lisburne forms smaller folds and more closely spaced thrust faults than the underlying Kanayut. Displacement on younger, lower thrust faults commonly caused folding of overlying structures and significant structural relief formed locally where multiple thrust faults overlapped to create antiformal stacks. Overall structural relief decreases northward within the allochthonous wedge, with more local changes in structural relief over antiformal stacks. The topography reflects where the erosion surface meets relief on underlying units that are more resistant to erosion. Most significantly, the range front marks the point where the erosion surface meets an abrupt southward increase in structural relief in the Lisburne in the central foothills, but locally in the Kanayut farther west.

The overlying Siksikpuk/Otuk and Okpikruak display less systematic folds and thrust faults that are smaller and typically sub-map-scale (Mull et al., 1997 and in press; Harris et al., 2002; Peapples et al., 2007). These units are less resistant to erosion than Lisburne and Kanayut, and typically are more poorly exposed in subdued topography north of the range front or surrounding more local structural and topographic highs.

The overlying Fortress Mountain Formation displays a generally simpler map-scale “rumpled rug” style of deformation (Mull, 1982; Peapples et al., 2007) (Figures 2.6 and 2.7) that probably reflects both its mechanical stratigraphy and the fact that it was deformed only after emplacement of the EMA. The structure is relatively well exposed because much of the unit is resistant to erosion. The unit typically forms rounded map-scale folds that locally are broken by thrust-faults that most commonly dip to the south. The folds display changes in plunge along trend that commonly are abrupt and steep, and which probably reflect east-west shortening superposed on the north-south shortening that formed the main folds. Local abrupt reversals in plunge along synclines have produced basin-shaped erosional remnants that commonly are referred to as “thumbprint synclines”.

The EMA, the overlying Fortress Mountain Formation, and the southernmost part of the Torok Formation define a northward-tapered structural wedge (Wallace et al., 1997, Moore et al., 2004) (Figure 2.6). This wedge originated as the northern leading edge of the Endicott Mountains allochthon. After emplacement of the allochthon, parts of the Fortress Mountain and Torok Formations were deposited on top of the wedge front, and then were structurally incorporated into the wedge as deformation propagated northward into the foreland basin. In addition to the “rumpled rug” folds in the Fortress Mountain Formation, this deformation included relatively steep and widely spaced (5-10 km) thrust faults that breached existing structures (Wallace et al., 1997; Moore et al., 2004; Peapples et al., 2007; Mull et al., in press) (Figure 2.6). These breaching thrusts are present at least from the range front northward to the belt of Torok exposure. The breaching thrusts cut across pre-existing structures in both the allochthon and the overlying Fortress Mountain and Torok and thrust-related folds commonly are associated with them. Surface exposures indicate that they cut through section at least from Kanayut through Torok, and seismic reflection data suggest that they may originate beneath the allochthon, from a detachment in Kayak Shale of the parautochthon (Figure 2.6).

The Torok Formation is exposed in a linear belt along strike that separates Fortress Mountain Formation to the south from the southern edge of the Nanushuk Formation (Peapples et al., 2007; Mull et al., in press) (Figure 2.7). The Torok-Nanushuk contact lies for much of its length at the base of the Tuktu escarpment, a prominent topographic feature that reflects the much greater resistance to erosion of the Nanushuk Formation above a gently north-dipping contact (Moore et al., 1994, 2004). Beneath the Tuktu Escarpment, the prevalence of south-vergent asymmetrical chevron folds and thrust faults in the upper part of the Torok supports the interpretation that the escarpment overlies a major zone of backthrusting (Duncan, 2007; Peapples et al., 2007). The location and geometry of this backthrust zone supports the interpretation that it is the roof thrust above a triangle zone that accommodated thickening of the underlying wedge by breaching thrusts and associated folds (Figure 2.6).

The Nanushuk Formation is characterized by wide flat-bottomed synclines separated by cusped anticlines (Mull, 1982, 1985; Moore et al., 1994, 2004; Peapples et al., 2007; Mull et al., in press) (Figures 2.6 and 2.7). The anticlines commonly are cut by relatively steep and low-displacement thrust faults. Both north- and south-vergent folds and thrust

faults are present, but south vergence is more common. Local exposure and seismic reflection data indicate that sub-map-scale folds and thrust faults in the Torok and distal Fortress Mountain accommodated thickening in the cores of the anticlines. The structural geometry supports the interpretation that folds in the competent Nanushuk formed as detachment folds above localized thickening in Torok and distal Fortress Mountain.

Structural evolution of the central Brooks Range foothills

Collision of an intra-oceanic arc resulted in detachment and structural stacking of the sedimentary cover of a south-facing passive margin in a series of allochthons (Mayfield et al., 1988; Moore et al., 1994) (Figures 2.2B and 2.9A). Emplacement of the allochthons involved very large displacements (hundreds of kilometers), but resulted in little or no sub-aerial relief, probably because the shortening involved mainly the sedimentary cover above previously thinned continental crust. The Endicott Mountains allochthon was the lowest and northernmost of the allochthons. It was emplaced between the youngest deposition of the Okpikruak Formation (Valanginian) and deposition of the Fortress Mountain Formation (Aptian to Albian) above an angular unconformity. The turbidites and olistostromes of the Okpikruak probably represent deposition on and ahead of the leading edge of the allochthon as it was emplaced (Crane, 1987; Peapples et al., 2007) (Figure 2.9A). During mid-Cretaceous time, major uplift, subaerial exposure, and erosion in the Brooks Range led to filling of the Colville foreland basin, with progradation of proximal Fortress Mountain northward from the mountains and progradation of Nanushuk eastward along the basin axis (Mull, 1985; Molenaar, 1988; Bird and Molenaar, 1992) (Figures 2.2C and 2.9B). Uplift and subaerial exposure resulted at least in part from extension in the southern Brooks Range (Little et al., 1994; Moore et al., 1994; Vogl, 2002), but continued contraction above a basal detachment that dropped into basement may also have allowed greater structural thickening and uplift despite a significant decrease in shortening (Till, 1992; Till and Snee, 1995; Gottschalk et al., 1998). Local growth strata and angular unconformities indicate that folding continued during Fortress Mountain through Nanushuk deposition (Cole et al., 1997; Mull et al., 2000; Finzel, 2004), although it probably was local and accommodated only minor shortening. Following a period of relative tectonic quiescence in Late Cretaceous time, contractional deformation resumed in Paleocene time (~60 Ma) and, at least in the eastern part of the central foothills, Eocene time (~45 Ma) (O'Sullivan, 1996; O'Sullivan et al., 1997). The existing orogenic wedge was reactivated and expanded northward as it incorporated the foreland basin deposits of the southern foothills and formed the conspicuous structures that they now display (Figures 2.2D, 2.6, and 2.9C). It is difficult to determine which structures within EMA formed during these later events except where those structures also involve the foreland basin deposits or where thermochronology supports activity of specific structures at this time. This evidence indicates that significant shortening, thickening, and displacement of the leading edge of EMA occurred by renewed folding and imbricate thrust faulting within the multi-level duplex wedge. Breaching thrusts and associated folds formed relatively later, probably when the basal detachment dropped into the autochthonous rocks beneath the EMA to allow thickening of the wedge (Figure 2.6). Displacement and shortening of the leading edge of EMA was accommodated by folding and local thrust faulting within the overlying

Fortress Mountain and Torok Formations. The leading edge of EMA and the overlying deformed foreland basin deposits form the wedge-shaped core of a triangle zone beneath a roof thrust with backthrust displacement sense within a detachment zone in the upper part of Torok. This roof thrust is probably localized above the tip of the EMA wedge and marked by the Tuktu escarpment. Additional shortening farther north was accommodated by a wedge with much lower taper that formed in distal Fortress Mountain and Torok and was capped by detachment folds in Nanushuk (Moore et al., 2004). Deformation dies out to the north where the basal detachment cuts up section to meet the roof thrust and marks the northern limit of structural thickening.

The effects of post-Paleocene deformation are most apparent east of the Ribdon and Sagavanirktok Rivers, where the rocks that are deformed and the character and orientation of structures differ significantly from in the central foothills. However, post-Paleocene, probably mainly Eocene (~45 Ma), deformation has also had less obvious effects on the central foothills at least as far west as the Cobblestone Creek area (O'Sullivan, 1996; O'Sullivan et al., 1997; Mull et al., in press). This is reflected most obviously by an eastward change in orientation from west-northwest to east-northeast of folds and faults, as well as the range front, the northern limits of exposure of pre-orogenic rocks in the Endicott Mountains allochthon, Okpikruak, and Fortress Mountain, and the southern limit of exposure of the Nanushuk Formation (Figure 2.7). The apex in the change of orientation of these boundaries is near Cobblestone Creek, so the boundaries are progressively farther north with increasing distance east of Cobblestone Creek. Apatite fission-track data from the Cobblestone Creek area also provide evidence of cooling at ~45 Ma apparently related to displacement on some breaching thrusts and folding of Nanushuk (Mull et al., in press).

Mechanical stratigraphy and structure of the eastern Brooks Range foothills

The foothills of the eastern Brooks Range differ significantly in both stratigraphy and structure from the central foothills farther west (Figure 2.1). Shortening continued in the eastern foothills after formation of the structures that characterize the foothills farther west (Wallace and Hanks, 1990; Wallace, 1993; O'Sullivan et al., 1998). As deformation progressed, it migrated northward out of the south-facing former passive margin into the gently south-dipping autochthonous platform and the overlying foreland basin deposits on the north side of the basin. The eastern foothills are entirely north of the northern edge of allochthonous rocks and their deformation occurred entirely after emplacement of the allochthons. This continued deformation resulted in growth of the orogenic wedge into parautochthonous rocks that formed the northward-convex salient of the northeastern Brooks Range and its foothills (Wallace and Hanks, 1990; Wallace, 1993).

The allochthonous rocks north of the present range front that characterize the central Brooks Range end eastward immediately west of the Ribdon River (Brosgé et al., 1979; Moore et al., 1997) (Figure 2.1). Farther north, a boundary near the Sagavanirktok River marks a major eastward transition in foreland basin stratigraphy (Molenaar, 1983; Molenaar et al., 1987; Bird and Molenaar, 1992; Mull et al., 2003) (Figure 2.3). The eastern foothills as defined for the purposes of this report are bounded to the west by the

Ribdon and Sagavanirktok Rivers and to the east by the boundary of the Arctic National Wildlife Refuge at the Canning River. The report does not address the foothills of the northeastern Brooks Range east of the Canning River and within the coastal plain of the Arctic National Wildlife Refuge.

The mechanical stratigraphy of both the pre-orogenic rocks and the foreland basin deposits of the eastern foothills differs greatly from that of the central foothills (Figures 2.3, 2.4, 2.10, and 2.11), with the result being a very different structural geometry and evolution from that of the central foothills (Figure 2.12). At the base of the orogenic wedge north of the range front, basement forms large thrust sheets with hangingwall anticlines above breaching faults that cut up into foreland basin deposits. Pre-orogenic platform cover conforms to the first-order structure of the underlying basement, but higher-order folds and thrust faults are present in several competent intervals above intervening detachments. The overlying foreland basin fill also displays folds and local thrust faults, but has less competency contrast than within the pre-orogenic section. The basal detachment of the orogenic wedge cuts up section to the north to a point at which deformation dies out. These structures all formed during episodic Tertiary deformation, but structural geometry did not vary sufficiently over time to serve as a basis to determine when a particular structure formed during this deformation.

Mechanical stratigraphy of the pre-orogenic units

As deformation progressed northward into the gently south-dipping north margin of the foreland basin, it involved the entire pre-orogenic section above a detachment in the basement (Bird and Molenaar, 1987; Wallace and Hanks, 1990; Wallace, 1993) (Figure 2.11). The pre-orogenic section includes several incompetent detachment intervals that separate competent intervals that generally decrease in thickness up-section.

The lowest competent interval includes pre-Middle Devonian basement unconformably overlain by a veneer of conglomerate and sandstone of the Lower Mississippian Kekiktuk Formation. Basement consists of lithologically diverse low-grade rocks. These rocks were overprinted in pre-Middle Devonian time by multiple generations of folds and faults and typically dip to the south (Wallace and Hanks, 1990; Wallace, 1993, Anderson et al., 1994). Basement and the overlying Kekiktuk Conglomerate acted as a single competent interval during Tertiary deformation. This competent interval forms thrust sheets several kilometers thick above a sub-horizontal detachment horizon, and related first-order folds.

The Lower Mississippian Kayak Shale (~100-300 m) forms an important incompetent detachment interval above the Kekiktuk Conglomerate. Carbonates of the Mississippian to Pennsylvanian Lisburne Group form a thick (~750 m) competent interval above Kayak. Bed thickness and grain size generally increase and argillaceous content decreases upward from Kayak through Lisburne. This gradational upward increase in competency favors the formation of map-scale second-order detachment folds in the Lisburne (Homza and Wallace, 1997; Atkinson and Wallace, 2003). Clastic rocks of the Permian to Lower Triassic Sadlerochit Group and Triassic Shublik Formation overlie the Lisburne. These units generally follow the second-order structure within the Lisburne,

but also form third-order folds and thrust faults above detachments in finer-grained intervals in Kavik Shale of Sadlerochit Group and within the Shublik Formation. The Jurassic to Lower Cretaceous Kingak Shale forms a thick (up to ~1200 m) and regionally important detachment interval.

Kingak and progressively older units down to basement are truncated at a low angle to the north-northeast beneath the regionally important Lower Cretaceous unconformity (LCu) (Bird and Molenaar, 1987). The LCu is largely north of the deformation front to the west-northwest, toward Prudhoe Bay, and is a conformity to the south-southwest within most of the eastern foothills. However, the LCu strikes south-southwest across the deformation front toward the east end of the Sadlerochit Mountains. The LCu has important structural implications where it is involved in deformation. Detachments that separate competent intervals terminate northward beneath the unconformity as progressively lower parts of the mechanical stratigraphy are truncated and missing to the north-northeast. Thus, important structural elements disappear northward beneath a structural boundary defined by the LCu.

The discontinuous and highly variable Kemik Sandstone overlies the LCu and its correlative conformity in the eastern foothills. Throughout most of the eastern foothills, the Kemik is detached above the incompetent Kingak Shale to form broken folds and imbricate thrust faults (Mull, 1987; Meigs, 1989; Wallace and Hanks, 1990; Wallace, 1993). In the northernmost exposures of Kemik in the northeastern Sadlerochit Mountains, it displays major facies changes northward where it unconformably overlies competent units from which it is not detached. A similar pattern likely exists in the subsurface west of the Canning River where the LCu is present south of the deformation front.

The Pebble shale unit overlies the Kemik Sandstone. It acts as a detachment both at the regional level as the lowest detachment above the LCu and at the more local level above folds and faults in the Kemik. Eastward within the eastern foothills, initial foreland basin deposits of the Hue Shale gradationally overlie the pebble shale unit, and the two units together form a thick incompetent interval dominated by clay shale.

Mechanical stratigraphy of the foreland basin deposits

The transition from north-derived pre-orogenic deposits to foreland basin fill and the fill itself are stratigraphically complex in the eastern foothills (Molenaar, 1983; Molenaar et al., 1987; Bird and Molenaar, 1987, 1992; Decker, 2007) (Figures 2.2 and 2.11). The foreland basin deposits differ greatly in their mechanical stratigraphy between the central and eastern foothills because of an eastward shelf-to-basin transition near the haul road (Figure 2.10). For these reasons, the stratigraphic nomenclature for the foreland basin deposits of the eastern foothills is complex and controversial. The Cretaceous foreland basin deposits of the eastern foothills are generally finer-grained and thinner-bedded than to the west (Figures 2.4, 2.10, and 2.11). Thick-bedded and coarse-grained competent intervals comparable to the proximal Fortress Mountain and the Nanushuk Formations are absent in the lower part of the foreland basin fill.

Immediately north of the range front in the western part of the eastern foothills, Hue Shale is absent and the thick but generally thin-bedded and fine-grained Gilead sandstone occupies the stratigraphic position of the Fortress Mountain to Nanushuk (Decker et al., in press). Farther north, the lower part of the stratigraphic transition between the western and eastern foothills consists of shale to fine-grained sandstone of the Seabee Formation. The Hue Shale marks the onset of foreland basin deposition to the east, within most of the eastern foothills. Hue Shale gradationally underlies the Canning Formation, which ranges from shale to fine-grained, thin-bedded sandstone. The overall thickening- and coarsening-upward trend within the Canning favors folding and local faulting within the interval, but folds tend to be complex and variable second- and third-order folds because of the mechanical character of the unit.

The foreland basin filled by progradation to the north and northeast, so thick-bedded and coarse-grained intervals succeed shale to thinner-bedded and finer-grained sandstone in the uppermost Cretaceous and Tertiary part of the foreland basin fill (Figures 2.10 and 2.11). Competent intervals that include part of the upper Schrader Bluff Formation and the Prince Creek and Sagavanirktok Formations intertongue to the northeast with finer-grained, less competent intervals assigned to the Canning or Schrader Bluff Formations (Molenaar, 1983; Molenaar et al., 1987; Decker, 2007).

Structural architecture of the eastern foothills

The eastern foothills is a northward-tapered orogenic wedge that includes and exposes progressively older rocks to the south (Figures 2.1, 2.12, and 2.13). This discussion is based primarily on surface exposures and seismic reflection data in the eastern half of the eastern foothills, between the Shaviovik and Canning Rivers. To the south, basement with a veneer of Kekiktuk forms thrust sheets that are several kilometers thick. Overlap of thrust sheets is minimal because the bounding thrusts are relatively widely spaced, steep, and of small displacement. Within most of the northeastern Brooks Range, these thrust faults cut up from a detachment in basement to one in the Kayak Shale to form a duplex of fault-bend folds (Wallace and Hanks, 1990; Wallace, 1993) (Figure 2.14A). However, seismic reflection data in the easternmost foothills show the thrusts to continue to cut at moderate to steep dips across the Kayak detachment and upward into Tertiary section (Figures 2.12 and 2.14B). Hangingwalls display rounded anticlines several kilometers in wavelength, with gentle backlimbs over footwall ramps and truncated forelimbs that are steep to overturned. Comparable synclines commonly are present in footwalls. These structures are very similar to those associated with the range-front faults of the northernmost ranges of the northeastern Brooks Range, the Sadlerochit and Shublik Mountains (Wallace and Hanks, 1990; Wallace, 1993) (Figure 2.13). Most of the basement-involved faults beneath the easternmost foothills dip to the south, but at least one major north-dipping backthrust is present and minor backthrusts locally cut the backlimbs of hangingwall anticlines.

An obvious and important question is: What controls the change in behavior of the basement-involved thrust faults? The answer is not evident from the seismic data, but a

possible explanation is suggested by surface exposures. The Sadlerochit and Shublik Mountains range-front faults that differ markedly in structural style from the rest of the northeastern Brooks Range also correlate with a significant change in pre-Middle Devonian stratigraphy. The pre-Middle Devonian stratigraphy of the Sadlerochit and Shublik Mountains consists of a very thick section of Proterozoic to Lower Devonian carbonates, mostly dolostone, that are underlain by basalt. This section dips to the south beneath the sub-Mississippian unconformity and is repeated in the Sadlerochit and Shublik Mountains, which indicates that the range-front faults are reactivated pre-Middle Devonian south-dipping thrust faults (Wallace and Hanks, 1990; Wallace, 1993). Their steep dip and the character of the pre-Middle Devonian stratigraphy further suggests that the pre-Middle Devonian thrust faults may have reactivated even older normal faults. The steep fault dip and the thick and very competent stratigraphic section may result in the fault cutting up section through its cover and the hangingwall being displaced upward without also bending forward (Figure 2.14B). By contrast, the basement fault-bend folds characteristic of the rest of the northeastern Brooks Range (Figure 2.14A) form above ramps that are not as steep and in rocks that are significantly less competent and hence bend more easily. The fact that the basement faults cut up section rather than flattening on the Kayak detachment accounts for the lack of detachment folding above the Kayak detachment: shortening is accommodated by faulting up-section and first-order hangingwall anticlines and footwall synclines rather than by second-order detachment folds that accommodate thrust faulting above a flat in Kayak.

Strata in the overlying pre-orogenic platform cover and foreland basin deposits generally conform to the first-order bends in the basement thrust sheets, but second- to third-order folds and thrust faults are locally present between detachment intervals (Figure 2.12). The Lisburne forms detachment folds above Kayak Shale in the northeastern Brooks Range (Wallace and Hanks, 1990; Wallace, 1993; Homza and Wallace, 1997; Atkinson and Wallace, 2003) (Figure 2.14A), but these appear to be absent in the subsurface of the foothills (Figure 2.14B) except perhaps immediately north of the range front, where seismic reflection data generally are very poor. The Sadlerochit Group and Shublik Formation display second-order thrust faults and associated folds in exposures near the range front, but these appear to be largely absent in the subsurface 10 to 15 km to the north. Imbricate thrust faulting of Kemik Sandstone between detachments in the Kingak Shale and pebble shale is common both in surface exposures and in the subsurface at least as far north as truncation of Kingak below the LCu. In well-known exposures in the Sadlerochit Mountains, Kemik forms duplexes in which thrust faults dip relatively gently and horses display considerable overlap (Mull, 1987; Meigs, 1989). However, Kemik displays a different structural style in exposures between the Canning and Echooka Rivers, in which open folds are locally cut by relatively steep low-displacement thrust faults that mostly dip south but locally dip north.

In outcrop, the Hue Shale and lower Canning Formation locally display very complex second- to third-order tight folds and minor thrust faults, both of which may verge either north or south. Folds generally become larger and more open and upright up-section, where grain size and bedding thickness increase. Rounded to boxy first-order folds are present where coarse-grained upper foreland basin deposits are exposed to the north.

Relief on basement decreases progressively to the north with decreasing displacement on basement faults, with a corresponding decrease in the magnitude of deformation and relief of overlying beds (Figure 2.12). A panel with gently north-dipping reflectors above basement relief and little internal deformation marks the northward termination of deformation.

The structure of the eastern foothills differs from that of the central foothills in several main ways (Figures 2.6 and 2.12):

- In the eastern foothills, a wedge with decreasing structural relief to the north formed in parautochthonous rocks above a detachment in basement with relatively little displacement. This contrasts with the central foothills, where a wedge in allochthonous rocks is succeeded northward by a wedge formed above a detachment near the base of the foreland basin deposits.
- In the eastern foothills, structures throughout the wedge formed at multiple levels separated by detachments. This contrasts with the central foothills, where a single set of folds (in Nanushuk and higher units) formed above a single major detachment (in Torok) north of the allochthonous rocks.
- The eastern foothills do not have an obvious regional triangle zone. This contrasts with the central foothills, where a single roof thrust exists at a stratigraphically fixed position (in Torok) and is prominently exposed along strike for a long distance (Tuktu escarpment).

Structural evolution of the eastern Brooks Range foothills

The Middle Jurassic to Early Cretaceous emplacement of allochthons was entirely south of the area that is now the eastern foothills of the Brooks Range (Figures 2.1 and 2.2). The Paleocene (~60 Ma) deformation that formed the structures of the central Brooks Range foothills and the mountain front to their south (Figure 2.9C) probably also continued along trend in the eastern foothills. Structures that formed the central Brooks Range mountain front at ~60 Ma continue eastward into the mountains to mark the southern boundary of the northeastern Brooks Range (Figure 2.1). Paleocene structures probably formed within the eastern foothills a considerable distance north of this paleo-mountain front, but they cannot generally be distinguished from later structures based on their structural character alone.

Evidence from fission-track thermochronology indicates that the eastern foothills were deformed throughout the Tertiary, mainly in events at about 45, 35, and 27 Ma (O'Sullivan, 1996; O'Sullivan et al., 1997, 1998; O'Sullivan and Wallace, 1998). Breaching of pre-existing detached structures by basement-involved structures indicates that structures at different levels were active at different times. However, thermochronologic evidence is required to determine the absolute age of the different

structures. Preliminary results suggest that deformation did not occur in a simple forward-propagating sequence, but rather was distributed complexly in time and space.

Seismicity, geomorphology, and offshore surface ruptures indicate that deformation continues to the present in and north of the coastal plain of the Arctic National Wildlife Refuge (Grantz et al., 1983). Deformation may also be continuing in the eastern foothills, but the evidence is less obvious and it may be at a slower rate.

The eastern Brooks Range mountain front between the Ribdon and Canning Rivers trends northeast, which is significantly different from the east trend of the central Brooks Range front (Figure 2.1). The northern deformation front also displays an east-northeast trend between the Colville and Canning Rivers. Structures in the northeastern Brooks Range that are detached from basement display east-northeast trends that indicate tectonic transport toward the north-northwest during post-Paleocene deformation (Wallace and Hanks, 1990; Wallace, 1993; O'Sullivan and Wallace, 2002). These lines of evidence suggest that northeast- to east-northeast-trending structures within the eastern foothills likely formed during post-Paleocene deformation as a reflection either of tectonic transport toward the north-northwest or the presence of oblique ramps.

East-west oriented structures, on the other hand, may be of either Paleocene or post-Paleocene origin. East-west oriented faults and folds analogous to those of the central foothills likely formed north of the mountain front in Paleocene time. Basement-involved structures typically are the latest in the local sequence and most, if not all, probably formed during post-Paleocene deformation. Faults and associated folds that involve basement commonly are oriented east-west, but this reflects reactivation of east-striking pre-Middle Devonian faults rather than the post-Paleocene north-northwest transport direction (Wallace and Hanks, 1990; Wallace, 1993). East-west oriented structures in cover rocks probably formed in Paleocene time if they are overprinted by east-northeast oriented structures, whereas east-west oriented basement-involved structures that overprint east-northeast oriented structures probably formed in post-Paleocene time.

References cited

- Anderson, A.V., Wallace, W.K., and Mull, C.G., 1994, Depositional record of a major tectonic transition in northern Alaska: Middle Devonian to Mississippian rift-basin margin deposits, upper Kongakut River region, eastern Brooks Range, Alaska, in Thurston, D., and Fujita, K., eds., 1992 Proceedings International Conference on Arctic Margins, U.S. Minerals Management Service Outer Continental Shelf Study 94-0040, p. 71-76.
- Atkinson, P.K., and Wallace, W.K., 2003, Competent unit thickness variation in detachment folds in the northeastern Brooks Range, Alaska: geometric analysis and a conceptual model: *Journal of Structural Geology*, v. 25, no. 10, p. 1751-1771.
- Bader, J.W. and Bird, K.J., 1986, Geologic map of the Demarcation Point, Mt. Michelson, Flaxman Island, and Barter Island quadrangles, northeastern Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1791, scale

1:250,000, 1 sheet.

- Bird, K.J., and Molenaar, C.M., 1987, Stratigraphy, *in* Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 37–59.
- Bird, K.J., and Molenaar, C.M., 1992, The North Slope foreland basin, Alaska, *in* Leckie, D.A., and Macqueen, R.W., eds., Foreland basins and foldbelts: American Association of Petroleum Geologists Memoir 55, p. 363–393.
- Brosigé, W.P., Reiser, H.N., Dutro, J.T. Jr., and Detterman, R.L., 1979, Bedrock geologic map of the Philip Smith Mountains Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-879B, scale 1:250,000, 2 sheets.
- Cole, F., Bird, K.J., Toro, J., Roure, F., O'Sullivan, P.B., Pawlewicz, M., and Howell, D.G., 1997. An integrated model for the tectonic development of the frontal Brooks Range and Colville basin 250 km west of the Trans-Alaska Crustal Transect, *Journal of Geophysical Research*, v. 102, no. B9, p. 20,685–20,708.
- Crane, R.C., 1987, Cretaceous olistostrome model, Brooks Range, Alaska, *in* Tailleux, I., and Weimer, P., eds., Alaskan North Slope Geology, v. 1: Bakersfield, California, Pacific Section, Society of Economic Paleontologists and Mineralogists and Alaska Geological Society, p. 433–440.
- Dahlen, F.A., and Suppe, J., 1988, Mechanics, growth, and erosion of mountain belts, *in* Clark, S.P., Jr., Burchfiel, B.C., and Suppe, J., eds., Processes in continental lithospheric deformation: GSA Special Paper 218, p. 161–178.
- DeCelles, P.G., and Giles, K.A., 1996, Foreland basin systems: *Basin Research*, v. 8, p. 105–123.
- Decker, P.L., 2007, Brookian sequence stratigraphic correlations, Umiat Field to Milne Point Field, west-central North Slope, Alaska: Alaska Division of Geological and Geophysical Surveys Preliminary Interpretive Report 2007-2, 19 p., 1 sheet.
- Decker, P.L., Wartes, M.A., Wallace, W.K., Houseknecht, D.W., Schenk, C.J., Gillis, R.J., and Mongrain, J., in press (2008), Stratigraphic and structural investigations in the Ivishak River and Gilead Creek areas: Progress during 2007: Alaska Division of Geological and Geophysical Surveys Preliminary Interpretive Report.
- Duncan, A.S., 2007, Evolution of fractures and Tertiary fold-and-thrust deformation in the central Brooks Range foothills, Alaska: Master of Science thesis, University of Alaska Fairbanks, 159 p.
- Finzel, E.S., 2004, Architectural analysis and fold geometry of syntectonic fluvial conglomerate in the Nanushuk Formation, Brooks Range foothills, Alaska: Master of Science thesis, University of Alaska Fairbanks, 230 p.
- Gottschalk, R.R., Oldow, J.S., and Ave Lallemand, 1998, Geology and Mesozoic structural history of the south-central Brooks range, Alaska, *in* Oldow, J.S., and Ave Lallemand, H., eds., Architecture of a fold and thrust belt: Central Brooks Range, Arctic Alaska: Geological Society of America Special Paper 324, p. 195–223.
- Grantz, A., Dinter, D.A., and Biswas, N.N., 1983, Map, cross sections, and chart showing late Quaternary faults, folds, and earthquake epicenters on the Alaskan Beaufort shelf: U.S. Geological Survey Miscellaneous Investigations Series Map I-1182C, scale 1:500,000, 3 sheets, 7 p.

- Harris, E.E., Mull, C.G., Reifenhuth, R.R., and Montayne, S., 2002, Geologic map of the Dalton Highway (Atigun Gorge to Slope Mountain) area, southern Arctic foothills, Alaska: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2002-2 (1 sheet, 1:63,360).
- Houseknecht, D.W., and Schenk, C.J., 2001, Depositional sequences and facies in the Torok Formation, National Petroleum Reserve—Alaska (NPRA), *in* Houseknecht, D.W., ed., NPRA core workshop: petroleum plays and systems in the National Petroleum Reserve—Alaska: SEPM Core Workshop 21, p. 179–199.
- Homza, T.X., and Wallace, W.K., 1997, Detachment folds with fixed hinges and variable detachment depth, northeastern Brooks Range, Alaska: *Journal of Structural Geology*, v. 19, nos. 3-4, p. 337–354.
- Huffman, A.C., Jr, ed., 1985, Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, 129 p.
- Huffman, A.C., Jr., Ahlbrandt, T.S., and Bartsch-Winkler, S., 1988, Sedimentology of the Nanushuk Group, North Slope, *in* Gryc, G., ed., Geology and exploration of the National Petroleum Reserve in Alaska, 1974–1982: U.S. Geological Survey Professional Paper 1399, p. 281–298.
- Kelley, J.S., 1990, Generalized geologic map of the Chandler Lake Quadrangle, north-central Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-2144A, scale 1:250,000, 1 sheet, 19 p.
- Kumar, N., Bird, K.J., Nelson, P.H., Grow, J.A., and Evans, K.R., 2002, A digital atlas of hydrocarbon accumulations within and adjacent to the National Petroleum Reserve—Alaska (NPRA): U.S. Geological Survey Open-File Report 02-71, 80 p.
- Little, T.A., Miller, E.L., Lee, J., and Law, R.D., 1994, Extensional origin of ductile fabric in the Schist Belt, central Brooks Range, Alaska—I. Geologic and structural studies: *Journal of Structural Geology*, v. 16, p. 899–918.
- Mayfield, C.F., TAILLEUR, I.L., and I. ELLERSIECK, I., 1988, Stratigraphy, structure, and palinspastic synthesis of the western Brooks Range, northwestern Alaska, Chapter 7, *in* Gryc, G., ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 143–186.
- Meigs, A.J., 1989, Structural geometry and sequence in the eastern Sadlerochit Mountains, northeastern Brooks Range, Alaska: Master of Science thesis, University of Alaska Fairbanks, 220 p.
- Molenaar, C.M., 1983, Depositional relations of Cretaceous and lower Tertiary rocks, northeastern Alaska: *American Association of Petroleum Geologists Bulletin*, v. 67, p. 1066–1080.
- Molenaar, C.M., 1988, Depositional history and seismic stratigraphy of Lower Cretaceous rocks in the National Petroleum Reserve in Alaska and adjacent areas, *in* Gryc, G., ed., Geology and exploration of the National Petroleum Reserve in Alaska, 1974–1982: U.S. Geological Survey Professional Paper 1399, p. 593–621.
- Molenaar, C.M., Bird, K.J., and Kirk, A.R., 1987, Cretaceous and Tertiary stratigraphy of northeastern Alaska, *in* TAILLEUR, I., and WEIMER, P., eds., *Alaskan North Slope Geology*, v. 1: Bakersfield, California, Pacific Section, Society of Economic Paleontologists and Mineralogists and Alaska Geological Society, p. 513–528.

- Moore, T.E., Wallace, W.K., Bird, K.J., Karl, S.M., Mull, C.G., and Dillon, J.T., 1994, Chapter 3: Geology of northern Alaska, in Plafker, G., and Berg, H.C., eds., *The geology of Alaska: The Geology of North America*, Geological Society of America, Boulder, Colorado, v. G1, p. 49-140.
- Moore, T.E., Wallace, W.K., Mull, C.G., Adams, K.E., Plafker, G., and Nokleberg, W.J., 1997, Crustal implications of bedrock geology along the Trans-Alaska Crustal Transect in the Brooks Range, northern Alaska: *Journal of Geophysical Research*, v. 102, no. B9, p. 20,645-20,684.
- Moore, T.E., Potter, C.J., O'Sullivan, P.B., Shelton, K.L., and Underwood, M.B., 2004, Two stages of deformation and fluid migration in the west-central Brooks Range fold and thrust belt, northern Alaska, *in* Swennen, R., Roure, F., and Granath, J.W., eds., *Deformation, fluid flow, and reservoir appraisal in foreland fold and thrust belts: American Association of Petroleum Geologists Hedberg series*, no. 1, p. 157-186.
- Mull, C.G., 1982, Tectonic evolution and structural style of the Brooks Range, Alaska: An illustrated summary, in Powers, R.B., ed., *Geological studies of the Cordilleran thrust belt*, v. 1, Rocky Mountain Association of Geologists, Denver, Colorado, p. 1-45.
- Mull, C.G., 1985, Cretaceous tectonics, depositional cycles, and the Nanushuk Group, Brooks Range and Arctic Slope, Alaska, in Huffman, A.C., Jr., ed., *Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin* 1614, p. 7-36.
- Mull, C.G., 1987, Kemik Formation, Arctic National Wildlife Refuge, northeastern Alaska, *in* Tailleur, I., and Weimer, P., eds., *Alaskan North Slope Geology*, v. 1: Bakersfield, California, Pacific Section, Society of Economic Paleontologists and Mineralogists and Alaska Geological Society, p. 405-431.
- Mull, C.G., R.K. Glenn, and K.E. Adams, 1997, Tectonic evolution of the central Brooks Range mountain front: Evidence from the Atigun Gorge region, *Journal of Geophysical Research*, v. 102, no. B9, p. 20,749-20,772.
- Mull, C.G., Harris, E.E., Reifenhuth, R.R., and Moore, T.E., 2000, Geologic map of the Coke Basin-Kukpowruk River area, DeLong Mountains D-2 and D-3 quadrangles, northwestern Alaska: Alaska Division of Geological and Geophysical Surveys Report of Investigations 2000-2, 1 sheet, scale 1:63,360.
- Mull, C.G., Houseknecht, D.W., and Bird, K.J., 2003, Revised Cretaceous and Tertiary stratigraphic nomenclature in the Colville Basin, northern Alaska: U.S. Geological Survey Professional Paper 1673, 51 p.
- Mull, C.G., Harris, E.E., and Peapples, P.R., in press. Geologic map of the Cobblestone Creek-May Creek area, east-central Brooks Range foothills, Alaska: Alaska Division of Geological and Geophysical Surveys Report of Investigations, 1 sheet, scale 1:63,360, and booklet.
- O'Sullivan, P.B., 1996, Late Mesozoic and Cenozoic thermo-tectonic evolution of the North Slope foreland basin, Alaska, *in* Johnson, M.J., and Howell, D.G., eds., *Thermal evolution of sedimentary basins in Alaska: U.S. Geological Survey Bulletin* 2142, p. 45-79.

- O'Sullivan, P.B., and Wallace, W.K., 2002, Out-of-sequence, basement-involved structures in the Sadlerochit Mountains region of the Arctic National Wildlife Refuge, Alaska: Evidence and implications from fission-track thermochronology: *Geological Society of America Bulletin*, v. 114, no. 11, p. 1356-1378.
- O'Sullivan, P.B., Murphy, J.M., and Blythe, A.E., 1997, Late Mesozoic and Cenozoic thermotectonic evolution of the Central Brooks Range and adjacent North Slope Foreland Basin, Alaska: Including fission track results from the Trans-Alaska Crustal Transect (TACT): *Journal of Geophysical Research*, v. 102, p. 20,821-20,845.
- O'Sullivan, P.B., Wallace, W.K. and Murphy, J.M., 1998b, Fission track evidence for apparent out-of-sequence Cenozoic deformation along the Philip Smith Mountain front, northeastern Brooks Range, Alaska: *Earth and Planetary Science Letters*, v. 164, no. 3-4, p. 435-449.
- Peapples, P.R., Wallace, W.K., Wartes, M.A., Swenson, R.F., Mull, C.G., Dumoulin, J.A., Harris, E.E., Finzel, E.S., Reifenhuth, R.R., and Loveland, A.M., 2007, Geologic map of the Siksikpuk River area, Chandler Lake Quadrangle, Alaska: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2007-1, 1 sheet, 1:63,360.
- Reifenhuth, R.R., Mull, C.G., Harris, E.E., LePain, D.L., Pinney, D.S., and Wallace, W.K., 2000, Geologic map of the Sagavanirktok B-1 quadrangle, eastern North Slope, Alaska: Alaska Division of Geological and Geophysical Surveys Report of Investigations 2000-1A, 15 p., 1 sheet, scale 1:63,360.
- Till, A.B., 1992, Detrital blueschist-facies metamorphic mineral assemblages in Early Cretaceous sediments of the foreland basin of the Brooks Range, Alaska, and implications for orogenic evolution: *Tectonics*, v. 11, no. 6, p. 1207-1223.
- Till, A.B., and Snee, L.W., 1995, $^{40}\text{Ar}/^{39}\text{Ar}$ evidence that formation of blueschists in continental crust was synchronous with foreland fold and thrust belt deformation, western Brooks Range, Alaska: *Journal of Metamorphic Geology*, v. 13, p. 41-60.
- Vogl, J.J., 2002, Late-orogenic backfolding and extension in the Brooks Range collisional orogen, northern Alaska: *Journal of Structural Geology*, v. 24, p. 1753-1776.
- Wallace, W.K., 1993, Detachment folds and a passive-roof duplex: Examples from the northeastern Brooks Range, Alaska, in Solie, D.N., and Tannian, eds., *Short notes on Alaskan geology 1993*: Alaska Division of Geological and Geophysical Surveys Geologic Report 113, p. 81-99.
- Wallace, W.K., and Hanks, C.L., 1990, Structural provinces of the northeastern Brooks Range, Arctic National Wildlife Refuge, Alaska: *American Association of Petroleum Geologists Bulletin*, v. 74, p. 1100-1118.
- Wallace, W.K., Moore, T.E., and Plafker, G., 1997, Multistory duplexes with forward dipping roofs, north central Brooks Range, Alaska: *Journal of Geophysical Research*, v. 102, no. B9, p. 20,773-20,796.
- Willett, S., Beaumont, C., and Fullsack, P., 1993. A mechanical model for the tectonics of doubly-vergent compressional orogens: *Geology*, v. 21, p. 371-374.

Figure 2.1. Generalized tectonic map of northern Alaska, showing major tectonostratigraphic elements and structural features. The main axis of the northern Brooks Range is separated from the northeastern Brooks Range by the “continental divide thrust front” (Wallace and Hanks, 1990; Wallace, 1993), the boundary shown between thrust faulted and folded rocks. Areas referred to in this report as central and eastern foothills are outlined with dashed lines. Modified from Moore et al., 1994.

Figure 2.2. (Next page) Schematic reconstruction of major phases in the tectonic evolution of the Brooks Range. Major faults bounding the actively deforming wedge at each time are shown as heavy lines; future trajectories of wedge-bounding thrust faults are shown as light dashed lines. Vertical exaggeration about 2x. Foreland and Arctic passive margin greatly foreshortened for the purposes of illustration. The two highest allochthons, Misheguk Mt. and Copter Peak, are part of the Angayucham terrane. The De Long Mts. subterrane includes four allochthons derived from the sedimentary passive-margin cover of the Arctic Alaska terrane. The Endicott Mts. allochthon is the fifth, lowest, and most extensive of the sedimentary allochthons.

A. Late Jurassic

B. Valanginian

C. Albian

D. Paleocene

- Koyukuk arc
- Misheguk Mt. allochthon
- Copter Peak allochthon and oceanic crust
- De Long Mts. allochthon

- trajectory of future wedge-bounding fault
- Okpikruak melange and olistostrome
- Endicott Mts. allochthon
- Hammond subterrane

- Nanushuk and younger and Yukon-Koyukuk basin
- Torok and distal Fortress Mt.
- Proximal Fortress Mt.
- North Slope cover
- North Slope basement and Coldfoot subterrane

Figure 2.3. Chronostratigraphic chart of central and eastern North Slope. Stratigraphy of Endicott Mountains allochthon is shown to left and stratigraphic transition from central to eastern foothills is shown to right. Base of foreland basin deposits marked by heavy dashed line. Vertical time scale doubles above Jurassic-Cretaceous boundary. Modified from Bird and Molenaar, 1992.

Figure 2.4. Lithostratigraphy and mechanical stratigraphy of the central Brooks Range foothills. Modified from Moore et al. (1994) and Wallace et al. (1997) by addition of Nanushuk Formation.

Figure 2.5. Foreland basin models, after DeCelles and Giles (1996). A. “Traditional” model in which orogenic wedge is thrust over foreland basin. B. Revised model of DeCelles and Giles (1996) in which proximal part of foreland basin (“wedge-top”) is deposited on top of orogenic wedge and becomes part of the orogenic wedge as deformation progresses and the wedge grows into the foreland basin.

Figure 2.6. (Next page) Structural geometry of the leading edge of the Endicott Mountains allochthon (EMA) and overlying foreland basin deposits in the Tiglupuk Creek area. Location of seismic reflection line and cross section shown on figure 7.

A. Interpretation of seismic reflection line. Data clearly show parautochthonous strata of the North Slope to extend southward beneath highly deformed rocks of the EMA. Seismic and surface data support a northward-tapered wedge of EMA and overlying Fortress Mountain and Torok beneath a roof of Nanushuk folded above a backthrust. The wedge has been thickened by breaching thrusts that appear cut up from the parautochthon. Rocks of the parautochthon (probably mostly Kingak Shale) are structurally thickened below and ahead of the interpreted tip of the EMA. Seismic reflection line courtesy of Western Geophysical. Depth correction by A. Duncan (2007).

B. Cross sectional structural interpretation based on interpretation of seismic reflection line and surface data from Peapples et al. (2007).

Figure 2.7. Generalized geologic map of the central Brooks Range foothills compiled by C.G. Mull. Important structural boundaries have been added with colored lines, including (from south to north): northern limit of exposed Endicott Mountains allochthon (beneath Okpikruak mélange), northern limit of exposed Okpikruak mélange, Desolation Creek fault (northernmost major breaching thrust), southern limit of exposed Nanushuk Formation (base of Tuktu escarpment and top of backthrust zone). Line shows location of seismic reflection line and cross section in figure 6.

Figure 2.8. Multistory duplex wedge model for Endicott Mountains allochthon (after Wallace et al., 1997). Competent units shorten independently in duplexes between incompetent detachment units. Thrusts dip hindward and folds verge forward, but detachments that bound duplexes dip forward. This results because the basal detachment cuts up-section in the direction of transport and internal thickening within the wedge decreases forward.

Figure 2.9. (Next page) Schematic reconstructions at three important stages of evolution of the frontal part of the Brooks Range orogenic wedge.

A. Berriasian-Valanginian. The De Long and Endicott Mts. allochthons have been emplaced on large-displacement thrust faults, but little or no sub-aerial exposure exists because of insufficient structural relief. The Okpikruak Formation is deposited on the active leading edge of the orogenic wedge as olistostromes and local coherent turbidites (piggy-back basins?). The Kingak Shale progrades toward the orogen on the distal side of the foreland basin.

B. Barremian-Early Albian. Uplift in the southern Brooks Range results in extensive sub-aerial exposure and erosion. The Fortress Mountain clastic wedge progrades northward from the mountain front into the foreland basin, with major grain-size and facies changes from the proximal mountain-front deposits to the distal basin-bottom deposits. Local growth folds and angular unconformities indicate continuation of contraction, although it is probably local and minor.

C. Paleocene. Renewed contraction results in thickening of Endicott Mountains allochthon and incorporation of overlying foreland basin deposits into orogenic wedge as it grows. Breaching thrusts cut EMA and proximal Fortress Mountain, and proximal Fortress Mountain is folded. Frontal part of EMA and thickened Fortress Mountain form a triangle zone with a roof thrust in Torok. Detachment folds in Nanushuk accommodate shortening of distal Fortress Mountain in low-taper frontal part of triangle zone.

A. Berriasian-Valanginian

B. Barremian-early Albian

C. Paleocene

Figure 2.10. Stratigraphic transition in foreland basin deposits from central to eastern foothills. Correlation diagram based on figure from Mull et al. (2003), with depositional setting and rock type added. Columns in color added to show mechanical stratigraphy in central foothills (Chandler River) and eastern foothills (Kavik River), with zone of transition around the haul road. Vertical scale is in time, not thickness.

Figure 2.12. Interpretation of seismic reflection line to show structural geometry of the eastern Brooks Range foothills in the Kavik River area. Location of seismic reflection line shown on figure 13. Seismic reflection line courtesy of Anadarko Petroleum Corporation.

Line shows steep faults that cut upward from basement into Tertiary deposits and that are bounded by curved hangingwall anticlines and footwall synclines. The entire section is folded harmonically above first-order folds in basement, but smaller second- and third-order folds and thrust faults form above detachments at multiple levels within the mechanical stratigraphy. Forward (north) vergent structures dominate, but subordinate hindward (south) vergent structures also are present

Figure 2.13. Generalized geologic map of the eastern part of the eastern Brooks Range foothills. Map from plate 1 of Bird (1999). Map shows basement-cored anticlinoria to south (Echooka anticlinorium) and east (Sadlerochit and Shublik Mts. anticlinoria) of the eastern foothills. Sadlerochit Mts. range-front fault projects to southern basement fault shown on seismic reflection line in figure 12. Location of seismic reflection line in figure 12 shown with heavy line.

Figure 2.14. Schematic diagram showing two major structural styles in basement and its cover in the northeastern Brooks Range and subsurface of the eastern foothills. To left is structure typical throughout most of the northeastern Brooks Range: Thrust sheet in basement is displaced onto a detachment in Kayak Shale. A basement-cored anticlinorium forms as a fault-bend fold. Displacement of the basement thrust sheet is accommodated by detachment folding above the Kayak Shale detachment. To right is structure typical of the Sadlerochit and Shublik Mountains and the subsurface of the eastern foothills: Steep thrust fault cuts from basement up-section across Kayak Shale, and detachment folds do not form above Kayak Shale. Thrust fault cuts through the forelimb of a basement-cored hangingwall anticlinorium. Modified from figures in Wallace and Hanks (1990) and Wallace et al. (1997).

CHAPTER 3

Structural character, fracture distribution, thermal and uplift history of a transect across the western foothills of the northeastern Brooks Range (Eastern Transect)

By

A. Loveland

Department of Geology and Geophysics, University of Alaska, Fairbanks, Alaska 99775
(present address: Alaska Division of Geological and Geophysical Surveys,
3354 College Rd Fairbanks, AK 99709)

C. Hanks,

Dept. of Petroleum Engineering and Geophysical Institute, University of Alaska,
Fairbanks, Alaska 99775; chanks@gi.alaska.edu

P. O'Sullivan

Apatite to Zircon, Inc.
1521 Pine Cone Road
Moscow, Idaho 83843 U.S.A.

M. Parris

Petro-Fluid Solutions LLC
(present address: Kentucky Geological Survey 228 Mining and Mineral Resources Bldg.
University of Kentucky, Lexington, KY 40506-0107)

W. Wallace and B. Coakley

Geophysical Institute and Department of Geology and Geophysics, University of Alaska,
Fairbanks, Alaska 99775

Introduction

This chapter summarizes the stratigraphy, subsurface and surface map-scale structures and fracture characteristics of the Eastern Transect (Fig. 1.1, Transect A; Figure 3.1). The Eastern Transect incorporates both exposed and subsurface portions of the northeastern Brooks Range fold-and-thrust belt (Figs. 3.2 and 3.3).

Surface Observations

Lithostratigraphy

This study focuses mainly on rocks of the Paleozoic and Mesozoic Ellesmerian Sequence, though the underlying Franklinian basement and overlying Pebble Shale and Hue Shale of the Brookian Sequence were also mapped and warrant discussion. The

stratigraphy and structural style of the units documented in the Eastern Transect are summarized in Figure 3.1. Unless otherwise cited, all unit thicknesses and interpretations of depositional environments in the following discussion are from Bird and Molenaar (1987). Lithostratigraphic descriptions are based on field observations from this study and from Reifenhuth et al. (2000).

The pre-Mississippian (“basement”) rocks consist of Precambrian to Devonian (Fig. 3.4). The Endicott Group unconformably overlies the basement, forms the base of the Ellesmerian Sequence and marks the beginning of transgressive sedimentation along a subsiding, south-facing passive margin (Moore et al., 1994). The Endicott Group consists of the Lower Mississippian Kekiktuk Conglomerate and Mississippian Kayak Shale. The Kekiktuk Conglomerate is approximately 140 meters thick at the type section, though the exposure in the study area is much thinner (Bird et al., 1987). In the study area, the basal 20-30 meters of the unit consists of coal-bearing mudstone and pebble conglomerate.

The Kayak Shale is dominantly composed of black, fissile, organic-rich shale, siltstone, and limestone. Regionally and locally, the marine and tidal deposits of the Kayak Shale form the roof thrust of the regional basement-cored duplex. It also allows formation of overlying detachment folds (Fig. 2.14). Because of its nature as a detachment unit, the observed thickness of the Kayak Shale is variable, though reasonable original stratigraphic thickness estimates range from 100-250 meters (LePain, 1993).

The Mississippian to Pennsylvanian Lisburne Group gradationally overlies the Kayak Shale and forms a 500-700 meter thick sequence of carbonate rocks which were deposited on an extensive passive continental margin. In the study area, the Lisburne Group is divided into three distinguishable map units: lower Lisburne, middle Lisburne, and upper Lisburne. These map units are approximately equivalent to the lower Alapah, upper and lower Alapah, and Wahoo Limestone which are formally used to describe the Lisburne Group in the northeastern Brooks Range (Reifenhuth et al., 2000; Watts et al., 1995). The lower Lisburne (lower Alapah equivalent) is a recessive, slope-forming package of dark gray to black mudstone and wackestone that weathers into rubble. Colonial coral fossils are abundant within this unit. The middle Lisburne (upper and middle Alapah equivalent) is a medium to dark gray banded limestone with thin, dark, fine-grained interbeds. It is transitional between the lower and upper Lisburne and alternates between resistant layers and rubble crop. The upper Lisburne (Wahoo equivalent) is a medium to light gray limestone succession with interbedded lime mud.

Between the Middle Pennsylvanian and the Early Permian, regression of the sea developed an erosional unconformity at the top of the Lisburne Group, and was followed by deposition of the Sadlerochit Group. Regionally, the Sadlerochit Group is a ~380 meter thick succession of shallow-marine sandstone, siltstone and shale (Bird, 1998). The Sadlerochit Group is subdivided into two formations which are mappable in the study area: the basal Echoka Formation and the overlying Ivishak Formation (Detterman

et al., 1975). The Permian Echooka Formation contains rusty red-brown sandstone and siltstone deposited during marine transgression above the erosional unconformity at the top of the Lisburne Group. Locally, the Echooka Formation is 90 meters thick (Reifenstuhl et al., 2000).

The Ivishak Formation (Lower Triassic) is composed of dark gray, sandstones and siltstones and can be further subdivided into two members. In the study area the 30-100 meter thick Kavik Shale Member of the Ivishak Formation (Lower Triassic) is a dark gray silty shale and thin-bedded, laminated siltstone. Coherent outcrop is limited in the study area and is usually exposed as rubble. The overlying Ledge Sandstone Member is a shallow-marine deposit consisting of massive deltaic sandstones and thin interbedded siltstone.

The Triassic Shublik Formation gradationally overlies the Sadlerochit Group and is composed of limestone and calcareous shale. In the study area, exposures are mainly shales weathered into chips. Regionally, the Shublik Formation is 70-100 meters thick (Keller et al., 1961; Reifenstuhl et al., 2000), though evidence from seismic interpretations indicates that it thins and becomes truncated toward the north by the Lower Cretaceous unconformity (LCU). The Shublik Formation exposed in the study area is approximately 120 meters thick.

The Jurassic to Lower Cretaceous Kingak Shale is an incompetent detachment unit composed of silty mudstone and fissile, organic-rich shale and very-fine-grained sandstone. It is well exposed in the map area. The thickness of the Kingak Shale is variable and regional estimates range between 45-900 meters (Detterman et al., 1975; Keller et al., 1961). The estimated thickness in the study area is about 350 meters (Molenaar, 1983; Reifenstuhl et al., 2000). In the study area, vegetation or rubble commonly covers exposures of the Kingak Shale. The Kingak Shale thins northward and becomes truncated by the LCU in the subsurface as interpreted from seismic reflection data (as addressed later in this chapter).

The Cretaceous Kemik Sandstone consists of shallow marine sediments that conformably to unconformably overlie the LCU (Bird, 1998). The Kemik Sandstone is composed of medium to dark gray, very-fine-grained quartz sandstone and is approximately 60 meters thick locally (Reifenstuhl et al., 2000). Most of the exposures of Kemik Sandstone in the field area consist of rubble-crop or are covered by vegetation.

The overlying pebble shale unit (Lower Cretaceous) is a poorly exposed, organic-rich, fissile shale. The pebble shale is overlain by the Hue shale, which marks the base of the Brookian Sequence. The Hue shale in the study area is composed of bentonitic clay shales and interbedded organic-rich shale, tuff, and bentonite seams. The combined thickness of the pebble shale unit and the Hue shale in the study area is <300 meters (Reifenstuhl et al., 2000). Both units are poorly exposed in the study area.

Mechanical Stratigraphy

Six mechanical-stratigraphic units have been identified in Franklinian through lower Brookian strata of the northeastern Brooks Range (Fig. 3.4). At the base of the stratigraphic section, the pre-Mississippian basement and the Kekiktuk Conglomerate form a mechanically competent unit that are interpreted to have deformed by fault-bend folding with a basal detachment within the basement, forming single-horse anticlinoria (Wallace and Hanks, 1990; Meigs and Imm, 1995). One of these anticlinoria, the Echooka Anticlinorium, is the southernmost anticlinorium in the map area (Meigs and Imm, 1995). The roof thrust to this anticlinorium is located within the overlying relatively incompetent Kayak Shale. The competent Lisburne Group and Echooka Formation deform into detachment folds above this roof thrust. These complexly deformed rocks are in turn overlain by the incompetent Kingak Shale (Wallace and Hanks, 1990; Atkinson and Wallace, 2003).

Although at the regional scale each of the competent units are described as a single mechanical layer, they are typically mechanically heterogeneous at the outcrop scale. For instance, the lower Lisburne has alternating decimeter-scale beds of shale and limestone that can result in mechanical decoupling within the lower Lisburne (Hayes, 2004). Also, though the Kayak Shale is considered incompetent, it contains thick beds of competent siltstone and mudstone with interbedded, weak shales.

Outcrop scale mechanical stratigraphy played a significant role in fracture development throughout the study area. The fractures typically terminate at bed boundaries, suggesting bedding interfaces act as significant mechanical boundaries. These mechanical variations often arrest the propagation of fractures, thereby confining them to single, mechanically homogeneous beds.

Structural Domains

The transect area can be divided into three structural domains based on mechanical stratigraphy, differences in structural style, and differences in fission-track age (Fig. 3.2).

Domain I is the southernmost exposed structural domain (Fig. 3.2) and includes the pre-Mississippian basement, Kekiktuk Conglomerate, and Kayak Shale. The style of deformation in Domain I consists of basement-cored single-horse anticlinoria.

Domain II is north of Domain 1 and is comprised of the Lisburne Group up section through the Shublik Formation (Fig. 3.2). This domain deforms primarily by large-scale detachment folding. Domain II is both underlain and overlain by mechanically incompetent detachment units.

Domain III is the northern-most domain and is composed of the Kingak Shale, Kemik Sandstone, and pebble and Hue Shales. The structural style in this domain is

characterized by small-scale duplex-related anticlines and short-wavelength folds and thrusts.

Faults

One major thrust fault exposed in the study area lies in the southern portion of the map area (Thrust 1, Figs. 3.2, 3.5 and 3.6). The fault is a south-dipping, east-west striking reverse fault that displaces the Kayak Shale in the hanging wall northward up and over the lower Lisburne in the footwall. This major thrust fault parallels the regional structural trend and is traceable across the entire southern part of the map area. Tracing the fault from west to east, it is apparent that the displacement on the fault increases. For instance, on the western edge of the map (Fig. 3.2), the fault cuts up section in the middle Lisburne, juxtaposing middle Lisburne against middle Lisburne. On the eastern side of the map, however, the same fault juxtaposes Kayak Shale and upper Lisburne and the entire thickness of the lower and middle Lisburne section is missing.

To the north, a backthrust in the Kingak is inferred to compensate for the increase in thickness of the Kingak adjacent to the mountain front (Thrust 2, Fig. 3.2). This thrust is not exposed at the surface (i.e., a blind thrust) but is assumed to be present in order to explain the observed increase in thickness of the Kingak Shale.

Smaller scale thrusts and backthrusts are documented in the Kingak Shale and Kemik Sandstone in the northern portion of the map area (Fig. 3.2). Similar imbricate faults in the Kemik Sandstone are well-documented in both the transect area and nearby localities (Mull, 1986; Meigs, 1989; Meigs and Imm, 1995; Reifenhuth et al., 2000). These faults cut up section, resulting in structural repeats of the Kemik section. These smaller scale faults are parallel to the structural trends in the study area.

Finally, north-trending transverse faults with down-to-the-east offset occur in the northern part of the map area (Fig. 3.2). Most of these faults have relatively minor displacement. The transverse fault with the most displacement observed is in the northwest corner of the map area and has a down-to-the-east sense of displacement that results in the exposure of the Kingak Shale between Kemik exposures. This particular transverse fault may also have a minor component of dextral strike-slip motion as it offsets an anticlinal axis.

Folds

The general style of folding in Domain I differs from the style observed in Domains II and III. In Domain I, the Kayak Shale displays a wide range in fold geometries, reflecting its nature as an easily deformed, incompetent detachment unit. Some folds in the Kayak are tight, isoclinal folds with overturned limbs while others are broad, open folds (Fig. 3.7). Most of these folds are fairly small (wavelengths <20 meters).

In contrast, the more competent rocks of Domain II (Lisburne through Shublik Formation) are dominated by broad (wavelength ~100 m), north-vergent folds with boxy geometries that plunge gently (~10°) to the west (Fig. 3.6).

North of the mountain front, most of the folds in the Kemik Sandstone of Domain III are north-vergent, west-plunging, open anticlines and synclines. The crests of the anticlines are often breached and less commonly slightly offset by north-trending transverse faults (Fig. 3.8). Tight, isoclinal folds are observed in the incompetent rocks of this domain, such as the Hue Shale (Fig. 3.9).

Subsurface Observations

Four seismic lines were acquired from Anadarko (Fig. 3.10). These lines and adjacent wells were used to constrain the subsurface stratigraphy and structure.

Stratigraphy

Formation tops from the Kemik 1 well (Nelson et al., 1998; written communication, Decker, 2005) were projected onto the most closely located seismic line (Figs. 3.10, 3.11, line X-X') and helped define reflectors that represent Ellesmerian sequence rocks. That information was projected onto all the seismic lines and used in their interpretation.

The map units used in the subsurface differ from those at the surface because of the difficulty of differentiating relatively thin units on the seismic lines. For instance, the Kayak Shale and Kekiktuk Conglomerate were not distinguishable from each other in the seismic data and were therefore interpreted as undifferentiated. Also, the Ivishak Formation and the Kavik Member of the Ivishak Formation and the Shublik Formation were distinguishable at the surface, but not in the seismic, so they were interpreted as undifferentiated and defined as the Sadlerochit Group. The Shublik Formation and the Sadlerochit Group were interpreted as undifferentiated. Similarly, the lower, middle, and upper Lisburne surface units were interpreted simply as Lisburne Group in the subsurface.

The formation top depths from the Kemik #1 well were used to convert two-way travel time into depth which was then tied to the remaining seismic lines. The error on formation top depths increases with increasing lateral distance from the Kemik #1 well and with increasing thickness of Brookian Sequence rocks because the geophysical properties of the additional material were not taken into account (verbal communication, Coakley, 2005).

Structure

Seismic Line W-W'

The interpreted, depth-corrected cross-section of line W-W' is shown in Figure 3.12. Ellesmerian sequence is displaced and folded into a hangingwall anticline above a north-vergent thrust fault that is traceable into the pre-Mississippian basement. A minor north-vergent thrust in the hangingwall displaces Kingak Shale and Kemik Sandstone.

Folding in the footwall of this thrust accommodates shortening to the north. North of the thrust, the Kingak Shale pinches out completely against a surface interpreted to be the Lower Cretaceous Unconformity (LCU). As a result of this truncation, the Kemik Sandstone directly overlies the Shublik-Sadlerochit Group.

Seismic Line X-X'

Similar to line W-W', the seismic section of line X-X' in Figure 3.11 shows a major basement-involved, north-vergent thrust fault. This fault is located along strike with the major thrust in line W-W' and is interpreted to be the trace of the same fault. In the hangingwall, several minor forethrusts and backthrusts offset the Kingak Shale and Kemik Sandstone to accommodate shortening on the main thrust. These minor thrusts result in duplexing of the Kemik Sandstone. Duplexing of the Kemik Sandstone is well-documented in the northeastern Brooks Range foothills (Mull, 1986; Meigs, 1989; Meigs and Imm, 1995; Reifentstahl et al., 2000).

Also in the hangingwall of the main thrust, a significant backthrust cuts up section from the base of the Lisburne Group, through the Shublik-Sadlerochit Group, and dies out in the Kingak Shale. This backthrust may have formed in response to the development of the hangingwall anticline or to accommodate shortening on the main thrust.

In the footwall, the LCU also truncates the Kingak Shale and the Shublik Sadlerochit Group. At the northernmost end of this section, Kemik Sandstone directly overlies the Lisburne Group. While most shortening in the footwall is accommodated by folding, a backthrust is also observed that cuts up section from the base of the Lisburne Group into the Kingak Shale.

Seismic Line Y-Y'

Two main basement-involved, north-vergent thrusts displace Ellesmerian stratigraphy in section Y-Y' (Fig. 3.13). The southernmost main thrust has displaced these rocks to a greater extent than the northern fault, but above each fault is a hangingwall anticline. The southern thrust is along strike with the major thrusts in lines W-W' and X-X' (Figs. 3.11 and 3.12) and is interpreted to be the same fault.

Between the thrusts, the LCU truncates the Kingak Shale, leaving the Kemik Sandstone directly over the Shublik-Sadlerochit Group. Minor north-vergent thrusting in the Kingak Shale and Kemik Sandstone accommodates shortening in hangingwall of the southern major thrust.

Seismic Line Z-Z'

Line Z-Z' is a strike line that parallels the dominant east-west structural trend (Fig. 3.14). Two east-dipping faults offset the top of the pre-Mississippian basement. These faults are interpreted to be lateral ramps with a component of left-lateral strike slip motion and are lateral extensions of two north-directed, basement-involved thrust faults.

Another notable feature in this strike line is that the stratigraphy deepens to the west. This is interpreted to be due to the western plunge of the Sadlerochit Mountains to the east.

Integration of surface and subsurface data

Figure 3.15 is a fence diagram showing an integrated interpretation that includes the four seismic lines (Figs. 3.11-3.14) and the cross section constructed from surface data (Fig. 3.5). The diagram serves to aid visualization of structures with respect to their spatial distribution.

The major basement-involved thrust faults are numbered (Fa (Fault-A), Fb, Fc, etc.) to help show the relationships between the faults. For instance, sections X-X', W-W', and Y-Y' display the lateral continuity of the basement-involved thrust fault (Fe) that cuts up section slightly north of strike line Z-Z'. The westernmost lateral ramp is interpreted to be a part of fault Fe while the eastern lateral ramp may be a subsidiary splay of Fe..

The fence diagram shows a northward change of deformational style in the basement. The southern part of the area documents well-developed fault-bend folds in the basement above which Ellesmerian rocks passively deform above a roof thrust in the Kayak Shale. Here, the basement-involved faults do not cut up section into the Ellesmerian section. However, in the subsurface to the north, basement faults cut up section and displace pre-Mississippian and Ellesmerian rocks.

The depth-corrected seismic sections and point data from wells in the area, combined with existing Alaska Oil and Gas Conservation Commission data were used to construct a contour map which marks the base of the Shublik Formation (AOGCC, 2004; Fig. 3.3). The map illustrates that the structural style in the basin is similar to that documented at the surface immediately to the south in that the structure is dominated by east-west trending folds and thrust faults with hangingwall anticlines. The slight northeast orientation to some of the fold axes and fault traces is probably due to contouring error resulting from the sparsity of data.

Figure 3.3 also shows the northern limit of the Kayak Shale and the Shublik-Sadlerochit Group where these formations are truncated by the LCU. Though the LCU truncates the Shublik-Sadlerochit Group in line X-X', that truncation is not traceable to adjacent lines W-W' and Y-Y' (Fig. 3.15).

Fracture Distribution and Character

Four prevalent fracture sets are present in the exposed part of the transect (Table 3.1). These include (in order from oldest to youngest): a N–S striking filled set (Set 1), an E–W striking filled set (Set 2), a N–S striking unfilled set (Set 3), and an E–W striking unfilled set (Set 4). Relative age relationships are based on cross-cutting and abutting relationships observed in both outcrop and thin section.

Set 1: N–S Striking Filled Fractures

Set 1 fractures trend N-S, dip steeply either to the east or west and are oriented perpendicular to sub-perpendicular to the regional structural trend and to bedding (Fig. 3.16). Set 1 fractures are common in Domains I and II. (Table 3.1), but did not occur in significant abundance in Domain III. Consequently, a quantitative fracture survey of Set 1 fractures was not possible in Domain III, but qualitative observations of these fractures suggest apertures, terminations, and spacing are similar to those of Set 1 in Domains I and II.

Set 1 fractures are filled with either calcite or quartz depending on the lithology of the host rock. Set 1 apertures range from <0.1 cm to 1.9 cm, with an average width of 0.33 cm (Table 3.2). Consistently narrow fractures (<0.1 cm) were found in Domain I in the anticlinal hinge of a fold exposed in the Kayak Shale. Average apertures in the limbs and hinges of folds throughout the field area are 0.43 cm and 0.12 cm, respectively.

Fracture terminations were generally determined in cross sectional profile of the outcrop rather than on bedding surfaces due to lack of pavement exposure. Set 1 fractures commonly terminate at interbed boundaries (mechanical stratigraphic interfaces) related to variations in lithologic character. Less commonly, Set 1 fractures terminate against adjacent Set 1 fractures with a hook geometry.

Petrographic analysis of Set 1 fractures show that the crystals forming the fracture cement are perpendicular to subperpendicular to fracture walls, suggesting an extensional origin. The crack-seal texture of fluid inclusions in the fracture fill suggests cementation occurred synchronously with opening of fracture walls.

The mean spacing of Set 1 fractures in Domains I and II are summarized in Table 3.3 and Fig. 3.17. A Mann-Whitney test indicates that that there is not a statistically significant

difference in Set 1 fracture spacing between the two domains (Table 3.4), suggesting that Set 1 fracture spacing is fairly consistent regardless of domain.

There is some variation in Set 1 fracture spacing when structural position is taken into consideration. Table 3.3 and Figures 3.18 and 3.19 show the distribution of Set 1 fractures between limbs and hinges of folds in Domains I and II, respectively. The Mann-Whitney test was used to evaluate if these apparent differences in spacing were statistically significant (Table 3.4). In Domain I, the difference was insignificant, but in Domain II, the spacing of fractures was statistically different between the limbs and hinges, with Set 1 fracture spacing greater in the hinge zones as compared to the limbs.

Set 2: E–W Striking Filled Fractures

Fracture Set 2 only occurs in Domains I and II. Set 2 fractures have an E-W trend and most commonly dip steeply to the north or south, though some of the fractures have shallow dips (Fig. 3.16). These fractures form at high angles to bedding and parallel the regional trends of fold axes.

Set 2 fracture apertures range from 0.1 cm to 2.3 cm, with an average width of 0.43 cm. Average fracture apertures in the hinges and limbs of exposed folds are 0.45 cm and 0.31 cm respectively (Table 3.2).

Set 2 fractures terminate at mechanical boundaries and within individual beds. These fractures also terminate against other Set 2 fractures with hook geometries, against Set 1 fractures, and within adjacent beds.

Quartz or calcite crystals filling the fracture are oriented perpendicular to subperpendicular to fracture surfaces. Fracture surfaces show no evidence of shear, such as slickenlines. Set 2 fractures are interpreted to have formed under tension.

Fracture spacing for all Set 2 fractures is summarized in Table 3.3 and illustrated Figure 3.20; Set 2 fracture spacing with respect to structural position is summarized in Table 3.3 and Figures 3.21 and 3.22. Mann-Whitney statistical test results for Set 2 fractures indicate that there is no statistical difference in fracture spacing between domains or with structural position (Table 3. 4)

Set 3: N–S Striking Unfilled Fractures

Set 3 fractures strike generally north-northwest (Fig. 3.16). These fractures strike perpendicular to fold axes in the study area and are at high angles to bedding. One observable discrepancy is that several data points indicate a very shallow dip that approaches horizontal. These data were collected on a bedding surface which was nearly vertical (in the Kemik Sandstone, Domain III), so though their orientations appear to

vary, it is an artifact from the orientation of the bedding from which the fracture data was collected.

Fracture Set 3 occurs throughout the stratigraphy in structural Domains I, II, and III. This fracture set is unfilled and interpreted to be extensional in origin based on the abundance of fracture surface ornamentation in the form of plumose structures.

Set 3 fractures apertures range from 0.05 cm to 1.5 cm with an average width of 0.36 cm (Table 3.2). The average aperture in the hinges of folds throughout the field area is 0.26 cm; average aperture on fold limbs is slightly greater at 0.39 cm.

Set 3 fractures generally terminate at bedding planes or internal to bedding. Less commonly, these fractures extend beyond bedding interfaces, penetrating multiple beds. Set 3 fractures also terminate against adjacent set 3 fractures.

Set 3 fracture spacing distribution between domains and between fold limbs and hinges within each domain is summarized in Table 3.3 and illustrated in Figures 3.23-26. The Mann-Whitney test (Table 3.4) indicates that there was not a statistically significant difference in the spacing of Set 3 fractures between domains or with structural position within domains.

Set 4: E–W Striking Unfilled Fractures

Set 4 fractures generally strike parallel to local fold axes and are at high angles to bedding (Figure 3.16). Set 4 fractures are present throughout the stratigraphy in structural Domains I, II, and III. These fractures are unfilled and, based on the common occurrence of plumose structures and the absence of shear indicators, are interpreted to be extensional.

Average Set 4 fracture aperture is 0.35 cm with a range of apertures of <0.01 cm to 2.5 cm (Table 3.2). The average aperture in hinges of folds (all domains) is 0.63 cm, and the average width of set 4 fractures in the limbs (all domains) is 0.1 cm.

Set 4 fracture termination is variable throughout the study area. These fractures most commonly terminate at bed boundaries and within individual beds, but also against Set 3 fractures and adjacent Set 4 fractures.

The spacing distribution of Set 4 fractures in each domain is shown in Figure 3.27 and summarized in Table 3.3; fracture spacing within in each structural domain with respect to structural position is shown in Figures 3.28-30 and summarized in Table 3.3. The Mann-Whitney test (Table 3.4) indicates that there is not a statistically significant difference in the spacing of Set 4 fractures between domains or with structural position within domains.

Fracture distribution in the subsurface

Log data from four wells on or adjacent to the transect were analyzed for potential fracture porosity (Kemik 1, Kemik 2, Beli 1, and West Kavik 1; Fig. 3.10 and Figs. 3.31-3.34). Intervals of secondary fracture porosity were identified by comparing sonic and density logs and assuming that fracture porosity occurred where the sonic-derived porosity is substantially greater than the density-derived porosity (Shafer, 1980; Rider, 1986).

In each of the wells, potential fracture porosity was identified in the Shublik-Sadlerochit Group. Fracture porosity also occurs abundantly in the Lisburne Group in each well with the exception of the West Kavik #1, in which the density log does not extend into the Lisburne.

The Kemik #1 well TD'd at the top of the Kayak Shale (Fig. 3.31). Two distinct zones of potential fracture porosity occur in the Shublik-Sadlerochit Group. The upper ~1300 feet of the Lisburne Group shows evidence of significant secondary porosity from fractures.

The Kemik #2 well reaches its total depth in the upper portion of the Lisburne Group (Fig. 3.32). As in the Kemik #1 well, there is substantial fracture porosity in the Lisburne Group and thinner zones of fracture porosity in the Shublik-Sadlerochit Group.

The Beli #1 well also TD'd in the Lisburne Group (Fig. 3.33). Though the zones of fracture porosity in the Lisburne are not as prominent as in Kemik #1 and Kemik #2, there is still significant secondary porosity throughout the Lisburne Group and intermittent zones in the Sadlerochit Group. The Beli 1 well also shows fracture porosity in the Brookian sequence, above the Hue Shale of the Ellesmerian sequence.

The West Kavik #1 well bottoms in the Lisburne Group, but the sonic and density logs in this well are not consistently recorded, resulting in an incomplete documentation of zones of fracture porosity (Fig. 3.34). There is, however, fracture porosity in the upper Sadlerochit Group, the Kingak Shale, and in the Brookian sequence above the Hue Shale.

Present day *in situ* stresses have been evaluated in wells adjacent to the northeastern Brooks Range thrust front (Hanks et al., 1999). *In situ* stresses could potentially hold fractures open and can therefore have an impact on reservoir quality. Hanks et al. (1999) evaluated the maximum horizontal *in situ* stresses in the Kavik #1 and #2 wells, the West Kavik #1 well, and the Gyr #1 well. Borehole breakouts in those wells suggests that the *in situ* maximum horizontal stress is oriented north-northwest, perpendicular to the active thrust front. There is also a strong correlation between the depths of the breakout intervals documented by Hanks et al. (1999) and the zones of secondary porosity identified in this study. This suggests that the open fractures in these wells are oriented roughly north-northwest-south. These open fractures would correlate to Set 4 open fractures documented at the surface in the study area.

Thermal constraints on faulting, folding, and fracturing

Fluid Inclusion Microthermometry

Fluid inclusion measurements from fracture cements were obtained from Set 1 and Set 2 fractures in Domains I, II, and III (Fig. 3.35). Fractures were filled with either quartz or calcite depending on the lithology of the host rock. Table 3.5 summarizes the distribution and types of fluid inclusions in the cements analyzed as well as homogenization temperature results. Fluid inclusion analysis was done by M. Parris of Petro-Fluid Solutions, Inc.

The fluid inclusion results in Table 3.5 suggest that Set 1 and Set 2 fractures in Domain I developed at $\sim 188^{\circ}\text{C}$ and $\sim 193^{\circ}\text{C}$, respectively. Homogenization temperatures for Set 2 samples in Domains II are slightly lower at $\sim 173^{\circ}\text{C}$.

Set 1 fractures

Primary aqueous inclusions from a quartz-filled Set 1 fracture (sample 03AL08b) in the Kekiktuk Conglomerate have a mean homogenization temperature of $188^{\circ}\text{C} \pm 13^{\circ}\text{C}$ (Table 3.5). This sample has deformation lamellae oriented perpendicular to the long axis of the quartz crystal, indicating post-cementation deformation.

Set 1 fracture fill analyzed from sample 03AL31d in Domain II is from the upper Lisburne (Table 3.5). Secondary inclusions from this sample indicate a mean homogenization temperature of 229°C and have experienced post-entrapment re-equilibration. This temperature is therefore not considered representative of the temperature of fluids during fracture filling. Rather, it represents a period after initial fracture opening and cementation.

Two quartz-filled Set 1 fractures from the Kingak Shale in Domain III were analyzed (sample 03AL20b, Table 3.5). One set of inclusions was secondary and yielded a mean homogenization temperature of $\sim 159^{\circ}\text{C}$. These inclusions were distributed along healed microcracks that post-date quartz fibers. The other Set 1 fracture contained primary aqueous and gas-rich inclusions and yielded a mean temperature of $\sim 173^{\circ}\text{C}$. Crack-seal fluid inclusion trails and bent crystal fibers suggest that filling occurred synchronously with fracture opening. The aqueous inclusion in this sample is coeval with the gas-rich inclusion, so the trapping temperature represents a true trapping temperature (Roedder, 1984).

Set 2 fractures

In Domain I, quartz–cemented fractures from Set 2 in the Kayak Shale showed synkinematic textures, indicating fracture filling occurred simultaneously with fracture opening. Mean homogenization temperatures for these samples were ~189 °C (03AL05g) and ~196 °C (03AL05b) (Table 3.5).

Fluid inclusions from Set 2 fracture cement from samples in Domain II have an overall average homogenization temperature of ~173 °C. Cements from primary inclusions in Set 2 fractures have textures consistent with syn-kinematic crystal growth (samples 03AL27a and 03AL16b; Table 3.5). A secondary inclusion in sample 03AL31d showed evidence of post-entrapment re-equilibration. The origins of inclusions from samples 03AL106a and 03AL07a were indeterminate. However, sample 03AL07a had a fibrous texture indicative of over-pressure (Parris, 2004 written communication).

Set 2 fracture cements from Domain III were not analyzed.

Vitrinite Reflectance

Surface samples

In order to constrain the thermal history of the study area, four new organic–rich samples were collected from shale and coal–bearing units exposed at the surface (Fig. 3.35) and analyzed for thermal maturity by the U.S. Geological Survey laboratories (courtesy of D. Houseknecht). These new data were coupled with data from previous studies (Bird et al., 1998) to provide insight into regional thermal maturity trends (Table 3.6, Fig. 3.36).

The mean reflectance values for 39 published and new outcrop samples were used to construct a surface thermal maturity contour map of the region (Fig. 3.36). The contour intervals were selected to reflect significant boundaries related to the limits of hydrocarbon generation, preservation, and destruction (0.6 %, 1.3%, and 2.0% R_o respectively).

The vitrinite reflectance contours in Figure 3.36 have an east–northeast trend across the northeastern Brooks Range foothills which, in general, parallels the strike of the mountain front. Exposures at the mountain front are overmature, with thermal maturity decreasing basinward. Mature rocks, those that have reached temperatures favorable for hydrocarbon generation, occur in surface exposures of Silurian through Cretaceous rocks in the foothills and in the western Sadlerochit Mountains. Farther north, Cretaceous and Tertiary rocks at the surface are primarily undermature and have not reached temperatures conducive to hydrocarbon generation.

Subsurface samples

No new vitrinite reflectance subsurface samples were collected during this study, but vitrinite reflectance data collected from Kemik #1, Kemik #2, West Kavik #1 and Beli #1 are publicly available (Bird *et al.*, 1998). Analysis of the R_o values in these show that thermal maturity generally increases with depth, as would be expected. Vitrinite reflectance values are plotted on well logs in Figures 3.31-34 and the corresponding level of thermal maturity is noted.

In the Kemik #1 well, the Kemik Sandstone and Kingak Shale are structurally repeated (Fig. 3.31). The structurally highest Kemik Sandstone and Kingak Shale are mature, but Kingak in the footwall is postmature. In the lower part of the Lisburne Group, the one vitrinite sample is (anomalously) immature.

Vitrinite reflectance values in the Kemik #2 well (Fig. 3. 32) are consistently postmature, though the data only spans part of the Kingak Shale through the top of the Lisburne Group. The data still show a slight increase in R_o with depth.

Rocks in the Beli # 1 well show a steady increase in thermal maturity from immature in the Brookian sequence, to mature, and finally postmature at the base of the Sadlerochit Group (Fig. 3.33).

In the West Kavik #1 well (Fig. 3.34), thermal maturity also increases steadily down section, though the base of the Sadlerochit Group and even the top of the Lisburne Group are classified as mature, rather than postmature as in the Beli #1 (Fig. 3.33). A comparison of thermal maturities in the Shublik-Sadlerochit Group in the West Kavik #1 and Beli #1 wells, which are ~26 kilometers apart, shows a decrease in thermal maturity toward the west (Fig. 3.36).

Bray *et al.* (1992) discusses a method in which vitrinite reflectance and/or apatite fission-track data can be used to estimate past burial amount. Down-hole vitrinite reflectance is converted to temperature and plotted as points against depth. The resulting best-fit line to the temperature values, when projected to the depth axis, provides an estimate of the amount of denudation. The resulting gradient is compared to the modern geothermal gradient. If the slope of the gradients are similar, then paleoheat flow was similar to modern heat flow.

The temperature versus depth plot in Figure 3.37 displays down-hole paleotemperatures from eight wells in the study area (computed from vitrinite reflectance values provided by Bird *et al.*, 1998) and the modern geothermal gradient (1.85 °C/100 ft or 27 °C/km) based on bottom-hole temperatures (from Verma *et al.*, 2005)). The graph in Figure 3.38 compares the estimated denudation from the 4 wells in the southern part of the map area. The least amount of denudation in the area (~4.2 km) occurred in the Kemik #1 well, while the Shaviovik well is shown to have experienced the greatest amount of denudation

at ~7.3 km. Figure 3.39 summarizes the amount of denudation experienced by the 4 wells in the northern portion of the study area in the proximity of the Kavik gas field. The Kavik #1 well experienced ~3.2 km of denudation, while the West Kavik #1 well (down-plunge on the same Sadlerochit structure) has experienced relatively little denudation (~0.9 km). These estimates are consistent with those calculated by Burns et al. (2007) were based on sonic-porosity logs from wells.

The paleogeothermal gradients in most of the wells are relatively similar to that of the modern geothermal gradient (Figs. 3.38, 3.39). However, the paleogeothermal gradients in the Shaviovik #1 and Fin Creek #1 wells are much steeper. This suggests that the temperature change with depth in these two wells was not as great as in the other wells. For instance, in the Kemik #1 well, the temperature difference between 4000 feet and 8000 feet depth was about 45°C, whereas the difference over the same depth interval in the Shaviovik #1 well was about 10 °C. This may be due to structural disruption in the Shaviovik #1 and Fin Creek #1 wells.

Conodont Alteration Indices

Seven new Lisburne and Echooka samples were collected during this study for conodont alteration analysis to provide additional constraints on the thermal history of the study area (Fig. 3.35, Table 3.7; analyzed by Andrea Krumhardt, UAF). The samples have CAI values ranging from 5–6.5, indicating that the samples experienced temperatures of 300–600 °C (Rejebian et al., 1987). A sugary texture was also observed on the conodonts, suggesting hydrothermal alteration.

Based on these temperatures, and assuming a geothermal gradient of 27 °C/km, the rocks would have been buried to a depth of 11-22 km, but the textures of the host rocks are not consistent with such deep burial. Rather, the sugary texture of the conodonts suggests these samples were exposed to hydrothermal fluids. During compaction, thermal maturation of organic-rich shales can release fluids with elevated temperatures. The Kayak Shale may be the source of these high temperature fluids (Hayes, 2004).

Geochronologic constraints on deformation

Apatite Fission Track Analysis

Fission-track samples were collected from sedimentary rock outcrops exposed along the southern part of the transect (Fig. 3.40). The samples were selected to help constrain the timing of deformation and uplift related to basement-involved detachment faulting. Analyses were performed by Paul O’Sullivan of Apatite to Zircon, Inc. The fission-track data for these samples are summarized in Table 3.8.

In each sample, the pooled apatite fission-track age is younger than the depositional age, implying exposure to elevated post-depositional temperatures (O'Sullivan and Wallace, 2002). In Domain I, samples located stratigraphically beneath the Lisburne Group, in the forelimb of the Echooka Anticlinorium, yielded apatite fission-track ages of 30 ± 5.8 to 34 ± 4.9 Ma and mean track lengths of 13.2 ± 0.31 to 14.1 ± 0.30 μm . Further north in Domain II, apatite grains in sedimentary rocks show a range of ages between 40.5 ± 6.8 and 49.8 ± 7.7 Ma. Track lengths in these samples range from 12.56 ± 0.54 to 14.59 ± 0.15 μm . In Domain III, one sample from the Kemik Sandstone produced an age of 23.2 ± 4.4 Ma and had a mean track length of 14.91 ± 0.24 μm .

The ages of uplift events implied by these data are consistent with results from other fission-track studies in the northeastern Brooks Range which suggest four major episodes of cooling at ~ 60 , ~ 45 , ~ 35 , and ~ 25 Ma (O'Sullivan et al., 1993; O'Sullivan, 1996; O'Sullivan and Wallace, 2002).

Discussion

Origin of fracture sets

Each of these fracture sets is interpreted to be extensional in origin based on the sense of displacement across the fracture surface, ornamentation, and the orientation of fracture cement crystals. The filled sets are interpreted to have formed at depth in the presence of fluids, whereas the unfilled sets are thought to have developed near the surface and/or in the absence of fluids.

The orientations of the fracture sets have implications for regional stresses at the time of fracture development. Set 1 is oriented perpendicular to regional fold axes, similar to the tectonic joints discussed by Engelder (1985) and Lorenz et al. (1991), which form under low differential stress and elevated pore fluid pressure ahead of the fold-and-thrust belt in flat-lying rocks.

Alternatively, these fractures could form during flexural slip folding where σ_1 is parallel to bedding and perpendicular to the fold axis, σ_2 is perpendicular to bedding and the fold axis, and σ_3 is parallel to bedding and the fold axis. This is similar to the pattern of inner-arc tangential longitudinal strain described by Stearns and Friedman (1972) (Fig. 3.41). Therefore, based on observations of fracture orientation alone, it is plausible that Set 1 fractures may have formed either in flat-lying rocks or during folding.

Set 2 fractures are interpreted to be related to folding. This set may be associated with outer-arc tangential longitudinal strain during flexural slip folding wherein σ_1 is perpendicular to bedding and parallel to the fold axis, σ_2 is parallel to bedding and the fold axis, and σ_3 is parallel to bedding and perpendicular to the fold axis (Fig. 3.41).

Sets 3 and 4 fractures have orientations consistent with near-surface unloading joints related to uplift (Davis and Reynolds, 1996) and imply stresses similar to those of the Sets 1 and 2, respectively.

Fracture spacing and structural position

he fracture spacing within of each fracture set in each structural domain shows only minor variations with respect to structural position (Figs. 3.17-3.30). Only Set 1 fractures in Domain II showed a statistically significant difference between fracture spacing in the limbs and hinges (Table 3.4). Though the differences were not significant for any other fracture sets throughout the structural domains, it is worth noting that the mean fracture spacing was generally slightly greater in hinge zones.

The Set 2, ostensibly fold-related, fractures documented in this study have a fairly uniform distribution across folds, contrary to the pattern that would be expected if a fixed-hinge detachment fold model is assumed (Homza and Wallace, 1997). Rather, the relative uniformity of fracture spacing across exposed folds suggests that material may have migrated through the hinges of folds during deformation. Alternatively, the kinematic history of the folds and the timing of fracturing during folding could be complex (Hayes and Hanks, 2008). Ideally, fracture surveys should follow a single bed throughout a fold in order to constrain these observations. However this was feasible in only two cases in the study area (one fold pair in the Kayak Shale, another in the Lisburne Group). A more detailed analysis of individual beds which are traceable across individual folds is required to test these alternatives.

Fractures and stratigraphic position

Pre-Mississippian rocks through the Cretaceous Pebble Shale were evaluated for the presence of each of the four fracture sets. The two filled fracture sets (Sets 1 and 2) occur only in pre-Mississippian rocks through the Cretaceous Kingak Shale and do not occur in strata above the LCU (Table 3.1). Explanations for this fracture distribution include:

- The filled fractures of Sets 1 and 2 may have developed prior to the deposition of units stratigraphically higher than the LCU.
- The LCU may have hindered migration of fluids to overlying strata. Filled fractures of Sets 1 and 2 could have formed in the presence of fluids below the LCU; above the LCU, Sets 3 and 4 formed in the absence of fluids.
- Fracture Sets 1 and 2 formed at depth and in the presence of fluids.. Higher stratigraphic levels did not experience the needed pressure and temperatures and/or did not have significant fluids present to form Sets 1 and 2.
- The unfilled fractures of Sets 3 and 4 formed at shallow depths or in the absence of fluids. These fractures are present throughout the exposed stratigraphic column because all the exposed rocks have experienced uplift and erosion.

The fact that most of the fractures in the study area are confined to individual beds suggests that mechanical stratigraphy played an important role in fracture propagation (Engelder and Geiser, 1980; Underwood et al., 2003; Hayes, 2004; Cooke et al., 2006; Hayes and Hanks, 2008). Lithologic differences between adjacent beds may have hampered fracture propagation across bedding planes. In contrast, some of the Set 3 fractures, particularly in the Echooka Formation, were fairly pervasive, indicating possible mechanical homogeneity. The pervasiveness of the Set 3 fractures is a characteristic common of joints that develop near the surface during uplift (Engelder, 1985; Hancock and Engelder, 1989).

Thermal and age constraints on faulting, folding, and fracturing

The regional thermal constraints provided by vitrinite reflectance analyses from surface samples show a basinward decrease in thermal maturity (Fig. 3.36). The data suggest that the rocks near the mountain front were exposed to greater maximum temperatures than those toward the basin, which reflects the increased degree of burial and uplift experienced by the strata at or near the front. Based on vitrinite reflectance values, rocks exposed at the surface in Domains I, II, and III are interpreted to have been exposed to maximum temperatures of ~195, ~180, and ~170 °C, respectively. The range in temperatures may be the result of different burial depth due to variation in stratigraphic position.

Fluid inclusions from quartz and/or calcite cemented fractures from Sets 1 and 2 both show evidence of syn-kinematic development (Table 3.5). Sets 1 and 2 have similar homogenization temperatures throughout the study area. These temperatures range from ~160–190 °C and approach the maximum temperatures estimated from vitrinite reflectance values in each structural domain. The range in homogenization temperatures between fracture sets in the different structural domains may simply reflect the varying depth of burial during fracture development as a result of stratigraphic level.

The average overall trapping temperature of the Set 1 inclusions (regardless of structural domain) is ~173 °C. Assuming a geothermal gradient of 27 °C/km (as estimated from the Kavik gas field by Verma et al., 2005), these fractures would have formed and filled at depths of about 6 km. Similarly, the Set 2 inclusions have an average overall trapping temperature of ~188 °C, corresponding to about 7 km depth.

Based on the range of CAI temperatures (300–600 °C) and assuming a geothermal gradient of 27 °C/km, Lisburne Group rocks would have been buried to depth of 11–22 km, but the textures of the host rocks are not consistent with such deep burial. Rather, the sugary texture of the conodonts supports the idea that these samples were exposed to hydrothermal fluids, possibly derived from the Kayak Shale (Hayes, 2004). The temperatures derived from the vitrinite reflectance data and the fluid inclusion analysis are probably more accurately reflect true paleotemperatures.

Average pooled fission-track ages used to reconstruct burial history show that in general, the stratigraphic units exposed in the southern part of the transect in Domain I cooled below 110 °C at ~45 Ma; rocks in the middle of the transect (Domain II) cooled below 110 °C at ~35 Ma; and rocks in the northern part of the transect (Domain III) cooled below 110°C at ~25 Ma (Fig. 3.40, Table 3.8). These fission-track ages correspond to major Mesozoic and Cenozoic tectonic events noted by O'Sullivan et al., (1993), O'Sullivan (1996), Moore and Potter (2003), and many others.

Fission-track ages and track length distributions for each sample were calculated for a series of randomly generated temperature histories (using AFTSolve software (©1996–2003 Apatite to Zircon, Inc. and Richard A. Ketcham). The histories were considered geologically reasonable based on the stratigraphic age and present-day geological temperature of each sample. A temperature history was considered a good fit when the model fission-track age and model track length distribution matched the measured value derived from the sample.

A schematic model showing one interpretation of the uplift history in the study area is shown in Figure 3.42. This model illustrates an apparent out-of-sequence pattern of thrust faulting in the basement rocks. Uplift of the basement horse in Domain II brought an Echooka Formation sample through the partial annealing zone first, giving it a fission-track age of ~60 Ma. At this point, the basement horse in Domain I may also have developed, but did not uplift enough to bring stratigraphically lower Kayak Shale samples through the partial annealing zone. At ~45 Ma, continued motion on the basement detachment in Domain I raised the Kayak Shale through the 110 °C geotherm. Finally, basement faulting in Domain III uplifted Kingak Shale samples through the partial annealing zone at ~25 Ma.

An alternative model does not require out-of-sequence thrusting (Fig. 3.43). In this model, horses 1 and 2 developed at ~60 Ma. The associated uplift and erosion of horse 1 brought the antiformal crest (including the Echooka samples) through the partial annealing zone. However, the stratigraphically lower Kayak Shale was located in the synclinorium between horses 1 and 2 and remained buried beneath the 110 °C isotherm. Slow erosion after emplacement resulted in the Kayak Shale cooling through the partial annealing zone later than the stratigraphically higher Echooka samples, giving it a younger fission-track age. Finally, development of horse 3 to the north at ~25 Ma uplifted the Kingak Shale through the partial annealing zone.

The vitrinite reflectance data, fluid inclusion results, fission-track models, and fracture character, distribution and relative age can be integrated and interpreted in terms of the history of burial, fracturing, deformation, and uplift (Fig. 3.44, 3.45). In these models, fracture Set 1 is interpreted to have developed in flat-lying rocks during the late stages of burial near maximum temperatures prior to detachment folding. Cementation occurred in these fractures contemporaneously with fracture opening. Set 2 fractures developed

during detachment folding, which occurred at different times depending on the structural domain. Fracture Sets 3 and 4 formed during the late stages of uplift near the surface.

This thermal/uplift/fracture model imposes reasonable limits on potential burial and uplift paths along the transect. The lack of filled fractures in higher stratigraphic units (e.g. Kemik Sandstone) suggests that these fractures developed at shallow depths or that fluids were absent from the unit altogether (Davis and Reynolds, 1996; Hanks et al., 2006).

Petroleum system implications

Figure 3.46 illustrates the timing of the essential components of the North Alaska hydrocarbon system in the vicinity of the Eastern Transect. In this diagram, the ‘critical moment’ represents the time of highest probability of entrapment and preservation of hydrocarbons, which occurs when a structural or stratigraphic trap precedes the generation, migration, and accumulation of hydrocarbons in a petroleum system (Magoon and Dow, 1994). However, multiple episodes of fracturing can make identification of that ‘critical moment’ difficult.

Fracturing can provide both hydrocarbon migration pathways and enhance reservoir. This study suggests the eastern part of the Alaska North Slope experienced multiple episodes of fracturing related to burial, structuring and later uplift (Fig 3.45) starting in Late Cretaceous time. According to the model for the development of fractures in the Eastern Transect, early Set 1 fractures would have coincided with hydrocarbon generation and provided a migration pathway out of the source rocks and into updip traps. Any stratigraphic traps existing at this time (e.g., in the Kingak Shale or Kemik Sandstone) could be sourced in this manner. However, at any one location, Set 1 fractures would have predated formation of fold-and-thrust-related traps and the associated Set 2 fractures. Sourcing of these structural traps by fracture-assisted migration would require remigration of earlier-generated hydrocarbons or later migration of hydrocarbons being generated north of the fold-and-thrust front. The reported trapping mechanism of the field adjacent to the transect, the Kavik gas field, is that of a thrust-faulted anticline with the Kingak Shale acting as the top and lateral stratigraphic seals (Verma et al., 2005). Thus the Kavik gas field may involve deformation of a pre-existing stratigraphic trap or remigrated gas.

The lack of fracture cement in fracture Sets 3 and 4 imply that these fractures formed in the absence of significant fluids. These late fractures probably only serve to breach existing petroleum traps and provide remigration pathways, especially for gas.

References

- Alaska Oil and Gas Conservation Commission website, 2004,
<http://www.state.ak.us/admin/ogc/annual/2004/2004annindex.shtml>.
- Atkinson, P.K., and Wallace, W.K., 2003, Competent unit thickness variation in detachment folds in the northeastern Brooks Range, Alaska: geometric analysis and a conceptual model, *Journal of Structural Geology*, v. 25, no. 10, p. 1751-1771.
- Bird, K.J. and Molenaar, C.M., 1987, Stratigraphy, *in* Bird, K.J. and Magoon, L.B., eds., *Petroleum Geology of the Northern Part of the Arctic National Wildlife Refuge, Northeastern Alaska*: U.S. Geological Survey Bulletin 1778, Chapter 5, p. 37-51.
- Bird, K.J.; Griscom, S.B.; Bartsch-Winkler, S.; and Giovannetti, D.M., 1987, Petroleum Reservoir rocks, *in* Bird, K.J. and Magoon, L.B., eds., *Petroleum Geology of the Northern Part of the Arctic National Wildlife Refuge, Northeastern Alaska*: U.S. Geological Survey Bulletin 1778, p. 79-99.
- Bird, K.J., 1998, Geographic and Geologic Setting, *in* The oil and gas resource potential of the 1002 area, Arctic National Wildlife Refuge, Alaska, by ANWR Assessment Team, U.S. Geological Survey Open File Report 98-34, Chapter GG, 47 p.
- Bird, K. J., Burruss, R.C., and Pawlewicz, M.J., 1998, Thermal maturity, *in* The oil and gas resource potential of the Arctic National Wildlife Refuge 1002 Area, Alaska, U.S. Geological Survey Open File Report 98-34, Chapter VR, 64 p.
- Bray, R.J., Green, P.F., Duddy, I.R., 1992, Thermal history reconstruction using apatite fission track analysis and vitrinite reflectance: a case study from the UK East Midlands and Southern North Sea, *in* Exploration Britain: Geological insights for the next decade, Hardman RFP, ed., Geological Society, p. 3-25.
- Burns, W.M, Hayba, D.O., Rowan, E.L., and Houseknecht, D.W., 2007, Estimating the amount of eroded section in a partially exhumed basin from geophysical well logs: an example from the North Slope, U.S. Geological Survey Professional Paper 1732-D, 18 p.
- Cooke, M.L., Rijken, P., Simo, J.A., and Underwood, C.A., 2006, Mechanical stratigraphic controls on fracture patterns within carbonates and implications for groundwater flow, *Sedimentary Geology*, v. 184, no. 3-4, p. 225-239.
- Davis, G.H., and Reynolds, S.J., 1996, *Structural Geology of Rocks and Regions*, 2nd ed., John Wiley & Sons, Inc., New York, 776 p.

- Detterman, R.L., Reiser, H.N., Broge, W.P., and Dutro, J.T., Jr., 1975, Post-Carboniferous stratigraphy, northeastern Alaska: U.S. Geological Survey Professional Paper 88, 46 p.
- Engelder, T., 1985, Loading paths to joint propagation during a tectonic cycle: an example from the Appalachian Plateau, U.S.A., *Journal of Structural Geology*, v. 7, pl 459-476.
- Engelder, T., and Geiser, P., 1980, On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian Plateau, New York: *Journal of Geophysical Research*, vol. 85, no. B11, pp.6319-63411
- Hancock, P.L., and Engelder, T., 1989, Neotectonic joints, *Geological Society of America Bulletin*, v. 101, p. 1028-1197.
- Hanks, C.L., Parker, M., and Jemison, E.B., 1999, Borehole breakouts and implications for regional in situ stress patterns of the northeastern North Slope, Alaska, *Short Notes on Alaska Geology*, Alaska Division of Geological & Geophysical Surveys.
- Hanks, C.L., Wallace, W.K., Atkinson, P.K., Brinton, J., Bui, T., Jensen, J., and Lorenz, J., 2004, Character, relative age and implications of fractures and other mesoscopic structures associated with detachment folds: An examples from the Lisburne Group of the northeastern Brooks Range, Alaska, *Bulletin of the Canadian Society of Petroleum Geologists*, v. 52, no. 2, p. 121-138.
- Hanks, C.L., Parris, T.M., Wallace, W.K., 2006, Fracture paragenesis and microthermometry in Lisburne Group detachment folds: implications for the thermal and structural evolution of the northeastern Brooks Range, Alaska, *American Association of Petroleum Geologists Bulletin*, v. 90, no. 1, p. 1-20.
- Hayes, M.R. and Hanks, C.L., 2008 (in press), Evolving mechanical stratigraphy during detachment folding, *Journal of Structural Geology*
- Hayes, M.R., 2004, The influence of mechanical stratigraphy on the development of detachment folds and associated mesoscopic structures: an examples from the Lisburne Group carbonates, northeastern Brooks Range, Alaska. M.S. thesis, University of Alaska Fairbanks.
- Homza, T.X., and Wallace, W.K., 1997, Detachment folds with fixed hinges and variable detachment depth, northeastern Brooks Range, Alaska, *Journal of Structural Geology*, v. 19, p. 337-354.
- Keller, A.S., Morris, R.H., and Detterman, R.L., 1961, Geology of the Shaviovik and Sagavanirktok Rivers region, Alaska: U.S. Geological Survey Professional Paper

303, p. 169-222.

- LePain, D.L., 1993, Transgressive sedimentation in rift-flank region: Deposition of the Endicott Group (Early Carboniferous), northeastern Brooks Range, Alaska, Ph.D. Thesis, University of Alaska Fairbanks, 325 pp.
- Lorenz, J.C., Teufel, L.W., and Warpinski, N.R., 1991, Regional Fractures I: A mechanism for the formation of regional fractures at depth in flat-lying reservoirs, *American Association of Petroleum Geologists Bulletin*, v. 75, p. 1714-1737.
- Magoon, L.B., and Dow, W.G., 1994, The petroleum system, *in* *The Petroleum System-From Source to Trap*, Magoon and Dow, eds., *American Association of Petroleum Geologists Memoir* 60, p. 3-24.
- Meigs, A.J., 1989, Structural geometry and sequence in the eastern Sadlerochit Mountains, northeastern Brooks Range, Alaska., M.S Thesis, University of Alaska Fairbanks.
- Meigs, A.J., and Imm, T.A., 1995, Geometry and deformation of a duplex and its roof layer: observations from the Echooka Anticlinorium, Northeastern Brooks Range, Alaska, *in* *Short Notes on Alaska Geology*, Combellick, R.A. , and Tannian, F., eds., *Professional Report* 117, Alaska Division of Geological & Geophysical Surveys, p. 19-31.
- Molenaar, C.M., 1983, Depositional relations of Cretaceous and lower Tertiary rocks, northeastern Alaska, *American Association of Petroleum Geologists Bulletin*, v. 67, no. 7, p. 1066-1080.
- Moore, T. E., Wallace, W.K., Bird, J.J., Karl, S.M., Mull, C.G., and Dillon, J.T., 1994, Chapter 3: Geology of northern Alaska, *in* Plafker, G., and Berg, H.C., eds., *The geology of Alaska: The Geology of North America*, Geological Society of America, Boulder, Colorado, v. G1, p. 49-140.
- Moore, T.E., and Potter, C.J., 2003, Structural plays in Ellesmerian Sequence and correlative strata of the National Petroleum Reserve, Alaska, U.S. Geological Survey Open-File Report 03-253.
- Mull, C.G., 1986, Kemik Sandstone, Arctic National Wildlife Refuge, northeastern Alaska, Alaska Division of Geological & Geophysical Surveys, Public Data File 86-1e, 61 p.
- Nelson, P.H., Kibler, J.E., and Giberson, C.P., 1998, Well data and well plots, *in* *The Oil and Gas Resource Potential of the 1002 Area, Arctic National Wildlife Refuge, Alaska*, by ANWR Assessment Team, U.S. Geological Survey Open File Report

98-34, Chapter WL, 84 p.

- O'Sullivan, P.B., Green, P.F., Bergman, S.C., Decker, J., Duddy, I.R., Gleadow, A.J.W., and Turner, D.L. , 1993, Multiple phases of Tertiary uplift and erosion in the Arctic National Wildlife Refuge, Alaska, revealed by apatite fission-track analysis, American Association of Petroleum Geologists Bulletin, v. 77, no. 3, p. 359–385.
- O'Sullivan, P.B., 1996, Late Mesozoic and Cenozoic thermotectonic evolution of the Colville Basin, North Slope, Alaska, in M.J. Johnsson and D.G. Howell, eds., Thermal evolution of sedimentary basins in Alaska, U.S. Geological Survey Bulletin , v. 2142, p. 45-79.
- O'Sullivan, P.B., and Wallace, W.K., 2002, Out-of-sequence, basement-involved structures in the Sadlerochit Mountains region of the Arctic National Wildlife Refuge, Alaska: evidence and implications from fission-track thermochronology, Geological Society of America Bulletin, v. 114, no. 11, p. 1356-1378.
- Reifenstuhl, R.R., Mull, C.G., Harris, E.E., LePain, D.L., Pinney, D.S., and Wallace, W.K., 2000, Geological map of the Sagavanirktok B-1 quadrangle, eastern North Slope, Alaska: Alaska Division of Geological & Geophysical Surveys Report of Investigation 2000-1A, 15 p., 1 sheet, scale 1:63,360.
- Rejebian, V.A., Harris, A.G., and Huebner, J.S., 1987, Conodont color and textural alteration: An index to regional metamorphism, contact metamorphism, and hydrothermal alteration, Geological Society of America Bulletin, v.99, p. 471-479.
- Rider, M.H., 1986, The geological interpretation of well logs. London: Blackie and Son Limited, 175 p.
- Roedder, E., 1984, Fluid inclusions: an introduction to studies of all types of fluid inclusions, gas, liquid, or melt, trapped in materials from earth and space, and their application to the understanding of geologic processes: Washington, D.C., Mineralogical Society of America, 644 p.
- Shafer, J.N., 1980, A practical method of well evaluation and acreage development for the naturally fractured Austin chalk formation, Log Analyst XXI(1), p. 10-23.
- Stearns, D.W., and Friedman, 1972, Reservoirs in fractured rock: *in* AAPG Memoir 16, no. 10, pp. 82-106
- Underwood, C.A., Cooke, M.L., Simo, J.A., and Muldoon, M.A., 2003, Stratigraphic controls on vertical fracture patterns in Silurian dolomite, northeastern Wisconsin,

- American Association of Petroleum Geologists Bulletin 87, no. 1, p. 121-142.
- Verma, M.K., Bird, J.J., Nelson, P.H., and Burruss, R.C., 2005, Evaluation of the stranded Kavik gas field, North Slope of Alaska, U.S. Geological Survey Open File Report 2005-1389, 7 p.
- Wallace, W.K. and Hanks, C.L., 1990, Structural provinces of the northeastern Brooks Range, Arctic National Wildlife Refuge, Alaska, American Association of Petroleum Geologists Bulletin 74, no. 7, p. 1100-1118.
- Watts, K.F., Harris, A.G., Carlson, R.C., Eckstein, M.K., Gruslovic, P.D., Imm, T.A., Krumhardt, A.P., Lasota, K.K., Morgan, S.K., Dumoulin, J.A., Enos, P., Goldstein, R.H., and Mamet, B.L., 1995, Results and synthesis of integrated geologic studies of the Carboniferous Lisburne Group of northeastern Alaska, U.S. Department of Energy, Final Report for 1989-1992 (DOE/BC/14471-19), Bartlesville Project Office, 433 p.

Figure 3.1. Generalized geologic map of the northeastern Brooks Range showing the location of the study area (modified from Hanks et al., 2004).

Figure 3.2. Generalized geologic map of the exposed part of the Eastern Transect study area. Small inset map shows locations of Domains I, II and III discussed in text.

Figure 3.3. Subsurface structural contour map of the base of the Shublik Formation. Map based on published interpretations (Alaska Oil & Gas, Conservation Commission (2003); outlined in pink), formation tops from nearby wells (blue) and interpretations of the seismic lines (this study, lines in red). The yellow line in southern part of map near Kemik #1 and #2 is the approximate location of cross section shown in Figure 3.5.

Era	System	Se- quence	Stratigraphic Unit	Regional Mechanical- Stratigraphic Units	Structural Domains
Cenozoic	Quaternary	Brookian	undifferentiated		
	Tertiary				
Mesozoic	Cretaceous	Brookian	Canning Fm.	Disharmonic, Short-Wavelength Folds & Thrusts, Duplex Anticlines	Domain III
			Hue Shale		
	Jurassic	Ellesmerian	Pebble Shale	Detachment Unit Small-Scale Duplex	Domain II
			Kemik SS		
			Kingak Shale	Detachment Unit	
			Shublik Fm.	Detachment Folds	
Ivishak Fm.	Detachment Unit				
Kavik Shale		Domain I			
Echooka Fm.	Detachment Unit				
Paleozoic		Permian	Lisburne Group	upper Lisburne	Detachment Unit
	middle Lisburne				
	Pennsylvanian	Lisburne Group	lower Lisburne	Detachment Unit	
			Kayak Shale		
Mississippian	Franklinian	Lisburne Group	Kekiktuk Conglomerate	Single-Horse Anticlinoria	
Precambrian	Proterozoic	Franklinian	pre-Mississippian rocks undifferentiated	Detachment Unit	

Figure 3.4. Stratigraphic column showing the ages of geologic units in the study area. Structural-stratigraphic units are defined by regional mechanical variations between adjacent units. Structural domains (pertaining to this study only) were assigned to packages of competent material bounded by incompetent detachment units (modified from Wallace and Hanks, 1990).

Figure 3.5. Cross section constructed from surface data in the exposed part of the transect area. See Figure 3.2 for the location of line of section. This line-length balanced cross section was constructed using structural data from the surface geologic map of the study area and shows an interpretation of the structural geometry of the exposed surface units as they continue into the subsurface.

Figure 3.6 West-facing photomosaic showing a north-vergent thrust fault placing Kayak Shale on the lower Lisburne. A) Uninterpreted, B) Annotated; box-fold axes in the Lisburne are shown with double arrows on the steeply dipping panel (photos by Wesley K. Wallace).

Figure 3.7. Syncline-anticline pair in the Kayak Shale. A) uninterpreted, B) annotated. Person for scale in red circle.

Figure 3.8. East-facing photograph of a breached anticline in the Kemik Sandstone.

Figure 3.9. East-facing photograph of a tightly folded Hue Shale syncline.

Figure 3.10 Generalized map of the range front of the northeastern Brooks Range (Sagavanirktok B-1 quadrangle) showing the locations of wells and seismic lines referred to in this chapter.

Figure 3.12. Seismic line W-W'. A) Uninterpreted, B) Interpreted, C) Interpreted and depth corrected.

Figure 3.13. Seismic line Y-Y'. A) Uninterpreted, B) Interpreted, C) Interpreted and depth corrected.

Figure 3.14. Seismic line Z-Z'. A) Uninterpreted, B) Interpreted, C) Interpreted and depth corrected.

Figure 3.15. Composite fence diagram of interpreted seismic sections. Basement-related faults are numbered (Fa, Fb, etc....) to show relationships between the faults. Note that fault Fe is continuous along strike and corresponds to one of the lateral ramps in strike line Z-Z'.

Figure 3.16. Stereonets showing the poles to fracture planes for each fracture set.

Figure 3.17. Box-whisker plot of Set 1 fracture spacing in Domains I and II. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ - 1.5 \cdot DQ$ or above $QU + 1.5 \cdot DQ$, where LQ=lower quartile, DQ=difference between quartiles, and QU=upper quartile.

Figure 3.18. Box-whisker plot of Set 1 fracture spacing in the limbs and hinges of folds in Domain I. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ - 1.5 \cdot DQ$ or above $QU + 1.5 \cdot DQ$, where LQ =lower quartile, DQ =difference between quartiles, and DQ =upper quartile.

Figure 3.19. Box-whisker plot of Set 1 fracture spacing in the limbs and hinges of folds in Domain II. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ - 1.5 \cdot DQ$ or above $QU + 1.5 \cdot DQ$, where LQ =lower quartile, DQ =difference between quartiles, and DQ =upper quartile.

Figure 3.20. Box-whisker plot of Set 2 fracture spacing in Domains I and II. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ - 1.5 \cdot DQ$ or above $QU + 1.5 \cdot DQ$, where LQ=lower quartile, DQ=difference between quartiles, and QU=upper quartile.

Figure 3.21. Box-whisker plot of Set 2 fracture spacing in the limbs and hinges of folds in Domain I. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ-1.5 \cdot DQ$ or above $QU-1.5 \cdot DQ$, where LQ =lower quartile, DQ =difference between quartiles, and DQ =upper quartile.

Figure 3.22. Box-whisker plot of Set 2 fracture spacing in the limbs and hinges of folds in Domain II. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ - 1.5 \cdot DQ$ or above $QU + 1.5 \cdot DQ$, where LQ =lower quartile, DQ =difference between quartiles, and DQ =upper quartile.

Figure 3.23. Box-whisker plot of Set 3 fracture spacing in Domains I, II, and III. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ - 1.5 \cdot DQ$ or above $QU + 1.5 \cdot DQ$, where LQ=lower quartile, DQ=difference between quartiles, and QU=upper quartile.

Figure 3.24. Box-whisker plot of Set 3 fracture spacing in the limbs and hinges of folds in Domain I. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ - 1.5 \cdot DQ$ or above $QU - 1.5 \cdot DQ$, where LQ =lower quartile, DQ =difference between quartiles, and DQ =upper quartile.

Figure 3.25. Box-whisker plot of Set 3 fracture spacing in the limbs and hinges of folds in Domain II. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ-1.5 \cdot DQ$ or above $QU+1.5 \cdot DQ$, where LQ =lower quartile, DQ =difference between quartiles, and QU =upper quartile.

Figure 3.26. Box-whisker plot of Set 3 fracture spacing in the limbs and hinges of folds in Domain III. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ - 1.5 \cdot DQ$ or above $QU + 1.5 \cdot DQ$, where LQ =lower quartile, DQ =difference between quartiles, and DQ =upper quartile.

Figure 3.27. Box-whisker plot of Set 4 fracture spacing in Domains I, II, and III. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ - 1.5 \cdot DQ$ or above $QU + 1.5 \cdot DQ$, where LQ=lower quartile, DQ=difference between quartiles, and QU=upper quartile.

Figure 3.28. Box-whisker plot of Set 4 fracture spacing in the limbs and hinges of folds in Domain I. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ - 1.5 \cdot DQ$ or above $QU - 1.5 \cdot DQ$, where LQ =lower quartile, DQ =difference between quartiles, and DQ =upper quartile.

Figure 3.29. Box-whisker plot of Set 4 fracture spacing in the limbs and hinges of folds in Domain II. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ-1.5 \cdot DQ$ or above $QU-1.5 \cdot DQ$, where LQ =lower quartile, DQ =difference between quartiles, and DQ =upper quartile.

Figure 3.30. Box-whisker plot of Set 4 fracture spacing in the limbs and hinges of folds in Domain III. The caps at the end of each box signify the minimum and maximum fracture spacing, the box represents the lower and upper quartiles and the line across the center of the box is the median. Diamonds represent outlier values, which are points that fall either below $LQ - 1.5 \cdot DQ$ or above $QU - 1.5 \cdot DQ$, where LQ =lower quartile, DQ =difference between quartiles, and DQ =upper quartile.

Figure 3.31. Well log for the Kemik #1 showing formation tops, zones of potential secondary porosity from fractures, vitrinite reflectance values and the associated level of thermal maturity. Note the repetition of the Kemik Sandstone and Kingak Shale which indicates a thrust fault.

Kemik # 2

Figure 3.32. Well log for Kemik #2 showing formation tops, zones of potential secondary porosity from fractures, vitrinite reflectance values and corresponding levels of thermal maturity.

Figure 3.33. Well log for Beli # 1 showing formation tops, zones of potential secondary porosity from fractures, vitrinite reflectance values and the associated stage of thermal maturity.

Figure 3.34. Well log from West Kavik #1 showing formation tops, zones of potential secondary porosity, vitrinite reflectance values and the corresponding stages of thermal maturity.

Figure 3.35. Generalized geologic map of the study area showing location of fluid inclusion (red dots), vitrinite reflectance (yellow diamonds) and conodont alteration indices (green squares) samples collected during this study.

Figure 3.36. Map showing the distribution of all publicly available vitrinite reflectance outcrop samples in the transect area and their associated range in Ro values. Contours show the boundaries between undermature to mature rocks (blue), mature to post-mature (yellow), and post-mature to overmature rocks (red).

Figure 3.37. Temperature versus depth plot based on down-hole vitrinite reflectance values from eight wells in the study area. Temperatures were calculated from reflectance values using the following equation: $T = (\ln(R_0) + 1.68) / 0.0124$. A modern geothermal gradient of 27 °C/km is plotted for comparison (Armstrong, 2005).

Figure 3.38. Temperature versus depth plot from wells in the southern part of the study area. Best-fit lines extended to the depth axis give estimates of the amount of denudation.

Figure 3.39. Temperature versus depth plot for wells in the northern part of the study area. Best-fit lines extended to the depth axis give estimates of the amount of denudation.

Figure 3.40. Generalized geologic map of the study area showing the locations of fission-track samples. Pooled fission-track ages (in Ma) and errors are shown in white boxes.

Figure 3.41. Schematic model of possible stresses related to folding and subsequent fracture orientations. From Hayes and Hanks (2008), modified from Stearns and Friedman (1972).

Figure 3.42. Schematic model showing an out-of-sequence progression of basement-involved thrust faulting, the timing of which is based on fission-track ages. The horizontal dashed line represents the 110 °C isotherm designating the partial annealing zone of apatite grains, above which a fission-track age may be determined. Black square is in the Kingak Shale in Domain I; Black triangle represents the Echooka Formation in Domain II; Black circle is in the Kingak Shale of Domain III.

Figure 3.43. Schematic model showing an in-sequence progression of basement-involved thrust faulting, the timing of which is based on fission-track ages. The horizontal dashed line represents the 110 °C isotherm designating the partial annealing zone of apatite grains, above which a fission-track age may be determined. Black square is in the Kingak Shale in Domain I; Black triangle represents the Echooka Formation in Domain II; Black circle is in the Kingak Shale of Domain III.

Figure 3.44. Time-temperature-depth plot illustrating the structural settings in which the different fracture sets developed. Average homogenization temperatures from fracture fill in set 1 and set 2 fractures were used along with an assumed geothermal gradient of 27 °C/km to estimate the depth at which fractures formed. There are no thermal constraints on the set 3 or set 4 fractures, though it is thought that they formed near the surface in response to uplift and erosion. Apatite fission-track ages from surface samples throughout the field area were incorporated to provide a generalized burial and uplift path for Ellesmerian Sequence stratigraphy. A maximum temperature of 250 °C is constrained by a lack of reset in zircon grains and by field-wide vitrinite reflectance values. Penetrative strain that post-dates the NSF and EWU fractures but pre-dates the NSU and EWU sets is well-documented throughout the northeastern Brooks Range (Hanks et al., 2006; Hayes, 2004). Schematic cross sections summarize the location of fracture development with respect to structural environment. The black dots in the schematic cross sections signifies the location of fracture set development.

Figure 3.45. Composite graph showing the time-temperature-depth paths of each structural domain. The paths are based on fission-track ages of each domain and the possible timing and conditions associated with fracture formation and filling. Fluid inclusion microthermometry in fracture fill constrains the temperature of filled fracture formation, but the timing of their formation is not directly constrained by fission-track ages. Maximum temperatures are estimated from vitrinite reflectance in each domain.

Figure 3.46. Tectonic events chart showing the proposed timing of the essential components of the Northern Alaska petroleum system in the vicinity of the Eastern Transect. Colors of fracture events keyed to colors used in Figure 3.45. Modified from Bird, 1998.

CHAPTER 4
Fracture distribution, thermal history and structural evolution of the
central Brooks Range Foothills, Alaska

By

A. Duncan

Department of Geology and Geophysics, University of Alaska, Fairbanks, Alaska 99775
(present address: BP Exploration (Alaska) Inc.
900 E. Benson Blvd.
Anchorage AK, 99519-6612)

C. Hanks,

Dept. of Petroleum Engineering and Geophysical Institute, University of Alaska, Fairbanks,
Alaska 99775; chanks@gi.alaska.edu

W. Wallace

Geophysical Institute and Department of Geology and Geophysics, University of Alaska,
Fairbanks, Alaska 99775

P. O'Sullivan

Apatite to Zircon, Inc.
1521 Pine Cone Road
Moscow, Idaho 83843 U.S.A.

M. Parris

Petro-Fluid Solutions LLC
(present address: Kentucky Geological Survey 228 Mining and Mineral Resources Bldg.
University of Kentucky, Lexington, KY 40506-0107)

B. Coakley

Geophysical Institute and Department of Geology and Geophysics, University of Alaska,
Fairbanks, Alaska 99775

ABSTRACT

Episodic deformation, triangle zone development and related backthrusting in the central Brooks Range foothills play a major role in the distribution of fractures and the thermal history of rocks involved in the deformation. Structural reconstructions suggests that the rocks forming the core of the orogen, the Endicott Mountains allochthon, were emplaced during Valanginian time at temperatures ~150°C. Fractures associated with that deformation are cement filled, indicating they formed in the presence of fluids. After a period of quiescence during the late Cretaceous, renewed deformation involved shortening of the orogenic wedge and the development of a

triangle zone and overlying backthrust in adjacent Late Cretaceous rocks of the foreland basin. This later deformational event and subsequent uplift resulted in two sets of unfilled fractures that affect all parts of the fold-and-thrust belt. Restriction of filled fractures to the older and structurally deeper parts of the orogen imply that fluids were not a significant factor in fracture development in the younger parts of the system. Thus the latest and most obvious fractures visible at the surface may not have played an important role in petroleum migration.

INTRODUCTION

Open fracture networks in foreland basin systems can enhance fluid flow and subsequent heat distribution throughout the basin system (Deming et al., 1992, 1996; Allen and Allen, 2005, Hanks et al., 2006). Understanding the distribution and character of open fracture networks therefore is critical to understanding the maturation, migration and charge history of any potential foothills petroleum system (Bachu, 1995; Moore et al., 2004; Hanks et al., 2006).

Fractures commonly form in foreland basins either as a result of anisotropic horizontal stress in flat-lying units or due to stress associated with fold-and-thrust deformation. The earliest fractures occur in flat-lying units, form parallel to the direction of maximum tectonic compression and are usually perpendicular to bedding (i.e. vertical in flat-lying units) (Hancock and Engelder, 1989; Lorenz and others, 1991, other more recent refs). When fold-and-thrust deformation incorporates these foreland basin sediments, another generation of fractures can form that is dependent on structural and stratigraphic position (Cooper, 1992; Hanks et al., 1997; Florez-Nino et al., 2005).

This study documents changes in the character and distribution of fractures along a transect across the central Brooks Range fold-and-thrust belt (Figures 4.1 and 4.2). This information and the general structural style are combined with apatite fission track (AFT), seismic and well data to develop balanced reconstructions that constrained the timing of fracturing in the foothills relative to the overall structural evolution of the fold-and-thrust belt.

While this study focuses specifically on the central Brooks Range, the data and concepts presented are relevant to understanding the evolution of fracture networks where triangle zones are a major structural element at the leading edge of the fold-and-thrust belt. In particular, it demonstrates how integration of field, subsurface and thermal data is critical for documenting the relationship between the relative timing of fracturing and the structural evolution of the fold-and-thrust belt.

REGIONAL GEOLOGY

Tectonic setting

The Brooks Range is the northernmost part of the North American Cordillera (Figure 4.1) In Alaska collision of an island arc resulted in the collapse of a south-facing Paleozoic passive continental margin and emplacement of at least seven allochthons (Moore et al., 1994).

Allochthon emplacement loaded the lithosphere and created the Colville basin, a strongly asymmetric foreland basin. While most shortening occurred during Late Jurassic to Early Cretaceous time (Moore et al., 1994), episodic post-collisional contraction during the Cretaceous and early Tertiary resulted in several episodes of fold-and-thrust deformation in the central Brooks Range, northward progradation of the fold-and-thrust belt and formation of the northeastern Brooks Range (O'Sullivan et al., 1997, 1998a; Moore et al., 2004; Wallace and Hanks, 1990).

Transect stratigraphy

The stratigraphy along the transect (Figures 4.2 & 4.3) consists of the structurally lowest allochthon, the Endicott Mountains allochthon (EMA) and overlying and adjacent basin-filling sediments derived from the Brooks Range (Brookian sequence). The dominant unit of the EMA in the transect area is the Carboniferous Lisburne Group, a northerly-derived carbonate platform and passive margin sequence of limestone, dolomite and interbedded shale (Figure 4.3). The Lisburne Group is unconformably overlain by northerly-derived, fine-grained clastic rocks of the Permian Siksikpuk and Triassic Otuk Formations. The Lisburne, Siksikpuk, and Otuk are mapped separately in surface portions of the transect but are considered as a single unit for subsurface analysis in this study.

Brookian clastic sedimentary rocks are dominantly Cretaceous and Tertiary in age and were derived from the ancestral Brooks Range to the south (Figures 4.1 and 4.3) (Moore et al., 1994, 2004). The oldest Brookian sediments are turbidites and olistostromes of the Lower Cretaceous Okpikruak Formation (Ko) that were deposited both in wedge-top piggy-back basins and in the foredeep (Wallace et al., 2006; Peapples et al., 2007). These rocks were subsequently incorporated into the thrust belt and are now a tectonic *mélange*.

The overlying Fortress Mountain Formation (Kfm, Figs. 4.2 and 4.3) was deposited both in the piggyback basins and in the proximal foreland basin (Wallace et al., 2006) and consists of laterally discontinuous, immature, marine and non-marine siltstone, sandstone and conglomerate (Bird and Molenaar, 1992; Mull et al., 2003). The Torok Formation (Kto, Figs 2 and 3) is the deep-water, distal basin equivalent of the Fortress Mountain Formation and consists of gray to black, nonresistant marine silty shale, mudstone and clay shale with interbedded medium to fine grained sandstone (Mull et al., 2003). The Torok is the most volumetrically significant unit in the transect map area.

The Torok grades vertically into overlying Albian to Cenomanian sediments of the Nanushuk Formation (Kn; Figures 4.2 and 4.3) (Mull, personal communication, 2004). The Nanushuk consists of marine to non-marine molasse sediments that are interpreted to have been deposited in a marine influenced, delta system that prograded from southwest to northeast (Bird and Molenaar, 1992; Mull et al., 2003; Finzel, 2004).

Regional fracture characteristics

Previous fracture studies in northern Alaska have focused on the northeastern Brooks Range (NEBR) (Hanks et al., 2004; Hayes, 2004; Shackleton et al., 2005). These studies have recognized four fracture sets that fall into three general categories: 1) pre-fold, 2) syn-fold and 3) post-fold fractures. Pre-folding fractures are oriented normal to the thrust front and are interpreted to form under high fluid pressures and low differential stresses in flat-lying strata in front of the advancing fold-and-thrust belt (Hanks et al., 2004; Hayes, 2004). Syn-folding fractures formed in different orientations depending on the type of fold and the degree of folding, but are generally due to outer-arc stretching during flexural slip, buckling and detachment folding. Both of these early sets of fractures are filled with calcite or quartz cement, suggesting that they formed in the presence of fluids.

Later syn-fold and/or post fold fractures are unfilled, suggesting that these fractures formed in the absence of fluids. Unfilled 'syn-fold' fractures are attributed to late flexural slip folding and/or relief of stored elastic strain during unroofing. Unfilled post-fold fractures parallel the filled pre-fold fractures and are potential reactivations of set 1 fractures. These fractures may have formed within the thickening orogenic wedge at shallow depths as the older and more hindward (orogen proximal) sections of the orogenic wedge were uplifted and unroofed and unroofed.

Timing of deformation and uplift

Previous apatite and zircon fission track studies indicate that the Brooks Range has undergone at least 5 episodes of rapid cooling (O'Sullivan et al., 1997). Only three of these events are recorded in the central Brooks Range and central foothills (Mull et al., 1997; O'Sullivan et al., 1997). The other two are exclusively related to the uplift and fold-and-thrust deformation of the NEBR (O'Sullivan et al., 1998b; O'Sullivan and Wallace, 2002).

The oldest cooling event recognized using apatite fission track (AFT) data is in the core of the Brooks Range and the foothills and yields cooling ages of ~100 Ma. This event is interpreted as cooling related to initial uplift of the core of the Brooks Range orogen (O'Sullivan et al., 1998a). The second regional cooling event occurred from ~70 to 60 Ma and is recorded over much the Brooks Range, Brooks Range foothills and Colville basin. This event is interpreted as the timing of cooling associated with regional fold-and-thrust deformation (Mull et al., 1997; O'Sullivan et al., 1997, 1998a; Moore et al., 2004). A third event at ~25 Ma is recorded north of the central Brooks Range in the distal Colville basin. This event is interpreted to represent Oligocene progression of fold-and-thrust deformation into the distal basin sediments (O'Sullivan et al., 1997; O'Sullivan, 1999).

The remaining two cooling events are recorded in the northeastern Brooks Range (NEBR) and occurred at ~45 Ma and ~35 Ma. These two events did not affect the central Brooks Range (O'Sullivan et al., 1998b; O'Sullivan and Wallace, 2002).

Thermal history of northern Alaska

Regionally, thermal maturity in the Colville basin is highest in the south and decreases with distance to the north, indicating deeper burial and, subsequently, greater amounts of uplift and erosion near the mountain front (Bird and Molenaar, 1992; Howell et al., 1992; Johnsson et al., 1994). The width of the oil window ($R_o = 0.6$ to 2.0%) increases from 1.5 km in the northern basin to 4.5 km in the foothills as a result of variations in geothermal gradient (Bird and Molenaar, 1992). Fold-and-thrust deformation and related uplift and erosion have exposed the oil and gas window at the surface throughout the southern foothills of the Brooks Range (Bird and Molenaar, 1992; Howell et al., 1992). In the foothills, deformation of the 0.6% R_o isograd indicates that deformation continued subsequent to maximum burial (Johnsson, et al., 1994). Based on mapping of the 0.6% R_o isograd, hydrocarbon potential in the central and northeastern Brooks Range foothills is limited primarily to gas due to the high thermal maturity (Howell et al., 1992; Bird, 2001).

Stable isotope data from fracture fill from areas west of this study suggest that the central Brooks Ranges has undergone two stages of deformation and associated fluid flow (Moore et al. (2004). Fluids in filled fractures associated with a 160 and 120 Ma deformational event reached temperatures of $\sim 250^{\circ}$ - 300° C. A second fracture event is interpreted to have occurred at temperatures of $\sim 150^{\circ}$ C during early Tertiary time.

METHODS

Surface mapping and data collection

A surface map of the transect (Figure 4.2) was compiled using both detailed mapping of representative areas (Duncan, 2007) and published maps (Mull and Sonnemann, 1975; Kelley, 1990; and Peapples et al., 2007). Fracture data (Table 4.1) were collected using the straight scan-line fracture survey method (reference?) and included fracture orientation, morphology, presence or absence of fill and relative age relationships. Representative oriented samples of filled fractures and fault gouge were collected for fluid inclusion analysis, including microthermometry, pressure conditions and the composition and density (i.e. salinity of fluids) of the fracture fill at the time of crystallization (Table 4.2; Roedder, 1984; analysis by Marty Parris and Petrofluid Solutions). 15 samples were collected for fission-track analysis from sedimentary units likely to have detrital apatite and/or zircon (Table 4.3; analysis by Paul O'Sullivan, A to Z Inc.)

Subsurface mapping

A 2D seismic reflection line provided by Western Geophysics was interpreted in two-way travel time and depth converted (WG 89-29, Figures 4.2 and 4.4). Seismic velocities for depth conversion were derived from sonic log velocities for units penetrated and from published velocities from wells on the North Slope (Mauch, 1989). Stratigraphic correlations between

wells, seismic data and surface exposures are based on previous work done in the National Petroleum Reserve, Alaska (NPRA) (Kumar et al., 2002), and other published data (Mauch, 1989; Bird and Molenaar, 1992; Moore and Potter 2003; Potter and Moore, 2003), as well as through personal communication with experienced North Slope geologists. Seismic data interpretation and subsequent reconstruction of structural cross sections used *LithoTect* software by GeoLogic Systems.

OBSERVATIONS:

Overall structural style of the transect:

The transect can be divided into three structural/stratigraphic packages (Figures 4.2 & 4.4): 1) the orogenic wedge of the Endicott Mountains allochthon (EMA); 2) underlying, relatively undeformed Paleozoic and lower Mesozoic passive margin sediments of the North Slope autochthon; and 3) the Brookian wedge-top and proximal foreland basin. Only the EMA and parts of the foreland basin are exposed at the surface.

The structurally lowest and thickest allochthon of the central Brooks Range, the Endicott Mountains allochthon, forms the core of the orogenic wedge in the transect area (Figures 4.2 & 4.4; Wallace et al., 1997; Moore et al., 2004; Peapples et al., 2007). The detailed, internal stratigraphy and structure of EMA are not discernable in the seismic line where it is characterized by chaotic seismic reflections with a few fold hinges. Where the EMA is exposed in the southern part of the transect, its structural style is controlled by the thick and mechanically rigid Carboniferous Lisburne Limestone which deforms into kilometer scale, fault-related folds that are detached from the underlying Mississippian Kayak Shale (Mky) (Figure 4.5). An example of one of these structures is the Tiglukpuk anticline (Figures 4.2 and 4.5). Overlying Permian and Triassic units (Siksikpuk and Otuk formations) remain structurally coupled to the Lisburne and deform with it. In contrast, turbidites and olistostromes of the Cretaceous Okpikruak Formation (Ko) act as a relatively weak mechanical layer and are detached from the underlying Carboniferous through Triassic rocks.

Cretaceous wedgetop and proximal basin deposits of the Fortress Mountain, Torok and Nunushak Formations are structurally decoupled from the underlying EMA. The relatively competent Fortress Mountain Formation deforms into roughly symmetric, ~0.5-1 km scale, open folds that are cut by mostly south-dipping faults (Figure 4.6). To the north, the laterally equivalent deep marine shales of the Torok Formation are deformed into smaller scale (meters to tens-of-meters) south-vergent folds and thrust faults (Figure 4.2). However, in the subsurface the Fortress Mountain and the Torok Formation are seismically indistinguishable and are lumped together in the seismic interpretation (Figure 4.4).

The overlying more structurally rigid sandstones of the Cretaceous Nanushuk Formation are deformed into kilometer-scale upright detachment folds visible in both the surface and subsurface data (Figures 4.2 and 4.4). The Nanushuk Formation provides strong coherent reflectors that fade in intensity with depth, presumably as the lower Nanushuk grades into the upper Torok Formation.

The North Slope autochthon that underlies the wedge of EMA is not exposed at the surface but is visible in the seismic data as parallel reflectors that underlie both the EMA and the Brookian sediments (Figure 4.4). These undeformed reflectors can be correlated to where the North Slope autochthon is penetrated by wells in the National Petroleum Reserve-Alaska (NPR) (Mauch, 1989; Kumar et al., 2002).

Several relatively steep, south-dipping, north-vergent faults cut both the EMA and Brookian clastic foreland basin deposits in the subsurface and are exposed at the surface (Figures 4.2 and 4.4). These 'breaching thrusts' post date EMA emplacement.

Structural domains

The exposed part of the transect can be subdivided into four characteristic structural domains (Figure 4.2) based on the deformation style, fracture characteristics, AFT cooling ages and fluid inclusion microthermometry data from filled fractures. These structural domains provide key constraints on the kinematic history of the transect. Domain characteristics are summarized in Table 4.4.

Domain I

Domain I is at the southern end of the transect and consists of the EMA exposed at the Tiglupuk anticline (Lisburne Limestone Siksikpuk, Otuk Okpikruak Formations (Figures 4.2 and 4.5). The Lisburne Limestone at Tiglupuk anticline deforms as a rigid structural package and is folded into a doubly-plunging, north-vergent, overturned, asymmetric anticline (Figure 4.5). The tight flexural slip folding resulted in outer arc extension and associated extension fracturing and small-scale normal faulting; inner arc compression resulting in shear fracturing and small-scale duplexing.

The Lisburne Limestone and overlying Siksikpuk and Otuk Formations of Domain I are intensely fractured with two sets of filled fractures (Sets 1 and 2, Table 4.1, Figure 4.7) and two sets of unfilled fractures (Sets 3 and 4, Table 4.1, Figure 4.7). Filled fractures of sets 1 and 2 dominantly exhibit crack-seal textures and aqueous and solid, single- and two-phase inclusions. Fluid inclusions from the latest generation of fracture fill in set 1 fractures yielded homogenization temperatures of $147^{\circ}\text{C} \pm 20^{\circ}$ (Table 4.2).

Apatite fission track (AFT) samples from the Okpikruak Formation to the south of Tiglupuk anticline indicate rapid cooling of these rocks through the annealing window at 68-60 Ma. (Table 4.3).

Interpretation

The two cement-filled fracture sets in Domain 1 suggests that there were two episodes of deep-seated fold-and-thrust deformation at Tiglupuk anticline. The high fracture density and the abundance of crack-seal textures in the fracture fill of both sets 1 and 2 suggest that both fracture

sets formed at depth with high fluid pressure contributing to repeated fracturing. Set 1 fractures are most likely related to the emplacement of the EMA onto the North Slope autochthon during Early Cretaceous time. The $\sim 150^{\circ}\text{C}$ homogenization temperature recorded in the latest generation of Set 1 fracture fill (Table 4.2) combined with the $250\text{--}300^{\circ}\text{C}$ temperatures seen to the west (Moore and others, 2004) is interpreted to indicate these fractures filled at depths from 6 to 12 km (assuming a geothermal gradient of $25^{\circ}\text{C}/\text{km}$, O'Sullivan, 2006 personal communication). The lower temperature is corroborated by conodont CAI (Color Alteration Index) from Tiglupuk anticline of 1.5-2.0 (Dumoulin, 2005, personal communication), corresponding to temperatures of 60°C – 140°C (Epstein et al., 1977). Set 2 fractures (Table 4.1) probably formed during early Tertiary fold-and-thrust deformation. However, no fluid inclusion data were obtained from these fractures that could constrain the temperature at which this deformation occurred.

Unfilled Set 4 fractures share a similar orientation to the older Set 1 filled fractures. This younger age and the conspicuous lack of fracture cement suggests that these fractures formed during uplift and unroofing under shallow, relatively dry conditions (e.g., Engelder, 1985; Hanks et al., 2004; Hayes, 2004).

AFT data from Domain I (EMA) indicate total annealing of AFT samples before rapid cooling due to uplift and unroofing between 70 and 60 Ma (Table 4.3)

Domain II

Domain II is located north of Tiglupuk anticline (Figure 4.2) and consists primarily of the Fortress Mountain Formation. Domain II is characterized by open, symmetrical, map-scale folds of Fortress Mountain clastic rocks that are structurally decoupled from the underlying Okpikruak Formation turbidites and mélangé (Figure 4.6). Faulting is not usually directly observed due to poor exposure, but can be inferred via juxtaposition of units, age relationships and AFT cooling ages. Where seen, small-scale faults generally dip south toward the mountain front and display offset from centimeters to meters.

The only fracture sets observed in Domain II are the unfilled fractures of sets 3 and 4 (Table 4.1, Figure 4.7). Because these fractures are unfilled, no temperature data from fluid inclusion studies are possible.

Domain II can be subdivided into two different but thermally similar regions based on the AFT cooling ages (Figure 4.2, Table 4.4). The southern part of Domain II (Domain II-S) yields cooling ages of 55-67 Ma. To the north, Domain II-N yields cooling ages of 75-100 Ma (Table 4.4). The two subdomains are separated by a south-dipping thrust fault of regional significance (Figure 4.6).

Interpretation

Deformation in Domain II was probably driven by shortening in the underlying EMA during Tertiary time. Shortening of the EMA caused fold-and-thrust deformation in the overlying Fortress Mountain and Torok Formations with associated formation of syn-folding fractures (Set 3; Stearns, 1968). The lack of any fracture fill, secondary mineralization, or leaching along these fractures suggest that Set 3 fractures formed under relatively dry conditions.

The widely spaced, vertically extensive and unfilled Set 4 fractures are consistent with unroofing fractures (Engelder 1985). Erosional unroofing was probably due to structural thickening of the Fortress Mountain and Torok Formations during Tertiary thrusting.

Besides constraining the age of uplift, further examination of the AFT cooling ages can constrain the amount and nature of the uplift. Samples from a single anticline in Domain II-N yield cooling ages of 100.7 ± 7.1 Ma from the structurally and topographically highest point and 75.7 ± 5.2 Ma from the structurally and topographically lowest point. Apatite from the topographically highest sample (100.7 ± 7.1 Ma) contains remnants of fission tracks that were not totally annealed, while the topographically lower sample contains apatite crystals that record both the ~ 100 Ma cooling and the 60-65 Ma cooling events. This suggests that the topographically higher sample stayed slightly cooler (i.e. was not buried quite as deeply) as the lower sample. The lower sample attained slightly higher temperatures and/or spent more time in the partial annealing zone (PAZ), and may have reached the total annealing temperature of 110°C . We can infer that the 110°C isotherm was likely constrained between the elevations of these two samples during maximum burial, indicating ~ 4.4 km of unroofing at this location (assuming a $25^{\circ}\text{C}/\text{km}$ geothermal gradient). These observations also suggest that folding occurred prior to the time of maximum burial because the higher sample did not reach the maximum temperature attained by the lower sample.

Domain II-S yielded two AFT cooling ages of 55.7 ± 3.5 Ma and 61.0 ± 4.5 Ma, suggesting that these samples attained hotter temperatures than samples from Domain II-N. Subsequent to burial, Domain II-S was thrust north on the thrust separating it from Domain II-N, juxtaposing the hotter rocks in the south with shallower, cooler rocks in the north.

Domain III

Domain III consists of the Torok Formation and is bounded to the south by the Fortress Mountain of Domain II and to the north by the Tuktu Escarpment, a prominent topographic ridge of relatively resistant Nanushuk Formation (Figures 4.2 and 4.7). Where exposed, the Torok is deformed by small-scale (meters to tens-of-meters) folds and thrust faults. Most of these structures are south-vergent with local north vergent structures. South-vergent structures become more prevalent closer to the Tuktu Escarpment,

A distinguishing structural characteristic of Domain III is the presence of rare set 2 filled fractures (Table 4.4, Figure 4.7). These filled fractures occur in coherent siltstone beds and are parallel to bedding, several centimeters in length, <3mm in aperture and filled with at least two and possibly three generations of calcite cement and inclusions (Table 4.1). The last generation of calcite fill yielded primary aqueous single- and two-phase inclusions and secondary aqueous single- and two-phase inclusions with homogenization temperatures of $113^{\circ}\text{C} \pm 11^{\circ}\text{C}$ (n=10) and $114^{\circ}\text{C} \pm 12^{\circ}\text{C}$ (n=10) respectively (Tables 4.2 and 4.4).

Both fracture Sets 3 and 4 are also present in Domain III and are similar in character and distribution to those seen elsewhere.

Samples for AFT analysis from sandy intervals in Domain III (Tables 4.3 and 4.4) yield partially reset annealing ages of xxx, indicating that the Torok in Domain III did not reside in the PAZ long enough and/or at high enough temperatures to fully anneal tracks recorded in detrital apatite.

Interpretation

Domain III is differentiated from Domain II to the south, and Domain IV to the north by its distinctive structural style, the presence of set 2 filled fractures and the thermal immaturity of the Torok Formation (Table 4.4). The abundance of south-vergent structures in the Torok suggests that the Tuktu Escarpment marks the top of a major zone of back thrusting associated with the formation of a triangle zone in the footwall (Figure 4.8). The mechanical contrast between the Torok, the overlying Nanushuk and underlying Fortress Mountain make the Torok the ideal location for a stratigraphically controlled back thrust (Couzens and Wiltschko, 1996; Jones, 1996). The presence of Set 2 filled fractures suggests that fluids were present during deformation.

The Domain III cooling curve indicates relative thermal immaturity of the Torok as the samples dipped into the PAZ but temperatures were not hot enough to anneal and overprint the thermal signature of cooling at ~100 Ma (Figure 4.8). The samples then were quickly uplifted and cooled between 70 and 60 Ma and never fully annealed.

Domain IV

Domain IV consists of the Nanushuk Formation, is bounded to the south by the Tuktu Escarpment and extends north for the remainder of the transect (Figures 4.2 and 4.8). The Nanushuk Formation is deformed into kilometer-scale, low amplitude, symmetrical open folds with no strong or consistent sense of vergence. Anticline hinges are narrow and commonly broken. In some locations, Torok Shale is exposed in the core of the anticlines (Peapples et al., 2007). Fold limbs are planar and exhibit relatively constant dip (10° - 15°), and synclines are broad, open and flat-bottomed. Similar folds continue far to the north into the Colville basin and are visible on the seismic data. Faults in the Nanushuk are most commonly south-dipping, north-vergent thrust faults, but are typically poorly exposed.

Only fractures Sets 3 and 4 are present in Domain IV (Tables 4.1 and 4.4, Figure 4.7). Lack of filled fractures precluded fluid inclusion analysis.

AFT results from Domain IV are very similar to that of Domain II (Tables 4.2 and 4.4). Apatite fission track cooling ages from the Nanushuk Formation indicate that the Nanushuk attained temperatures hot enough ($\geq 110^{\circ}\text{C}$) to anneal fission tracks and record a cooling age of $\sim 64\text{-}60$ Ma.

Interpretation

Domain IV Nanushuk fold trains are interpreted as detachment folds based both mechanical contrast between the Torok and Nanushuk and on the geometry of Nanushuk folds (Dahlstrom, 1990). Shortening of the more competent Nanushuk is interpreted to be above a triangle zone within the less competent Torok (Figure 4.8). According to this interpretation, the Nanushuk has been transported southward (relative motion) above a regional back thrust and along a detachment surface at the base of the Nanushuk Formation. The presence of unfilled fold-related fractures (Set 3) suggests that folding and associated fracturing occurred under conditions where hot fluids were not preferentially exploiting open fracture networks.

RECONSTRUCTIONS

Field observations of structural style, fracture characteristics, AFT and fluid inclusion data and subsurface interpretation were combined into a coherent structural model that incorporates important structural and thermal observations. The structural model extends from Tulugak #1 in the north to the range front and includes the seismic line WG 89-29 (Figure 4.2), and all four domains. *LithoTect* software was used to develop a geometrically consistent reconstruction of the evolution of the transect.

The deformed section and three stages of restoration are shown in Figure 4.9. Figure 4.9 A is the deformed section; Figure 4.9 B represents an intermediate step at $\sim 60\text{-}70$ Ma, and Figure 4.9 C is a final restoration to a time after emplacement of the EMA and deposition of the Fortress Mountain, Torok, and Nanushuk Formations. Figure 4.9 D is the same stage of deformation as Figure 4.9 C, but restores all thermal data points to a minimum burial depth with respect to an assumed paleo-ground surface.

Primary elements of the model:

The model incorporates five primary structural elements: the North Slope autochthon, the EMA wedge (Domain I), Brookian 'wedge-top deposits' (Domain II), the Torok Formation (Domain III), and the Nanushuk foreland basin deposits (Domain IV).

The primary observations and assumptions that are integral to the reconstruction are:

- 1) The deformational, fracture and fluid flow history of domain suggest that the EMA in Domain I has undergone at least two episodes of deformation.
- 2) Domains II, III and IV have experienced only one episode of deformation.

- 3) The uplift history of the four domains is not a simple south to north, older to younger progression
- 4) A regional back thrust separates Domains III and IV
- 5) The majority of structural relief at Tiglukpuk anticline occurred prior to Tertiary time.
- 6) The geothermal gradient is assumed to be 25°C/km.

Restorations:

Deformed state

Some important observations about the deformed state cross section (Figure 4.9 A) are crucial to understanding the steps taken in the subsequent restorations:

High angle breaching thrust faults in the Endicott Mountains allochthon (location a, Figure 4.9 A) are interpreted as early Tertiary fold-and-thrust deformation because they clearly cross cut incoherent, internally deformed EMA stratigraphy in seismic data and the displaced Brookian stratigraphy where exposed at the surface. These high angle breaching thrust faults reduce the overall horizontal displacement of the wedge during fold-and-thrust deformation by accommodating a significant proportion of strain by vertical, rather than horizontal, displacement.

The structurally thickened interval underlying the northern tip of the orogenic wedge (location b, Figure 4.9 A) is interpreted to be the Kingak Shale (Jk) and the basal detachment unit above which the orogenic wedge was emplaced. Because of structural thickening, the original thickness of Kingak Shale is difficult to determine. The stratigraphic thickness used in the restoration is based on the thickness at the northern end of the line on the assumption that the Kingak there is least deformed and most closely represents the original thickness.

The original thickness of the Okpikruak Formation (location c, Figure 4.9 A) is not known because topography of the wedge top at the time of deposition is unknown and because the Okpikruak Formation is now a tectonic mélangé. For this reason, the Okpikruak Formation maintains equal area but is not restored.

Restoration, stage 1:

The first stage of restoration (Figure 4.9 B) removes the major displacement on the high angle breaching thrust faults (Figure 4.8 A, locations A) in the EMA wedge and cover. The Brookian units not cut by breaching faults are allowed to passively deform above the reconstructed wedge deformation.

Slip on the back thrust in the Torok and across the Torok/Nanushuk contact is also restored. Restoration of the back thrusting alone in this stage of deformation is not sufficient to return AFT data points to an appropriate depth.

Restoration, stage 2a:

In this stage (Figure 4.9 C), penetrative strain and structural thickening in the Torok, Kingak and Shublik Formations was restored by area balancing of the Torok and underlying units and by restoration of the Nanushuk to original horizontality. Unit thicknesses observed at the northern end of the section are assumed to be original depositional thicknesses

Restoration, stage 2b: Incorporation of AFT and fluid inclusion data:

Figure 4.9 D incorporates the AFT and thermal results into the reconstruction. Time vs. temperature cooling curves summarize the overall trends in each domain.

Vertical lines on the topographic profiles indicate the projected location of nearby AFT analyses. The height of the lines represents the amount of overburden necessary for samples to reach 60°C, the top of the apatite annealing window (2.4 km, assuming 25°C/km). The resulting assumed paleo-ground surface indicates the minimum amount of unroofing necessary to be consistent with the thermal history recorded by AFT results.

DISCUSSION:

Surface and subsurface structural style, fracture distribution, AFT data and fluid inclusion data constrain the relative timing of deformation within the orogenic wedge of the Brooks Range foothills. Deformation in the foothills can be subdivided into three separate deformational stages: 1) deformation within the orogenic wedge during Early Cretaceous time, lasting at least into Valanginian time, 2) reactivation of the wedge driving fold-and-thrust deformation and back thrusting between 70 and 60 Ma and 3) late stage, post-tectonic uplift and unroofing driven by the isostatic response to erosion. These events are summarized in schematic form in Figure 4.10; Figure 4.11 shows the temperature history of the transect during these events and where fracture sets formed.

Early Cretaceous deformation

In the central Brooks Range, thrusting and related folding of the Lisburne Group, Siksikpuk Formation, and Otuk Formation (EMA), and the formation of the overlying tectonic mélange in the Okpikruak Formation are probably related to deformation within the orogenic wedge during EMA emplacement (Figure 4.10 A). Set 1 filled fractures in the EMA of Domain I are interpreted to have formed during this early phase of deformation (Figure 4.11). Crack-seal textures in filled fractures and the presence of multiple generations of fracture fill (Table 4.2) suggest that deformation was either a single long-lived episode or episodic. The structural position, the abundance of filled fractures and the crack-seal textures are consistent with fracture formation in an actively deforming antiform with high fluid pressures.

Thermal data from fluid inclusions and conodont alteration indices indicate that the maximum temperature achieved at Tiglukpuk anticline was ~150°C. The fluid inclusions contain methane, indicating that gas generation may have been active within the orogenic wedge. These data suggest that the fracture network could have acted as a migration route for hydrocarbons generated at depth within the wedge.

Deposition of Colville basin sediments during late Cretaceous time.

A period of tectonic quiescence occurred after Albian time, lasting until the latest Cretaceous or Paleocene. During this period, the Brookian clastic units of the southern foothills and foreland basin were deposited on top of the leading edge of the orogenic wedge and basinward into the adjacent foreland basin (Figure 4.10 B). While most of the earlier deformation was complete prior to deposition of these sediments, minor deformation likely continued as suggested by Set 2 fractures (Figure 4.10), growth folds in the Nanushuk (Finzel, 2004) and the extreme and abrupt facies variations within the Fortress Mountain Formation.

Tertiary deformation

Fold-and-thrust deformation resumed in the early Tertiary and resulted in transport of the orogenic wedge farther into the basin, shortening of the orogenic wedge via breaching thrust faults, and shortening of the foreland basin sediments above a south-directed backthrust (Figure 4.10 C). A triangle zone formed within the Fortress Mountain and Torok, with the main zone of back thrusting probably located just south of the Tuktu Escarpment. The overlying Nanushuk Formation was shortened via detachment folding and thrust southward, out of the basin.

Fracture Sets 2 and 3 are interpreted to have formed during this time. Set 2 filled fractures are restricted to the orogenic wedge and to a few occurrences in the older part of the basin fill. Set 2 fractures probably are restricted to these areas because they were either deep enough to still be experiencing high fluid pressures (orogenic wedge) or were actively or locally dewatering (deep foredeep basin).

Set 3 fractures occur throughout the transect and are also probably associated with folding, but are not filled with cement, suggesting that they formed later during Tertiary deformation and/or during dryer conditions.

Late stage uplift and unroofing:

The latest deformational event was post-tectonic uplift and unroofing driven by erosion and isostatic rebound of thickened crust. Set 4 unfilled fractures are interpreted to have formed during this time due to release of residual stress in the rock as overburden is removed or due to cooling and contraction (Engelder, 1985; Hanks, 2004; Hayes, 2004).

Cooling History recorded by AFT

This shortening pattern resulted in a complex cooling history. While total burial was sufficient to anneal detrital apatite crystals in the Fortress Mountain Formation of Domain II, the southern area of Domain II (II-S) attained higher temperatures than the northern area (II-N). This may have been due to: 1) Domain II-S being closer to the sediment source, resulting in deeper burial and/or 2) Domain II-S undergoing more uplift along the breaching thrust that separates it from domain II-N.

The Torok of Domain III did not reach maximum annealing temperatures ($\sim 110^{\circ}\text{C}$), and AFT samples did not record the 65-60 Ma cooling event. While AFT thermal data indicate that samples from Domain III did reach temperatures in the PAZ, the samples did not remain at that temperature long enough to erase the thermal record from the ~ 100 Ma event and to record the 65 Ma event. These data are interpreted as representing minor burial before, and little uplift as a result of, fold-and-thrust deformation.

AFT samples from the Nanushuk north of the Tuktu Escarpment in Domain IV indicate that the entire Nanushuk cooled to $<60^{\circ}\text{C}$ between 65 and 60 Ma, presumably as a result of between 2.4 and 4.4 km (or more) of uplift and unroofing. Uplift is interpreted to have occurred largely along the regional back thrust, with displacement sufficient to exhume thermally reset AFT samples. Displacement along the back thrust resulted in deeply buried Nanushuk being juxtaposed against the less deeply buried samples from the Torok of Domain III.

Implications for fluid flow

Fractures formed in at several times and under a variety of conditions along the transect. Early fractures that formed during formation of the orogenic wedge could have acted as conduits for migration of fluids, including oil and gas out of the wedge into updip traps in the wedge itself or in the foredeep basin. These fractures could continue to serve as fluid conduits as the wedge evolved if they remained open. Fluids that entered the system through deformation-driven topographic highs in the hinterland or range-front areas may have created areas of high hydraulic head that drove shallow fluid circulation in the proximal foreland basin.

CONCLUSIONS

Surface and subsurface structural, thermal and geochronologic data are integrated into a structural model of a transect through the central Brooks Range foothills and adjacent Colville basin that may provide important clues to the evolution of the central Brooks Range petroleum system. Deformed Mississippian through Cretaceous rocks of the Endicott Mountains allochthon (EMA) and wedge-top and foredeep deposits of the Brookian Okpikruak Formation from an orogenic wedge that extends north and underlies Brookian wedge-top and proximal foreland basin deposits of the Cretaceous Fortress Mountain, Torok and Nanushuk Formations. The northern tip of the orogenic wedge underlies a triangle zone consisting of strongly deformed

shales of the Torok Formation. A south-directed backthrust overlies the triangle zone and underlies detachment folds within the Nanushuk Formation.

Reconstruction of this structural model constrains the geometry and sequence of Cretaceous and early Tertiary deformation and uplift in the region. The earliest deformation along the transect was Valanginian and older in age and involved emplacement of the orogenic wedge and deformation of the adjacent proximal foreland basin deposits of the Fortress Mountain Formation. A complex sequence of filled fractures (Sets 1 and 2) is associated with this deformational event. Fluid inclusion homogenization temperatures and conodont alteration indices suggest that deformation occurred at temperatures of $\sim 150^{\circ}\text{C}$.

After a brief period of relative quiescence in the late Cretaceous and deposition of the Fortress Mountain, Torok and Nanushuk Formations of the Colville basin, fold-and-thrust deformation resumed during the early Tertiary. Shortening affected all parts of the transect. Breaching thrusts within the orogenic wedge facilitated shortening and northward translation of the wedge. A triangle zone formed within the Torok and allowed south-directed backthrusting and detachment folding of the Nanushuk Formation. Set 3 unfilled fractures formed at this time in all parts of the transect, suggesting that most of the deformation occurred in the absence of significant fluids. This event is recorded by AFT unroofing ages of 70 and 60 Ma.

A late period of uplift and unroofing is represented by Set 4 unfilled fractures that occur across the entire transect area. These fractures are interpreted as unloading fractures that formed in the absence of fluids as the result of erosional unroofing after fold-and-thrust related uplift.

The restriction of filled fractures to the orogenic wedge and rocks immediately overlying it implies that these fractures were the open fractures during fluid generation and migration. However, these filled fractures do not occur in younger and structurally higher sediments. Only unfilled fractures related to folding and/or uplift and unroofing occur in rocks above the backthrust are unfilled, implying that fluids were not prevalent at this structural position and at this time.

REFERENCES

- Adams, K.E., 1991, Permian sedimentation in the northcentral Brooks Range, Alaska: Implications for tectonic reconstructions, M.S. thesis, Univ. Alaska, Fairbanks, 122 p.
- Allen, P.A., and Allen, J.R., 2005, Basin Analysis, Principles and Applications: Oxford, UK, Blackwell Publishing Ltd. p. 317.
- Bachu, S., 1995, Synthesis and model of formation-water flow, Alberta Basin, Canada: AAPG Bulletin, v. 79, p. 1159-1178.
- Bernet, M., and Garver, J.I., 2005, Fission-track analysis of detrital zircon: Reviews in Mineralogy & Geochemistry, v. 58, p. 205-238.
- Bird, K.J., 2001, Alaska: A twenty-first century petroleum province, in M.W. Downey, Threet, J.C., and Morgan, W.A., eds., Petroleum provinces of the twenty-first century: AAPG Memoir 74, p. 137-165.
- Bird, K.J., and Molenaar, C.M., 1992, The North Slope foreland basin, Alaska, in Leckie, R.W.M.D.A., ed., Foreland Basins and Fold belts, Volume 55, AAPG Memoir, p. 363-393
- Brown, P.J., II, Saltus, R.W. et. al., 2007, High-resolution gravity study reveals structural style and forward limit of tectonic wedge, central Brooks Range foothills, Alaska: in prep.
- Coakley, B.J., and Watts, A.B., 1991, Tectonic controls on the development of unconformities: The North Slope, Alaska: Tectonics, v. 10, p. 101-130.
- Cole, F., Bird, K.J., Toro, J., Roure, F., O'Sullivan, P.B., Pawlewicz, M., and Howell, D.G., 1997, An integrated models for the tectonic development of the frontal Brooks Range and Colville Basin 250 km west of the Trans-Alaska Crustal Transect: Journal of Geophysical Research, v. 102, no. B9, p. 20,685-20,708.
- Cooper, M., 1992, The analysis of fracture systems in subsurface thrust structures from the Foothills of the Canadian Rockies, in McClay, K., ed., Thrust Tectonics: London, Chapman & Hall, p. 391-405.
- Cosgrove, J.W., 2000, Forced folds and fractures: An introduction, in Cosgrove, J.W., Ameen, M.S., ed., Forced folds and Fractures: London, Geological Society of London Special Publication 169, p. 1-6.
- Couzens, B.A., and Wiltchko, D.V., 1996, The control of mechanical stratigraphy on the formation of triangle zones: Bulletin of Canadian Petroleum Geology, v. 44, p. 165-179.

- Dahlen, F.A., and Suppe, J., 1988, Mechanics, growth, and erosion of mountain belts, in Processes in continental lithospheric deformation, Clark, SP, Jr., Burchfiel, BC, and Suppe, J., eds., Geological Society of America, Special Paper no. 218 p. 161-178.
- Dahlstrom, C.D.A., 1990, Geometric constraints derived from the law of conservation of volume and applications to evolutionary models for detachment folding: AAPG Bulletin, v. 74, p. 336-344.
- Davis, G.H., and Reynolds, S.J., 1996, Structural Geology of Rocks and Regions: New York, John Wiley & Sons, Inc.
- Davis, D., Suppe, J., and Dahlen, F.A., 1983, Mechanics of fold-and-thrust belts and accretionary wedges: Journal of Geophysical Research, v. 88, p. 1153-1172.
- Decelles, P.G., and Giles, K.A., 1996, Foreland basin systems: Basin Research, v. 8, p. 105-123.
- Deming, D., Sass, J.H., Lachenbruch, A.H., and De Rito, R.F., 1992, Heat flow and subsurface temperature as evidence for basin-scale ground-water flow, North Slope of Alaska: Geological Society of America Bulletin, v. 104, p. 528-542.
- Deming, D., Sass, J.H., and Lachenbruch, A.H., 1996, Heat flow and subsurface temperature, North Slope of Alaska, in Johnsson, M.J., and Howell, D.G., eds., Thermal Evolution of Sedimentary Basins in Alaska, U.S. Geological Survey Bulletin 2142, p. 27-44.
- Dickin, A.P., 1995, Radiogenic Isotope Geology: Cambridge, UK, Cambridge University Press.
- Dumoulin, J.A., Whalen, M.T. and Harris, A.G., Lithofacies, Age, and Sequence Stratigraphy of the Carboniferous Lisburne Group in the Skimo Creek area, Central Brooks Range, Alaska, USGS Professional Paper, Alaska Studies Volume (in press).
- Engelder, T., 1985, Loading paths to joint propagation during a tectonic cycle: an example from the Appalachian Plateau, U.S.A.: Journal of Structural Geology, v. 7, p. 459-476.
- Epstein, A.G., Epstein, J.B., and Harris, L.D., 1977, Conodont Color Alteration- an Index to Organic Metamorphism: U.S. Geological Survey Professional Paper 995, p. 1-27.
- Ferket, H., Roure, F., Swennen, R., and Ortuno, S., 2000, Fluid migration placed into the deformation history of fold-and-thrust belts: an example from the Veracruz basin (Mexico): Journal of Geochemical Exploration, v. 69-70, p. 275-279.
- Finzel, E.S., 2004, Architectural analysis and fold geometry of syntectonic fluvial conglomerate in the Nanushuk Formation, Brooks Range foothills, Alaska [M.S. thesis]: Fairbanks, AK, University of Alaska Fairbanks.

- Florez-Nino, J.M., Aydin, A., Mavko, G., Antonellini, M., and Ayaviri, A., 2005, Fault and fracture systems in a fold and thrust belt: An example from Boliva: AAPG Bulletin, v. 89, p. 471-493.
- Hancock, P.J., and Engelder, T., 1989, Neotectonic joints: Geological Society of America Bulletin, v. 101, p. 1197-1208.
- Hanks, C.L., Lorenz, J., Teufel, L., and Krumhardt, A.P., 1997, Lithologic and structural controls on natural fracture distribution and behavior within the Lisburne Group, Northeastern Brooks Range and North Slope subsurface, Alaska: AAPG Bulletin, v. 81, p. 1700-1720.
- Hanks, C.L., Paris, T.M., and Wallace, W.K., 2006, Fracture paragenesis and microthermometry in Lisburne Group detachment folds: Implications for the thermal and structural evolution of the northeastern Brooks Range, Alaska: AAPG Bulletin, v. 90, p. 1-20.
- Hanks, C.L., Wallace, W.K., Atkinson, P.K., Brinton, J., Bui, T., Jensen, J., and Lorenz, J., 2004, Character, relative age and implications of fractures and other mesoscopic structures associated with detachment folds; an example from the Lisburne Group of the northeastern Brooks Range, Alaska: Bulletin of Canadian Petroleum Geology, v. 52, p. 121-138.
- Hayes, M., R., 2004, The influence of mechanical stratigraphy on the development of detachment folds and associated mesoscopic structures: An example from the Lisburne Group carbonates, Northeastern Brooks Range, Alaska [M.S. thesis]: Fairbanks, University of Alaska Fairbanks.
- Howell, D.G., Bird, K.J., Huaifu, L., and Johnsson., M.J., 1992, Tectonics and Petroleum potential of the Brooks Range fold and thrust belt- a progress report, in Bradley, D.C., and Ford, A.B., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1990: U.S. Geological Survey Bulletin 1999, p. 112-126.
- Johnsson, M.J., Howell, D.G., and Bird, K.J., 1994, Thermal maturity patterns in Alaska: Implications for tectonic evolution and hydrocarbon potential: AAPG Bulletin, v. 77, no. 11, p. 1874-1903.
- Jones, P., B., 1996, Triangle zone geometry, terminology and kinematics: Bulletin of Canadian Petroleum Geology, v. 44, p. 139-152.
- Kelley, J.S., 1990, Generalized geologic map of the Chandler Lake quadrangle, north-central Alaska, U.S. Geological Survey Map MF-2144-A, scale 1: 250,000, 1 sheet, 19 p.
- Kelly, L.N., Whalen, M.T., McRoberts, C.A., Hopkin, E., and Tomsich, C.S., 2007, Sequence stratigraphy and geochemistry of the upper Lower through Upper Triassic of Northern

- Alaska: Implications for paleoredox history, source rock accumulation, and paleoceanography, 50 p.
- Kumar, N., Bird, K.J., Nelson, P.H., Grow, J.A., and Evans, K.R., 2002, A digital atlas of hydrocarbon accumulations within and adjacent to the National Petroleum Reserve-Alaska (NPRA), U.S. Geological Survey Open-File Report 02-71, p. 1-80.
- Laderia, F.L., and Price, N.J., 1981, Relationship between fracture spacing and bed thickness: *Journal of Structural Geology*, v. 3, p. 179-183.
- Lorenz, J.C., Teufel, L.W., and Warpinski, N.R., 1991, Regional fractures: A mechanism for the formation of regional fractures at depth in flat-lying reservoirs: *AAPG Bulletin*, v. 75, p. 1714-1737.
- Machel, H.G., and Cavell, P.A., 1999, Low-flux tectonically-induced squeegee fluid flow ("hot flash") into the Rocky Mountain foreland basin: *Bulletin of Canadian Petroleum Geology*, v. 47, p. 510-533.
- Majorowicz, J.A., Jones, F.W., Lam, H.L., and Jessop, A.M., 1984, The variability of heat flow both regional and with depth in southern Alberta, Canada; Effect of ground-water flow: *Tectonophysics*, v. 106, p. 1-24.
- Mauch, E.A., 1989, Stratigraphic and structural interpretation of selected seismic lines, Ikpikpuk-Umiat Basin, National Petroleum Reserve, Alaska, in *Atlas of seismic stratigraphy AAPG Studies in Geology Volume 27: United States*, American Association of Petroleum Geologists, Tulsa, OK, p. 116-128.
- Moore, T.E., and Potter, C.J., 2003, Structural plays in the Ellesmerian Sequence and correlative strata of the National Petroleum Reserve, Alaska, U.S. Geological Survey Open-File Report 03-253, p. 1-58.
- Moore, T.E., Potter, C.J., O'Sullivan, P.B., Shelton, K. L., and Underwood, M.B., 2004, Two stages of deformation and fluid migration in the west-central Brooks Range fold and thrust belt, northern Alaska, in Swennen, F.R., and Granath, J.W., eds., *Deformation, fluid flow, and reservoir appraisal in foreland basin fold and thrust belts: AAPG Hedberg Series No. 1*, p. 157-186.
- Moore, T.E., Wallace, W.K., Bird, K.J., Karl, S.M., Mull, C.G., and Dillion, J.T., 1994, *Geology of Northern Alaska*, in Plafker, G., and Berg, H.C., eds., *The Geology of Alaska, The Geology of North America, Volume G-1: Boulder, CO*, The Geological Society of America.

- Mull, C.G., Glenn, R.K., and Adams, K.E., 1997, Tectonic evolution of the central Brooks Range mountain front: Evidence from the Atigun Gorge region: *Journal of Geophysical Research*, v. 102, p. 20,749-20,772.
- Mull, C.G., Houseknecht, D.W., and Bird, K.J., 2003, Revised Cretaceous and Tertiary stratigraphic nomenclature in the Colville Basin, northern Alaska, US Geological Survey Professional Paper 1673, p. 51.
- Mull, C.G., and Sonnemann, H.S., 1975, Portion of a Geologic Map of the Chandler Lake Quadrangle, (Unpublished).
- Narr, W., and Suppe, J., 1991, Joint spacing in sedimentary rocks: *Journal of Structural Geology*, v. 13, p. 1037-1048.
- Nunn, J.A., and Hanor, J.S., Lee, Y., 2005, Migration pathways in the central North Slope foreland basin, Alaska USA: solute and thermal constraints on fluid flow simulations: *Basin Research*, v. 17, p. 403-416.
- O'Sullivan, P.B., 1999, Thermochronology, denudation and variations in paleo surface temperature: a case study from the North Slope foreland basin, Alaska: *Basin Research*, v. 11, p. 191-204.
- O'Sullivan, P.B., Moore, T.M., and Murphy, J.M., 1998a, Tertiary uplift of the Mt. Doonerak antiform, central Brooks Range, Alaska: Apatite fission-track evidence from the Trans-Alaska Crustal Transect, in Oldow, J.S., Ave Lallemant, H.G., eds., *Architecture of the Central Brooks Range Fold and Thrust Belt, Arctic Alaska*: Geological Society of America Special Paper 324, p. 179-193.
- O'Sullivan, P.B., Murphy, J.M., and Blythe, A.E., 1997, Late Mesozoic and Cenozoic thermotectonic evolution of the central Brooks Range and adjacent North Slope foreland basin, Alaska: Including fission-track results from the Trans-Alaska Crustal Transect (TACT). *Journal of Geophysical Research*, v. 102, p. 20,821-20,845.
- O'Sullivan, P.B., and Wallace, W.K., 2002, Out-of-sequence, basement-involved structures in the Sadlerochit Mountains region of the Arctic National Wildlife Refuge, Alaska: Evidence and implications from fission-track thermochronology: *GSA Bulletin*, v. 114, p. 1356-1378.
- O'Sullivan, P.B., Wallace, W.K., and Murphy, J.M., 1998b, Fission-track evidence for apparent out-of-sequence Cenozoic deformation along the Philip Smith Mountain front, northeastern Brooks Range, Alaska: *Earth and Planetary Science Letters*, v. 164, p. 435-449.

- Parris, T.M., and Burruss, R.C., O'Sullivan, P.B., 2003, Deformation and the timing of gas generation and migration in the eastern Brooks Range foothills, Arctic National Wildlife Refuge, Alaska: AAPG Bulletin, v. 87, p. 1823-1846.
- Peapples, P.R., Wallace, W.K., Wartes, M.A., Swenson, R.F., Mull, C.G., and Dumoulin, J.A., 2007, Geologic map of the Siksikpuk River Area, Chandler Lake quadrangle, Alaska: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2007-1, 1 sheet, scale 1:63,360.
- Potter, C.J., and Moore, T.E., 2003, Brookian structural plays in the National Petroleum Reserve, Alaska: U.S. Geological Survey Open-File Report 03-266, p. 1-49.
- Ramsay, J.G., and Huber, M.I., 1987, The Techniques of Modern Structural Geology, Volume 2: Folds and Fractures: London, Academic Press.
- Ratliff, B., 1999-2006, LithoTect Help Manual: Geo-Logic Systems, LLC.
- Roedder, E., 1984, Fluid Inclusions: An introduction to studies of all types of fluid inclusions, gas, liquid, melt, trapped in materials from earth and space, and their application to the understanding of geologic processes, in Ribbe, P.H., ed., Reviews in Mineralogy, Volume 12, p. 646.
- Shackleton, J.R., 2003, The relationship between fracturing, asymmetric folding, and normal faulting in Lisburne Group carbonates: Porcupine Lake Valley, northeastern Brooks Range, Alaska [M.S. thesis]: Fairbanks, University of Alaska Fairbanks. p. 189.
- Shackleton, J.R., Cooke, M.L., and Sussman, A.J., 2005, Evidence for temporally changing mechanical stratigraphy and effects on joint-network architecture: Geology, v. 33, p. 101-104.
- Siok, J.P., 1985, Geologic history of the Siksikpuk Formation on the Endicott Mountains and Picnic Creek allochthons, north-central Brooks Range, Alaska: M.S. thesis, University of Alaska, Fairbanks, 253 p.
- Stearns, D.W., 1968, Certain aspects of fractures in naturally deformed rocks, in Reiker, R.E., National Science Foundation Advanced Science Seminar in Rock Mechanics: Special Report, Air force Cambridge Research Laboratories, Bedford, MA, v. AD66993751, p. 97-118.
- Stearns, D.W., and Friedman, M., 1972, Reservoirs in fractured rock, in King, R.E., ed., Stratigraphic oil and gas fields- Classification, exploration methods, and case histories: AAPG Memoir 16, p. 82-106.

- Tanner, P.W., 1989, The flexural-slip mechanism: *Journal of Structural Geology*, v. 11, p. 635-655.
- Wallace, W.K., Duncan, A.S., Peapples, P.R., Swenson, R.F., Wartes, M.A., O'Sullivan, P.B., and Finzel, E.S., 2006, Geometry and evolution of the frontal part of an orogenic wedge, central Brooks Range foothills, Alaska: *Geological Society of America Abstracts with Programs*, Vol. 38, No. 5, p. 24.
- Wallace, W.K., Moore, T.M., and Plafker, G., 1997, Multistory duplexes with forward dipping roofs, north central Brooks Range, Alaska: *Journal of Geophysical Research*, v. 102, p. 20773-20796.

Figure 4.1. Regional geologic map of northern Alaska showing location of study area. Modified from Moore and others, 1994.

B

Figure 4.2:

A. Simplified geologic map of the transect area. Grey boxes delineate detailed map areas; remainder of map is compiled from Mull and Sonnemann (1974); Kelley (1990) and Peapples and others (2007). White line is location of seismic line WG 89-29 shown in

Figure 4.

B. Simplified version of geologic map showing the structural domains and the AFT sample locations and the cooling ages associated with each domain. Black lines indicate the location of domain cross sections shown in Figures 5, 6 and 7.

Figure 4.3. Stratigraphic column showing the relationship between the Endicott Mountains allochthon (EMA) and the stratigraphy of the North Slope autochthon. Abbreviations: MDk, Kekiktuk Cgl; Mky, Kayak Sh; Ko, Okpikruak Fm; Kfmv, lower Fortress Mountain Fm; Kfm, Fortress Mountain Fm.; Kto, Torok Fm.; Kn, Nanushuk Fm. Modified from Moore et al. (2004)

Figure 4.4.

A. Seismic line WG 89-29, uninterpreted. Location of line shown on Figure 2. Data provided by Western Geophysical.

B. Seismic line WG 89-29, depth converted and interpreted. Interpretation is extended to the north by incorporating Tulugak #1 and to the south by incorporating surface data from Tiglukupuk anticline. Stratigraphic tops in Tulugak #1 provided by P. Decker (Alaska Department of Oil and Gas, personal communication, 2006).

Domain I cross section with location of AFT samples and pooled ages. Cooling curve represents best model of cooling path represented by AFT ages and track lengths. Location of section line shown in Figure 2 B. No vertical exaggeration.

Figure 4.6.

Domain II cross section with location of AFT samples and pooled ages. Cooling curve represents best model of cooling path represented by AFT ages and track lengths. Location of section line shown in Figure 2 B.

Figure 4.7. Fracture orientation data, presented by domain. Fracture orientation data are not representative of the distribution observed in the field because of sampling bias introduced by poor exposure and fracture spacing relationships, resulting in under-representation of fractures with wider average set spacing. Filled fracture Sets 1 and 2 in Domain I can not be definitively distinguished by field relationships because Set 1 fractures are reactivated and refilled during formation of Set 2 fractures. The orientation of unfilled, Set 3 fractures represents a range of conjugate fractures and acute bisectors. Unfilled fractures of Set 4 are the only unfilled fractures present in Domain I.

Figure 4.8.

Cross section of Domains III and V with location of AFT samples and pooled ages. Cooling curve represents best model of cooling path represented by AFT ages and track lengths. Location of section line shown in Figure 2 B; symbols and abbreviations same as Figures 5 and 6.

Figure 4.9. Sequential restoration of balanced cross section of transect. Balancing and restorations done using LithoTect.

A. Initial, deformed state section. A: Breaching thrusts; B: Structurally thickened Kingak Shale/Shublik; D: Structurally thickened Torok/Fortress Mountain. Vertical lines above ground surface represent addition overburden needed for AFT samples to be at top of annealing window, assuming a geothermal gradient of 25°C/km.

B. Step one of the reconstruction. This step removes slip from high-angle thrust faults (A) within the orogenic wedge of the EMA, displacement along the back thrust and along the Torok/Fortress Mountain and Nanushuk contact.

Figure 4.9 (continued)

C. Step two of reconstruction. Removal of structural thickening of Torok/Fortress Mountain (D) and Kingak Shale/Shublik (B) results in flattening of the Nanushuk Formation.

D. Integration of thermal data into restoration. Solid line represents paleotopography needed to account for AFT data. Modelled time vs. temperature uplift curves based on AFT data are shown by domain.

South

North

Neocomian

Aptian-Albian (i)

Late Cretaceous-early Tertiary (ii)

Figure 10. Schematic reconstruction of transect showing the stages of deposition and fracture set distribution along the transect. Stratigraphy is simplified to show deformation. Stars represent filled fracture sets; rectangles unfilled fractures.

A: Deposition of Okpikruak Fm. (Ko) onto the top of orogenic wedge coeval with internal deformation within the wedge. Formation of Set 1 filled fractures in Domain I.

B. Stage 2 deformation begins as the orogenic wedge thickens and deforms the overlying Ko during deposition of the foreland basin stratigraphy. Formation of Set 2 fractures in orogenic wedge.

C. Continued fold-and-thrust deformation is responsible for Set 2 and Set 3 fractures in the foreland basin. Deformation in the wedge uplifts the Fortress Mtn. (Kfm) in Domain II and back thrusting shortens and uplifts the Nanushuk (Kn) in Domain IV. Stage 3 deformation is driven by isostatic uplift and is not the result of tectonic deformation. Erosion of the foothills results in regional unroofing, forming late-stage, unfilled Set 4 fractures in all domains.

Figure 4.11. Time vs Temperature path for transect area. Shaded ovals along curve indicate the timing and conditions of formation of fracture sets (stars 1-4) with respect to temperature. There is no constraint on the timing of the beginning of fracture set 1 and fluid inclusion data does not constrain the maximum temperature during fracture filling events in Domain I. Letters refer to different time/temperature paths exhibited by the rocks along the transect. Rocks of the Endicott Mountains allochthon (EMA) of Domain 1 have followed path A/A' and contain all four fracture sets; rocks of Domain IV have followed path B and only contain fracture sets 3 & 4.

Set	Domain	Fracture characteristics	Spacing and morphology in typical outcrop	Relative age with respect to deformation		
				Valanginian and earlier emplacement of EMA	Main Tertiary deformation	Post deformation uplift
1	I = A	Calcite filled extension fractures, conjugate sets and en echelon fractures with closest average spacing of all orientations in EMA. Set 1 fracture orientations formed coeval with each other as no clear cross cutting relationships are apparent. Set 1 fractures are ~bedding normal	Only present in Domain I. cm-scale fracture spacing common. Fracturing occurs in the EMA stratigraphy of domain I only. Fracture orientation varies with structural position.			
	II = M					
	III = M					
	IV = M					
2	I = A	Calcite filled fractures are closely spaced, sub-vertical fractures. Appearance is similar to set 1 fractures. Occur as both extension and conjugate compression fractures in domain I. In domain III fractures are bedding parallel and do not occur as conjugate fractures.	Only present in domains I and III. Filled fractures reactivate set 1 fractures. In domain III set 2 fractures are present but rare, occurring only in resistant lithologies.			
	II = M					
	III = R					
	IV = M					
3	I = M	Unfilled fractures are highly irregular and vary with changes and variations in lithologic properties. Domain II & IV fractures show no evidence of mineralization or leaching around open fractures and no evidence of fill in open fractures. Domain III unfilled fractures are only surveyed in resistant beds.	Set 3 unfilled fractures are irregular in dimension and orientation depending on structural position and lithology. Fracture spacing is dependant on lithology and structural position.			
	II = C					
	III = C					
	IV = C					
4	I = C	Set 4 fractures are unfilled and are not constrained by bedding units. Average spacing is typically much greater than sets 1-3. Fractures are ~north-south striking, cross-cut structure and are longer, higher and have larger aperture than set 1-3 fractures.	Fractures in outcrop are widely spaced and are rarely represented in all fracture surveys but are apparent in all domains.			
	II = C					
	III = C					
	IV = C					

Table 4.1. The characteristics, distribution, and relative timing of fracture sets 1-4. 'Domain' column shows in which domains each fracture set is present in outcrop and in what abundance: A = Abundant; C = Common; R = Rare; M = Missing.

Sample (Station #, Unit, Lith)		Fracture Set	Character of fracture and fill	Fluid inclusion results			
				Origin, room temp Phase relations	Mean Th (aqueous)	Mean Tm (ice)/salinity	Mean Th (gas)
Lisb. LS	006- 04A*	1 or 2	Post kinematic calcite fill, no crack-seal texture, well defined fracture walls. Calcite fill heavily twinned.	Primary solid inclusions, aqueous two-phase and single-phase gas or liquid. Secondary solid and aqueous two-phase inclusions	No data ****	No data ****	No data ****
Lisb. LS	007- 04D FIA#4	1 or 2	Two generations of post kinematic calcite fill with crack-seal texture. Cement growth occurred in the presence of CO ₂ , CH ₄ , and aqueous fluids. All measurements from younger fill generation.	Secondary aqueous two-phase inclusions along healed microcrack.	145° +/- 18°C (n=17)	-0.8° +/- 0.4°C (n=5)/ 1.4 wt.% NaCl equiv.	No data ****
	007- 04D FIA#2	1 or 2	As above	Secondary aqueous two-phase inclusions along healed microcrack.	156° +/- 23°C (n=10)	No data ****	No data ****
	007- 04D FIA#3	1 or 2	As above	Possible primary gas-rich single-phase inclusions (azonal distribution) in relatively untwined calcite.	No data ****	No data ****	Tm _{CO2} = -89.5 to -72.0°C (n= 3) Th _{CH4} = -76.5 to -76.0 (n= 1)
	007- 04D FIA#5	1 or 2	As above	Secondary gas-rich single-phase inclusions along healed microcrack.	No data ****	No data ****	Tm _{CO2} = -90° to -80°C (n= 2) Th _{CH4} = -89° to -76°C (n= 9)
	007- 04D FIA#7	1 or 2	As above	Secondary aqueous two-phase inclusions along healed microcrack in area of FIA#3.	142° +/- 18°C (n=5)	-1.1° +/- 0.3°C (n=7)/ 1.9 wt.% NaCl equiv.	No data ****
Siksik- puk CaCO ₃	009- 04A*	1 or 2	Two possible generations of fracture-fill. Fracture w/ widest aperture filled w/ calcite followed by quartz and bitumen. Thinner fractures have similar paragenesis, but no quartz.	Calcite and quartz contain single- and two-phase aqueous, and possible oil inclusions of secondary and unknown origin.	No data ****	No data ****	No data ****
Siksik- puk CaCO ₃ mud- stone	010- 04B*	1 or 2	1 st generation is fine-grained calcite along fracture walls and coarse calcite in geopetal structure. 2 nd generation cross cuts and cemented with bitumen, calcite and quartz.	Quartz cement contains two-phase and single-phase of probable primary origin. Single-phase may be gas or aqueous?	No data ****	No data ****	No data ****

Lisb. LS	012- 04A*	Fault slicks	Slicks are med to coarse-crystalline CaCO ₃ spar that is moderately to heavily twinned.	Abundant secondary aqueous two-phase inclusions and single-phase inclusions that are likely all liquid.	No data ****	No data ****	No data ****
Kto/ Kfm	026- 04A*	Fault slicks	Slicks cemented with two generations of fill. (1) Minor heavily twined calcite and quartz, (2) equant blocky untwined calcite.	Aqueous two-phase and one-phase gas of definite secondary and possible primary origin. Some mixing of single and two-phase inclusions is possible evidence of immiscible trapping.	No data ****	No data ****	No data ****
Kto mud-stone	036- 04A	2	Fill is authigenic, finely granular or crystalline carbonate, contains no organics from host rock.	Sample contains no workable inclusions	No data ****	No data ****	No data ****
Kto Silty mud-stone	040- 04C	2	Fracture narrows and widens possibly reflecting releasing bends in an extensional-shear fracture. Two or three generations of calcite. Early generation is feathery and bladed calcite. Generation 3 is equant blocky calcite.	Inclusions sparse. Early generation(s) has abundant solid inclusions and possible single and two-phase inclusions that are too small to work. Generation 3: single population of possible primary aqueous single and two phase (gas or liquid).	No data ****	No data ****	No data ****
	040- 04C #1	2	As above	Primary growth-zoned single- and two-phase aqueous inclusions.	113°±11°C (n= 10)	-1.4°±0.6°C (n= 14) 2.4 wt. % NaCl equiv.	No data ****
	040- 04C #2	2	As above	Secondary single- and two-phase aqueous inclusions along healed microcrack.	114°±12°C (n= 10)	-1.2°±0.6°C (n= 9) 2.4 wt. % NaCl equiv.	No data ****

Table 4.2. Results from fracture fill petrography and fluid inclusion analysis. Key: Lisb. LS, Lisburne Group Limestone; Qtz., Quartz; CaCO₃, Calcium Carbonate (calcite); Frac, Fracture; ****, data not yet available; Th, Homogenization Temperature; Tm, Melting Temperature if ice (yields percentage of salt in liquid); XXX, Large difference in phase-change temperatures recorded. This is indicative of inclusions that leaked gas after initial inclusion entrapment. Samples with asterisk (*) have only been described and mapped and await fluid inclusion analysis.

TABLE 4.3. Apatite fission track results. A summary of a total of 10,000 fission track measurements.

Sample ID	Unit	Domain	Mean Track Length (µm)	Pooled AFT Age	Data Quality*
05WKW047	Okpikruak	I	13.95 ± 0.15	63.2 ± 4.0 Ma	5
05WKW052	Okpikruak	I	14.00 ± 0.13	68.6 ± 3.9 Ma	7
05WKW104	Okpikruak	I	14.09 ± 0.11	61.2 ± 4.7 Ma	6
ASD 021-04A	Lower Fortress Mtn	II	13.86 ± 0.15	61.0 ± 4.5 Ma	8
ASD 022-04A	Lower Fortress Mtn	II	13.55 ± 0.16	55.7 ± 3.5 Ma	7
05ASD009	Lower Fortress Mtn	II	13.94 ± 0.15	67.4 ± 6.3 Ma	6
05ASD021	Lower Fortress Mtn	II	13.90 ± 0.18	62.7 ± 4.4 Ma	6
05ASD052	Fortress Mtn.	II	13.18 ± 0.18	100.7 ± 7.1 Ma	6
05ASD052*	Fortress Mtn.	II	13.21 ± 0.16	75.7 ± 5.2 Ma	7
ASD 040-04	Torok	III	13.72 ± 0.16	101.5 ± 7.7 Ma	6
ASD 041-04	Torok	III	13.70 ± 0.18	96.7 ± 5.6 Ma	4
05ASD029	Torok	III	12.79 ± 0.41	114.6 ± 8.0 Ma	6
05WKW083	Torok Sandstone	III	12.77 ± 0.27	71.5 ± 6.2 Ma	3
ASD 044-04	Nanushuk	IV	13.58 ± 0.33	63.9 ± 7.2 Ma	1
ASD 046-04	Nanushuk	IV	12.86 ± 0.93	60.6 ± 7.2 Ma	3
					* 1 = poor, 10 = excellent

Table 4.3. Apatite fission track results. Analysis by P. O'Sullivan and A-Z Inc.

D	Fracture Set	Fracture Characteristics	FI temperatures	AFT	Structural Style
I	1	Set 1 are filled fractures in domain I carbonates. Low average fracture spacing with compressional shear fractures in the core of Tiglupuk antiline and mode I extension fractures in the outer arc. Fractures have crack-seal textures and calcite fill. Set 1 filled fractures are coeval.	147°C ± 20°	61-68 Ma ~180° 200°C	Multiple generations of intense deformation. Within the Lisburne, km-scale, north vergent, asymmetric, overturned Tiglupuk antiline with duplex zone in its core. Bedding surface define planes of interlayer slip.
	2	Set 2 filled fractures not distinguishable from Set 1 fractures in domain I.			
	3	Set 3 absent			
	4	Unfilled fractures do not terminate at bed boundaries			
II	1	Set absent	None present	75-100 Ma 55-67 Ma	Broad, open, upright, ~symmetric folds and north vergent faults.
	2	Set absent			
	3	Fractures in Fortress Mtn. Fm. are all unfilled, no surface morphology or evidence of fluid flow. The fractures have irregular wavy nature. Orientation and avg. spacing vary with lithology and bed thickness.			
	4	Unfilled regional fractures			
III	1	Set absent	114° ±12°C	96-114 Ma ~100°C	Meter to 10's of meters scale folds and faults, generally south vergent in mechanically weak Torok Formation.
	2	Filled fractures are sparse and are bedding-parallel within rare, coherent siltstone beds. Fractures contain several generations calcite fill.			
	3	Unfilled fractures only identifiable in coherent beds. Friable, fissile siltstone and shale not conducive to fracture analysis.			
	4	Unfilled regional fractures present but hard to find in fissile mudstone.			
IV	1	Set absent	None present	60-64 Ma	Km-scale, broad, open, low amplitude, ~symmetric folds defined within mechanically competent Nanushuk Formation.
	2	Set absent			
	3	Similar to domain II, Set 2. Fracture orientation consistent,			
	4	Difficult to discern between Set 2 and Set 4			

Table 4.4. Domain (D) characteristics. Fracture Set 1 = Filled fractures, Valanginian and earlier deformation within EMA, Set 2 = filled fractures, Tertiary fold-and-thrust deformation, Set 3 = Unfilled fractures, Tertiary fold-and-thrust deformation (?), Set 4 = Unfilled unroofing, relaxation fractures. Fluid inclusion (FI) data = homogenization temperature from fluid inclusions in filled fractures. AFT data = cooling age (Ma) and avg. maximum modeled temperature for samples from each domain.

CHAPTER 5

Present-day *in situ* stress distribution in the Colville Basin, northern Alaska and implications for fracture development

By

A. Klek

Department of Geology and Geophysics, University of Alaska, Fairbanks, Alaska 99775

C. Hanks

Dept. of Petroleum Engineering and Geophysical Institute, University of Alaska,
Fairbanks, Alaska 99775; chanks@gi.alaska.edu

J. Payne

Department of Geology and Geophysics, University of Alaska, Fairbanks, Alaska 99775

Introduction

The orientation of open fractures within a basin is controlled by the minimum and maximum horizontal stresses (SHmin and SHmax respectively), along with the inherent strength of the rock. These fractures, if present, often have permeabilities that are orders of magnitude greater than that of the unfractured rock in which they form. An understanding of fracture location, orientation, and timing is therefore an invaluable tool for understanding (1) fluid migration pathways from the source rock to the reservoir rock, (2) the timing of that fluid migration, and (3) how best to utilize fractures during well production.

This chapter summarizes a study that explored the relationship between horizontal *in situ* stress (SHmin and SHmax), vertical stress (Sv) and open fractures in the Colville Basin (Fig. 5.1). The scope of this work includes (1) the regional mapping of SHmin and SHmax orientations based on borehole breakouts in wells in the Colville Basin, (2) determination of Sv from density logs, (3) and comparison of the length and number of breakouts with Sv to determine a potential ‘fracture window,’ and 4) backstripping of selected North Slope wells to identify when key source intervals entered this ‘fracture window.’

Geologic Setting

The North Slope is part of a continental fragment, the Arctic Alaska plate that extends from Northern Canada into northeastern Siberia. What is now the southern edge of this plate was part of a Paleozoic to early Mesozoic passive continental margin that was rifted from the North American plate and rotated to its current position during Jurassic-Cretaceous time (Bird, 1994). The passive margin sediments, known as the Ellesmerian Sequence are relatively thin (2 to 3 km) and unconformably overlie the Pre-Mississippian metamorphic rocks that constitute the basement (Howell et. al., 1990)

The Brooks Range formed as the result of a collision during Late Jurassic and Early Cretaceous time between the Arctic Alaska plate and an island arc to the south. During orogenesis, the Colville foredeep formed and filled with the relatively thick (7 to 10 km.) flysch known as the Brookian Sequence (Howell et. al., 1990). The Colville Basin is a late Mesozoic and Cenozoic Basin that spans the entire width of the North Slope of Alaska (Bird and Molenaar, 1992). It extends from the Brooks Range north to the Barrow Arch and from the Canadian Border west to a location beneath the Chukchi Sea.

Deformation of the Brooks Range consisted of two periods of orogenesis, one during Late Jurassic and Early Cretaceous time and another from Late Cretaceous into the Tertiary with the latter being primarily constrained to the northeastern portion of the fold-and-thrust belt. As a consequence, the Colville Basin has grown progressively wider through time, with the depocenter migrating from the west (Early Cretaceous) to the northeast (present day).

Measurement of *In Situ* Stress

In order to ascertain the current state of stress to which a body of rock is subjected, direct observations of stress indicators must be made *in situ*. In regions that have been explored for petroleum, several approaches procedures useful data for stress analysis. In this study, two such testing procedures were used: dipmeter log borehole breakout analysis and vertical stress calculation from density logs.

Borehole breakouts are well bore wall phenomena that occur when a circular hole is drilled into pressurized rock (Bell, 1990). The introduction of a free surface, in this case the borehole wall, reorients the stress field around that free surface, increases applied stress in some places, and decreases applied stress in others. These stress field changes result in the generation localized fracture sets that coalesce perpendicular to the maximum applied stress on the cross-sectional plane of the borehole. These intersecting fracture sets weaken the well bore wall which may then subsequently fail and spall off into the hole. This failure results in the borehole growing horizontally, resulting in an elliptical cross section that is elongated perpendicular to the direction of the maximum *in situ* horizontal stress, aka a borehole breakout.

The most common method of observing borehole breakouts involves the observation of unprocessed dipmeter log data. The sonde used to produce dipmeter logs consists of three or more equally spaced caliper arms with resistivity measurement tools on their ends, a gyroscopic compass, and a level to measure the sonde's vertical inclination. When a sonde is lowered into a hole, the tension of its suspending cable produces a torsion which causes it rotate in the hole. When the dipmeter tool reaches a well bore section that is not in gauge (i.e., that has 'broken out,') one set of caliper arms locks into the larger diameter of the broken out section of wall and arrests the rotation of the tool until that section has been passed.

From an unprocessed four arm dipmeter log, borehole breakouts can be picked and their azimuths and depths recorded. The log signature of a borehole breakout is reasonably

simple to recognize: one pair of calipers records the drilled diameter (in gauge hole) of the hole and the other will record a larger diameter (Figure 5.2). Furthermore, the azimuth will cease to change and will record one consistent value throughout the area of spalling.

Although in ideal circumstances borehole breakouts are easily picked from logs, there are other phenomena, the most common of which are washouts and key seats, with which they may be easily confused (Figure 5.3). Washouts occur when the bore wall material is literally washed away by either drilling fluid or escaping formation water. The resultant log records include well bore diameters from both caliper sets that are greater than that of the actual gauge hole. It is possible, however, that a washed out area may be broken out as well, but if these observations are to be used, extra care must be taken. For example, in young basins, poorly consolidated sediments (which are more easily washed out) are often closer to the surface where the rate of tool rotation is relatively slow compared to that at greater depths. It may therefore be difficult or impossible to tell if the tool has stopped rotating in the hole thereby indicating a breakout. It is also possible, at any washout at any depth, that the well bore diameter has exceeded the maximum measurable diameter of the tool. In that case, one or more of the caliper arms may not be in contact with the well bore thereby rendering the data useless.

Another log signature easily misinterpreted as a borehole breakout is a “key seat.” Key seats occur in wells that have deviated to the point that the drill pipe has cut into the well bore wall. The resultant log produced by a key seat will show one caliper set with a greater than in-gauge hole diameter, the other set with a less than in-gauge hole diameter, and a single azimuth over the length of the key seat. It is important, however to observe a suspected key seat relative to the logged sections surrounding it. For example, an in-gauge hole may appear to have a diameter less than that of the drill bit because of a build up of mud cake on the borehole wall.

Borehole breakouts provide a means to determine the orientations and relative magnitudes of stresses *in situ* but do not provide quantitative measurements of absolute stress (Bell, 1990; McLellan et al., 2005). Although it has been proposed that it may be possible to determine absolute stresses by comparing borehole breakout shape with mathematical models of borehole failure, horizontal stress is most often measured by performing a leakoff test on an uncased well. During the performance of a leakoff test, bore fluid pressure is increased to the point that hydraulic fractures are artificially generated in the rock surrounding the well bore. The pressure needed to fracture the rock in this fashion is a quantitative measure of the *in situ* stress. However, no leakoff tests were available or conducted during this study.

The magnitude of the vertical stress (S_v) is the pressure at a given depth exerted by the material overlying the material at that given depth. One method for determining S_v from bulk density logs entails plotting a best-fit function to a plot of bulk density vs. depth (e.g., McLellan, 2005; Zoback et al., 2003). Once that function is determined and defined mathematically, its integral is a function of pressure with respect to depth. An alternative method entails the numeric integration of pressures produced by discrete

increments of the rock column for which measurements of bulk density (ρ_b) are recorded in bulk density logs. This method precludes the computation of a best-fit function for data sets that frequently exceed 10,000 data points and reduces error by avoiding approximation.

For a given well, the magnitude of S_v is determined through analysis of neutron density logs. The digital well log files used in the study are in the Schlumberger .LAS file format which is a space-delimited table that can be opened using a spreadsheet program. In that program the pressure exerted over every increment of logged depth is calculated by:

$$dS_v = \rho * g * dd$$

where dS_v is the pressure exerted by a thickness of rock dd with a density ρ and g is the acceleration due to gravity. At a given depth, S_v is simply the sum of each overlying dS_v . Density log data is, unfortunately, often absent at shallow depths. To accommodate this fact, a plot is made of S_v vs. depth which will under most circumstances be approximately linear. Using the slope of a linear fit to this data and assuming that (1) there are no major near surface density fluctuations and (2) $S_v = 0$ at the surface, an equation relating depth and S_v is determined.

Wells used in the borehole breakout portion of this study are shown in Figure 5.4. Additional wells were used to calculate regional S_v gradients and are listed in Table 5.1. Well data for both the borehole breakout and S_v analysis were obtained through the Alaska Oil and Gas Conservation Commission in Anchorage, AK and via the world wide web from the USGS NPRA Legacy Data Archive.

Results

i) Horizontal Stresses

Borehole breakout orientation data are compiled into a table (Table 5.2) where the averages and standard deviations of breakout orientations are recorded along with Zoback (1992) well ratings for each well. The orientation of breakouts for each well is summarized in rose diagrams (Fig. 5.5) and with depth (Fig. 5.6). The majority of the wells surveyed in this study appear to display single mode breakout orientations; several (e.g., Kugrua #1, S. Meade #1, Walakpa #1 and Tulageak #1) display bimodal orientations.

Orientations of new and previously published borehole breakouts (Hanks et al., 1999) are compiled in Fig. 5.7. Assuming that SH_{max} is oriented perpendicular to the long direction of the borehole breakout, a regional stress field was hand fit to these data (Fig. 5.7).

ii) Vertical Stresses

For all the wells for which a neutron density log was available, a S_v vs. depth plot was generated (e.g., Fig. 5.8). Assuming that the vertical stress gradient remains consistent throughout unlogged depth sections and that $S_v=0$ at the surface for onshore wells, the y-intercept of the linear best fit function was set to zero. For all the wells used in this study, plots of S_v vs. depth approximated a linear function. Consequently, the S_v of individual wells can be compared simply by comparing the S_v gradient (Table 5.1).

Regional variations in the vertical stress gradient are depicted in Figure 5.9.

iii) Borehole breakouts vs. S_v

Several plots were generated in order to evaluate the relationship between S_v and the location of borehole breakout. For all of these plots, borehole breakout depth was converted to a vertical stress value using the previously calculated vertical stress gradient for that well.

The likelihood of breakout occurrence with respect to S_v is summarized in three plots. In Figure 5.10, stress values are divided into 5 MPa intervals and the number of breakouts in each interval is counted. This graph shows breakout peaks at MPa values of ~20-25, ~80 and ~120 MPa. A similar distribution of breakouts vs. S_v is illustrated on a plot of cumulative breakout count vs. S_v (Fig. 5.11).

Breakout length is one measure of the 'quality' of the breakout—longer breakouts are considered a better indicator of SH_{max} orientation than shorter breakouts (Zoback, 1992). Figure 5.12 summarizes the relationship between S_v and breakout length. Peaks in breakout length occur at 15 – 35 MPa, ~70 – 100 MPa and ~115 – 135 MPa

iv) Backstripping

Backstripping and decompaction of select wells established when major source rock intervals entered this interval of maximum breakouts. The two source rocks of interest were the Triassic Shublik Formation and the Cretaceous pebble shale unit.

'Subside!' (Hsui, 1989) was used to decompact and backstrip individual wells. Figure 5.13 shows the results for Inigok #1, located eastern NPRA. Figures 5.14-5.16 illustrate the progression of Shublik burial to the depth of maximum borehole breakouts—10,000 feet--and the orientations of SH_{max} at key times. The orientation of SH_{max} is assumed to be perpendicular to the orientation of the Brooks Range deformation front at that time, consistent with the present-day orientation of SH_{max} . Similarly, Figures 5.17 and 5.18 illustrate burial of the Cretaceous pebble shale unit to >10,000 ft at key times and the corresponding proposed orientation of SH_{max} .

Discussion

i) Regional Distribution of In Situ Horizontal Stresses

In general, maximum regional horizontal stress orientations in Northern Alaska are oriented perpendicular to the active deformation front of the Northeastern Brooks range with some perturbation along the boundaries of the Colville Basin (Fig. 5.7). There are, however, areas where stress orientations are shifted away from the normal to regional modern deformation front: near the deformation fronts of the west and central Brooks Range, over the Barrow Arch, and near the edge of continental shelf. These shifts may be the result of edge effects on the stress field of the basin or they may be caused by real applied stresses applied by other far field stress input.

ii) Sv and breakout distribution

There appear to be three ranges of Sv that are conducive to the formation of borehole breakouts with depth: a low range at ~20-25 MPa, an intermediate range at ~80 MPa, and a high range at ~120 MPa. Over these ranges both the breakout count and the length of breakouts are notably higher than in other vertical stress ranges (Figs. 5.10, 5.11 & 5.12). These values of MPa roughly correspond to depths of 750-1000 m (2500-3300 ft), 3300 m (10800 ft) and 4700 m (15400 ft) respectively.

There is however a notable degree of uncertainty involved in this type of analysis. When observing data from relatively deep wells with complete (or near complete) log coverage, breakouts appear to occur in greater numbers at greater depth. However, dipmeter logs are not run on all wells for all depths. Consequently, plots of breakout number and length vs. depth (Figs. 5.10, 5.11 & 5.12) are probably skewed because of preferential sampling of shallower depths, making it appear that a large percentage of breakouts occur at shallow depths.

In addition, while breakouts appear to be abundant at ~750-1000 m depth, they are not consistent in orientation (Fig. 5.6, E. Simpson #2, Tulageak#1, Walakpa #1 and Hanks et al, 1999). This suggests that the apparent breakout peak may be either a sampling bias and/or not a true reflection of in situ stresses.

iii) Implications for Set 1 fracture orientations

The earliest fractures observed in both transect areas (Eastern Transect, Ch. 3; Western Transect, Ch. 4) are interpreted to have formed at depth in the foreland basin in advance of the growing fold-and-thrust belt, under low differential pressures and high fluid pressures. In this interpretation, these fractures would have been oriented parallel to the current SHmax within the basin. Similar fractures would be forming at depth in the Colville basin today.

Borehole breakouts will be accentuated in zones that have fractures or other zones of weakness oriented perpendicular to the direction of breakout elongation. Peaks in the number and length of borehole breakouts at Sv's corresponding to depths greater than 3000 m (10,800 ft) suggest that there is an abundance of extension fractures oriented perpendicular to the active thrust front starting at these depths.

iv) Implications of backstripping

Backstripping and decompaction of selected northern NPRA wells illustrate that the location and extent of this 'fracture window' has varied significantly through time as the Colville basin evolved. Ellesmerian sequence rocks first entered the 'fracture' window' in a narrow linear belt in the southernmost parts of the northern Colville basin during middle Cretaceous time. Open fractures at this time would most likely have been oriented north-south. This zone of potential subsurface fracturing widened and extended to the north-northeast during the remainder of the Cretaceous. Overlying basal Brookian sediments did not enter the 'fracture window' in the northern parts of the basin until Late Cretaceous. However, in most parts of NPRA, the younger Brookian sediments (Nanushuk and Colville Groups) were never buried deeply enough to enter the 'fracture window.'

References

- Bell, J.S., 1990, Investigating stress regimes in sedimentary basins using information from oil industry wireline logs and drilling records, in Hurst, A. Lovell, M.A., and Morton, A.C., eds., Geological applications of wireline logs: Geological Society Special Publications, v. 48, p. 305–325.
- Bird, K. J. 1994, Ellesmerian(!) petroleum system, North Slope, Alaska, U.S.A. AAPG Memoir, vol.60, pp.339-358.
- Bird, K.J., and Molenaar, C.M., 1987, Stratigraphy: in Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 37–59.
- Hanks, C. L. , Parker, M., and Jameson, E., 2000, Regional stress patterns of the northeastern North Slope, Alaska: Alaska Division of Geological and Geophysical Surveys' Short Notes on Alaskan Geology, 1999, p. 33-44.
- Howell, D.G., Bird, K.J., Huafu, L., and Johnsson., M.J., 1992, Tectonics and Petroleum potential of the Brooks Range fold and thrust belt- a progress report, in Bradley, D.C., and Ford, A.B., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1990: U.S. Geological Survey Bulletin 1999, p. 112-126.
- Hsui, A.T. (1989): Subside. *Callidus Software*. Urbana, U.S.A.: 9 p.
- Lorenz, J.C., Teufel, L.W., and Warpinski, N.R., 1991, Regional fractures 1: A mechanism for the formation of regional fractures at depth in flay-lying reservoirs: American Association of Petroleum Geologists Bulletin, v. 75, no. 11, p. 1,714–1,737
- McLellan, P J; Gillen, K P; Podetz, C G Dallimore, S R; Inoue, T., Hancock, S H, 2005, In situ stresses in the Mallik area Bulletin of the Geological Survey of Canada, Report: 585, 15 pp., 2005
- Plumb, R.A., and Hickman, S.H., 1985, Stress-induced borehole elongation; a comparison between the four arm dipmeter and the borehole televiewer in the Auburn geothermal well: Journal of Geophysical Research, v. 90, B7, p. 5,513–5,521.
- USGS, NPRA Legacy Data Archive, <http://nerslweb.cr.usgs.gov/default.htm>.
- Wallace, W.K., Moore, T.M., and Plafker, G., 1997, Multistory duplexes with forward dipping roofs, north central Brooks Range, Alaska: Journal of Geophysical Research, v. 102, p. 20773-20796.

Zoback, M.L., 1992, First- and second-order patterns of stress in the lithosphere; The World Stress Map Project, in Zoback, M.L., leader, The World Stress Map Project: Journal of Geophysical Research, v. 97, no. B8, p. 11,703–11,728.

Zoback, M.D. Barton, C A; Brudy, M; Castillo, D A; Finkbeiner, T; Grollimund, B R; Moos, D B; Peska, P; Ward, C D; Wiprut, D J, 2003, Determination of stress orientation and magnitude in deep wells: International Journal of Rock Mechanics and Mining Sciences. 2003. Pp. 1049-1076

Figure 5.1. Tectonic map of northern Alaska, showing distribution of major structural features. Outlined area is focus of in situ stress study discussed in this chapter. Modified from Wallace et al., 1997.

Figure 5.2. Example of a borehole breakout.

Figure 5.3. Four common borehole geometries and their corresponding caliper separations. Modified from Plumb and Hickman (1985).

Figure 5.4. Map of northern Alaska showing major structural elements as well as NPR-A (green outlined area) and ANWR (purple outlined area). Wells used in the borehole breakout portion of this study include both published data (numbered wells) and wells analyzed as part of this study (lettered wells). Well names are listed in Table 2. The location of additional wells not posted on this map that were used during the Sv study are listed in Table 1.

Figure 5.5. Orientation of the long axes of the borehole in breakout intervals in NPRA wells examined during this study. Depth and orientation of individual breakouts are summarized in Table 2. The orientation of the maximum in situ horizontal stress (Shmax) is interpreted to be perpendicular to the long axis of the borehole breakout.

Figure 5.6. Results of borehole breakout analyses of selected NPRA wells. Summarized by well, depth and azimuth.

Figure 5.6 (cont). Results of borehole breakout analyses of selected NPRA wells. Summarized by well, depth and azimuth.

Figure 5.7. Map of northern Alaska showing orientation of long axis of borehole breakouts and interpretation of Sh_{max} orientation.

Figure 5.8. Graphs of S_v vs. depth for selected North Slope wells.

Figure 5.8 (cont). Graphs of S_v vs. depth for selected North Slope wells.

Figure 5.8 (cont). Graphs of S_v vs. depth for selected North Slope wells.

Figure 5.8 (cont). Graphs of S_v vs. depth for selected North Slope wells.

Figure 5.8 (cont). Graphs of S_v vs. depth for selected North Slope wells.

Figure 5.8 (cont). Graphs of S_v vs. depth for selected North Slope wells.

Figure 5.8 (cont). Graphs of S_v vs. depth for selected North Slope wells.

Figure 5.8 (cont). Graphs of S_v vs. depth for selected North Slope wells.

Figure 5.8 (cont). Graphs of S_v vs. depth for selected North Slope wells.

Figure 5.9. Map of northern Alaska showing regional variation in Sv gradient.

Figure 5.10. Number of breakouts vs. Sv

Fig 5.11. Cumulative distribution of number of breakouts vs. S_v . In this type of plot, line sections with a high relative slope indicate relatively high rates of breakout formation and vice versa.

Figure 5.12. Distribution of breakout length vs. Sv

Inigok #1

Figure 5.13. Decompression and backstripping of Inigok #1. Location of fracture window is based on depth of observed maximum in borehole breakout density and length in present-day Colville basin.

Figure 5.14. Depth to top of Shublik during Lower Cretaceous time, based on decompaction and backstripping of selected NPRA wells. The Shublik is not buried below 10,000 feet in this area at this time and so has not entered the fracture window.

Figure 5.15. Depth to top of Shublik during Lower Cretaceous (Torok) time, based on decompaction and backstripping of selected NPRA wells. Yellow region indicates where Shublik is buried below 10,000 feet and has entered the fracture window. Blue arrows represent postulated trajectory of Shmax at this time.

Figure 5.16. Depth to top of Shublik during Tertiary time, based on decompaction and backstripping of selected NPR wells. Yellow region indicates where Shublik is buried below 10,000 feet and has entered the fracture window. Blue arrows represent postulated trajectory of Shmax at this time.

Figure 5.17. Depth to top of Pebble shale during Lower Cretaceous (Torok) time, based on decompaction and backstripping of selected NPRA wells. Yellow region indicates where Pebble shale is buried below 10,000 feet and has entered the fracture window. Blue arrows represent postulated trajectory of Shmax at this time.

Figure 5.18. Depth to top of Pebble shale during Tertiary time, based on decompaction and backstripping of selected NPRA wells. Yellow region indicates where Pebble shale is buried below 10,000 feet and has entered the fracture window. Blue arrows represent postulated trajectory of Shmax at this time.

name	lat	long	slope Sv
Atigaru Point #1	70.556	-151.717	0.0258
Awuna Test Well 1	69.153	-158.023	0.0251
Cape Halket #1	70.767	-152.467	0.0252
Drew Point #1	70.880	-153.900	0.0241
E Teshekpuk #1	70.570	-152.944	0.0252
E. Simpson Test Well #1	70.918	-154.618	0.024
East Simpson #2	70.978	-154.674	0.0241
franklin bluffs unit 1	69.719	-148.697	0.0219
Iko Bay #1	71.171	-156.168	0.024
Ikpikpuk Test Well #1	70.455	-154.331	0.0231
Inigok Test Well #1	70.005	-153.099	0.0232
J W Dalton	70.920	-153.138	0.0245
Koluktak #1	69.752	-154.611	0.0245
Kugrua Test Well #1	70.587	-158.662	0.0235
Kuyanuk Test 1	70.932	-156.065	0.0229
Lisburne Test Well #1	68.479	-155.693	0.0247
N Inigok #1	70.258	-152.766	0.0234
N Kalikpik #1	70.509	-152.368	0.024
Northstar 1	70.528	-148.856	0.0225
NW eileen st 2	70.365	-149.359	0.0206
OCS Y-0180	70.492	-148.693	0.0222
OCS Y-0181	70.492	-148.693	0.0247
PBU 1-2	70.242	-148.395	0.0226
PBU 1-4	70.241	-148.395	0.0228
PBU 2-1 23-25-11-14	70.270	-148.476	0.0231
PBU 3-6	70.232	-148.272	0.0228
PBU 4-1	70.268	-148.281	0.023
PBU 7-4	70.267	-148.576	0.024
PBU 9-7	70.248	-148.236	0.0237
PBU A-1	70.265	-148.751	0.0239
PBU B-3A	70.270	-148.673	0.0218
PBU D-1	70.295	-148.752	0.0229
PBU F1 23-02-11-13	70.335	-148.767	0.0235
PBU G-3 12-11-13	70.323	-148.717	0.023
Peard Test Well #1	70.716	-155.001	0.0243
S Barrow 13	71.254	-156.628	0.0242
S Barrow 14	71.233	-156.303	0.0243
S Barrow 16	71.282	-156.546	0.0239
S Barrow 18	71.240	-156.311	0.0242
S Barrow 20	71.233	-156.336	0.0247
S Barrow 9	71.268	-156.609	0.0245
S Simpson Test Well #1	70.807	-154.982	0.0246
S. Meade #1	70.615	-156.890	0.0236
Seabee #1	69.380	-152.175	0.0247
Seal island 1	70.492	-148.693	0.0253
Shaviovik unit 1	69.542	-147.516	0.0243
Term well A	70.355	-148.593	0.0228
Tulageak Test Well #1	71.189	-155.734	0.0244
Tunalik Test Well #1	70.206	-161.069	0.0246
TW 24-11-14	70.297	-148.449	0.0221
W Channel no 1-3	70.162	-148.317	0.022
W Dease #1	71.159	-155.629	0.0246
W Fish Creek 1	70.327	-152.061	0.0255
W Kuparuk st 3-11-11	70.335	-149.307	0.0229
W T Foran	70.832	-152.303	0.0239
Walakpa Test Well #1	71.099	-156.884	0.0244
Walakpa Test Well #2	71.050	-156.953	0.0236
WT Foran	70.832	-152.303	0.0246

Table 5.1. Sv gradients by well.

#	name	lat (°)	lon (°)	Av. breakout azim (°)
1	Brontosaurus	70.91	157.25	2
2	Ocs 0267 (Fireweed 1)	71.09	152.60	7
3	Big Band 1	69.16	152.27	31
4	W Sak 25590 15	70.25	150.15	63
5	Kou W Sak 26	70.15	149.52	62.5
6	Highland State	70.29	149.22	153
7	Beechy Pt 1	70.38	149.14	173
8	SE Eileen St. 1	70.26	149.02	153
9	Nora Federal 1	69.55	148.75	133
10	Pu't River St 1	70.24	148.68	151
11	PB Unit Term A	70.35	148.59	336
12	Gull Island St 1	70.37	148.36	186
13	E Bay St. 1	70.31	148.32	41.7
14	Lake St 1	70.21	148.21	42
15	Sag Delta 31-10-16	70.18	148.16	134
16	Kadler 15-9-16	70.13	148.04	146
17	Delta St 1	70.24	148.03	173
18	Delta St 2	70.26	148.01	320
19	Karluk 1	70.32	147.51	78.7
20	W Mikkelsen St 1	70.18	147.38	111
21	Gyr 1	69.66	147.28	191
22	W Mikkelsen Unit 2	70.22	147.19	182.5
23	W Kavik 1	69.77	147.19	152
24	Kavik Unit 2	69.63	146.66	313
25	Kavik 1	69.63	146.57	73
26	E De K Leffingwell 1	70.02	146.52	177
27	Canning River Unit B 1	69.66	146.28	117
28	Alaska St A 1	70.19	146.01	69
29	Ocs 094/3(Aurora) 1	70.11	142.78	181
30	Ocs 0917(Belcher)1	70.28	141.51	83
A	Tunalik	70.21	161.07	228
B	Kugrua 1	70.59	158.66	237
C	Awuna Test Well No. 1	69.15	158.02	174
D	Walakpa Test Well No. 2	71.05	156.95	242
E	S Meade 1	70.61	156.89	203
F	Walakpa Test Well No. 1	71.10	156.88	215
G	Kuyanuk 1	70.93	156.06	339
H	Tulageak 1	71.19	155.73	258
I	Lisburne 1	68.48	155.69	230
J	W Dease 1	71.16	155.63	47
K	Peard 1	70.72	155.00	55
L	E Simpson 1	70.92	154.62	208
M	Koluktak 1	69.75	154.61	234
N	Ikpiukuk Test Well No. 1	70.46	154.33	48
O	Inigok 1	70.00	153.10	226

Note : Numbered wells from Hanks et al. 1999. Lettered wells, this study

Company	Name	API	Azimuth (°)	Std Dev (°)	# Breakouts	BO length fm.	Zoback class
Husky	Awuna Test Well 1	50-155-20001	135.1	14.4	3	79.6	C
Husky	E. Simpson Test Well #1	50-279-20007	111.4	65.8	13	352.3	A
Husky	Ikpiukuk Test Well #1	50-279-20004	63.2	36.7	14	496.5	A
Husky	Inigok Test Well #1	50-279-20003	100.8	53.6	8	155.1	B
USGS	Koluktak #1	50-119-2001	58.2	17.1	5	76.5	C
Husky	Kugrua Test Well #1	50-133-20002	85.1	42.3	13	214.6	B
Husky	Lisburne Test Well #1	50-137-20003	125.2	37.6	20	432.8	A
USGS	Peard Test Well #1	50-301-2002	61.4	9.9	4	65.2	C
Husky	S. Meade #1	50-163-20001	121.0	70.8	4	53.9	C
Husky	Tulageak Test Well #1	50-209-20018	118.5	54.7	8	177.4	B
Husky	Tunalik Test Well #1	50-301-20001	86.9	61.7	6	132.9	B
Husky	W Dease #1	50-023-20014	47.2	7.2	7	120.1	B
Husky	Walakpa Test Well #1	50-023-20013	99.2	48.7	9	112.5	B
USGS	Walakpa Test Well #2	50-023-20019	66.2	23.7	15	475.5	A

Table 5.2. Wells used in this study with number of breakouts, average breakout orientation and Zoback classification (this study only). Numbered wells are from Hanks et al., 2000; lettered wells are from this study.

CHAPTER 6

Integration and Conclusions

By

Catherine L. Hanks

Dept. of Petroleum Engineering and Geophysical Institute, University of Alaska
Fairbanks, Alaska 99775 chanks@gi.alaska.edu

Introduction

The goal of this study was to develop a model of the evolution of fractures in northern Alaska, both spatially and temporally. In this chapter, several different types of data and observations (both generated by this study and previously published) are combined to arrive at an internally consistent model. These data include:

- regional observations on structural style and timing of deformation (Ch. 2)
- detailed observations on the fracture distribution with respect to location, structural style and stratigraphy (Ch. 3 & 4)
- thermal and geochronologic data (Ch. 3 & 4)
- subsurface in situ stress distribution (Ch. 6)

Key observations

- Two surface-to -subsurface transects document the two main structural styles of the Brooks Range range front—a complex frontal duplex/triangle zone in the west and a simpler passive roof duplex in the east.
- Despite the difference in structural style of the two transects, both transects had the same four main fracture sets:
 - an early filled fracture set related to regional stresses prior to folding and thrusting;
 - a later, filled fracture set that formed during thrusting;
 - two younger, unfilled fracture sets that are related to late folding and/or uplift and unroofing.
- In both transects, all four fracture sets only occur in the oldest rocks. Older, filled fracture sets are restricted to Triassic and older rocks Ellesmerian sequence rocks; for the most part, Brookian Jurassic and younger rocks filling the Colville basin exhibit only unfilled fractures related to late folding and/or uplift. This suggests that filled fractures develop at depth, in the presence of fluids and higher pressures.
- Apatite fission track ages suggest that deformation and uplift have been episodic during the late Cretaceous and early Tertiary, with different parts of each transect active at any one time. These deformation events are summarized as follows:

- Early Neocomian (Valanginian 144-119 mybp) emplacement of Endicott Mountains allochthon
 - Albian (118-98 mybp) deposition of the basal sediments in the Colville basin (Fortress Mountain/Torok Fm)
 - Latest Cretaceous/Paleocene (97-60 mybp) development of breaching thrusts and formation of Tuktu Escarpment (triangle zone) in the central Brooks Range
 - Eocene and younger (<60 mybp) formation of northeastern Brooks Range fold-and-thrust belt.
- Thermal data from fracture fill implies that the early fractures that formed in the foreland basin prior to incorporation in the Brooks Range fold-and-thrust belt initially formed at temperatures in or exceeding the oil generation window, but were subsequently overprinted by higher temperature structures. This implies that these fractures might have been good migration pathways at one time, but were destroyed by later deformation and would not be good exploration targets. However, fractures that have formed under similar conditions in the Colville basin but have not yet been subject to fold-and-thrust deformation could still act as migration pathways.
 - These early fractures are interpreted to have formed in the basin, parallel to the maximum in situ stress and perpendicular to the active thrust front. Fractures of similar origin and orientation are probably forming today in response to the in situ stress regime. Borehole breakout analysis of wells in the Colville basin indicate that present-day maximum horizontal in situ stress within the Colville basin is oriented NNW. The highest number and greatest length of breakouts occur at $S_v > 80$ Mpa, which corresponds to a depth of ~10,000 feet. This is interpreted as the top of the zone of active fracturing or the ‘fracture window.’
 - Backstripping and decompaction of stratigraphy from boreholes on the northern margin of the Colville basin suggest that the basal Ellesmerian sequence rocks (Endicott and Lisburne Groups) first entered the ‘fracture window’ in Late Jurassic to Early Cretaceous time. Fractures formed at this time would have been oriented NS, perpendicular to the active Brooks Range thrust front. Brookian sequence rocks did not enter the ‘fracture window’ in the northern Colville basin until significantly later, in Tertiary time.

Integration into a regional model

These key observations and interpretations can be integrated into a regional model of how the different fracture sets evolved in concert with the evolution of the Brooks Range/Colville basin system.

This model assumes that the basic sequence of fracturing events as shown in Figure 6.1 is correct throughout the system, but the absolute age of each event at any location is determined by depth of burial, proximity to the range front and/or involvement in fold-and-thrust deformation. Because well data is lacking in most of the southern part of the Colville basin, published distribution and thickness of Brookian sediments was used to constrain depth of the basin at any one time (Figure 6.2, Moore and others, 1994). The resulting paleogeographic reconstructions show the evolution of the fracture sets 1, 2 and 3 through time (Figures 6.3-6.6).

Late Jurassic/Early Cretaceous time

Collision of an intraoceanic arc with the south-facing passive continental margin of Arctic Alaska led to detachment and hundreds of kilometers of northward displacement of both oceanic and continental-margin rocks. The Endicott Mountains allochthon that forms the southern portion of the central Brooks Range transect. Despite the large magnitude of shortening, little sub-aerial topography formed and the Colville basin began as a deep-water foreland basin (e.g., Mayfield and others, 1988; Bird and Molenaar, 1992; Moore and others, 1994), with thin sediment accumulation.

Because of this thin sediment accumulation, the underlying passive margin sediments of the Ellesmerian sequence did not experience significant burial, except in those areas immediately adjacent to the range front, where there was significantly structural loading. Set 1 fractures in Ellesmerian sequence rocks would have been areally restricted to a thin zone immediately ahead of or underlying the thrust front. Set 2 fractures would have developed in those Ellesmerian sequence rocks that were incorporated in the fold-and-thrust belt.

Early Cretaceous (Aptian-Albian) time

By the end of Early Cretaceous time, emergence of the Brooks Range as a significant topographic feature had resulted in increased sediment accumulation in the Colville basin. The basin filled from the southwest, with sediment thicknesses in excess of 6 km in this area (Figure 6.4 A).

Due to this sediment thickness, the Ellesmerian sequence rocks were buried to depths in excess of 3 km in much of the central and western parts of the Colville basin. This would have provided excellent conditions for the development of Set 1 fractures in the Ellesmerian sequence north of the actual thrust front (Figure 6.4 B). These extension fractures would have been oriented parallel to the in situ maximum stress direction, which would have been NS-oriented, perpendicular to the thrust front. Set 2 fractures in the Ellesmerian sequence rocks would have been restricted to those pre-Jurassic rocks actually involved in the thrusting.

A much smaller portion of the Cretaceous Colville basin sedimentary fill would have been buried in excess of 3 km and thus be within the 'fracture window' (Figure 6.4 C). The zone of Cretaceous rocks lying within the 'fracture window' would have been in the southwest corner of the Colville basin. Set 1 fractures in this part of the basin would have also been NS-oriented extension fractures perpendicular to the Brooks Range range front. Little deformation had progressed into the basin itself, however, so there was little to no Set 2 fracture development in the Cretaceous sediments.

Late Cretaceous/Paleocene time

Renewed deformation in the central Brooks Range and the early phases of uplift in the northeastern Brooks Range resulted in migration of the Colville basin depocenter to the east. Incorporation of Colville basin sediments into the fold-and-thrust belt occurred in the south of the basin, near the range front.

As the Colville basin sediments thickened to the east, more of the underlying Ellesmerian passive margin sedimentary rocks were buried to depths >3 km (Figure 6.5 B). Set 1 fractures developed north and east of the Set 1 fractures that developed during Aptian-Albian time. These fractures would have been ~NS striking, perpendicular to the active range front. Active dewatering of the host sediments resulted in the fractures filling with cement. To the south, Set 2 filled fractures would have continued to form in Ellesmerian rocks deep in the orogenic wedge; Ellesmerian rocks in the upper portion of the wedge would have experienced fold-related fracturing that was relatively dry (Set 3).

The areal extent of Cretaceous sediments that were buried in excess of 3 km grew northward and eastward due to the increase in Colville sediment fill (Figure 6.5 C). Set 1 fractures in Cretaceous sediments would have continued to form perpendicular to the thrust front. Set 2 filled fold-related fractures would have developed in those Colville basin sediments incorporated into the tip of the orogenic wedge/triangle zone where the sediments were deep enough to be actively dewatering. Cretaceous rocks that were too shallow to be experiencing significant dewatering but were being deformed at the leading edge of the fold-and-thrust belt would have developed Set 3 unfilled fold-related fractures. Note that the presence of both Set 1 and Set 2 fractures that developed at this time within the Colville basin sediments would have been constrained by depth of overburden.

Tertiary (Eocene and younger) time

Most deformation and uplift in the central Brooks Range had ceased by this time, but the northeastern Brooks Range continued to grow northward onto the eastern end of the Barrow Arch. Deposition in the Colville basin centered on the northeastern corner, immediately north of the northeastern Brooks Range (Figure 6.6 A).

With final filling of the eastern Colville basin and structurally loading, the Ellesmerian sequence forming the basement of the foreland basin north of the northeastern Brooks Range finally reached depths >3 km and entered the 'fracture window' (Figure 6.6 B). The arcuate shape of the northeastern Brooks Range range front would result in the orientation of Set 1 fractures changing from NS striking in the east to NW striking in the west. Ellesmerian sequence rocks involved in the fold-and-thrust deformation would have experienced fold-related fracturing, both filled (Set 2) and later unfilled (Set 3).

Similarly, basal Brookian sequence rocks in the eastern Colville basin entered the fracture window as they were buried to depths >3 km (Figure 6.6 C), but the areal extent of Set 1 fracture development is much less than that for the Ellesmerian sequence. Closer to the range front, Brookian sedimentary rocks incorporated into the fold-and-thrust belt would have developed Set 2 filled and/or Set 3 unfilled fractures.

Implications for hydrocarbon migration and reservoir enhancement

Set 1 extension fractures that formed at depth in the basin during dewatering and/or hydrocarbon maturation would have been ideal conduits for large-scale lateral transport of hydrocarbons from the southern Colville basin to reservoirs and traps on the Barrow Arch. These fractures formed diachronously across the basin, with the earliest fractures forming in the west in Early Cretaceous time. Set 1 fracture developed would have moved north and east as the Colville basin filled from the west.

During most of the history of the Brooks Range/Colville basin system, these Set 1 extension fractures would have been oriented NS, perpendicular to the active deformation front. Hydrocarbon accumulations that resulted from these migration pathways would be expected to occur along this orientation. However, the orientation of SHmax changed to a NNW orientation in Tertiary time with the growth of the northeastern Brooks Range, resulting in a change in the projected orientation of actively forming Set 1 extension fractures. Consequently hydrocarbon accumulations that developed at this time along the Barrow Arch might be expected to have a source in the southeast instead of the south.

Set 1 fractures would not have served as effective conduits for structural traps related to fold-and-thrust belt deformation because these fractures would have predated trap formation. However, Set 2 fractures related to folding and thrusting could have served as vertical migration conduits for overlying structural traps. This could have been an effective migration mechanism for sources and traps in deformed parts of the Colville basin.

Fracture Sets 1, 2 and Set 3 all could have enhanced the permeability of existing reservoirs. In the case of Set 1 fractures, these reservoirs would have to be in the relatively undeformed rocks in advance of the Brooks Range fold-and-thrust belt. This could be the origin of some fractured reservoirs on the southern flank of the Barrow Arch. The only such reservoir identified to date is the Lisburne field (e.g., Hanks and others, 1997), but other potential fractured reservoirs may exist in the Ellesmerian and basal Brookian sequences.

Fracture Sets 2 and 3 would impact reservoirs involved in fold-and-thrust related traps. If migration occurred prior to cementation, these fractures could enhance reservoir permeability; if migration occurred after cementation, these fractures could serve as reservoir baffles or barriers to flow.

Conclusions

Fractures formed episodically throughout the evolution of northern Alaska, due to a variety of mechanisms. The earliest fractures formed in deep parts of the Colville basin and in the underlying Ellesmerian sequence rocks as these rocks experienced compression associated with the growing Brooks Range fold-and-thrust belt. Subsequent incorporation of these sediments into the fold-and-thrust belt resulted in overprinting of these early fractures by fractures caused by thrusting and related folding. The youngest fractures developed as rocks were uplifted and exposed.

While this general order of fracturing remains consistent across the Brooks Range and adjacent Colville basin, the absolute age at any one location varies. Fracturing started in the southwest during the Late Jurassic and Early Cretaceous, moving northeastward as the Colville basin filled from the west. Active fracturing is occurring today in the northeastern parts of the Colville basin, north of the northeastern Brooks thrust front.

In all locations, the early deep basin fractures were probably synchronous with hydrocarbon generation. Initially, these early fractures would have been good migration pathways. The orientation of these fractures was controlled by the maximum in-situ horizontal stresses in the basin at the time of their formation, which was perpendicular to the active Brooks Range thrust front. This orientation stayed consistently NS-striking for most of the early history of the Brooks Range and Colville basin, but changed to NW-striking with the development of the northeastern Brooks Range during the early Tertiary.

These early deep basin fractures would have been destroyed where subsequently overridden by the advancing Brooks Range fold-and-thrust belt. However, at these locations younger fracture sets related to folding and thrusting could have served as vertical migration pathways to overlying structural traps and/or enhanced reservoir permeability.

References

- Bird, K.J., and Molenaar, C.M., 1992, The North Slope foreland basin, *in* Macqueen, R.W., and Leckie, D.A., eds., Foreland basins and foldbelts: American Association of Petroleum Geologists Memoir 55, p. 363-393.
- Hanks, C. L., Lorenz, J., Teufel, L., and Krumhardt, A.P. 1997, Lithologic and structural controls on natural fracture distribution within the Lisburne Group, northeastern Brooks Range and North Slope subsurface, Alaska: American Association of Petroleum Geologists Bulletin, vol. 81, no. 10, p. 1700-1720.
- Hanks, C. L., Parris, T. and Wallace, W.K., 2006, Fracture paragenesis & microthermometry in Lisburne Group detachment folds: implications for the thermal and structural evolution of the northeastern Brooks Range, Alaska: AAPG Bulletin, vol. 90, no. 1, p. 1-20.
- Mayfield, C.F., Tailleux, I.L., and Ellersieck, I., 1988, Stratigraphy, structure, and palinspastic synthesis of the western Brooks Range, northwestern Alaska, *in* Gryc, G., ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 143-186.
- Moore, T.E., Wallace, W.K., Bird, K.J., Karl, S.M., Mull, C.G., and Dillon, J.T., 1994, Chapter 3: Geology of northern Alaska, *in* Plafker, G., and Berg, H.C., eds., The geology of Alaska: Geological Society of America, Boulder, Colorado, The Geology of North America, v. G1, p. 49-140.

Figure 6.1. Time-Temperature-Depth chart showing tectonic environments of fracture formation and possible burial and uplift paths of the Lisburne Group and Permian to Triassic Echooka Formation in the northeastern Brooks Range (curves i, ii and iii). Schematic cross sections A-E illustrate the proposed structural conditions during the development of different fracture sets, with fracturing occurring at the ☆. See Hanks et al, 2006 for complete discussion.

Figure 6.2. Observed preserved thickness of Colville basin fill by age. Thick red lines: Early Cretaceous (Aptian to Albian); Green lines: Late Cretaceous to Eocene; thin, dashed red lines: post Eocene. Thicknesses in km. Modified from Moore and others, 1994.

Figure 6.3. Fracture development during Late Jurassic/Early Cretaceous time

Figure 6.4. Fracture development during Early Cretaceous time

A. Early Cretaceous (Aptian-Albian) sediment thickness (in km) in the Colville basin (from Moore and others, 1994).

B. Fractures forming in the Ellesmerian sequence rocks. Arrows represent postulated Sh max at this time.

C. Fractures forming in the Brookian sequence rocks. Arrows represent postulated Sh max at this time.

In Ellesmerian and older rocks:

In Brookian sed:

- In Ellesmerian and older rocks:**
- S1 Frax: filled, orogen normal basin fractures
 - S2 frax: filled, fold-related
 - S3 frax: unfilled, fold-related
- In Brookian sediments:**
- S1 Frax: filled, orogen normal basin fractures
 - S2 frax: filled, fold-related
 - S3 frax: unfilled, fold-related

Figure 6.5. Fracture development during Late Cretaceous/Paleocene time

- A. Late Cretaceous sediment thickness (in km) in the Colville basin (from Moore and others, 1994).
- B. Fractures forming in the Ellesmerian sequence rocks. Arrows represent postulated Sh max at this time.
- C. Fractures forming in the Brookian sequence rocks. Arrows represent postulated Sh max at this time.

Figure 6.6. Fracture development during Tertiary time

A. Tertiary sediment thickness (in km) in the Colville basin (from Moore and others, 1994).

B. Fractures forming in the Ellesmerian sequence rocks. Arrows represent modern Sh max.

C. Fractures forming in the Brookian sequence rocks. Arrows represent modern Sh max.

BIBLIOGRAPHY

The following publications were produced during the contract period. The work covered in these publications was funded in full or in part by this contract.

- Brown, P.J. II, Saltus, R.W., Peapples, P.R., Swenson, R.F., Duncan, A.S., and Wallace, W.K., 2006, Reduction procedures and implications of a high-resolution gravity traverse in the Brooks Range foothills, Alaska: Geological Society of America Abstracts with Programs, v. 38, no. 5, p. 83.
- Duncan, Alec S., 2007, Evolution of fractures and Tertiary fold-and-thrust deformation in the central Brooks Range foothills: M.S. thesis, University of Alaska Fairbanks, 159 pp.
- Duncan, Alec S., Hanks, Catherine L., Wallace, Wesley K., O'Sullivan, Paul B., and Parris, Thomas M, 2005, Evolution and timing of fractures and related map-scale structures of the central Brooks Range fold-and-thrust belt, northern Alaska: 2005 Geological Society of America Abstracts with Programs, vol. 37, no. 7., p. 210.
- Duncan, Alec S., Hanks, Catherine L., Wallace, Wesley K., O'Sullivan, Paul B., and Parris, T.M., 2006, Evolution and timing of fractures and related map-scale structures of the central Brooks Range fold-and-thrust belt, northern Alaska: GSA/AAPG/SPE joint Cordilleran Section meeting, Geological Society of America Abstracts with Programs, Vol. 38, No. 5, p. 89.
- Hanks, C. L. , Parris, T. and Wallace, W.K., 2006, Fracture paragenesis & microthermometry in Lisburne Group detachment folds: implications for the thermal and structural evolution of the northeastern Brooks Range, Alaska: AAPG Bulletin, vol. 90, no. 1, p. 1-20.
- Kleck, Alfred and Hanks, Catherine, 2006, In situ stress and fractures in the Colville basin, Alaska: GSA/AAPG/SPE joint Cordilleran Section meeting, Geological Society of America Abstracts with Programs, Vol. 38, No. 5, p. 86.
- O'Sullivan, P.B., Moore, T.E., Wallace, W.K., and Potter, C.J., 2006, Timing of Brooks Range and North Slope uplift and denudation: A summary of the fission-track results: Geological Society of America Abstracts with Programs, v. 38, no. 5, p. 24.
- Payne, J., Hanks, C., Kleck, A., Duncan, A., O'Sullivan, P., and Parris, M., 2008, Present Day Fracture and in Situ Stress Distribution in the National Petroleum Reserve of Alaska (NPR): implications for the evolution of a 'fracture window' through time: 2008 AAPG National Meeting, San Antonio.

- Peapples, P.R., Wallace, W.K., Finzel, E.S., and Mull, C.G., 2006, New detailed (1:63,360-scale) mapping of the Brooks Range northern foothills, Siksikpuk River area, central Brooks Range, Alaska: American Association of Petroleum Geologists Annual Convention, Official Program, v. 15.
- Peapples, P.R., Swenson, R., Wartes, M.A., Wallace, W.K., Finzel, E.S., Mull, C.G., Decker, P., Dumoulin, J.A., Reifenhuth, R., and Harris, E.E., 2006, New detailed (1:63,360-scale) mapping of the Brooks Range northern foothills, Siksikpuk River area, central Brooks Range, Alaska: Geological Society of America Abstracts with Programs, v. 38, no. 5, p. 83.
- Peapples, P.R., Wallace, W.K., Wartes, M.A., Swenson, R.F., Mull, C.G., Dumoulin, J.A., Harris, E.E., Finzel, E.S., Reifenhuth, R.R., and Loveland, A.M., 2007, Geologic map of the Siksikpuk River area, Chandler Lake Quadrangle, Alaska: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2007-1, 1 sheet, 1:63,360.
- Strauch, Andrea L., Hanks, Catherine L., Wallace, Wesley K., O'Sullivan, Paul B., and Parris, Thomas M., 2005, Fracture evolution in a fold-and-thrust belt and the associated deformed foreland basin: an example from the northeastern Brooks Range and Colville basin, Alaska: 2005 Geological Society of America Abstracts with Programs, vol. 37, no. 7., p. 79.
- Strauch, Andrea L., Hanks, Catherine L., Wallace, Wesley K., O'Sullivan, Paul B., and Parris, Thomas M., 2006, Constraints on fracture evolution in the northeastern Brooks Range fold-and-thrust belt and Colville basin, Alaska: GSA/AAPG/SPE joint Cordilleran Section meeting, Geological Society of America Abstracts with Programs, Vol. 38, No. 5, p. 84.
- Wallace, W.K., Duncan, A.S., Peapples, P.R., Swenson, R.F., Wartes, M.A., O'Sullivan, P.B., and Finzel, E.S., 2006, Geometry and evolution of the frontal part of an orogenic wedge, central Brooks Range foothills, Alaska: Geological Society of America Abstracts with Programs, v. 38, no. 5, p. 24.

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

One West Third Street, Suite 1400
Tulsa, OK 74103-3519

1450 Queen Avenue SW
Albany, OR 97321-2198

539 Duckering Bldg./UAF Campus
P.O. Box 750172
Fairbanks, AK 99775-0172

Visit the NETL website at:
www.netl.doe.gov

Customer Service:
1-800-553-7681