AN INTEGRATED MODEL FOR THE TECTONIC DEVELOPMENT OF THE NORTH-CENTRAL BROOKS RANGE AND COLVILLE BASIN, NORTHERN ALASKA

A THESIS
SUBMITTED TO THE DEPARTMENT
OF GEOLOGY AND ENVIRONMENTAL SCIENCES
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

BY
FRANCES COLE
MARCH 1998

AN INTEGRATED MODEL FOR THE TECTONIC DEVELOPMENT OF THE NORTH-CENTRAL BROOKS RANGE AND COLVILLE BASIN, NORTHERN ALASKA

A THESIS
SUBMITTED TO THE DEPARTMENT
OF GEOLOGY AND ENVIRONMENTAL SCIENCES
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

BY
FRANCES COLE
MARCH 1998

Approved for the Department:

Adviser

Second Reader

ACKNOWLEDGMENTS

This research was supported by funding from the U.S. Geological Survey, and by generous intellectual support from Ken Bird and David Howell. Ken Bird, Jaime Toro, Gil Mull, and Bill Brosgé provided many helpful suggestions that led to improvements in the manuscript. Paul O'Sullivan provided apatite fission-track data, analyses, and interpretations. François Roure, William Sassi, and Noelle Shoellkopf provided access to Thrustpack, the software that was used for the kinematic modelling.

TABLE OF CONTENTS

LIST OF TABLES

Table

LIST OF ILLUSTRATIONS

Figure

Plate

ABSTRACT

I constructed a kinematic model for the sequence of deformation and sedimentation in the frontal Brooks Range and adjacent Colville Basin in northern Alaska. The model is based on a tectonic subsidence analysis of the foreland basin, combined with structural, stratigraphic, and thermal studies of the northern edge of the Brooks Range thrust belt. I interpret six discrete tectonic events that led to the present-day configuration of the thrust belt in this area: (1) emplacement of ophiolitic allochthons over the distal continental margin rocks in Valanginian time, hundreds of kilometers south of this study, (2) Hauterivian uplift of the Barrow Arch rift margin, affecting the northern part of the Colville Basin, (3) Barremian contraction involving emplacement of distal continental margin and ophiolitic allochthons onto the Endicott Mountains allochthon and creation of a southward dipping flexural basin on the North Slope autochthon, (4) mid-Cretaceous exhumation of imbricated rocks in the Brooks Range during northward propagation of the thrust front into the foreland, (5) minor thrusting in Late Cretaceous-Paleocene in the northern foreland to the northern limit of contractional structures, and (6) regional exhumation of the orogen and the foreland in Paleocene-Eocene time. This sequence of deformation agrees well with a simple model of a forward propagating thrust system.

INTRODUCTION

The Brooks Range orogen and Colville Basin, in Alaska, are a prime example of an orogen and foreland basin linked by their geodynamic history. Rocks preserved in the basin record flexural subsidence and rapid clastic sedimentation that resulted from tectonic thickening and widespread exhumation in the orogen. Structures exposed in the fold and thrust belt reveal the geometric style of deformation, and where these structures interact with synorogenic deposits, the age of thrusting can be inferred. The timing and nature of deformation in the Brooks Range are critical to unraveling the plate tectonic evolution of Arctic Alaska, and the relative timing between individual thrusting episodes and sedimentary basin development is fundamental to understanding the region's oil and gas potential.

In this thesis, I present an integrated kinematic model for the sequential development of the thrust belt in the north central Brooks Range. The model combines a tectonic subsidence analysis of the foreland basin, with structural, stratigraphic, and thermal analyses in the thrust belt. I begin with a one-dimensional backstripping model in the foreland basin and use this to infer episodes of tectonic loading and uplift in the orogen. I follow this with a discussion of the geometric development of the fold and thrust belt, in the context of a balanced cross section, utilizing detailed vitrinite reflectance and apatite fission track data to track the timing and magnitude of tectonic and sedimentary burial and uplift. The kinematic model begins with a palinspastic restoration of the thrust belt and proceeds through successive stages of thrusting, subsidence, and sedimentation.

This work is the outgrowth of a cooperative effort to collect data and formulate a tectonic synthesis of the north central Brooks Range. Although the tectonic modelling and interpretations are my own, many scientists contributed expertise, data, analyses, and ideas to this study. These include: Kenneth Bird, David Howell, and Mark Pawlewicz (U.S. Geological Survey), C.G. Mull (State of Alaska, Division of Geological and Geophysical Surveys), Michael Underwood and Jonathan Meier (University of Missouri), Paul O'Sullivan (La Trobe University), Wang Chengshen (Chengdu College), and François Roure and William Sassi (Institut Français du Pétrole).

REGIONAL TECTONIC SETTING

Northern Alaska, from the Brooks Range northward, is part of the Arctic Alaska microplate [Hubbard et al., 1987]. This microplate is characterized in its southern part by a collisional orogen (Brooks Range), in the central part by its foreland basin (Colville Basin), and in the northern part by a rifted margin (Barrow Arch; Figure 1). It is generally agreed that the Brooks Range resulted from the collision of an island arc with the south facing (present-day coordinates) Devonian to Jurassic passive margin on the seaward edge of the Arctic Alaska microplate [e.g. Moore et al.,

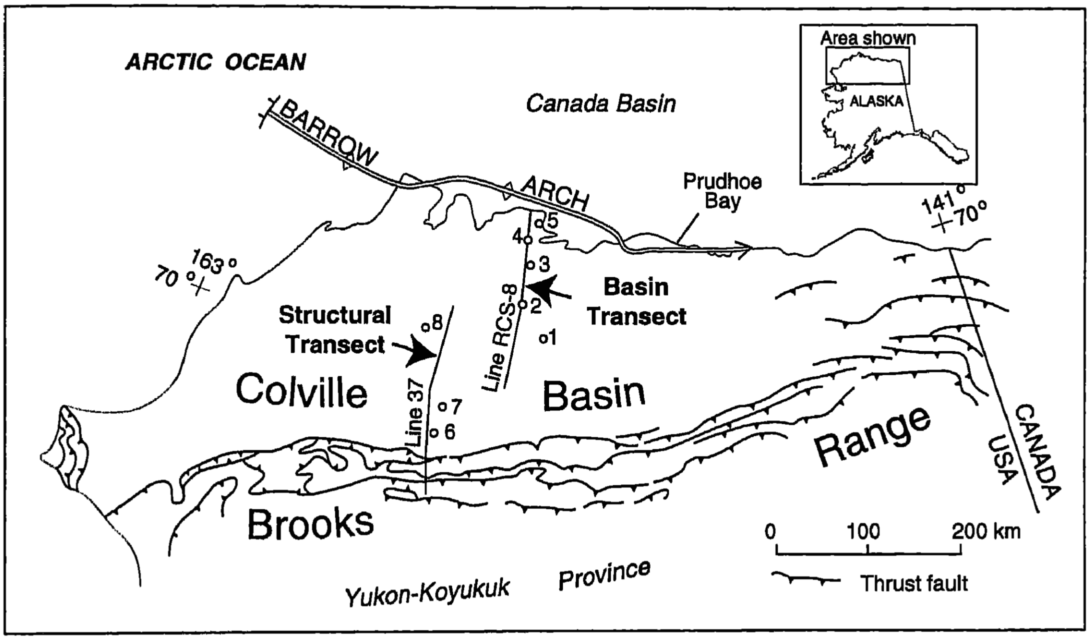


Figure 1. Location of transects in this study. Lines RCS-8 and 37 refer to seismic lines, circles 1-8 to wells used in this study: (1) Seabee 1, (2) Inigok 1, (3) North Inigok 1, (4) East Teshekpuk 1, (5) Cape Halkett 1, (6) Lisburne 1, (7) West Kurupa 1, and (8) Oumalik 1.

1994]. However, neither the timing nor the magnitude of the resultant contraction has been well-established. Up to 600 km of crustal shortening has been hypothesized based on structural and paleogeographic reconstructions [Mayfield et al., 1988; Oldow et al., 1987], although such extreme shortening has been challenged recently [Kelley and Brosgé, 1995].

The age of deformation in the Brooks Range and the foreland is inferred to be Middle Jurassic and younger, based on stratigraphic and structural constraints in the northern thrust belt and foreland basin, as well as radiometric dating in the metamorphic hinterland [e.g. Mayfield et al., 1988; Mull, 1989]. Thrusting probably began in the Middle Jurassic, according to $^{40}Ar/^{39}Ar$ hornblende ages obtained from a metamorphic sole of obducted ophiolitic rocks in the western Brooks Range [Wirth and Bird, 1992]. Blueschist-facies metamorphism in the southern Brooks Range may represent continental subduction and regional contraction in the orogen. The age of blueschist metamorphism is poorly constrained but is generally regarded as Late Jurassic to Early Cretaceous [Armstrong et al., 1986; Till and Snee, 1994].

The oldest stratigraphic evidence for convergence and orogenesis is the Okpikruak Formation, which crops out in allochthonous thrust sheets in the northern Brooks Range. The Okpikruak Formation consists of highly deformed turbidites with a poorly known stratigraphy, interpreted as syntectonic deposits shed northward from an advancing early Brookian thrust front. The turbidites are mostly early Neocomian (Berriasian and Valanginian) in age, except for one locality in the western Brooks Range with latest Jurassic (Tithonian) fossils [Curtis et al., 1984]. In several localities in the northern Brooks Range, highly folded and imbricated rocks of the Okpikruak and older units are overlain unconformably by less deformed Barremian to Albian strata of the Fortress Mountain Formation [Mull, 1989]. Therefore the most intense contractional deformation in the orogen was probably complete by Barremian time.

Fission track analyses in northern Alaska have revealed younger episodes of contraction in the Brooks Range and the Colville Basin [O'Sullivan, 1993; O'Sullivan et al., 1993; Murphy et al., 1994; Blythe et al., 1996; O'Sullivan et al., 1997]. In the study area, foreland basin strata as young as Maastrichtian have been deformed by relatively minor folding and faulting [Brosgé and Whittington, 1966; Frederiksen et al., 1988], and in the northeastern Brooks Range contraction is active today. Some workers argue for ongoing contractional deformation from the Late Jurassic to the present [Oldow et al., 1987], while others envision a more episodic history of thrusting and quiescence [Mull, 1989; O'Sullivan, 1993].

A major cooling episode affected the hinterland of the Brooks Range between 120 and 90 Ma, based on K/Ar, $^{40}Ar/^{39}Ar$, and fission track ages, as summarized by Moore et al. [1994]. Coarse-grained molasse deposits accumulated in the Colville Basin at this time, indicating rapid erosion of an emergent source area. In addition, extensional structures of inferred mid-Cretaceous age occur in the southern Brooks Range [Gottschalk and Oldow, 1988; Miller and Hudson, 1991], suggesting unroofing by down-to-the-south normal faulting on the south flank of the orogen. This extension may have been concurrent with some of the shortening in the foreland. I address some of these timing questions in the analyses and discussion that follow.

STRATIGRAPHY OF THE FORELAND BASIN AND THRUST BELT

I conducted tectonic subsidence modelling along the basin transect shown in Figure 1. This transect lies north of the Brooks Range deformational front, in an area underlain by autochthonous North Slope sedimentary and metasedimentary rocks. The kinematic modelling was conducted in the Brooks Range thrust belt, along the structural transect shown in Figure 1. In that area, several allochthons have been characterized, based on the internal stratigraphy and stacking order of the main thrust sheets [Mull et al., 1994]. These allochthons are thought to represent a collapsed ocean basin and continental margin sequence that originally lay outboard of the North Slope autochthon. In this section I summarize the stratigraphic relations between the allochthons in the area of the structural transect, and the autochthonous North Slope rocks in the area of the basin transect.

North Slope and Colville Basin Stratigraphy

The stratigraphy of the North Slope autochthon, as summarized by Moore et al. [1994], is divided into three sequences separated by regional unconformities (Figure 2): (1) deformed pre-Mississippian metasedimentary rocks and local Devonian granites of the Franklinian sequence, (2) Mississippian through Lower Cretaceous passive margin sedimentary rocks of the Ellesmerian sequence, and (3) Cretaceous and Tertiary clastic sediments of the foreland basin known as the Brookian sequence. The Ellesmerian sequence includes Mississippian through Early Cretaceous sedimentary rocks, with a composite thickness of approximately 3 to 4 km. It is believed to represent a south facing passive margin sequence [e.g. Moore et al., 1994], although in detail the paleogeography may be more complicated.

Near the top of the Ellesmerian sequence is the regional Lower Cretaceous unconformity (Figures 2 and 3). Hundreds of meters of Ellesmerian rocks are missing below the unconformity at the northern end of the foreland basin transect, along the Barrow Arch, but southward this surface becomes paraconformable. The age of the Lower Cretaceous unconformity in this area is interpreted to be intra-Hauterivian based on (1) the presence of Hauterivian to Barremian microfossils above the unconformity in all five wells of the subsidence study [Haga and Mickey, 1983], and (2) the presence of probable Hauterivian microfossils below the unconformity in the southernmost wells of the basin transect (Inigok and Seabee wells) where seismic and well data

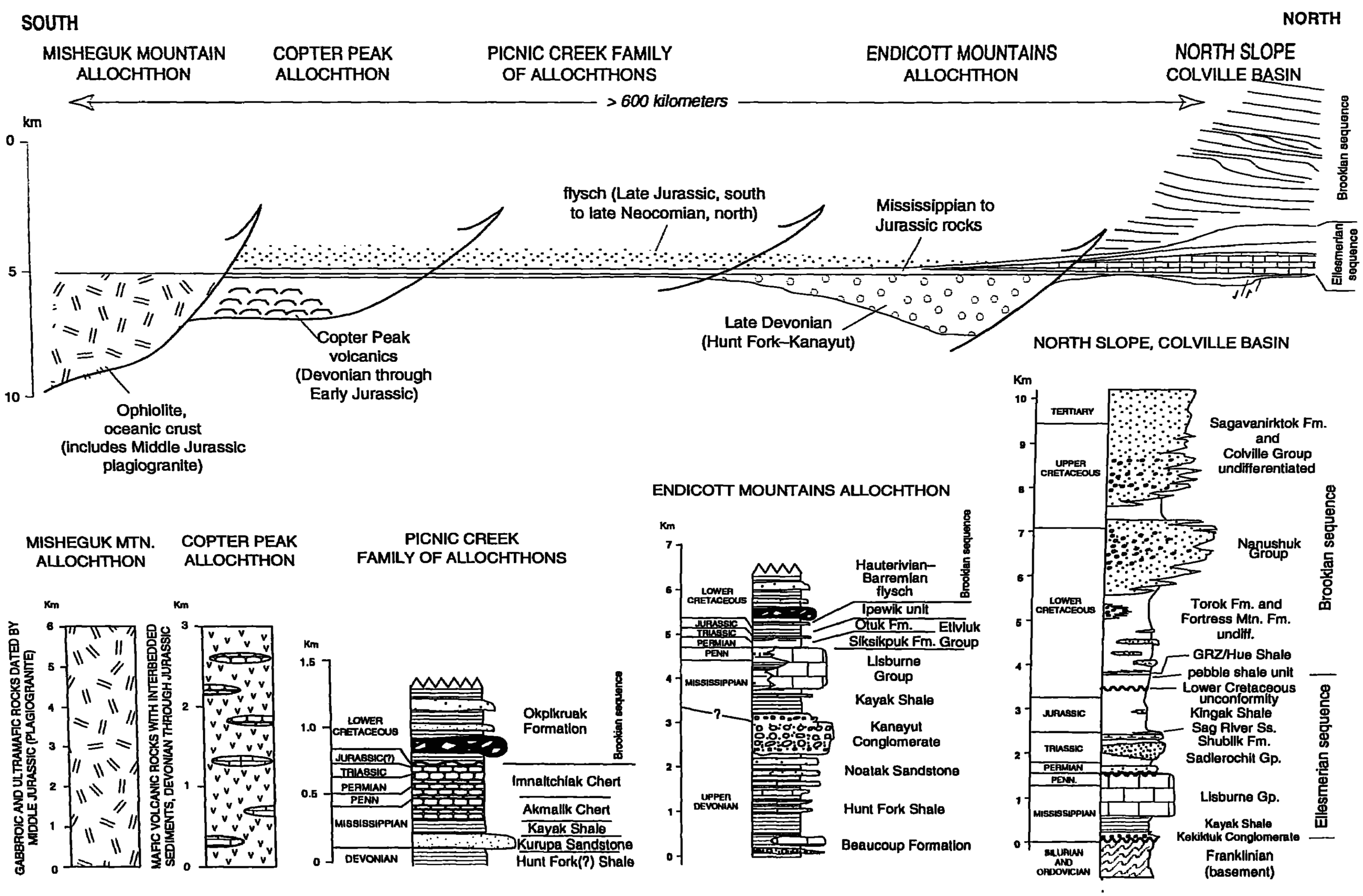


Figure 2. Summary of stratigraphic relationships and nomenclature for the central North Slope and central Brooks Range area. (top) Schematic palinspastic restoration. (bottom) Generalized stratigraphic columns revised from Moore et al. [1994]. GRZ, gamma ray zone.

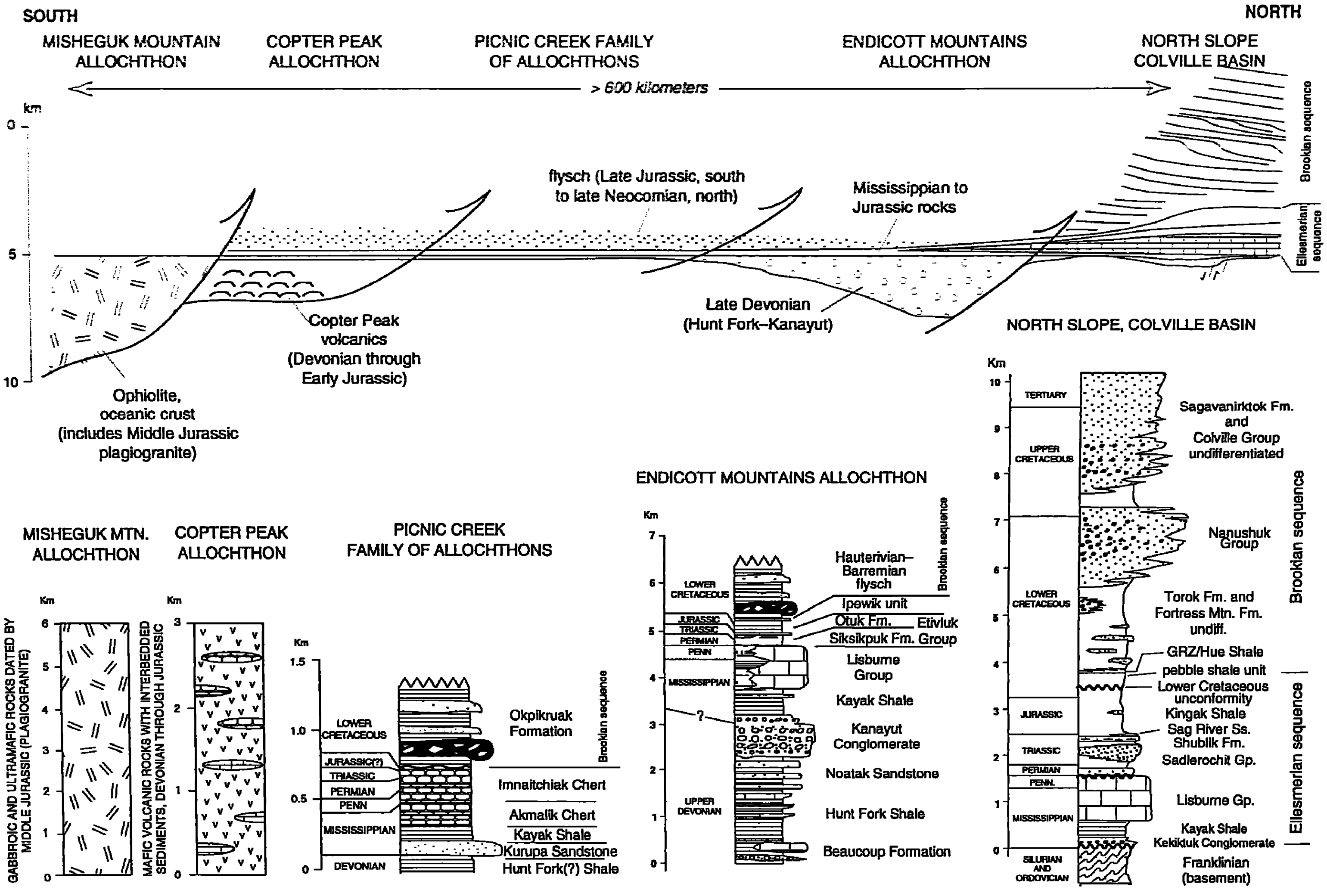


Figure 2. Summary of stratigraphic relationships and nomenclature for the central North Slope and central Brooks Range area. (top) Schematic palinspastic restoration. (bottom) Generalized stratigraphic columns revised from Moore et al. [1994]. GRZ, gamma ray zone.

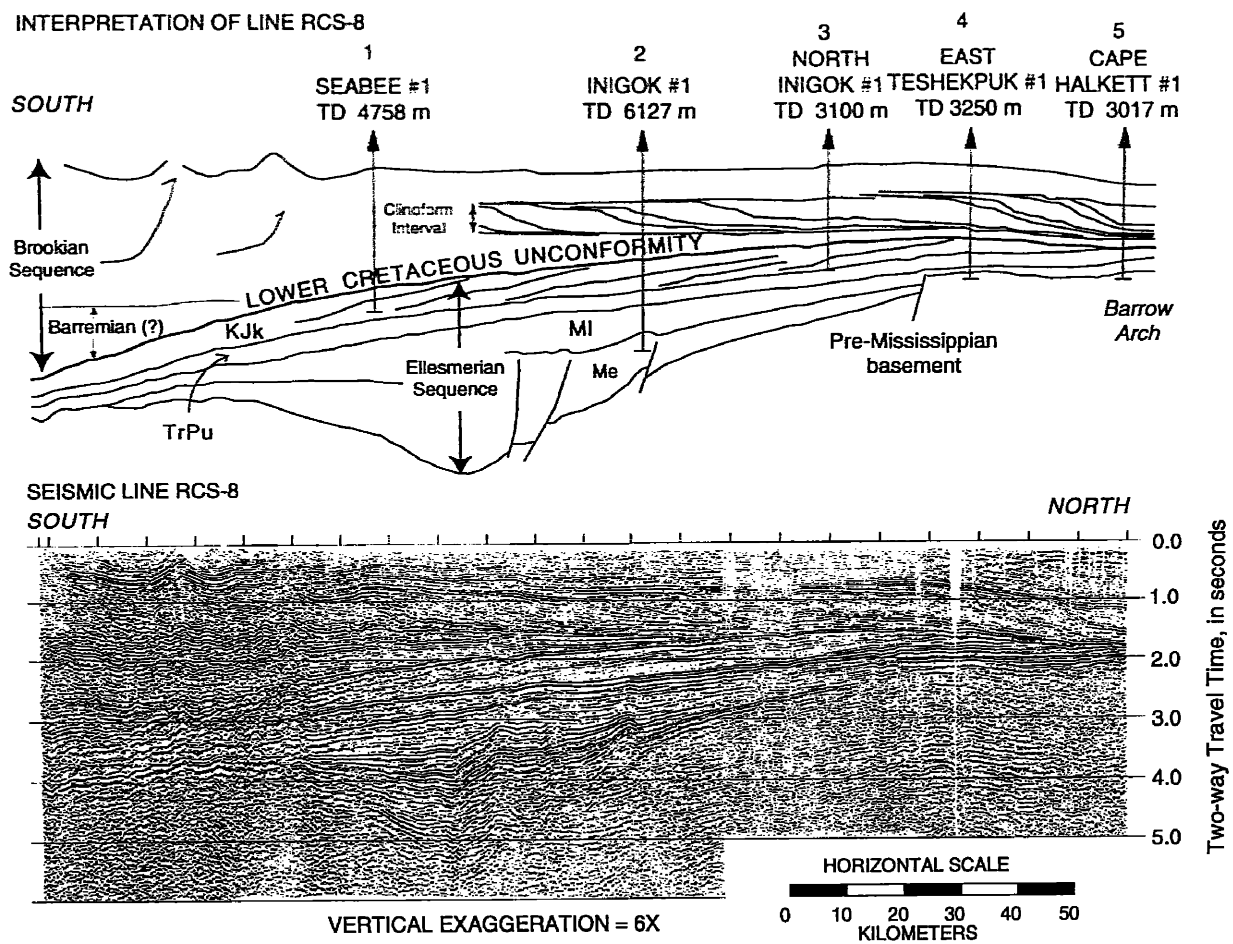


Figure 3. Seismic line RCS-8 (location shown in Figure 1), interpreted line drawing and stacked data, showing south-dipping Ellesmerian sequence, and onlapping Brookian sequence. Wells from Figure 1 are projected onto the line of section. Ellesmerian sequence includes Me, Endicott Group; Ml, Lisburne Group; TrPu, undivided Permo-Triassic rocks; KJk, Kingak Shale. Brookian sequence includes Torok and Fortress Mountain Formations and Nanushuk Group.

indicate minimal or no erosion of the upper part of the Kingak Shale [Haga and Mickey, 1983]. On the basis of the Harland et al. [1990] timescale, the unconformity is about 133 Ma. It is interpreted as the breakup unconformity related to the opening of the Canada basin at the present-day site of the Beaufort Sea [Grantz et al., 1990].

The unconformity is overlain by a thin Hauterivian (131.8-135 Ma) to Barremian (124.5-131.8 Ma) transgressive marine shale (pebble shale unit), characterized by frosted quartz grains and chert pebbles, and discontinuous quartz sandstones in its lower part [Schenk and Bird, 1993]. The pebble shale unit is interpreted to be the end of Ellesmerian sequence deposition.

The Brookian sequence consists of a basal condensed shale section and thick flysch and molasse deposits. The condensed shale (Hue Shale) is rich in organic matter and is thought to represent pelagic deposition in a starved basin, after the northern source area became drowned [Molenaar et al., 1987]. In the area of the foreland basin transect, this unit is represented by a zone of high gamma ray readings, the gamma ray zone (GRZ; Figure 2). This horizon appears to merge southward and westward with lower Brookian deposits of the Torok Formation, indicating that the Hue Shale and GRZ were derived in part from a southern or Brookian source area [Creaney and Passey, 1993]. The Hue Shale and all of the overlying southern-sourced units are strongly time transgressive, oldest in the southwest and youngest in the northeast, reflecting the overall direction of sedimentary transport and depocenter migration [Molenaar et al., 1987].

The Torok and Fortress Mountain Formations consist of deep-water shales and turbidite sandstones of a typical flysch sequence. In general, the Fortress Mountain Formation is thought to represent a more proximal, coarser facies that grades laterally into and intertongues with the finer-grained and more distal facies of the Torok Formation [Molenaar et al., 1988]. For the purpose of this study, I do not attempt to separate them. The age of the Torok and Fortress Mountain Formations is usually reported to be Aptian (?) to Albian [Bird and Molenaar, 1992]. However, Torok strata in the Seabee 1 well were indentified as probable Barremian age by Mickey and Haga [1987], and roughly 1.8 km additional strata are observed to onlap the south dipping passive-margin sequence at the south end of seismic line RCS-8 (Figure 3) [Cole et al., 1995]. Because these onlapping strata are clearly sourced from the south and because their upper part is correlative with probable Barremian rocks of the Torok Formation in the Seabee well, I interpret these strata as Barremian and possibly upper Hauterivian age. This reinterpreted age for the basal Torok Formation requires the influence of a southern source area in Barremian or possibly late Hauterivian time in this area, in contrast to earlier studies that do not require a southern source area for the Torok and Fortress Mountain Formations until Aptian (?) or Albian time [Molenaar et al., 1988]. Micropaleontology studies in the western DeLong Mountains have also yielded Hauterivian-Barremian ages for the lower Brookian sequence [Mickey et al., 1995]. Similar age rocks occur in the upper 2000 m of the Lisburne well, lending further support to this revised age for the basal Torok and Fortress Mountain Formations.

In the upper part of the Torok and Fortress Mountain sequence is a distinctive interval of sigmoidal clinoforms that are thought to represent the northeastward prograding shelf margin [Molenaar et al., 1986]. Above this interval the flysch grades into deltaic molasse-type deposits of the Nanushuk Group, mostly of Albian to early Cenomanian age [Witmer et al., 1981a,b; Mickey and Haga, 1990]. In seismic line RCS-8 (Figure 3), the Nanushuk Group forms most of the reflective topsets (shelf and delta plain facies) that give way to Torok foresets and bottomsets (slope and basinal facies). Based on my seismic interpretation for the southern part of this line, the total thickness of the Fortress Mountain, Torok, and Nanushuk sequence to be about 10 km adjacent to the thrust belt.

The Nanushuk Formation is overlain by the Cenomanian and Turonian Shale Wall Member of the Seabee Formation. This shale sequence represents the youngest major marine transgression recorded in the stratigraphy along the basin transect. The remainder of Late Cretaceous time is represented by deltaic sandstone, shale, conglomerate, and coal of the Colville Group. At the northern end of the basin transect, the upper few hundred meters of strata are lower Tertiary Sagavanirktok Formation [Molenaar et al., 1986; Magoon et al., 1988]. The Upper Cretaceous and lower Tertiary sediments represent a second cycle of flysch and molasse whose depocenter is located east of the basin transect. On the basis of the thermal maturity of rocks now at the surface, it is likely that a greater thickness of these Upper Cretaceous and Lower Tertiary rocks once extended over the area of the basin transect.

Brooks Range Foothills Stratigraphy

In the foothills of the Brooks Range, rocks that probably represent the distal equivalents of the Ellesmerian sequence on the North Slope, and mafic igneous rocks of the adjacent ocean basin, are stacked in thrust sheets (Figure 2). In the western Brooks Range, seven allochthon sequences are recognized, based on the structural position and internal stratigraphy of each major thrust sheet [Ellersieck et al., 1979; Mayfield et al., 1988]. The principal allochthons in the area of the structural transect are the Endicott Mountains allochthon and the Picnic Creek family of allochthons [Tailleur et al., 1966; Mull et al., 1994]. Also present as small klippen are the Copter Peak and Misheguk Mountains allochthons. The internal stratigraphy and schematic paleogeography for these allochthons are shown in Figure 2. In general, the structurally higher allochthons contain ophiolitic and deep-water sedimentary rocks, while the lower allochthons contain shallow-water sedimentary rocks [Mull et al., 1985], which is the expected stacking order for a forward-propagating thrust system.

The Endicott Mountains allochthon occupies most of the Brooks Range front in the area of this study. The total thickness of the Upper Devonian rocks, including the Hunt Fork Shale, Noatak Sandstone and Kanayut Conglomerate is about 2.5 km in the Killik River quadrangle (Figure 2) [Mull et al., 1985, 1994]. This thick Devonian section is thought to represent a fluvial-deltaic complex that prograded southwestard across a freshly rifted continental margin, toward an ocean basin that lay to the south [Nilsen et al., 1980]. The Devonian section is overlain by a 400-m-thick succession of shale, carbonate, and chert of Carboniferous through Jurassic age, representing an outboard portion of the North Slope passive margin sequence. Jurassic shale and chert at the top of the passive margin succession are overlain by a thin but distinctive coquinoid limestone (Ipewik Formation) of Valanginian age and shale and graywacke of Hauterivian to Barremian age (Figure 2). The total thickness of the Upper Devonian through Lower Cretaceous rocks of the Endicott Mountains allochthon is about 3.4 km in this area [Mull et al., 1994].

In the upper part of the Lisburne well, the Endicott Mountains allochthon also includes Hauterivian-Barremian and Aptian to early Albian [Mickey and Haga, 1980] clastic rocks similar in lithology and age to the Torok/Fortress Mountain Formations of the North Slope autochthon (Figure 4). They include steeply dipping and highly sheared mudstone, siltstone, and minor sandstone and conglomerate, previously assigned to the Okpikruak Formation [Magoon et al., 1988; Mull et al., 1994] but closer in age to the Torok/Fortress Mountain Formations. Foraminifera and palynomorphs indicate that the interval from 300 to 600 m is Aptian to early Albian in age, and the interval from 600 to 1800 m is Hauterivian to Barremian in age [Mickey and Haga, 1980].

The Hauterivian to Barremian interval is mostly fine-grained shale and siltstone, with rounded quartz sand and pebbles near the base, and increasing proportions of mica and lithics in its upper part. This sequence probably represents a transition from northern sourced pelagic deposits (pebble shale equivalent) to southern sourced turbidites (Fortress Mountain/Torok equivalent).

The Aptian-Albian section in the upper 600 m of the Lisburne well (Figure 4) contains a 20-m interval of poorly sorted sandstone and conglomerate, which correlates with a southward dipping debris flow exposed a short distance northwest of the well. Both are very poorly sorted and matrix-supported. Cobbles and boulders of limestone, greenish mudstone, and chert appear to be locally derived from the Lisburne, Siksikpuk, and Otuk Formations, respectively. Rare basalt clasts suggest that this basin was also receiving detritus from the Copter Peak allochthon in Aptian-Albian time. The Lower Cretaceous interval in the Lisburne well indicates the existence of a southern source area in Hauterivian to Barremian time, becoming more proximal in Aptian to Early Albian time. This timing agrees with the age of basal Brookian sediments in the the Seabee well and in the western DeLong Mountains, described above.

The Picnic Creek family of allochthons consists mainly of Carboniferous through Triassic sedimentary rocks that are thinner and richer in chert than coeval units in the Endicott Mountains

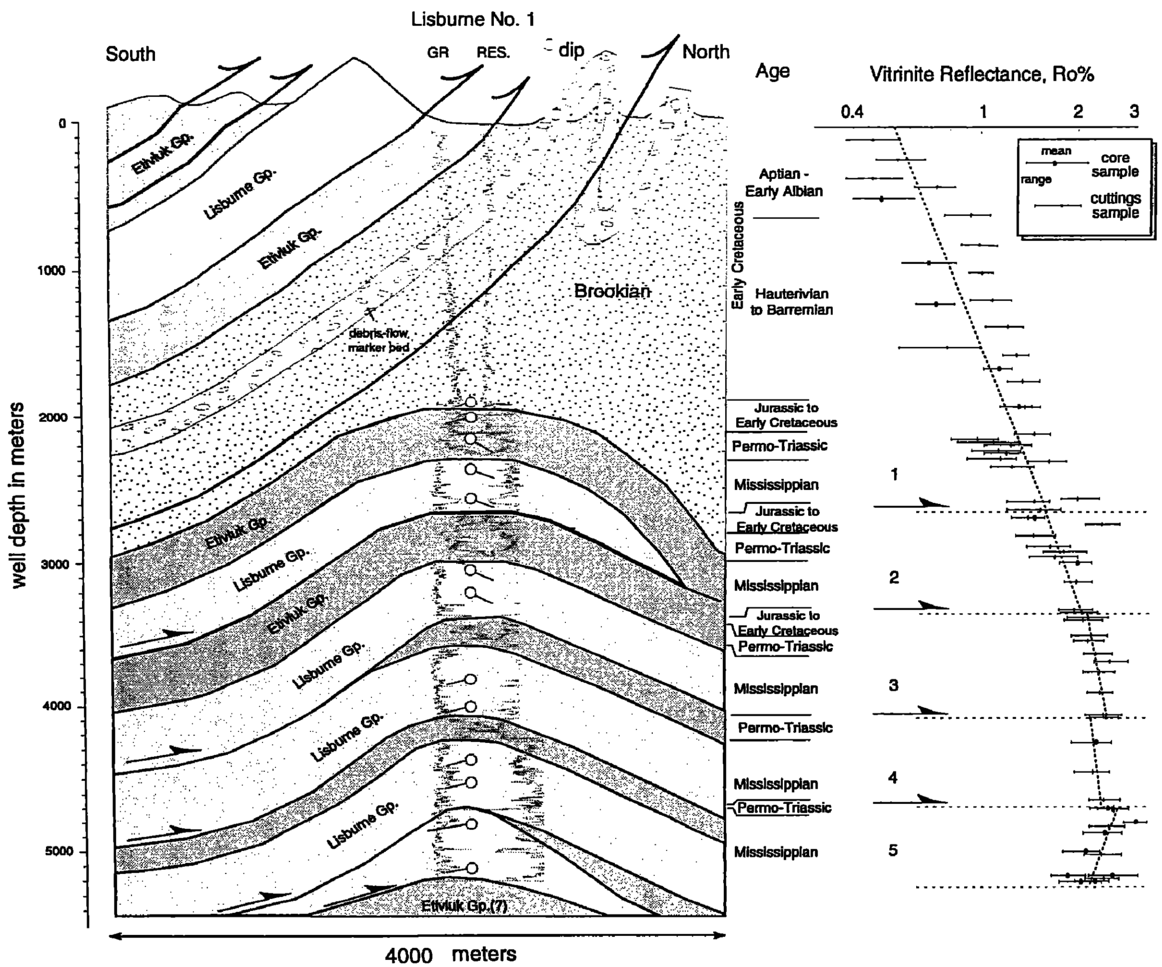


Figure 4. Structural, stratigraphic, and thermal maturity data from the Lisburne 1 well. Gamma ray and resistivity logs show approximate location of borehole and log response to alternating Lisburne and Etivluk Group lithologies repeated in thrust sheets. Stipple pattern is Cretaceous shale and siltstone, with congomerate at ~600 m depth correlated with south dipping debris flow in outcrops north of the well (our interpretation). Paleontology shown at right, vitrinite reflectance at far right [Mickey and Haga, 1980; Gryc, 1988].

allochthon (Figure 2). The Picnic Creek and related allochthons also include Buchia-bearing graywacke, assigned to the Okpikruak Formation. The thickness of the Okpikruak Formation is not well known, but locally it attains 600 m. It is thought to represent early flysch derived from an ancestral Brooks Range orogen [Mull, 1985]. Locally, it contains mafic to intermediate igneous clasts probably derived from the Copter Peak and Misheguk Mountains allochthons, signalling their arrival by Valanginian time in this area. The total thickness of the Carboniferous through Lower Cretaceous rocks that comprise the Picnic Creek allochthon is at least 700 m [Mull et al., 1994]. The Picnic Creek family of allochthons lacks the thick Upper Devonian sedimentary sequence that characterizes the Endicott Mountains allochthon.

The Copter Peak and Misheguk Mountain sequences are shown schematically in Figure 2. The Copter Peak allochthon comprises <3 km of pillow basalt, diabase, and gabbro [Nelson and Nelson, 1982], and the Misheguk Mountain sequence is mainly gabbro and dunite with a reconstructed thickness of 6 km [Harris, 1995]. These sequences are thought to be parts of an ophiolite assemblage representing an ancestral ocean basin that lay to the south of the passive margin and was obducted during the Brookian orogeny. Although in the area of the structural transect I see only isolated outcrops of these allochthons, I present evidence below that these igneous rocks once extended as a continuous sheet across much of this region. This agrees with previous models that have been proposed for the western Brooks Range [Ellersieck et al., 1979; Mayfield et al., 1988].

TECTONIC SUBSIDENCE ANALYSIS

Colville Basin Transect

The Colville Basin contains the sedimentary record of the regional-scale development of the fold and thrust belt. When thrust plates load the lithosphere in an orogen, the foreland responds with flexural subsidence [Beaumont, 1981], which is recorded by increased water depth and thick accumulation of sedimentary basin fill. My aim has been to model the geodynamic history in the Colville Basin in order to determine the timing and magnitude of tectonic activity in the northern Brooks Range. Previous studies demonstrate the causal relationship between the Brooks Range orogen and the Colville Basin [Hawk, 1985; Nunn et al., 1987; Coakley and Watts, 1991; Flemings, 1992].

I analyzed the basin subsidence history using stratigraphic information from five wells (Seabee 1, Inigok 1, North Inigok 1, East Teshekpuk 1, and Cape Halkett 1) and a regional seismic line, RCS-8, in a transect spanning 200 km across the northern flank of the foreland basin (Figures 1 and 3). The basin transect was intentionally located north of the main structures in the thrust belt to avoid structural complications in the basin stratigraphy. This means that it also lies north of the thickest Brookian deposits, so that the tectonic subsidence magnitudes should be considered minima. For a more complete discussion of the tectonic subsidence analysis of the Colville Basin, see Cole et al. [1994]. In this thesis, I focus on the Cretaceous and Tertiary part tectonic subsidence history because it is during this time that the basin evolution becomes dominated by tectonic events in the adjacent Brooks Range.

Backstripping Method

To generate the subsidence histories that follow, I used the delithification and one-dimensional backstripping program "decem2," provided by M. Kominz at the University of Texas at Austin. The program delithifies sedimentary units by making corrections for compaction, according to the method of VanHinte [1978], and for cementation according to Bond and Kominz [1984] and Bond et al. [1989]. The delithified sedimentary units are backstripped using the one-dimensional (Airy) isostatic adjustment developed by Steckler and Watts [1978]. Each sedimentary unit, beginning with the lowest unit, is first restored to its initial thickness and density. Then the isostatic subsidence of the basement caused by the weight of the sedimentary unit is calculated and removed. The resulting tectonic subsidence curves show the elevation of the basement in the absence of the sedimentary load, which can be viewed as the subsidence caused by mechanisms other than local sedimentary loading. One-dimensional backstripping underestimates tectonic subsidence near basin depocenters and overestimates it near the edges. For a two-dimensional treatment of the Colville Basin, see Flemings [1992].

Stratigraphic thicknesses for the wells in the basin transect were taken from Bird [1988], biostratigraphic ages from well reports [Mickey and Haga, 1980; Magoon et al., 1988], and paleobathymetry from biofacies, lithofacies, and seismic analysis of clinoforms. Paleobathymetry estimates based on clinoform amplitudes revealed rapid changes in local water depth, which had a strong effect on the resulting trends in tectonic subsidence. For a complete discussion of these estimates and methodologies, please refer to Cole et al. [1994].

The thickness of section of the Kingak Shale eroded beneath the Lower Cretaceous unconformity in the Inigok, North Inigok, East Teshekpuk, and Cape Halkett wells was estimated from the morphology of the Kingak shelf interpreted from seismic line RCS-8 [Bird, 1994]. According to this projection, at least 50 m of Kingak Shale is missing due to erosion in the area of the Inigok well, and about 200 m is missing at Cape Halkett.

I used a similar method to estimate the thickness of eroded Upper Cretaceous and Tertiary section at each well. Strata of this age are poorly preserved along the basin transect, yet I know they were once present because the vitrinite reflectance values of sediments at the land surface are quite high [Johnsson et al., 1992]. In order to estimate the amount of missing section along the transect, I projected the missing units from the Prudhoe Bay area, where they are best preserved. This yields general agreement with vitrinite reflectance values, producing a smooth gradient for the missing section and paleoland surface between wells. I estimated no more than 2500 m of missing section at the Seabee well and 800 m of missing section at the Cape Halkett well. I assumed a Paleocene age for maximum burial, based on apatite fission track cooling ages in wells on the basin transect and elsewhere on the North Slope [O'Sullivan, 1993].

Results of Backstripping

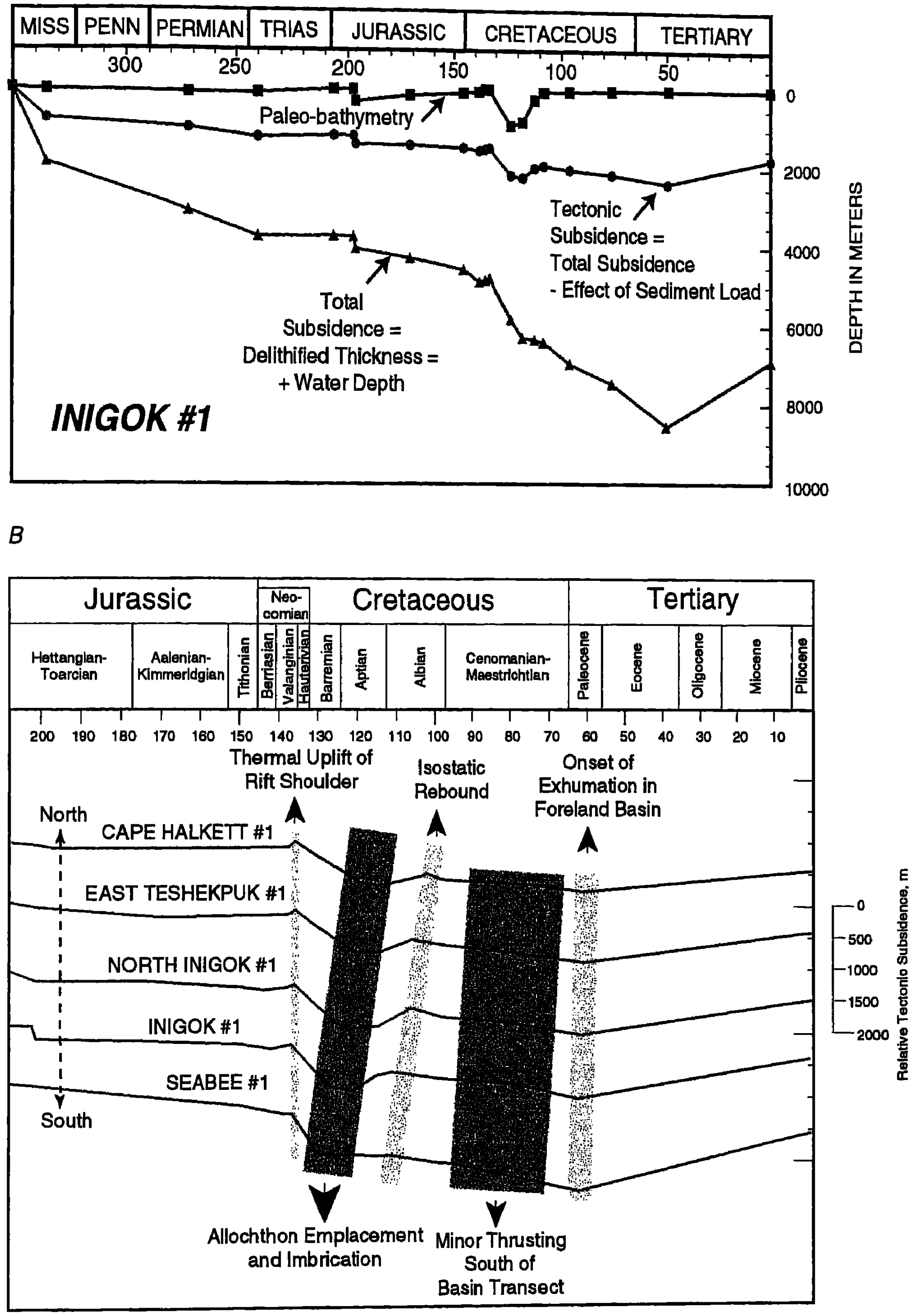
Paleobathymetry and subsidence curves are shown for the Inigok 1 well in Figure 5a. The uppermost curve tracks the paleowater depth through time; the lower curve represents the total basement subsidence curve, based on the delithified sediment thicknesses and paleobathymetry. It models the burial depth of the basement through time. The middle curve is the tectonic residual subsidence curve that results when the local (Airy) isostatic effects of sediment loading are removed. This curve represents the changes in basement elevation that cannot be accounted for by the local sedimentary load.

The tectonic subsidence curves for all five wells in the basin transect show three main subsidence events (Figure 5b): (1) slow, passive-margin style subsidence during Paleozoic through Jurassic time, corresponding to deposition of most of the Ellesmerian sequence, (2) rapid subsidence in the Early Cretaceous corresponding to a rapid increase in water depth prior to northward progradation of the Torok Formation, and (3) modest Late Cretaceous subsidence corresponding to deeper-water deposition of a transgressive marine shale.

At the Inigok, North Inigok, East Teshekpuk, and Cape Halkett wells, I see synchronous uplift in Hauterivian time (circa 133 Ma; Figure 5b) corresponding to the uplift of the Barrow Arch and the development of the Lower Cretaceous unconformity. The magnitude of tectonic uplift decreases from 90 m at Cape Halkett to 0 m at the Seabee well. Hauterivian uplift is followed by rapid subsidence beginning in Barremian time, involving roughly 700 m of tectonic subsidence in 15 m.y. (Figure 5b), with the largest values at the Seabee well in the south and the smallest at Cape Halkett in the north. I infer that the largest magnitude tectonic subsidence occurred south of the Seabee well, where the flysch sediments are thickest.

Barremian and Aptian tectonic subsidence was followed by a period of rapid shoaling during the main (Albian) episode of northeastward progradation of the sediments comprising the Torok/Fortress Mountain Formations and Nanushuk Group (Figure 5b). The dominance of lateral progradation over vertical aggradation at this time suggests that vertical accommodation space was limited and sediments were required to bypass the continental shelf to find space to accumulate.

A



B

Figure 5. Foreland basin subsidence curves. (a) Paleobathymetry, total subsidence, and tectonic subsidence history for the Inigok 1 well. (b) Comparison of tectonic subsidence curves for all five wells, with interpreted tectonic events shaded and labelled.

Shoaling bathymetry during sedimentation suggests that the basin substrate had ceased to subside even though the sedimentary load was very large. This requires some component of tectonic rebound in the foreland, as illustrated by the Albian portions of tectonic subsidence curves in Figure 5b. Modest tectonic subsidence resumed in Cenomanian to early Tertiary time and was followed by uplift and erosion in Paleocene time.

Tectonic Interpretation of Subsidence History

I ascribe Hauterivian uplift of the Barrow Arch to thermal uplift along the southern margin of the Canada basin, as suggested by previous workers [Grantz and May, 1983; Hubbard et al., 1987]. In this scenario, the lower Cretaceous unconformity is the breakup unconformity marking the initiation of spreading in this part of the Canada basin. The Barrow Arch may have been reactivated as a flexural bulge associated with tectonic loading in the Brooks Range orogen [Nunn et al., 1987; Coakley and Watts, 1991], but there is no direct evidence for this in the Colville Basin. A flexural bulge would be expected to sweep from south to north across the basin through time, reflecting the migration direction of the thrust load in the orogen. Instead, the Lower Cretaceous unconformity appears to be synchronous in time (intra-Hauterivian) and localized in space (Barrow Arch) across the basin transect, not northward migrating [Cole et al., 1994].

In Barremian time (circa 125 Ma) major flexural subsidence occurred, amounting to >700 m in the southern part of the basin transect and lesser amounts to the north. I attribute the Barremian subsidence episode mainly to flexural loading in the Brooks Range orogen, but a small part may be the result of thermal relaxation of the uplifted Hauterivian rift shoulder. The component of subsidence due to cooling should simply counterbalance Hauterivian thermal uplift, which has a maximum value of 90 m at Cape Halkett. Subtracting the thermal component from the tectonic subsidence leaves greater than 600 m of presumed flexural subsidence throughout the basin transect. This is the component of basin subsidence that I ascribe to tectonic loading in the Brooks Range. The magnitude of subsidence and the subsidence rates decrease with distance from the Brooks Range orogen, as expected for a flexural basin [Homewood et al., 1986; Kominz and Bond, 1986]. At this time, subsidence outpaced sedimentation, and the basin was grossly underfilled.

Tectonic rebound in the foreland basin occurred during the progradational filling of the basin by molasse sediments in Albian time (112-97 Ma). I ascribe this rebound to a progressive reduction in the size of the tectonic load, during erosion and tectonic denudation in the orogen.

Modest subsidence resumed in the foreland basin in Cenomanian time and continued until early Tertiary time, when the basin began its final phase of tectonic uplift. This final phase of subsidence and uplift corresponds to a second depositional cycle of flysch and molasse represented by the Colville Group (including the transgressive Shale Wall Member of the Seabee Formation) and the Sagavanirktok Formation. The exact timing of the onset of uplift is poorly constrained because of incomplete preservation of Upper Cretaceous and Tertiary strata in this part of the foreland basin. However, I believe that a Paleocene age for the onset of uplift agrees well with fission track ages, which range between 50 and 60 Ma in this area [O'Sullivan, 1993]. I believe that the Cenomanian and younger subsidence represents a second period of thrusting south of the foreland basin, as suggested by Flemings [1992]. The Paleocene onset of uplift and erosion marks the arrival of the deformation front at the Seabee well and associated regional rebound farther north.

KINEMATIC ANALYSIS

Many examples showing the geometric development of thrust belts are available in the literature [e.g. Boyer and Elliot, 1982; Dahlstrom, 1968; Price, 1981], yet it is rare that the data necessary to fully constrain the timing of the deformation and the thermal history that accompanied it are available. I have compiled such an integrated data set and used it to produce a kinematic model of the deformation of the Brooks Range frontal thrust belt. The model is based on a balanced cross section constructed from field observations gathered by a team of U.S. Geological Survey geologists in the Killik River and Howard Pass quadrangles, plus well and seismic data available from Gryc [1988] and existing geologic map compilations [Whittington and Troyer, 1948; Webber et al., 1948; Chapman et al., 1964; Tailleur et al., 1966; Mull et al., 1994; Mull and Werdon, 1994]. I incorporate timing constraints from the tectonic subsidence history in the foreland basin and vitrinite reflectance and apatite fission track analyses to infer periods of active deformation, burial (tectonic and sedimentary) and exhumation of the main structural elements along the cross section.

Kinematic modeling was conducted with Thrustpack, a proprietary program developed by the Institut Français du Pétrole and a consortium of oil companies, and used with their permission. I input the palinspastically restored cross section, representing the initial undeformed state of the thrust belt, and I modeled the main stages of successive thrusting and sedimentation. Rates of thrusting and sedimentation were adjusted to fit observations and thermal constraints. Thrustpack is not capable of modeling back thrusts, so the final model geometry is a simplified version of the observed structure.

Balanced Cross Section

The cross section was drawn using standard line length balancing techniques [Woodward et al., 1989]. From the range front northward, the section was constructed along seismic line 37 (Figures 1 and 6), interpreted according to the surface geology and subsurface geology in three nearby wells: Lisburne 1, West Kurupa 1, and Oumalik 1. Available fossil ages for synorogenic

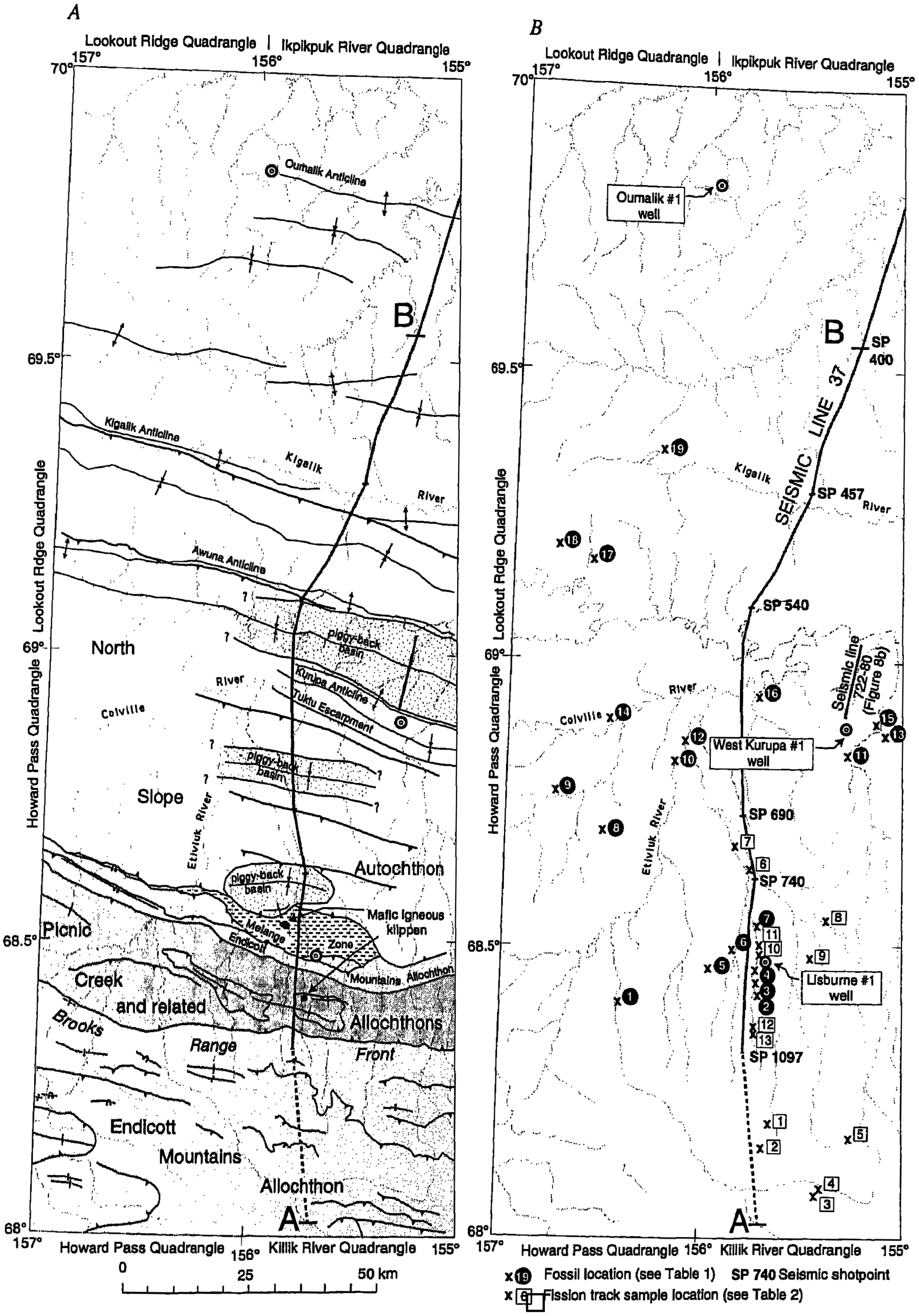


Figure 6. (a) Simplified geologic map of the area of the balanced cross section (Plate 1), showing locations of major allochthons, structural trends, and piggy-back basins. The line of cross section (line AB, Plate 1) is shown, solid where it follows seismic line 37, dashed where it extends south of the seismic coverage. (b) Sample locality map of same area as Figure 6a, showing locations of samples, wells, and seismic lines discussed in text.

Table 1. Fossil Ages from Cretaceous Rocks along the Structural Transect.

Map Locality (Fig. 6b)	Original Field Number	Locality in Elder et al., 1989	Latitude, North	Longitude, West	Formation	Age	Reported Fossils	Reference
1	49ADt39	115	68° 24.0'	156° 25.0'	Okpikruak	Berriasian	Buchia subokensis	*Elder et al.* [1989]*
2	93FC58	N/A	68° 24.8'	155° 43.8'	Okpikruak	Oxfordian to Valanginian	Buchia sp.	W.P.Elder, written commun., 1993
3	82AKy51	128	68° 26.5'	155° 43.5'	Okpikruak	Valanginian	Buchia sublaevis	*Elder et al.* [1989]*
4	93FC20	N/A	68° 27.5'	155° 43.5'	Okpikruak (?)	Hauterivian or Barremian	Palynomorphs	H.Haga, written commun., 1995
5	75Mu51	N/A	68° 28.2'	155° 59.0'	Okpikruak	Probably Neocomian	Foraminifera	A.Marianos, written commun., 1976
6	90Mu86-2	N/A	68° 30.0'	155° 49.0'	Okpikruak	Early Valanginian	Buchia sublaevis	W.P. Elder, written commun., 1991
7	83Bo66	N/A	68° 32.2'	155° 43.3'	Okpikruak	Valanginian	Mollusks	*D.A. Bodnar* [1984]
8	50AKt2000	298	68° 41.6'	156° 29.5'	Fortress Mtn, near base	middle early Albian	Mollusks	*Elder et al.* [1989]*
9	AB41	294	68° 45.5'	156° 45.0'	Torok (?)	middle early Albian	Mollusks	*Elder et al.* [1989]*
10	25ASmF7	301	68° 49.5'	156° 08.5'	Torok, upper part	middle early Albian	Mollusks	*Elder et al.* [1989]*
11	46ATh106	309	68° 51.0'	155° 17.0'	Nanushuk	early middle to middle middle Albian	Mollusks	*Elder et al.* [1989]*
12	53AB194	300	68° 51.7'	156° 06.0'	Torok, upper part	middle early Albian	Mollusks	*Elder et al.* [1989]*
	53AB1100	300	68° 51.7'	156° 06.0'	Torok, upper part	late early Albian	Mollusks	*Elder et al.* [1989]*
13	78ACG2ka	307	68° 53.2'	155° 05.5'	Nanushuk	middle to late Albian	Mollusks	*Elder et al.* [1989]*
14	47ATh324	295	68° 53.5'	156° 29.0'	Torok, upper part	late early Albian	Mollusks	*Elder et al.* [1989]*
15	46ACh120	305	68° 54.3'	155° 08.5'	Nanushuk	middle middle Albian	Mollusks	*Elder et al.* [1989]*
16	53AB1108	303	68° 56.8'	155° 45.0'	Nanushuk	middle Albian	Mollusks	*Elder et al.* [1989]*
17	52AWh17	275	69° 10.0'	156° 37.7	Torok, upper part	middle Albian	Mollusks	*Elder et al.* [1989]*
18	52AWh40	273	68° 11.2'	156° 46.6'	Torok, upper part	probably early middle Albian	Mollusks	*Elder et al.* [1989]*
19	47AWh174	271	68° 12.0'	156° 59.0'	Torok, upper part	early middle to middle middle Albian	Mollusks	*Elder et al.* [1989]*
20	47AWh119	283	69° 21.7'	156° 14.2'	Nanushuk	middle Albian	Mollusks	*Elder et al.* [1989]*

*Locations and ages reported in Elder et al., 1989 were modified according to W.P. Elder, written commun., Menlo Park, Calif., 1995.

deposits in the area of the cross section are shown in Figure 6b and Table 1. These were critical for constraining the timing of thrusting in this area. The cross section was converted from time to depthusing a simple linear velocity function of 2438 m/s, based on an average of stacking velocities and calculated interval velocities.

The cross section extends from the highly imbricated Devonian rocks south of the range front to nearly undeformed sedimentary fill in the foreland basin 200 km to the north (Plate 1). The basement slopes from a depth of 8 km at the northern end of the section to 12 km at the southern end of seismic line 37. The total thickness of the Brookian sequence is about 10 km at this latitude, compared with 4 km at the Seabee 1 well, at the southern end of the basin transect.

At the southern end of the cross section, south of the range front, a thick stack of imbricated Devonian clastic rocks within the Endicott Mountains allochthon is well-exposed at the surface (Figure 6 and Plate 1). This structural wedge lies south of seismic line RCS-37, so the subsurface geometry is not well-constrained. I projected observed stratal and structural dips from the surface into the subsurface and relied on seismic lines from the Inyorurak Pass and Howard Pass area, 25-35 km along strike to the west, to constrain the subsurface geometry of the thrust sheets. In the seismic lines to the west, the thrust sheets are visible as coherent, thick panels of south dipping reflections, so I drew the subsurface geometry of the Devonian imbricate wedge accordingly. The imbricate wedge includes repetitions of the Hunt Fork and Kanayut units, detached above a basal decollement in Hunt Fork shale (Plate 1). At the range front, this stack terminates in a regionally extensive upright anticline, traceable along strike to the west for at least 30 km in adjacent seismic lines and surface mapping. Along the northern margin of the anticline, forming the topographic break at the range front, is a major zone of thrusting in the Kayak shale, which I believe represents a regional roof thrust at the top of the Devonian imbricate wedge. Similar imbricate stacks, enclosed between regional detachment horizons, have been described in the northeastern Brooks Range and along the Dalton Highway [Wallace and Hanks, 1990; Wallace et al., 1997].

Figure 7 shows a line drawing and seismic data spanning the portion of the cross section from the range front to the Lisburne 1 well, at approximately true scale. The range front anticline, representing the leading edge of the Devonian imbricate wedge, is visible as a group of arching reflections in the southern end of the section, beneath shot point 1090, at 1.8 s.

About 8 km north of the Devonian imbricate wedge is the axis of a synform containing the Picnic Creek allochthon, according to field mapping by Mull et al. [1994]. The synform is visible in the shallow part of the seismic line, as concave-up reflections between shot points 1040 and 1080 (Figure 7 and Plate 1). At the surface, several isolated remnants of gabbro, probably belonging to the Copter Peak allochthon, lie in fault contact on the Picnic Creek allochthon. These are too small to show on the cross section, but they are labeled on the geologic map (Figure 6). These klippen are significant because they indicate that mafic and ultramafic rocks were thrust over Valanginian

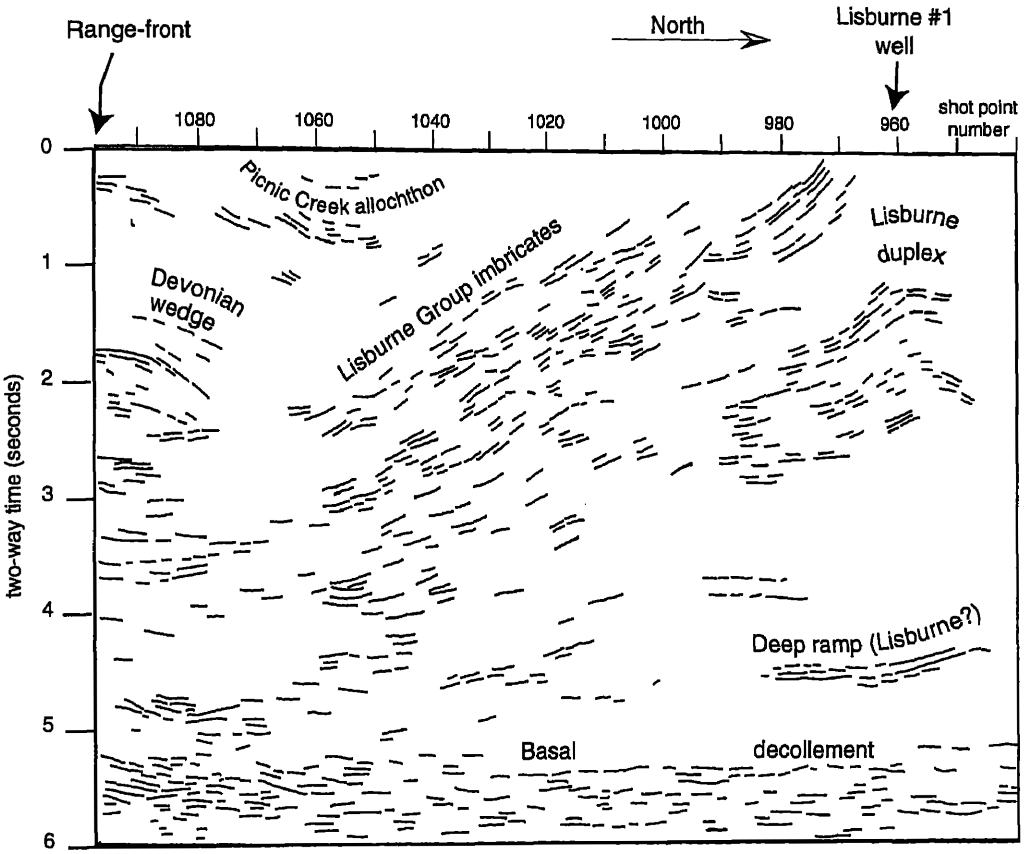


Figure 7. Line drawing of seismic line 37 (see Figure 6b for location), from the Brooks Range front to the Lisburne well, showing main structural elements interpreted in Plate 1. Horizontal and vertical scales are approximately equal.

rocks (Okpikruak Formation) of the Picnic Creek allochthon in this area. As mentioned above, the Okpikruak Formation locally contains mafic igneous clasts, probably derived from these allochthons. These relationships suggest that the ophiolitic allochthons were shedding detritus onto the Picnic Creek allochthon, and overthrusting those clastic deposits in the Valanginian [C.G. Mull, oral communication, 1996].

Along the northern margin of the Picnic Creek synform, Picnic Creek rocks lie in fault contact on Lower Cretaceous and older strata of the Endicott Mountains allochthon (Plate 1). The Endicott Mountains allochthon includes Hauterivian-Barremian shale in this area, suggesting that the Picnic Creek and higher allochthons were probably thrust over the Endicott Mountains allochthon during or after Hauterivian-Barremian time.

North of the Picnic Creek synform is the Lisburne duplex, the northernmost major structural culmination in this part of the thrust belt. It involves numerous repetitions of the Lisburne and Etivluk group rocks. At least five of these repetitions were penetrated in the Lisburne 1 well (Figure 4). Lower Cretaceous rocks are involved in a thrust sheet in the upper part of the well, beneath a thin tectonic sliver of Jurassic chert, recognized in the upper few hundred feet of the well and in outcrops along strike to the west. South of the well site, two additional thrust sheets of the Lisburne and Etivluk Groups lie in fault contact above these cherts and can be projected over the top of the Lisburne well. Several additional thrust repetitions are suspected at depth, based on the presence of strong south dipping seismic reflections beneath the well bottom (Plate 1). Thus a total of nine thrust repetitions can be identified, representing intense localized shortening in the Lisburne duplex. The scale of the cross section is too small to show the smaller horses. These represent less than 5% of the total shortening in the duplex, so their omission does not significantly alter the kinematic model. Imbrication of the Lisburne Group occurs above a detachment in the Kayak shale and mainly beneath a detachment in the Etivluk Group (Figure 4).

North of the Lisburne duplex is a zone of intense shearing and imbrication, which I mapped as a tectonic melange. At the surface, the melange is characterized by 0.1-10 m blocks of chert, limestone, mudstone, basalt, and coquinoid limestone beds, all with highly sheared margins, in a sheared argillite matrix. Many of the melange blocks belong to the Otuk, distal Lisburne, and Okpikruak Formations, so I believe that they are offscraped parts of the distal continental terrace stratigraphy, imbricated and sheared at the leading edge of the overthrust belt. Alternatively, they may be slide blocks in a sedimentary melange or an olistostrome that was tectonized after deposition [Crane, 1987].

In this melange zone is a klippe of basaltic rocks that have been correlated with the Copter Peak allochthon (Figure 6a), based on similarities with the Kikiktat Mountain Klippe 65 km along strike to the east [Mull et al., 1994; Solie and Mull, 1991]. This is a critical observation because it suggests that the higher allochthons including the Copter Peak extended as far north as the melange zone in the area of the structural transect.

North of the melange zone the deformation is much milder, characterized by shallow level thrust-cored anticlines and synorogenic piggy-back basins in the Cretaceous sedimentary rocks at the north end of the line (Figure 6a and Plate 1). I identified three piggy-back basins, based on their internal seismic stratigraphy, structural positions, and character of sediments where exposed. They are synformal basins filled with relatively coarse clastic deposits, and they are characterized by multiple unconformities separating steeper dips at depth from shallower dips near the surface.

The southernmost piggy-back basin has a well-exposed unconformity along its northern margin, as illustrated in Figure 8a. Beneath the unconformity are highly folded and steeply dipping shale and siltstone turbidites, with northwest vergent fold axes. These are overlain in angular unconformity by gently southward dipping conglomerate and sandstone. Immediately above the unconformity the conglomerate contains rip-up clasts and 1/2-m blocks of shale derived from the underlying deformed turbidites. The total thickness of the coarse clastic rocks above the unconformity is about 80 m at the surface, but these units are traceable downdip and southward into a broad zone of reflections, representing 350-400 m of correlative strata in the bottom of the synform. These relationships suggest that deposition of the conglomerate and sandstone took place while the synformal basin was growing, with thick deposition in the axial zone concurrent with uplift and erosion along the basin margins. The coarse clastic rocks are probably lower Albian in age, so this area was undergoing contractional deformation by Albian time. The tightly folded rocks beneath the unconformity attest to basin development in a regime of active northwest-southeast contraction. The southern margin of the basin may have been tilted northward in response to the progressive development of the Lisburne antiform, while the northern margin of the basin was tilted southward as the strata began to climb northward up an underlying thrust ramp.

Farther north, another synformal basin of probable early Albian age occurs between the Lisburne well and the West Kurupa well (Figure 6 and Plate 1). It contains intrabasinal unconformities that suggest early Albian northward motion on a thrust fault recognized from seismic geometries south of the West Kurupa well. North of that well is a third, well-developed piggy-back basin on the northern margin of the Kurupa anticline (Figure 8b). It appears to have formed by passive folding above the thrust ramp that cores the Awuna anticline. Syntectonic sediments in this basin are of early to middle Albian age, and a throughgoing unconformity within the basin projects to outcrops of basal middle Albian age. The timing of growth in these three basins, which I interpret as thrust-related piggy-back basins, is indicative of a northward propagating thrust sequence in early and middle Albian time.

Figure 8a. Photograph taken near shot point 740 on (Figure 6b and Plate 1). View to southwest of northern margin of synformal piggy-back basin. Unconformity near middle of photo is the base of the piggy-back basin. Shale below unconformity is deformed by north-vergent folding, conglomerate and sandstone above unconformity are tilted gently toward southwest at this locality.

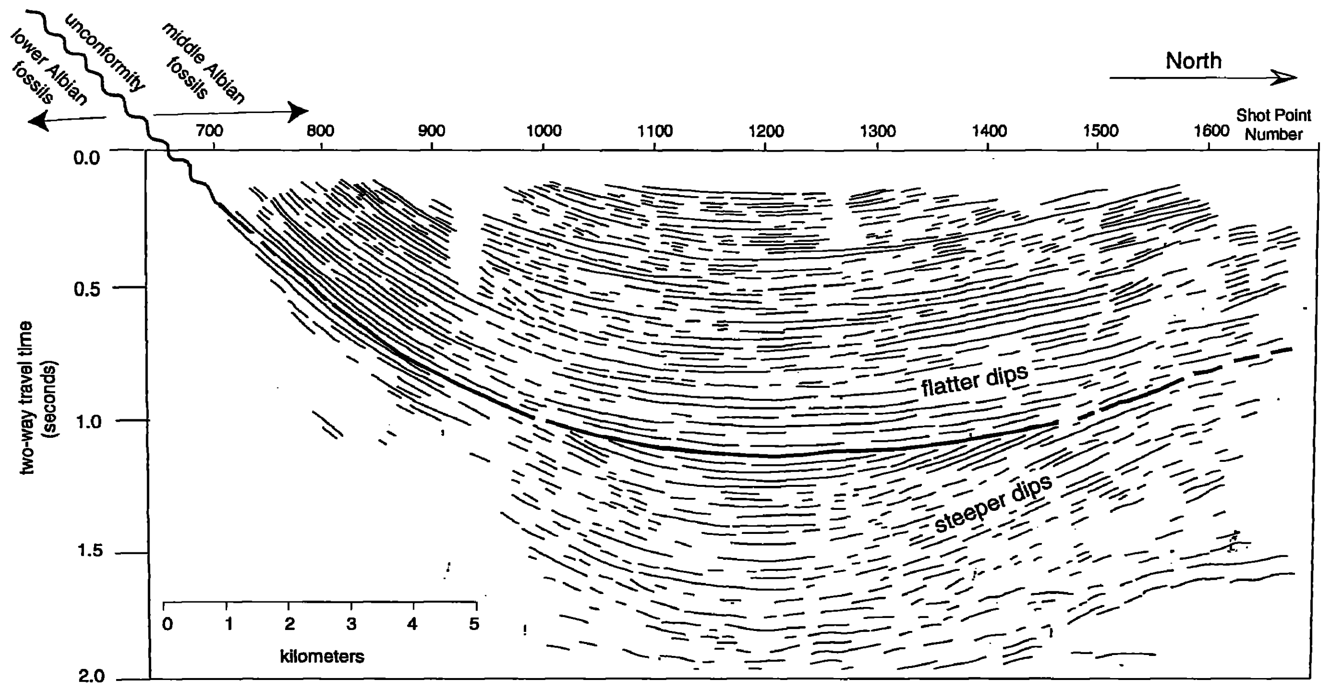


Figure 8b. Line drawing of seismic line 722-80 (location shown on Figure 6b and Plate 1), showing progressively steeper dips in the basal part of a piggy-back basin. Lower to middle Albian intra-basinal unconformity dates progressive deformation as mid-Cretaceous in age.

Summary of Structural Geometry

On the basis of the regional nature of the range front anticline and the presence of arching reflections in the subsurface beneath it, I interpret this structure as a major hanging wall cutoff at the leading edge of a thick Devonian imbricate stack. South of my section, this basal thrust must root into a deep-seated detachment in the Hunt Fork shale. Distal continental margin fragments (i.e., Picnic Creek family of allochthons) and ophiolitic remnants (Copter Peak, Misheguk Mountains allochthons) are preserved in two synformal areas, one immediately north of the range front and the other in the melange zone on the northern margin of the Lisburne duplex. The ophiolitic klippen probably overrode the Picnic Creek in Valanginian time according to the age of synorogenic deposits of the Okpikruak Formation. These higher allochthons lie in fault contact on Lower Cretaceous rocks of the Endicott Mountains allochthon. This suggests that they were emplaced onto the Endicott Mountains allochthon in Early Cretaceous time.

The Lisburne duplex represents a second major imbricate stack, formed mainly above a detachment in the Kayak shale and below a roof thrust in Triassic to Lower Cretaceous cherts and shales. To the north, the upper detachment climbs to successively shallower stratigraphic horizons in the Cretaceous Torok sequence of the foreland basin. Anticlines and syntectonic piggy-back basins in the foreland basin sediments north of the Lisburne duplex attest to minor contraction north of the Lisburne well after deposition of the flysch and during molasse deposition in the foreland, in early to middle Albian time.

THERMAL CONSTRAINTS

I employed three independent geothermometers (apatite fission track, vitrinite reflectance analyses, and conodont alteration indices) to infer the depth of burial and timing of exhumation of the main structural elements in the cross section. More than 200 vitrinite reflectance analyses were carried out for this study by M. Pawlewicz (U.S. Geological Survey). Fourteen sandstone samples were collected for this study and analyzed by P. O'Sullivan of LaTrobe University. Apatite sample localities are shown in Figure 6 and Plate 1. Nearby vitrinite reflectance values were projected onto the cross section (Plate 1). I also utilized existing apatite fission track analyses [O'Sullivan, 1993] and vitrinite analyses [Magoon et al., 1988; Johnsson et al., 1992] from the Lisburne well (Figure 4), as well as conodont alteration indices [Dumoulin and Harris, 1993; Johnsson et al., 1992].

Vitrinite Reflectance

Vitrinite reflectance (Ro) values were determined on shale samples, measured with the in situ method. The Ro values are presumed to represent maximum burial temperatures experienced by the rock and can be converted to estimated paleotemperature according to the burial-heating curve of Barker and Pawlewicz [1994], which follows the equation ln(Ro) +1.68)/ 0.0124. The highest Ro values were found in the Devonian rocks of the Endicott Mountains allochthon, south of the range front, as shown in Plate 1. These rocks yielded Ro values near 4.0, corresponding to paleotemperatures of nearly 250°C. Immediately north of the range front, Carboniferous rocks in the Endicott Mountains allochthon exhibit Ro values of 2-2.5, corresponding to paleotemperatures of about 200°C. Farther north, in the Picnic Creek allochthon, I obtained Ro values of 1-1.5 corresponding to 150°C.

Surface samples near the Lisburne well yielded anomalously low Ro values, ranging between 0.35 and 0.52, probably due to the high organic content of the Etivluk Group shales in this area. Bodnar [1984] reported similarly low Ro values from the Otuk Formation type section 6 km north of the Lisburne well. Conodonts from the outcrop of the Lisburne limestone just south of the well site have conodont alteration indices of 1-1.5 [Dumoulin and Harris, 1993], corresponding to an Ro of about 0.6, or a paleotemperature of about 90°C. This agrees quite well with vitrinite reflectance of 0.4-0.6 determined from samples in the upper part of the Lisburne well, as shown in Figure 4.

Several vitrinite reflectance gradients are present in the Lisburne well. These are shown with regression lines in Figure 4. The upper two allochthons in the well have Ro values that increase linearly with depth, from less than 0.5 near the surface to 2.0 at a depth of 3300 m. Using the Barker and Pawlewicz [1994] burial heating curve, this corresponds to a paleogeothermal gradient of roughly 35°C/km. Thrust sheets 3 and 4 exhibit a very slow increase in Ro with depth; from 3300 m to 5181 m, Ro values between 2.0 and 2.5 are reported, corresponding to paleotemperatures near 100°C. It is not possible to fit a reasonable gradient to these trends. They require a structural explanation, which is presented below.

Less than a kilometer to the north, synorogenic clastics that correlate with Aptian to Albian rocks in the upper part of the Lisburne well exhibit very low thermal maturity (Ro=0.48) and unreset apatites. Vitrinite reflectance values in the melange zone, farther north of the well, are extremely variable, probably because of the complicated mixture of tectonic blocks or sedimentary olistostromes in this area [Crane, 1987]. In the Cretaceous rocks of the foreland basin, Ro values are much less variable, ranging between 0.6 and 0.8, corresponding to paleotemperatures of 100°C.

Inferred Burial Depth for the Devonian Imbricate Wedge

Vitrinite reflectance values, reported above, were used to estimate depth of burial for rocks now at the surface, based on a presumed paleothermal gradient of 30°C/km. This is the paleothermal gradient predicted by vitrinite reflectance over an interval of 3366 m in the West Kurupa well [K.J. Bird, oral commun., 1997]. When vitrinite reflectance isograds are reconstructed according to this gradient, they can be used to estimate the depth of burial of the sampled rocks during the time of maximum burial (Figure 9). The estimated depth of burial is 3 km over the northern portion of the cross section, indicating uniform burial and uniform subsequent uplift in this area. The isograd surfaces become steeply inclined at the range front, indicating increasing degrees of uplift in the Devonian imbricate wedge.

On the basis of the high thermal maturity in the Endicott Mountains allochthon at the range front (Plate 1), I believe that the allochthon was structurally buried beneath several kilometers of higher allochthons. Mississippian rocks near the range front have been heated to about 200°C, or a depth of roughly 6.5 km. Only 1 km of this can be accounted for by the stratigraphic thickness of younger sediments deposited above it, assuming that these rocks were too far south to have received thick Brookian deposits. The remaining 5.5 km of burial require tectonic burial, probably by emplacement of the Picnic Creek and Copter Peak allochthons, as well as imbrication and thickening within the Endicott Mountains allochthon itself.

The Hunt Fork shale, which occupies a deeper structural and stratigraphic position within the Endicott Mountains allochthon has vitrinite reflectance values corresponding to paleotemperatures near 250°C, or burial depths of 8.5 km. This additional 2 km of burial for the Hunt Fork Shale as compared with the Kayak Shale, corresponds roughly to the thickness of Upper Devonian Kanayut and Noatak sediments deposited above the Hunt Fork Shale. Taking its additional sedimentary burial into account, the thermal maturity of the Hunt Fork shale is consistent with tectonic burial beneath thrust sheets totaling 6.5 km. The thermal maturity in the lower part of the Picnic Creek allochthon is consistent with tectonic burial beneath 5 km or so. I argue that the Copter Peak allochthon originally extended across this region from its present-day outcrop areas to the east and west and is responsible for the deep burial of the rocks near the range front. Mafic igneous clasts in the Okpikruak and Fortress Mountain Formations attest to the presence of a mafic source area in Early to middle Cretaceous time.

Inferred Burial Depth for the Lisburne Duplex

On the basis of the low thermal maturity indicated by vitrinite reflectance values and conodont alteration indices from samples in the upper 500 m of the Lisburne well and in nearby

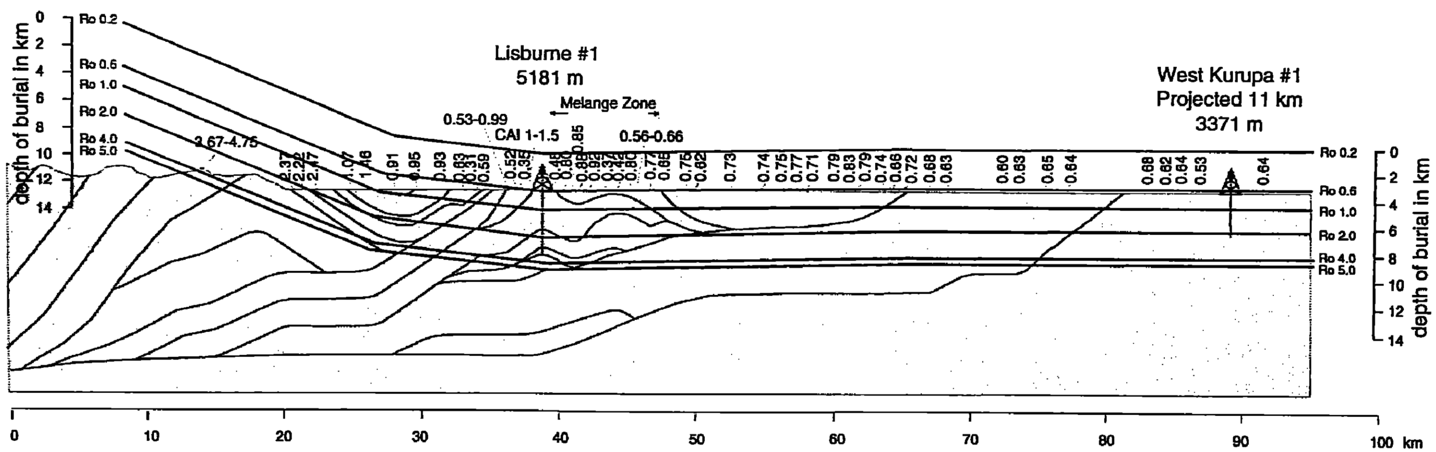


Figure 9. Cross section, corresponding to southern part of cross section AB of Plate 1, showing the positions of vitrinite reflectance isograds Ro 0.2, 0.6, 1.0, 2.0, 4.0, and 5.0 estimated from surface Ro values. Spacing of isograds is based on an inferred paleothermal gradient of 30° C/km. Vitrinite reflectance values converted to paleotemperature according to burial heating curve of Barker and Pawlewicz [1994].

surface outcrops, the near-surface portion of the Lisburne duplex was never buried to depths greater than 3 km. Yet my seismic interpretation of line 37, in the southernmost part of the foreland basin (Plate 1), indicates that roughly 10 km of combined Torok, Fortress Mountain, and Nanushuk sediments of Barremian to Albian age were laid down in this area. If the Lisburne duplex had formed after this episode of thick sedimentation in the foreland basin, I would expect to see very high thermal maturity in the core of the antiform. Instead, vitrinite values at the surface are less than 0.6 in the core of the antiform. This indicates that the duplex was initiated prior to the accumulation of thick sedimentary deposits in the foreland, so prior to Albian time. Because it was already a structural high, it escaped deep sedimentary burial.

In the vitrinite reflectance gradients in the Lisburne well, I see evidence for two episodes of imbrication in the duplex. The upper two thrust sheets in the Lisburne well were first imbricated, then heated by burial beneath 3 km or less of overburden. The lower three thrust sheets all have Ro values in the range of 2-2.5, suggesting that these rocks attained maximum burial before they were stacked by thrusting. This would have the effect of repeating the prethrusting paleothermal gradient in vertically stacked sheets.

The low thermal maturity in the upper part of the Lisburne duplex also suggests that these rocks never underwent the deep tectonic burial. Only 3 km of sedimentary and/or tectonic burial are permitted by the low maturity of the rocks near the surface. This constrains the overall combined thickness of the Picnic Creek, Copter Peak, and Misheguk Mountains allochthons in this area to 3 km or less.

Apatite Fission Track Ages

Apatite concentrates were separated using conventional magnetic and heavy liquid techniques. Grains were prepared for irradiation in the X-7 facility of the HIFAR reactor, Lucas Heights, New South Wales, Australia. The external detector method has been used exclusively throughout this study. Fission track ages were calculated using the zeta calibration method and standard fission track age equation [Naeser, 1979; Hurford and Green, 1982]. Errors were calculated using the techniques of Green [1981]. The c^2 statistic is used to detect the probability that all age grains analyzed belong to a single population of ages [Galbraith, 1981]. A probability of <5% is evidence of an asymmetric spread of single-grain ages. In instances where a spread in ages is found, the "conventional analysis" (as defined by Green [1981]), based purely on Poissonian variation, is not valid and the "central age" [Galbraith and Laslett, 1993], which is essentially a weighted-mean age, is reported. Confined fission tracks were measured following the recommendations of Laslett et al. [1982].

Thermal history interpretations are based on a quantitative treatment of annealing achieved by forward computer modeling [Green et al., 1989] of track shortening and age evolution through likely thermal histories for an average apatite composition (Durango apatite 0.4 wt % Cl), while making appropriate adjustments for the actual Cl composition likely in each sample. This model by Laslett et al. [1987] for annealing of fission tracks in apatite gives predictions that are consistent with geologic constraints on annealing behavior, as explained by Green et al. [1989]. Predictions based on an average composition of 0.4 wt % Cl should slightly overestimate the actual amount of annealing, although in thermal histories resulting from continuous cooling, as in this study, compositional effects play a relatively minor role [Green et al., 1989].

Table 2 presents the locality and apatite fission track analytical results of the surface samples collected for this study and previously analyzed samples from the Lisburne 1 well. The sample locations are shown in Figure 6b and Plate 1. Thirteen of the original 14 surface samples yielded sufficient apatite grains for meaningful age determinations. Single grain ages and track length distributions are available upon request from P. O'Sullivan. On the basis of forward modeling of the track length distributions and age data, following the procedures outlined by Green et al. [1989], two principle cooling events were recorded by these samples: (1) a mid-Cretaceous event (90-110 Ma), evidenced by a grouping of high-precision single-grain ages in 4 of the 13 samples, and (2) an Early Tertiary, Paleocene-Eocene event (50-60 Ma) present in all 13 samples (Table 2). Several samples record both events, suggesting partial cooling during the mid-Cretaceous followed by more complete cooling in Paleocene to Eocene time. These samples contain apatites of varying grain compositions; grains tested from 8 of the 13 samples analyzed for this study (n=160) have apatite compositions that are predominantly fluorine-rich (~0.0 to 0.02 wt % Cl) with ~15% of grains ranging between 0.05 and 0.08 wt % Cl [P.B. O'Sullivan, unpublished data, 1993]. The chlorine-rich grains with higher blocking temperatures (>120°C) record the mid-Cretaceous age, while fluorine-rich grains with lower blocking temperatures (90°C) record the younger Paleocene-Eocene age.

I have five apatite fission track ages from the Endicott Mountains Allochthon south of the range front (Figure 6, Plate 1, and Table 2). All five samples were collected from Upper Devonian Noatak sandstone. Data from all five samples suggest rapid Tertiary cooling, in the neighborhood of 50-60 Ma, while two of the samples also record mid- Cretaceous cooling, between 90 and 110 Ma. Data from two samples from the Picnic Creek allochthon north of the range front also indicate rapid cooling during the mid-Cretaceous and Paleocene-Eocene. From these ages I conclude that the wedge of imbricated Devonian rocks at the range front, as well as the allochthons carried piggy-back, were emplaced prior to mid-Cretaceous time, when they underwent partial cooling. They were affected by a second episode of cooling in Paleocene-Eocene time.

Table 2. Fission Track Sample Locations, Counting, and Age Data

Locality	Sample	Latitude, North	Longitude, West	Elevation, m	Number of crystals	Spontaneous Rho-S	Spontaneous NS	Induced Rho-I	Induced NI	$P(X^2)$, %	Age ± σ, Ma	Interpreted Age, Ma	Formation
						Surface Samples							
1	DH93-095	68° 11' 45"	155° 38' 00"	1510	25	1.031	592	2.521	1447	1.20	97.6±7.5	90-110, 50-60	Dn
2	DH93-096	68° 09' 19"	155° 40' 05"	1370	25	0.6061	437	1.933	1394	1.40	75.4±5.2	90-110, 50-60	Dn
3	DH93-098	68° 03' 49"	155° 26' 10"	1240	25	0.4280	205	2.261	1083	58.60	44.7±3.5	50-60	Dn
4	DH93-099	68° 04' 55"	155° 24' 53"	860	25	0.4795	187	2.238	873	79.80	50.6±4.2	50-60	Dn
5	DH93-100	68° 10' 17"	155° 14' 52"	1670	7	0.1551	29	0.7487	140	91.30	48.9±10.0	50-60	Dn
6	DH93-118	68° 38' 20"	155° 46' 10"	405	27	0.5181	400	1.885	1455	0.50	59.8±6.3	50-60	Kft
7	DH93-120	68° 41' 01"	155° 51' 34"	380	25	0.1929	65	0.8605	290	91.30	52.9±7.3	50-60	Kft
8	DH93-122	68° 33' 37"	155° 24' 27"	500	25	0.2683	154	1.157	664	69.80	54.8±5.0	50-60	Kft
9	DH93-124	68° 29' 08"	155° 26' 04"	705	26	0.2792	184	0.7709	508	7.50	85.3±7.5	50-60	Kft
10	FC93-047	68° 29' 20"	155° 42' 50"	540	25	0.3582	245	1.215	831	0.00	72.2±9.9	50-60	Kft
11	FC93-051	68° 29' 55"	155° 42' 42"	540	25	0.6559	612	2.900	2706	29	55.1±2.7	50-60	Ko
12	FC93-084	68° 20' 58"	155° 43' 40"	810	25	0.8591	500	2.476	1441	0.90	81.2±6.3	90-110, 50-60	Mku
13	FC93-086	68° 21' 25"	155° 43' 35"	810	25	0.7042	338	3.002	1441	0.10	51.6±5.3	90-110, 50-60	Mku
						Lisburne 1 Well							
1	89POS06	68° 29' 06"	155° 44' 36"	-634	20	0.3068	119	0.7141	277	5.1	92.1±10.3	90-110, 50-60	Kl
2	89POS05	68° 29' 06"	155° 44' 36"	-1190	26	0.2552	158	0.8366	518	24.0	65.6±6.2	90-110, 50-60	Kl
3	89POS04	68° 29' 06"	155° 44' 36"	-1896	8	0.1187	14	0.6955	82	18.0	36.8±10.7	50-60	JPe
4	89POS03	68° 29' 06"	155° 44' 36"	-2663	10	0.0475	8	0.6538	107	91.4	16.1±5.9	50-60	JPe
5	89POS01	68° 29' 06"	155° 44' 36"	-4148	6	0.0570	2	0.5983	21	62.7	20.5±15.2	50-60	JPe

Location numbers refer to Figure 6b and Plate 1. Formations and units: Dn, Devonian Noatak sandstone; Kft, Cretaceous Fortress Mountain formation; Ko, Cretaceous Okpikruak Formation; Mku, Mississippian Kurupa sandstone; Kl, Lower Cretaceous undivided, and JPe, Permian to Jurassic Etivluk Group. Interpreted ages, based on analyses of single grain ages, are thought to represent the main cooling episodes that affected this area. Samples with two interpreted ages have bimodally distributed single grain ages.

Apatite fission track data from five samples in the Lisburne well yield similar cooling ages [O'Sullivan, 1993]. Two samples (localities 1 and 2, Table 2) from depths of less than 1200 m, record both the mid-Cretaceous and the Early Tertiary cooling episodes. Samples from localities 3, 4, and 5, from depths greater than 1890 m, show only Paleocene and younger individual grain ages. Presumably, these deeper samples remained above 110°C during the mid-Cretaceous cooling episode.

Fission track data from all six samples of Cretaceous age rocks in the foreland basin suggest that these rocks experienced rapid cooling during the Early Tertiary between ~50 and 60 Ma. In most cases, cooling occurred from temperatures >110°C to temperatures in the range of ~50-70°C. However, data from two samples (localities 9 and 10 in Table 2, Figures 6b, and Plate 1) indicate that the samples were not completely reset prior to Early Tertiary cooling and seem to have cooled from maximum paleotemperatures in the range of ~90-110°C. These two samples are in the Aptian to Albian clastics that correlate with the upper part of the Lisburne well, so they provide further evidence that the Lisburne Duplex was not deeply buried relative to surrounding areas.

Summary of Thermal Constraints

Vitrinite reflectance values and apatite fission track ages along the cross section place the following constraints on the timing of deformation. The Endicott Mountains and Picnic Creek allochthons near the range front were very deeply buried, and I argue that at least 5 km of this burial was tectonic. Apatite fission track ages from these allochthons indicate that they were cooling by 90-110 Ma, and again at 50-60 Ma. This requires initial emplacement and imbrication of allochthons now found at the range front, prior to mid-Cretaceous time. Subsequent mid-Cretaceous exhumation was probably coeval with the molasse phase of sedimentation in the foreland basin.

The Lisburne duplex is a long-lived structure. It was initiated during early Brookian deposition in the foreland basin and remained a structural high during the major influx of sediments into the basin. The entire area was exhumed in Paleocene time to produce the younger fission track ages. This corresponds to a second episode of coarse clastic sedimentation to the northeast of my foreland basin transect.

CHRONOLOGY OF DEFORMATION

On the basis of the thermal and stratigraphic arguments described above and the timing of tectonic subsidence and flysch-molasse cycles in the foreland basin, I present an integrated model for the sequence and timing of deformation and sedimentation along this structural transect. The main stages of thrusting and sedimentation are shown in Plate 2, a kinematic model produced with

Thrustpack, and modified to include a schematic representation of the Picnic Creek, Copter Peak, and Misheguk Mountains allochthons. I do not formally model the imbrication history among the higher allochthons because they originated some unknown distance south of my structural transect. However, I include them schematically to show their approximate regional extent and their probable time of emplacement onto the Endicott Mountains allochthon. Thus my model begins in Valanginian time, when the distal continental margin and ophiolitic allochthons were undergoing imbrication far to the south of this structural transect.

Valanginian

Copter Peak and Misheguk Mountains allochthons were thrust onto the Picnic Creek allochthon at this time, during deposition of the orogenic sediments of the Okpikruak Formation. These allochthons originated hundreds of kilometers south of my structural transect, at the projected southern edge of the retrodeformed Endicott Mountains allochthon.

Hauterivian

Regional thermal uplift affected the northern margin of the Colville Basin, including the basin transect, in Hauterivian time, marked by the development of the Lower Cretaceous unconformity. Because this uplift was regionally synchronous and strongly focused along the Barrow Arch, I interpret this event as thermal uplift of the rift shoulder as spreading was initiated in the Canada Basin. The Barrow Arch may have played a dual role as a flexural bulge, but my basin analysis lends no direct support to this interpretation. This uplift had no direct influence in the region of this structural transect, nearly 200 km south of the Barrow Arch.

Barremian

Dramatic downward flexure affected the Colville Basin in Barremian time. I argue that this flexure was produced by crustal thickening during the emplacement of the distal continental margin and ophiolitic allochthons onto the Endicott Mountains allochthon (Plate 2b) and by internal imbrication in the Endicott Mountains allochthon itself (Plate 2c). Along the structural transect, this episode was manifested by deep tectonic burial in the Endicott Mountains and Picnic Creek allochthons (Plate 2b), and formation of the orogenic wedge of Upper Devonian rocks south of the range front (Plate 2c). The Lisburne Duplex began to form at this time. This episode of thrusting resulted in deep-water flysch sedimentation in the foreland basin.

This is the main episode of thrusting in the frontal Brooks Range. During this stage, continental margin rocks (Endicott Mountains allochthon) became intensely involved in contraction, and the North Slope autochthon underwent lithospheric flexure and began to receive flysch sediments from the orogen. The timing of this event (Barremian) is soon after the initiation of spreading in the Canada basin (Hauterivian), suggesting that the two events are related.

Mid-Cretaceous

Albian time was a period of widespread exhumation in the Brooks Range, according to apatite fission track ages in the thrust belt, and the age of molasse-type sediments in the foreland basin. The Lisburne duplex continued to grow at this time (Plate 2d), with imbrication of the lower thrust sheets. This is also the time when syndeformational piggy-back basins formed in lower to middle Albian rocks, indicating that minor thrusting advanced into shallow strata of the foreland basin.

Mid-Cretaceous apatite cooling ages (90-110 Ma) along the structural transect are broadly synchronous with a host of other mineral cooling ages in the hinterland of the Brooks Range, suggesting substantial orogen-scale exhumation during this time. This exhumation was probably achieved by a combination of tectonic and erosional unroofing of the orogen. The evidence for tectonic unroofing is on the southern flank of the Brooks Range, where extensional faults have been recognized by several workers [Gottschalk and Oldow, 1988; Miller and Hudson, 1991]. The first, coarse-grained molasse deposits in the foreland basin (Nanushuk Group) are also mid-Cretaceous in age, suggesting rapid erosion at this time. Tectonic rebound in the foreland basin, based on my tectonic subsidence analysis, may have been a response to decreasing the size of the orogenic load during this time. I suggest that tectonic and erosional unroofing in mid-Cretaceous time was an isostatic response to crustal thickening in the Early Cretaceous. Alternatively, it may have been a response to thermal reequilibration and expansion of lithosphere that was subducted in the earlier phases of the orogeny.

Late Cretaceous to Paleocene

Late Cretaceous time brought a period of very modest tectonic subsidence in the foreland basin, as indicated by a second cycle of flysch and molasse progradation, mainly northeast of the basin transect. I suggest that mild subsidence in the northern foreland may have been driven by minor shallow level thrusting south of the basin transect (Plate 2d), toward the present limit of contractional deformation near the Seabee well. The foreland basin reached its maximum burial depth at this time.

Paleocene to Eocene

Paleocene-Eocene time was a second period of regional exhumation, according to apatite fission track cooling ages (50-60 Ma) in the Brooks Range and the foreland basin. Several kilometers of sedimentary overburden were removed from foreland basin, and erosion continues to the present-day. The approximate position of the present-day erosion level is shown on Plate 2e). Coarse clastic sediments were deposited in the Sagavanirktok Delta, indicating rapid erosion at this time. This episode of exhumation coincides with a period of deformation in the Doonerak area along the TACT line [O'Sullivan et al., 1996; Moore et al., 1997], and in the northeastern Brooks Range [O'Sullivan et al., 1993].

CONCLUSIONS

Tectonic subsidence analysis in the Colville Basin, combined with geometric and thermal analyses in the northern Brooks Range, provides an integrated view of sedimentation and deformation resulting from the Brookian orogeny. I have developed a kinematic model for the sequence of deformation at the juncture between the thrust belt and the foreland basin, starting in Valanginian time with the imbrication of the distal continental margin and ophiolitic allochthons south of the modelled area. This was followed by thermal uplift along the Barrow Arch in Hauterivian time. The main episode of deformation in the frontal Brooks Range was a Barrremian thrusting event, which produced intense flexure of the North Slope, followed by the arrival of deep-water flysch sediments from southern source area into the newly formed foreland basin. This was followed in mid-Cretaceous time by widespread exhumation in the Brooks Range during accumulation of coarse clastic rocks in the foreland basin, some in active piggy-back basins. In Late Cretaceous to Paleocene time the thrust front propagated forward to its northern limit, and deformed Upper Cretaceous rocks in the central part of the basin. From the Paleocene time to the present, ongoing erosion unburied the rocks now exposed at the surface.

REFERENCES

Armstrong, R.L., J.E. Harakal, R.B. Forbes, B.W. Evans, and S.P. Thurston, Rb-Sr and K-Ar study of metamorphic rocks o fthe Seward Peninsula and southern Brooks Range, in Blueschists and Eclogites, edited by B.W. Evans and E.H. Brown, Mem. Geol. Soc. Am. 164, 185-203, 1986.

Barker, C.E., and M.J. Pawlewicz, Calculation of vitrinite reflectance from thermal histories and peak temperatures: A comparison of methods, in Vitrinite Reflectance as a Maturity Parameter: Applications and Limitations, edited by P.K. Mukhopadhhay and W. Dow, ACS Symp. Ser. 570, 1994.

Beaumont, C., Foreland basins, Geophys.J. R.Astron. Soc. 65, 291-329, 1981.

Bird, K.J., Alaskan North Slope stratigraphic nomenclature and data summary for government-drilled wells, in Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982, edited by G. Gryc, U.S. Geol. Surv. Prof. Pap., 1399, 317–354, 1988.

Bird, K.J., The Ellesmerian petroleum system, North Slope of Alaska, USA, in The Petroleum System--From Source to Trap, edited by L.B. Magoon and W.G. Dow, AAPG Mem. 60, 339-358, 1994.

Bird, K.J., and C.M. Molenaar, The North Slope foreland basin, Alaska, in Foreland Basins and Foldbelts, edited by R. Macqueen and D. Leckie, AAPG Mem., 55, 363-393, 1992.

Blythe, A.E., J.M. Bird, and G.I. Omar, Deformational history of the central Brooks Range, Alaska: Results from fission track and $^{40}Ar/^{39}Ar$ analyses, Tectonics, 15(2), 440-455, 1996.

Bodnar, D.A., Stratigraphy, age, depositional environments, and hydrocarbon source rock evaluation of the Otuk Formation, north-central Brooks Range, Alaska, M.S. thesis, 232 pp., Univ. of Alaska, Fairbanks, 1984.

Bodnar, D.A., Stratigraphy of the Otuk Formation and a Cretaceous coquinoid limestone and shale unit, northcentral Brooks Range, in Dalton Highway, Yukon River to Prudhoe Bay, Alaska: Bedrock Geology of the Eastern Koyukuk Basin, Central Brooks Range, and East Central Arctic Slope, Guideb. 7, edited by G.C. Mull and K.E. Adams, pp. 285-292, Alaska Div. of Geol. and Geophys. Surv., Fairbanks, 1989.

Bond, G.C., and M.A. Kominz, Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains: Implications for subsidence mechanisms, age of breakup, and crustal thinning, Geol. Soc. of Amer. Bull., 95(2), 155-173, 1984.

Bond, G.C., M.A. Kominz, M.S. Steckler, and J.P. Grotzinger, Role of thermal subsidence, flexure and eustasy in the evolution of early Paleozoic passive-margin carbonate platforms, in

Controls on carbonate platform and basin development, edited by P.D. Crevello, J.J. Wilson, J.F. Sarg, and J.F. Read, Soc. of Econ. Paleontol. Mineral., 44, Tulsa, Okla., 1989.

Boyer, S.E., and D. Elliot, Thrust systems, AAPG Bull., 66, 1196-1230, 1982.

Brosgé, W.P., and C.L. Whittington, Geology of the Umiat-Maybe Creek region, Alaska, U.S. Geol. Surv. Prof. Pap., 303-H, 501-638, 1966.

Chapman, R.M., R.L. Detterman, and M.D. Mangus, Geology of the Killik-Etivluk Rivers region, Alaska, report, US Geol. Surv., Reston, Va., 1964.

Coakley, B.J., and A.B. Watts, Tectonic controls on the development of unconformities: The North Slope, Alaska, Tectonics, 10(1), 101–130, 1991.

Cole, F., K.J. Bird, and D.G. Howell, Preliminary results of a tectonic subsidence analysis of the central North Slope, Alaska, in Geologic Studies in Alaska by the U.S. Geological Survey, 1993, edited by A. Till and T. Moore, U.S. Geol. Surv. Bull., 2107 , 115-132, 1994.

Cole, F., K.J. Bird, J. Toro, F. Roure, and D.G. Howell, Kinematic and subsidence modeling of the north-central Brooks Range and North Slope of Alaska, U.S. Geol. Surv. Open File Rep., 95-0823, 1995.

Crane, R.C., Cretaceous olistostrome model, Brooks Range, Alaska, in Alaskan North Slope Geology, edited by I. Tailleur, and P. Weimer, pp. 433-440, Pac. Sect., Soc. of Econ. Paleontol. and Mineral., Bakersfield, Calif., 1987.

Creaney, S., and Q.R. Passey, Recurring patterns of total organic carbon and source rock quality within a sequence stratigraphic framework, American AAPG Bull., 77 , 386-401, 1993.

Curtis, S.M., I. Ellersieck, C.F. Mayfield, and I.L. Tailleur, Reconnaissance geologic map of the southwestern Misheguk Mountain quadrangle, Alaska, report, U.S. Geol. Surv., Reston, Va., 1984.

Dahlstrom, C.D.A., Balanced cross-sections, Bull. Can. Pet. Geology, 18, 332-406, 1968.

Dillon, J.T., Structure and stratigraphy of the southern Brooks Range and northern Koyukuk basin near the Dalton Highway, in Dalton Highway, Yukon River to Prudhoe Bay, Alaska: Bedrock Geology of the Eastern Koyukuk Basin, Central Brooks Range, and East Central Arctic Slope, Guideb. 7, edited by G.C. Mull and K.E. Adams, pp. 157-188, Alaska Div. of Geol. and Geophys. Surv. Fairbanks, 1989.

Dumoulin, J.A., and A.G. Harris, Lithofacies and conodonts of Carboniferous strata in the Ivotuk Hills, western Brooks Range, Alaska, in Geologic Studies in Alaska by the U.S. Geological Survey During 1992, edited by C. Dusel-Bacon and A.B. Till,, U.S. Geol. Surv. Bull., 2068, 31-47, 1993.

Elder, W.P., J.W. Miller, and D.P. Adam, Maps showing fossil localities and checklists of Jurassic and Cretaceous macrofauna of the North Slope of Alaska, U.S. Geol. Surv. Open File Rep., 89-556, 1989.

Ellersieck, I., C.F. Mayfield, I.L. Tailleur, and S.M. Curtis, Thrust sequences in the Misheguk Mountain quadrangle, Brooks Range, Alaska, in The United States Geological Survey in Alaska: Accomplishments During 1978, edited by K.M. Johnson and J.R. Williams, U.S. Geol. Surv. Circ., 804-B, B8, 1979.

Flemings, P.B., Three-dimensional foreland basin stratigraphic geometry and subsidence history: Colville trough, Alaska, paper presented at annual meeting, Am. Assoc. of Pet. Geol., Calgary, Alberta, Canada, 1992.

Frederiksen, N.O., T.A. Ager, and L.E. Edwards, Palynology of Maastrichtian and Paleocene rocks, lower Colville River region, North Slope of Alaska, Can. J. Earth Sci., 25, 512-527, 1988.

Galbraith, R.F., On statistical models for fission-track counts, Math. Geol., 13, 471-488, 1981.

Galbraith, R.F., and G.M. Laslett, Statistical models for mixed fission-track ages, Nucl. Tracks, 21, 459-470, 1993.

Gottschalk, R.R., Jr., and J.S. Oldow, Low-angle normal faults in the south-central Brooks Range fold and thrust belt, Alaska, Geology, 16, 395-399, 1988.

Grantz, A., and S.D. May, Rifting history and structural development of the continental margin north of Alaska, in Studies in Continental Margin Geology, edited by J.S. Watkins and C.L. Drake, AAPG Mem., 34, 77-100, 1983.

Grantz, A., S.D. May, and P.E. Hart, Geology of the Arctic continental margin of Alaska, in The Geology of North America, vol. L, The Arctic Ocean Region, edited by A. Grantz, pp. 257-288, Geol. Soc. of Am., Boulder, Colo., 1990.

Green, P.F., A new look at statistics in fission-track dating, Nucl. Tracks, 5, 77-86, 1981.

Green, P.F., I.R. Duddy, G.M. Laslett, A.J. Hegarty, A.J.W. Gleadow, and J.F. Lovering, Thermal annealing of fission-tracks in apatite, 4, Qualitative modeling techniques and extensions to geological timescales, Chem. Geol., 79, 155-182, 1989.

Gryc, G. (Ed.), Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982, U.S. Geol. Surv. Prof. Pap. 1399, 940 pp., 1988.

Haga, H., and M.B. Mickey, Jurassic-Neocomian seismic stratigraphy, NPRA: A report of work performed for the U.S. Geological Survey, Biostratigraphics, Inc., San Diego, Calif., 1983.

Harland, W.B., R.L. Armstrong, A.V. Cox, L.E. Craig, A.G. Smith, and D.G. Smith, A Geologic Time Scale 1989, 263 pp., Cambridge Univ. Press, New York, 1990.

Harris, R.A., Geochemistry and tectonomagmatic affinity of the Misheguk Massif, Brooks Range Ophiolite, Alaska, Lithos, 35(1-2), 1-25, 1995.

Hawk, J.M., Lithospheric flexure, overthrust timing, and stratigraphic modelling of the central Brooks Range and Colville foredeep, M.A. thesis, Rice Univ., Houston, Tex., 1985.

Homewood, P., P.A. Allen, and G.D. Williams, Dynamics of the Molasse Basin of western Switzerland, Spec. Publ. Int. Assoc. Sedimentol., 8, 199-217, 1986.

Hubbard, R.J., S.P. Edrich, and R.P. Rattey, Geologic evolution and hydrocarbon habitat of the 'Arctic Alaska Microplate', in Alaskan North Slope Geology, edited by I. Tailleur and P. Weimer, pp. 797–830, Pac. Sect., Soc. Econ. Paleontol. and Mineral., Bakersfield, Calif., 1987.

Hurford, A.J., and Green, P.F., A users' guide to fission-track dating calibration: Earth Planet. Sci. Lett., 59, 343-354, 1982.

Johnsson, M.J., M.J. Pawlewicz, A.G. Harris, and Z.C. Valin, Vitrinite reflectance and conodont color alteration index data from Alaska: Data to accompany the thermal maturity map of Alaska, U.S. Geol. Surv., Menlo Park, Calif., 1992.

Kelley, J.S., and W.P. Brosge, Geologic framework of a transect of the central Brooks Range; Regional relations and an alternative to the Endicott Mountains Allochthon, AAPG Bull., 79, 1087-1116, 1995.

Kominz, M.A., and G.C. Bond, Geophysical modelling of the thermal history of foreland basins, Nature, 320, 252-256, 1986.

Laslett, G.M., P.F. Green, I.R. Duddy, and A.J.W. Gleadow, Thermal modelling of fission-tracks in apatite, 2, A quantitative analysis, Chem. Geol., 65, 1-13, 1987.

Laslett, G.M., W.S. Kendall, A.J.W. Gleadow, and I.R. Duddy, Bias in measurement of fission-track length distributions, Nuc. Tracks, 6, 79-85, 1982.

Magoon, L.B., K.J. Bird, G.E. Claypool, D.E. Weitzman, and R.H. Thompson, Organic geochemistry, hydrocarbon occurrence, and stratigraphy of government-drilled wells, North Slope, Alaska, in Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982, edited by G. Gryc, U.S. Geol. Surv. Prof. Pap., 1399, 483-488, Plates 19.1-19.39, 1988.

Mayfield, C.F., I.L. Tailleur, and I. Ellersieck, Stratigraphy, structure, and palinspastic synthesis of the western Brooks Range, northwestern Alaska, in Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982, edited by G. Gryc, U.S. Geol. Surv. Prof. Pap., 1399, 143–186, 1988.

Mickey, M.B., and H. Haga, Paleontology reports for NPRA wells, Anderson, Warren and Assoc., San Diego, Calif., 1980.

Mickey, M.B., and H. Haga, Jurassic-Neocomian biostratigraphy, North Slope, Alaska, in Alaskan North Slope Geology, edited by I. Tailleur and P. Weimer, pp. 397-404, Pac. Sect., Soc. of Econ. Paleontol. and Mineral., Bakersfield, Calif., 1987.

Mickey, M.B., and H. Haga, North Slope database biostratigraphy summaries, report, Micropaleo Consult., Inc., San Diego, Calif., 1990.

Mickey, M.B., H. Haga, and C.G. Mull, Paleontologic data: Tingmerkpuk sandstone and related units, northwestern De Long Mountains, Brooks Range, Alaska, report, Alaska Div. of Geol. and Geophys. Surv., Fairbanks, 1995.

Miller, E.L., and T.L. Hudson, Mid-Cretaceous extensional fragmentation of a Jurassic-Early Cretaceous compressional orogen, Alaska, Tectonics, 10, 781–796, 1991.

Molenaar, C.M., Subsurface correlations and depositional history of the Nanushuk Group and related strata, North Slope, Alaska, in Geology of the Nanushuk Group and Related Rocks, North Slope, Alaska, edited by A.C. Huffman, Jr., U.S. Geol. Surv. Bull., 1614, 37–59, 1985.

Molenaar, C.M., K.J. Bird, and T.S. Collett, Regional correlation sections across the North Slope of Alaska, U.S. Geol. Surv. Misc. Geol. Stud. Map, MF-1907, 1 p., 1986.

Molenaar, C.M., K.J. Bird, and A.R. Kirk, Cretaceous amd Tertiary stratigraphy of northeastern Alaska, in Alaskan North Slope Geology, edited by I. Tailleur and P. Weimer, Pac. Sect., Soc. of Econ. Paleontol. and Mineral., Bakersfield, Calif., 513–528, 1987.

Molenaar, C.M., R.M. Egbert, and L.F. Krystinik, Depositional facies, petrography, and reservoir potential of the Fortress Mountain Formation (Lower Cretaceous), central North Slope, Alaska, in Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982, edited by G. Gryc, pp. 257–279, U.S. Geological Survey Professional Paper 1399, 1988.

Moore, T.E., W.K. Wallace, K.J. Bird, S.M. Karl, C.G. Mull, and J.T. Dillon, Geology of northern Alaska, in The Geology of North America, vol. G1, in The Geology of Alaska, edited by G. Plafker and H.C. Berg, pp. 49-140, Geol. Soc. of Am., Boulder, Colo., 1994.

Moore, T.E., W.K. Wallace, C.G. Mull, K.E. Adams, G. Plafker, and W.J. Nokleberg, Crustal implications of bedrock geology along the trans-Alaska Crustal Transect (TACT) in the Brooks Range, northern Alaska, J. Geophys. Res., 102, 20797-20820, 1997.

Mull, C.G., Cretaceous tectonics, depositional cycles, and the Nanushuk Group, Brooks Range and Arctic Slope, Alaska, in Geology of the Nanushuk Group and Related Rocks, North Slope, Alaska, edited by A.C. Huffman Jr., U.S. Geol. Surv. Bull., 1614, 7–36, 1985.

Mull, C.G., Summary of structural style and history of Brooks Range deformation, in Dalton Highway, Yukon River to Prudhoe Bay, Alaska: Bedrock Geology of the Eastern Koyukuk Basin, Central Brooks Range, and East Central Arctic Slope, Guideb.7, edited by C.G. Mull and K.E. Adams, pp. 47–56, Alaska Div. of Geol. and Geophys. Surv., Fairbanks, 1989.

Mull, C.G., K.E. Adams, D.A. Bodnar, and J.P. Siok, Stratigraphy of Endicott Mountains and Picnic Creek allochthons, Killik River and Chandler Lake quadrangles, north-central Brooks Range, Alaska, AAPG Bull., 69 , 671, 1985.

Mull, C.G., T.E. Moore, E.E. Harris, and I.L. Tailleur, Geologic map of the Killik River quadrangle, scale 1:125,000, U.S. Geol. Surv. Open File Rep., 94-679, 1994.

Mull, C.G., and M.B. Werdon, Generalized geologic map of the western Endicott Mountains, central Brooks Range, Alaska, scale 1:250,000, Alaska Div. of Geol. and Geophys. Surv., Public Data File, 94-55, Fairbanks, 1994.

Murphy, J.M., P.B. O'Sullivan, and A.J.W. Gleadow, Apatite fission-track evidence of episodic Early Cretaceous to Late Tertiary cooling and uplift, Central Brooks Range, Alaska, in 1992 Proceedings International Conference on Arctic Margins, Outer Continental Shelf Study, MMS 94-0040, edited by D. Thurston and K. Fujita, U.S. Miner. Manage. Serv., Anchorage, Alaska, 257-262, 1994.

Naeser, C.W., Fission-track dating and geologic annealing of fission-tracks, in Lectures in Isotope Geology, edited by E. Jager and J.C. Hunziker, pp. 154-169, Springer-Verlag, New York, 1979.

Nilsen, T.H., T.E. Moore, J.T. Dutro, Jr., W.P. Brosge, and D.M. Orchard, Sedimentology and stratigraphy of the Kanayut Conglomerate and associated units, central and eastern Brooks Range, Alaska--Report of the 1978 field season, U.S. Geol. Surv., Open File Rep., 80-0888, Reston, Va., 1980.

Nelson, S.W., and W.H. Nelson, Geology of the Siniktanneyak Mountain ophiolite, Howard Pass quadrangle, Alaska, scale 1:63360, U.S. Geol. Surv. Misc. Field Stud. Map, MF-1441, 1982.

Nunn, J.A., M. Czerniak, and R.H. Pilger Jr., Constraints on the structure of Brooks Range and Colville Basin, northern Alaska, from flexure and gravity analysis, Tectonics, 6, 603-617, 1987.

Oldow, J.S., C.M. Seidensticker, J.C. Phelps, F.E. Julian, R.R. Gottschalk, K.W. Boler, J.W. Handschy, and H.G. Avé Lallement, Balanced cross sections through the central Brooks Range and North Slope, Arctic Alaska, report, Am. Assoc. of Pet. Geol., Tulsa, Okla., 1987.

O'Sullivan, P.B., Late Mesozoic to Cenozoic thermal and uplift history of the North Slope foreland basin, northern Alaska and northwestern Canada, Ph.D. thesis, 419 pp., La Trobe Univ., Bundoora, Victoria, Australia, 1993.

O'Sullivan, P.B., P.F. Green, S.C. Bergman, J. Decker, I.R. Duddy, A.J.W. Gleadow, and D.L. Turner, Multiple phases of Tertiary uplift in the Arctic National Wildlife Refuge, Alaska, revealed by apatite fission track analysis, AAPG Bull., 77 , 359-385, 1993.

O'Sullivan, P.B., T.E. Moore, and J.M. Murphy, Tertiary uplift of the Mt. Doonerak antiform, central Brooks Range, Alaska: Apatite fission-track evidence from the Trans-Alaska Crustal Transect, Mem. Geol. Soc. Am., 1996.

O'Sullivan, P.B., J. Murphy, and A.E. Blythe, 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), J. Geophys. Res., 102, 20821-20845, 1997.

Price, R.A., The Cordilleran fold and thrust belt in the southern Canadian Rocky Mountains, in Thrust and Nappe Tectonics, edited by K.R. McClay and N.J. Price, Geol. Soc. Spec. Publ., 9, London, 427-448, 1981.

Schenk, C.J., and K.J. Bird, Depositional sequences in Lower Cretaceous rocks, Atigun syncline and Slope Mountain areas, Alaskan North Slope, in Geologic Studies in Alaska by the U. S. Geological Survey, 1992, edited by C. Dusel-Bacon and A.B. Till, U.S. Geol. Surv. Bull., 2068, 48-58, 1993.

Solie, D.N., and C.G. Mull, Kikiktat Mountain klippe: A link between the Copter Peak and Nuka Ridge allochthons, northcentral Brooks Range, Alaska, in Short Notes on Alaskan Geology 1991, edited by R.D. Reger, Prof. Rep. 111, Alaska Div. of Geol. and Geophys. Surv., Fairbanks, 77-88, 1991.

Steckler, M.S., and A.B. Watts, Subsidence of the Atlantic type continental margin off New York, Earth Planet. Sci. Lett., 42, 1-13, 1978.

Tailleur, I.L., B.H. Kent Jr., and H.N. Reiser, Outcrop geologic map of the Nuka-Etivluk region, northern Alaska, U.S. Geol. Surv. Open File Rep., 66-128, 1966.

Till, A.B., and L.W. Snee, $^{40}Ar/^{39}Ar$ evidence that formation of blueschists in continental crust was synchronous with foreland fold and thrust belt deformation, western Brooks Range, Alaska, J. Metamorph. Geol., 13, 41-60, 1994.

VanHinte, J.E., Geohistory analysis-Application of micropaleontology in exploration geology, AAPG Bull., 62, 201-222, 1978.

Wallace, W.K., and C.L. Hanks, Structural Provinces of the Northeastern Brooks Range, Arctic National Wildlife Refuge, Alaska, AAPG Bull., 74, 1100-1118, 1990.

Wallace, W.K., T.E. Moore, and G. Plafker, Multistory duplexes with forward dipping roofs, north central Brooks Range, Alaska, J. Geophys. Res., 102, 20773-20796, 1997.

Webber, E.J., R.G. Ray, and W.A. Fischer, Geologic map of the area of the Titaluk and upper Ikpikpuk and Meade Rivers, Naval Petroleum Reserve no. 4, Alaska, U.S. Geol. Surv., Reston, Va., 1948.

Whittington, C.L., and M.L. Troyer, Geologic map of the area of the Kigalik and Awuna Rivers, Alaska, U.S. Geol. Surv., Reston, Va., 1948.

Wirth, K.R., and J.M. Bird, Chronology of ophiolite crystallization, detachment, and emplacement: Evidence from the Brooks Range, Alaska, Geology, 20 , 75–78, 1992.

Witmer, R.J., H. Haga, and M.B. Mickey, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska, U.S. Geol. Surv., Menlo Park, Calif., 1981a.

Witmer, R.J., M.B. Mickey, and H. Haga, Biostratigraphic correlations of selected test wells of National Petroleum Reserve in Alaska, U.S. Geol. Surv., Menlo Park, Calif., 1981b.

Woodward, N.B., S.E. Boyer, and J. Suppe, Balanced Geological Cross-Sections, an essential technique in geological research and exploration, in Short Course in Geology, edited by M.L. Crawford, Am. Geophys. Union, Washington, DC, 132 pp., 1989.

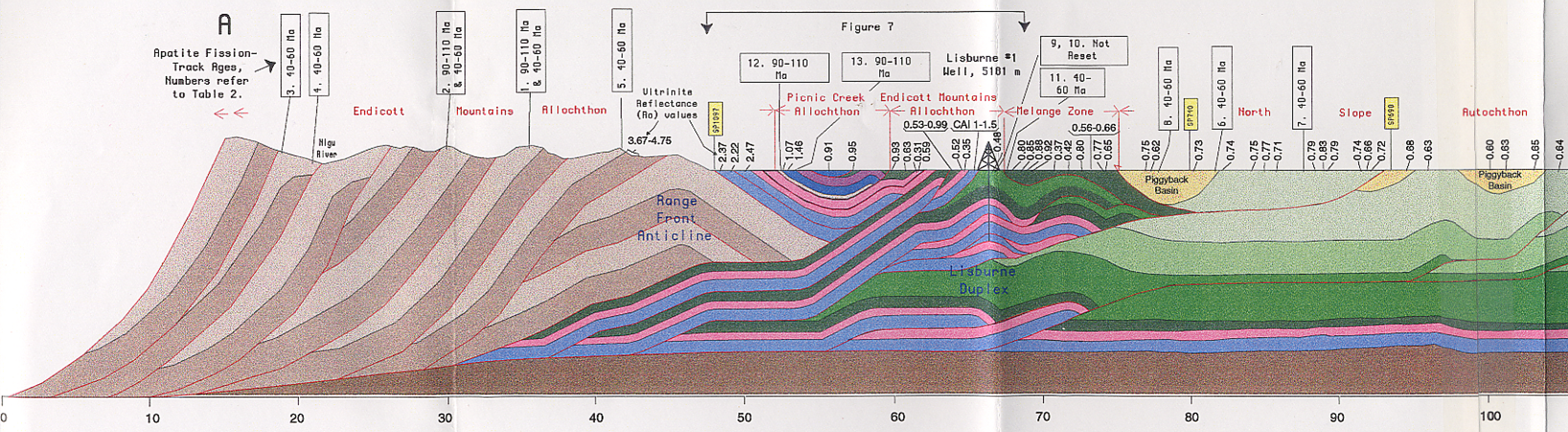
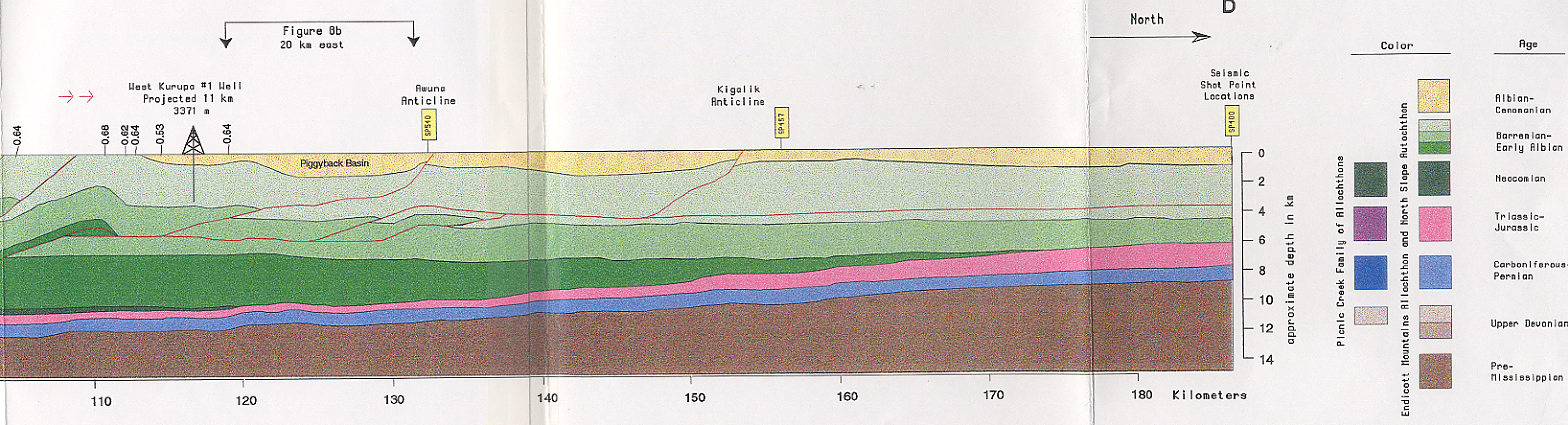


Plate 1. Balanced cross section (location AB shown on Figure 6), constructed from surface geology and subsurface relationships interpreted from seismic line 37 (Figure 7). Well control shown at top of section. Vitrinite reflectance (Ro) values and interpreted apatite f



atite fission track ages plotted along top. Shot point numbers for seismic line 37 shown in yellow.

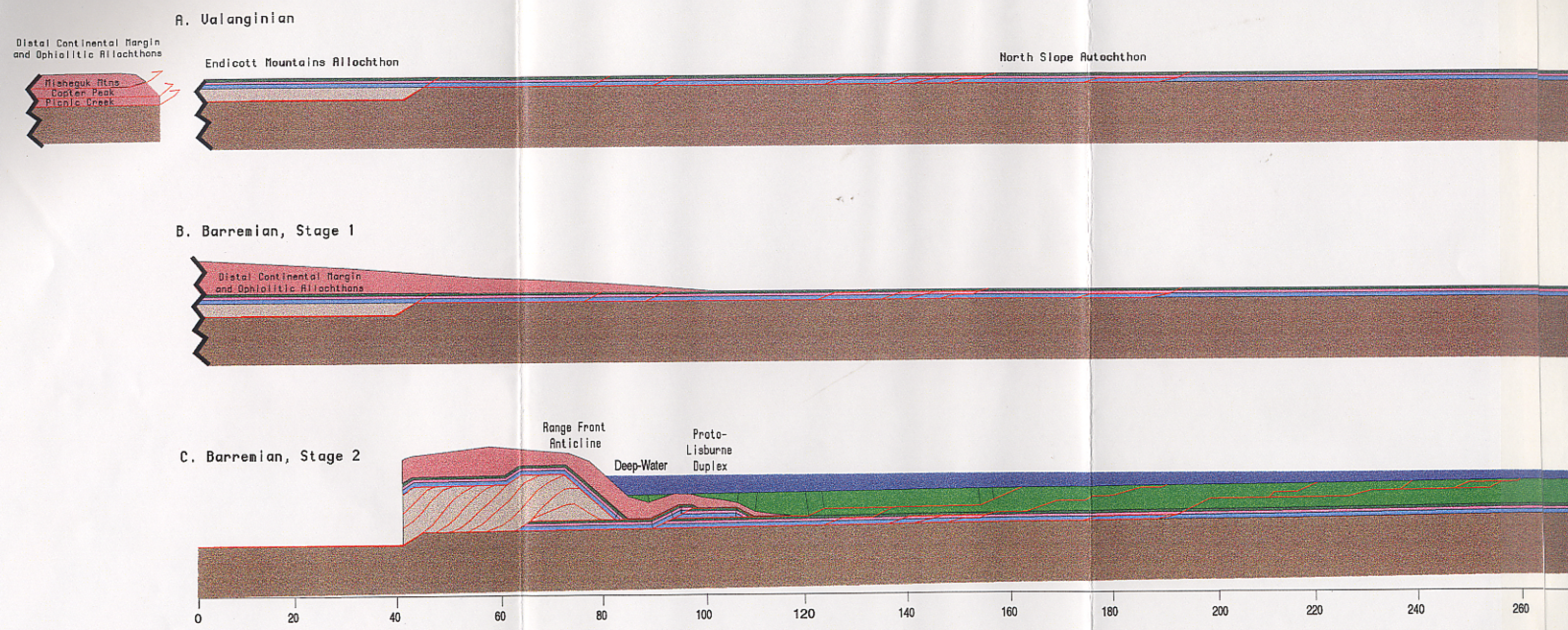
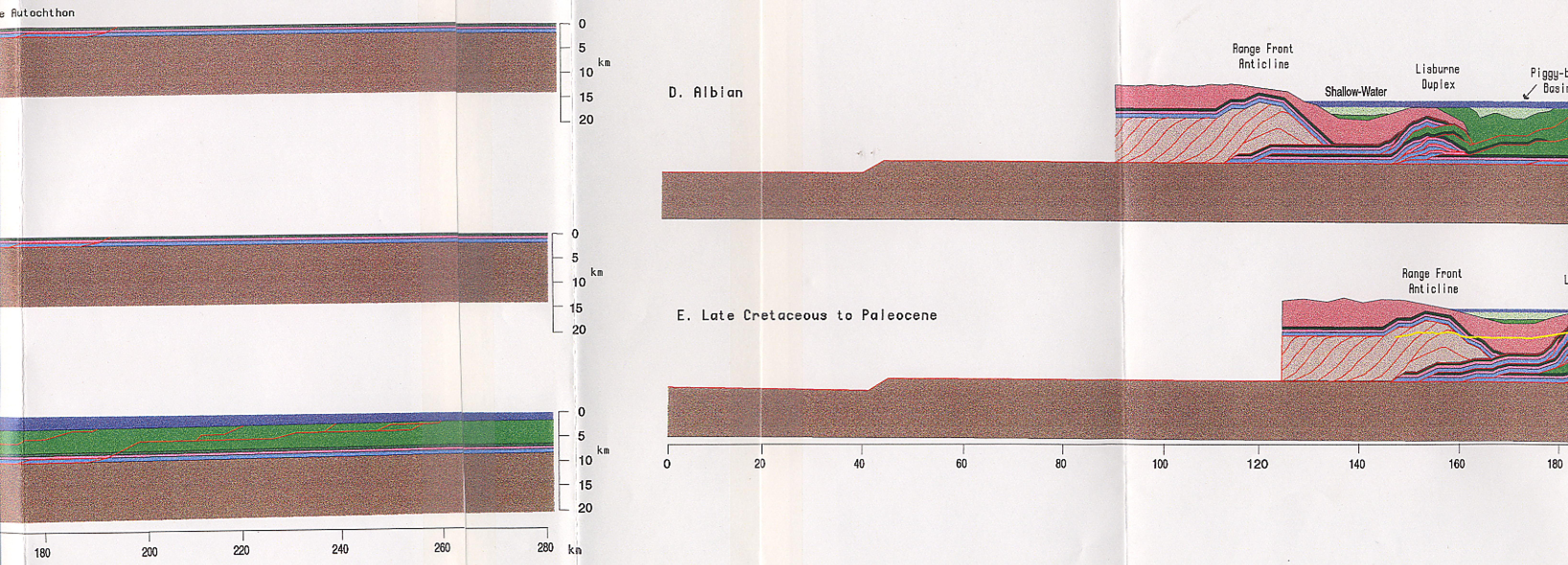
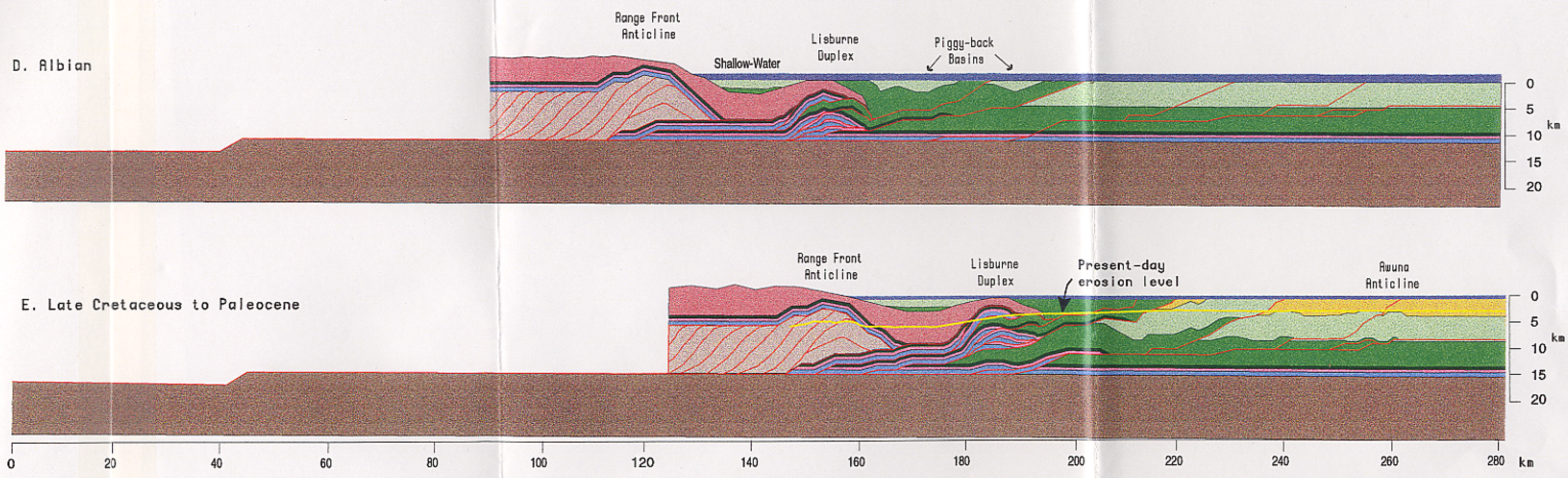


Plate 2. Kinematic model for the sequence of thrusting in the north central Brooks Range. (a) Valanginian, palinspastic restoration of cross section AB of Plate 1, with Picnic Creek and Copter Peak-Misheguk Mountains allochthons imbricated some unknow Mountains allochthon, (c) Barremian, stage 2, internal imbrication and northward emplacement of Endicott Mountains allochthon, with higher allochthons carried passively; initiation of Lisburne duplex; initiation of flexural basin, deposition of earliest Br formation of piggy-back basins in the foreland; regionally and locally, deeply buried rocks are getting exhumed at this time, (e) Late Cretaceous to Paleocene, maximum sedimentary burial during forward propagation of thrusting into the foreland basin. This is



c Creek and Copter Peak-Misheguk Mountains allochthons imbricated some unknown distance south of the structural transect, (b) Barremian, stage 1, emplacement of Picnic Creek and ophiolitic allocthons onto the Endicott ; initiation of Lisburne duplex; initiation of flexural basin, deposition of earliest Brookian flysch, (d) Albian, imbrication of Lisburne and Etivluk Groups in lower part of Lisburne duplex; rapid deposition of molasse and nentary burial during forward propagation of thrusting into the foreland basin. This is followed by a second period of exhumation in the orogen and the foreland beginning in Paleocene time and continuing to the present day.



structural transect, (b) Barremian, stage 1, emplacement of Picnic Creek and ophiolitic allocthons onto the Endicott
ian, imbrication of Lisburne and Etivluk Groups in lower part of Lisburne duplex; rapid deposition of molasse and
period of exhumation in the orogen and the foreland beginning in Paleocene time and continuing to the present day.