Conversation Contents

NPR-A Map for Today's Secretary Briefing

Attachments:

/71. NPR-A Map for Today's Secretary Briefing/1.1 LeaseTracts_Suggested_RecentDiscoveries (Zinke Briefing 30May2017).jpg
/71. NPR-A Map for Today's Secretary Briefing/3.1 2009 Houseknecht et al Clinoform Sequences.pdf
/71. NPR-A Map for Today's Secretary Briefing/3.2 Nanushuk-Torok seismic facies map.pdf

"Gieryic, Michael" <mike.gieryic@sol.doi.gov>

From:	"Gieryic, Michael" <mike.gieryic@sol.doi.gov>
Sent:	Tue May 30 2017 10:15:21 GMT-0600 (MDT)
To:	David Houseknecht <dhouse@usgs.gov>
Subject:	NPR-A Map for Today's Secretary Briefing
Attachments:	LeaseTracts_Suggested_RecentDiscoveries (Zinke Briefing 30May2017).jpg

See light green "pencil sticks".

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"Houseknecht, David" <dhouse@usgs.gov>

From:	"Houseknecht, David" <dhouse@usgs.gov>
Sent:	Tue May 30 2017 10:19:02 GMT-0600 (MDT)
To:	"Gieryic, Michael" <mike.gieryic@sol.doi.gov>
Subject:	Re: NPR-A Map for Today's Secretary Briefing

Yes, those green lines look familiar! Thanks for sending.

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Sent:	Tue May 30 2017 11:43:51 GMT-0600 (MDT)
To:	"Gieryic, Michael" <mike.gieryic@sol.doi.gov>
Subject:	Re: NPR-A Map for Today's Secretary Briefing
Attachments:	2009 Houseknecht et al Clinoform Sequences.pdf Nanushuk-Torok seismic facies map.pdf

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From:	"Gieryic, Michael" <mike.gieryic@sol.doi.gov>
Sent:	Wed Jun 07 2017 10:05:28 GMT-0600 (MDT)
To:	"Houseknecht, David" <dhouse@usgs.gov>
Subject:	Re: NPR-A Map for Today's Secretary Briefing

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Please give me a call to discuss section 4(b) of Secretarial Order 3352.

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Sent:	Wed Jun 07 2017 11:11:41 GMT-0600 (MDT)
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Subject:	Re: NPR-A Map for Today's Secretary Briefing

I was hoping to get a quick sense of what you have been tasked with, regarding putting together a plan that addresses section 4b of the Secretarial Order, so that we (BLM-AK and I) are not duplicating efforts as we draft a response to the order. My sense is that would be a 5 minute conversation.

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Subject:	Re: NPR-A Map for Today's Secretary Briefing

OK, I'll give you a call a bit later - in a meeting now.

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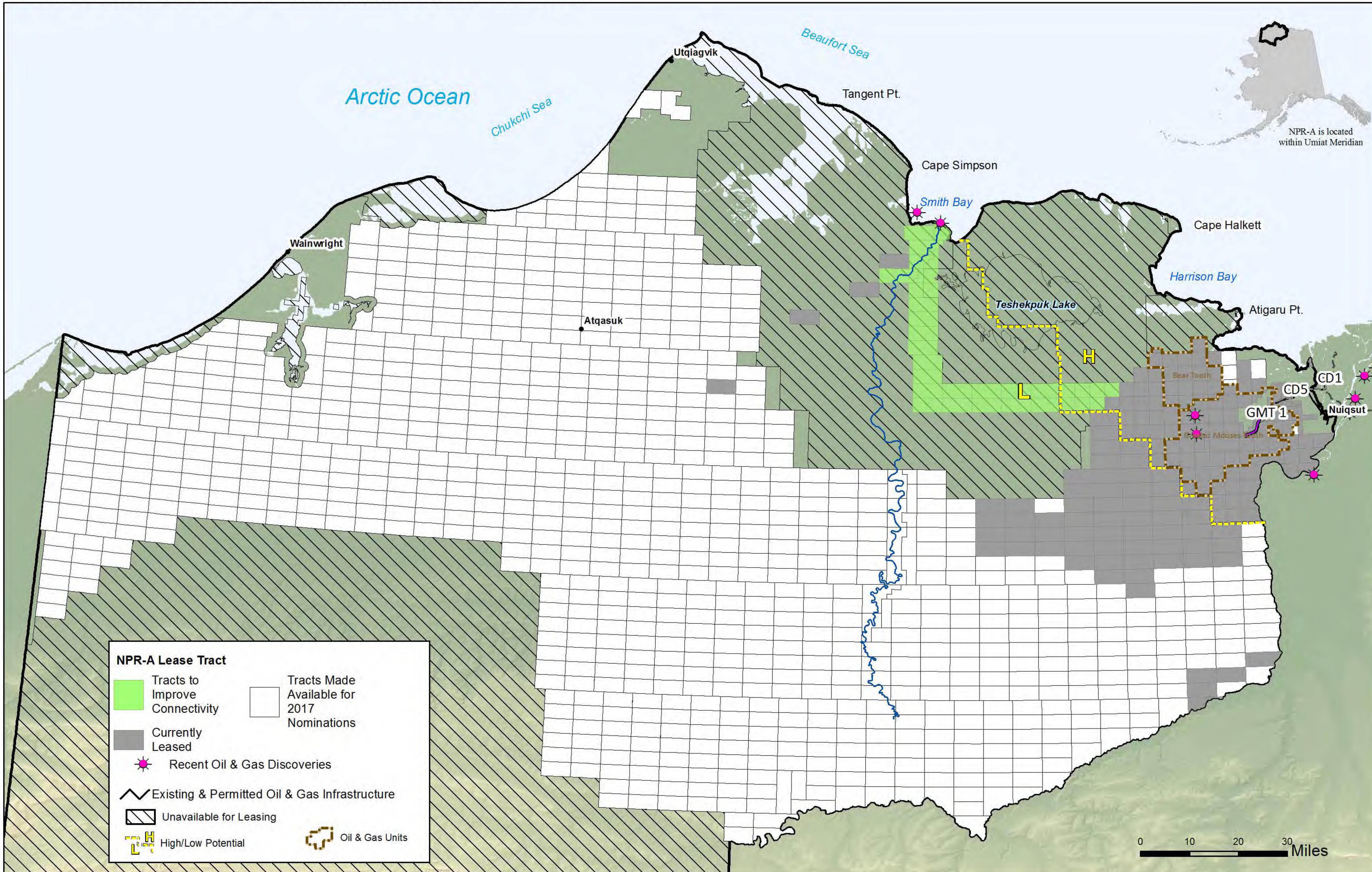
National Petroleum Reserve in Alaska

DEPT. OF INTERIOR | BUREAU OF LAND MANAGEMENT | ALASKA | ARCTIC DISTRICT OFFICE



Basin Research (2009) **21**, 644–654, doi: 10.1111/j.1365-2117.2008.00392.x

Seismic analysis of clinoform depositional sequences and shelf-margin trajectories in Lower Cretaceous (Albian) strata, Alaska North Slope

David W. Houseknecht*, Kenneth J. Bird† and Christopher J. Schenk‡

*US Geological Survey, Reston, VA, USA
†US Geological Survey, Menlo Park, CA, USA
‡US Geological Survey, Denver, CO, USA

ABSTRACT

Lower Cretaceous strata beneath the Alaska North Slope include clinoform depositional sequences that filled the western Colville foreland basin and overstepped the Beaufort rift shoulder. Analysis of Albian clinoform sequences with two-dimensional (2D) seismic data resulted in the recognition of seismic facies inferred to represent lowstand, transgressive and highstand systems tracts. These are stacked to produce shelf-margin trajectories that appear in low-resolution seismic data to alternate between aggradational and progradational. Higher-resolution seismic data reveal shelf-margin trajectories that are more complex, particularly in net-aggradational areas, where three patterns commonly are observed: (1) a negative (downward) step across the sequence boundary followed by mostly aggradation in the lowstand systems tract (LST), (2) a positive (upward) step across the sequence boundary followed by mostly progradation in the LST and (3) an upward backstep across a mass-failure décollement. These different shelf-margin trajectories are interpreted as (1) fall of relative sea level below the shelf edge, (2) fall of relative sea level to above the shelf edge and (3) mass-failure removal of shelf-margin sediment. Lowstand shelf margins mapped using these criteria are oriented north–south in the foreland basin, indicating longitudinal filling from west to east. The shelf margins turn westward in the north, where the clinoform depositional system overstepped the rift shoulder, and turn eastward in the south, suggesting progradation of depositional systems from the ancestral Brooks Range into the foredeep. Lowstand shelf-margin orientations are consistently perpendicular to clinoform-foreset-dip directions. Although the Albian clinoform sequences of the Alaska North Slope are generally similar in stratal geometry to clinoform sequences elsewhere, they are significantly thicker. Clinoform-sequence thickness ranges from 600–1000 m in the north to 1700–2000 m in the south, reflecting increased accommodation from the rift shoulder into the foredeep. The unusually thick clinoform sequences suggest significant subsidence followed by rapid sediment influx.

INTRODUCTION

Petroleum exploration in the Alaska North Slope (Fig. 1) during the past decade has focused increasingly on stratigraphic traps, including objectives in clinoform strata of the Cretaceous–Tertiary Brookian sequence (Fig. 2). Exploration targets have included sandstone reservoirs in both the lower and upper parts of clinoforms, interpreted as deep-marine (toe-of-foreset) and shallow-marine to non-marine (topset) facies, respectively. Several oil discoveries have been developed in Upper Cretaceous and Palaeogene reservoirs and, most recently, in Lower Cretaceous reservoirs of both deep- and shallow-water facies that have been developed as satellite pools (Nanuq and Qannik pools, respectively, Fig. 3) within the larger Alpine oil field, whose main reservoir is a Jurassic shoreface sandstone (Houseknecht & Bird, 2004). The development of the Nanuq and Qannik pools, together with the occurrence of oil-stains in outcrops of lower-slope sandstone facies (Houseknecht & Schenk, 2007), demonstrate the exploration potential in Lower Cretaceous clinoforms beneath the western North Slope and Chukchi Sea (Fig. 1).

Although the regional stratigraphic framework of the Lower Cretaceous clinoforms is well known, few published reports have interpreted the sequence stratigraphy of these strata. The objectives of this paper are to describe the stratal geometry and shelf-margin trajectories of Lower Cretaceous clinoform depositional sequences in the eastern part of the National Petroleum Reserve in Alaska (NPRA) and adjacent areas (Fig. 1) and to interpret their sequence stratigraphy.

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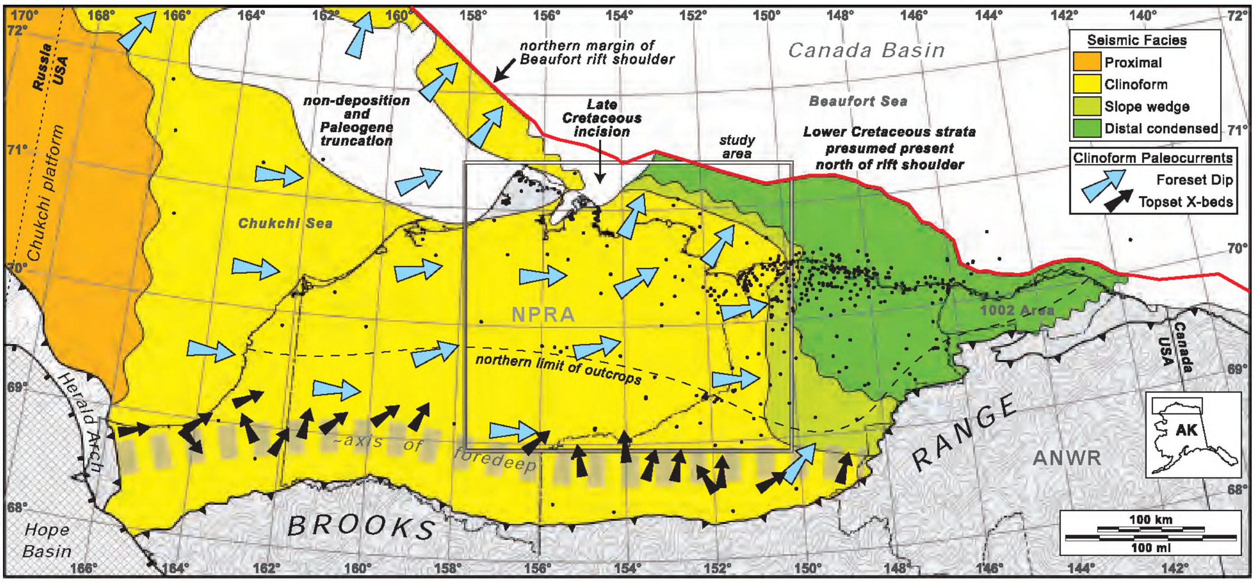

Fig. 1. Map of the Alaska North Slope (onshore area north of Brooks Range), Chukchi Sea and Beaufort Sea showing main geologic elements, seismic facies and palaeocurrent data from Lower Cretaceous first-order depositional sequence, study area shown in Fig. 3, and exploration wells (black dots). The Lower Cretaceous sequence is presumed to be present north of the Beaufort rift shoulder, but is buried too deeply to resolve with available seismic data. Outcrops of this sequence occur between the northern front of the Brooks Range and the dashed line labelled 'northern limit of outcrops'. Note that sequence is partly to completely absent in the north due to non-deposition on part of Beaufort rift shoulder, truncation by Late Cretaceous incision and truncation across Palaeogene uplift. Ultimate shelf margin of Lower Cretaceous depositional sequence is indicated by the solid line between clinoform and slope-wedge seismic facies. Foreset dip directions are based on original work and work by Bird & Andrews (1979); topset cross-bed directions are from Huffman *et al.* (1985). Federal boundaries shown include the National Petroleum Reserve in Alaska (NPRA), the Arctic National Wildlife Refuge (ANWR), and the ANWR 1002 area. Hope basin is a Tertiary successor basin unrelated to this study.

GEOLOGIC SETTING

The tectonics of Arctic Alaska during the Early Cretaceous included the simultaneous development of the Beaufort rift shoulder on the north (rift opening of the Canada basin), the Brooks Range orogenic belt on the south, and the Herald arch thrust belt on the west (Fig. 1). The Colville foreland basin formed in response to tectonic loading by the ancestral Brooks Range and Herald arch (Bird & Molenaar, 1992; Moore *et al.*, 1994). The Lower Cretaceous fill of the Colville foreland basin extends from the Chukchi platform, a pre-Mississippian ancestral high whose axis is coincident with the Russia – United States maritime boundary, to the southeastern North Slope, where it was mostly eroded during Tertiary uplift of the eastern Brooks Range (Fig. 1).

The Brookian sequence (Fig. 2) includes Lower Cretaceous through Tertiary strata comprising sediment derived from the Brooks Range and tectonic uplands in eastern Siberia (west of the map in Fig. 1) and deposited in the foreland basin, on the Beaufort rift shoulder, and in the Canada basin north of the rift shoulder (Bird & Molenaar, 1992; Moore *et al.*, 1994; Houseknecht *et al.*, 2009). With the rift shoulder acting as an accommodation sill, filling of the Colville foreland basin generally progressed from west to east as indicated by the age and stratal geometry of the basin fill (Molenaar, 1983, 1988; Bird & Molenaar, 1992; Houseknecht *et al.*, 2009). Within the Colville foreland basin, Lower Cretaceous clinoforms and their component formations have been documented in studies of regional stratigraphy (Molenaar, 1983, 1985, 1988; Bird & Molenaar, 1992), sequence stratigraphy (McMillen, 1991; Houseknecht & Schenk, 2001), petroleum geology (Bird, 1985, 2001), submarine mass-wasting (Weimer, 1987; Homza, 2004) and stratal geometry of source rocks (Creaney & Passey, 1993).

This paper is focused on clinoform depositional sequences that cross formation boundaries of the Hue Shale, Torok Formation and Nanushuk Formation (Fig. 2). These clinoform strata are mostly of Albian age in the study area (Mull *et al.*, 2003) and range into the Cenomanian in their easternmost extent. The Hue Shale is a mudstone that accumulated in the most distal part of the depositional system. This mudstone includes oil-prone source rocks, mostly in highly condensed beds that include the informally named 'gamma-ray zone' (GRZ; also known as the 'highly radioactive zone' or HRZ) (Carman & Hardwick, 1983; Molenaar, 1983, 1985, 1988; Molenaar *et al.*, 1987; Bird & Molenaar, 1992; Creaney & Passey, 1993). The Hue Shale is expressed as bottomset reflections in seismic sections. The Torok Formation is mostly silty mudstone that represents a spectrum of facies ranging from the toe of a marine slope to the outer shelf. This formation includes sandstone beds that are interpreted as deposits of basin-floor submarine fans and incised slope channels (Molenaar, 1985, 1988; Bird & Molenaar, 1992; Houseknecht & Schenk,

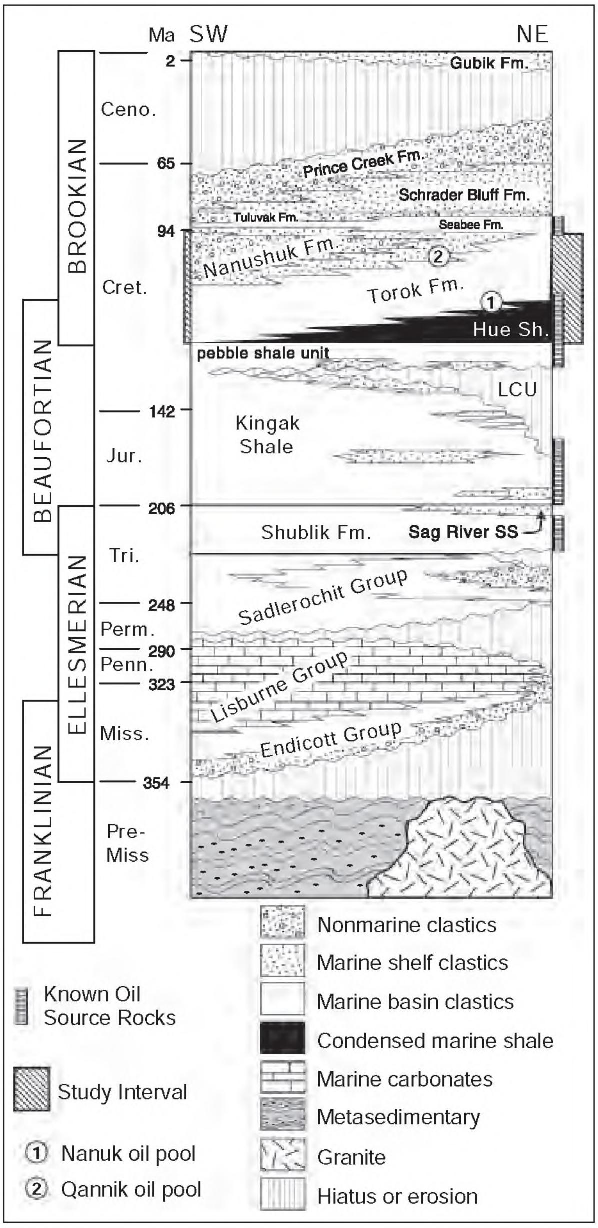

Fig. 2. Stratigraphy in National Petroleum Reserve in Alaska (NPRA) showing tectonostratigraphic sequences (at left) and stratigraphic positions of study interval, known oil source rocks and Nanuk and Qannik oil pools. LCU, Lower Cretaceous unconformity. Modified from Houseknecht & Bird (2004).

2001, 2007). The Torok Formation is expressed mostly as foresets in seismic sections. The Nanushuk Formation includes mudstone, sandstone and coal beds that similarly represent a spectrum of facies, including deposits of the marine shelf, shoreface, deltas, fluvial systems and coastal plain interfluves (Ahlbrandt *et al.*, 1979; Huffman *et al.*, 1985, 1988; LePain & Kirkham, 2001; LePain *et al.*, 2008). The Nanushuk Formation is expressed as topsets in seismic sections.

In the study area, clinoforms in Lower Cretaceous strata are part of a first-order depositional sequence that extends across the entire width of Arctic Alaska (Fig. 1). The western part of this sequence onlaps the Chukchi platform and displays proximal seismic facies that do not include clinoforms. To the east, Lower Cretaceous clinoforms are present from the central Chukchi Sea to an ultimate (farthest basinward) shelf margin (illustrated with seismic data by Houseknecht & Schenk, 2005) that defines the eastern limit of the study area (Figs 1 and 3). Thus, the clinoform sequences in the study area were primarily fed by a longitudinal sediment dispersal system that was 300–500 km long (from vicinity of Herald arch and Chukchi platform; Fig. 1) and may have been influenced by a transverse sediment dispersal system that was > 75 km long (from ancestral Brooks Range; Fig. 1). The distal part of the sequence, east of the ultimate shelf margin, includes a wedge of mudstone and sandstone representing slope facies that grade basinward into condensed mudstone (Fig. 1). Palaeocurrent indicators in the clinoform sequence reflect the complexity of regional sediment dispersal patterns. Foreset dip observed in two-dimensional (2D) seismic data (this study; Bird & Andrews, 1979) indicates a predominance of longitudinal eastward progradation within the foreland basin (Fig. 1). Exceptions occur in the following two areas where northeastward dip of clinoforms is evident: (1) in the north, where the depositional system overstepped the rift shoulder, and (2) in the south, where progradation into the foredeep from the ancestral Brooks Range is inferred (Fig. 1). Palaeocurrent data from the topset facies (Nanushuk Formation) are limited to outcrops in the Brooks Range foothills. These data indicate mostly northward sediment dispersal, except in the west where an eastward component of sediment dispersal is indicated (Fig. 1).

METHODS

Regional analysis of depositional sequences was completed using a grid of public-domain, mostly 1974–1981 vintage, 2D seismic data (Fig. 3; Miller *et al.*, 2000). This grid was supplemented by proprietary, 1980–1995 vintage, 2D seismic data along the northern and eastern margins of the study area (Fig. 3). Sparse well control (Fig. 3) was integrated into the analysis by correlating wireline logs to seismic data using synthetic seismograms generated from sonic logs.

Depositional facies and sequences were interpreted by integrating seismic expression, wireline log patterns, core descriptions and biostratigraphic data as described elsewhere (Houseknecht & Schenk, 2001). Results of field work in the Brooks Range foothills also were integrated into these interpretations (Houseknecht & Schenk, 2001, 2007; Houseknecht *et al.*, 2007), although it generally is not possible to correlate depositional sequences defined in seismic data directly to specific outcrops because of structural complexity in the Brooks Range foothills and poor near-surface seismic resolution. Neither the lateral continuity of outcrops nor biostratigraphic control are adequate for correlating and dating specific bounding surfaces and stratigraphic sequences.

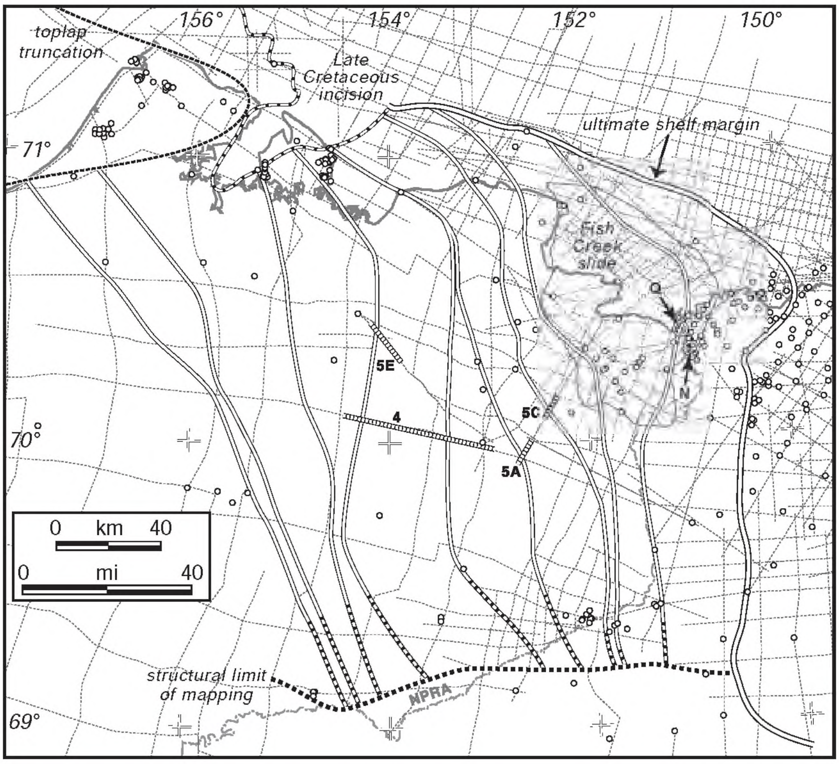

Fig. 3. Map of study area showing locations of several lowstand shelf margins, the Fish Creek slide (Homza, 2004), Nanuk (N) and Qannik (Q) oil pools, seismic images shown in Figs 4 and 5, seismic lines used in this study (grey-dotted lines), and exploration wells used in this study (white dots with black outlines). Structural deformation precludes correlation of sequence boundaries and shelf margins south of dotted line labelled 'structural limit of mapping'.

CLINOFORM SEQUENCES

Analysis of Lower Cretaceous clinoform sequences is based on a regional framework established by mapping of high-amplitude seismic reflections that correlate to beds of condensed mudstone in wells. Hence, the mapping of our depositional sequences is related to the genetic-sequence stratigraphic approach of Galloway (1989). These beds of condensed mudstone, which are interpreted as flooding events, can be recognized even in low-resolution seismic data, and they define a repetitive motif of stratal geometry that is the basis for our regional mapping. This generalized motif is inferred to represent four stages of clinoform sequence development, including lowstand, transgression, highstand-aggradation and highstand-progradation (Fig. 4).

Lowstand

The base of each clinoform sequence is defined by abrupt basinward termination of topset strata at the shelf edge and local termination of foreset strata on the upper to middle slope (Fig. 4). These terminations are inferred to indicate the presence of an erosional surface (unconformity) on the outer shelf and upper slope. Above the unconformity, most clinoform sequences display a thin and seismically transparent interval that onlaps at mid-slope and generally thickens basinward as it offlaps and becomes interbedded with high-amplitude reflections that coalesce with the GRZ (Fig. 4). Well penetrations show that this transparent interval is mostly sandstone, and interpretations of cores and outcrops suggest that this sandstone-rich interval includes deposits of sediment-gravity flows and turbidites (Houseknecht & Schenk, 2001, 2007). Higher up the slope and above the unconformity, some clinoform sequences include a wedge of strata that onlaps the outermost shelf or uppermost slope and downlaps the middle slope (Fig. 4). Most clinoform sequences, however, contain no such wedge of strata on the upper slope (Fig. 4).

The unconformity at the base of each clinoform sequence is interpreted as a sequence boundary, and the immediately overlying strata are interpreted as a lowstand-systems tract (LST). The seismically transparent intervals that onlap the mid-slope and interfinger basinward with the GRZ are interpreted as the deposits of submarine-fan aprons and basin-floor fan systems (Houseknecht & Schenk, 2007). At mid to lower slope, where it onlaps the sequence boundary, the LST likely includes incised sediment-gravity-flow deposits (slope channels), as inferred from seismic reflection geometries and studies of Torok successions in outcrop and core (Houseknecht & Schenk, 2001, 2007). Wedges of strata perched on the upper slope of some clinoform sequences are interpreted as the deposits of lowstand shelf-margin deltas. Thus, the basal part of the clinoform motif is interpreted as the product of a late falling stage through lowstand in relative sea level (Fig. 4). It is likely equivalent to the LSTs interpreted by McMillen (1991).

Transgression

The inferred LST is overlain by a thin interval of strata, characterized by high-amplitude seismic reflections, that downlaps basinward and coalesces with the GRZ (Fig. 4).

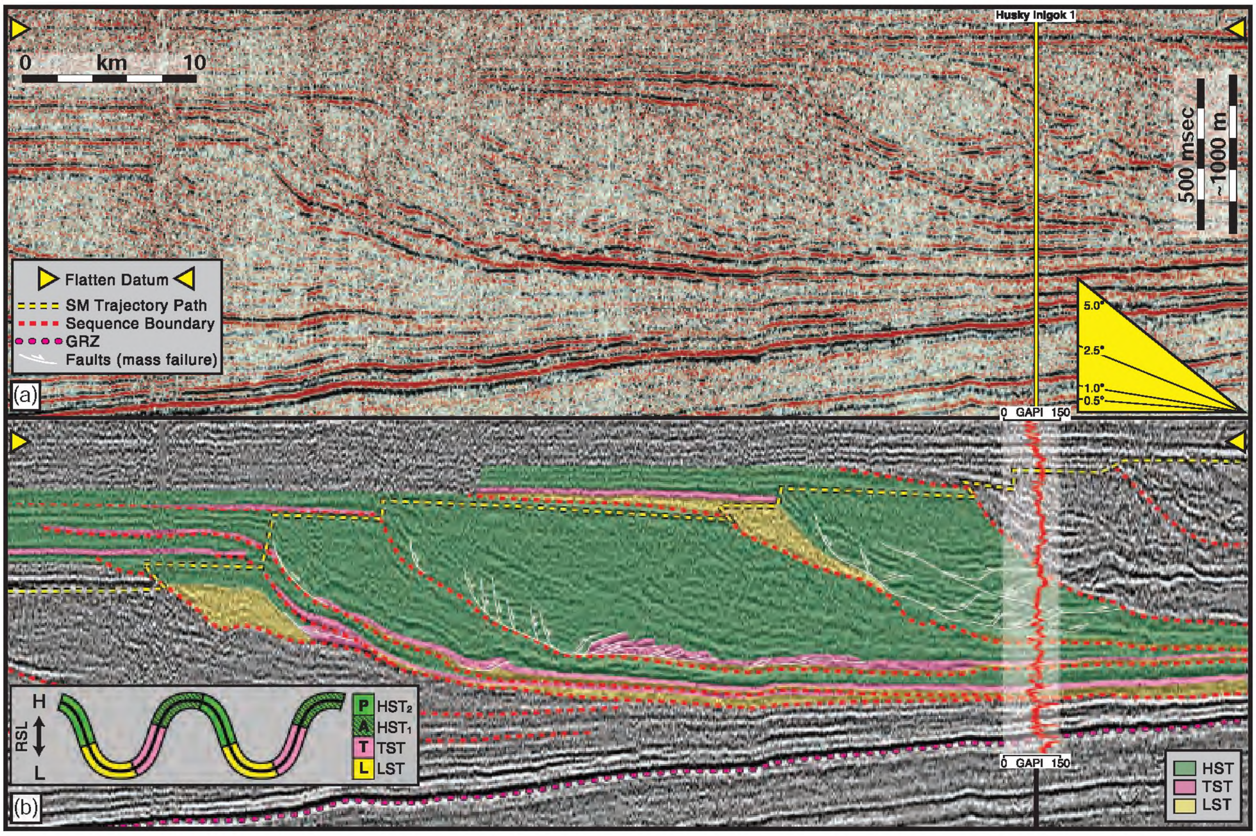

Fig. 4. Non-interpreted (a) and interpreted (b) images of public-domain seismic data illustrating clinoform geometry and generalized interpretations of clinoform-sequence stratigraphy. Images are flattened on a prominent topset seismic reflection. Location of Husky Inigok #1 well is shown in (a), and γ-ray log of the clinoform succession is shown in (b). Inset curve of relative sea level (RSL) with no accommodation included illustrates generalized interpretation of seismic expression inferred to represent lowstand (L), transgression (T), highstand-aggregation (A) and highstand-progradation (P). Positive reflection coefficient represented by black in colour display and by white in greyscale display. Negative reflection coefficient represented by red in colour display and by black in greyscale display. Images are plotted in time and approximate depth scale based on average velocity of clinoform sequence also is shown. Large yellow triangles indicate approximate dip. See text for additional explanation. Location of line segment is shown in Fig. 3.

Up dip, this interval typically onlaps the sequence boundary (or the overlying lowstand-shelf-margin-delta deposits, where present) on the middle to upper slope. In most clinoform sequences examined in this study, this interval rolls over into high-amplitude topset reflections on the outer shelf. In other clinoform sequences, this interval is absent on the middle to upper slope and on the lower slope displays contorted or duplex repetitions (Fig. 4). In those cases, high-amplitude topset reflections terminate abruptly at the shelf margin. The high-amplitude topset reflections typically grade into medium- and then low-amplitude reflections over a distance of 30–50 km landward of the shelf margin.

This interval is interpreted as a transgressive systems tract (TST) comprising condensed mudstone that accumulated when marine waters drowned the shelf during rising sea level (Fig. 4). The high-amplitude reflections correlate to lower velocity shale, likely higher in organic content than other slope facies, and are essentially basinward-coalescing tongues of the GRZ (Creaney & Passey, 1993). The deformation commonly displayed by this transgressive facies and overlying deposits suggests that condensed mudstones of the TST commonly served as the sole for slope failure.

Highstand aggradation

The TST is overlain by an interval characterized by thick topset strata that display evidence of significant vertical aggradation and little basinward progradation of the shelf margin. Seismic geometries commonly display 300–500 m of vertical aggradation of the shelf margin with just a few kilometres of progradation (Fig. 4). The shelf margin is defined by topset seismic facies with moderate- to high-amplitude reflections that terminate or offlap into slope facies. In some clinoform sequences, the topset reflections display basinward-thickening, wedge-shaped geometries near the shelf margin. Basinward from the aggradational shelf margin, correlative seismic facies display a poorly defined foreset geometry comprising low- to medium-amplitude reflections that commonly display contorted geometries. At the toe of the slope, broadly mounded, contorted and duplex repetitions of reflections are commonly present within this seismic interval.

This interval is interpreted as the aggradational part of a highstand systems tract comprising marine shelf and slope sediments that accumulated during late rising stage to highstand of relative sea level (Fig. 4) and near equilibrium between sediment-influx and accommodation. The stratal geometry suggests that a large volume of sediment accumulated on the broad expanse of the shelf and a relatively modest volume accumulated on the smaller area of the slope prism, where facies are predominantly silty mudstones that display seismic evidence of mass wasting at small to medium scale. Mounded, contorted, and duplexed seismic facies at the toe of slope are interpreted as piles of sediment displaced basinward by slumping or sliding.

Highstand progradation

Highstand-aggradational facies are overlain by an interval characterized by thick foreset strata and thin topset strata that display evidence of significant progradation and little aggradation of the shelf margin. Seismic geometries commonly display 20 km or more of shelf margin progradation with just 100–200 m of topset aggradation (Fig. 4). The topset strata are defined by moderate- to high-amplitude seismic reflections that step basinward across the top of a large volume of crudely defined foreset strata. Internally, these foreset strata display low- to medium-amplitude seismic reflections that toplap the overlying beds and display contorted geometries. The foreset strata typically display downlap onto the TST (Fig. 4).

This interval is interpreted as the progradational part of a highstand systems tract comprising marine shelf and slope sediments that accumulated during late highstand to early falling stage of relative sea level (Fig. 4), when sediment influx exceeded accommodation. The stratal geometry of this interval suggests that a relatively large volume of sediment accumulated on the slope as compared with the shelf. Slope facies are mostly silty mudstone and display seismic evidence of mass wasting at medium to large scale. The large volume of mud that accumulated on the slope appears to have been highly prone to slope failure, ranging from relatively ductile creep and slumping that produced large masses of coherent seismic reflections displaying folded and duplexed internal geometries to relatively fluidized failure that produced mounds of seismic reflections with chaotic internal geometries.

SHELF-MARGIN TRAJECTORIES

In this section, we use higher resolution 2D seismic data to refine our interpretations of shelf-margin trajectories and clinoform-sequence development. We generally follow the concepts, if not the specific terminologies, of Galloway (1989), Helland-Hansen & Martinsen (1996), Steel & Olsen (2002), Porêbski & Steel (2003), Bullimore *et al.* (2005) and Johannessen & Steel (2005). Throughout this discussion, toplap surfaces or offlap slope breaks are used to define shelf margin trajectories. Three distinct shelf-margin trajectories that commonly occur in Albian clinoform sequences are discussed below (Fig. 5).

Case 1: negative shelf-margin trajectory across sequence boundary

In some clinoform sequences, the toplap surface steps downward in a basinward direction across the sequence boundary (Fig. 5a and b). In this case, the oldest topset seismic reflections that onlap the sequence boundary are lower in elevation than the toplap surface below the sequence boundary. This geometry suggests that relative sea level during erosion of the sequence boundary fell below the shelf edge, and perhaps below the toplap surface of the preceding HST (Fig. 5b). In this case, the LST includes a wedge of shelf-margin strata perched high on the slope just basinward of the knickpoint. This wedge of strata likely represents a lowstand, shelf-margin delta (Fig. 5b). Note that the inferred LST is actually a composite of an older wedge of sediment that completely onlaps the sequence boundary on the upper slope and a younger wedge of sediment that onlaps the sequence boundary a short distance landward of the knickpoint. Within the older lowstand wedge, the toplap surface steps basinward in both aggradational and progradational steps, although the former is predominant. In contrast, within the younger lowstand wedge, the toplap surface is strongly progradational. Alternatively, the younger wedge of sediment may represent a smaller scale sequence.

Each lowstand wedge is capped by a high-amplitude seismic reflection, which likely represents a condensed mudstone that accumulated during flooding. The younger high-amplitude seismic reflection is slumped off the upper slope and is present near the base of the slope as a slide complex (not shown in Fig. 5b). The high-amplitude seismic reflections that cap the topset strata of the two lowstand wedges coalesce landward near the knickpoint. We interpret the younger high-amplitude seismic reflection as the approximate maximum flooding surface (MFS).

Above the MFS, this clinoform sequence displays a small amount of shelf-margin aggradation followed by significant progradation in the HST (Fig. 5b). The slight negative trajectory of the toplap surface in the HST is interpreted to result from compaction of the thick foreset mud during progradation.

Case 2: positive shelf-margin trajectory across sequence boundary

In other clinoform sequences, the toplap surface steps upward in a basinward direction (apparent aggradation in seismic data) across the sequence boundary (Fig. 5c and d). This geometry suggests that relative sea level during erosion of the sequence boundary fell to a level no lower than the shelf edge of the preceding HST, and was higher than the toplap surface of the preceding HST (Fig. 5d). In this case, the LST is a wedge of sediment perched mostly on the slope, and the topset seismic reflections of the LST

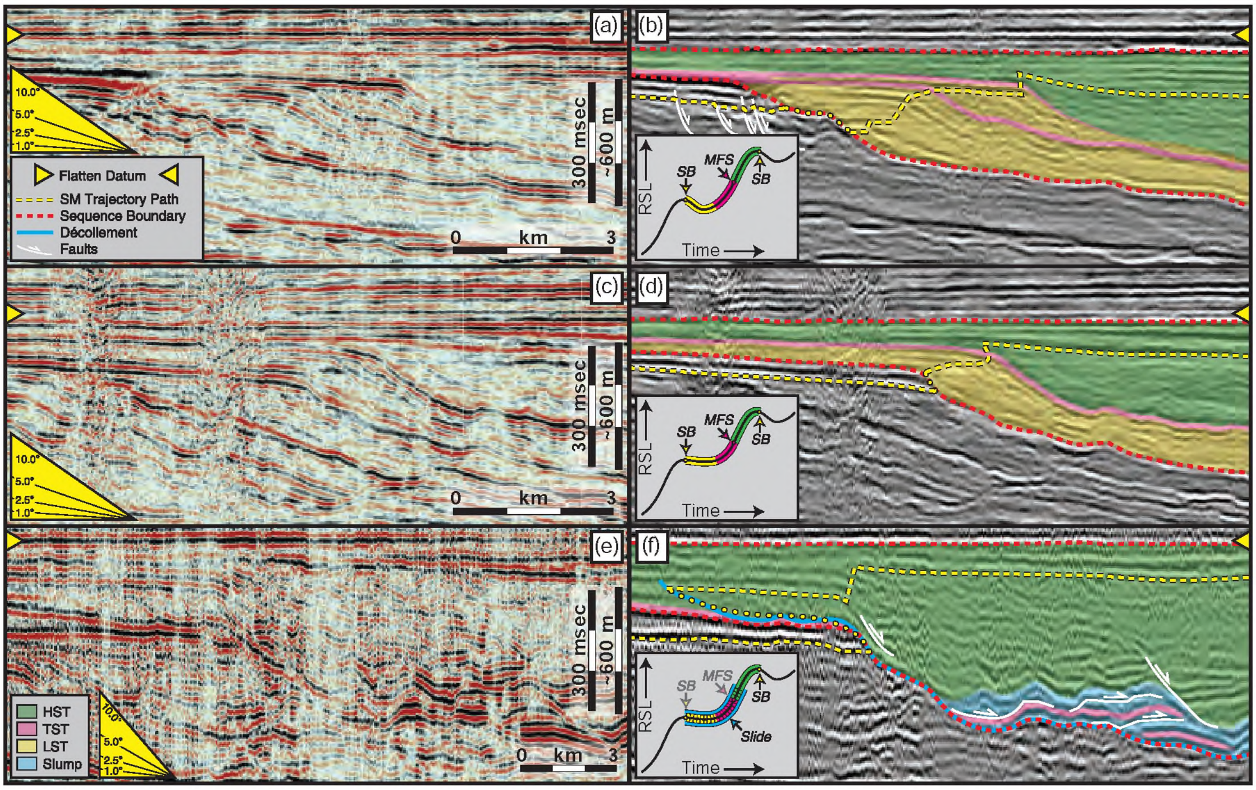

Fig. 5. Three pairs of seismic images, non-interpreted and interpreted, illustrating variability in stratal geometry and shelf-margin trajectory across sequence boundaries. (a, b) Negative shelf-margin trajectory across sequence boundary. (c, d) Positive shelf-margin trajectory across sequence boundary. (e, f) Backstepping shelf-margin trajectory across surface interpreted as mass-failure décollement localized along sequence boundary. Insets show inferred relative sea level (RSL) curves for each case with generalized accommodation included. Shelf-margin trajectory line is dashed on toplap surface and dotted where it steps across sequence boundary and mass-failure décollement. Large yellow triangles indicate approximate dip. Positive reflection coefficient represented by black in colour displays and by white in greyscale displays. Negative reflection coefficient represented by red in colour displays and by black in greyscale displays. Images are plotted in time and approximate depth scale based on average velocity of clinoform sequence also is shown. Figures (a–d) shown courtesy of WesternGeco; (e–f) are public-domain data.

onlap the basinward-dipping sequence boundary on the shelf across a broad area landward of the knickpoint. The toplap surface within the LST is progradational with a minor amount of aggradation (Fig. 5d).

The LST is capped by a high-amplitude seismic reflection that is interpreted as a condensed mudstone that approximates the MFS. The HST of this sequence is characterized by modest aggradation followed by significant progradation (Fig. 5d). As in the previous example, the slight negative trajectory of the toplap surface in the HST is likely related to compaction of the underlying foreset mud during progradation.

Case 3: backstepping shelf-margin trajectory across mass-failure surface

A third type of shelf-margin trajectory involves significant backstepping of the toplap surface (Fig. 5e and f). A surface with geometry similar to a sequence boundary truncates underlying seismic reflections, both landward and basinward of the shelf margin, and can be correlated to a sequence boundary near the shelf margin on nearby seismic lines. However, extending from the middle slope to the basin floor the surface is overlain by a large mass of contorted, faulted and otherwise chaotic seismic reflections (Fig. 5e and f). These features bear some similarities to the 'Fish Creek slide' (Weimer, 1987; Homza, 2004), a large mass-failure deposit involving mostly middle and lower slope deposits in the Torok Formation (Fig. 3).

We interpret these deformed seismic reflections as products of mass failure of the shelf margin and slope, perhaps with the décollement localized at or near a sequence boundary. The mass failure must have occurred during highstand because (1) the slump mass includes a stratigraphy (albeit deformed) similar to a TST overlain by a HST, (2) there are no associated lowstand deposits evident and (3) the detachment surface is overlain directly by progradational HST deposits landward from the shelf edge (Fig. 5f). In this case, the toplap surface is progradational in the preceding HST, backsteps and rises in section along the mass-failure surface, and includes both progradational and aggradational phases in the HST above the slump mass (Fig. 5f).

DISCUSSION

Systems tract interpretations

Interpretations of sequence stratigraphy presented in the preceding sections include uncertainty, especially in the assignment of strata to systems tracts. Our interpretations are based largely on the recognition in seismic data of (1) reflection terminations at the shelf margin and on the upper slope and (2) high-amplitude reflections that either onlap the middle to upper slope or roll over into topset reflections at the shelf margin, and that downlap basinward and coalesce with the GRZ (Figs 4 and 5). These features are interpreted as (1) sequence boundaries and (2) a drape of transgressive mudstone, respectively.

We have interpreted all strata above the inferred sequence boundary and below the high-amplitude drape as a LST. However, we cannot preclude the possibility that part – or all – of these strata were deposited during rising stage and might more appropriately be interpreted as part of the TST. Similarly, we have interpreted all strata above the high-amplitude drape and below the next higher sequence boundary as a HST, which we subdivide into aggradational and progradational segments based on shelf-margin trajectories. However, both MFS (contact between TST and HST-aggradation) and the successive sequence boundary are difficult to pick precisely in 2D seismic data.

Although our interpretations are based on all available information, including wireline log and core interpretations (Houseknecht & Schenk, 2001), insufficient well control is available to constrain the interpretation of every shelf margin considered in this study (Fig. 3). Our interpretation of systems tracts based on well-defined seismic criteria, therefore, is probably the most objective approach for regional mapping.

Reservoir implications

In all three examples of shelf-margin trajectories, two significantly progradational HST shelf-margin trajectories are separated by net aggradation across a relatively short distance. However, the 'net aggradation' involves very different shelf-margin stratal geometries and depositional processes. In case 1, net aggradation includes a *negative* step across a sequence boundary, multiple progradation and aggradation steps within a LST, and aggradation during and following maximum flooding (Fig. 5b). In case 2, net aggradation includes a *positive* step across the sequence boundary, progradation and minor aggradation within the LST, and aggradation during and following maximum flooding (Fig. 5d). In case 3, net aggradation includes mass-failure removal of strata deposited during a net rise in relative sea level and a significant backstepping of the toplap surface.

The potential for coarse sediment by-pass and sandstone reservoir quality are different in these three cases. Case 1, which represents the most significant drop in relative sea level, holds the greatest potential for coarser-grained reservoir facies in lowstand deposits, both in shelf-margin deltas and in lower slope channel and fan systems. The recognition of a lowstand shelf-margin wedge onlapping the upper slope is an indication that sediment was delivered to the shelf margin and beyond. This stratal geometry also favours the occurrence of relatively coarse grained, incised channel deposits in fluvial systems landward of the shelf margin. Case 2, which represents a smaller drop in relative sea level, is probably the most commonly observed in Albian clinoform sequences in NPRA and is less likely to be characterized by significant by-pass of coarser sediment. In this case, a shelf-margin sediment wedge onlapping the outer shelf may have been prone to extensive wave reworking of generally fine-grained sand, a combination demonstrated to produce generally poor reservoir quality in this basin (LePain *et al.*, 2008). Moreover, in this case, there is less potential for transport of coarser-grained sand to deeper-water depositional systems. Case 3, which appears to represent a mass-failure process, carries no implications regarding the presence or quality of sandstone reservoirs.

Shelf-margin orientation and clinoform dimensions

The criteria described above were used to map lowstand shelf margins in the study area (Fig. 3). Across the central part of the area, which represents the gradation between the southern flank of the Beaufort rift shoulder and the northern flank of the Colville foreland basin, the overall shelf-margin orientation swings from $\sim 330^\circ$ in the west to $\sim 0^\circ$ in the east (Fig. 3). To the north, all the shelf margins turn westward to approximately parallel the northern margin of the rift shoulder (Figs 1 and 3), across which accommodation increased abruptly into the Canada basin. Along the southern margin of the area, there are subtle indications that the shelf margins turn eastward to parallel the axis of the foredeep, and this is confirmed by regional mapping of the ultimate slope wedge east of the study area and by the presence of outcrops of Albian topset strata in the Brooks Range foothills east of the study area (Figs 1 and 3). This eastward turn of lowstand shelf margins likely reflects the influx of sediment into the foredeep from the ancestral Brooks Range to the south, as suggested by palaeocurrent data from topset strata (Fig. 1). Throughout the study area, the foreset-dip direction of these clinoform sequences is consistently perpendicular to the lowstand shelf margins.

The dimensions of clinoform sequences generally reflect their location relative to the Beaufort rift shoulder and Colville foredeep. In the northern part of the study area, where the clinoform sequences overstep the relatively high-standing rift shoulder, total clinoform sequence thickness is 600–1000 m. This dimension increases gradually southward and is 1700–2500 m at the structural limit of mapping (Fig. 3), located on the north flank of the foredeep. This southward increase in clinoform-sequence thickness is a direct indication of increased accommodation from the rift shoulder into the foredeep. Moreover, this range of thickness provides an approximate indication of water depth during deposition. The foreset length (distance from toplap to downlap of a seismic reflection) varies from an average of ~30 km (25–40 km range) in the north to ~70 km (45–125 km) in the south. Average foreset dip, calculated as a linear slope from toplap to downlap, ranges from 0.6 to 2.5°. No spatial variation in foreset dip is evident across the accommodation domains, although both the sequence boundaries and depositional foresets are asymptotic (Fig. 4). On the upper slope, maximum dips are estimated to be 3–8° on both erosional sequence boundaries and depositional foresets. From the lower slope basinward, maximum dip is typically < 1°. The steepest dip associated with the clinoform sequences is observed on the extensional décollements associated with mass failure on the upper slope (Fig. 5f). These décollement surfaces commonly display dips > 10° and locally as much as 20°, although these dips are difficult to estimate from the available seismic data.

The Albian clinoform sequences described in this paper are significantly larger than most reported in the literature. For example, well-documented clinoform sequences in the Central Tertiary basin of Spitsbergen (Johannessen & Steel, 2005), Porcupine basin of offshore Ireland (Johannessen & Steel, 2005), Karoo basin of South Africa (Johnson *et al.*, 2001; Wild *et al.*, 2007), West Siberian basin of Russia (Zharkov, 2001; Ulmishek, 2003) and Carpathian foredeep of Poland (Porêbski *et al.*, 2003) typically display a thickness of ~250–500 m. Most examples of thicker clinoforms occur on passive margins and, even in that setting, a thickness > 1 km is rare (Adams & Schlager, 2000; Porêbski & Steel, 2003; Cummings & Arnott, 2005). Such unusually thick clinoform sequences are interpreted as having formed as the result of significant subsidence followed by rapid sediment influx at the temporal scale of the Lower Cretaceous first-order depositional sequence, although this generalized interpretation may be revised as an ongoing analysis of Cretaceous strata in Arctic Alaska is completed. The range of foreset dip in the Albian clinoforms is similar to other examples cited, except for the Karoo basin, where dip is typically < 0.6° (Johnson *et al.*, 2001; Wild *et al.*, 2007).

CONCLUSIONS

Low-resolution seismic data can be used to identify and map clinoform depositional sequences by using stratal geometry, foreset-dip directions, and interpretations of shelf-margin trajectory. Sequence boundaries and lowstand shelf margins can be inferred near the base of seismic intervals with apparently aggradational shelf-margin trajectories. However, a higher resolution approach is required to identify the components of aggradational trajectories and to interpret the character of associated sequence boundaries and lowstand deposits.

In the Alaska North Slope, Lower Cretaceous (Albian) clinoform sequences display the following three common shelf-margin trajectories that appear aggradational in low-resolution seismic data: (1) A negative step across the sequence boundary followed by aggradation > progradation in the LST and mostly progradation in the HST. This geometry occurs when relative sea level falls below the toplap surface of the preceding HST. (2) A positive step across the sequence boundary followed by progradation > aggradation in the LST and mostly progradation in the HST. This geometry occurs when relative sea level falls to a level not lower than the shelf edge of the preceding HST. (3) A retrogradational backstep occurs when a mass-failure décollement develops along or near a sequence boundary during highstand. In all these cases, the shelf-margin trajectory is predominately progradational in the HST. Recognition of these contrasting shelf-margin geometries may provide insights for anticipating the presence and quality of sandstone reservoirs in both deep- and shallow-water facies of Albian clinoform sequences.

Lowstand shelf-margin orientations, which are consistently perpendicular to clinoform foreset dip direction, reflect the longitudinal west-to-east filling of the foreland basin across most of the study area. In the north, where the clinoform depositional systems overstepped the Beaufort rift shoulder, lowstand shelf margins turn westward and approximately parallel the northern margin of the Beaufort rift shoulder, which represents a huge accommodation increase into the Canada basin to the north. In the south, the lowstand shelf margins appear to turn eastward, likely reflecting influx of sediment into the foredeep from the ancestral Brooks Range.

The Albian clinoform sequences of the Alaska North Slope are significantly thicker than most reported in the literature, suggesting significant subsidence followed by rapid sediment influx. But how this generalized interpretation fits into the regional tectonic history awaits further analysis.

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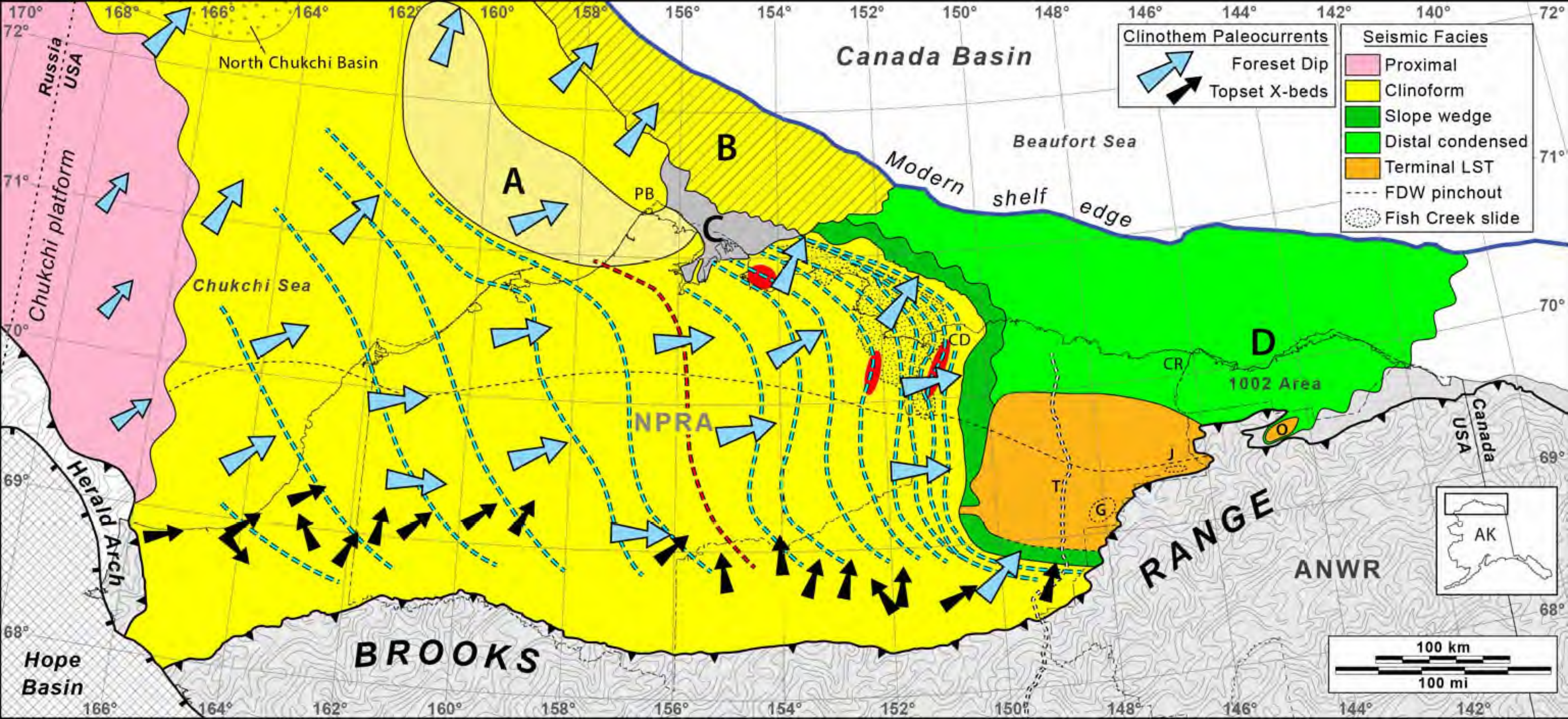

Canada Basin
Beaufort Sea
Modern shelf edge
North Chukchi Basin
Chukchi platform
Russia
USA
Chukchi Sea
A
B
C
D
PB
CD
CR
NPRA
1002 Area
T
J
G
O
Herald Arch
Hope Basin
BROOKS
RANGE
ANWR
USA
Canada
AK
Clinothem Paleocurrents
Foreset Dip
Topset X-beds
Seismic Facies
Proximal
Clinoform
Slope wedge
Distal condensed
Terminal LST
FDW pinchout
Fish Creek slide
100 km
100 mi