Late Jurassic–Early Cretaceous Inversion of Rift Structures, and Linkage of Petroleum System Elements across Postrift Unconformity, U.S. Chukchi Shelf, Arctic Alaska

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Abstract

Basin evolution of the U.S. Chukchi shelf involved multiple phases, including Late Devonian–Permian rifting, Permian–Early Jurassic sagging, Late Jurassic–Neocomian inversion, and Cretaceous–Cenozoic foreland-basin development. The focus of ongoing exploration is a petroleum system that includes sag-phase source rocks; inversion-phase reservoir rocks; structure spanning the rift, sag, and inversion phases; and hydrocarbon generation during the foreland-basin phase.

Interpretation of 2-D seismic and sparse well data documents the presence, in the south-central part of the shelf, of a series of en-echelon, north-south trending monoclonal fold limbs that display up to 1+ km (3,300 ft) of structural relief. These folds, which are located above the tips of rift-phase normal faults, are interpreted as inversion structures formed by maximum compressive stress oriented obliquely to the strike of rift-phase normal faults. Erosional relief on a Jurassic unconformity, growth strata in the overlying Upper Jurassic to Neocomian strata, and east-dipping clinoforms in a high accommodation depocenter east of the inversion structures indicate profound structural influence on sedimentation.

Oil-prone source rocks, reservoir-quality sandstone, migration pathways, and structural closure are linked intimately across the Jurassic unconformity, which reflects inversion. Thus, all these key petroleum systems elements were in place when Triassic source rocks entered the oil generation window during Cretaceous–Cenozoic stratigraphic burial.

Introduction

The U.S. Chukchi shelf, offshore northwest Alaska, is one of the largest and least explored petroleum provinces in North America. The most oil prospective part of the shelf, north of the Wrangel-Herald arch (thrust belt; Fig. 1), covers more than 170,000 km^2 (66,000 mi^2) and water depths are less than 100 m (330 ft). The shelf was tested by five exploration wells during 1989–1991, and those wells documented the presence of at least one viable petroleum system (Sherwood *et al.*, 2002). After a long hiatus in activity, Outer Continental Shelf (OCS) lease sale 193 in 2008 garnered more than $2.6 billion in winning bids for leases covering more than 29 million acres. No exploration wells have been completed following that lease sale, although drilling is under way as of this writing (August, 2015).

Strata of the Chukchi shelf can be divided generally into deposits associated with rift, sag, "inversion-rift," and foreland phases of basin development (Fig. 2). Petroleum-systems elements and oil and gas prospectivity are present in strata associated with each phase. However, the main focus of current exploration is a petroleum system whose key elements span strata associated with the sag and inversion-rift phases, and are separated by a regional Jurassic unconformity (Fig. 2).

Objectives of this paper are to provide an overview of Chukchi shelf tectonics and stratigraphy, and to illustrate the linkage between tectonics and paleogeography in Upper Jurassic through Lower Cretaceous strata. We also illustrate and interpret relationships among key petroleum systems elements in strata that are the main focus of current exploration.

Geologic Framework

Tectonic elements and stratigraphy

The stratigraphy of the Chukchi shelf (Fig. 2) generally can be considered in the context of four tectonostratigraphic sequences recognized across the North American Arctic: the Franklinian, Ellesmerian, Beaufortian, and Brookian (Lerand, 1973; Hubbard *et al.*, 1987; Bird, 2001; Sherwood *et al.*, 2002). Although not penetrated by drilling, acoustic basement beneath the Chukchi shelf is presumed to comprise mainly metasedimentary rocks of the Devonian and older Franklinian sequence (Fig. 2), which is well known from outcrops and subsurface penetrations in Alaska and Canada (*e.g.*, Dumoulin, 2001; Sherwood *et al.*, 2002; Macdonald *et al.*, 2009). Broadly deformed during the Devonian Ellesmerian orogeny, the Franklinian sequence beneath the Chukchi shelf locally displays relict stratigraphy in reflection seismic data (Figs. 3 to 5; Sherwood, 1994; Kumar *et al.*, 2011).

Upper Devonian (?) and younger, petroleum-prospective strata of the Chukchi shelf rest on the Franklinian acoustic basement and bear the influence of several regional tectonic elements (Fig. 1). Although the oldest strata penetrated by Chukchi wells are Mississippian, we accept the interpretation that Upper Devonian strata may be present (Sherwood *et al.*, 1998; Bird, 2001) and use "Upper Devonian" and "Late Devonian" without queries hereafter. The north-south-trending Hanna trough, a graben system commonly considered to be a failed rift (Sherwood *et al.*, 1998; Bird, 2001), was active during the Late Devonian to middle or late Permian as evidenced by growth strata (Figs. 3 to 6). Although graben-bounding normal faults form a complex array and display a variety of dip directions (Sherwood *et al.*, 2002, plate 3), most of the large-displacement normal faults dip generally westward, forming half grabens (Figs. 3 to 5).

Hanna trough is flanked by high standing blocks of acoustic basement. The Chukchi platform on the west was a persistent high as evidenced by onlap and thinning of Upper Devonian through Cretaceous strata (Figs. 1, 3 to 5). The Arctic platform on the east similarly persisted as a high-standing block following the Ellesmerian orogeny, and likely was uplifted further as the western part of the Alaska rift shoulder during Jurassic to Early Cretaceous opening of the Canada Basin (Figs. 1, 3 to 5; Saltus and Bird, 2003; Houseknecht and Bird, 2011). Additional uplift may have occurred during the Late Cretaceous to early Paleogene as suggested by apatite fission track analysis of well samples from the adjacent onshore (Houseknecht *et al.*, 2011).

Upper Devonian to mid-upper Permian rift strata of the lower Ellesmerian sequence (Fig. 2) were deposited during Hanna trough extension. Along the deepest part of the Hanna trough, a composite of half grabens accommodates at least 7 km (23,000 ft) of lower Ellesmerian strata (Figs. 3 to 5). West of Hanna trough, lower Ellesmerian strata thin by onlap onto, and are absent due mainly to nondeposition on the highest parts of the Chukchi platform (Fig. 3; Sherwood *et al.*, 2002). At the eastern margin of Hanna trough, lower Ellesmerian strata thin abruptly against a large displacement normal fault (Figs. 3 to 5). On the Arctic platform east of that normal fault, a thin veneer of lower Ellesmerian strata further thins by onlap, and is truncated completely by a younger unconformity (Fig. 5; Bird, 1988; Sherwood *et al.* 2002).

Active extension along the Hanna trough waned during the Permian, and the geometry of Upper Permian to Lower Jurassic (upper Ellesmerian) strata indicates deposition in a sag basin (Fig. 2; Sherwood *et al.*, 2002). The axis of sagging lies above the former axis of extension, and upper Ellesmerian strata are as much as 2 to 3 km (6,600 to 9,800 ft) thick along that axis. West of Hanna trough, upper Ellesmerian strata thin to a zero edge on the Chukchi platform, partly by depositional onlap and partly by truncation by the Jurassic unconformity (Figs. 3 to 5; Sherwood *et al.*, 2002). East of Hanna trough, upper Ellesmerian strata thin to less than 1 km (3,300 ft) and are truncated completely by the Jurassic and/or Lower Cretaceous unconformities, on the Arctic platform (Fig. 5; Bird, 1988; Sherwood *et al.*, 2002).

During the Late Jurassic to Early Cretaceous, the Chukchi shelf has been influenced by multiple tectonic events in adjacent areas, including convergent tectonism associated with the Chukotka orogen (Wrangel-Herald arch), rift opening of the Canada Basin, and extensional tectonism in the North Chukchi basin (Fig. 1; Thurston and Theiss, 1987; Johnson, 1992; Sherwood *et al.*, 2002; Kumar *et al.*, 2011; Houseknecht and Bird, 2011; Craddock and Houseknecht, in press). Strata associated with this phase of tectonic activity, which we refer to as the "inversion-rift" phase (Fig. 2), include the Beaufortian sequence in Alaska (Houseknecht and Bird, 2004), the upper part of which is called the "Rift sequence" by Sherwood *et al.* (2002; see Fig. 2). Although this stratigraphic interval is relatively thin (maximum thickness about 1.5 km, 4,900 ft), it includes multiple unconformities of tectonic significance and at least one key interval of reservoir-quality sandstone. These strata will be a main focus of the following discussion.

During the post-Neocomian Cretaceous and Cenozoic, the Chukchi shelf evolved into a foreland basin, albeit characterized by relatively modest subsidence. Resulting strata are divided by the widespread mid-Brookian unconformity into the Cretaceous lower Brookian and Cenozoic upper Brookian sequences (Fig. 2), inferred to have been influenced mainly by Chukotkan and Brooks Range tectonism, respectively (Houseknecht and Bird, 2011; Craddock and Houseknecht, in press; Houseknecht *et al.*, in press). These Brookian strata commonly are deformed, probably as a result of reactivation of deeper faults (Thurston and Theiss, 1987; Lothamer, 1994). A complex history of uplift and erosion is recorded by Brookian strata, including significant high-angle faulting in places (Fig. 4). Thurston and Theiss (1987) and Lothamer (1994) interpret some of the structural relief across these faults as positive and negative flower structures associated with wrench faulting at depth.

Petroleum systems

The five Chukchi exploration wells document essential elements of one or more viable petroleum systems (Sherwood *et al.*, 2002). Oil-prone source rocks have been penetrated in the Shublik Formation and Sadlerochit Group (sag phase of basin development; Fig. 2). Based on data from Alaska onshore and Beaufort shelf areas, additional source rock potential exists in the Lisburne Group (rift phase), lower Kingak Formation (sag phase), and lower Brookian sequence (foreland 1 phase) (Thurston and Theiss, 1987; Sherwood *et al.*, 1998, 2002; Peters *et al.*, 2006; Dumoulin *et al.*, 2011; Houseknecht *et al.*, in press). Reservoir-quality strata, commonly accompanied by oil or gas shows, have been penetrated throughout the stratigraphic section, and at least one gas and condensate accumulation (Burger) has been discovered (Craig and Sherwood, 2004; Sherwood, 2006; Wilson *et al.*, 2014). A spectrum of structural, stratigraphic, and combination traps are evident in reflection-seismic data, and well penetrations indicate numerous seals of good quality. Significantly, data from the exploration wells and results of regional thermal maturation and thermal history modeling indicate a favorably thick and widely distributed oil window (Sherwood *et al.*, 1998, 2002; Houseknecht *et al.*, 2012; Craddock and Houseknecht, in press). Although multiple exploration objectives can be defined on the basis of these elements, most ongoing exploration appears to be focused on a petroleum system comprising Shublik source rocks and Kuparuk reservoir rocks (*e.g.*, Wilson *et al.*, 2014).

Observations and Interpretations

Database

The following interpretations are based on correlation and mapping across a grid of proprietary and public domain, 2-D seismic lines that totals approximately 100,000 km (62,000 mi). Grid spacing generally ranges from 5 to 10 km (3 to 6 mi) across the main part of the shelf from the USA-Russia maritime boundary to within 10 km (6 mi) of the Alaska coast. Our analysis extends onshore through a coarser grid of public domain and proprietary data in the National Petroleum Reserve in Alaska (NPRA) and the onshore area west of NPRA. Correlation between the shelf and onshore is hampered by the absence of seismic data within 10 km (6 mi) of the coast, and by the low density and low quality of vintage seismic data within 20 to 40 km (12 to 25 mi) of the coast, both onshore and offshore. Interpreted stratigraphic horizons are based on either direct ties to wells on the Chukchi shelf and onshore (Fig. 1), or by jump ties from onshore to offshore.

Structural inversion

Regional seismic images clearly illustrate the presence of positive-relief structures in Ellesmerian and Beaufortian strata above structurally deep parts of the Hanna trough (Figs. 3 to 5). For example, the Klondike and Burger exploration wells (Figs. 3 and 4, respectively) are located on anticlines that display hundreds of meters (up to 1,000 ft) of relief at the Jurassic unconformity (JU), Lower Cretaceous unconformity (LCU), or

Brookian unconformity (BU) (Fig. 2; Thurston and Theiss, 1987; Craig and Sherwood, 2004; Wilson *et al.*, 2014). Brookian strata also commonly display complexly faulted anticlines, or significant erosion at the mid-Brookian unconformity (MBU) overlain by thick upper Brookian strata that display an overall sag basin geometry (*e.g.*, Fig. 4). These observations suggest graben inversion, commonly followed by collapse and subsidence.

Our regional correlation and mapping indicate that the earliest phase of inversion is coeval with deposition of the Beaufortian sequence, at least in that part of the basin near and south of the Klondike well (Fig. 3), along the western margin of the Hanna trough, which is the focus of this paper (Fig. 1). For example, Figure 6 illustrates significant growth of lower Ellesmerian strata across a west-dipping normal fault (fault A) that defines the eastern margin of a syn-rift half graben. However, the top of lower Ellesmerian strata (Permian unconformity at top of Lisburne Group carbonates; Fig. 2) and the top of upper Ellesmerian strata (Jurassic unconformity; Fig. 2) display structural relief above regional trends, suggesting reverse displacement along the same fault (Fig. 6). Above the tip of fault A is a clearly defined fold limb associated with the inversion, suggesting probable trishear kinematics (Allmendinger, 1998) associated with the inversion. Furthermore, the Beaufortian sequence thickens abruptly across fault A, and to a lesser extent across fault B (Fig. 6), suggesting that inversion of the rift-phase normal fault occurred during deposition of the Beaufortian strata. These observations imply that the wedge-shaped Beaufortian strata are synkinematic and associated with the contraction (Shaw *et al.*, 2005). Note that above fault A there is no post-LCU relief and almost no normal faulting in Brookian strata, additional evidence that inversion predated Brookian deposition.

On this particular seismic line (Fig. 6) Brookian strata display minor positive relief that coincides with the structure associated with fault B. It should be noted, however, that the dips in these Brookian strata are 1 to 2 degrees (the image is exaggerated approximately 3:1), and thus the implied shortening is minor. Furthermore, Brookian strata display greater positive relief than the underlying LCU, and the normal faults do not penetrate below the LCU, suggesting a detachment near LCU level and local thickening in lower Brookian strata. Moreover, this coincidence of the Brookian high with the deeper high is not observed in seismic lines to the north. These observations suggest that an additional, minor contractional event postdates the inversion documented here. The spatial and temporal details of this Brookian contraction are beyond the scope of this paper.

These different inverted stages likely are the result of stress related to Chukotka orogenesis and contractional tectonism along the Wrangel-Herald arch. This convergence likely has been applied at an oblique angle to any rift-phase normal faults. Thus there is a possible, even likely, oblique component to these inverted structures.

Influence of inversion on stratigraphy and paleogeography

The structural inversion discussed above and illustrated in Figure 6 exerts a significant influence on Beaufortian stratigraphy and paleogeography. Beaufortian strata thicken eastward, from generally less than 300 m (1,000 ft) west of the inverted structures (323 m, or 1,060 ft, in the Klondike well, 48 km (30 mi) north of Fig. 6 seismic image) to as much as 1,500 m (5,000 ft) in a depocenter east of the inverted structures (Fig. 7). The increase in thickness occurs in two steps, an abrupt increase across fault A and a more subtle increase across fault B (Figs. 6 and 7). We interpret the abrupt increase in thickness across fault A as a significant accommodation step directly related to structural inversion along the fault.

The stratal architecture of Beaufortian strata changes with thickness. In the high accommodation depocenter east of the inverted structures, the lower part of the sequence is a clinothem comprising low-amplitude foreset and high-amplitude topset reflections (Fig. 6, below blue horizon labeled FS). The east-dipping foresets downlap the JU and toplap the base of the topsets. The topsets thickens westward, their base onlaps the JU a few km east of fault A, and they pinch out by onlapping the JU at the accommodation step above the tip of fault A (Fig. 7). This clinothem is capped by a high-amplitude reflection (blue horizon labeled FS in Fig. 6) that is overlain by a mostly transparent interval that extends to the top of the Beaufortian sequence and includes the LCU (Fig. 7). This upper part of the sequence grades westward into a thin interval of moderate to high amplitude reflections that comprise the entire Beaufortian sequence west of the Fault A tip.

We interpret the clinothem part of the sequence as a prograding shoreface to shelf-margin system that prograded eastward into the high accommodation depocenter, where water depth likely exceeded 500 m (1,600 ft) based on clinoforms amplitude. The westward pinchout of the clinothem against the accommodation step above the tip of fault A suggests that sediment was derived from the inverted block west of fault A, and perhaps from the broader Chukchi platform farther west. The high amplitude reflection that caps the clinothem (blue horizon labeled FS, Fig. 6) is interpreted as a flooding surface overlain by condensed mudstone.

The upper part of the Beaufortian sequence, comprising the section above the blue FS horizon and the entire sequence west of the tip of fault A (Fig. 6) does not display stratal geometry diagnostic of a particular depositional setting, although the presence of the LCU within this interval suggests at least one pulse of erosion related to lowering of base level. East of the accommodation step above the tip of fault A we interpret the entire interval as mainly marine mudstone deposited in shallow shelf depths. West of the accommodation step, we interpret the entire interval as mainly middle to upper shoreface deposits that contain winnowed sandstone facies, including potential reservoir rocks in the Kuparuk sandstone.

The Beaufortian shelf margins south of Klondike trend north-south, parallel to the inverted fault blocks described above (Fig. 7). Southeast of Klondike, the shelf margins curve to the east and appear to merge with a northwest-southeast trend of shelf margins projected from onshore (Fig. 7; Houseknecht and Bird, 2004). The northwest-southeast-oriented shelf margins, as well as the southwestward sediment transport implied by clinoform dip, reflect resurgent uplift of the Arctic platform during rift-shoulder uplift associated with opening of the Canada Basin (Houseknecht and Bird, 2004). Thus, the Beaufortian shelf margins appear to document the intersection of two tectonic trends, inversion of older structures along the Chukchi platform–Hanna trough boundary on the west and rift-shoulder uplift along the Arctic platform on the northeast. The main Beaufortian depocenter, indicated by the hot colors in Figure 7, has developed in the high accommodation embayment formed by these intersecting positive tectonic elements.

Petroleum systems elements

The unique geometry of Beaufortian and older strata across the inverted structures sets up a favorable relationship among petroleum systems elements. Oil-prone source rocks in the upper Ellesmerian sequence (upper Sadlerochit Group, Shublik Formation, and perhaps lower Kingak Formation; pink interval in Fig. 6) are beveled gradually westward by the JU across the inverted blocks above faults B and A, and the Shublik (considered the main source rock) is truncated completely above fault A (Fig. 6, about 30 km, or 19 mi, from the west end of the image). Beaufortian topset facies, known to include reservoir-quality sandstone at least locally, directly onlap the JU or occur within 100 m (330 ft) above the JU. This favorable geometry is present in the Klondike well, for example, where more than 300 m (980 ft) of oil-prone source rocks in the upper Sadlerochit Group and Shublik Formation underlie the JU and reservoir-quality Kuparuk sandstone is present about 75 m (250 ft) above the JU (Sherwood *et al.*, 2002, plate 5).

Beaufortian sandstone facies typically are overlain by shale or mudstone in either the upper Beaufortian or basal Brookian strata, and hydrocarbon discoveries and shows in Chukchi exploration wells indicate adequate seal quality to retain significant oil and gas columns (*e.g.*, Craig and Sherwood, 2004). Finally, relict horsts along the Chukchi platform as well as the inverted structural blocks discussed above commonly are the highest standing structures across the central and western shelf, or provide up-dip drainage to higher structures. Many of these positive features have structural closure across hundreds of thousands of acres (Thurston and Theiss, 1987; Sherwood *et al*., 2002; Wilson *et al*., 2014), thus providing potential traps of significant size.

Therefore, key petroleum systems elements were in place when Triassic source rocks entered the oil generation window during Brookian stratigraphic burial (Sherwood *et al*., 1998; Houseknecht *et al*., 2012)

Conclusions

Ongoing exploration efforts on the U.S. Chukchi shelf are focused mainly on a petroleum system related to a history of rifting, sagging, and inversion that spans the Late Devonian through Early Cretaceous. Late Devonian to Permian rifting accommodated as much as 7 km (23,000 ft) of lower Ellesmerian strata deposited in the Hanna trough while little or no coeval strata were deposited on flanking highs, the Chukchi platform on the west and Arctic platform on the east. Permian to Early Jurassic sagging accommodated up to 2 to 3 km (6,500 to 9,800 ft) of upper Ellesmerian strata, including known oil-prone source rocks in Triassic strata. Late Jurassic to Early Cretaceous contraction to the south (Chukotka and Brooks Range orogens) and extension to the north (rifting in Canada Basin and North Chukchi basin) generated both contractional and extensional structures in the Hanna trough and influenced the accommodation of up to 1.5 km (4,900 ft) of Beaufortian strata.

The area near and south of the Klondike well, along the western margin of the Hanna trough, has been deformed by structural inversion during the Late Jurassic to Early Cretaceous. Seismic evidence suggests that rift-phase normal faults were inverted in contraction, thereby folding Ellesmerian strata above the fault tips and generating erosional relief on the Jurassic unconformity (JU) at the base of the Beaufortian sequence. Inversion likely has been induced by application of stress oblique to the predominant north-south strike of rift-phase normal faults. We speculate that the stress is related to contractional tectonism along the Wrangel-Herald arch, the structural expression of the Chukotka frontal thrust belt.

Erosional relief on the JU not only reflects structural relief but fundamentally controls Beaufortian accommodation. Beaufortian strata thicken eastward in distinct accommodation steps across inverted structures. Lower Beaufortian strata comprise a clinothem that thins westward and pinches out against an abrupt accommodation step above the tip of an inverted fault. Upper Beaufortian strata are thin above inverted structures and thicken eastward across the abrupt accommodation step. We interpret Beaufortian deposits as a spectrum of upper shoreface through offshore facies in water depths ranging from zero to about 500 m (1,640 ft).

Beaufortian shelf margins defined by seismic toplap are oriented north-south along the boundary between the Chukchi platform and Hanna trough, reflecting the influence of inverted structures on accommodation and sediment dispersal. This shelf-margin trend curves abruptly to the east near the Klondike well to merge with northwest-southeast shelf margins projected from onshore. The merger of these shelf-margin trends represents the intersection of two tectonic trends, the inverted fault system on the west and the Canada Basin rift shoulder on the northeast.

Essential petroleum systems elements are closely related to the inverted structures. The JU bevels Triassic source rocks westward across the inverted structures, and reservoir-quality sandstone in Beaufortian strata occur above the JU. Some inverted structures display structural closure on the JU or LCU, and others provide up-dip drainage to structural closures on relict horsts. Thus, oil-prone source rocks, reservoir-quality sandstone, migration pathways, and structural closure are linked intimately across strata associated with postrift sag and inversion phases of basin development. All these key petroleum systems elements were in place when Triassic source rocks entered the oil generation window during Brookian stratigraphic burial.

Acknowledgments

We thank ION Geophysical for permission to include seismic images. We appreciate constructive reviews of the manuscript by Ken Bird (USGS, retired) and Jim Coleman (USGS), as well as feedback on our Chukchi shelf interpretations from Kirk Sherwood and Peter Johnson (BOEM Alaska OCS Region). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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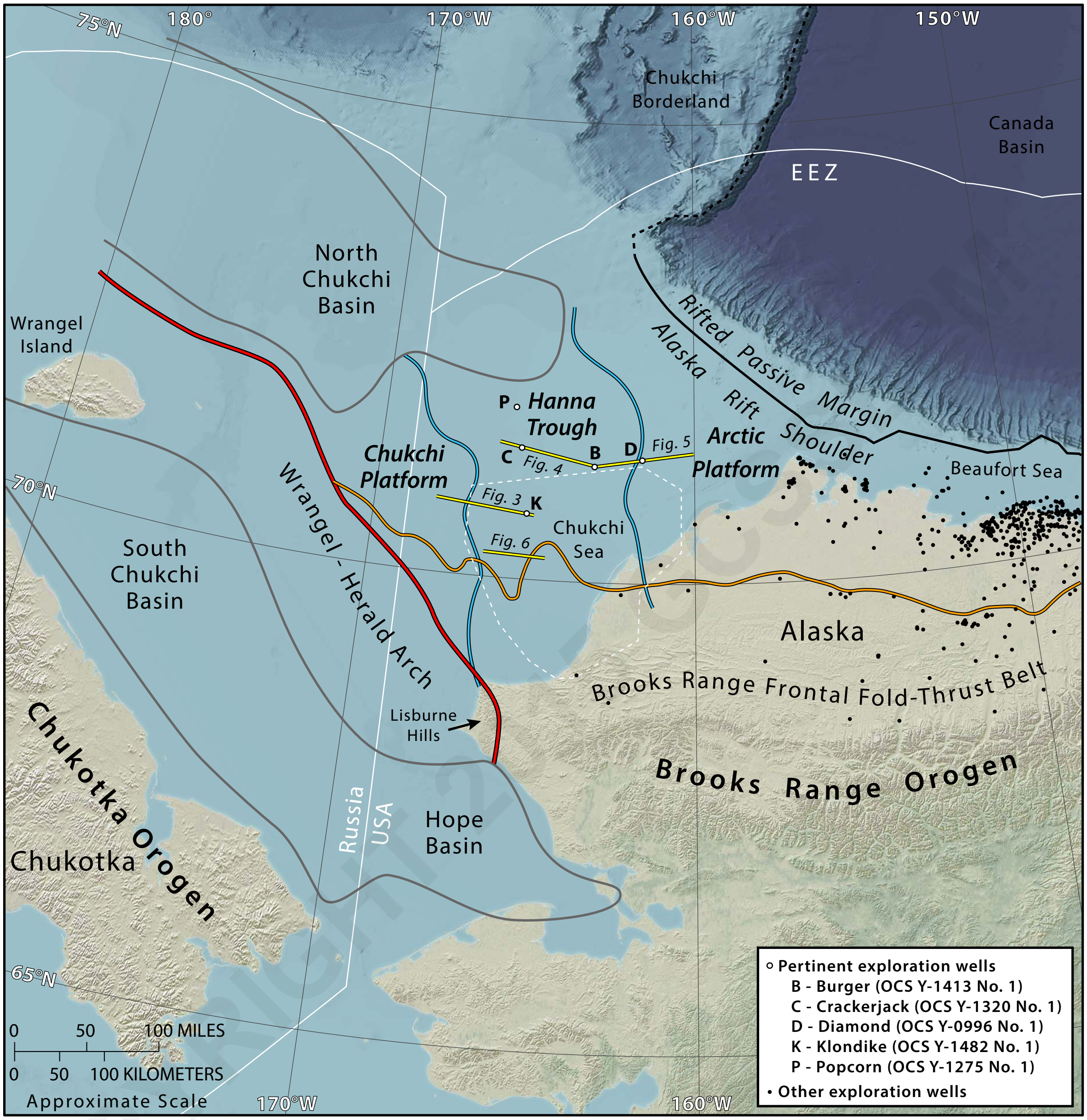

Figure 1. **Map of Chukchi shelf and surrounding region showing main tectonic elements and locations of pertinent wells. Approximate margins of Hanna trough graben system shown in blue; northern limit of Wrangel-Herald arch (thrust belt) shown in red; northern limit of Cenozoic fold belt shown in orange; locations of seismic lines in Figures 3 to 6 shown in yellow. White dashed line is outline of JU-LCU isochron grid shown in Figure 7. White solid lines are international boundaries and northern limits of exclusive economic zones. Chukchi shelf exploration wells labeled as: B, Burger; C, Crackerjack; D, Diamond; K, Klondike; P, Popcorn.**

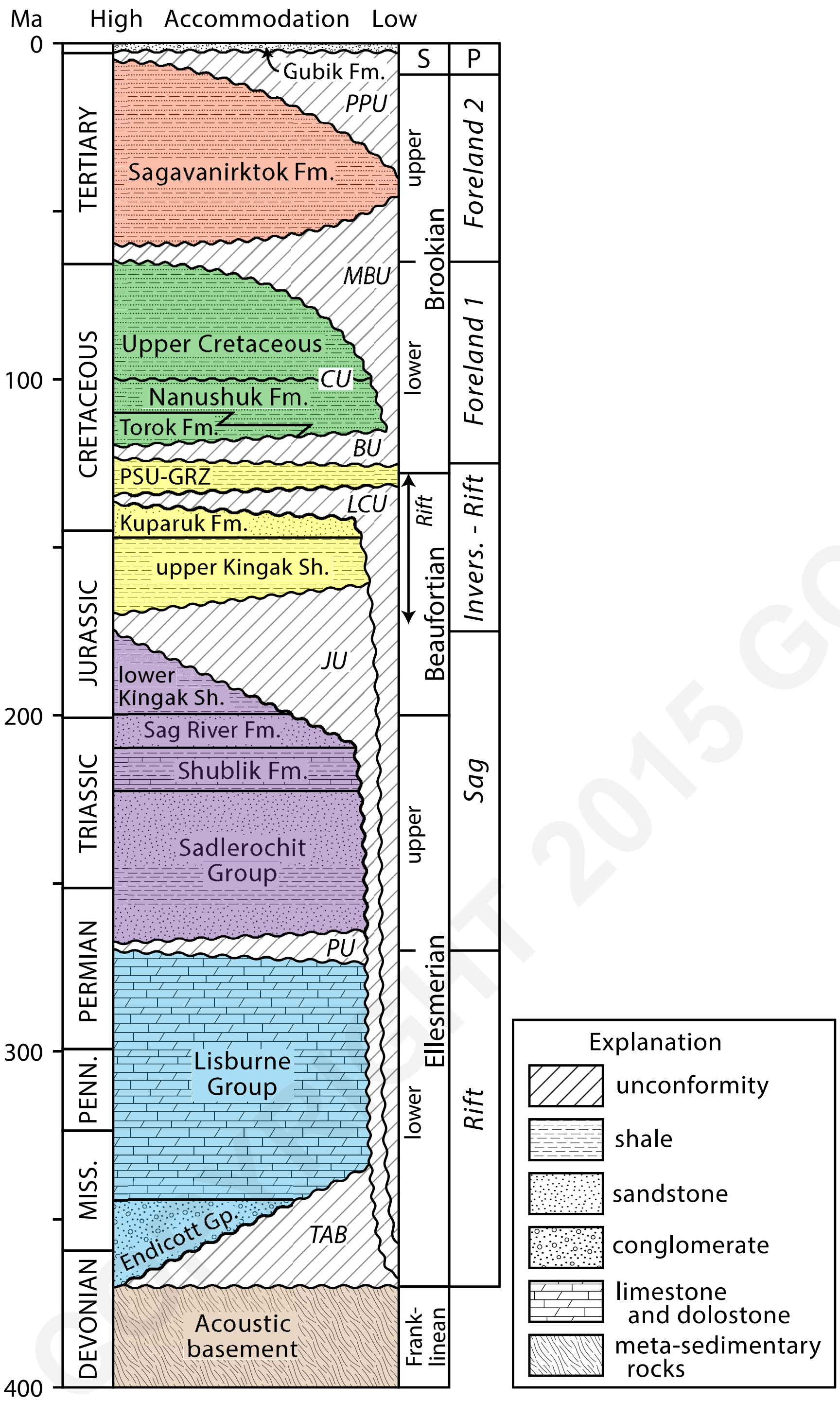

Figure 2. Generalized chronostratigraphy of the Chukchi shelf, revised from Sherwood *et al.* (2002). Column S shows tectonostratigraphic sequences recognized throughout North American Arctic; column P shows phases of basin evolution discussed in text. For detailed description and interpretation of Ellesmerian rift- and sag-phase strata, see Sherwood *et al.* (2002). BU, Brookian unconformity; CU, Cenomanian unconformity; JU, Jurassic unconformity; LCU, Lower Cretaceous unconformity; MBU, mid-Brookian unconformity; PPU, Plio-Pleistocene unconformity; PU, Permian unconformity; TAB, top acoustic basement. Unconformities after Sherwood *et al.* (2002), except CU and PPU after Craddock and Houseknecht (in press).

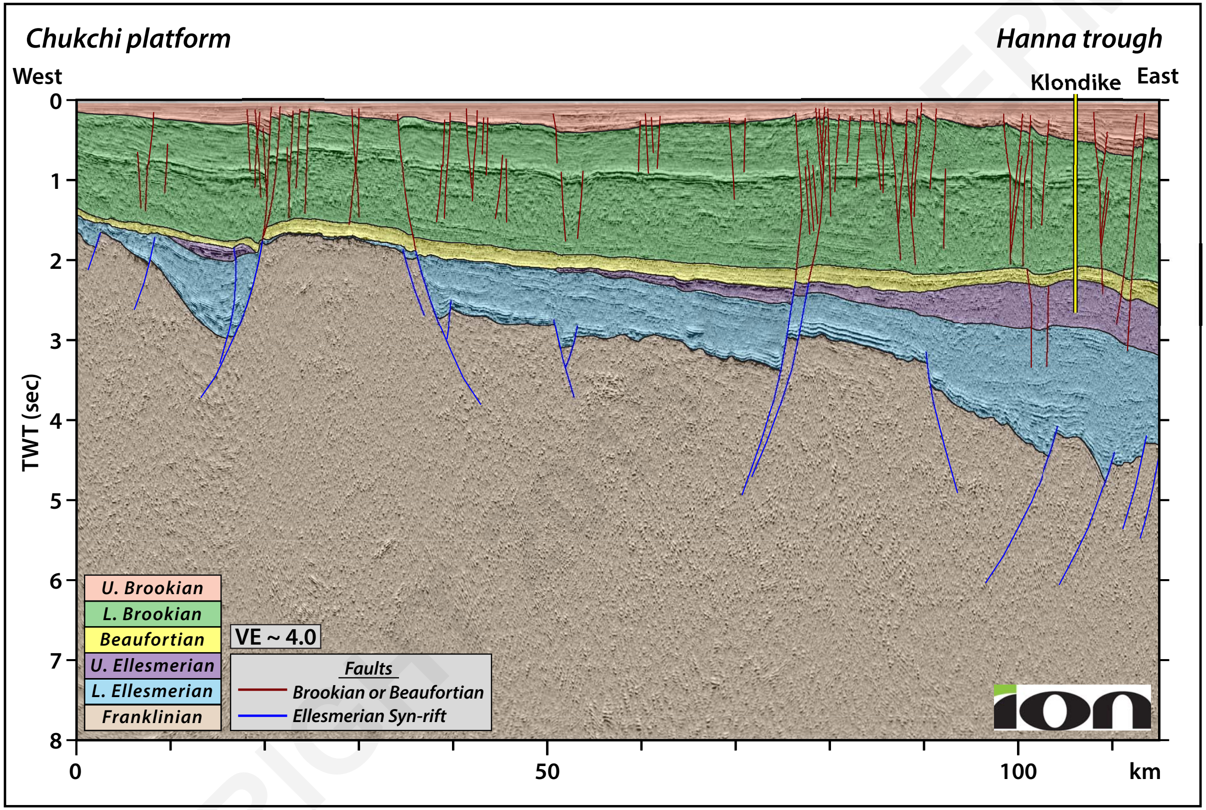

Figure 3. West-east seismic image through Klondike well showing structure and stratigraphy from Chukchi platform to western margin of Hanna trough. Farther west, Ellesmerian and Beaufortian sequences are absent owing to onlap pinchout and erosion, and thinned lower Brookian sequence rests on Franklinian basement. TWT, two-way travel time in seconds. Location of seismic line shown in Figure 1. Image shown courtesy of ION Geophysical.

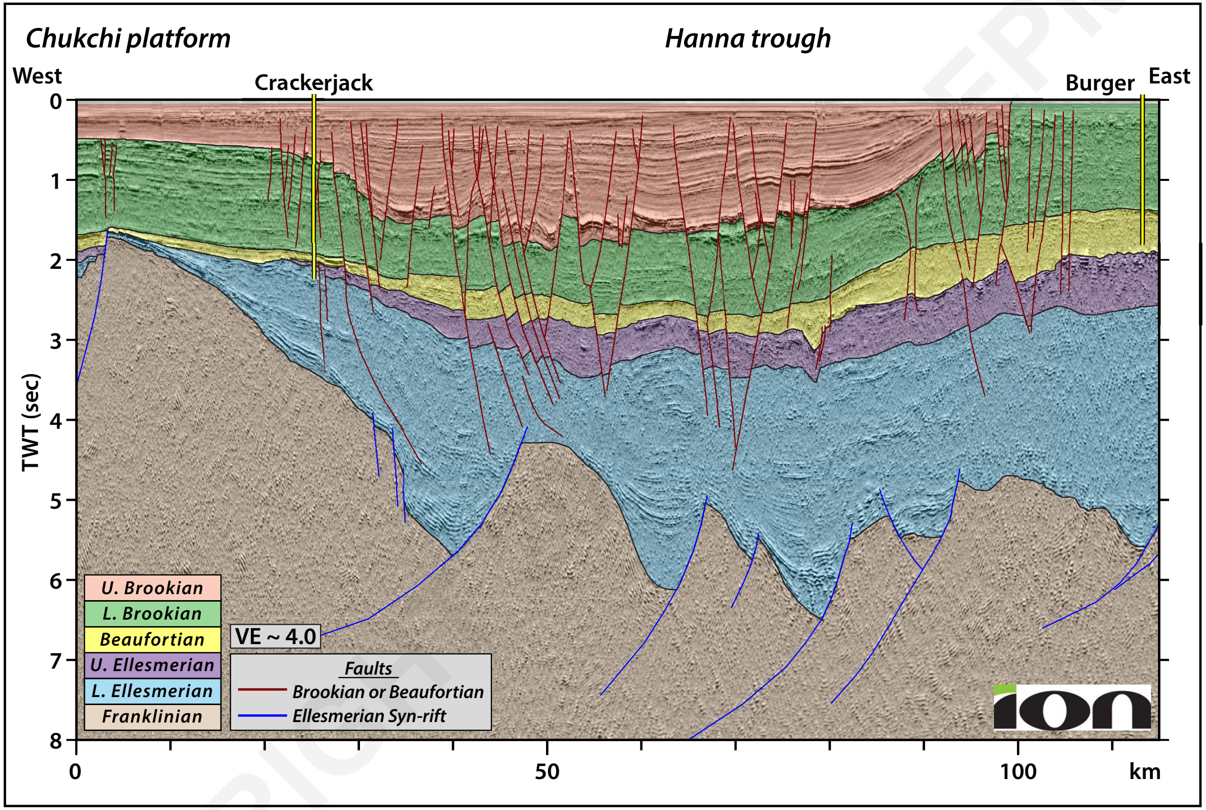

Figure 4. West-east seismic image through Crackerjack and Burger wells showing structure and stratigraphy across main part of Hanna trough. TWT, two-way travel time in seconds. Location of seismic line shown in Figure 1. Image shown courtesy of ION Geophysical.

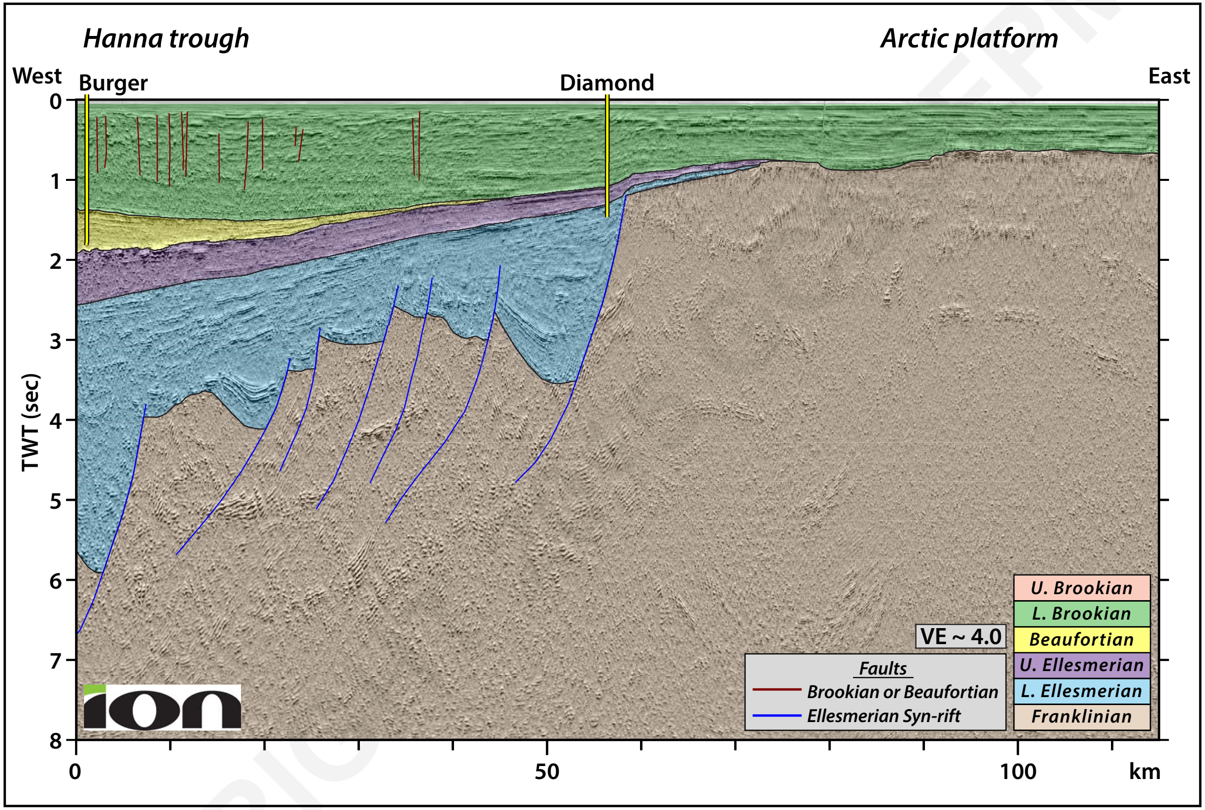

Figure 5. West-east seismic image through Burger and Diamond wells showing structure and stratigraphy across eastern margin of Hanna trough onto Arctic platform. Location of seismic line shown in Figure 1. TWT, two-way travel time in seconds. Image shown courtesy of ION Geophysical.

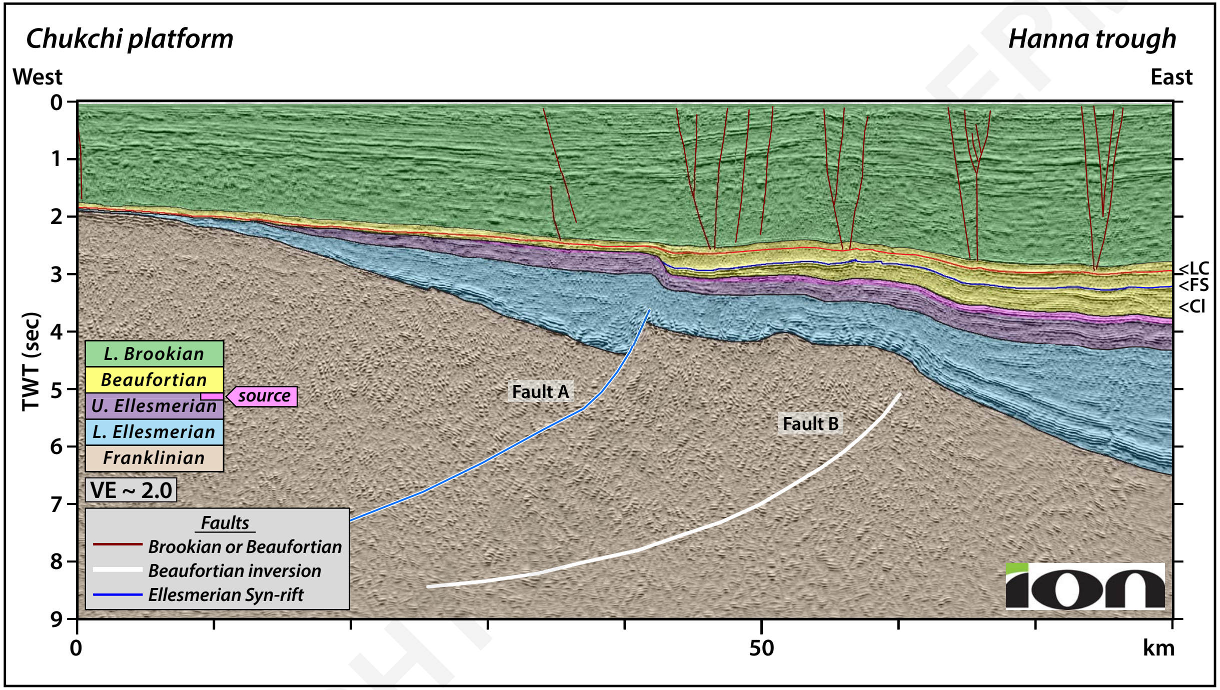

Figure 6. West-east seismic image across western margin of Hanna trough south of Klondike well. Fault A is interpreted as syn-rift normal fault active during deposition of lower Ellesmerian strata, and reactivated as reverse fault during deposition of Beaufortian strata. Fault B is interpreted as reverse fault active during deposition of Beaufortian strata with no previous movement apparent. Main source rock interval of Shublik Formation shown in pink. Red horizon labeled LC at right is Lower Cretaceous unconformity; blue horizon labeled FS at right is flooding surface at top of clinothem, which is labeled Cl at right. TWT, two-way travel time in seconds. Location of seismic line shown in Figure 1. Image shown courtesy of ION Geophysical.

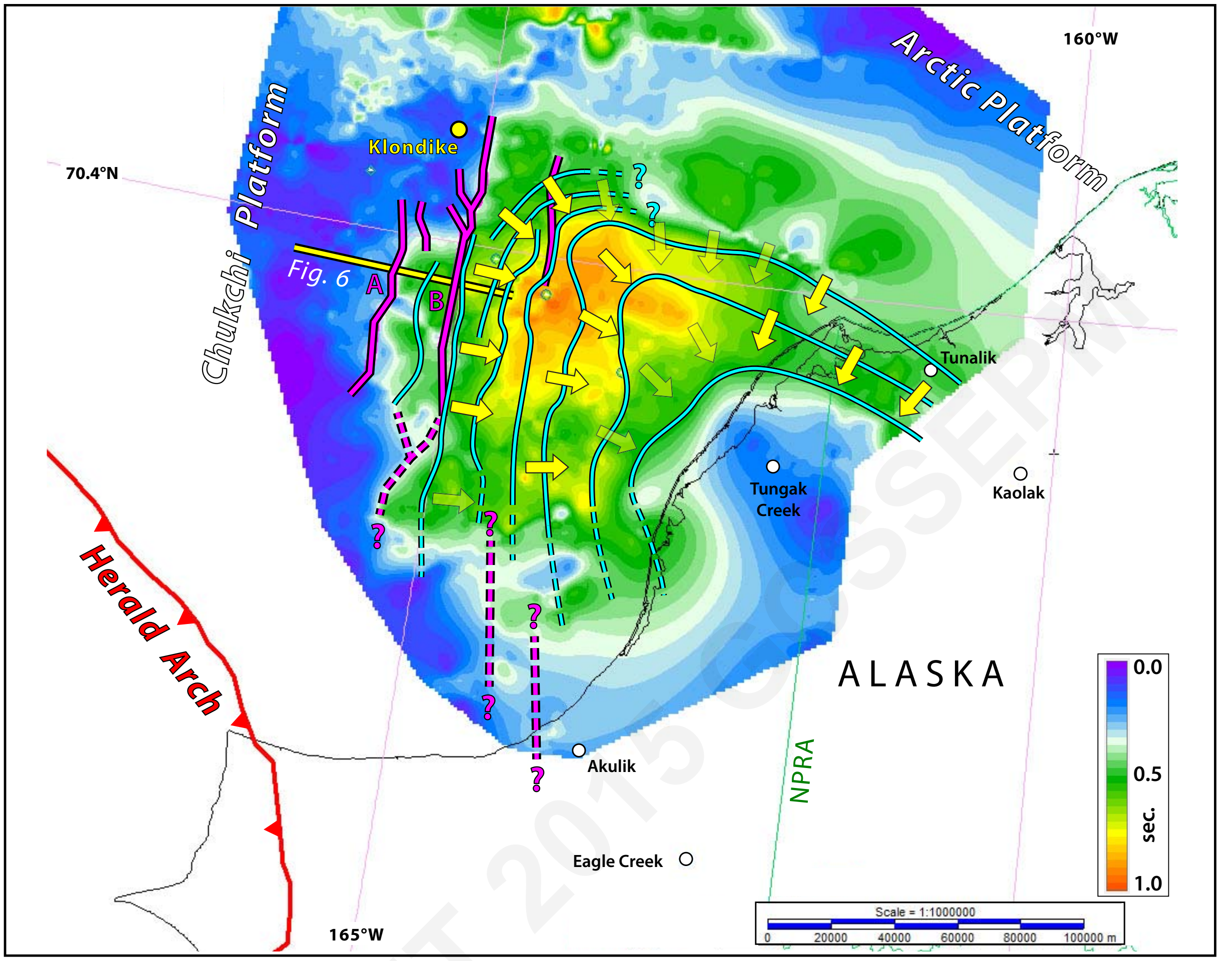

Figure 7. Map of central and southern Chukchi shelf and northwestern coast of Alaska showing isochron grid of stratigraphic interval between Jurassic unconformity and Lower Cretaceous unconformity. This map illustrates the high accommodation depocenter located east of the Chukchi platform and southwest of the Arctic platform. Reverse faults formed during inversion of older normal faults along western margin of Hanna trough are shown in magenta, and labeled A and B as in Figure 6; dashed magenta lines with queries inferred to be similar reverse faults in areas where seismic data quality inhibits interpretation; shelf margins defined by clinoform toplap are shown in cyan; sediment dispersal directions inferred from clinoform dip direction are shown by yellow arrows; certainty of clinoform dip is indicated by transparency of arrows; NPRA, National Petroleum Reserve in Alaska. Onshore exploration wells shown with white-filled circles and name; only the Tunalik well penetrates Beaufortian strata (Houseknecht and Bird, 2004). Klondike well shown by yellow-filled circle and name; all other offshore wells are north of map area. Small circles with blue outline and white fill are locations of shallow cores that penetrate Cretaceous bedrock (Houseknecht *et al.*, in press).