Influence of Late Jurassic Inversion Structures on Sedimentary Basin Uplift, Chukchi Shelf, Offshore Alaska

Arthur F. Stier

Thesis Advisor: Dr. Christopher Connors

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ABSTRACT

This thesis examines the existence of a reactivated fault interpreted to be an inversion structure associated with a Jurassic tectonic event in the Chukchi Shelf off the NW coast of Alaska. Brookian, Jurassic, Ellesmerian, and Franklinian stratigraphic horizons were interpreted in a sequence stratigraphic framework along several thousand kilometers of 2D seismic lines along the Chukchi Platform and Hanna Trough, as well as all faults related to the tectonic history of the study area. Seismic interpretation was based off of a tie to the Klondike test well in the Chukchi Sea.

Using isopach and structure contour maps, as well as mapped horizons along the 2D seismic data, structural and stratigraphic history was determined. Through this seismic interpretation, events such as basin thickening and crustal shortening that had previously been documented as tectonic history of the study are were in in conjunction with what was found in this study. Evidence of normal faulting as well as reverse faulting based off both offset of a seismic horizon in a normal sense and in a reverse sense based on the presence of sedimentary uplift supports the presence of an inversion structure. This indicates that during a regional extensional Jurassic event, a local contractional event occurred, causing shortening in all horizons older than 131 million years old.

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INTRODUCTION

Hanna Trough and U.S. Chukchi Shelf

The Hanna Trough and the U.S. Chukchi Shelf are located under the Chukchi Sea off the Northwest coast of Alaska. The U.S. Chukchi Shelf extends 110-400 km west from the Alaskan to Russian waters and 530 km north from Point Hope to the shelf edge near latitude 73° N (Figure 1). The U.S. Chukchi Shelf is flanked on the north by the oceanic Canada Basin and the Chukchi borderland and on the west by the Russian Chukchi and East Siberian shelves off northeast Siberia (Sherwood et al., 2002). The Hanna Trough is a rift basin that trends south beneath the U.S. Chukchi Shelf and sits between the Chukchi Platform to its west and the Arctic Platform to its east (Figure 2). It joins the west-trending Arctic Alaska Basin that is beneath northern Alaska (Sherwood et al., 2002).

Motivation

While quite a few studies have been done on the structural and stratigraphic geology of onshore Alaska, such as in the National Petroleum Reserve – Alaska (NPRA) on the North Slope of Alaska, relatively few have been done on the geology of offshore Alaska. Despite the intriguing geology of the region, there is still a great deal of structural and stratigraphic uncertainty in the Hanna Trough and U.S. Chukchi Shelf. Previous pioneer studies were carried out by Grantz et al. (1975, 1982a, 1982b, 1987) and Grantz and May (1987) that established the basic geologic framework for the Chukchi Shelf. Building from that, Hubbard et al. (1987) and Haimila et al. (1990) were the first to publish regional studies of the Chukchi and Beaufort Seas based on seismic data. Eventually, Mineral Management Service (MMS) agency reports by Thurston and Theiss (1987), Craig et al. (1985), and Sherwood et al. (1998) were produced based on seismic data. Sherwood et al. (2002) documented in detail the structures and stratigraphy of the Hanna Trough as reveled by seismic mapping by the MMS and by the analysis of petroleum industry wells on the Chukchi Shelf. This study further explores the structures and stratigraphy of the U.S. Chukchi Shelf and Hanna Trough using seismic data and specifically examines apparent inversions structures initially discovered by Houseknecht (2013) in conjunction with the United States Geological Survey (USGS).

Additionally, the U.S. Chukchi Shelf is a highly perspective petroleum province with estimated mean technically recoverable resources of more than 29 billion barrels of oil equivalent (MMS, 2006). While only one round of leasing and drilling more than 20 years ago has been seen in the study area, industry has shown a renewed interest in the area (Dinkelman et al., 2009). Considering this renewed interest, it is critical and necessary to interpret the structural and stratigraphic features of the U.S. Chukchi Shelf and Hanna Trough in order to gain a better understanding of the petroleum province at hand.

GEOLOGY OF THE STUDY AREA

Overview

The Chukchi Shelf is underlain by “normal” continental crust (30-40 km thick) with some suggestion of an attenuated crust in the northern and northwestern part of the area (Dinkelman et al., 2009). The geologic evolution of the Canadian Arctic and Arctic Alaska can be organized into four major sedimentary cycles (Sherwood, 1992). With these three sedimentary cycles included, the rocks that underlie the Chukchi Shelf can be divided into four main sequences shown in a stratigraphic column (Figure 3) from Sherwood et al. (2002). The oldest is known as the Franklinian Sequence, also known as the acoustic or economic basement composed of deformed and metamorphosed rocks aged Devonian and older (Lerand, 1973). The next oldest is known as the Ellesmerian Sequence, which is composed of the principal fill for the rifting-related Hanna Trough and ranged from Late Devonian to Late Jurassic time. Above that is the Rift Sequence (Sherwood et al., 2002) that is known as the sequence that formed the North Chukchi Basin from Jurassic rifting events. The youngest sequence is the Brookian Sequence, which is represented as an orogenic event ranging in possible age from Middle-Jurassic to Early Cretaceous (Sherwood et al., 2002). Many of these sequences are split up into upper and lower portions and are generally divided by key unconformities existing across all rocks in Arctic Alaska. It is also important to note that Chukchi Shelf sequences are correlated with their equivalent and better understood stratigraphic elements beneath onshore Alaska (Figure 3).

Franklinian Sequence

The Franklinian basement is most likely represented by a collapsed basin and accreted terranes that joined together as a single crustal block. The rocks discovered by few onshore wells that penetrated deep enough were Argillite, Slate, Phyllite, and minor Quartzite inferred to be tectonized siliclastics deposited between Precambrian and Late Devonian ages (Sherwood et al., 2002). The Franklinian is known as the acoustic basement because seismic waves do not penetrate it well. This causes the last good reflector at depth on a seismic line to represent the top of the acoustic basement (Sherwood, 1994).

Ellesmerian Sequence

The Ellesmerian Sequence is divided into the lower Ellesmerian Sequence and the Upper Ellesmerian Sequence, separated by the regional Permian Unconformity (PU in Figure 3) (Craig et al., 1985). Ellesmerian strata were deposited in the north-trending Hanna Trough, which is flanked by the Arctic platform on the east and the Chukchi platform on the west. The lower Ellesmerian Sequence contains platform carbonate strata deposited between the Late Devonian and Middle Permian (Thurston and Lothamer, 1991). An early phase of subsidence in the Hanna Trough corresponds with the lower Ellesmerian Sequence and is thought to be rift driven or fault driven (Figure 4A) (Sherwood et al., 2002). Above the Permian unconformity sits the upper Ellesmerian Sequence, which contains clastic and carbonate strata deposited between the Middle Permian and the Late Jurassic (Thurston and Lothamer, 1991). A second phase of regional subsidence, largely unaccompanied by faulting (Figure 4B), governed deposition of the upper Ellesmerian Sequence and is known as the "Sag Phase" (Sherwood et al., 2002). The Ellesmerian Sequence ultimately filled the Hanna Trough with over 11,600 m of strata.

Rift Sequence

Subsidence of the Hanna Trough and the Ellesmerian cycle of sedimentation were concluded with the development of the regional Jurassic Unconformity (JU in Figure 3) that marks the base of the overlying Rift Sequence (Sherwood et al., 2002). This Rift Sequence involved rifting along the Beaufort continental margin that extended into the northern Chukchi Shelf during the Jurassic and opened a new rift that ultimately became the North Chukchi basin (Figure 4C) (Grantz et al., 1994). Structural features of the Rift Sequence include grabens and flexural downwraps that became filled with thick sequences of clastic sediments. Such features represent a distinct tectonic Rift Sequence (Craig et al., 1985), or sometimes called the Beaufortian Sequence (Hubbard et al., 1987). The clastic rocks from this sequence are Late

Jurassic to Early Cretaceous in age and a key unconformity called the Lower Cretaceous Unconformity (LCU in Figure 3) has been discovered in the Hanna Trough (Thurston and Theiss, 1987).

Brookian Sequence

The Brookian Sequence is divided from the Rift Sequence by the Brookian Unconformity (BU in Figure 3) from the lower Cretaceous and the Brookian Sequence itself is divided into and upper and lower component by the middle-Brookian Unconformity (mBU in Figure 3). The Brookian Sequence is a product of the Brookian orogeny (Moore et al., 1994) that completely reorganized the tectonic framework of northern Alaska and the Chukchi Shelf (Sherwood et al., 2002). The Brookian Sequence as a whole was deposited during the Cretaceous and the Tertiary and consists of a thick deltaic wedge shed northward from the Chukotka Range (Houseknecht and Bird, 2004). The Early to Late Cretaceous aged lower Brookian Sequence is composed of pro-delta shale, deltaic sandstone, and coal; while the upper Brookian Sequence consists of Early Tertiary to Late Tertiary continental to marine clastic deposits (Thurston and Lothamer, 1991). These sediments that came from the Chukotka Range filled several basins beneath the Chukchi Shelf (Figure 4D). Deformation during the Late Cretaceous into the Early Tertiary reactivated the north-trending faults within the Hanna Trough (Figure 4, E and F) (Sherwood et al., 2002). For later reference to mapped horizons in the seismic data it is important to note that an onshore equivalent sedimentary group is called the Nanushuk. The Nanushuk horizon is a known stratigraphic group of the North Slope and is classified as shallow marine to non-marine deltaic sequence of sandstone, siltstones, and pro-delta shale (Scherr et al., 1991).

Structural Features of the Hanna Trough

Generally, the faults in the Hanna Trough and on the Chukchi platform originated at the onset of subsidence during the Late Devonian and earlier. Following Permian to Early cretaceous dormancy, they were reactivated with minor displacements during Cretaceous and Tertiary events (Sherwood et al., 2002). The Hanna Trough is segmented by a transform fault and is characterized as a horst-graben terrane with relatively shallow normal faulting. Half-grabens are thought to be the fundamental structures of the Chukchi platform and Hanna Trough (Sherwood et al., 2002). During the lower Ellesmerian Sequence, a widely observed yet discontinuous Mississippian Unconformity (MU in Figure 3) in the Hanna Trough seems to mark a "pause in rift extension associated with uplift and erosion, and was followed by renewed faulting and graben subsidence" (Sherwood et al., 2002). When the Hanna Trough was in the "Sag Phase" mentioned above, subsidence had become unaccompanied by faulting, but Sherwood et al. (2002) believed that it was instead possibly driven by thermal contraction of the extended, heated crust beneath the Hanna Trough.

METHODS

Data

Petroleum industry investigations of the U.S. Chukchi Shelf prompted by oil and gas lease in 1988 and 1991 resulted in the collection of 161,000 line km of high-quality 2D seismic reflection data, nearly all of which are located south of latitude 73° N (Sherwood et al., 2002). Of these 161,000 line km of public domain seismic data from the petroleum industry, a subset of seismic lines and wells were selected for analysis and interpretation for this study. This subset of data consists of industry seismic data and data acquired by the USGS. Many of these seismic lines are tied by Ken Bird of the USGS to five prospect wells drilled in the Chukchi Sea (Burger, Klondike, Crackerjack, Popcorn, Diamond) between 1989 and 1991 (MMS, 2006). To see the locations of these test wells, refer to Figure 1. Due to time constraints, only a portion of the provided seismic data was used in this study. All seismic lines to the south of the Klondike test well were set aside to be structurally and stratigraphically interpreted for the purposes of this study (Figure 5). To see similar thesis studies done on seismic data north of the Klondike test well, see the work of my two colleagues Andy Roberts (2015) and Charlie Gentry (2015). Formation tops from wells demark lithostratigraphic unit tops from Ken Bird of the USGS, and were correlated to the seismic data for stratigraphic interpretation.

Overview of Seismic Interpretation

Seismic reflectors are the product of impedance contrasts between rock layers (Badley, 1985) (Figure 6), which makes seismic imaging a valuable tool for mapping rock layers and the unconformity surfaces that bound stratigraphic sequences. This is particularly true for structural and stratigraphic exploration in the Chukchi Shelf, due to the fact that it is a rather remote, offshore location. Lithostratigraphic formation tops that were previously picked by the USGS through well data were used to correlate formation tops to the seismic data (Figure 7). The horizons were then mapped across each of the lines to generate an internally consistent interpretation with reliable ties between seismic line intersections (Figure 7). The interpretation was done in IHS's Kingdom Suite© 8.8. Interpretations of major unconformities such as the Jurassic Unconformity (JU) and the Lower Cretaceous Unconformity (LCU) were fully reinterpreted throughout the study site using Houseknecht's (2013) interpretation as reference. Faults were added to the interpretation where clear offset was seen between reflectors in the seismic data (Figure 8). It is also important to note that deeper faults offsetting older mapped horizons were added to some of the data by Christopher Connors.

Mapped Horizons and Faults

Each horizon was mapped based on the following criteria that are explained below this paragraph. Figure 9 shows the stratigraphic location of each horizon in the Chukchi Shelf. To map each horizon or unconformity surface, we followed a continuous reflector or a boundary between reflectors known as a zero-crossing. If the seismic imaging became poor we made our best guess mapping the horizon by tying with intersecting seismic lines.

Brookian Units – Four Cretaceous to Tertiary aged continuous shale horizons were mapped and referred to as B4, B3, B2, and B1 (youngest to oldest). The B2 horizon was tied to the onshore equivalent Nanushuk lithostratigraphic pick in the Klondike test well. All four of these units were mapped across continuous reflector peaks (Figure 9). In particular, onlapping of younger sediments onto these reflector peaks was also used as viable criteria while mapping these horizons. In the study area, the two way travel time to the Brookian Units ranges from approximately 0.4 to 0.7 seconds.

Lower Cretaceous Unconformity - The Lower Cretaceous Unconformity (LCU) is laterally continuous unconformity that spans throughout the entire study area within the Hanna Trough. The LCU was tied to the LCU USGS pick in the Klondike test well. The fact that the LCU is laterally continuous in the area makes it one of the most critical horizons in the study area because it allows us to determine where we are in the stratigraphic column anywhere in the basin. The character of the LCU varies throughout the study area, but is generally seen as an erosional surface particularly while going through the middle of the Hanna Trough as it angularly truncates the underlying strata. Onlapping is seen on the LCU as well, particularly on the eastern and western extremities of the Hanna Trough where truncation is also seen, in the middle of the deposition. In general, the LCU in the study area is mapped at a zero crossing above a trough and below a peak (Figure 9). Onshore, this peak is thought to be the pebble shale unit and gamma-ray zone overlying the LCU (Houseknecht and Bird, 2004). The LCU acts as a detachment surface for many of the younger faults where they flatten and terminate along that horizon. LCU regional highs are generally located in the northwest, west, and southwest parts of the study area based on an LCU structure contour map (Figure12). LCU lows are generally located in the southeast part of the study area. Along east-west trending seismic lines, the LCU tends to stratigraphically drop as the horizon moves eastward. Throughout the majority of the east-west trending seismic lines, this drop from a stratigraphic high to a low seems to occur due to structural attributes as seen in the seismic data. In the study area, the two way travel time to the LCU ranges from approximately 1.0 to 2.8 seconds (Figure 10).

Upper Jurassic Unconformity - Of the two Jurassic Unconformities in this study area in the Chukchi Sea, this upper one is approximately 140 million years old, based on lithostratigraphic well picking. The upper Jurassic Unconformity is overlain by Upper Jurassic rocks at the Klondike test well (Sherwood et al 2002). This unconformity truncates Hanna Trough strata and ultimately overlies basement across the western parts of the study area. As a whole, this upper Jurassic Unconformity is both structurally and stratigraphically low throughout most of the study area with the exception of the north and northeast parts of the study area, as well as towards the west. This thickness is likely due to thermal subsidence, as is a common occurrence in regards to sediments in the Hanna Trough. Where it sometimes overlies basement on the western part of the study area, it pinches out against the LCU. This upper Jurassic Unconformity is classified as representing an erosional event due to changes in eustatic sea level and ranges in depths from 1.2 to 3.1 seconds of two way travel time. When looking at the seismic data in the study area, the upper Jurassic Unconformity is interpreted as the surface below a trough and above a peak showing reflection amplitudes (Figure 9).

Lower Jurassic Unconformity - Of the two Jurassic Unconformities in this study area in the Chukchi Sea, this lower one is approximately 180 million years old, based on lithostratigraphic well picks described by Bird and Molenaar (1987). Unlike the upper Jurassic Unconformity, it is laterally continuous across the study area, much like the LCU. Also much like the LCU, the upper Jurassic Unconformity is stratigraphically and structurally low in the eastern part of the study area in the Chukchi Sea and structurally high in the western part of the study site. This unconformity truncates Ellesmerian strata and ultimately overlies basement across the western parts of the study area, much like its upper component. Refer to the western Arctic Platform in in Figure 10 to gain perspective of this geology. Where it sometimes overlies basement on the western part of the study area, it pinches out against the LCU. This lower Jurassic Unconformity is classified as representing an erosional event and ranges in depths from 1.0 to 3.3 seconds of two way travel time. When looking at the seismic data in the study area, the upper Jurassic Unconformity is interpreted as the surface below a peak and above a trough showing reflection amplitudes.

Lisburne Group – Well documented from onshore studies, this is a group that represents a period of marine transgression when a diverse assortment of transgressive and platform carbonate facies were deposited (Armstrong and Bird, 1976). Characterized by regionally continuous limestone and some dolostone, the Lisburne Group is dated to be approximately 290 million years old. Its equivalent Chukchi Shelf stratigraphy is in the Lower Ellesmerian Sequence. It is important to note that this group was partially interpreted in the study area by Christopher Connors.

Endicott Group – Also well documented from onshore studies, this is a group that is the basal unit of the lower Ellesmerian Sequence and is composed of non-marine sediments and coals overlain by marine shale (Bird and Molenaar, 1987). Characterized by interbedded conglomerates, sandstones, thin coals, and shale, the Endicott Group is dated to be approximately 330 million years old. Its equivalent Chukchi Shelf stratigraphy is in the Lower Ellesmerian Sequence. It is important to note that this group was partially interpreted in the study area by Christopher Connors.

Acoustic Basement – Dated to be approximately 354 million years old, the top of the Franklinian Basement is interpreted as the last strong reflector visible in the seismic data (Figure 9). These rocks are heavily deformed and metamorphosed, making it difficult for seismic waves to penetrate them. It is important to note that this group was partially interpreted in the study area by Christopher Connors.

DISCUSSION

Structural Style

While only one of the many seismic lines interpreted could be shown in this study, a fully interpreted line was shown that best represents the overall structural and stratigraphic style of the study area (Figure 10). This line shows the general trend of a structurally high Chukchi platform to the west, moving into a structurally low Hanna Trough in the east. It is inferred that the structural low in the east seen in the seismic is representative of Sherwood et al.’s (2002) interpretation of the filling of the Hanna Trough with more than 11 km of sediments during the Ellesmerian Sequence. When looking at the structural high in the west, a horst-graben structural style is seen in the seismic data, which is in agreement with Sherwood et al.’s (2002) interpretation of structures seen as a result of Ellesmerian Rifting. When looking at the west part of the shown line, a classic graben is interpreted (Figure 10), as well as numerous shallow normal faults. These all give evidence of a once-extensional environment, in agreement with all prior interpretations of the geology of the Chukchi Shelf. When zooming in on the eastern half of the shown seismic line (Figure 11), two deep normal faults with significant offset are seen through the basement. Highlighted by the red rectangle in Figure 11, significant basin growth was interpreted between horizons, which fits with Sherwood et al.’s (2002) interpretation of subsidence possibly driven by thermal contraction of the extended, heated crust beneath the Hanna Trough.

Looking at the shown seismic line in Figure 10, it is accompanied by a structure contour map of the LCU horizon (Figure 10 lower right, and Figure 12), to show modern day highs and lows and how they change with respect to the seismic line itself. In addition to the LCU, a structure contour map was also made of the Lower Jurassic Unconformity horizon (Figure 13). They each have very similar geometry, yet moving from west to east the Lower Jurassic Unconformity begins to deepen before the LCU does. Both of these maps further show the interpretation of the movement into the Hanna Trough coming off the Chukchi platform, moving west to east. Figure 14 shows an isopach contour map displaying the thickness difference between these two unconformities. Where thickness is greatest is in agreement with

Sherwood et al.’s (2002) interpretation of where greatest subsidence exists due to thermal contraction and extensional structural forces. This idea also agrees with the Chukchi Platform and Hanna Trough tectonic relief being reflected in accommodation patterns persisting through the Jurassic and Cretaceous (Sherwood, 2002).

Inversion Structure

Looking again at Figure 11, a deep fault has been colored green to indicate that it was interpreted as a reactivated fault. Where the basement horizon clearly is offset on the hanging wall of the fault, the green zoomed in circle in Figure 11 shows subtle yet abrupt uplift. With these observations, it is interpreted that this fault originally occurred as a normal fault in an extensional tectonic environment yet was reactivated as a reverse fault in a contractional tectonic environment. This interpretation led to the conclusion that this reactivated fault was an inversion structure, which is in agreement with the interpretation done by Houseknecht (2013). Structural inversion occurs when basin-controlling extensional faults reverse their movement during compressional tectonics, and, to varying degrees, basins are turned inside out to become positive features (Williams et al., 1989). For a visual example of this phenomenon, see Figure 15. The depiction of sedimentary uplift in Figure 15 is more or less a direct representation of what is seen at the top of the reactivated fault in Figure 11. This particular fault, given the structural style around it, is interpreted as an Ellesmerian normal fault that was then reactivated as a reverse fault during either the Cretaceous or Jurassic. This is in agreement with Houseknecht’s (2013) interpretation of these normal faults as transpressional structures during the Jurassic/Cretaceous. A large conclusion that can be taken away from this inversion structure is that it gives evidence of a contraction event during extensional Jurassic rifting. Shortening is observed and interpreted in all horizons below the LCU at the peak of the reactivated fault, which gives great evidence of the timing of the fault being reactivated during the late Jurassic or early Cretaceous.

Conclusions

Structural and stratigraphic seismic interpretation of the rock strata of the U.S. Chukchi Shelf off the northwest coast of Alaska below the Chukchi Sea show a move from the structurally high Chukchi platform to the west into the Hanna Trough in the east (Figure 10). This regional interpretation is in agreement with the documented stratigraphic and structural history of the study area and when parts of this regional interpretation are examined locally, certain features are found that further agree with the documented history of the area. A deep structural low in the east is consistent with sediments providing the principal fill during the Ellesmerian Sequence. Shallow normal faulting, half-grabens, and grabens are consistent with the extensional structural style involved with the Jurassic Rift Sequence. Reactivation of normal faults during the Brookian is consistent with the interpreted inversion structure that shows a deep fault with evidence of both normal and reverse faulting. This interpreted inversion structure is very significant as it shows evidence of a local contractional crustal shortening event during a time of regional extension and crustal thickening.

Future Work

Restoration and balancing of cross-sections would further improve the validity of the seismic interpretation. In order to do this data would need to be converted from time into depth. Additionally, deeper structural and stratigraphic examination of the inversion structure could tell much more about the complexity of the area and further explain bed formation thicknesses. The combination of these two things would show the original thickness of undeformed strata as they were during the Jurassic and Cretaceous.

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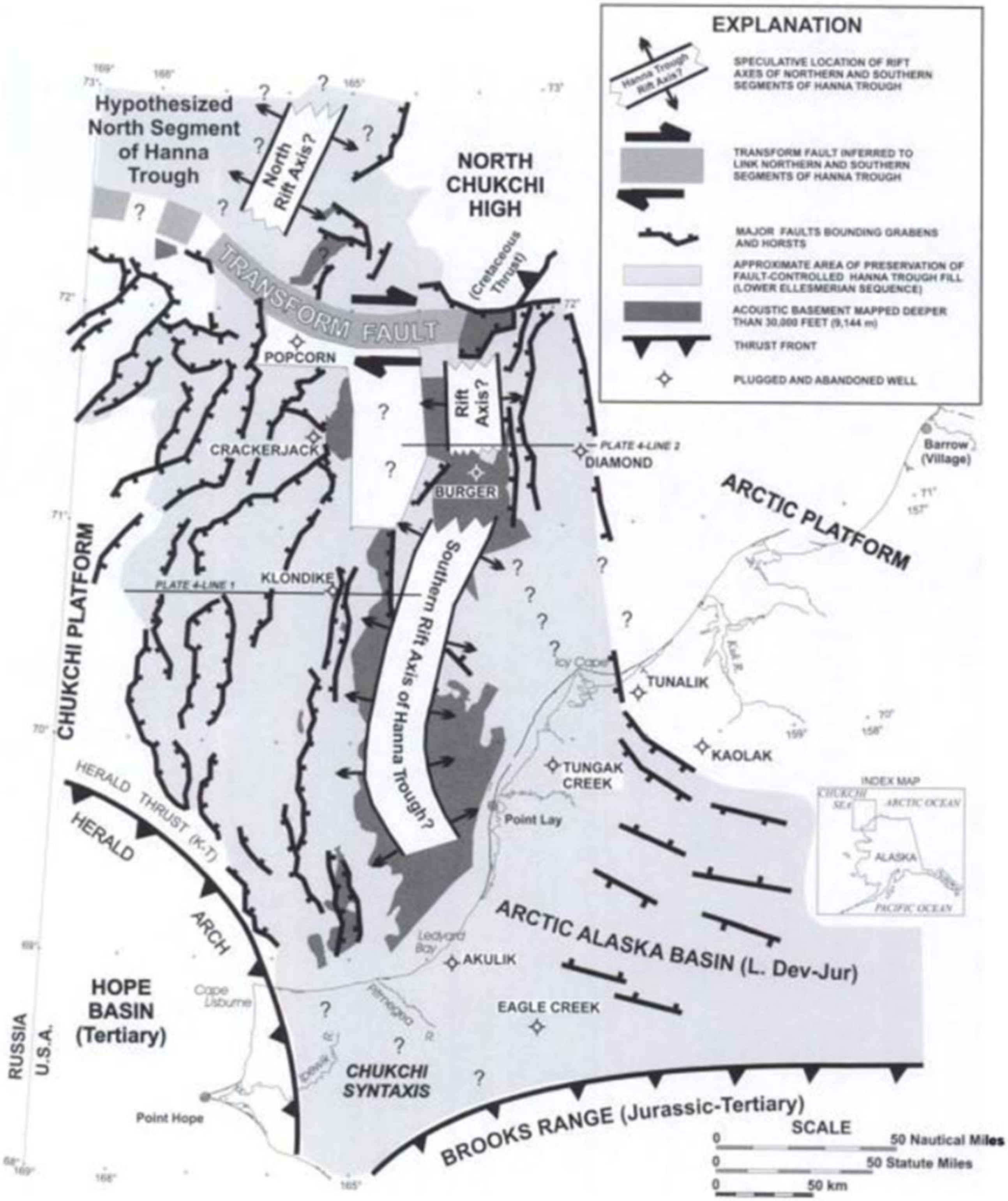

Figure 1: Major tectonic elements of the Hanna Trough in the U.S. Chukchi Shelf, Alaska (Sherwood et al., 2002)

Figure 2: Zoom in on the study area (Google Earth)

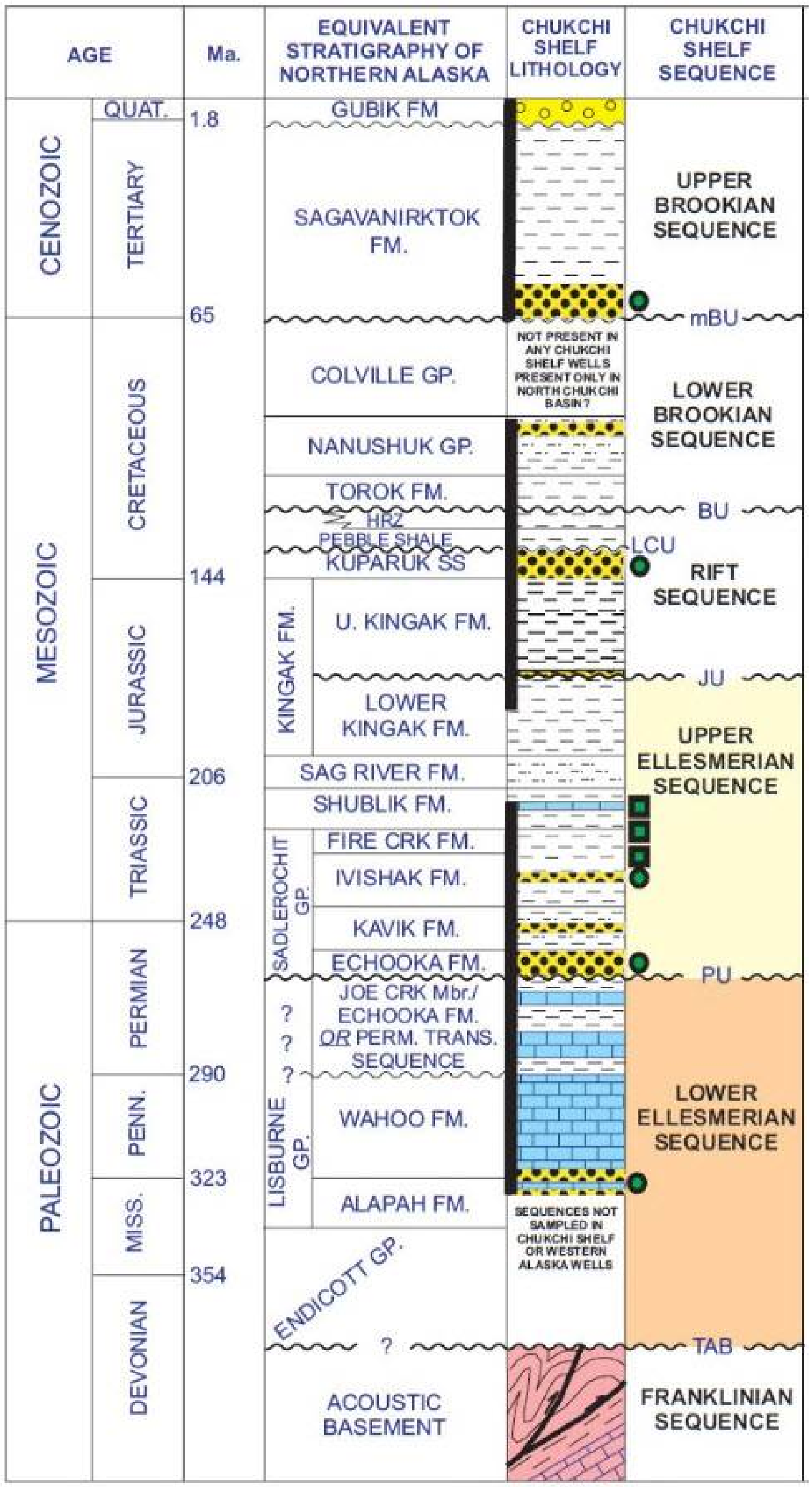

Figure 3: A stratigraphic column of the study area (Sherwood et al., 2002)

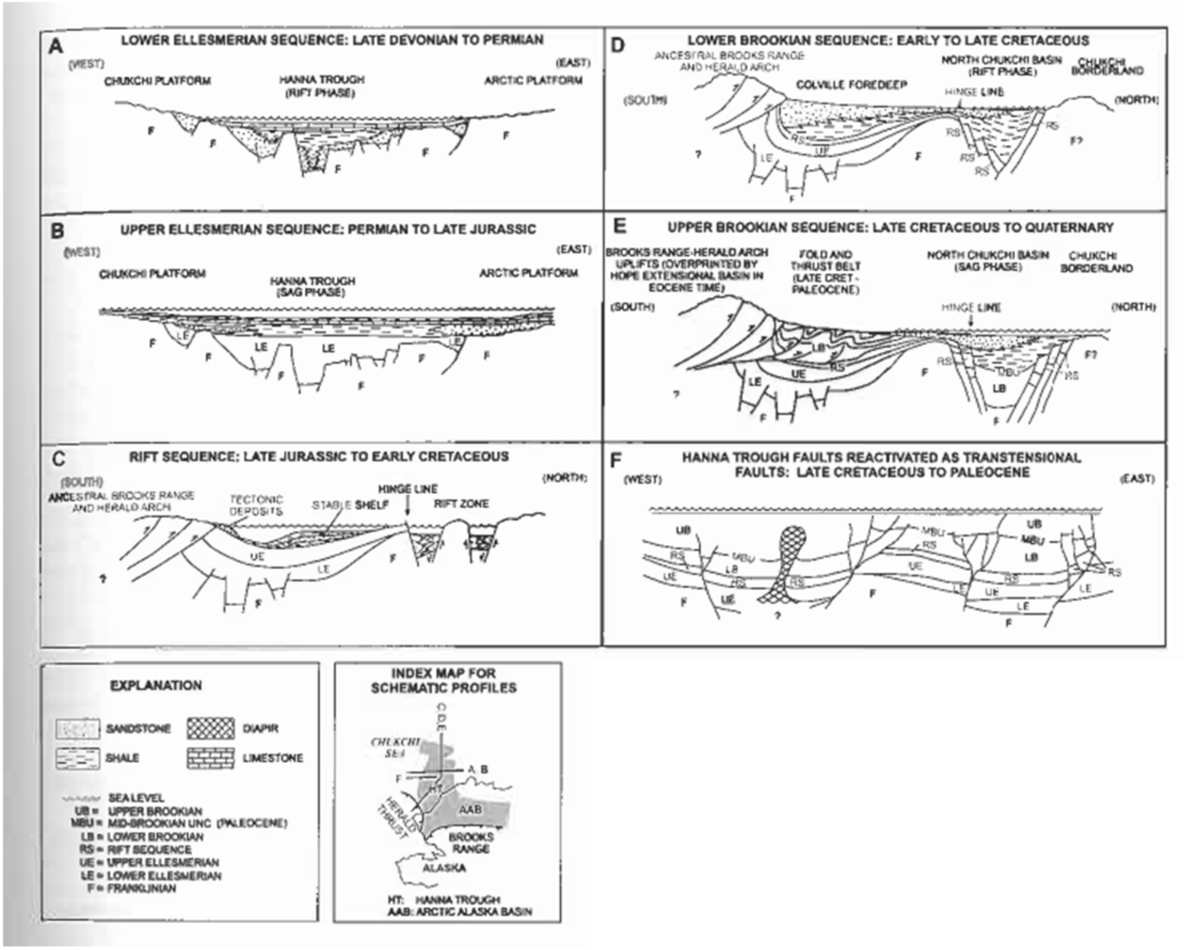

Figure 4: Geologic evolution of the Chukchi Shelf: 6 main basin forming events labeled A-F (Sherwood et al., 2002)

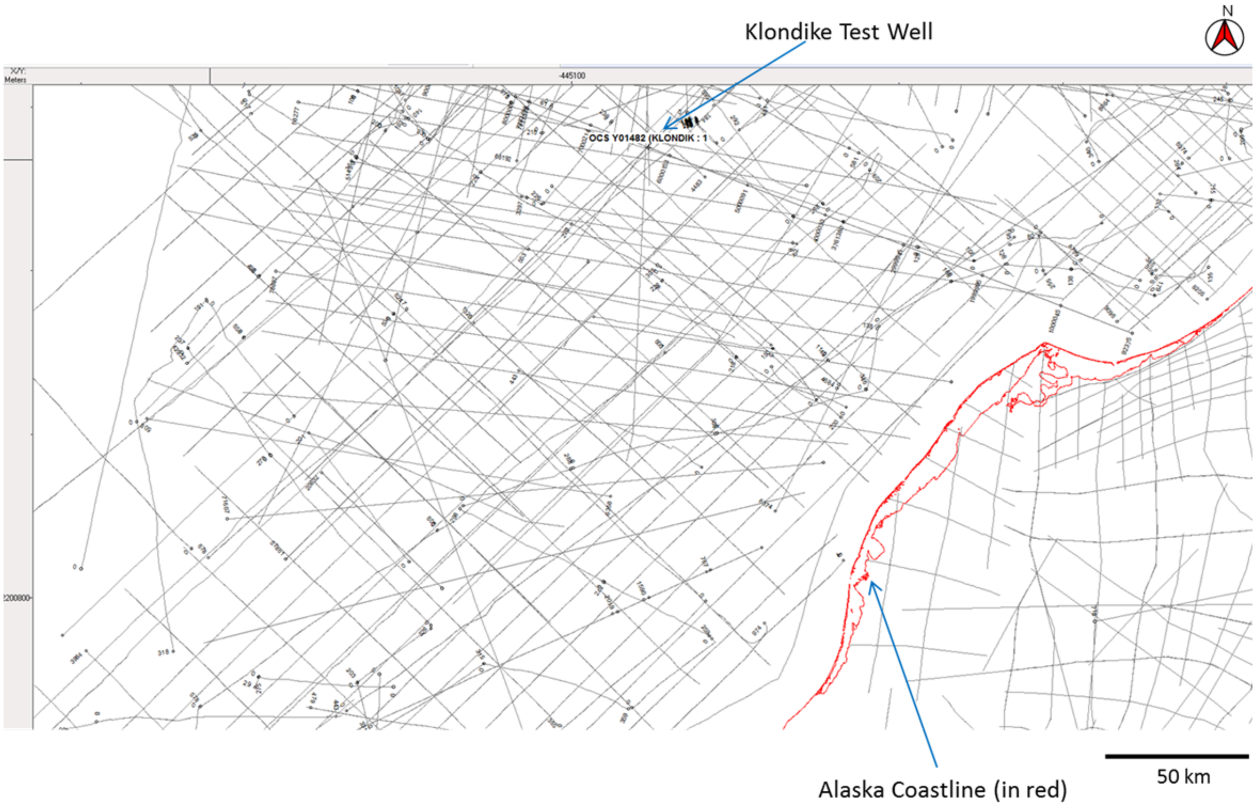

Figure 5: Relative transect positions of 2D seismic data in study area off the coast of Alaska and south of the Klondike Test Well

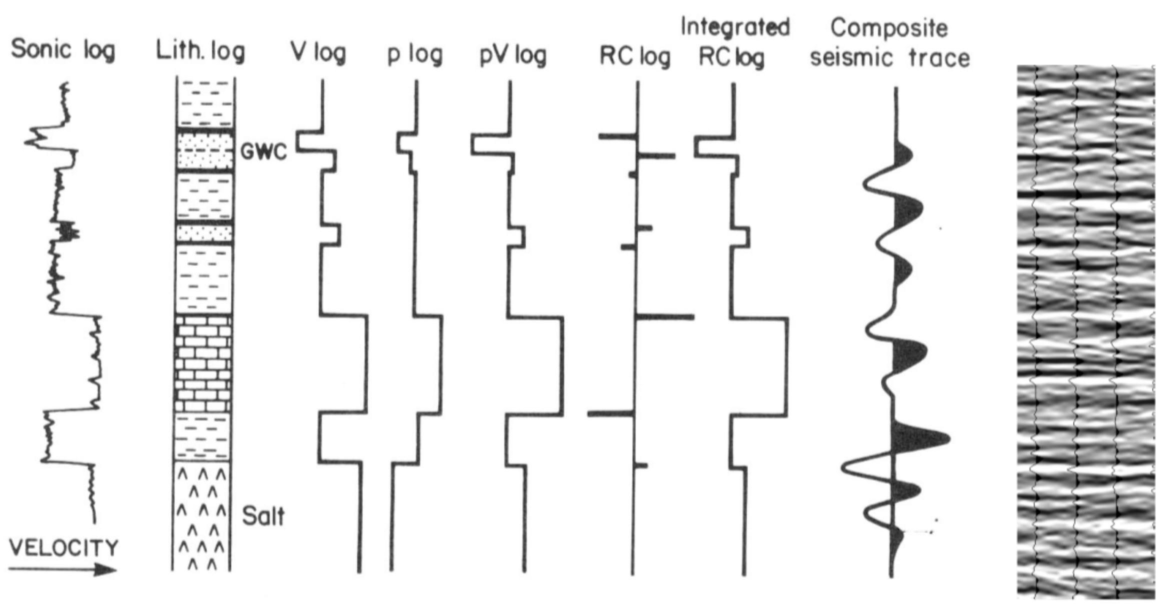

Figure 6: The various types of log data, along with a composite seismic trace. Composite seismic traces along a line can be used to create a 2D seismic image, as shown in the far right. Modified from Badley, 1985.

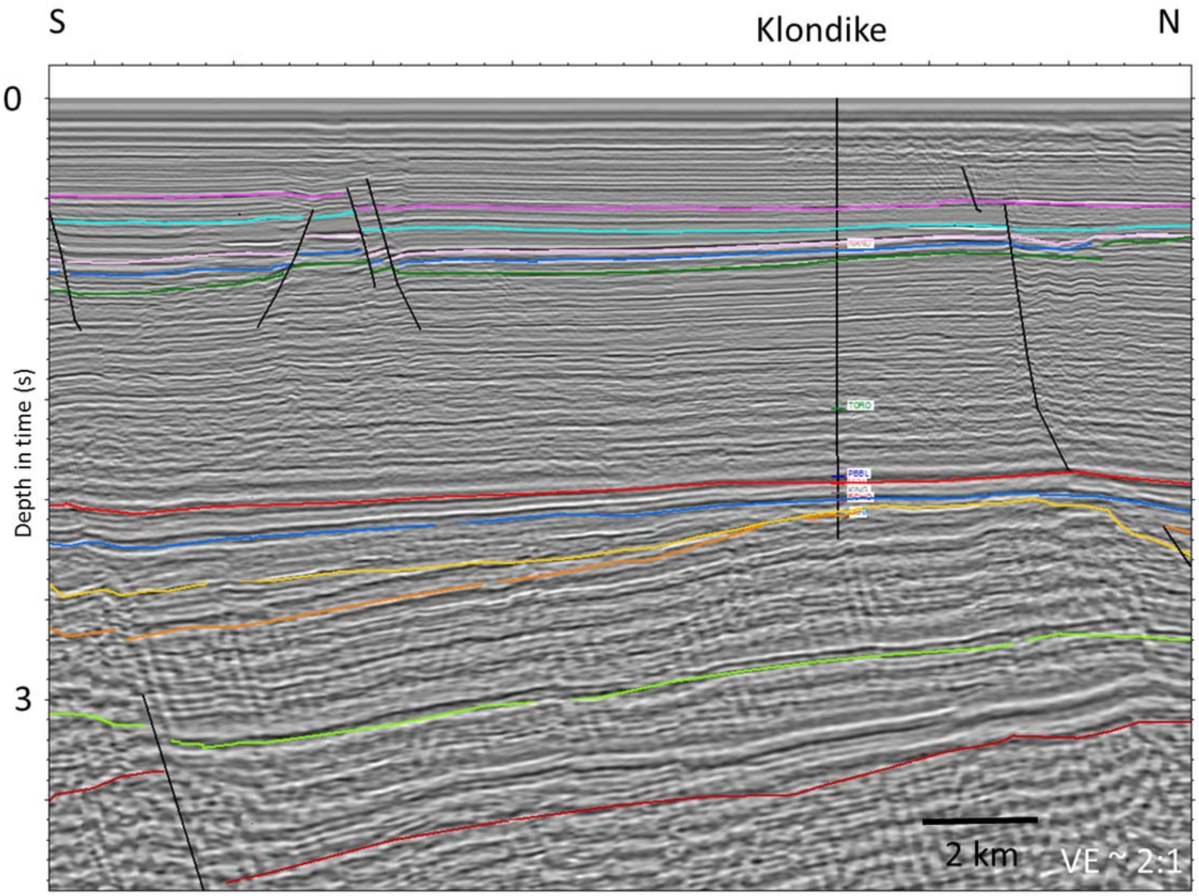

Figure 7: Portion of a seismic line showing USGS well tops tied to mapped horizons

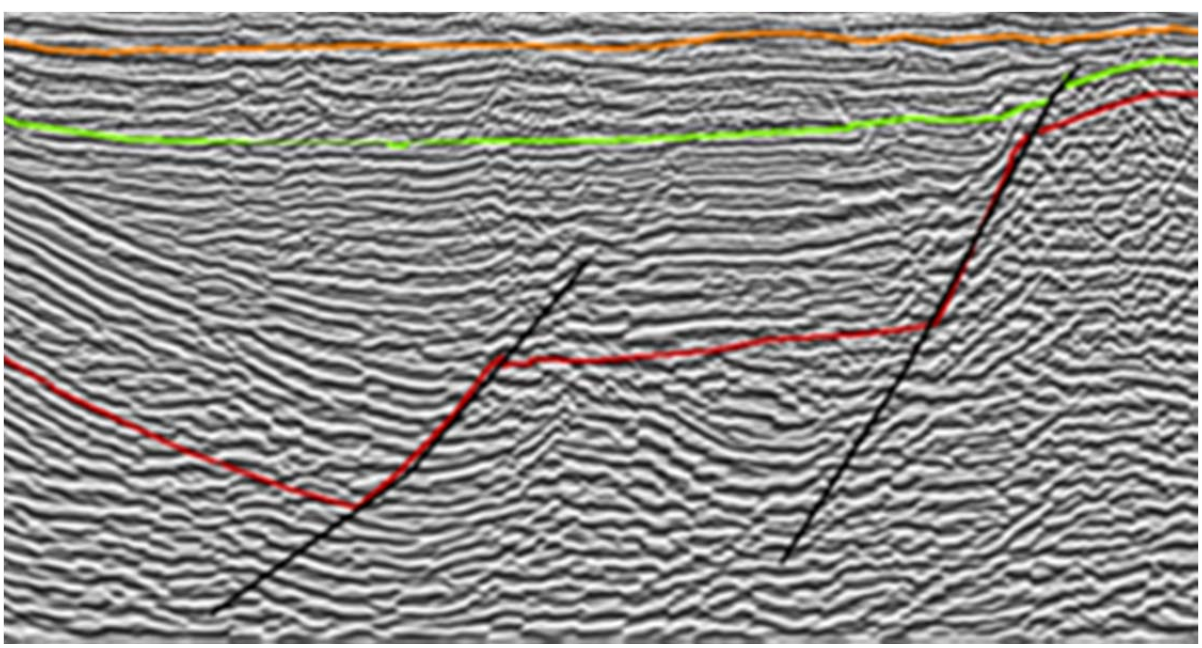

Figure 8: Shows major offset in a mapped horizon, indicating the presence of faults

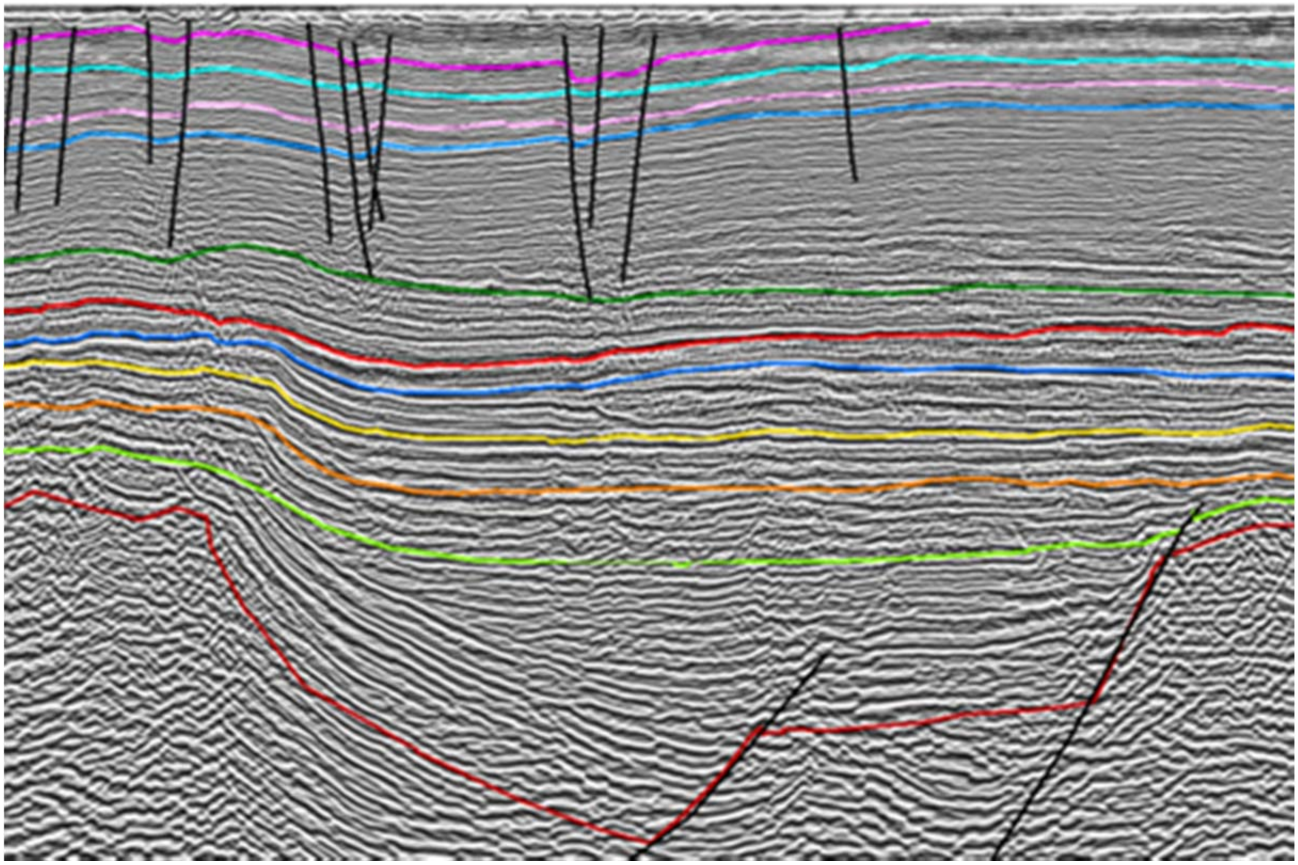

Figure 9: Image showing all interpreted and mapped horizons based on seismic reflector packages unique to each one

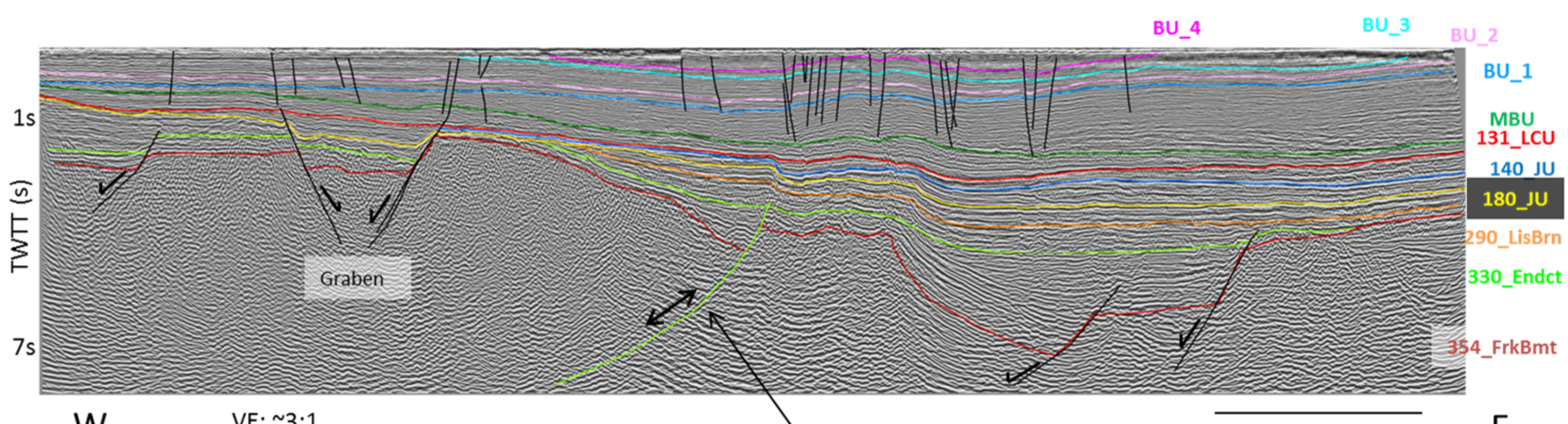

Figure 10: A fully interpreted 2D seismic line courtesy of WesternGeCo, with horizons labeled on the side

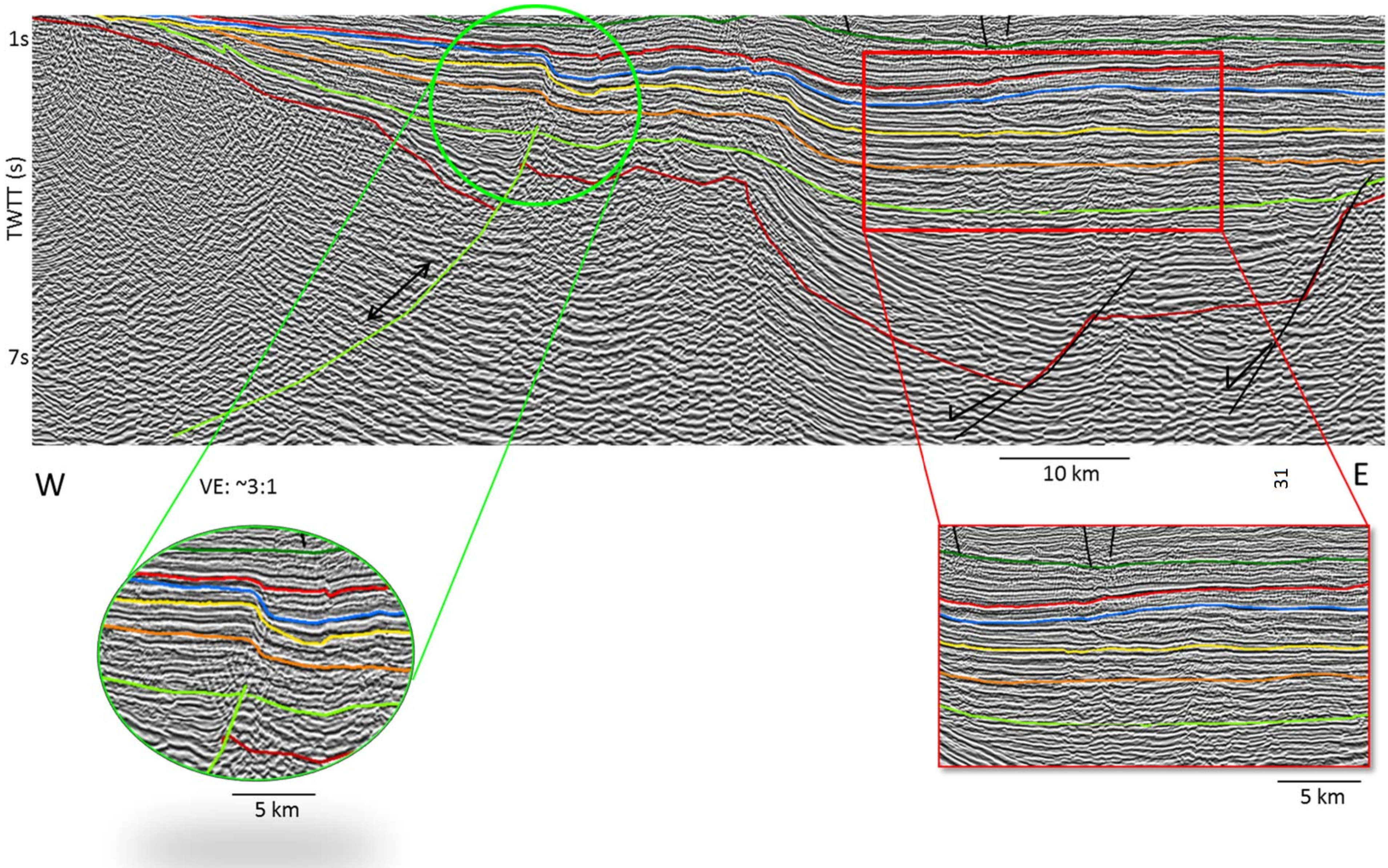

Figure 11: A zoom in on the eastern part of the seismic line shown in Figure 10: shows additional zoom on the inversion structure and basin thickening. This line is roughly 50 km south of the Klondike test well

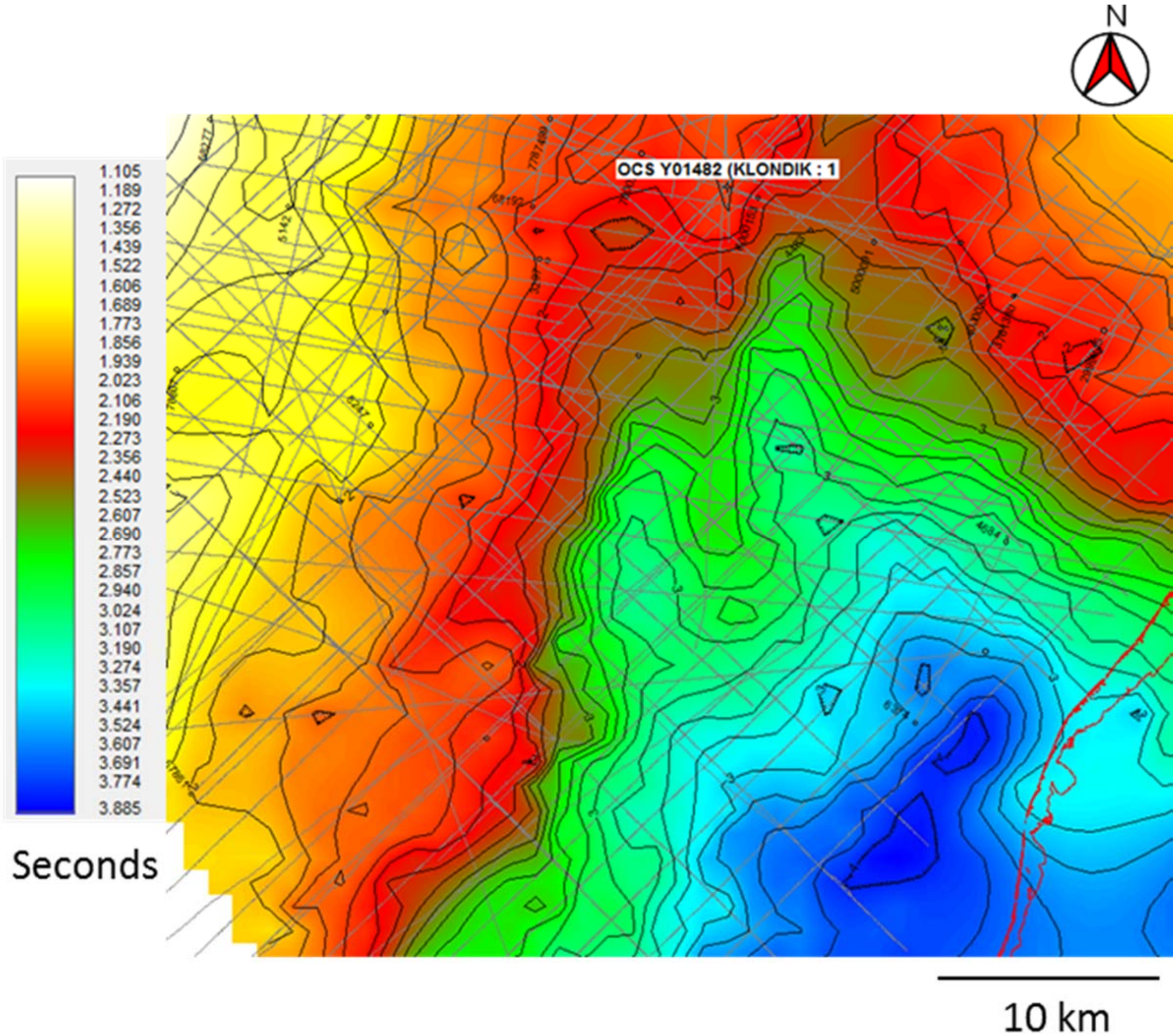

Figure 12: A structure contour map of the LCU horizon (contour interval = 0.1 s)

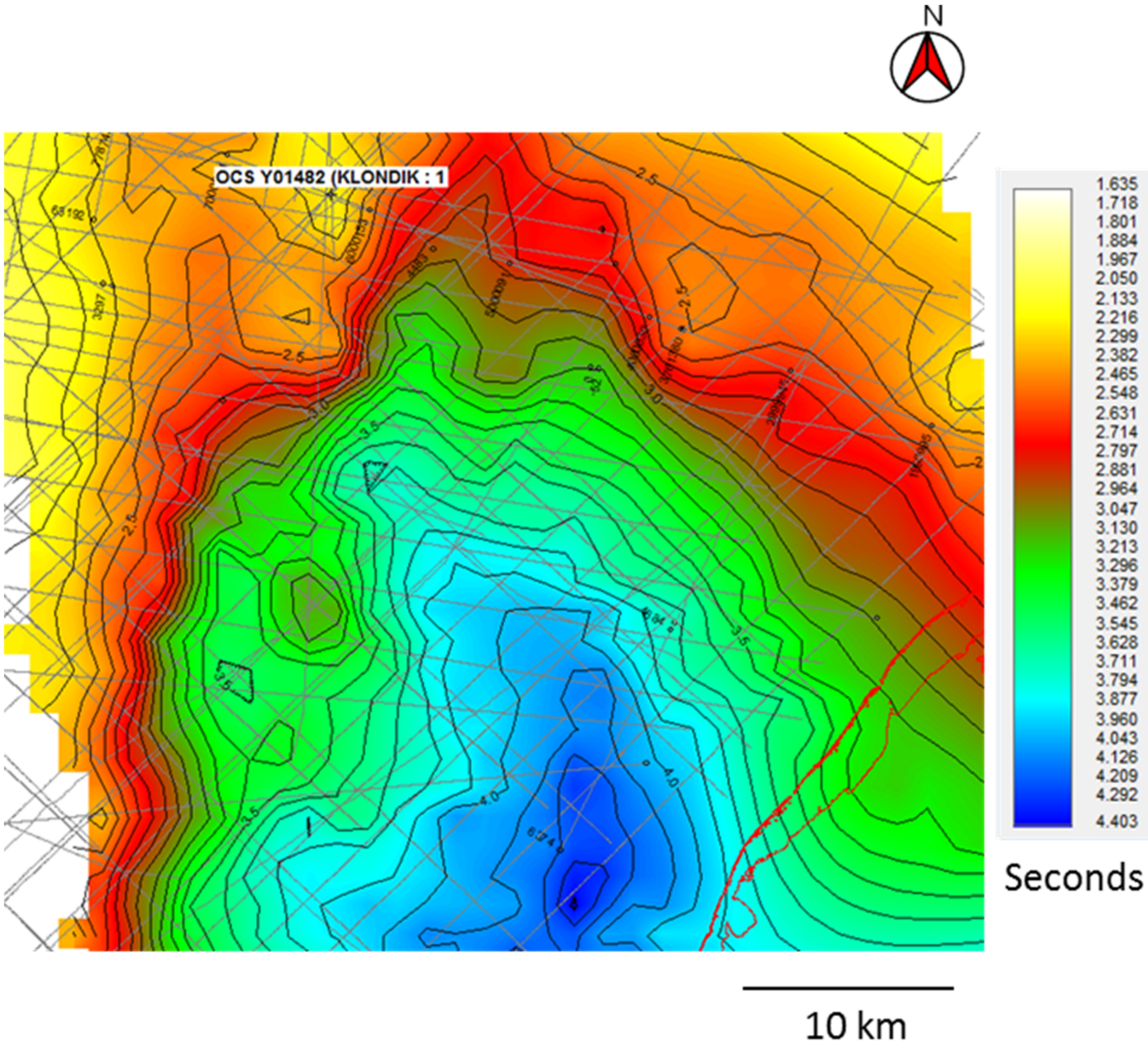

Figure 13: A structure contour map of the Lower Jurassic Unconformity horizon (contour interval = 0.1 s)

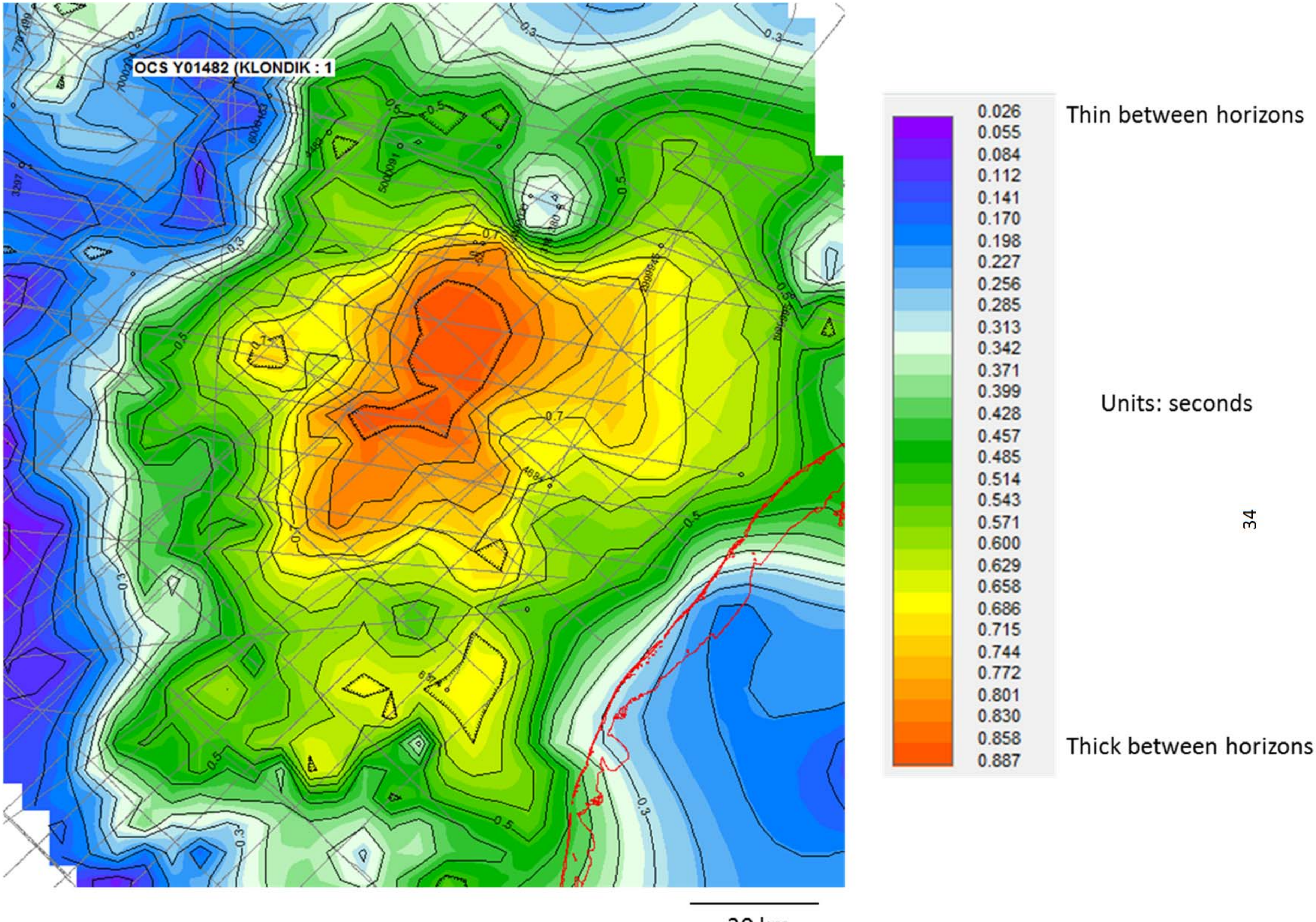

Figure 14: An isopach contour map of the thickness between the LCU and Lower Jurassic Unconformity horizons (contour interval = 0.04 s)

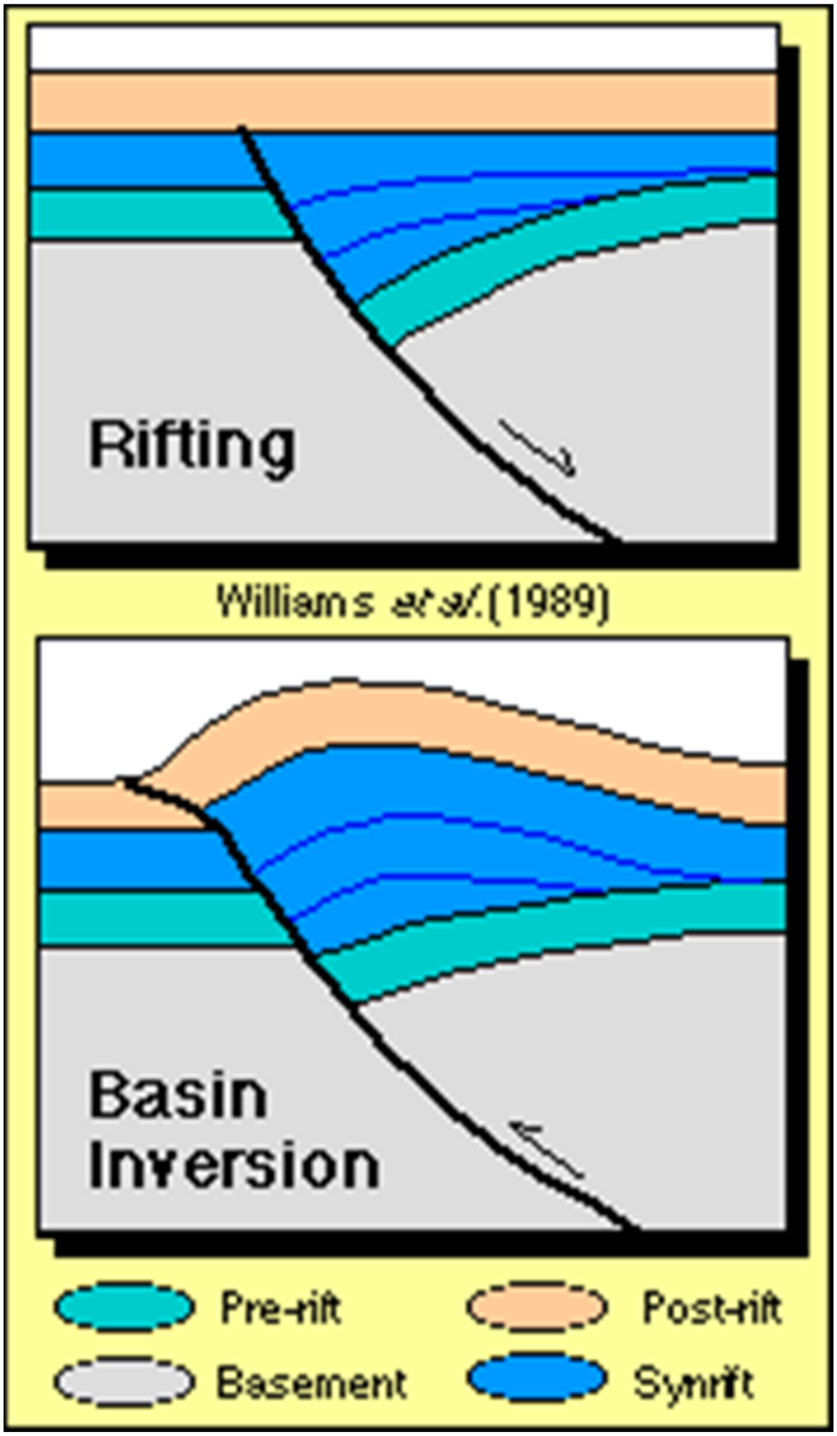

Figure 15: A visual representation of what an inversion structure does to a sedimentary basin