Influence of the Kingak Formation Ultimate Shelf Margin on Frontal Structures of the Brooks Range in National Petroleum Reserve - Alaska

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Undergraduate Honors Thesis in Geology
Washington and Lee University
April 13, 2012

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ACKNOWLEDGMENTS

I would first like to thank Dr. Christopher D. Connors. Chris put in an incredible amount of his time to work with me on this project despite being extremely busy as the department head of Washington and Lee Geology. His expertise in structural geology and the principles of fault related folding were instrumental in writing my thesis. I am very lucky to have been Chris's student and advisee for the past four years, and I have gained an invaluable amount of knowledge from him.

I would also like to thank Dr. David W. Houseknecht and the United States Geological Survey for hiring me as an intern this past summer where I worked with this data set. Dave is profoundly knowledgeable in the area of Arctic Alaska and is an excellent sequence stratigrapher. He introduced me to the principles of sequence stratigraphy over the summer and I would also like to thank him for the guidance he gave me while writing this thesis. Seismic Micro-Technology, Inc. supplied their interpretation software Kingdom Suite© 8.7 and were able to provide excellent technical support when I was making my synthetics in SMT.

The Washington and Lee Geology Department has been amazing to me over the past four years. The department will be sponsoring my trip to the American Association of Petroleum Geologist annual meeting in Long Beach, California where I will present this project on April 25. And very importantly, in addition to Chris, thank you to Dr. Lisa Greer, Dr. Paul Low, Dr. Jeffrey Rahl, and Dr. David Harbor for providing me with an excellent undergraduate education in geology.

ABSTRACT

Well and seismic data in the National Petroleum Reserve in Alaska (NPRA) demonstrate that the Jurassic—Lower Cretaceous Kingak Shale is present throughout NPRA. Several southward progradational depositional sequences within the Kingak culminate in an ultimate shelf margin in southern NPRA, across which the formation thins dramatically. However the exact limit of the formation is obscured by frontal structures associated with Brooks Range tectonism.

These changes in Kingak facies and stratigraphic architecture are interpreted to have influenced the frontal structures of the Brooks Range foothills during Brookian thrusting and folding. The ultimate Kingak shelf margin is arcuate, reaching its most southern point in southwest NPRA. Here, this shelf margin controls an abrupt change in detachment level, stepping up from the top of Shublik Formation (Upper Triassic) to the top the Torok Formation (Aptian – Albian). The ramp in this area appears to be associated with the shelf margin because the Kingak is thicker in the footwall of the thrust system than in the hanging wall. This imbricate of repeated Kingak through Nanushuk Formation (Albian) underlies the Carbon Creek anticline. This prominent northwest-southeast trending fold marks a change in structural grain in the foothills region of southwestern NPRA from east-west trending anticlines to the south.

We propose that the abrupt change in structural grain is the result of northward verging thrust sheets impinging obliquely on the ultimate shelf margin of the Kingak in southwest NPRA. In southeast NPRA there is a more gradual thinning of the Kingak with the shelf margin lying farther to the north. Here the detachment at the top of the Shublik Formation gently rises to the top of the Kingak, and into the Torok Formation. Low-relief folds form over this

detachment, and involve Brookian strata, where the Carbon Creek anticline plunges to the southeast.

INTRODUCTION

National Petroleum Reserve – Alaska

The 23.5 million acres of land on the western North Slope of Alaska makes up The National Petroleum Reserve – Alaska (NPRA) (Figure 1). Gryc (1985) discussed how it was formerly known as the Naval Petroleum Reserve No. 4, the Naval Petroleum Reserves Production Act of 1976 transferred responsibility to the Department of the Interior renaming it NPRA. On June 1, 1977 the exploration program and other related activities of NPRA were assigned to the United States Geological Survey (USGS). USGS conducted studies ranging from detailed stratigraphy and geochemistry to synthesis and interpretation of the geological framework of NPRA. Bird (2001) explained that NPRA is a geologically complex region including prospective strata within passive margin, synrift, and synorogenic sequences. Multiple source rocks are present, as well as ample structural and stratigraphic traps. In most recent USGS assessment in 2010 (Houseknecht et al. (2010) estimated the amount of conventional, undiscovered, recoverable oil at 895 billion barrels, but recent emphasis on unconventional resources will possibly raise this number considerably.

Motivation

The 112th Congress 1st session on June 13, 2011 brought up the bill H.R.2150. It will require the Department of the Interior to complete a comprehensive assessment of NPRA. The resource assessment will be carried out by USGS in cooperation with the State of Alaska and the American Association of Petroleum Geologists (AAPG). If the bill goes through, this will need to be done within 24 months of the bill's enactment (United States Congress, 2011). No one has looked at a large area in southern NPRA since the USGS exploration program that began in

1977. The Carbon Creek Fault Zone, a large structural break in this area, forms the boundary between the Northern and Southern Foothills of the Brooks Range. This zone is critical in understanding the structure of the area. Moore and Potter (2003) have done some seismic correlations in this area, but no one has published any structural interpretation since 1988.

GEOLOGY OF THE STUDY AREA

Overview

Moore et al. (1994) divided Northern Alaska into three provinces, The Brooks Range, the Arctic Foothills, and the Arctic Coastal Plain (Figure 1). The Brooks Range is an arctic east – west trending mountain belt. North of the Brooks Range are the Arctic Foothills which are divided into the Northern and Southern Foothills, and decrease in elevation to the north. The Coleville Basin lies within the arctic coastal plain that slopes into the Arctic Ocean. The Ellesmerian (Mississippian – Triassic), Beaufortian (late Triassic – early Cretaceous), and Brookian (Cretaceous – Tertiary) tectonostratigraphic sequences were deposited in Northern Alaska over Franklinian basement (Pre-Mississippian) (Figure 2). Several unique formations compose each of these megasequences, each with its own characteristic depositional environment. Houseknecht and Bird (2004) discussed the Kingak Shale which makes up the entirety of Beaufortian sequence. The Lower Cretaceous Unconformity defines the top of the Kingak Shale, and Shublik formation defines its base. The Kingak Shale is a series of sequences that prograded southward on the passive flank of the Arctic Ocean rift shoulder This prism of strata thins north and south from its zone of maximum thickness.

Paleogeography

Colpron and Nelson (year) stated that the North American Cordillera follows the west coast of North America, and ranges from the Northern Yukon to Arctic Alaska Terrane. They concluded the North American Cordillera is the result of progressive addition of terranes to the Laurentian Craton whose crustal elements distinguish them from their neighbors. Moore et al. (1994) discussed the Late Proterozoic breakup of Rhodinia, which lead to a passive margin of western Laurentia. This passive margin, thick carbonate-platform and fine-grained quartzose rock comprise the Franklinian basement rock of the Arctic Alaska Terrane.

This Laurentian margin transformed into a subduction zone in mid-Paleozoic times, as evidenced by Devonian magmati c rocks formed in a back-arc setting. Colpron and Nelson (2009) recognized that this convergent margin has prevailed along the western margin of North America up until present times. Pre-Mississippian episodes of contraction and extension, along with the Brookian orogeny, complicated the Franklinian basement rock. There is evidence that a pre-Mississippian angular unconformity presents itself throughout the subsurface of the North Slope. This unconformity involves the widespread absence of lower Devonian strata which suggests there was an orogenic episode affecting Northern Alaska in the Early Devonian or Silurian (Moore et al., 1994). This idea is consistent with Colpron and Nelson's (2009) idea of consistent convergence in the area since the mid-Paleozoic. They add that the Endicott Group at the base of the Ellesmerian megasequence, more closely resembles synorogenic sediment than the postorogenic passive margin sediment that comprises the rest of the Ellesmerian megasequence.

Hubbard et al. (1987) concluded the Beaufort Sea rifting episode deposited Beaufortian strata, which will be discussed in detail in later. The Beaufortian megasequence records the full extent of the rifting which opened the oceanic Canadian Basin. The rifting episode lasted for about 100 million years, from the Early Jurassic to the Early Cretaceous. The lower part of the Beaufortian megasequence records the episodes of Jurassic failed rifting, while the upper part of the megasequence records successful Cretaceous rifting.

Hubbard et al. (1987) also determined the Brookian Orogeny occurred as the result of collisions between exotic terranes and the Arctic Alaska terrane beginning in the Middle Jurassic. Convergence obducted island arcs and oceanic crust onto the Arctic Alaska terrane up to the Late Jurassic, and tectonic processes heightened in the Early Cretaceous. The majority of crustal shortening in the Brooks Range occurred by the Albian. Moore et al. (1994) stated that the rapid uplift of the Arctic Alaska terrane in the late Early Cretaceous resulted in deposition of huge volumes of clastic sediment dispersal to the northeast. Renewed north-vergent thrusting in the Tertiary resulted in further northward migration of synorogenic sediment.

During the Early Cretaceous, arc-continent collisions explained by Moore et al. (2004) deformed the Ellesmerian and Beaufortian strata. They recognized that competent stratigraphic units became imbricated and less competent units served as detachments. Thrusting in the late Early Cretaceous occurred above a deep detachment that ramped up onto the Kingak Shale. This period of thick-skinned thrusting was what caused formation of crustal scale duplexes in the Brooks Range and deposition of sediment in the north. In the foothills, thin-skinned very late Cretaceous to early Tertiary thrusting resulted in thrust faults that truncate older deposits. Golanka (2011) and Lawver et al. (2011) addressed the Chukotka Terrane which may have been approach Arctic Alaska from the west in the lower Cretaceous. The Chukotka tectonic belt developed along the western plate boundaries of Arctic Alaska. Seismic clinoform dip direction show that sediment dispersal associated with the lower Cretaceous in the Colville foreland basin was eastward.

History of the Kingak Shale

Beaufortian strata (Jurassic – Early Cretaceous) comprise the Kingak Shale, deposited in a succession of sequences (Fig. 3) during the rift opening of the Arctic Ocean (Houseknecht and Bird, 2004). It became the primary focus of exploration in NPRA with the 1994 discovery of the Alpine field, a stratigraphic trap in which the reservoir consists of Upper Jurassic marine sandstone filling incised channels. The Kingak thins to the north and south from a zone of maximum thickness in northeast NPRA. Irregularities in thickness of the Kingak Shale at it southern limit may be a result of local tectonic thickening in southern NPRA. Hubbarrd et al. (1987) divided Beaufortian strata into four unique sequence sets that are linked to stages of rifting, prerift lower to middle Jurassic strata, Upper Jurassic failed rift strata, Lower Cretaceous prerift strata, and Lower to middle Cretaceous successful strata. Houseknecht and Bird (2004) elaborated on these four sequence sets, and refer to them as K1 thought K4. The Kingak Shale is rarely present in outcrop, and what is exposed lacks significant data on the nature of depositional sequences present in NPRA. Houseknecht and Bird (2004) did most of their interpretation and mapping on the Kingak Shale using a regional grid of 1974-1981 vintage, public-domain, 2-D seismic data, supplemented by core description.

Houseknecht and Bird (2004) defined the base of Kingak Shale, the K1 unit (Lower to middle Jurassic), as the contact with the Triassic Shublik formation at the top of Ellesmerian strata. Houseknecht and Bird interpreted the contact between the Kingak shale and Ellesmerian strata as a flooding surface, because a maximum regressive surface is apparent at the top of the Sag River or Shublik formations. A high gamma response in these strata lead them to interpret it as a thin shale present above the flooding surface and they interpreted the shale as a transgressive systems tract. Transgressive and regressive successions are apparent throughout the K1 sequence. To the south the K1 sequence consist mostly of shales and mudstones. These represent the ultimate shelf margin at the time of deposition. Hannon et al. (2000) interpreted the lower Kingak as the probable source of oil in the Alpine field. Houseknecht and Bird recognized that the K1 organic carbon rich facies draped across the ultimate shelf margin may be that source rock.

Houseknecht and Bird (2004) defined the K2 sequence (Upper Jurassic) by the truncation of the K1 sequence and stratal geometry defined by seismic data. The K2 sequence thins over the K1 shelf and then thickens at the K1 ultimate shelf margin. K2 developed as the result of forced regression cause by tectonic uplift related to failed rifting. These forced regressions caused widespread erosion, then deposition at the shelf margin followed by flooding which deposited transgressive systems tracts. Due to this transgressive-regressive trend most of the beds in K2 grade from thin shales up to sandstones. A thick glauconitic sandstone, present in the K2 sequence, is the main reservoir at the Alpine field. This makes the sandstone a very important anomaly in the K2 sequence (Houseknecht and Bird, 2004).

The K3 sequence (Lower Cretaceous) is defined by Houseknecht and Bird (2004) by high-amplitude reflections that indicate a downlap surface at the top of the K2 sequence. Erosional truncation by the Lower Cretaceous unconformity (LCU) defines its top in the north, but erosional truncation by the overlying K4 sequence defines its top in the south. At least two transgressive-regressive sequences make up the K3 sequence with overall thin transgressive systems tracts overlain by thick regressive systems tracts. At the time of K3 sequence deposition, normal regressive conditions prevailed, relative sea level was high, and most of NPRA was underwater (Houseknecht and Bird, 2004).

Successful rifting of the Arctic Ocean Basin in the Lower to middle Cretaceous deposited what is defined as the K4 sequence by Houseknecht and Bird (2004). They define top of the K4 sequence by the LCU, and an erosional contact with either K2 or K3 define its base. Rift shoulder uplift caused forced regression and deposition at the ultimate shelf margin. This produced a shelf-margin wedge with thin transgressive system tracts overlain by thick regressive systems tracts. The K4 sequence has facies that indicate a high energy depositional system with higher rates of sedimentation than the K1-K3 sequences had (Houseknecht and Bird, 2004).

The Pebble Shale Unit and Torok Formation

The Pebble shale unit is part of the basal condensed section of Brookian strata that lies unconformable above the Kingak formation. Black, organic rich, fairly fissile marine shale characterize this thin widespreaed unit (Moore et al., 1994). Bird (1987) concluded that Isopachs of the pebble shale unit are irregular and range from 60 to 160m, the thickest area being near Barrow.

The Torok Formation is a middle Cretaceous clinoform depositional sequence composed mostly of silty mudstone which represent the toe of a marine slope to the outer shelf, and sandstone beds which represent submarine fans (Houseknecht and Bird, 2009).Moore et al.

(1994) determined that the thickness of the Torok ranges from about 100m to 6000m near the Colville River. Torok deposition resulted from sediment shed from the tectonic highlands during the Brookian and Chukotka orogenies (Houseknecht and Bird, 2011).

Carbon Creek Anticline

Kirschiner and Rycerski (1984) defined the Carbon Creek Fault (?) Zone as the fundamental boundary between the northern and southern foothills (Figure 4). They stated that the Carbon Creek Fault(?) Zone includes anticlines, but they suggest that northeast extension and dextral strike-slip displacement also are possible. They stated a rifted fragment of the Arctic platform was displaced relatively westward by oblique right-lateral extension across the Carbon Creek Fault (?) Zone. The United States Geological Survey drilled the Awuna well into an anticline along this mapped zone in 1980. Awuna's total depth is 11,200 feet, and it penetrates only the Torok formation (Bird, 1985).

METHODS

Seismic Interpretation in Fold and Thrust Belts

Faults and Folds are prevalent throughout fold and thrust belts such as the Brooks Range. Shaw et al. (2005) addressed the challenges in seismic imaging of fold and thrust belts. First, reflections can overlap if the data are not migrated or under-migrated in sections. Second, steeply dipping fold limbs are difficult to image. It is important to notice these kinds of problems in data when interpreting a poorly imaged zone, because it is easy to mistake a high-angle fold limb as a fault. If a fault is present, there will be actual displacement in reflections, over a short distance, whereas reflections may simply be truncated across a fold limb of finite width. Furthermore, most thrusts will have dips that are low-angle, and thus the offset across the thrust should be of low angle. A kink band of low dip will more likely be imaged.

The anticlines seen in the Carbon Creek area are a result of fault-related folding. Fault-related folds are very common in fold and thrust belts, and are formed due to displacement along fault surfaces (Suppe, 1985). It is important to distinguish between thrust ramps, detachments, and fold limbs. Shaw et al. (2005) define detachments as faults that generally parallel bedding and run along stratigraphic horizons. Seismic does not image detachments directly, but they are interpreted at the base or top of thrust ramps. A thrust ramp can cause a fault-bend fold (Figure 5), or a fault-propagation fold (Figure 6). A fault-bend fold forms as the hanging-wall rocks move over bends in an underlying fault. Anticlinal fault-bend folds form where the fault concaves down. Usually the axial surface of the fault will stay pinned to the bend in the fault. Fault-propagation folds form at the tips of faults and consume slip. These generally asymmetrical folds have highly dipping forelimbs (Shaw et al., 2005). In both of these cases relating fold shape to fault shape leads to more accurate interpretations.

Background on Sequence Stratigraphy

Embry (2002) defineed sequence stratigraphy as follows. “Sequence stratigraphy consists of the recognition and correlation of changes in depositional trends in the rock record. Such changes, which were generated by the interplay of sedimentation and shifting base level, are now recognized by sedimentological criteria and geometrical relationships.”

To understand this definition of sequence stratigraphy, it is necessary to define base level and a sequence. Mitchum et al. (1977) defined a sequence as a stratigraphic unit composed of genetically related strata bounded at top and bottom by unconformities and their correlative conformities. Base level is where equilibrium exists between sedimentation and erosion. Embry (2002) used the idea of base level as a ceiling for sedimentation (Figure 7). If base level exists below sea level then no sedimentation will occur, and the earth's surface will be eroded. If base level exists above sea level then the area between base level and sea level is accommodation in which sediment will accumulate. Embry (2002) explained that a change in base level is a combination of sea level rise or fall, and changes in sedimentation rates. Sea level rise and fall result from one of two things, eustacy or tectonics. Eustasy is a term used to describe global sea level, or sea surface, with respect to a fixed datum (Dutton, 1889). Sea level can also change relative to a surface due to uplift during an orogeny. It is impossible to determine the effect of one factor by itself on base level, therefore the net effects of sedimentation and sea level must be determined. Sequence stratigraphy recognizes depositional trends and determines the interactions between accommodation and sedimentation necessary to produce these trends.

Embry (2002) stated that during a cycle of base level rise and fall there are six distinct depositional trends. These trends involve the movement of the shoreline (transgression or regression), and sedimentation (accumulation or erosion). These six unique depositional trends result in identifiable surfaces in the sedimentary record. Four of these surfaces are formed during base level rise (the maximum regressive surface, shoreface ravinement-unconformable, shoreface ravinement-normal, and maximum flooding surface), while two develop during base level fall (the subaerial unconformity, and regressive surface of marine erosion) (Figure 8).

When base level rise begins, the shoreline continues to advance basinward (regression), but when the rate of base level rise exceeds the rate of sedimentation the shoreline begins to move landward (transgression). When this occurs, the maximum regressive surface forms and marks the change from regression to transgression. This change to transgression also may result in the formation of the shoreface ravinement surface (either unconformable or normal). This erosive surface is formed by wave action cutting away the shoreface and transporting sediments basinward. Shoreface ravinement occurs throughout the entire period of transgression. It is unconformable if it cuts down through the underlying subaerial unconformity, and normal if it does not. When the rate of sedimentation starts to exceed the rate of base level rise the maximum flooding surface is formed, and once base level starts to fall erosion of earth's exposed surface produces a subaerial unconformity. The regressive surface of marine erosion also forms from base level fall when the inner shelf erodes in order to remain at equilibrium. This erosion occurs throughout the entire time of base level fall.

Embry (2002) described how these unique surfaces can be used to define a type of sequence. He stated that a transgressive-regressive sequence "is the only type that meets all the criteria for practicality and usefulness." This unconformable part of this type of sequence is defined by either a subaerial unconformity or shoreface ravinement-unconformable, but it differs from other type of sequences in that its conformable part is simply defined by the maximum regressive surface. Embry (2002) also discussed how a sequence can further be subdivided into systems tracts, which are bounded by recognizable surfaces. He states that there are only two kinds of practical systems tracts, regressive systems tracts and transgressive systems tracts. The transgressive systems tract refers to strata between the subaerial unconformity and the maximum flooding surface. The regressive systems tract refers to the strata between the maximum flooding surface and either the subaerial unconformity, shoreface ravinement-unconformable, or the maximum regressive surface. The transgressive-regressive sequence, along with transgressive and regressive systems tracts were used by Houseknecht and Bird (2004) in their discussion of the Kingak Formation.

Mapped Horizons and Faults

Interpretation of the subsurface in this study area relied highly on seismic interpretation due to the sparseness of wells in this area. The interpretation was done in SMT's Kingdome Suite© 8.7. Interpretation of the stratigraphy and structure of the Brooks Range foothills used the 26 regional seismic lines in NPRA that were reprocessed using post-stack time processing techniques (Miller et al., 2000; Miller et al.,2001). The interpreted horizons were tied to USGS formation tops after time-depth functions were generated for each well in the study area (Appendix A). Faults and folds were mapped using the principles of fault-related folding outlined by Shaw et al. (2005). The K1 through K4 of the Kingak Formation were fully reinterpreted throughout NPRA using both principals of modern sequence stratigraphy outlined by Embry (2002) and Houseknecht and Bird's (2004) interpretation as a reference (Figure 9).

Each horizon was mapped based on the following criteria. Figure 10 shows the stratigraphic location of each horizon in Arctic Alaska. To map each horizon we followed a continuous reflector. If the seismic imaging became poor we made our best guess mapping the horizon by ties with intersecting seismic lines

Shublik Formation – This Shublik Formation is a mixture of carbonate, mudstone, shale and sandstone deposited on a southward sloping margin and represents a regional marine transgression (Moore et al., 1994). This horizon was mapped by tying it to the USGS pick in the

Inigok well (Bird, 1985) (Figure 11) after a time-depth function was generated for that well (Appendix A).

Kingak Formation – The Kingak Shale was deposited in a succession of sequences during the rift opening of the Canada basin. The first strong trough below the Lower Cretaceous Unconformity defines the top of the Kingak Formation and this horizon was mapped by tying it to the USGS pick in the Inigok well (Bird, 1985) (Figure 11). The top could be K1, K2, K3, or K4 depending on the position in NPRA.

K1 Sequence –Interpretation of this sequence within the Kingak Shale was done by referencing Houseknecht and Bird's (2004) interpretation of seismic lines R-1, R-14, and R-21. The first strong continuous trough above the Shublik representing a sequence boundary was followed in order to map this horizon (Figure 12).

K2 Sequence– Interpretation of this sequence within the Kingak Shale was done by referencing Houseknecht and Bird's (2004) interpretation of seismic lines R-1, R-14, and R-21. The first strong continuous trough above the K1 sequence on northern part of line R-21 was followed in order to map this horizon. This is not always the first strong trough above K1, because K2 thickens where K1 is thin (Figure 12).

K3 Sequence - Interpretation of this sequence within the Kingak Shale was done by referencing Houseknecht and Bird's (2004) interpretation of seismic lines R-1, R-14, and R-21. The first strong continuous trough below the Lower Cretaceous unconformity was followed on the northern part of line R-21 in order to map this horizon. K3 is the top of the Kingak formation in northern NPRA (Figure 3), and then its shelf margin pinches out into in the K2 sequence to the south (Figure 12).

K4 Sequence – Interpretation of this sequence within the Kingak Shale was done by referencing Houseknecht and Bird's (2004) interpretation of seismic lines R-1 and R-21. The first strong continuous trough below the Lower Cretaceous Unconformity at the ultimate Kingak shelf margin was followed in order to map this horizon. The K4 sequence thickens south of the K3 shelf margin (Figure 12). Following the strong continuous trough to the north the K4 sequence is truncated by the Lower Cretaceous Unconformity (Figure 12).

Pebble Shale – This is thin organic rich black shale that lies uncomformably on the LCU (Kingak Shale across most of study area) (Moore et al., 1994). The horizon was mapped as the first strong continuous trough above the top of the Kingak Formation (Figure 13) and it can also be tied to the Inigok well (Bird, 1985) (Figure 11).

Torok Formation – This is a series of clinoform depositional sequences composed of dark marine shale and sandstone deposited in the Colville basin by an eastward–northeastward sediment dispersal system (Houseknecht et al., 2009; Houseknecht and Bird, 2001). The top of the Torok formation was not picked, but three sequences within it were, the lower, middle, and upper Torok. The middle Torok is the first strong fairly continuous trough above the pebble shale, and the upper Torok is the strong fairly continuous trough above the lower Torok (Figure 11). Fairly continuous is used because both these horizons eventually pinch out to the east into the pebble shale (Figure 12). The lower Torok is only present in southern NPRA near the Kingak shelf margin before it quickly downlaps to the north onto the pepple shale either right before or after the shelf margin (Figure 14). What we are calling the lower Torok in this study could possibly the Fortress Mountain Formation. The strong reflectors that were used to map these horizons are drapes of condensed shale on flooding surfaces.

DISCUSSION

Results

Structural Style

The structure in NPRA decreases in complexity northward as stated by Moore et al., 1994 and many others. All the faults mapped in the study area are thrust faults, most of which dip to the south or slightly southwest (Figures 15 and 16).The structures are fault-related folds that show a greater degree of imbrication in southern NPRA (Figures 15 and 16). The thrusts step up from a detachment in the basal condensed section which is made up of the Shublik Formation, Kingak Shale, and the pebble shale. There are places where each of these horizons can be seen acting as the detachment in seismic lines (Figure 17). The thrusts then ramp up and detach again within the Kingak formation, at the top of the Kingak, or in the Torok (Figures 15 and 16).

Most folds observed in the study area are fault-bend folds as described by Shaw et al. (2005). Figure 18 shows a very simple fault-bend fold that is not imbricated. This is because this section of R-22 is in the northern foothills and structures are not as complicated. Imbricated break-forward fault-bend folds are observed at the boundary between the northern and southern foothills (Figure 19). Break forward means that the younger fault is structurally lower than and has further deformed the older fault and older fault-bend fold. Backthrusting is present in some of the structures that have a large amount of slip (Figures 15, 16, and 19). These backthrusts dip to the north or slightly northeast and have occurred in order to form a wedge that can accommodate the large amount of slip. The wedge is made up of a thrust and the backthrust and slip along both of the faults accommodates the input slip (Shaw et al., 2005). Some of the faults involved with the imbricated fault-bend folding appear to break through to the surface, although it is hard to tell due to the truncation of the seismic lines beneath the surface. The major imbricate systems at the boundary of the northern and southern foothills show a total slip of about 10km.

Depositional Trends

Depositional trends observed in the study area are consistent with those documented in previous work. The K3 and K4 sequences of the Kingak Shale, as well as the clinoform depositional profiles within the sequences, dip to the southwest near their respective shelf margins (Figure 12). This is in agreement with the interpretation of Houseknecht and Bird (2004). Isopach were generated in SMT's Kingdome Suite© 8.7 of the Kingak Shale (Figure 20) and of the K1-K4 sequences (Figure 21). The isopachs are fairly consistent with ones generated by Houseknecht and Bird (2004) (Figure 3), which validates that interpretation of the Kingak sequences in this study. Because the isopachs were constructed by subtracting the depth of the shallower horizon from the deeper horizon, the lack of the presence of the K3 sequence in the south made the isopach of K4 sequence incomplete. It is important to note that Houseknecht and Bird (2004) generated isopachs in depth whereas the ones generated in this study are in time.

Carbon Creek Fault (?) Zone

This study proposes part of the Carbon Creek fault (?) zone as the Carbon Creek anticline (Figure 22). An imbricate of repeated Kingak through Torok Formation underlies the Carbon Creek anticline, and its trend is ultimately controlled by the distribution and thickness of the Kingak Shale. The Carbon Creek fault (?) zone is only oblique to other structure where the

Carbon Creek anticline is present (Figure 22). This Carbon Creek anticline is the southeastern oblique part of a structure mapped as the Carbon anticline by Kirshiner et al. (1987).

Structures in the Carbon Creek anticline is oblique to other structures in southwestern NPRA because the Kingak shelf margin controlled the locations of thrust ramps (Figure 23), and the Kingak shelf margin is oblique to the strike of the Brooks Range in this area. The Kingak margin is striking northwest-southeast, and the Brooks Range is striking west-east. Figure 15 shows the four seismic lines that are associated with the Carbon Creek anticline, and shows the imbricated fault-bend folding occurring at the Kingak shelf margin. Figure 24 shows how the strike of the Brooks Range differs from the strike of the Kingak Shelf margin in western NPRA.

Structural features near the southeastern part of the Carbon Creek fault (?) zone are not oblique to the strike of the Brooks Range. They both trend southeast – northwest (Figure 24). Figure 16 shows that the major imbricated fault-bend folds no longer occur at the Kingak shelf margin although there is still thrusting associated with the Kingak margin because it is a good surface for ramp localization. The major structural break is south of the Kingak margin where the Carbon Creek fault (?) zone has been mapped (Figure 25).

Conclusion

The stratigraphy of southern NPRA had a major influence on the structure. The major detachment is the basal condensed section which is made up of the Shublik Formation, Kingak Shale, and the pebble shale unit. Thrust faults step up from this detachment to the top of the Kingak, another depositional sequence within the Kingak Formation, or a sequence boundary within the Torok Formation. The structural style is imbricate fault-bend folding. There is some fault-propagation folding, and thrusts with large amounts of displacement locally incorporate backthrusting to form a wedge in order to accommodate large amounts of slip. These major imbricate systems and other smaller thrusts make use of the Kingak ultimate shelf margin, which is an easy surface for thrusts to ramp up on.

The obliqueness of the Carbon Creek anticline is due to the Kingak shelf margin. The Kingak margin is oblique to the strike of the Brooks Range in the area of the Carbon Creek anticline and, therefore, thrusting influenced by the margin becomes structurally oblique. In the southeastern portion of the Carbon Creek fault (?) zone the strike of the Brooks Range changes from east-west to northwest-southeast. Therefore, even though structures in this area are striking northwest-southeast, just as the Carbon Creek anticline does, they are not oblique to the Brooks Range.

Future Work

Balanced cross-sections would further improve the validity of the interpretation. In order to do this data would need to be converted into depth. Further definition of sequences within the Torok Formation would help constrain where in the section the upper detachments reside. The interplay of thrusting as the Torok thins to the east could also be constrained. Balanced cross-sections combined with further interpretation within the Torok Formation would show retrodeformed Torok clinoform sets and therefore their original thicknesses could then be delineated.

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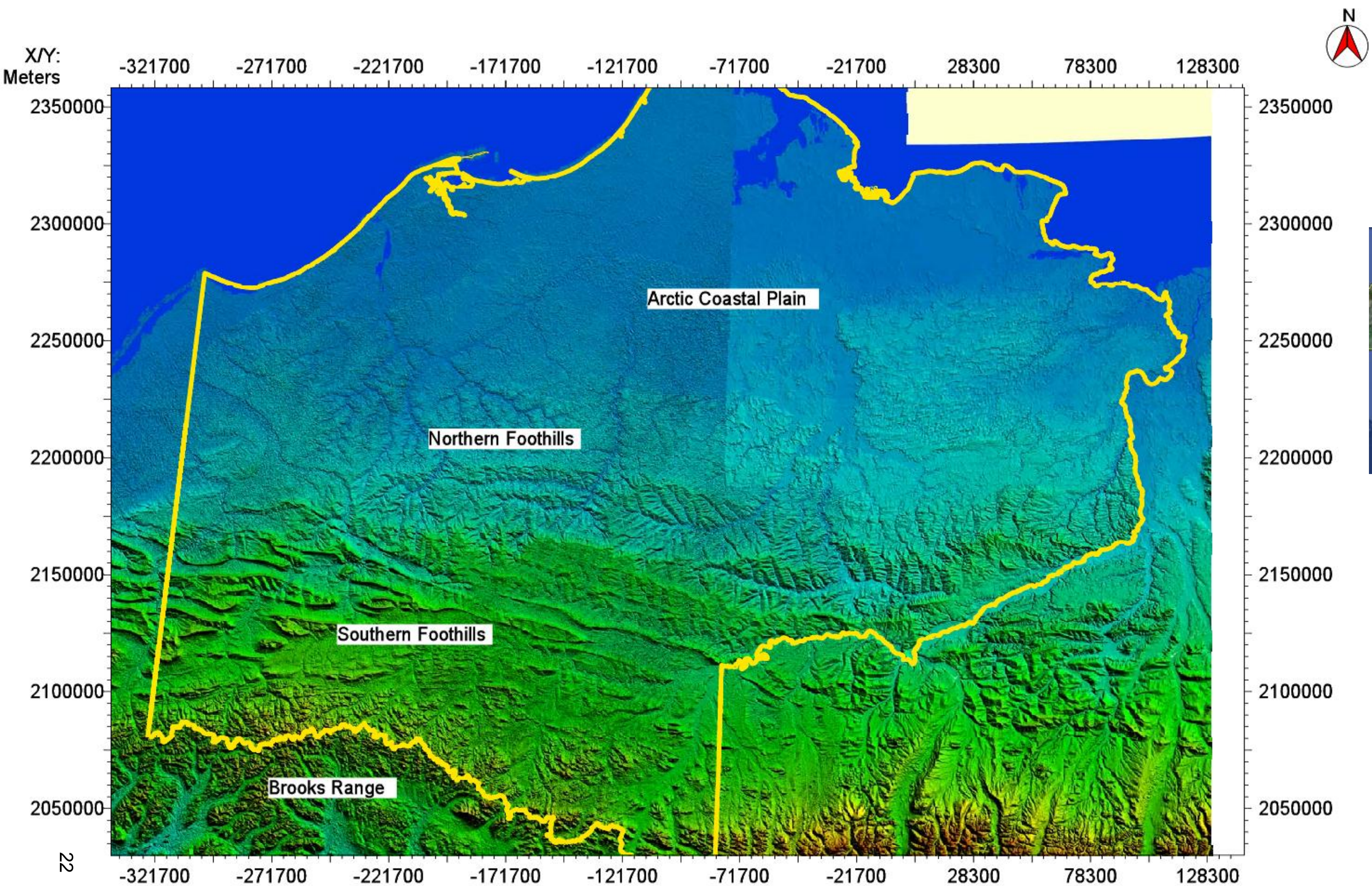
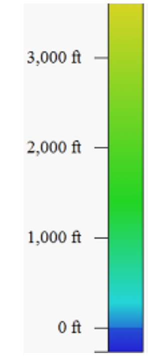




Inset: Google Earth image of Alaska with National Petroleum Reserve - Alaska (pictured in Figure 1) outlined in red.

Figure 1: This is a digital elevation model from NASA Aster data. NPRA is outlined in yellow, and the division of the Brooks Range, foothills, and coastal plain is based on interpretation done by Kirschiner et al. (1987). The scale is based on an Albers Conic projection where the central meridian is -154, the origin latitude is 50 the false easting is 0 meters, and the false northing is 0 meters.

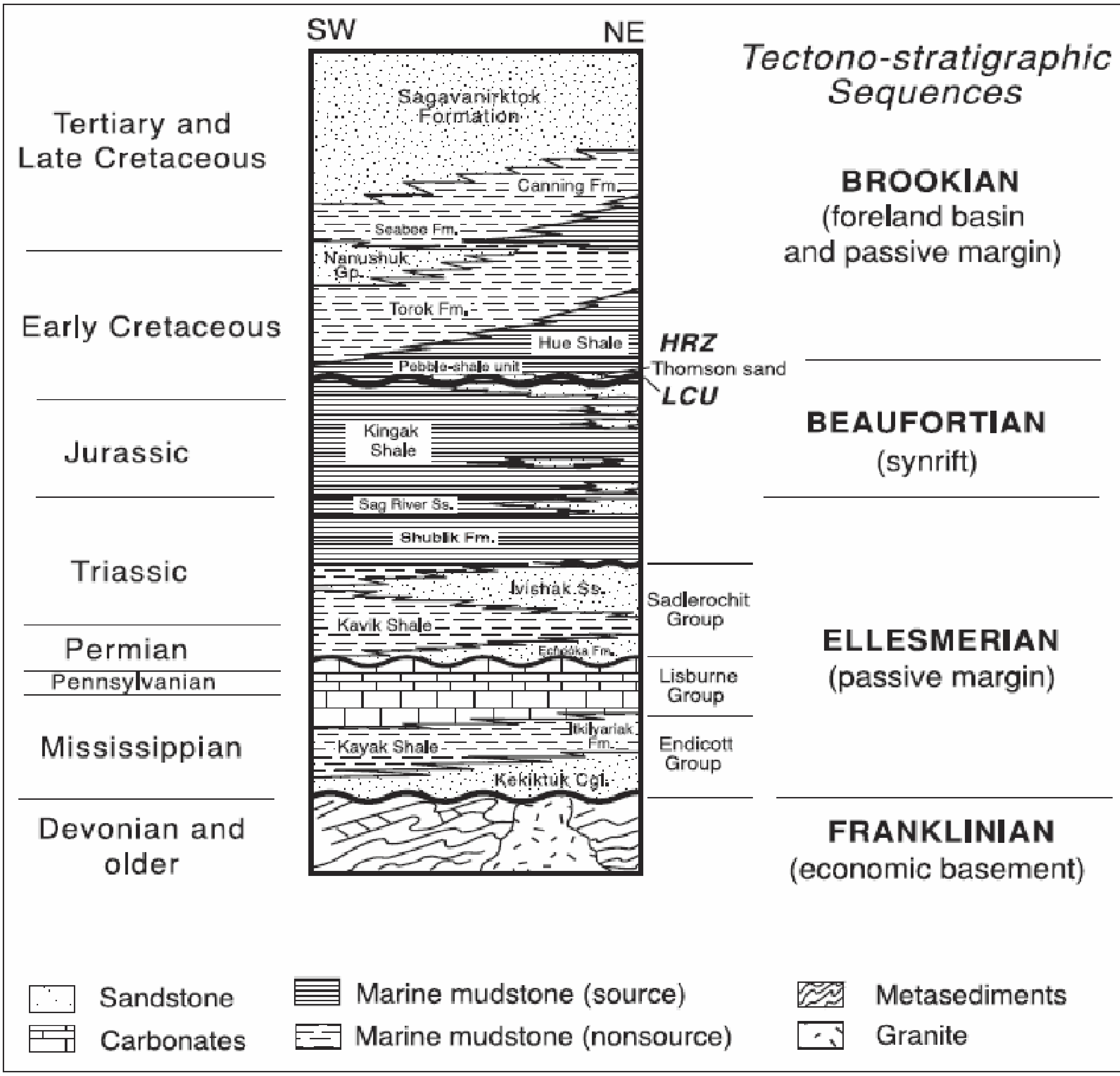


Figure 2: Generalized stratigraphic column for northern Alaska and its tectono-stratigraphic sub-division, reflecting tectonic development of the region. HRZ =highly radioactive zone of the Hue Shale; LCU = the regional Lower Cretaceous Unconformity (from Bird, 2001)

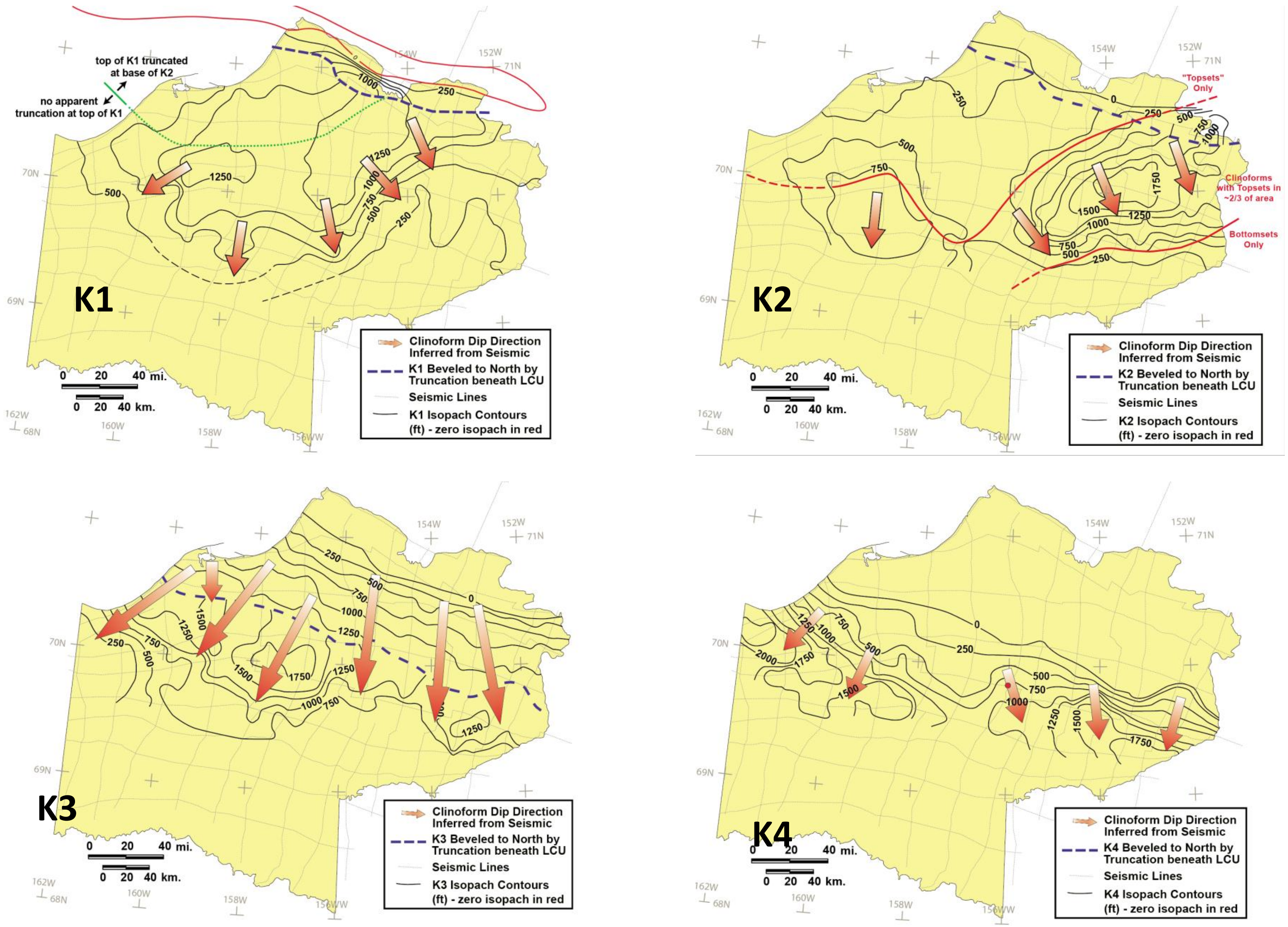


Figure 3: This is the progression of Kingak sediment deposition and flow direction from K1 to K4 (Modified from Houseknecht and Bird, 2004).

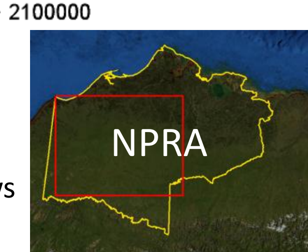


Figure 4: This structure map of the area of NPRA outlined in red modified from Kirshiner et al., 1987 shows the location of what they map as the Carbon Creek Fault (?) Zone.

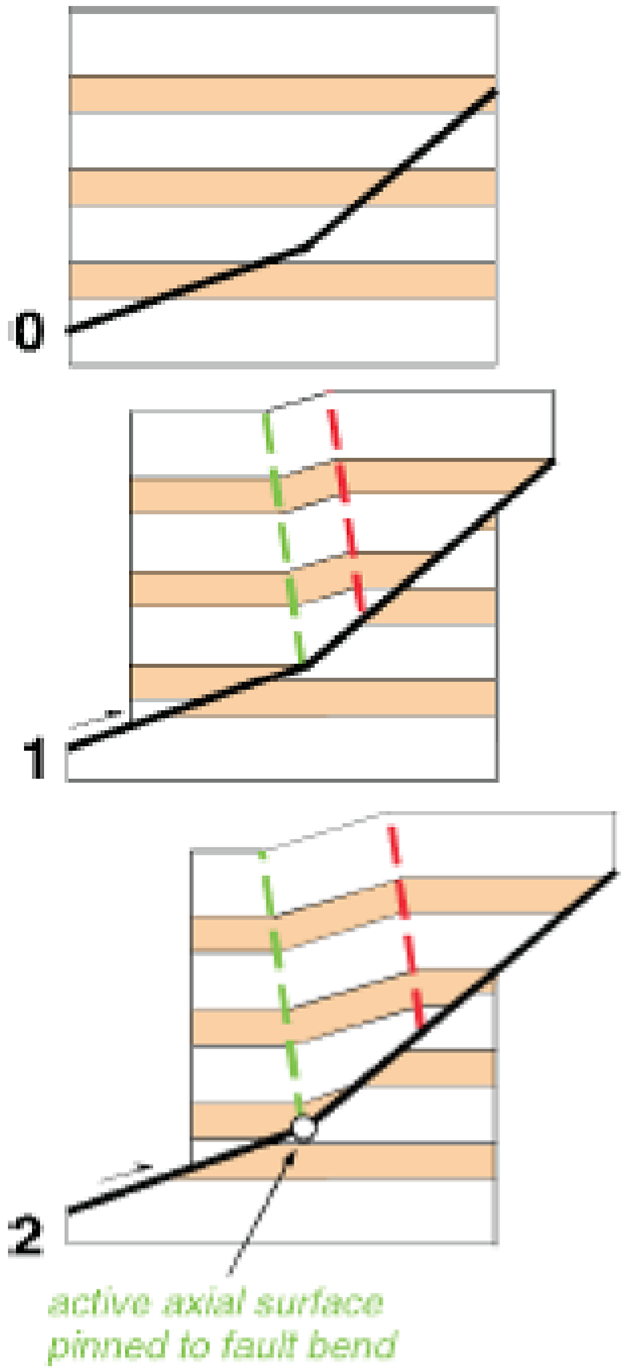


Figure 5: A kinematic model of a fault-bend fold progressing from 0-2. The active axial surface is pinned to the fault bend where as the inactive axial surface moves with increased slip (from Shaw et al., 2005).

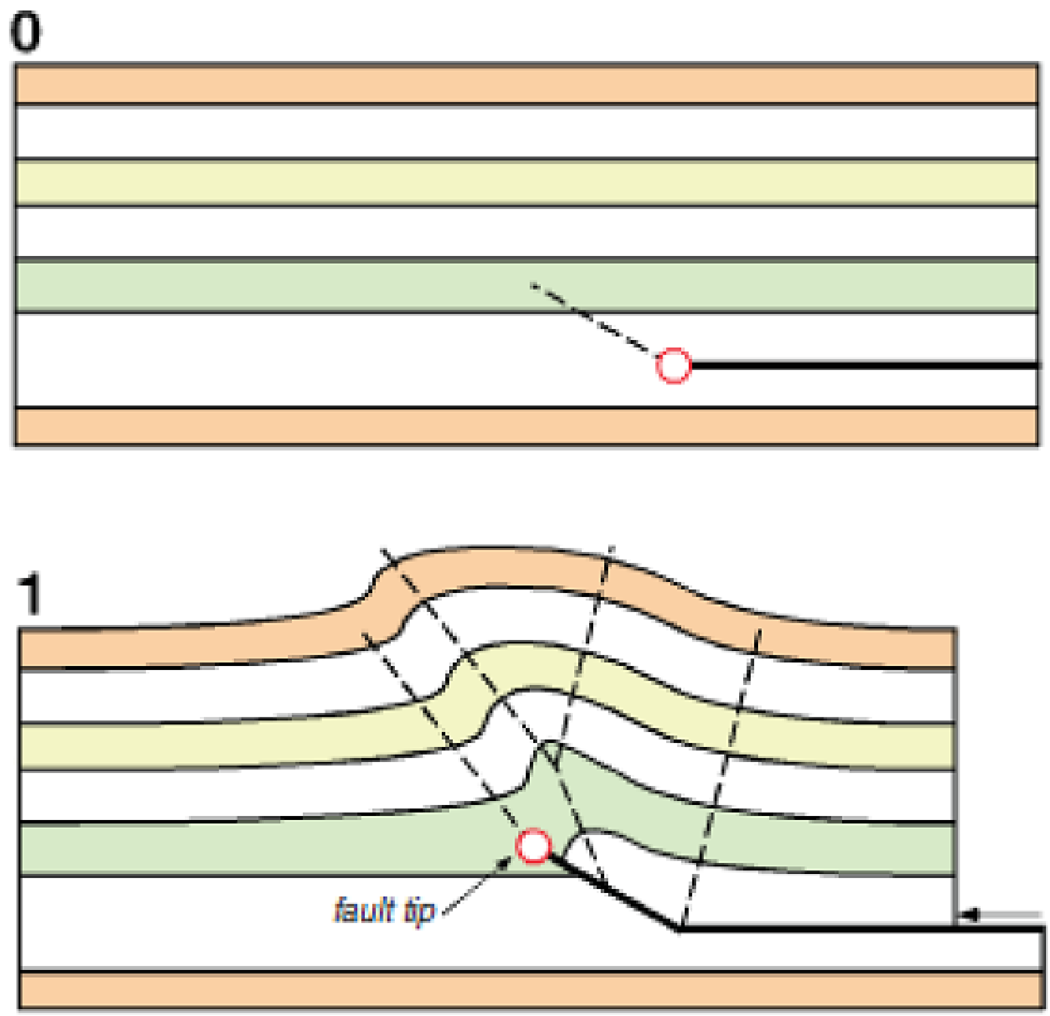


Figure 6: A kinematic model of a fault-propagation fold progressing from 0-1. A fault-propagation fold typically has an asymmetric geometry and all of the slip is consumed before reaching the fault tip. The forelimb is much narrower and steeper than the corresponding backlimb (from Shaw et al., 2005).

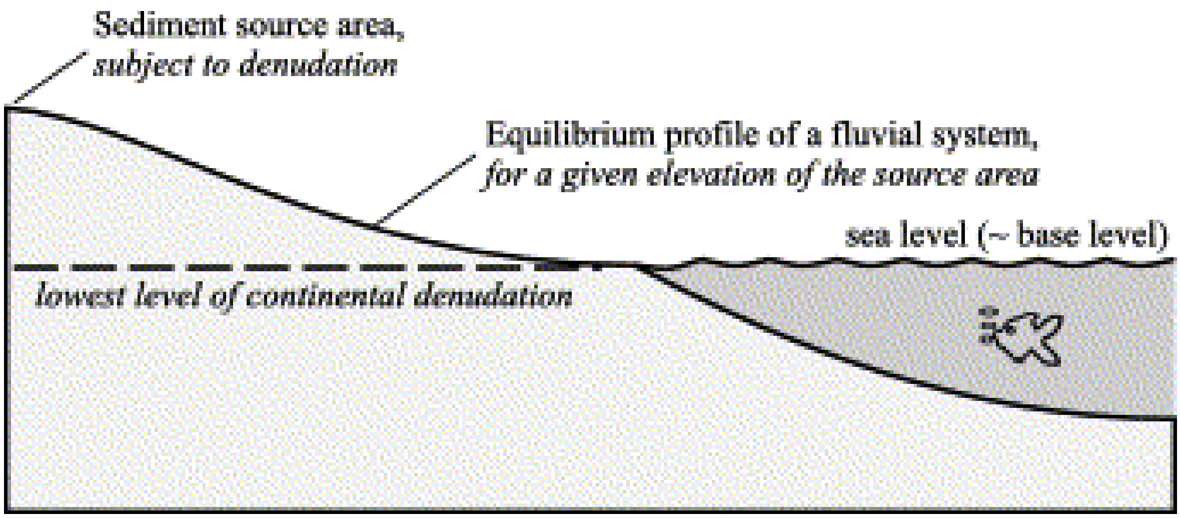


Figure 7: A diagram showing the relationship between sedimentation and erosion with respect to base level in which below base level sedimentation occurs, and above base level erosion occurs (from Catuneanu, 2002)

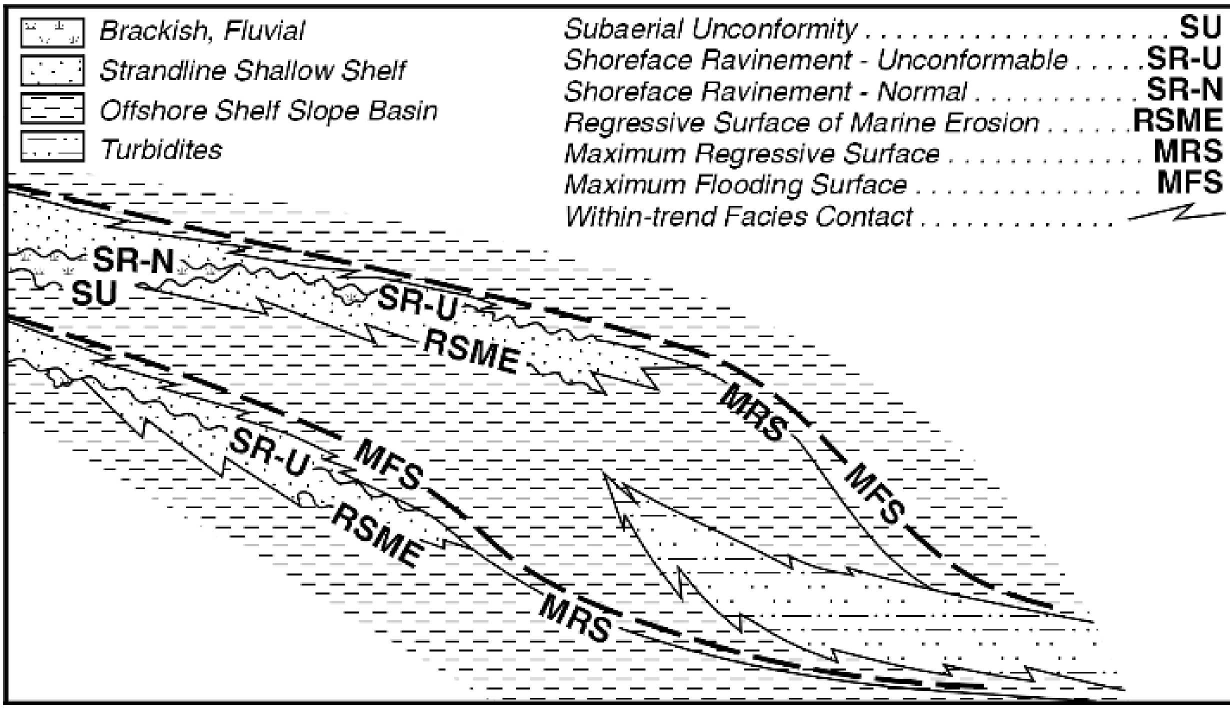


Figure 8: A schematic cross section which shows the spatial relationships of the six surfaces of sequence stratigraphy: subaerial unconformity, regressive surface of marine erosion, shoreface ravinement-unconformable, shoreface ravinement-normal, maximum regressive surface, and maximum flooding surface. Because these surfaces are generated during specific times of a base-level transit cycle, they always have a similar relationship to one another, and this arrangement of surfaces constitues a model for sequence stratigraphy (from Embry, 2002).

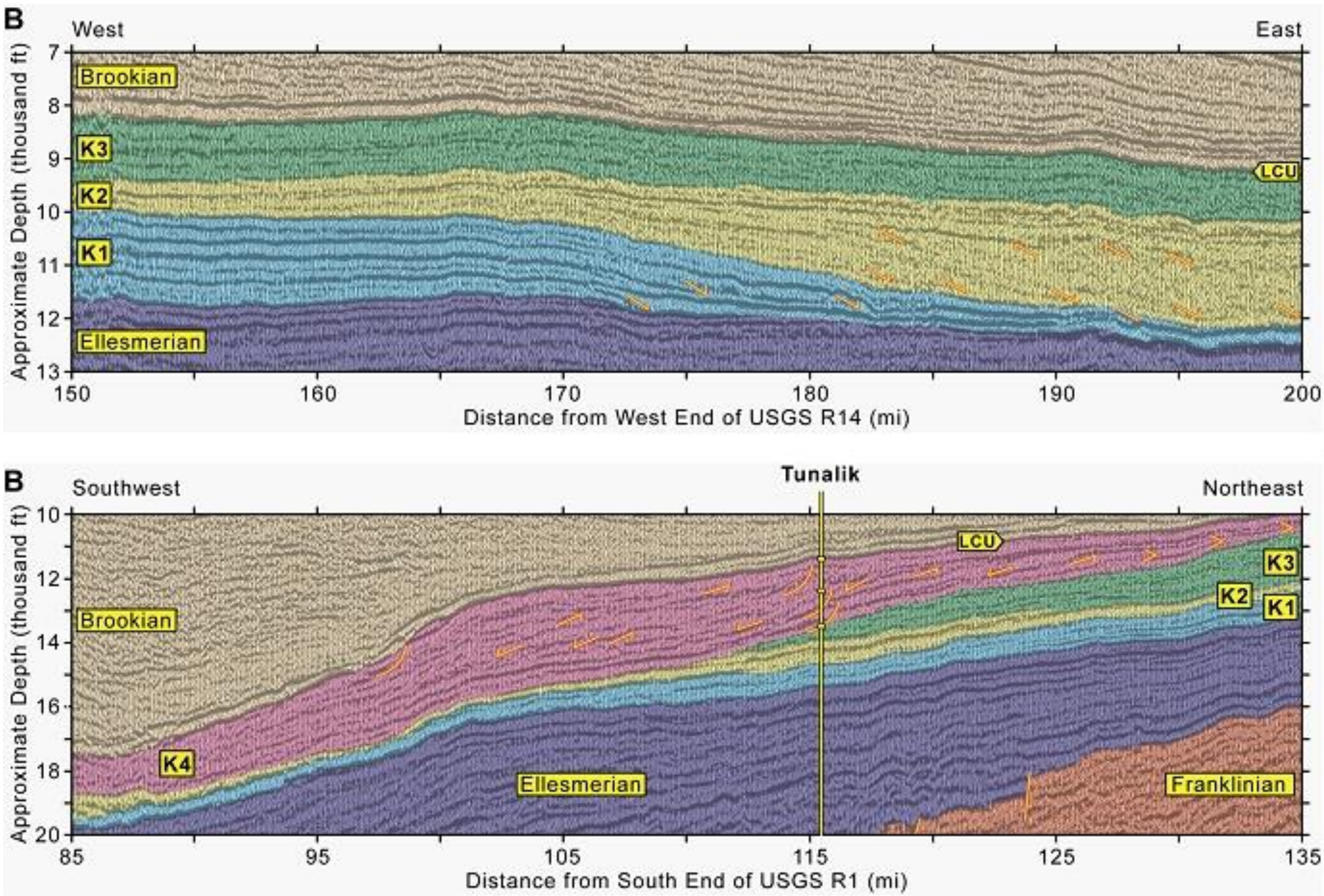


Figure 9: Sequences mapped within the Kingak Formation on the R1 and R14 lines. The interpretation by Houseknecht and Bird (2004) on these lines was used as a reference when interpreting these sequences throughout NPRA (from Houseknecht and Bird, 2004).

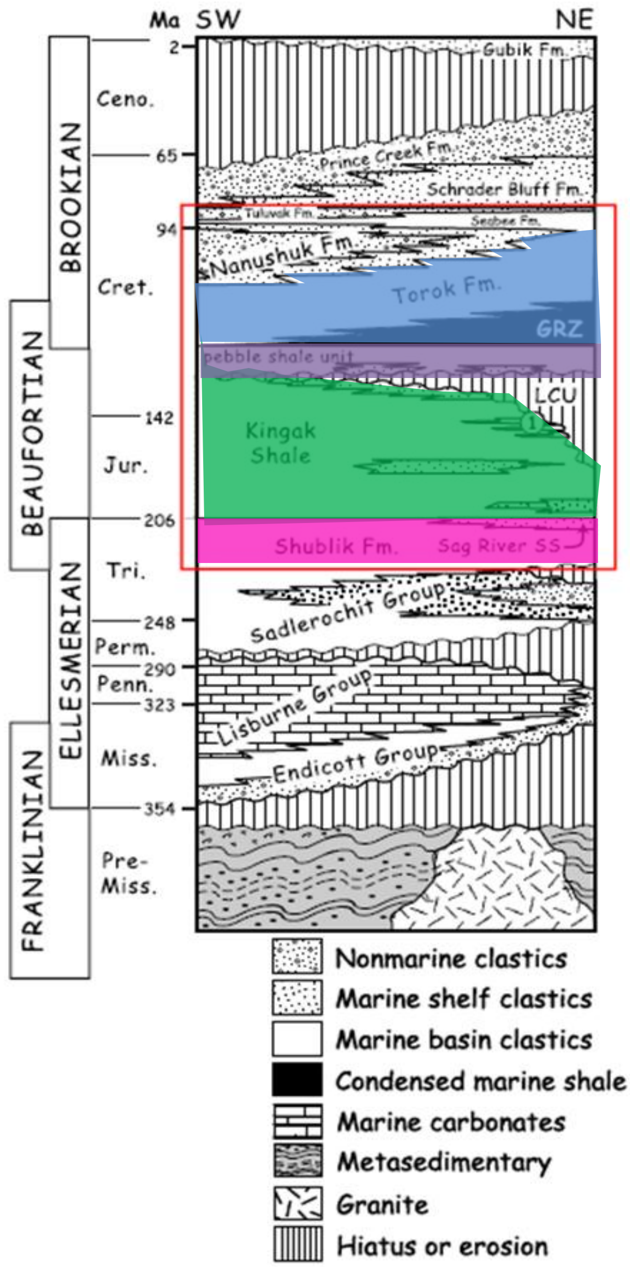


Figure 10: Stratigraphy of Northen Alaska showing tectonostratgraphic sequences. The sequences involved in this study are outlined in red, and the color given to each sequence corresponds to the color using to map it on each seismic line (modified from Houseknecht and Bird, 2004).

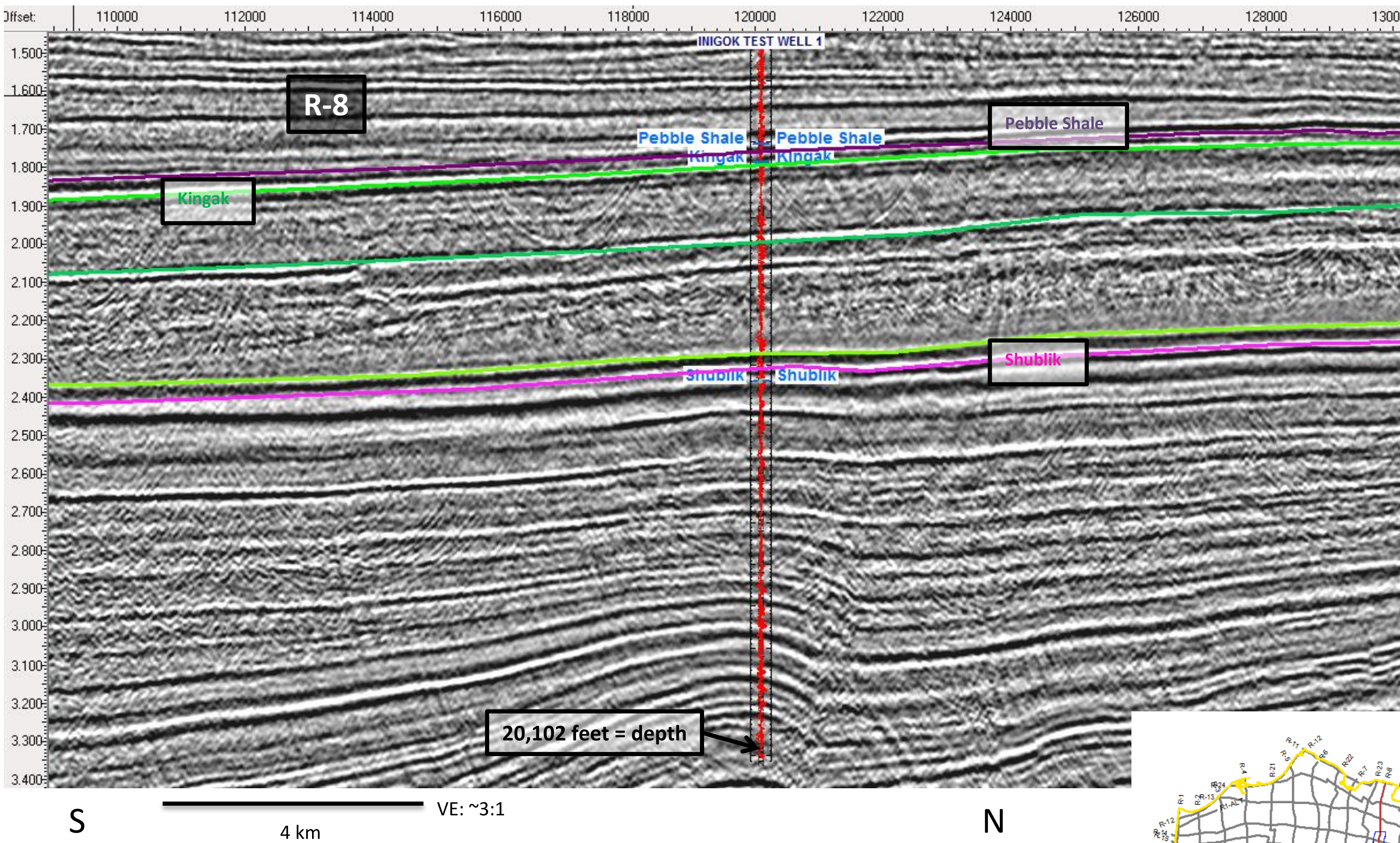
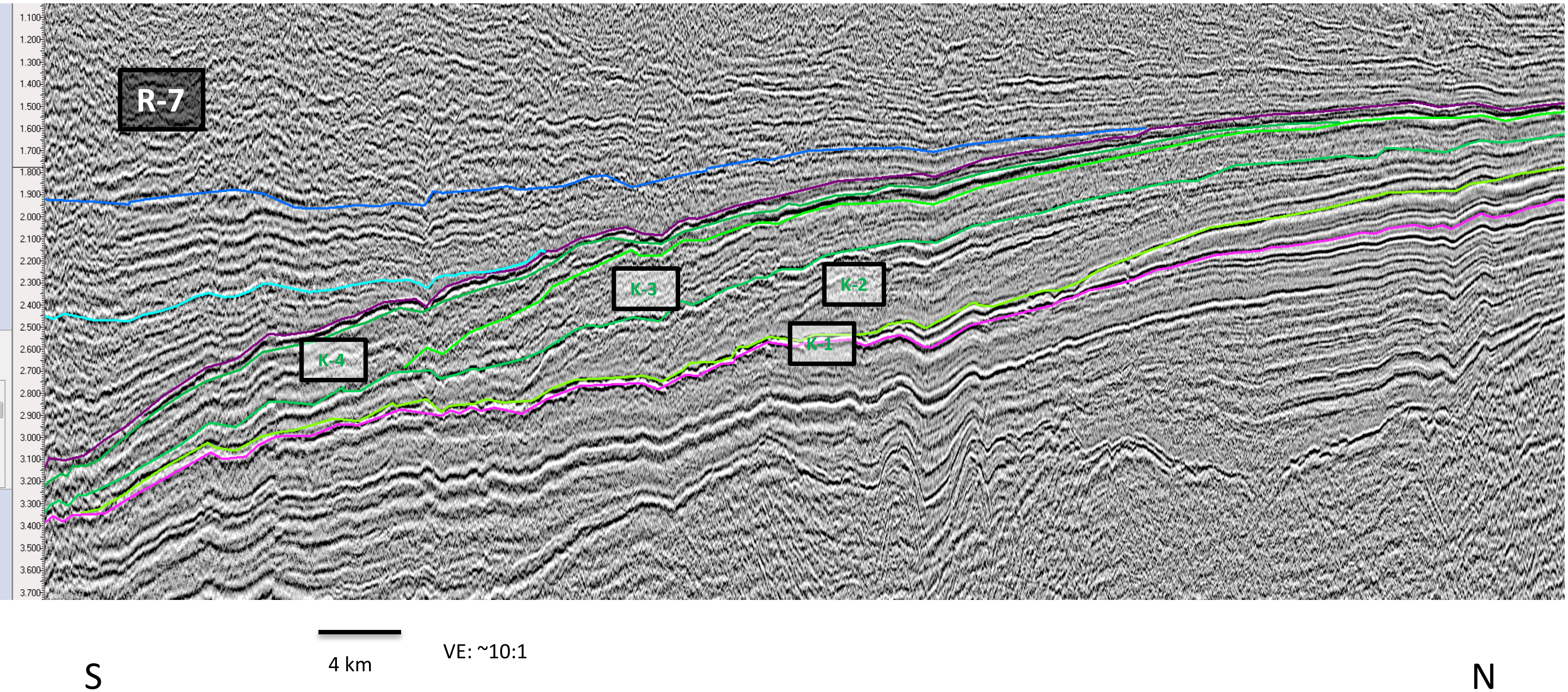


Figure 11: The Pebble Shale, Kingak Formation, and Shublik Formation can all be tied to USGS picks in the Inigok well after a time-depth function was generated for the well (Appendix A). Inigok's total depth is 20,102 ft. The Pebble Shale, Kingak, and Shublik are picked at 9,040, 9,260, and 12,190 ft. respectively (Bird, 1985).



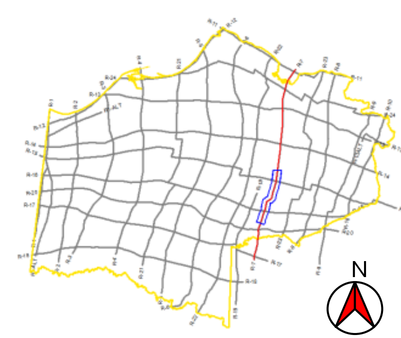
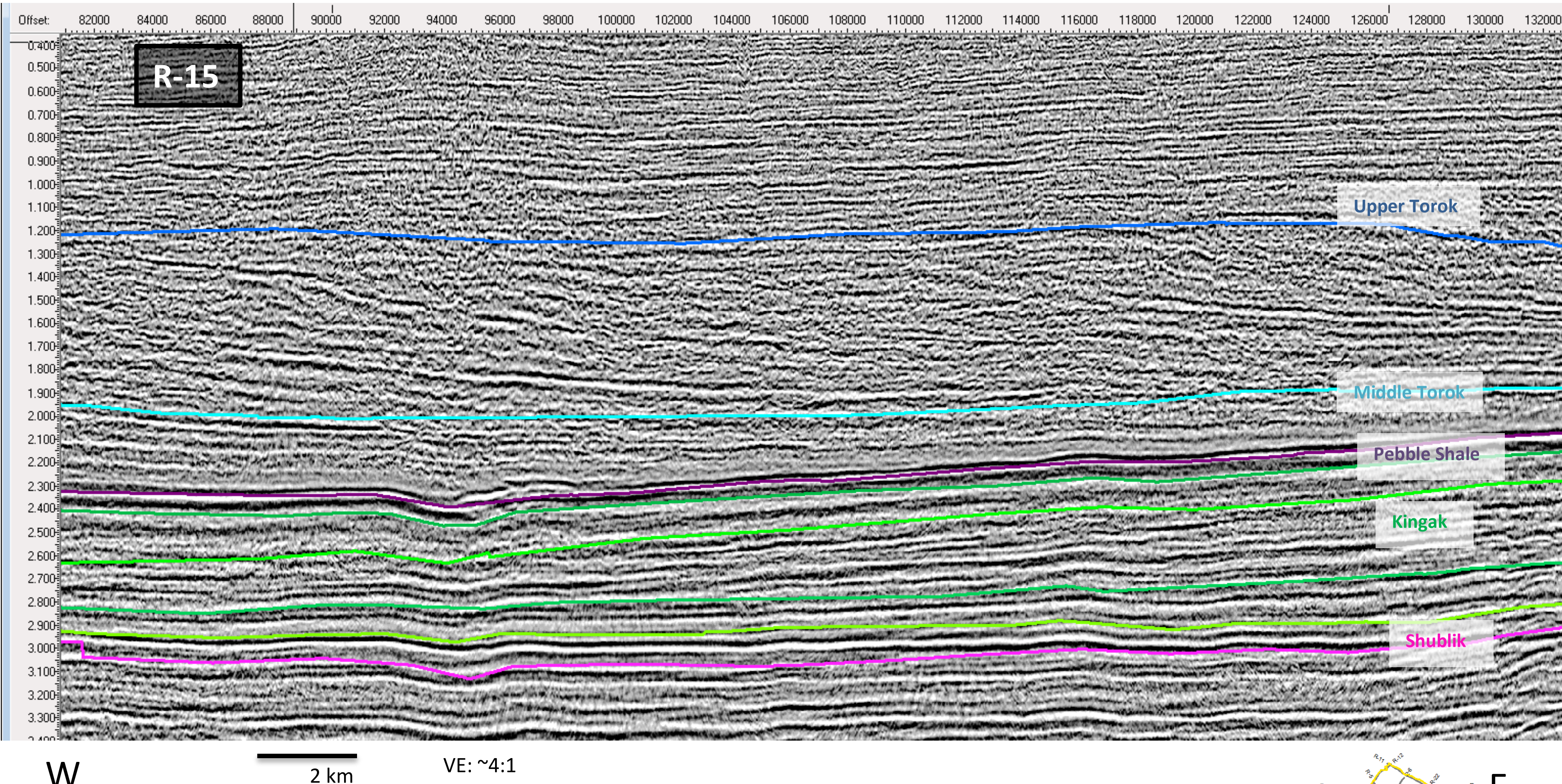


Figure 12: This is the interpretation of the Kingak Shelf Margin on line R-7. The units within the Kingak Formation were mapped using Houseknecht and Bird's (2004) interpretation as a reference. This seismic line is vertically exaggerated to make it easier to see where the ultimate shelf margin is, where the K3 unit pinches out to the south, and where the K4 unit pinches out to the north. The Lower Cretaceous Unconformity is in between the Pebble Shale and the Kingak Formation.



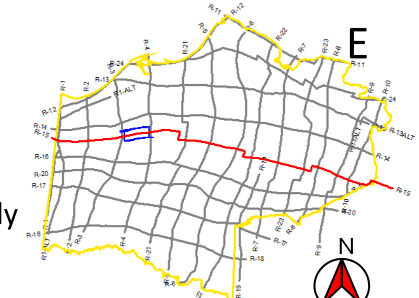


Figure 13: This vertically exaggerated line shows were horizons were mapped in a relatively undeformed area. Clinoforms within the Torok Formation dip to the East.

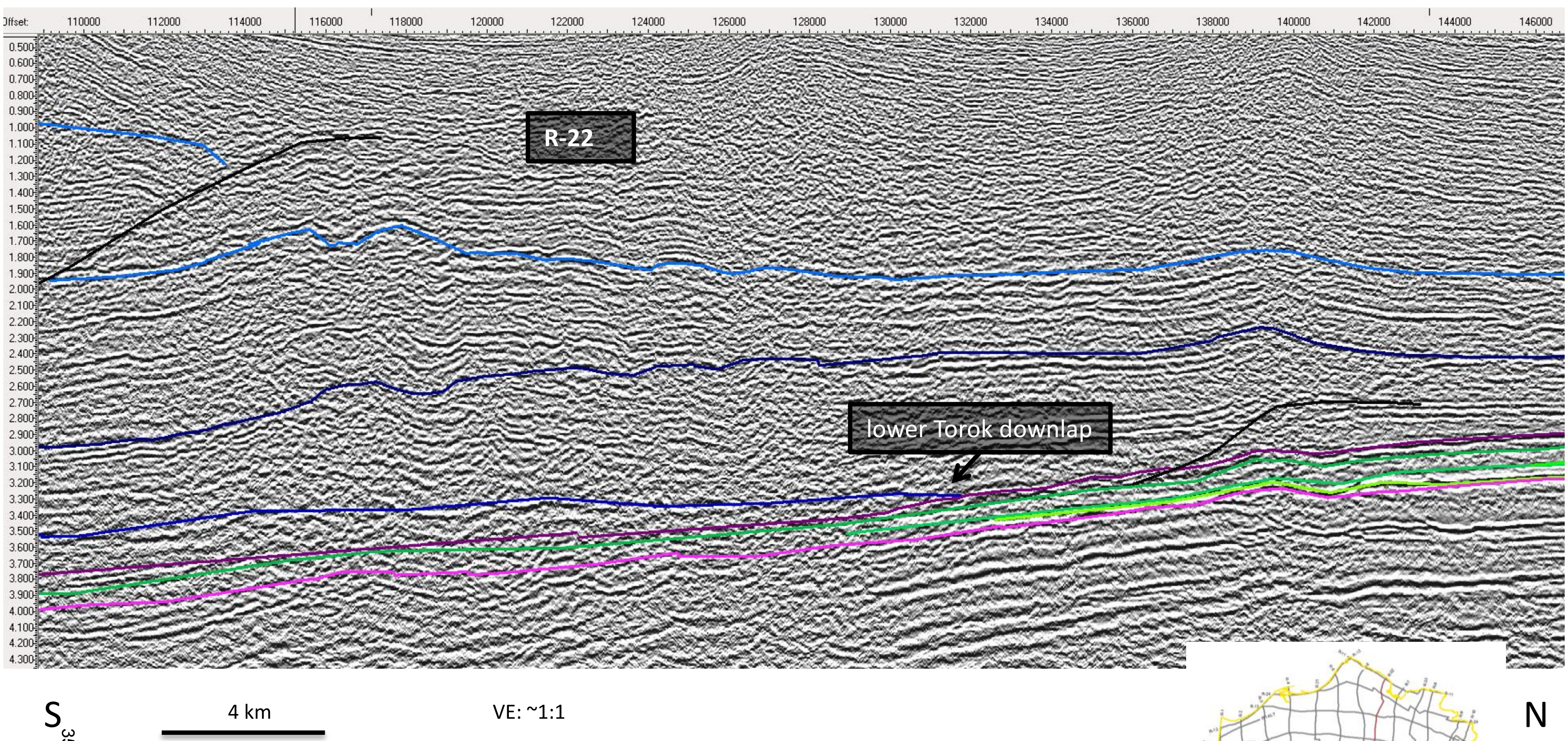
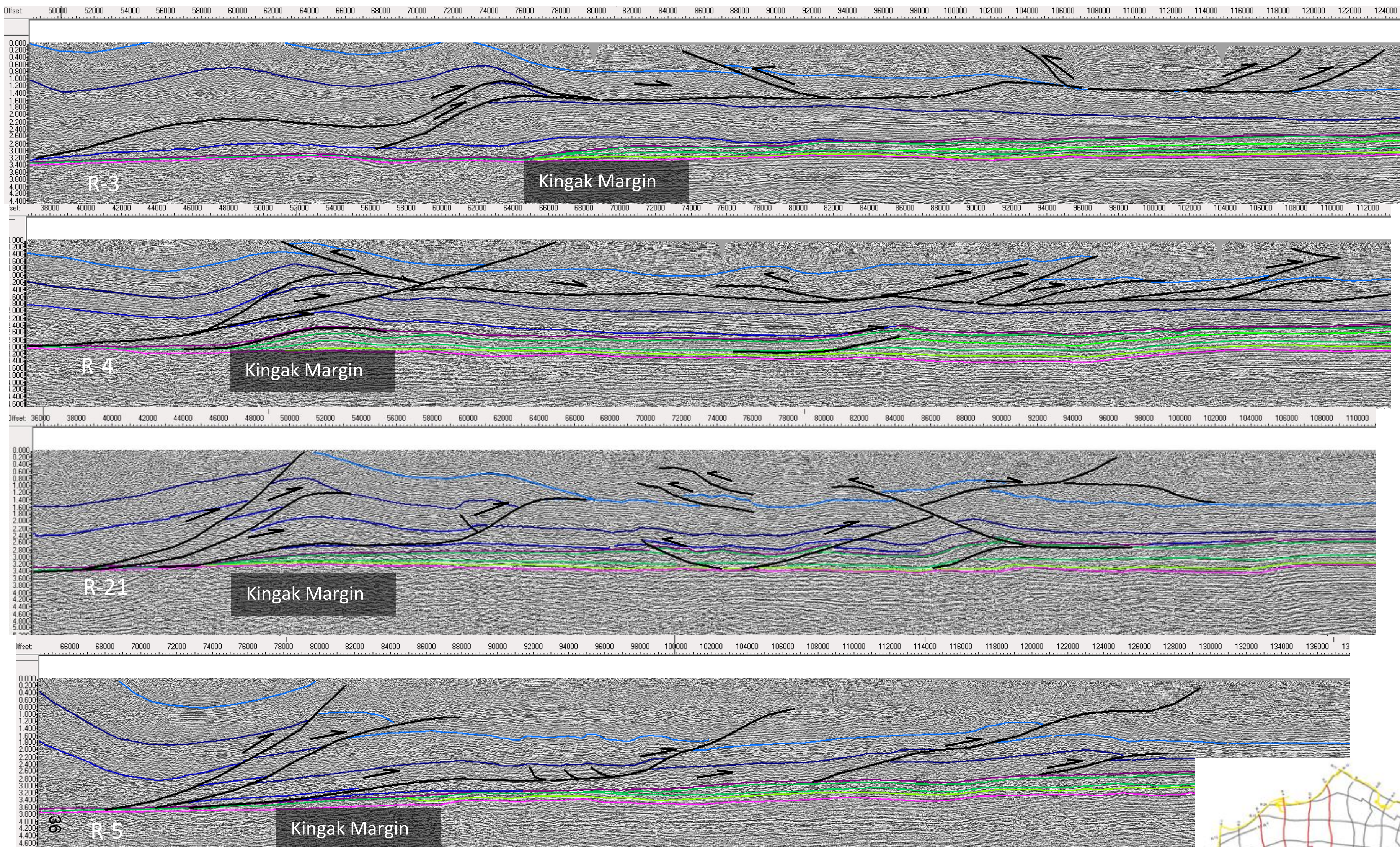


Figure 14: This shows the lower Torok downlappoing onto the pebble shale unit right on the Kingak Shale shelf margin. In some areas of southern NPRA it downlaps slightly north of the Kingak Shale shelf margin. This can be seen in Figure 15.



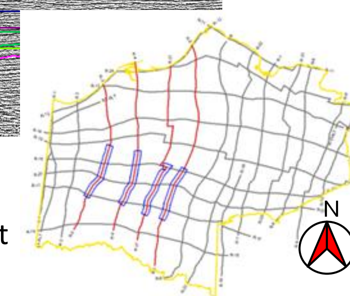
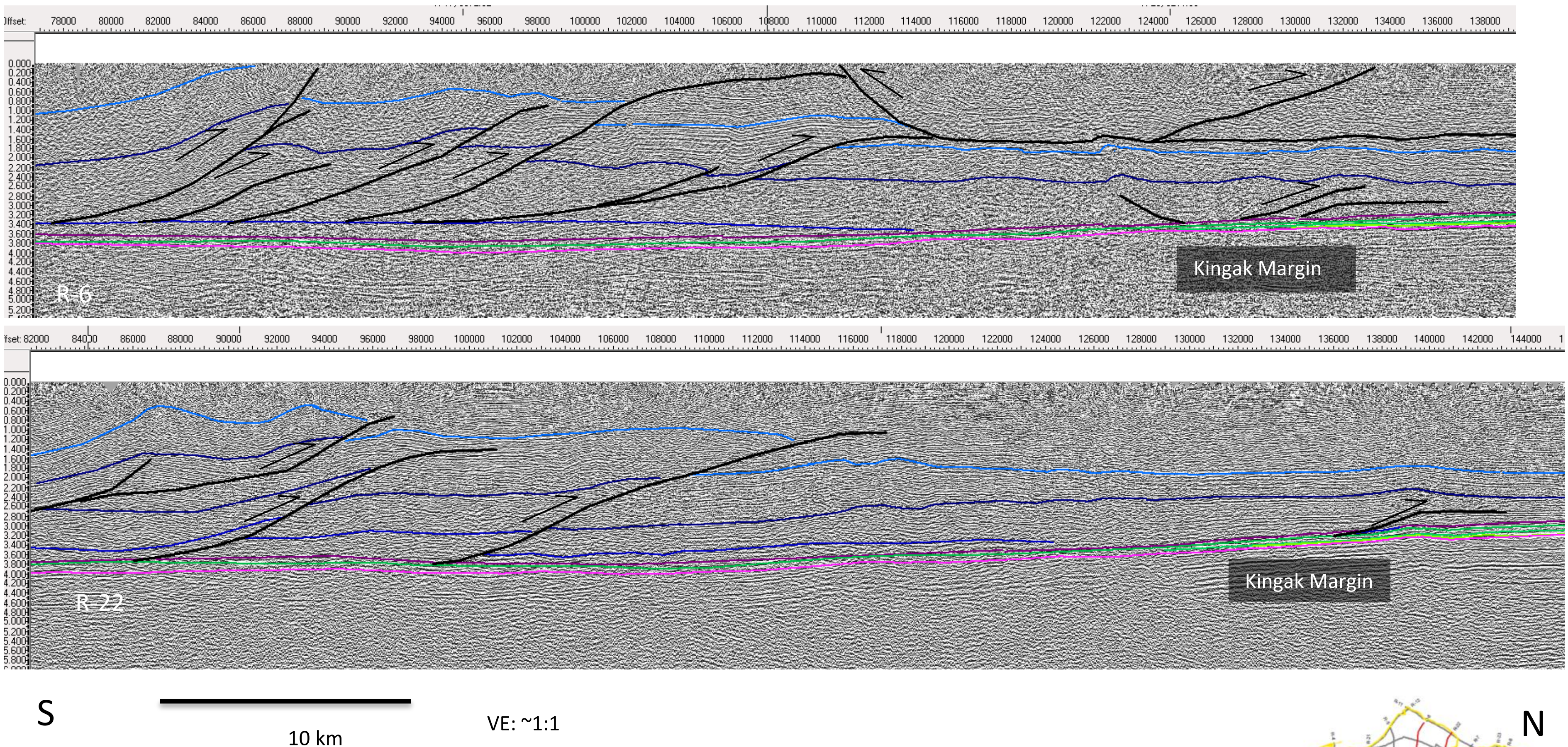


Figure 15 : These are the four seismic lines that show the oblique carbon creek anticline. Imbricated fault bend folds are associated with the Kingak Margin. The faults are less imbricated moving to the north.



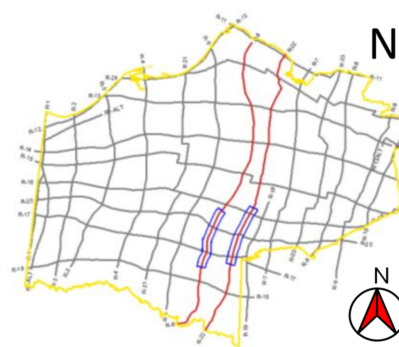
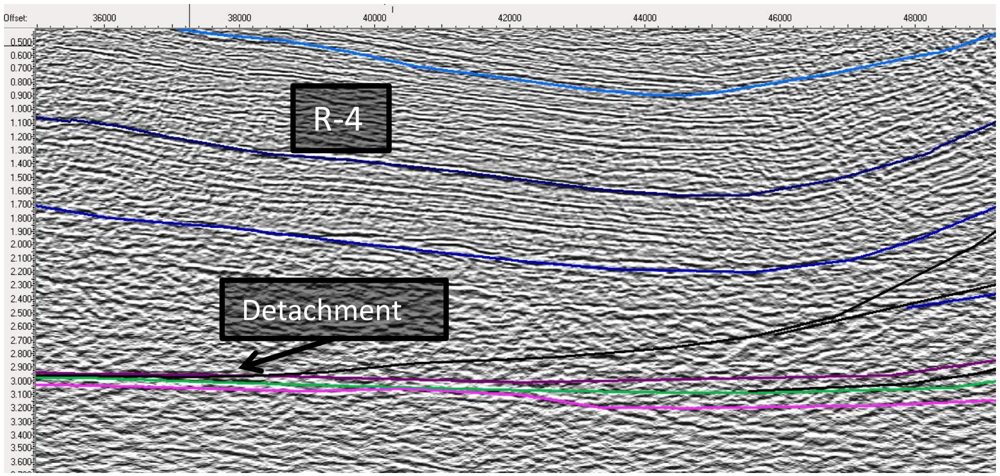
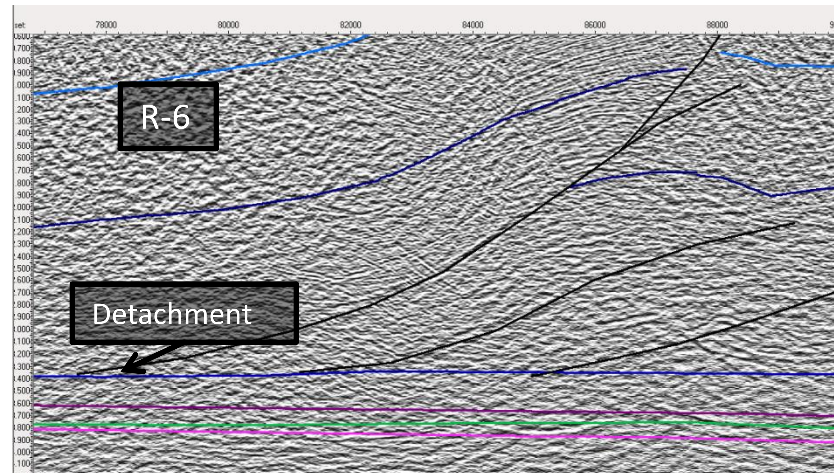
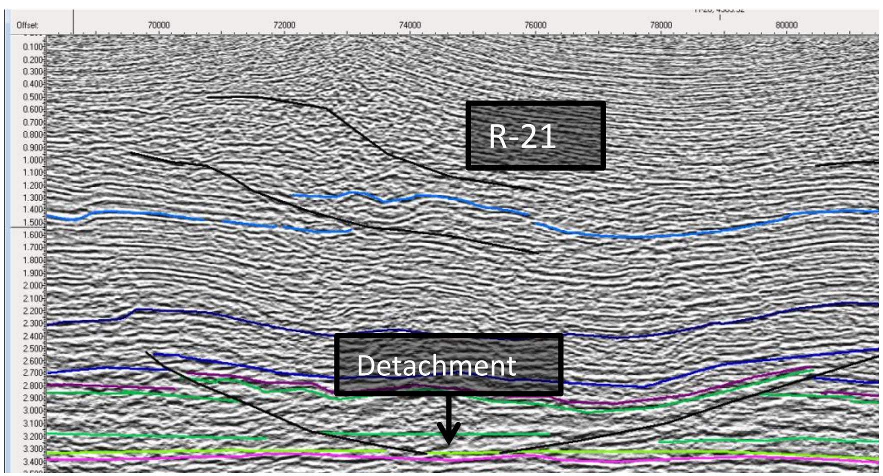


Figure 16: Southeast of the Carbon Creek Anticline the structure is no longer oblique and major thrusting is not influenced by the Kingak shelf. The Kingak shelf does still provide an easy surface for thrusts to ramp up on which be seen on the north side of the seismic lines. The faults are less imbricated moving to the north.







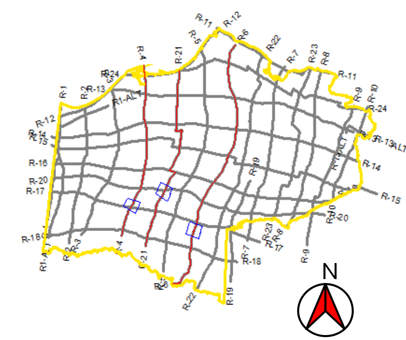


Figure 17: This shows the different part of the basal condensed section serving as the lower detachment surface on different seismic lines. The Kingak Formation, Lower Torok, and Shublik Formation are the detachments in lines R-4, R-6, and R-21 respectively. The weak shale that is present in all 3 of the sequences is responsible for the good detachment surface.

VE: ~1:1

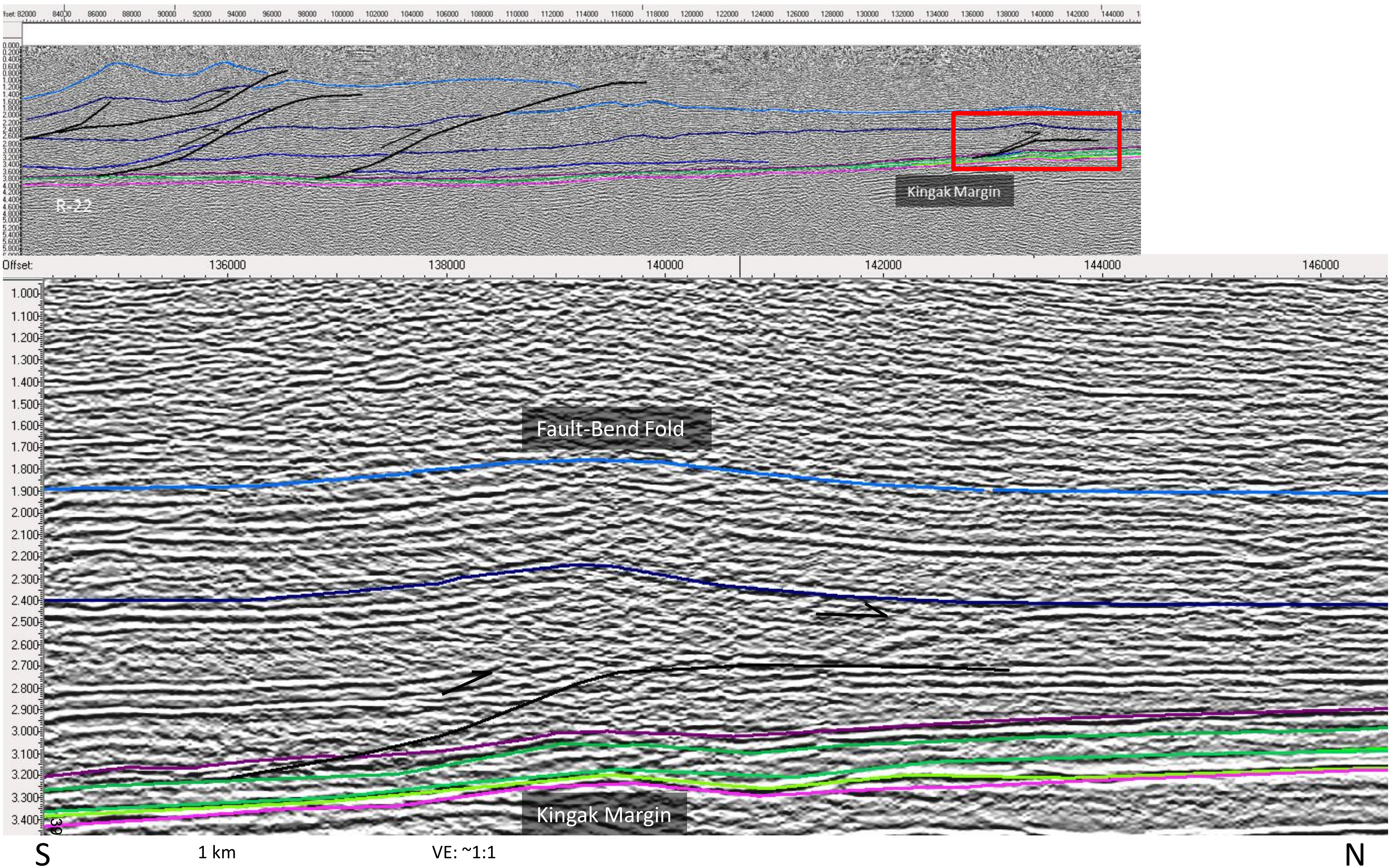


Figure 18: A simple unimbricated fault-bend fold see on line R-22. The Kingak margin is a good surface for thrust to ramp up on, and the structural style in this section of line R-22 is fault-bend folding. This particular thrust is detaching in the Torok Formation, but on a lower level than the mapped Middle Torok.

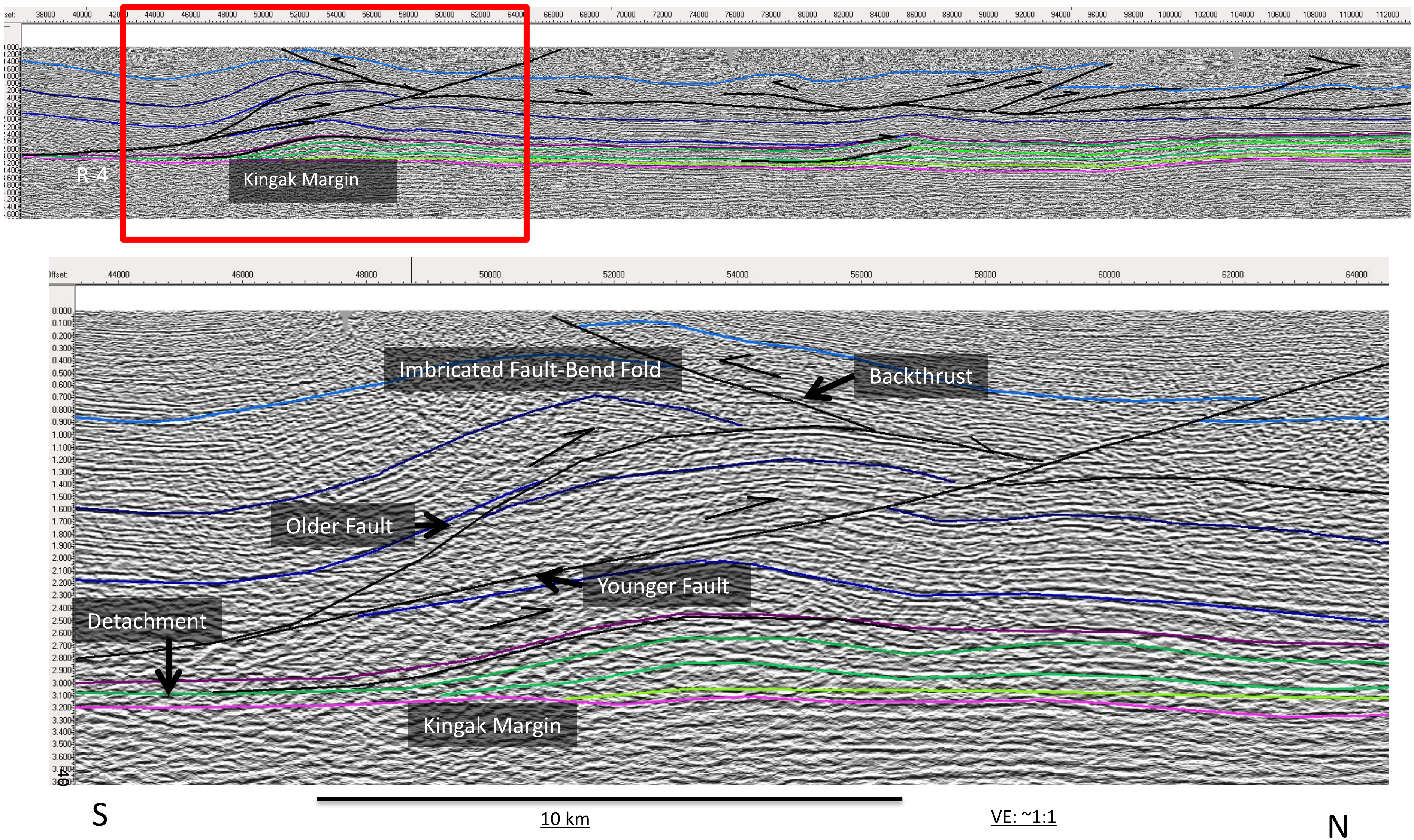


Figure 19: This is a section of the R-4 line right where the thrust ramps up over the Kingak shelf margin. The structurally lower thrust has further deformed the older fault and the two faults now form an imbricated fault-bend fold. The imbricate is break forward because the younger fault is structurally lower.

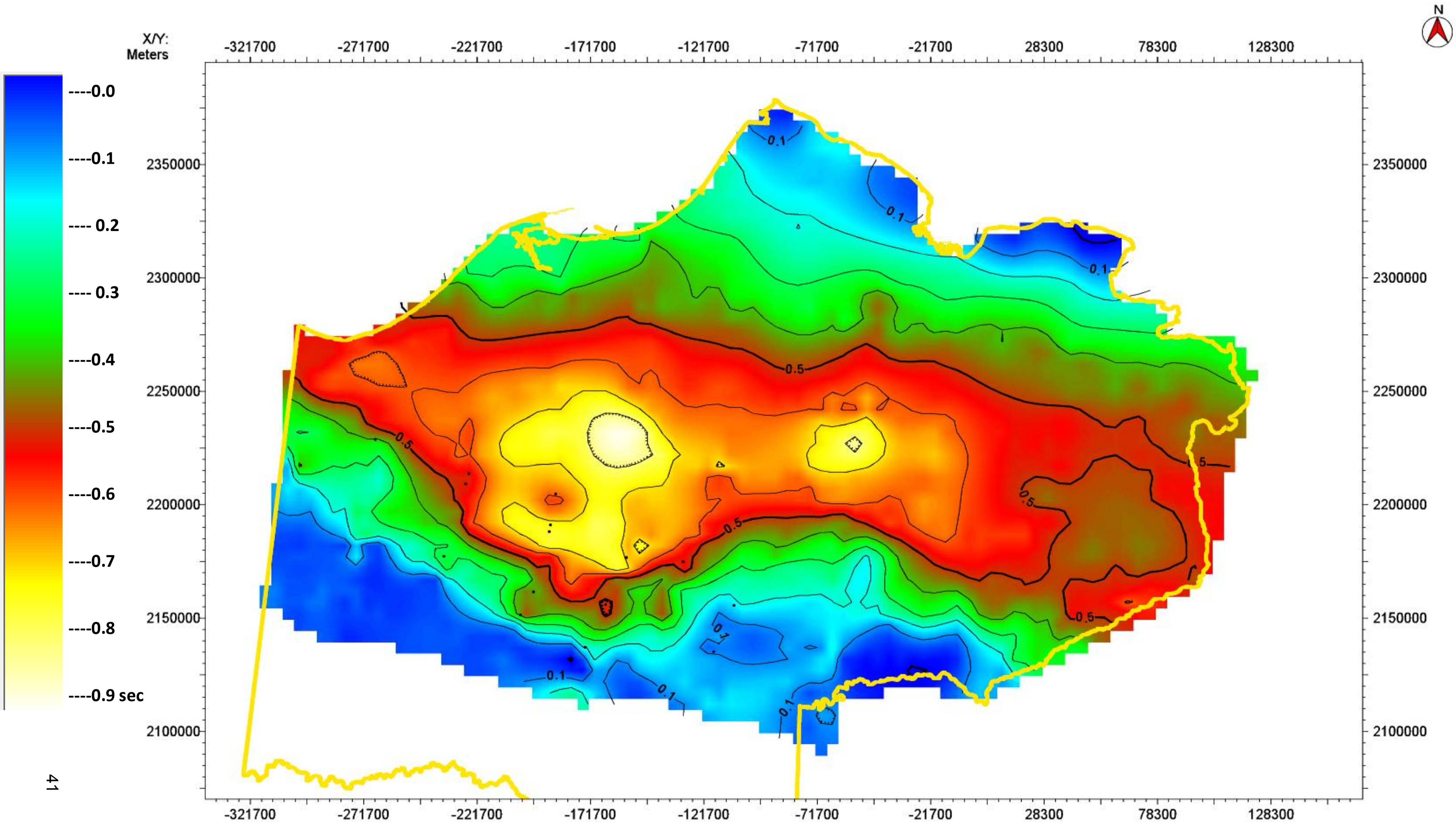


Figure 20: This is an isopach map of the Kingak Formation. Thickness is displayed in seconds he contour interval is 0.1 seconds. Thickness is from the top of the Kingak Formation (K1, K2, K3, K4) to the top of the Shublik Formation.

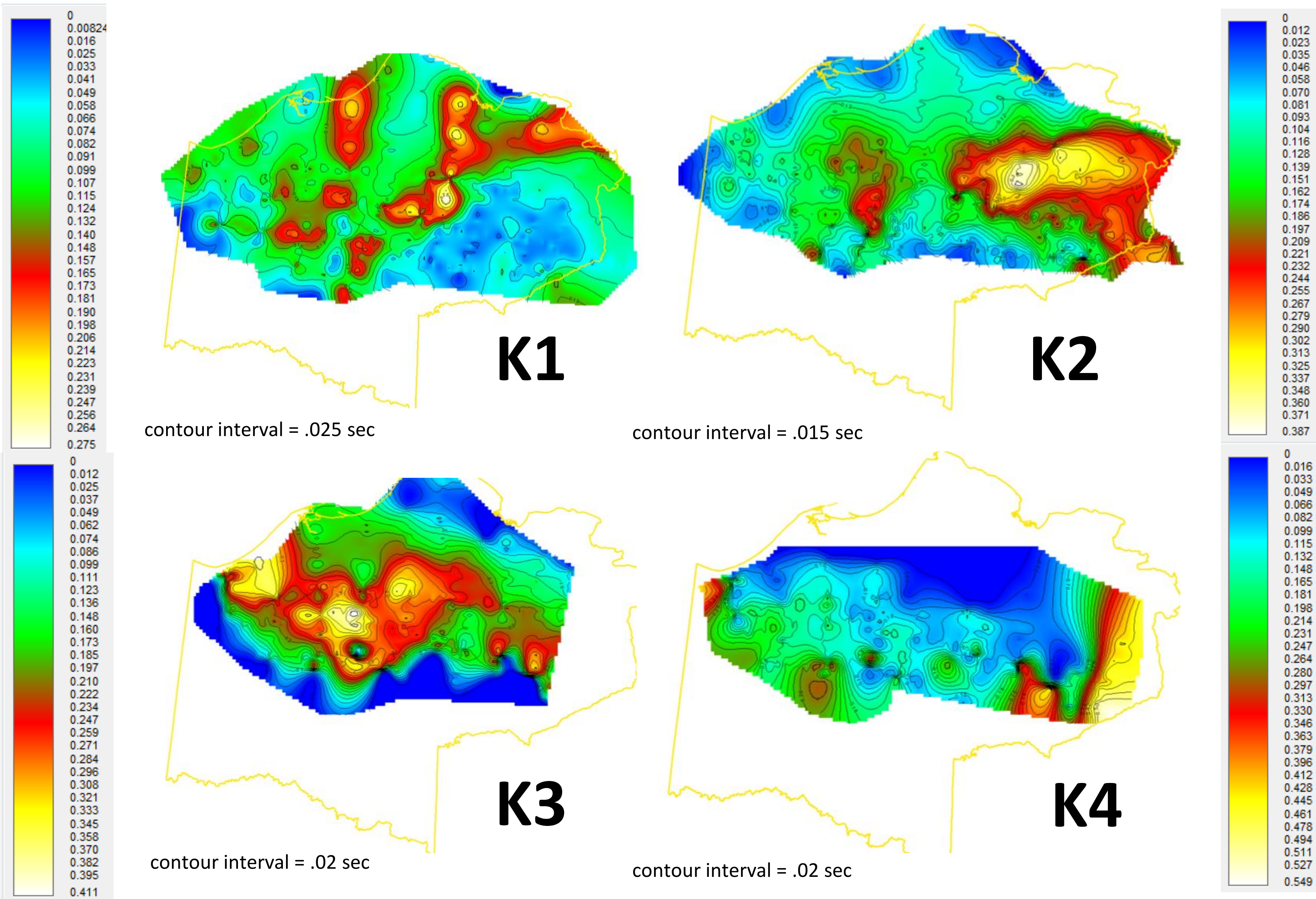


Figure 21: These are the isopachs of the K1 through K4 units generated by the interpretation of this study. If they are compared with the isopachs generated by Houseknecht and Bird (2004) in Figure 3 they are similar, but are in time rather than depth. The K4 map is incomplete due to the fact that K3 is not present in the south. The scale of the color bars is different for each sequence and is in seconds.

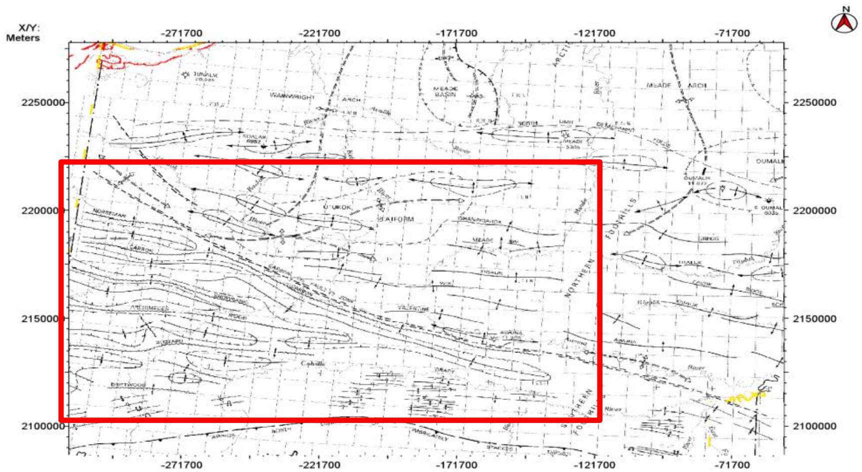
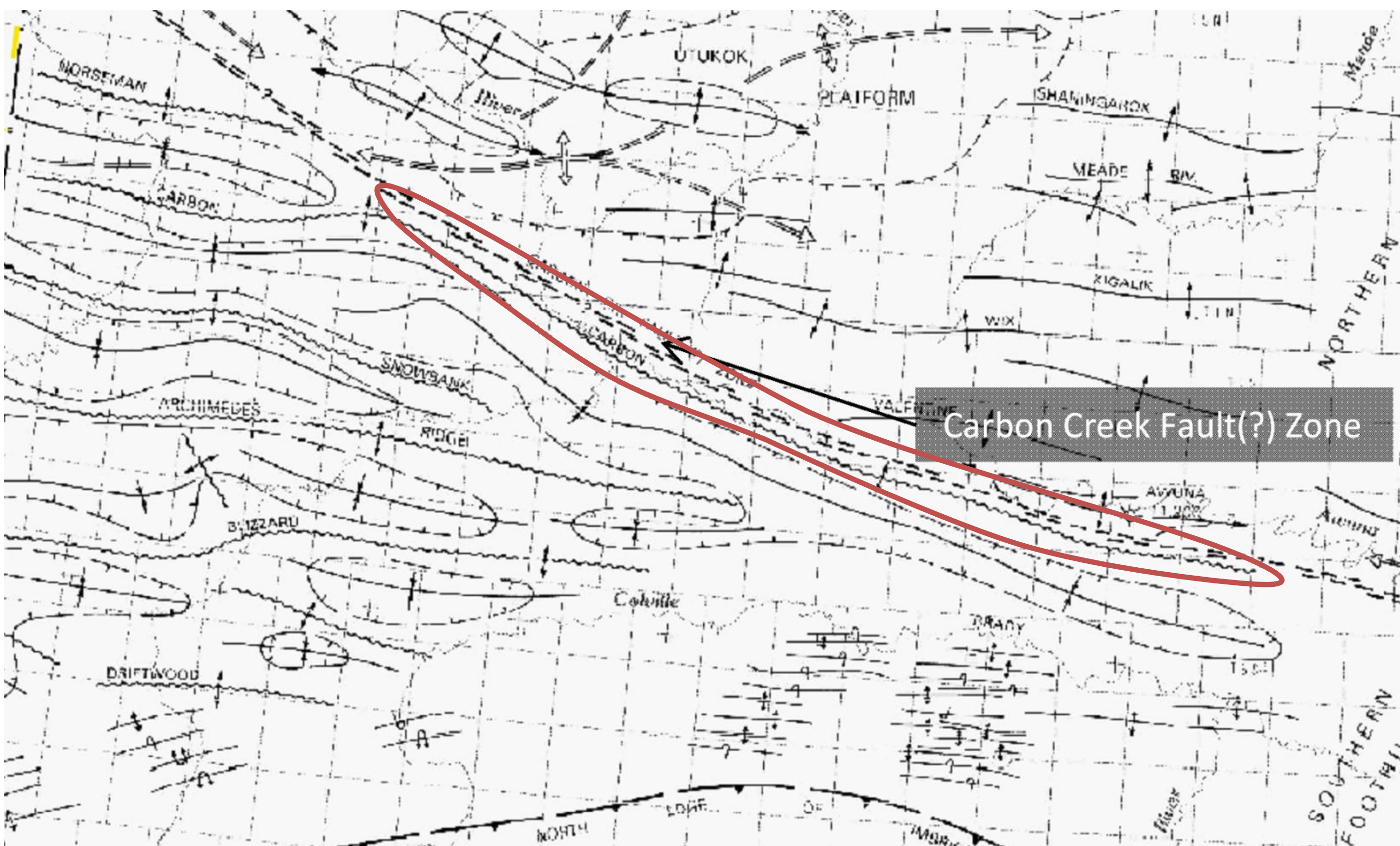
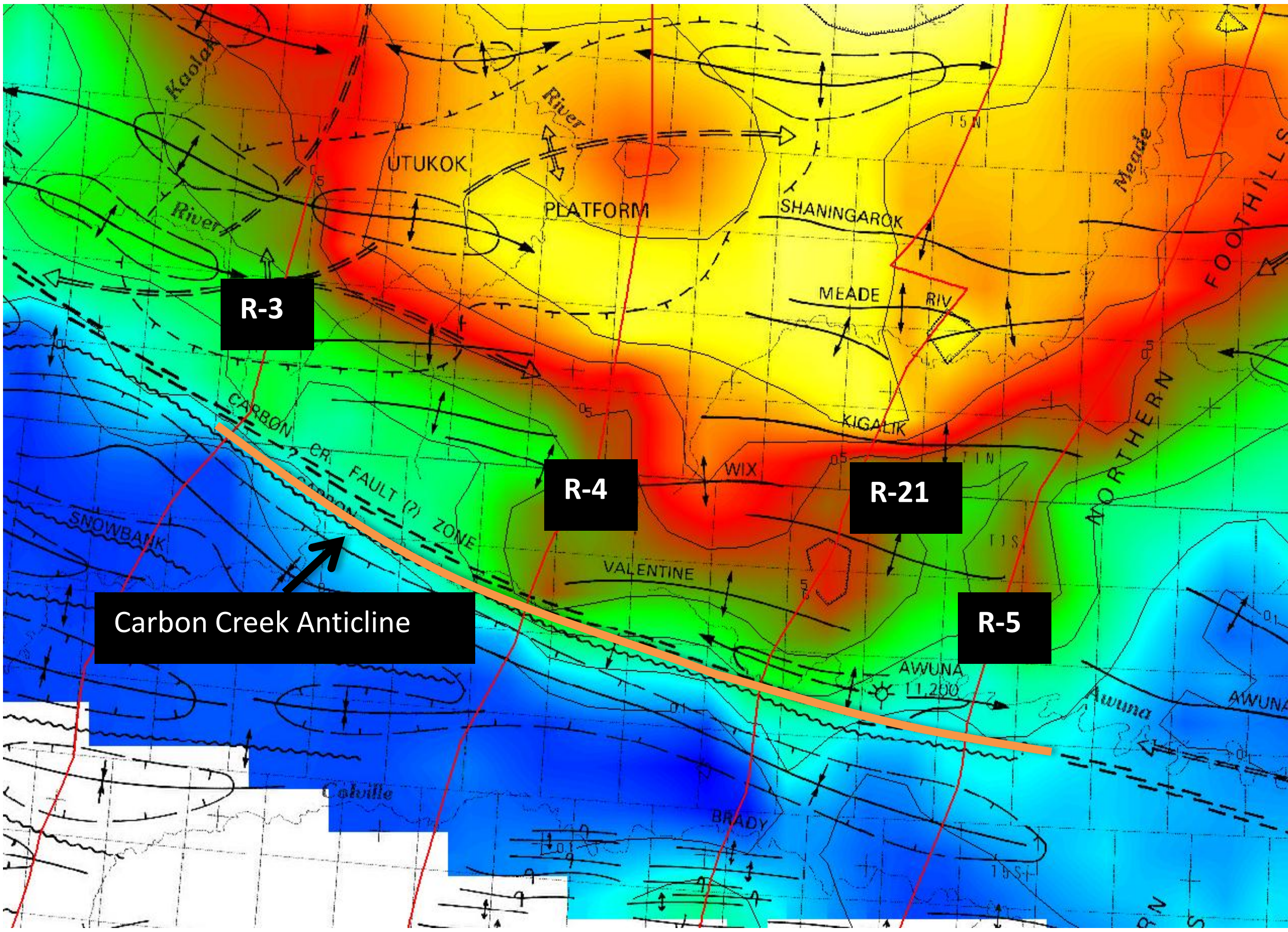
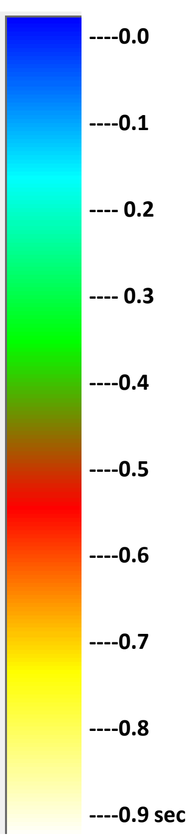


Figure 22: The area outlined in red is what this study calling the Carbon Creek Anticline. It is the southeastern part of a structure that has previously been mapped as the Carbon Anticline. The northwestern part of the Carbon Anticline is not oblique to other structure where as what is called the Carbon Creek Anticline is oblique to other structure (modified from Kirshiner et al., 1987).







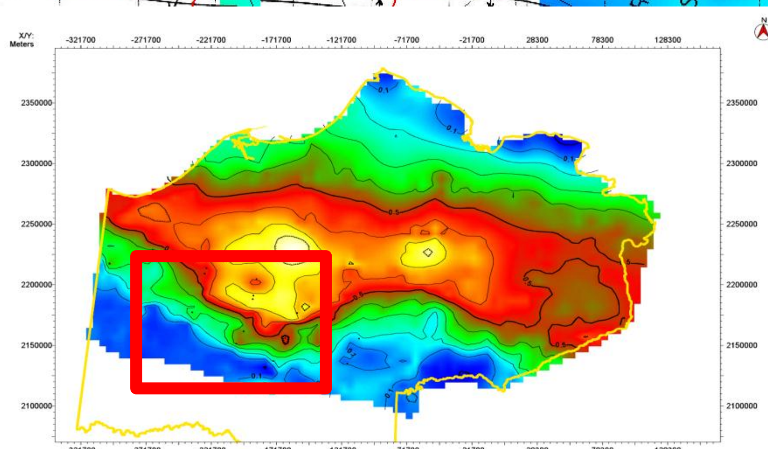


Figure 23: This isopach map of the Kingak formation, along with the structure map show that the shelf margin of the Kingak formation is influencing what this study is calling the Carbon Creek Anticline. In this area of NPRA the strike of the Brooks Range is oblique to the Kingak shelf margin.

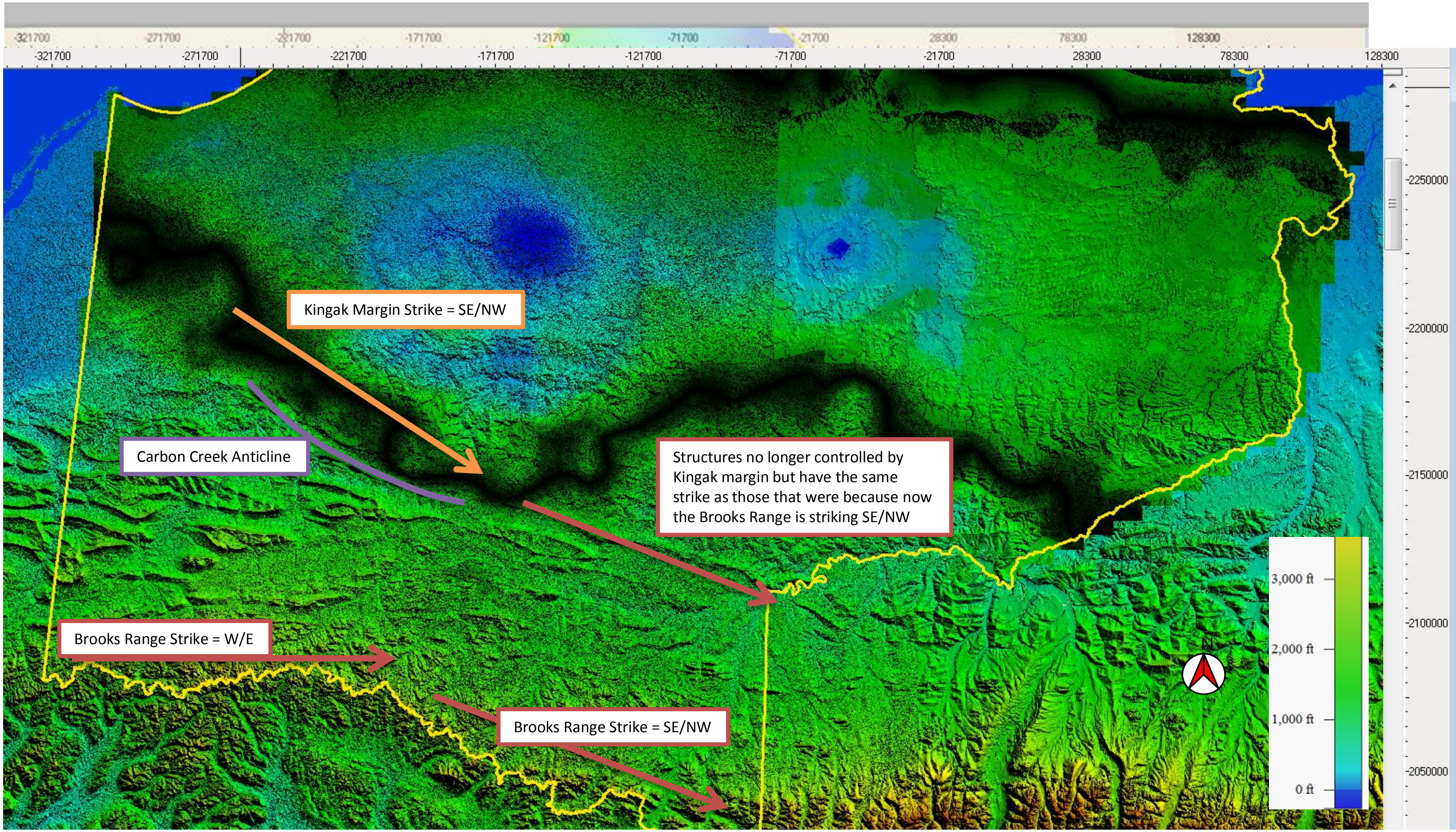
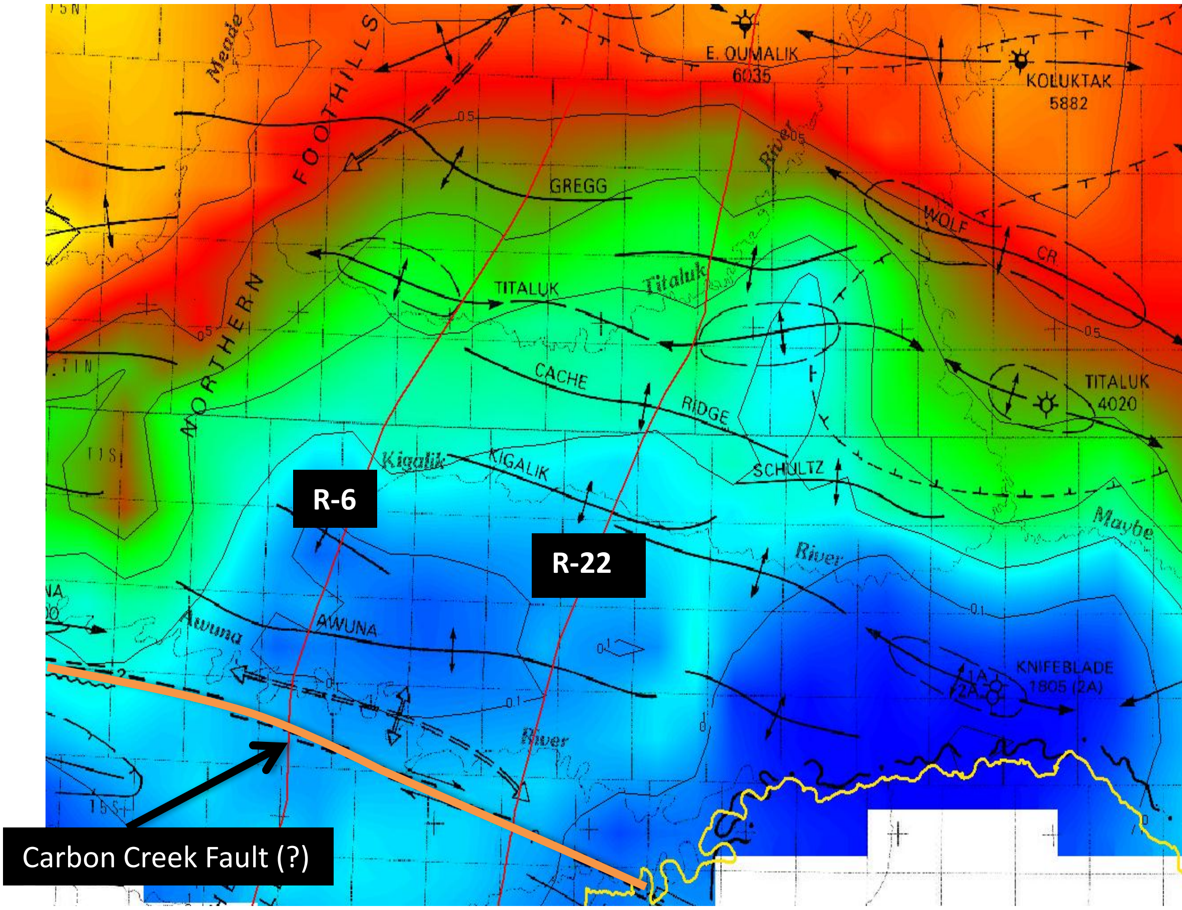
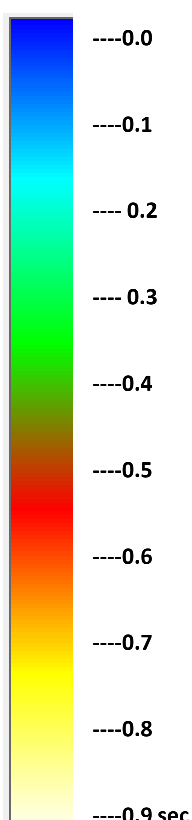


Figure 24. In this image the isopach map of the Kingak Formation is displayed with the digital elevation model. It is easy to see that where the Carbon Creek Anticline is the Kingak margin is oblique to the strike of the Brooks Range, and where the Kingak margin does not control the major thrusting the structures are not oblique to the strike of the Brooks Range. The yellow line outlines the NPRA federal boundary. The scale of NPRA is in meters while the scale of the digital elevation model is in feet.





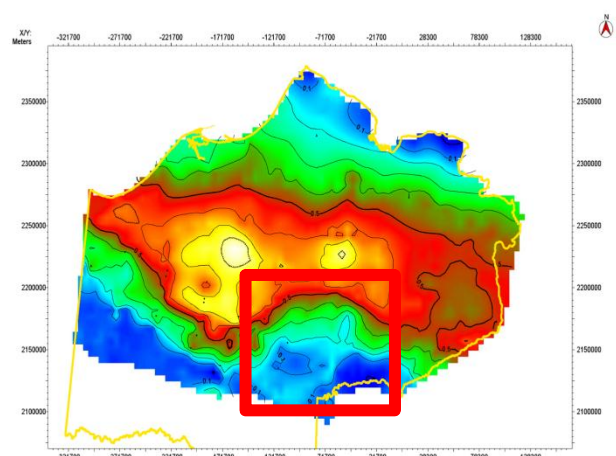


Figure 25: In the southeastern portion of the Carbon Creek Fault (?) Zone the structural break happens south of the Kingak shelf margin. There is still thrusting controlled by the Kingak shelf margin but not the large imbricated fault-bend folds. The strike of the Brooks Rang is not oblique to the Kingak shelf margin in this part of NPRA.

APPENDIX A

Wells in NPRA are in depth and the seismic lines are in time therefore time-depth (T-D) charts needed to be generated for wells in the study area. This was done using SynPAK in SMT's Kingdome Suite© 8.7.

Synthetics Generation

Time-depth (T-D) charts were generated for the wells in the study area that had both a sonic and density log. The initial skeleton T-D chart was created using an average velocity given by the sonic curve and contained only two points. The values used to generate these simple functions are shows in Table A-1. The first point was created using Kelly Bushing elevation for the well and was negative. The second point was created using the Total Depth – the Kelly Bushing elevation. These velocities ranged from 11000 ft/s to 16000 ft/s. The equation used to calculate these times was:

$$t_3 = (2*E_s)/v$$

Well Name	KB (m)	TD (m)	TD - KB (m)	Velocity ft/s	Initial Time (s)	Final Time (s)
Akulik	24	17038	17014	12000	-0.004	2.836
Awuna	1129	11200	10071	14000	-0.161	1.439
Colville 2	372	3254	2882	12000	-0.062	0.480
East Umiat 2	357	2841	2484	12000	-0.060	0.414
Inigok	108	20102	19994	12000	-0.018	3.346
Kolutak	205	5882	5677	12000	-0.034	0.946
Lisburne	1862	17000	15138	16000	-0.233	1.892
Seabee	322	15611	15289	12000	-0.054	2.548
Tulaga	180	11742	11562	11000	-0.033	2.102
Tungak Creek	118	8212	8094	11000	-0.021	1.472
West Karupa	1369	11060	9691	12000	-0.228	1.615

Table A-1. This shows the values used to generate the initial skeleton T-D functions. The initial time is calculated using the KB elevation and is negative because it is above sea level. Therefore the initial point is entered as 0m elevation and a negative time. The final time is calculated using the TD-KB and is positive because it is below sea level. Therefore the final point is entered as TD and a positive time. In this way the entire depth is accounted for, but positive time still begins at 0m elevation.

The final T-D chart was created in SMT using the "Create a T-D Chart by Integrating a Log" function in SynPAK. This took the skeleton T-D chart made for each well and applied to it a sonic log. The skeleton T-D chart was also applied to density logs. The synthetic generated by SynPAK was then compared to traces on nearby imported seismic lines in order to validate the T-D functions (Figures A-1 through A-20).

Akulik

50207200010000

- Line - W71-20
- Radius – 10500m
- Trace (9) – Nearest trace in radius
- Trace (11) – Average of traces in radius
- Trace (12) – All 142 traces in radius
- Start Velocity – 12000 ft/s

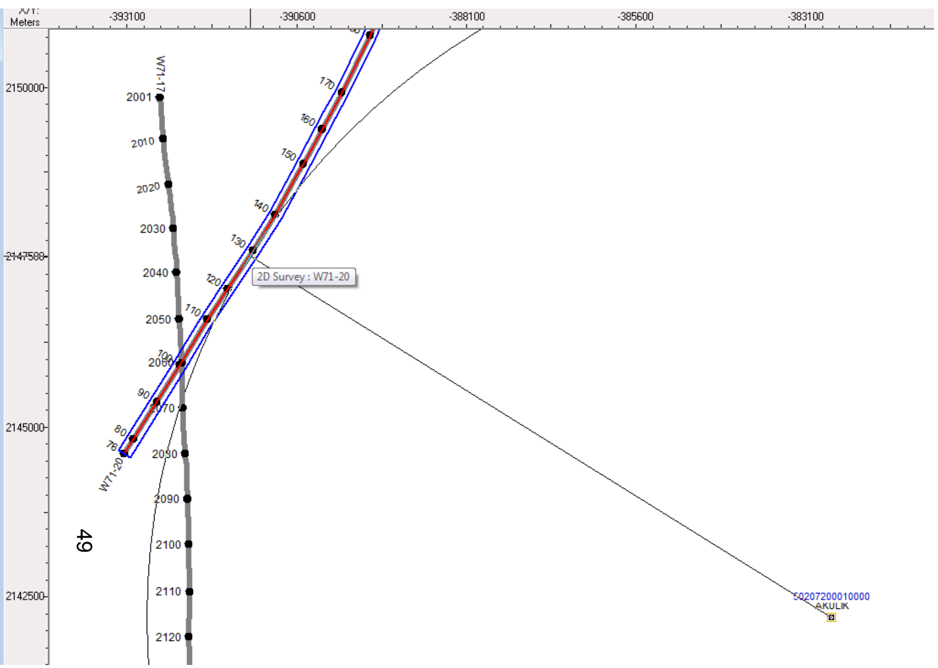
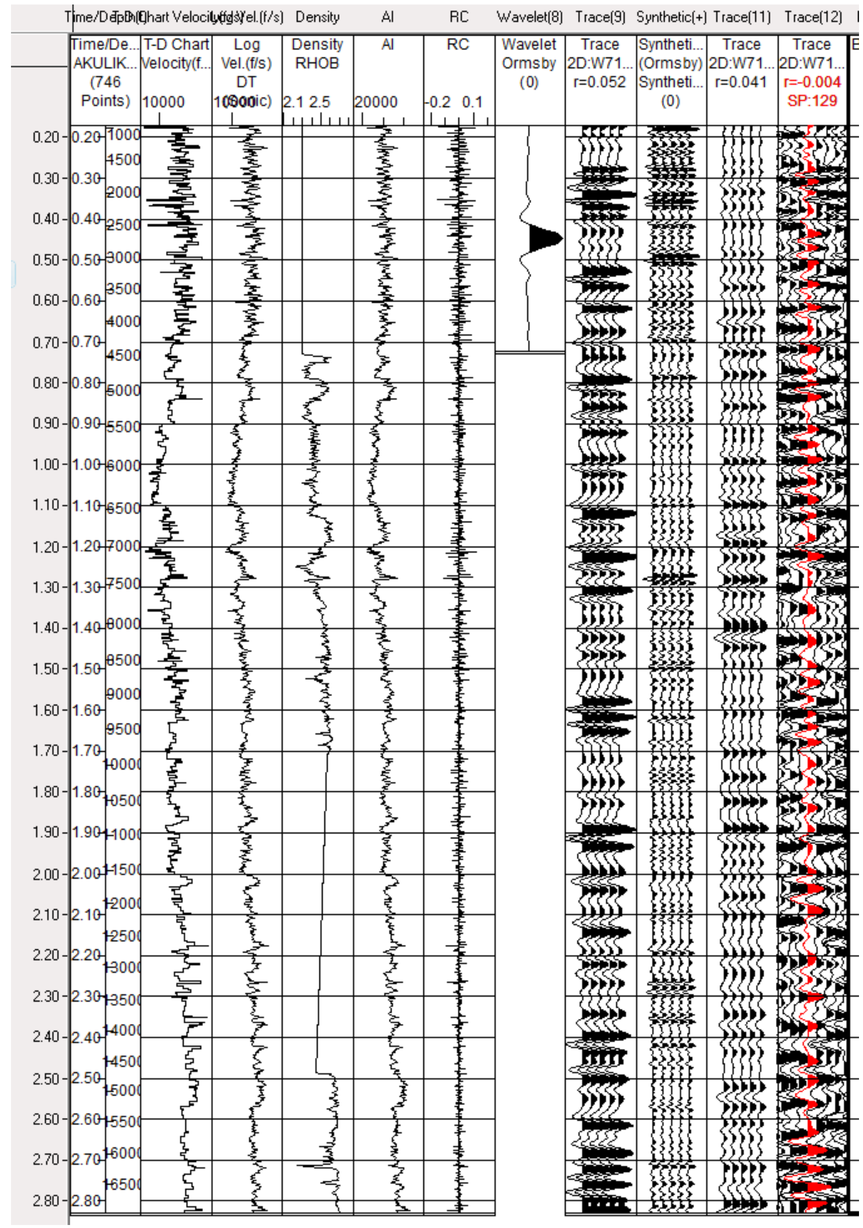


Figure A-1



Akulik

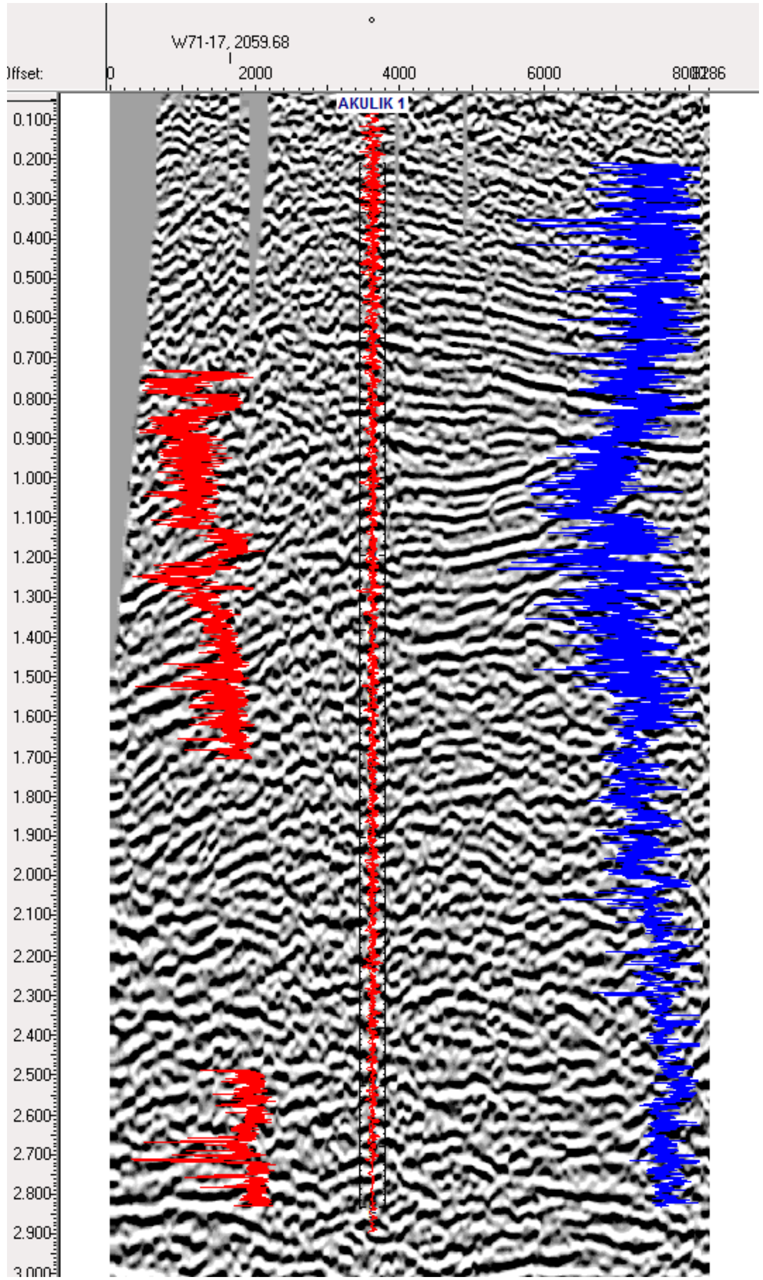
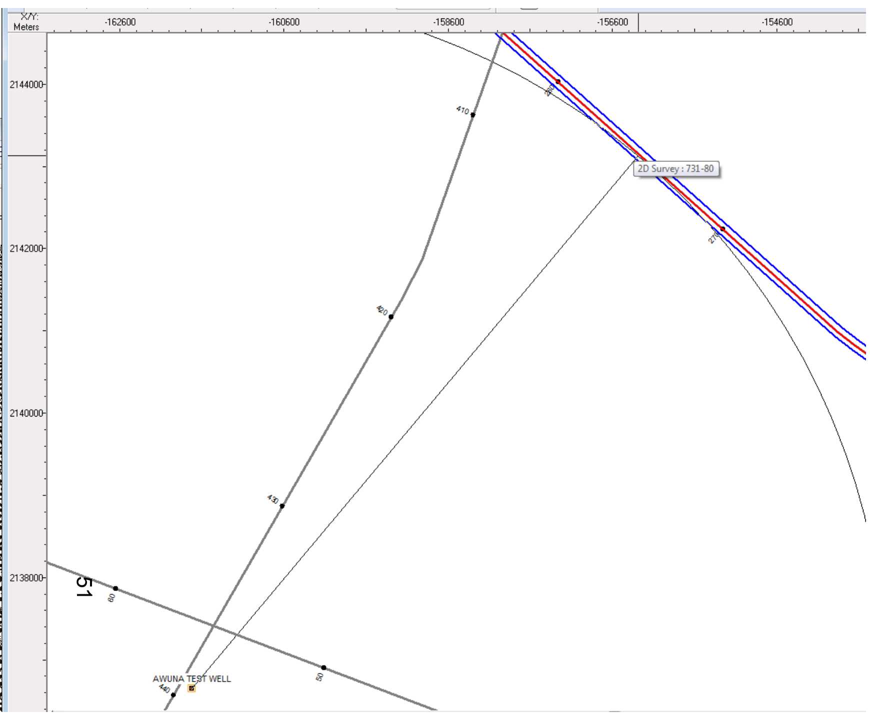


Figure A-2

Awuna Test Well

50155200010000

- Line – 731-80
- Radius – 8500m
- Trace (9) – Nearest trace in radius
- Trace (11) – Average of traces in radius
- Trace (12) – All 4 traces in radius
- Start Velocity 14000 ft/s



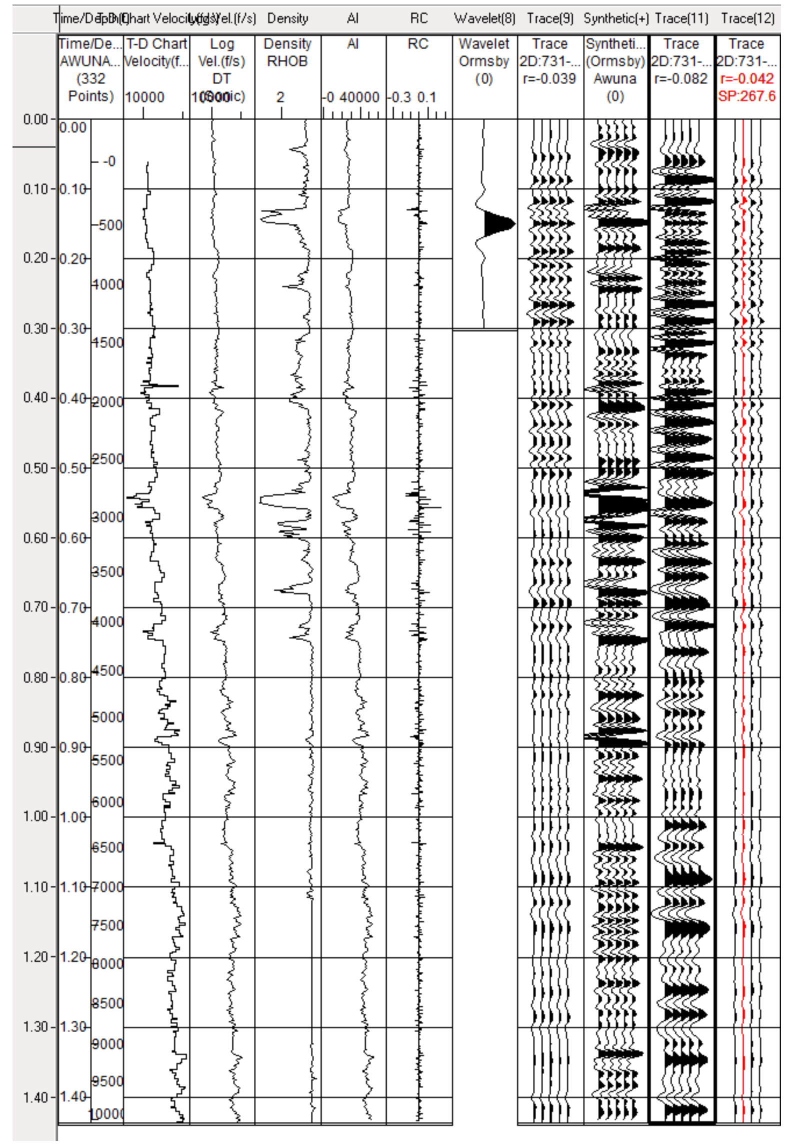


Figure A-3

Awuna Test Well

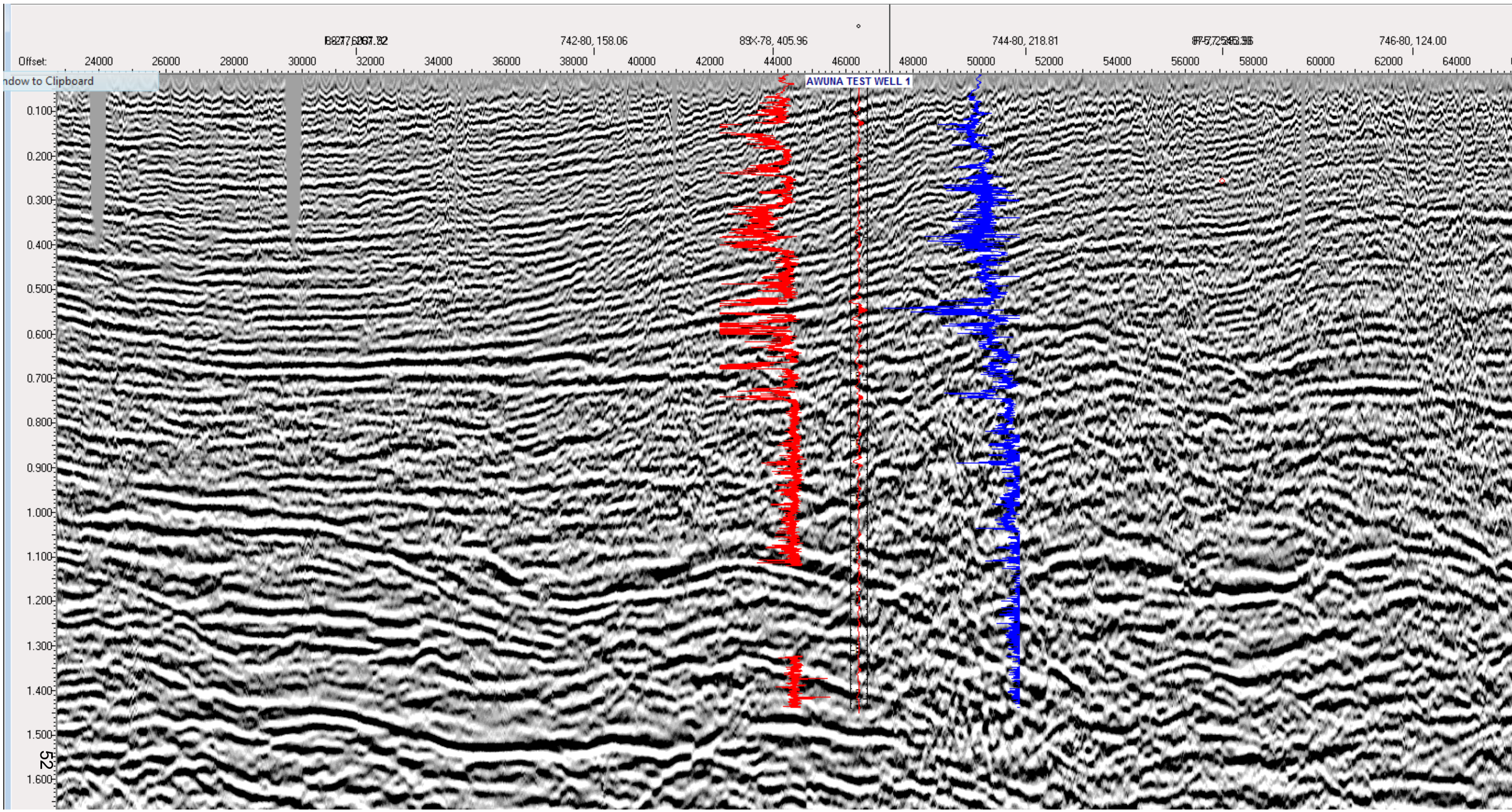
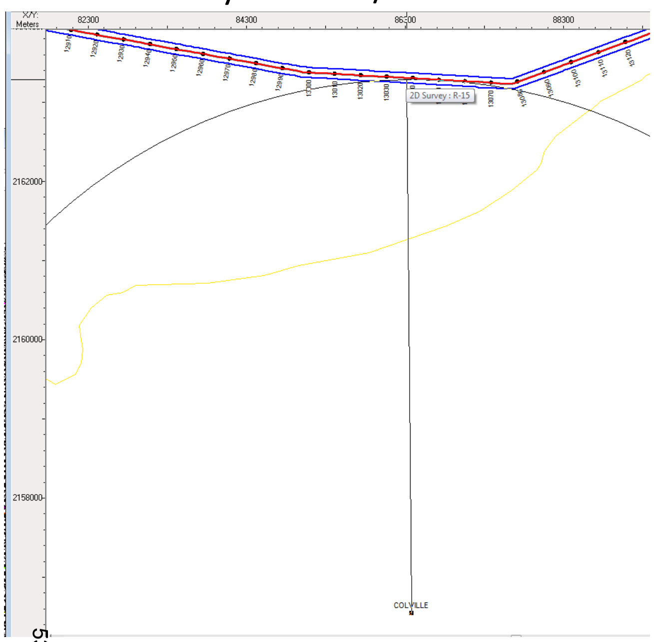


Figure A-4

Colville-2

50287200040000

- Survey – R-15
- Radius - 7000
- Trace (9) – Nearest trace in radius
- Trace (11) – Average of traces in radius
- Trace (12) – All 69 traces in radius
- Start Velocity 12000 ft/s



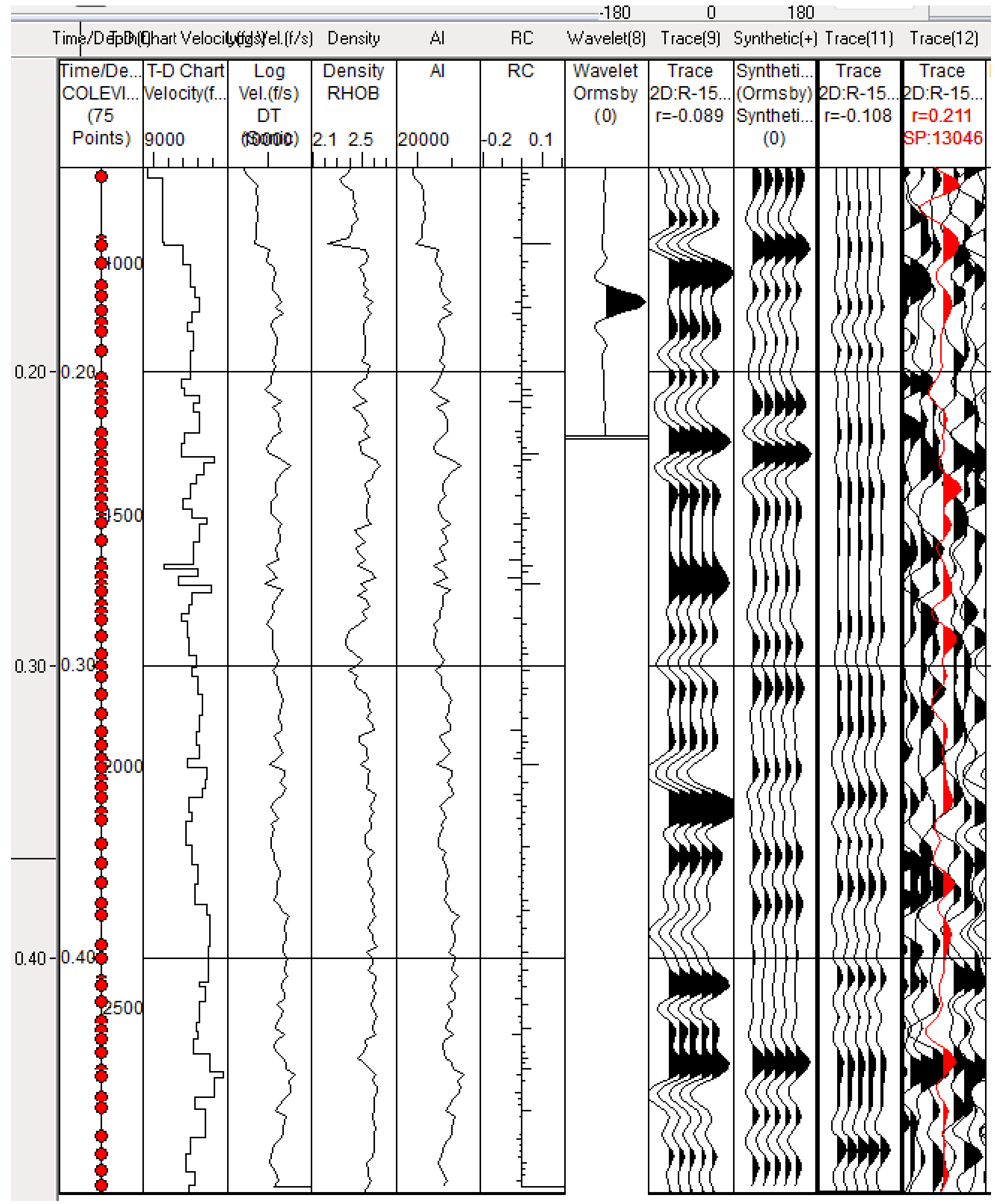


Figure A-5

Colville - 2

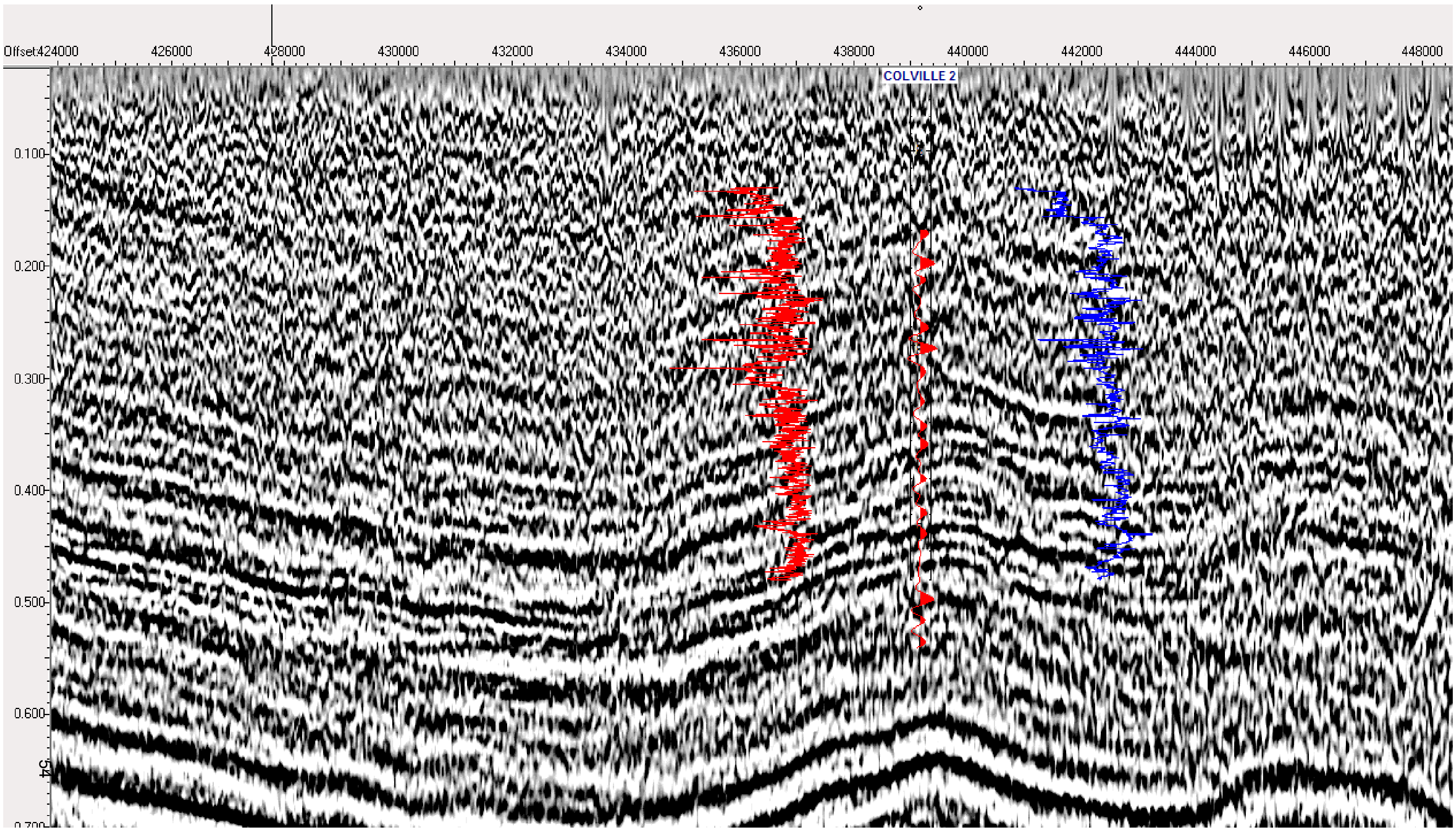
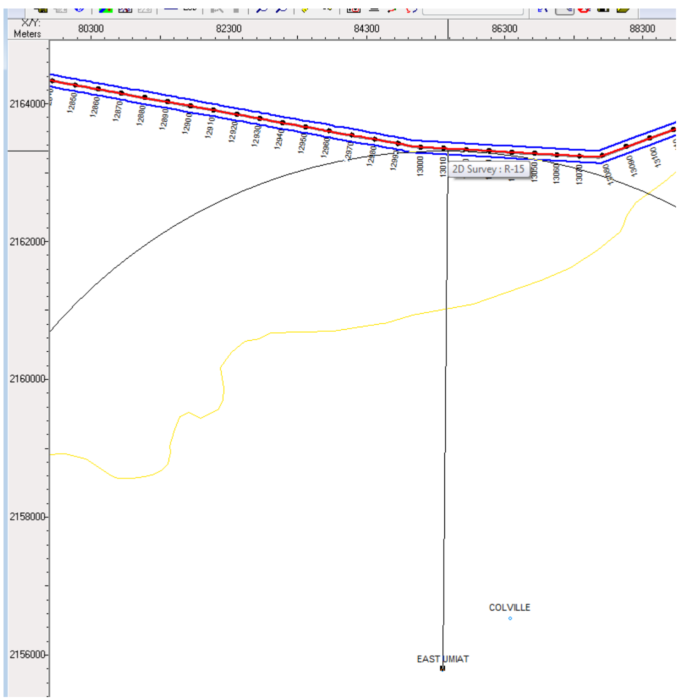


Figure A-6

East Umiat 2

50287200020000

- Survey – R-15
- Radius - 8000
- Trace (9) – Nearest trace in radius
- Trace (11) – Average of traces in radius
- Trace (12) – All 112 traces in radius
- Start Velocity 12000 ft/s



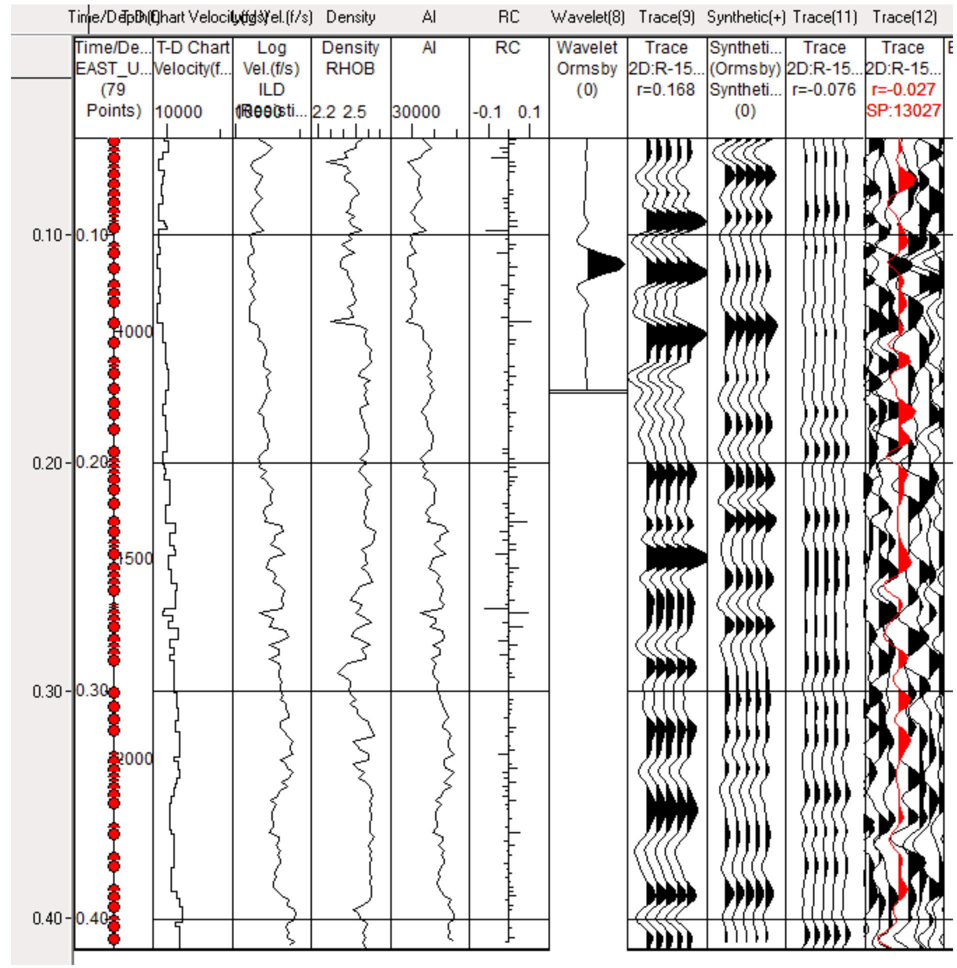


Figure A-7

East Umiat 2

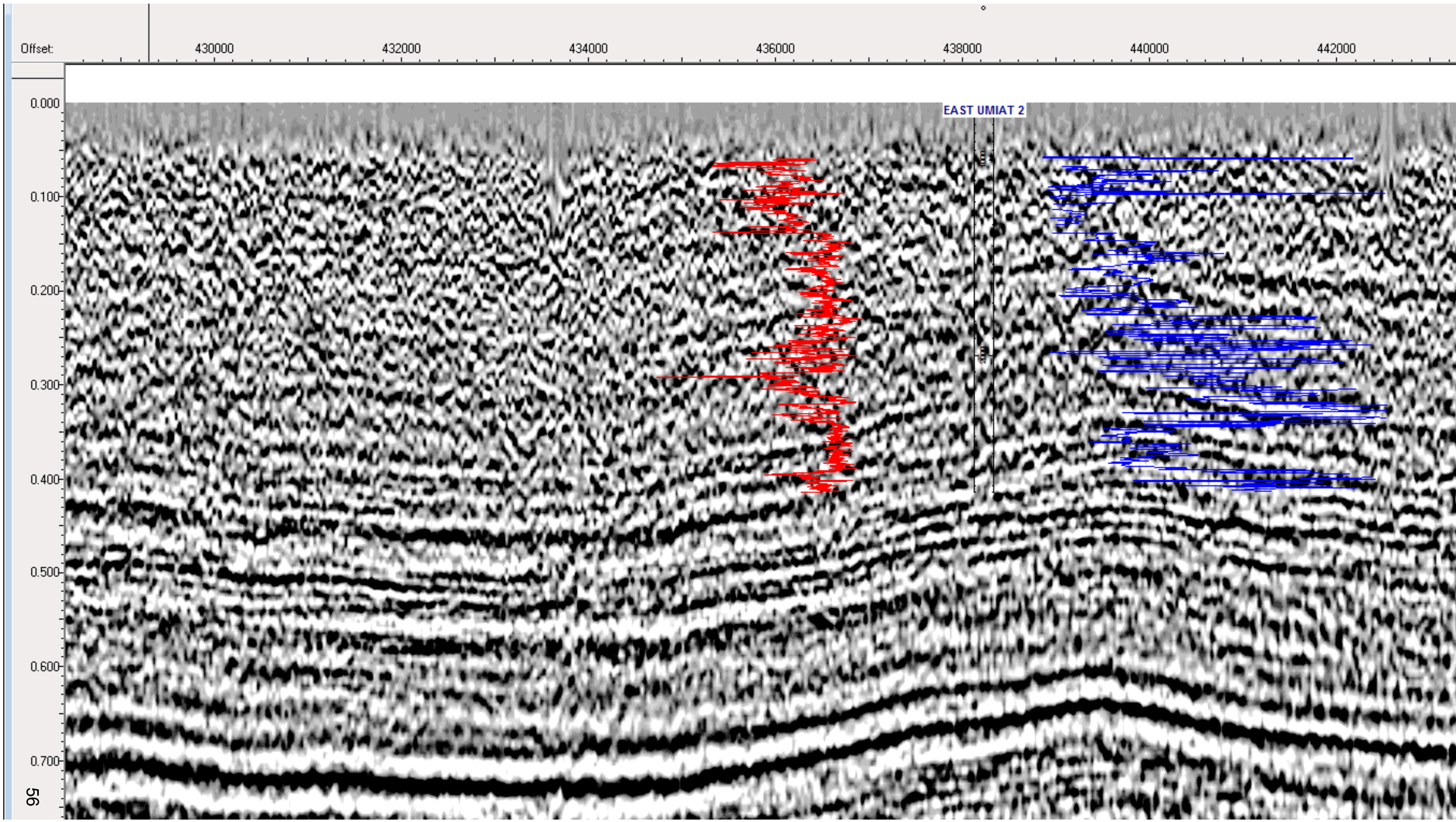
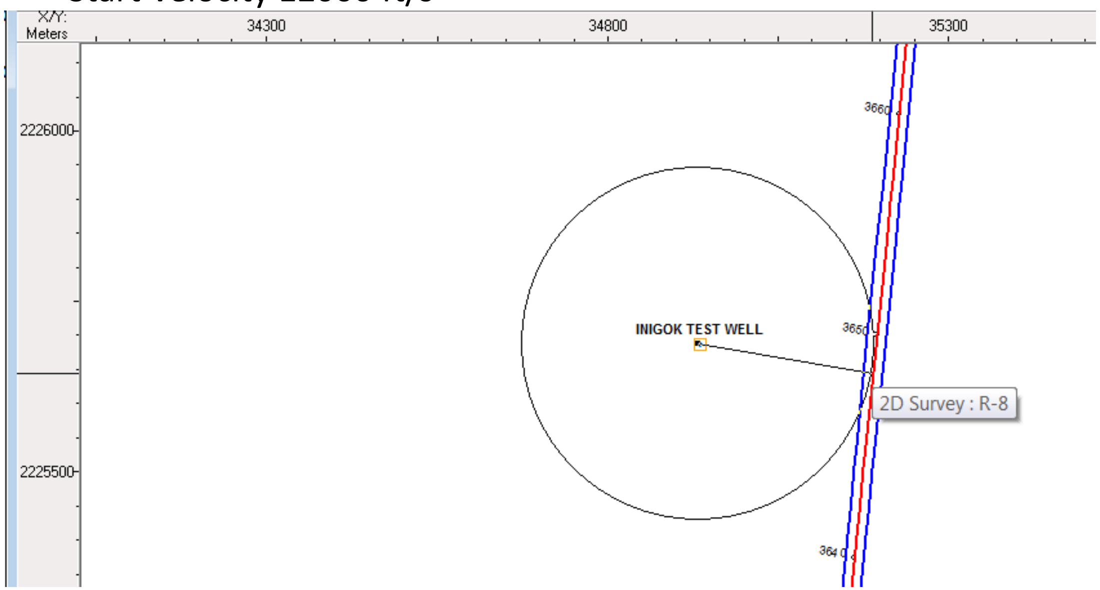


Figure A-8

Inigok

50279200030000

- •Survey – R-8
- •Radius – 500m
- •Trace (9) – Nearest trace in radius
- •Trace (11) – Average of traces in radius
- •Trace (12) – All 26 traces in radius
- •Start Velocity 12000 ft/s



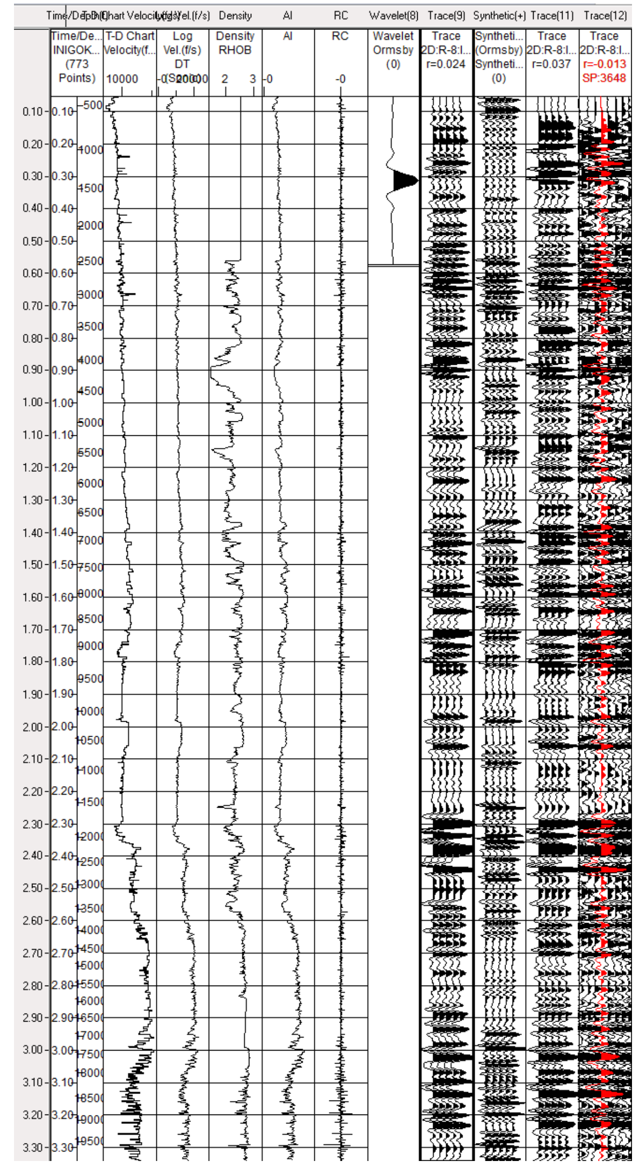


Figure A-9

Inigok

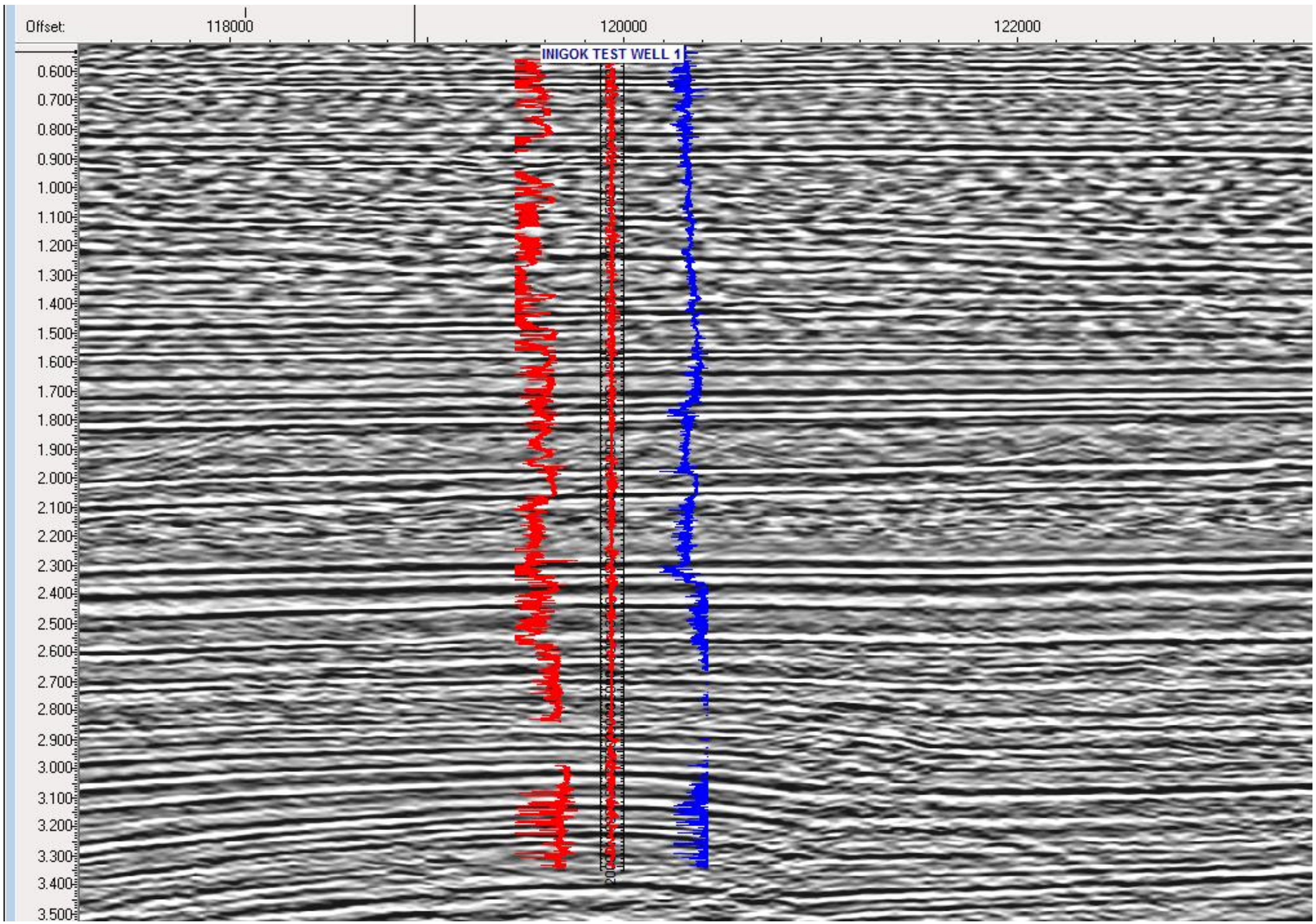
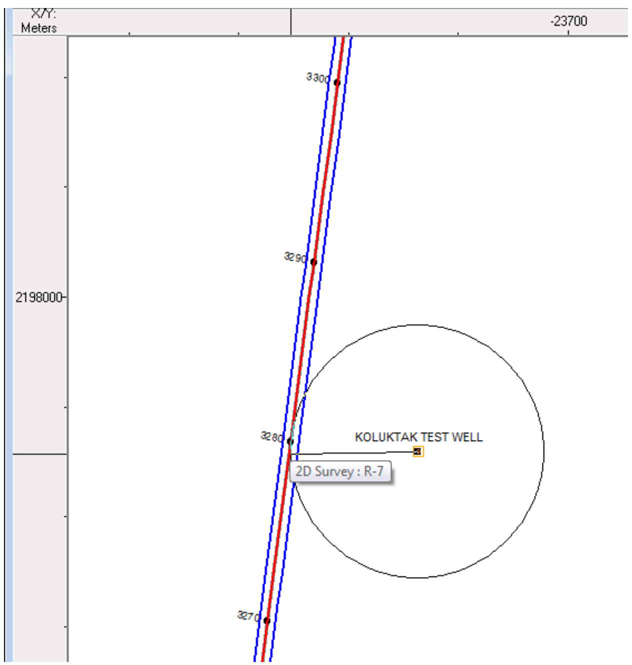


Figure A-10

Koluktak Test Well

50119200010000

- •Survey – R-7
- •Radius - 500
- •Trace (9) – Nearest trace in radius
- •Trace (11) – Average of traces in radius
- •Trace (12) – All 26 traces in radius
- •Start Velocity 12000 ft/s



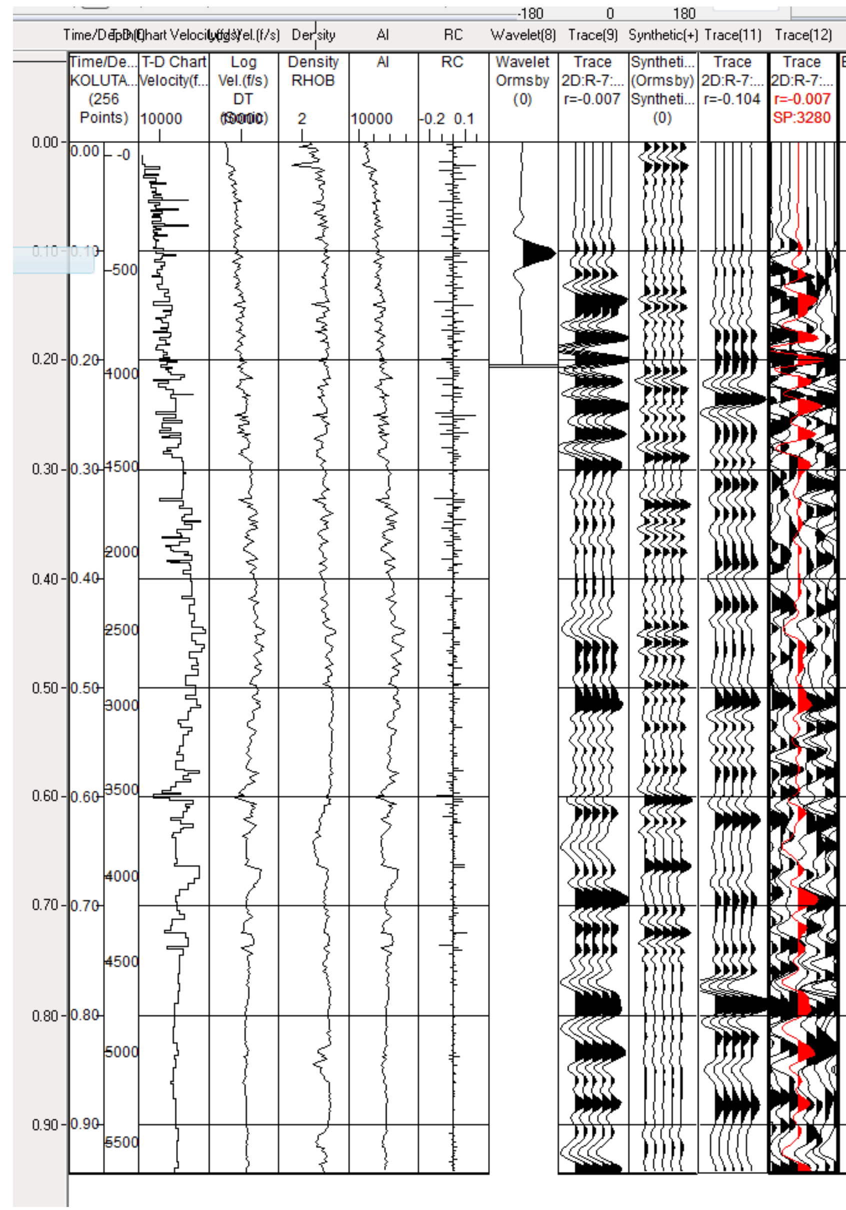


Figure A-11

Koluktak Test Well

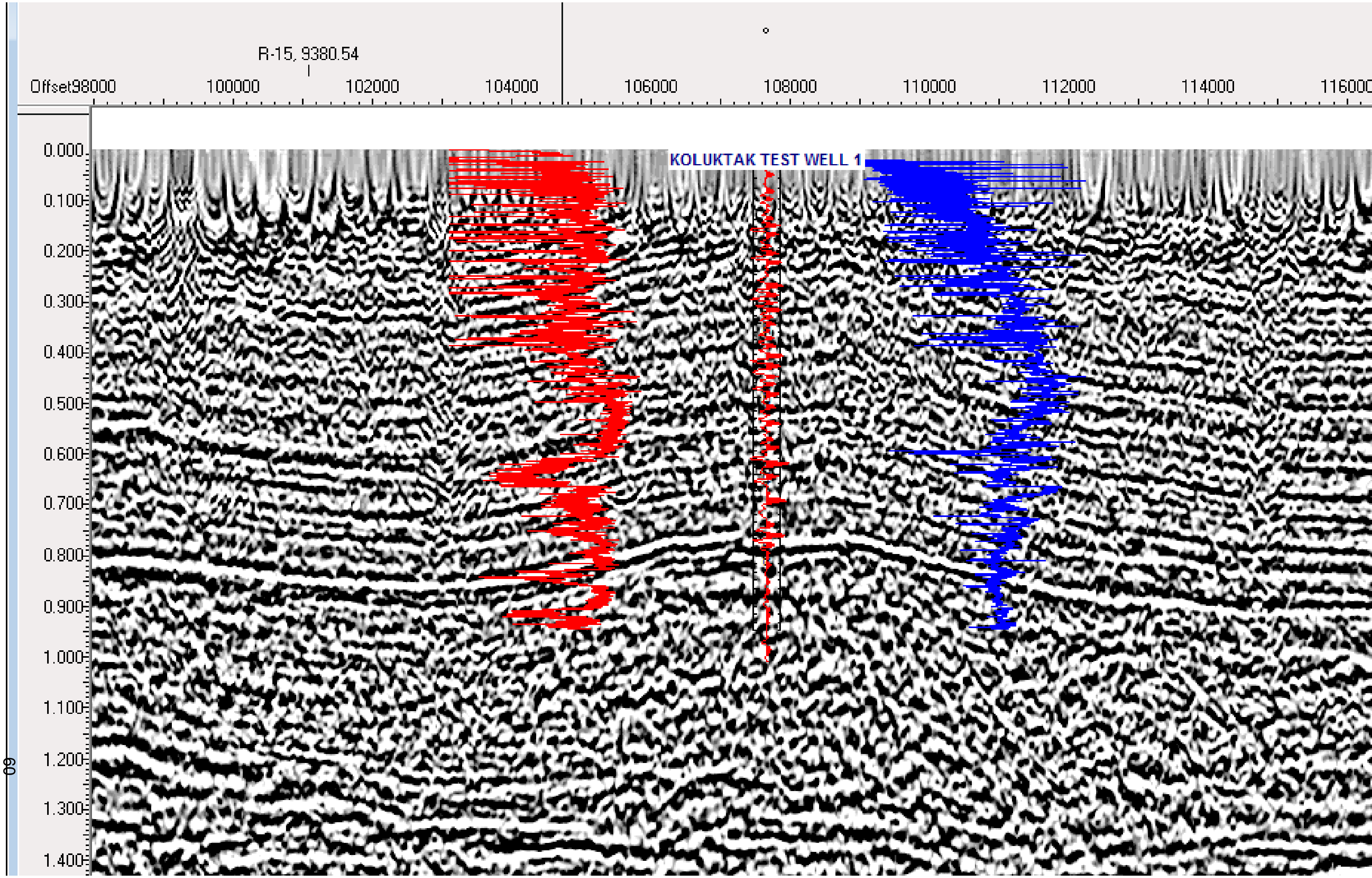
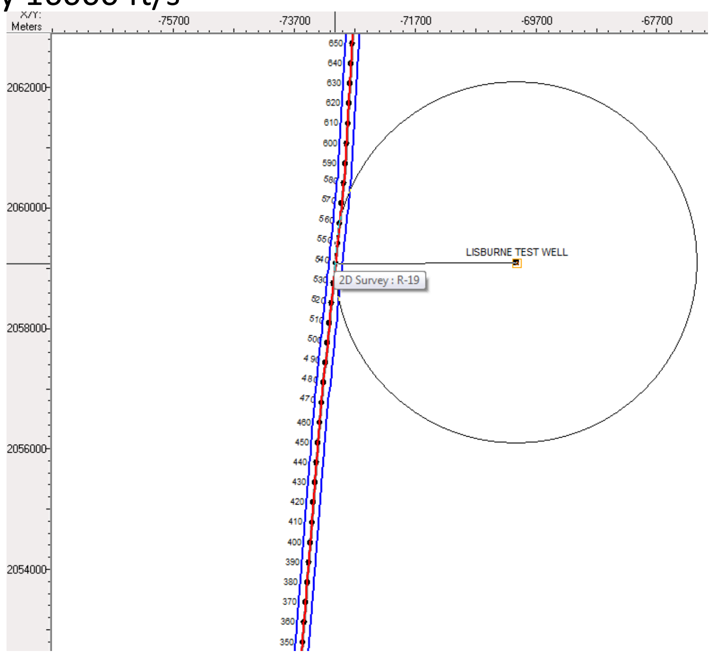


Figure A-12

Lisburne Test Well

- Line – R-19 **50137200030000**
- Radius - 3200
- Trace (9) – Nearest trace in radius
- Trace (11) – Average of traces in radius
- Trace (12) – All 62 traces in radius
- Start Velocity 16000 ft/s



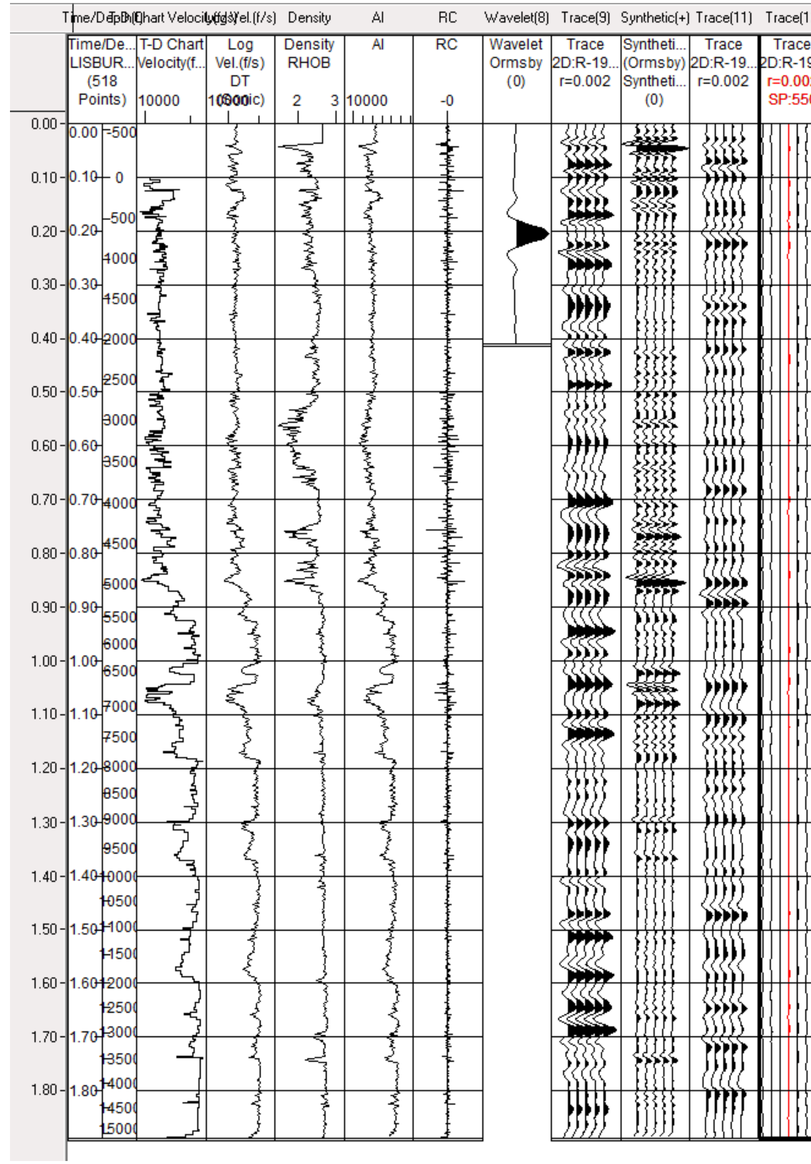


Figure A-13

Lisburne Test Well

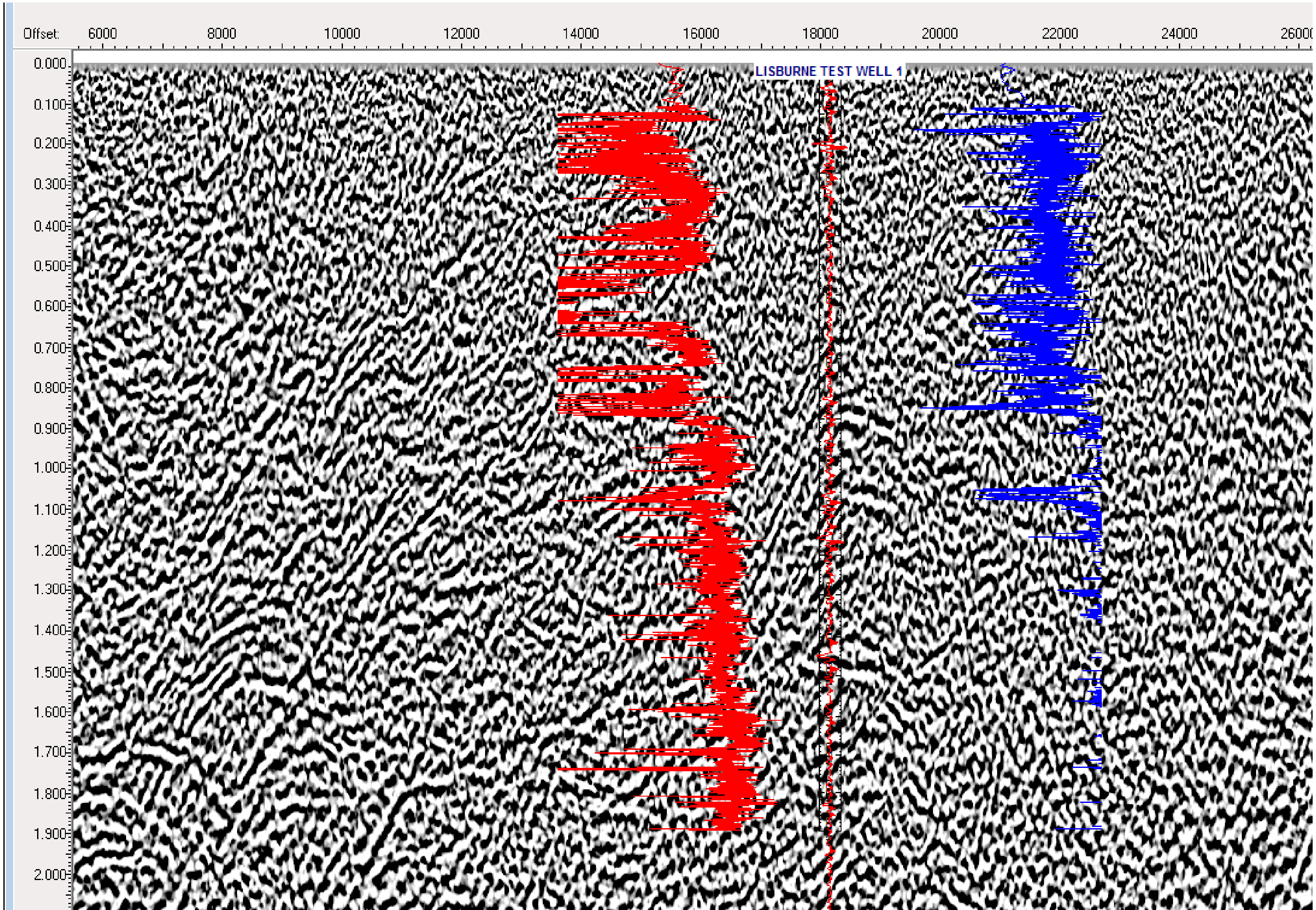
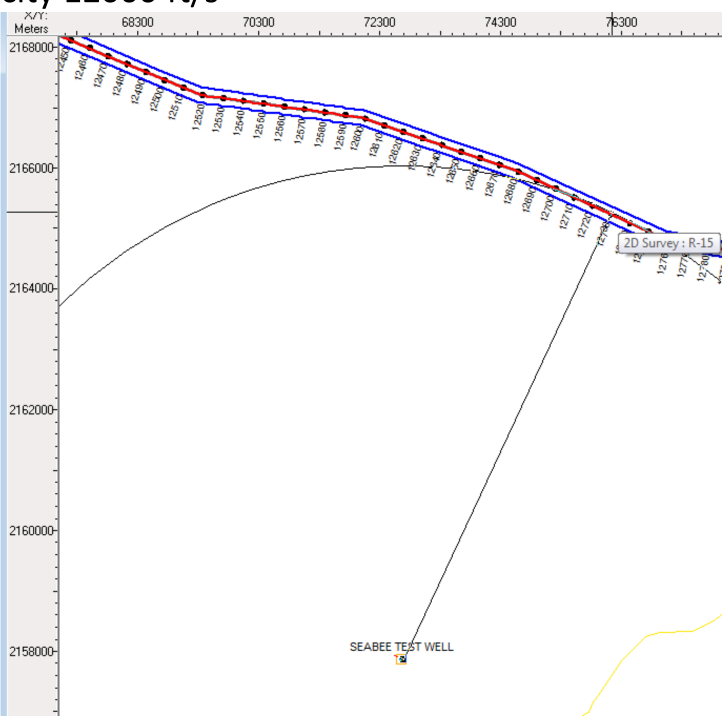


Figure A-14

Seabee

50287200070000

- Line – R-15
- Radius - 8200
- Trace (9) – Nearest trace in radius
- Trace (11) – Average of traces in radius
- Trace (12) – All 17 traces in radius
- Start Velocity 12000 ft/s



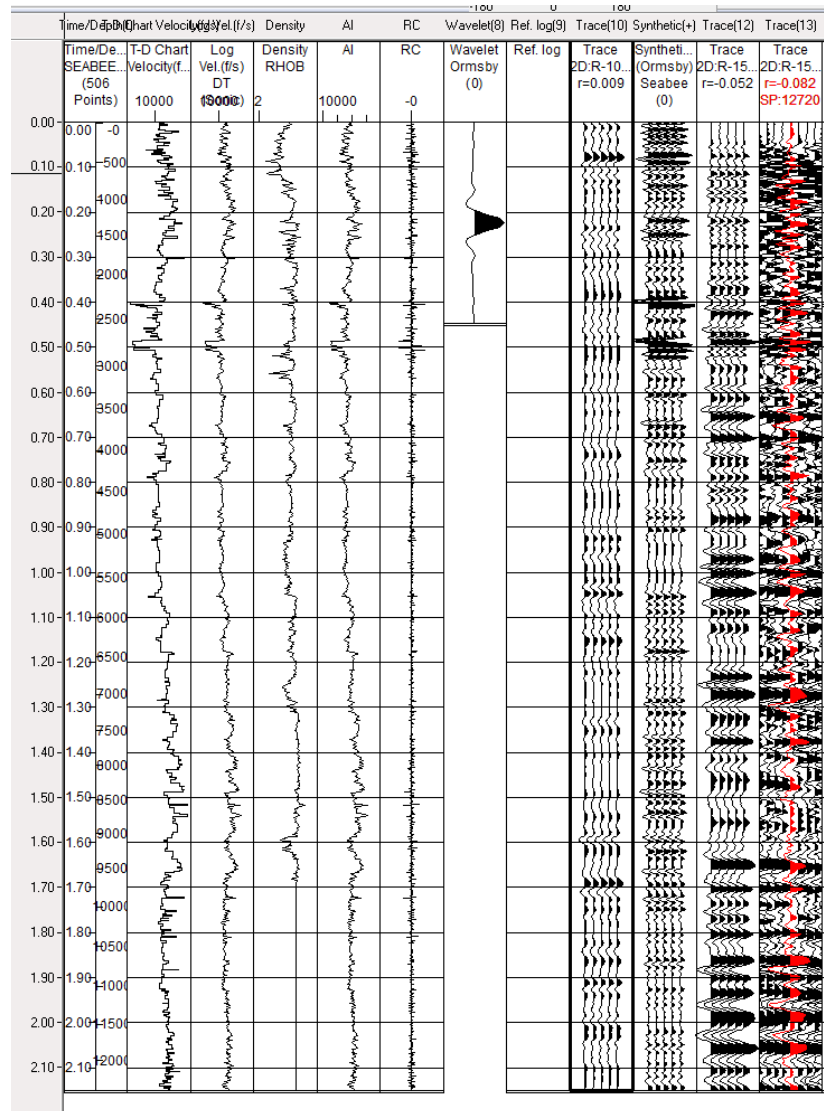


Figure A-15

Seabee

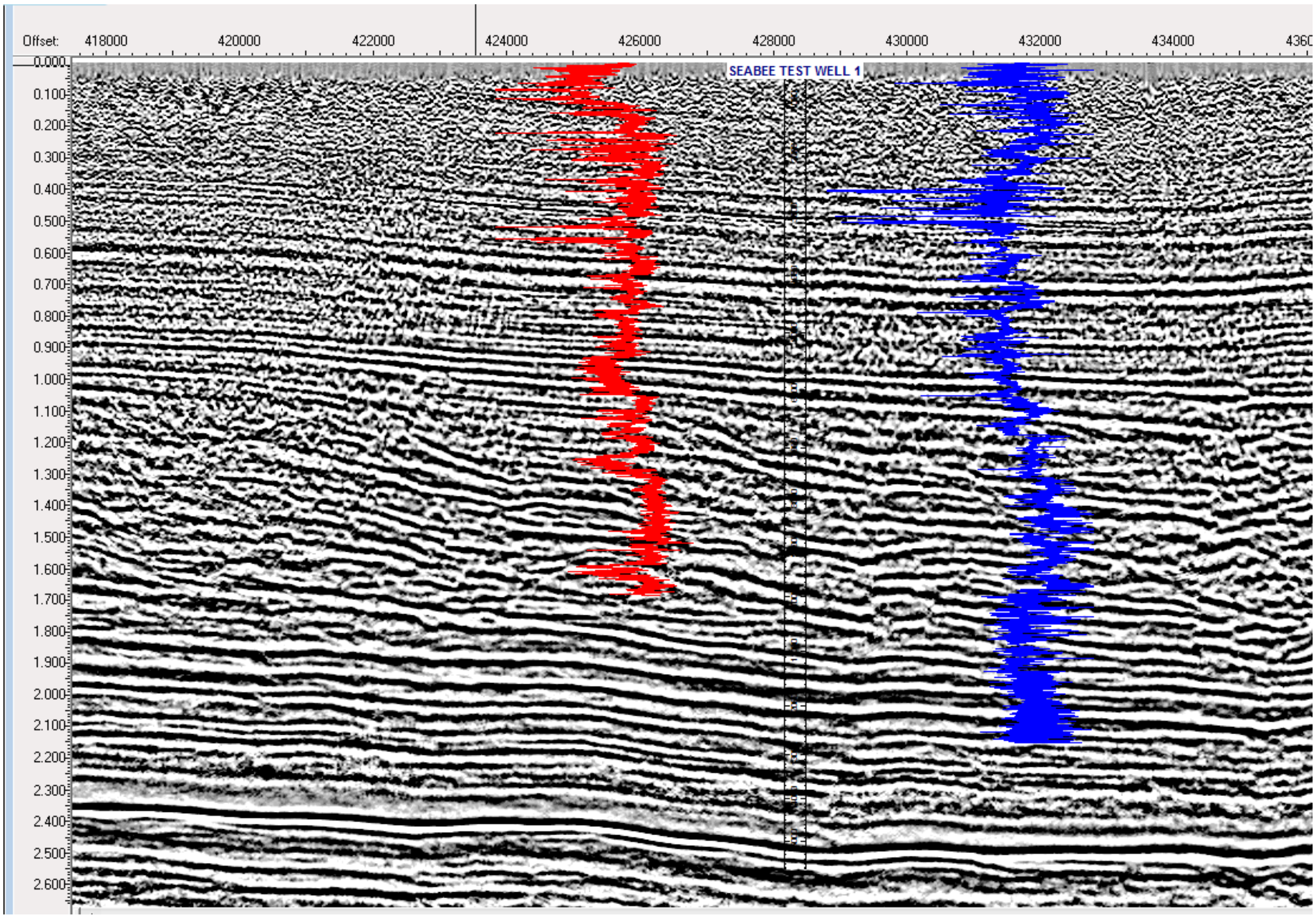
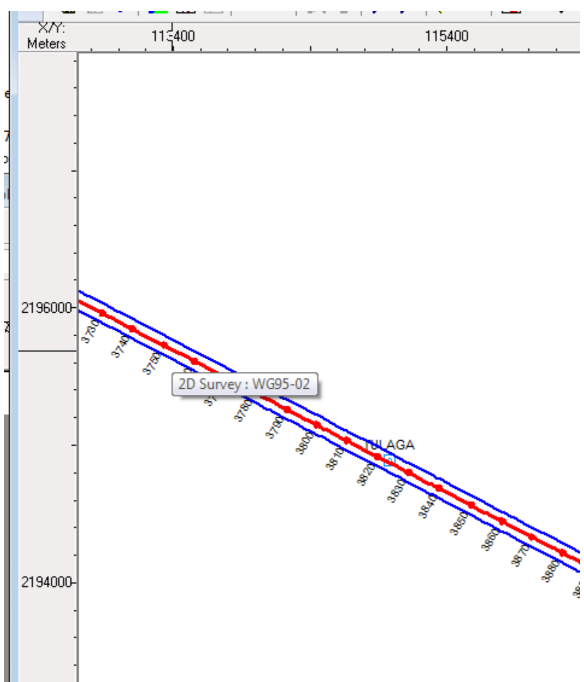


Figure A-16

Tulaga

50287200120000

- Line – WG95-02
- Radius - 200
- Trace (9) – Nearest trace in radius
- Trace (11) – Average of traces in radius
- Trace (12) – All 31 traces in radius
- Start Velocity 11000 ft/s



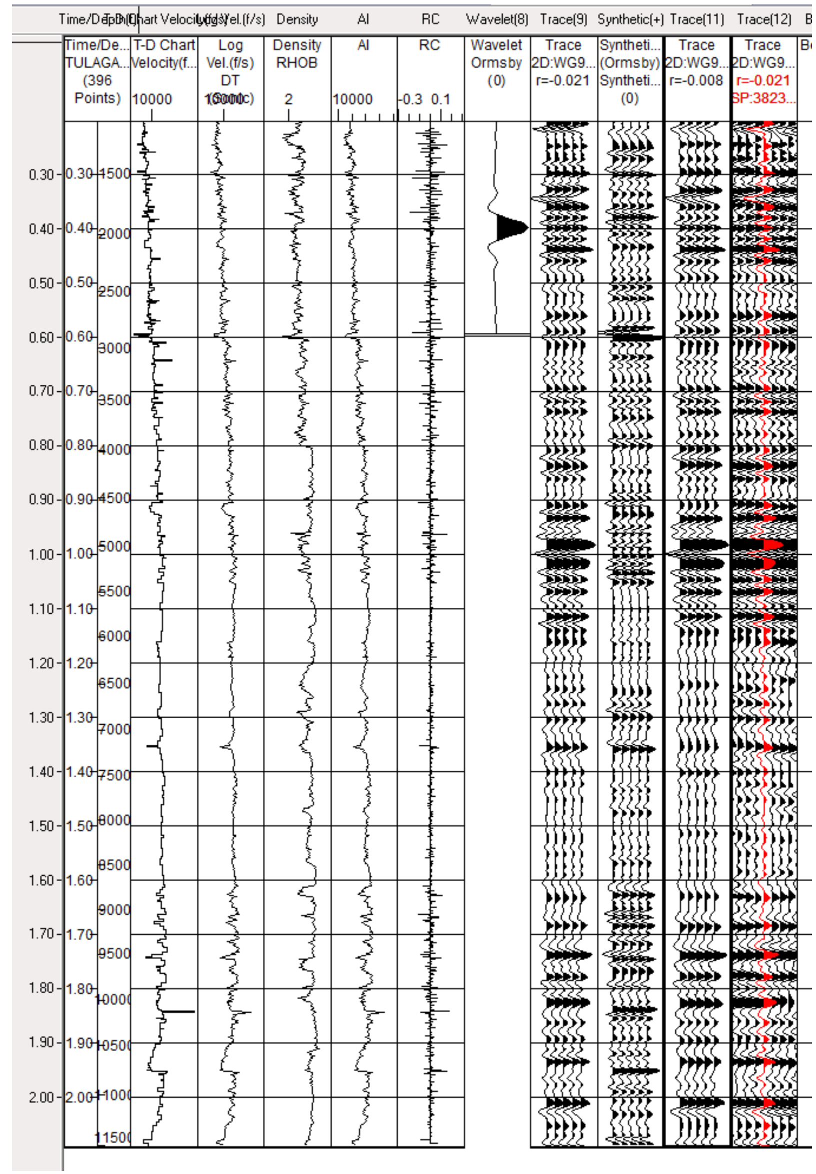


Figure A-17

Tulaga

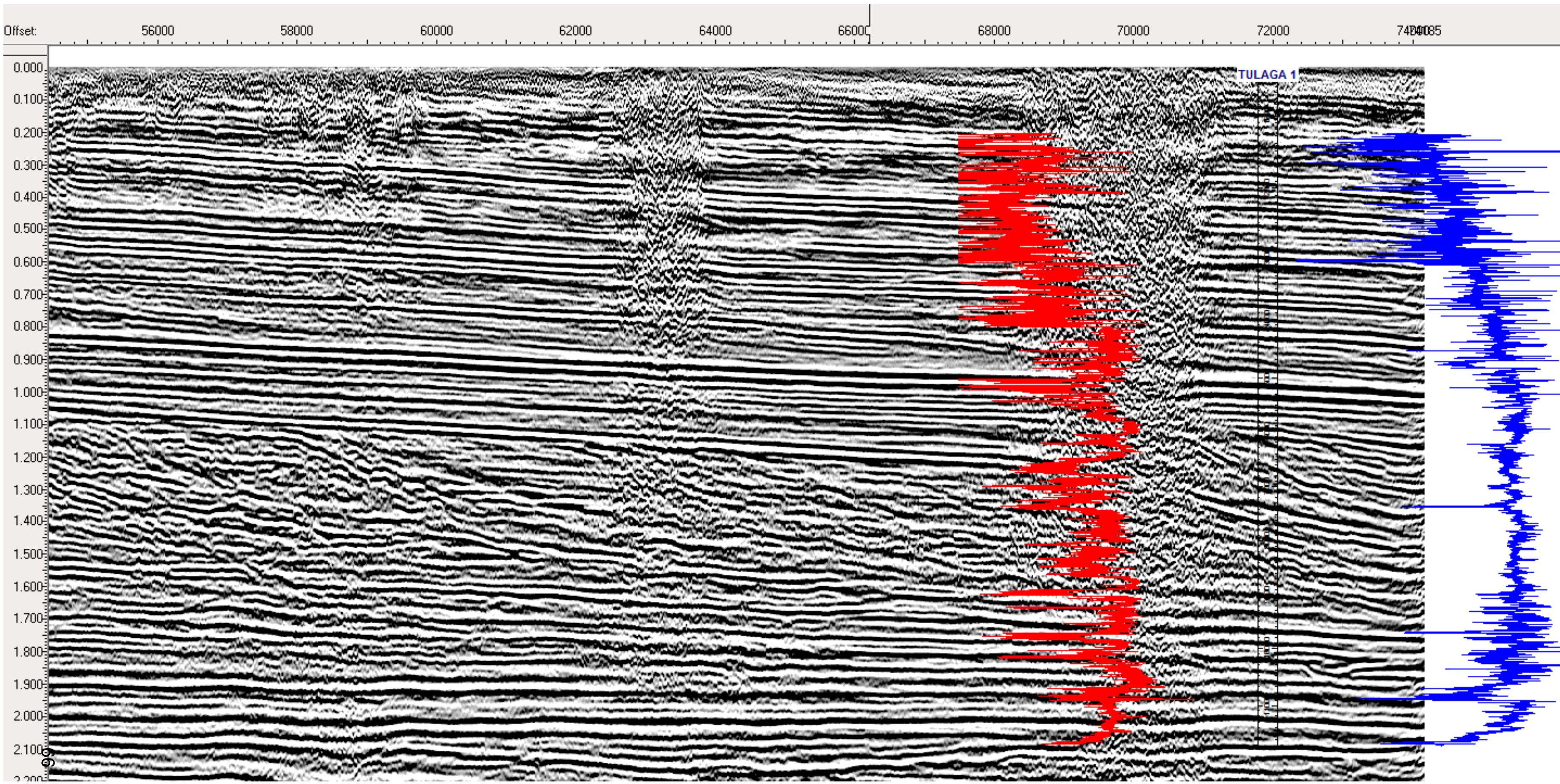
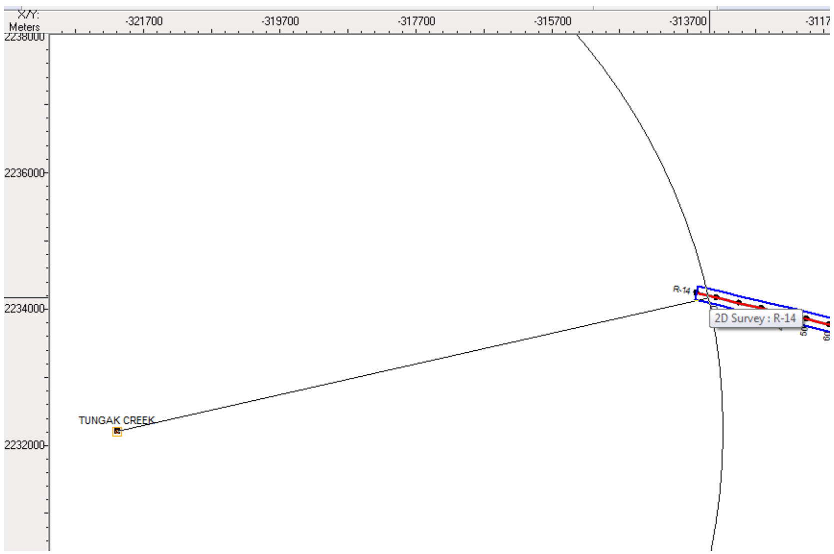


Figure A-18

Tungak Creek

50207200020000

- Line – R-14
- Radius - 9200
- Trace (9) – Nearest trace in radius
- Trace (11) – Average of traces in radius
- Trace (12) – All 9 traces in radius
- Start Velocity 11000 ft/s



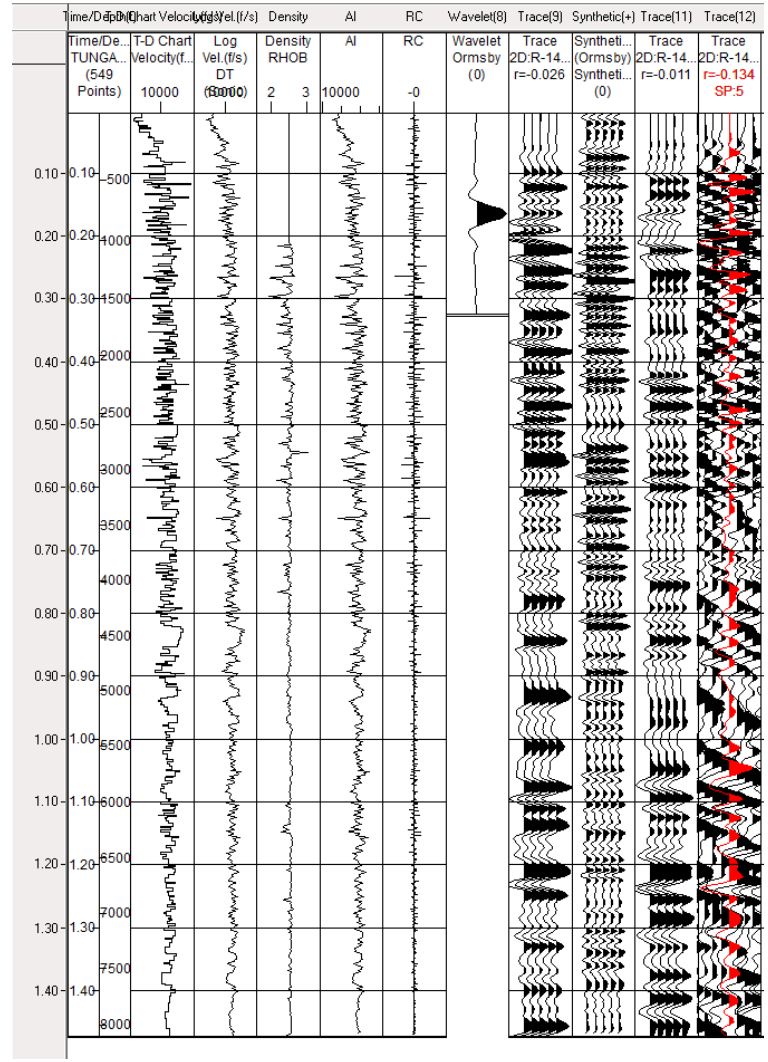


Figure A-19

Tungak Creek

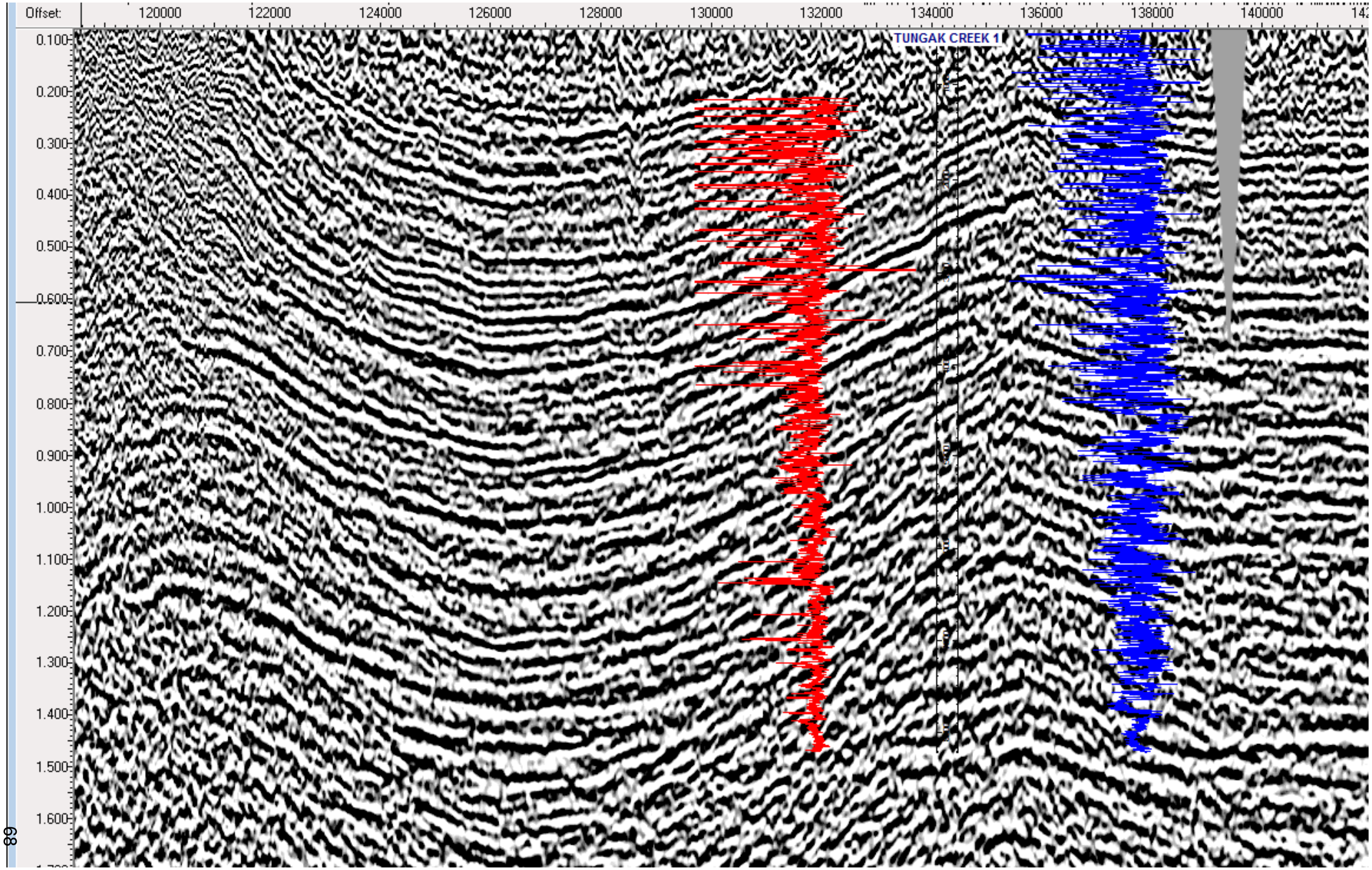


Figure A-20

West Karupa

50137200010000

- Line – R-7
- Radius - 200
- Trace (9) – Nearest trace in radius
- Trace (11) – Average of traces in radius
- Trace (12) – All 11 traces in radius
- Start Velocity 12000 ft/s

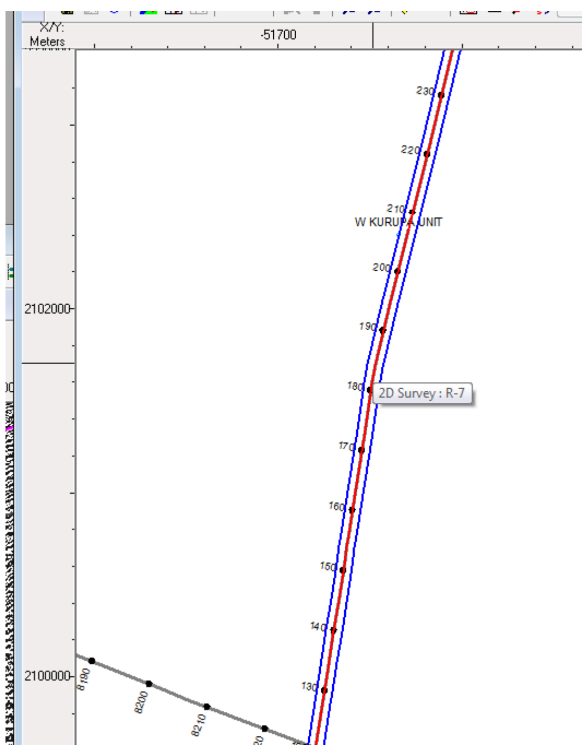
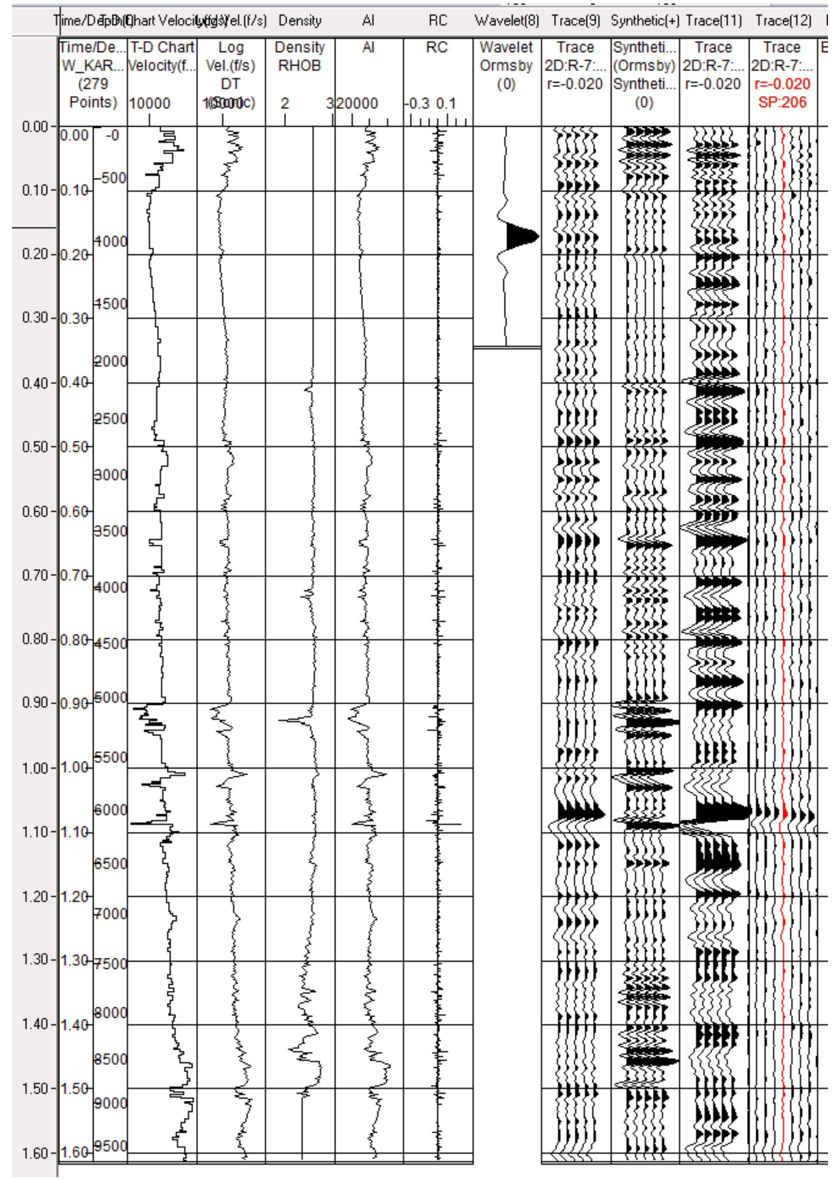


Figure A-21



West Karupa

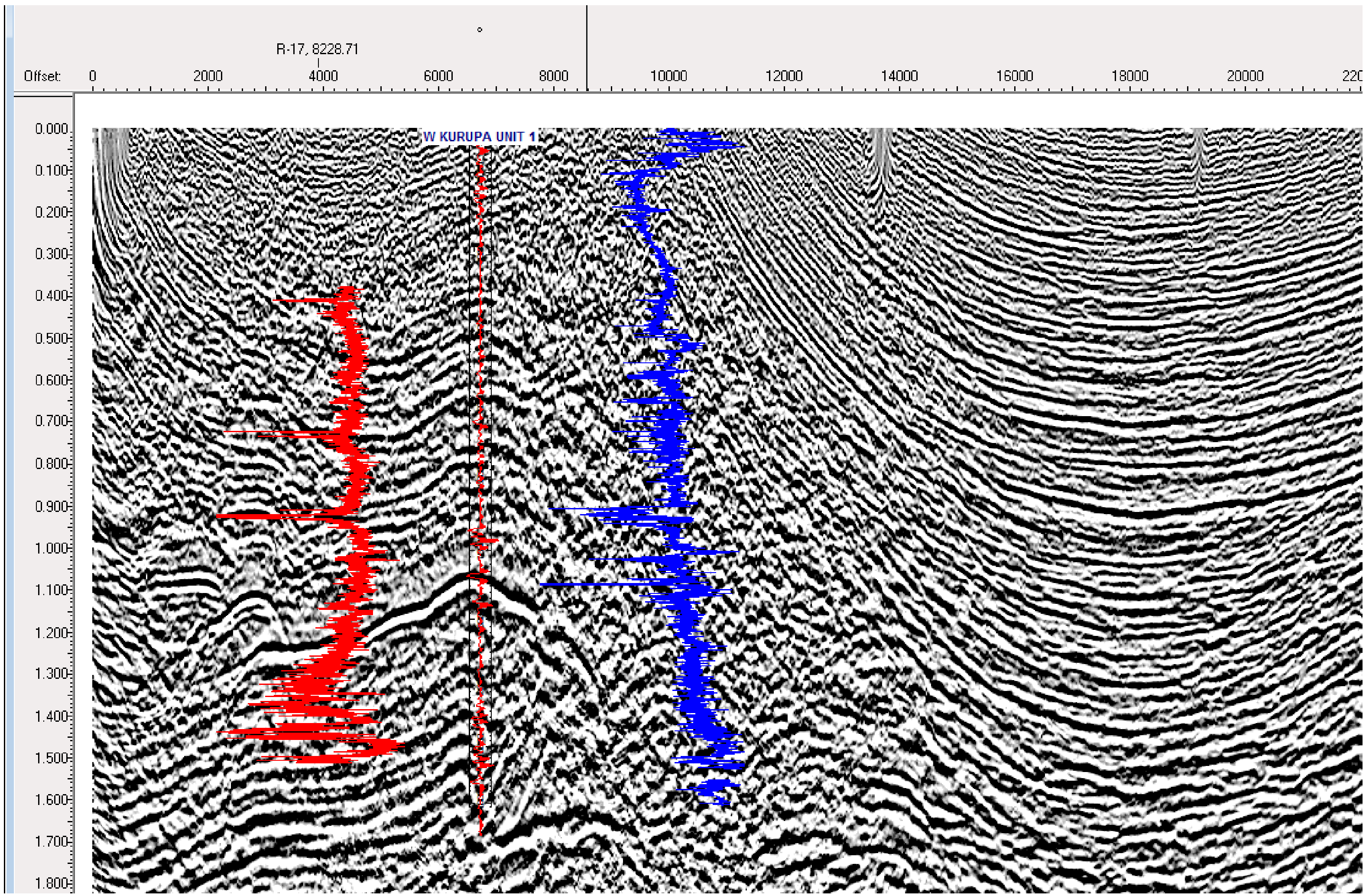


Figure A-22