Sequence Stratigraphic and Structural Interpretation, Modeling and Restoration in the National Petroleum Reserve in Alaska (NPRA)

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Undergraduate Honors Thesis in Geology

Washington and Lee University

April 12, 2013

TABLE OF CONTENTS

Abstract

This thesis examines Mesozoic progradational clinoform sequences, as well as deformation associated with the Brooks Range orogeny in the National Petroleum Reserve in Alaska (NPRA). Brookian, Beaufortian and upper Ellesmerian stratigraphic horizons were interpreted in a sequence stratigraphic framework along several thousand kilometers of 2D seismic lines in NPRA, and thrusting and resulting folding were interpreted in the foothills of the Brooks Range. An internally consistent 3D model of the region with detailed attention to both structural and sequence stratigraphic inputs was generated using seismic and well log constraints, extending from the Brooks Range foothills to approximately the Arctic coastline. The model makes use of previous interpretations of several depositional sequences in the Shublik Formation and Kingak Shale. Additionally, this model contributes refinement of stratigraphic interpretations of the significant clinoform sequences in the Torok and Nanushuk. In particular, more than ten distinct sequence packages that can be tied across 5000 line kilometers of regional seismic lines were interpreted. Structural interpretations of the faulting and deformation in the foothills of the Brooks Range were also developed, incorporating principles of fault-related folding.

We recognize progradation of the Torok shelf margin consistent with previous work, and contribute a more detailed interpretation across the NPRA with the additional clinoform sequences. Our model maps the Kingak relict shelf margin geometry prior to deformation, which controlled accommodation for subsequent deposition of the Torok and Nanushuk formations. Progradation of the Torok and Nanushuk sequences to the northeast has a

significant impact on stratigraphic interpretation in the region, as sequence layer thickness can have considerable variation through space, independent of structural deformation.

This sequence stratigraphic architecture also aids interpretation of deformed regions. For example, the positions of certain stratigraphic intervals appear to control structural deformation to a large extent. Detachments form along sequence boundaries associated with the Carbon Creek fault system, thickening in the northern foothills occurs in slope facies in the Torok, and the stratigraphic position of local detachment horizons appears to be associated with sequence boundaries, with upper detachments localized in the slope facies of the Torok Formation. We recognize buried thrusts in the northern foothills that require transport of multiple km of slip to the paleo-surface.

ACKNOWLEDGEMENTS

I would first like to acknowledge my thesis advisor, Professor Christopher Connors for his supervision of my senior honors thesis project throughout this academic year and the previous summer. I have been very fortunate throughout this time to have his guidance and input on my project, and his expert understanding of structural geology has been invaluable in the successful completion of my thesis work. This introduction to answering meaningful geologic questions has been perhaps the most valuable part of my undergraduate education, and I am very thankful to Chris for the support he provided for this project.

I would also like to thank David Houseknecht at the U.S. Geological Survey, who provided guidance and feedback on my project, based on his extensive experience with the geology of Arctic Alaska and sequence stratigraphy. Additionally, I would like to acknowledge Natalie Stier ’12, an alumna of the Washington and Lee Department of Geology for her previous and continued work in the region, which was very helpful in generating the regional structural and stratigraphic interpretation. I would also like to acknowledge Joseph Stockmeyer ’11 and Allen Frierson ’11 for their previous work in the region on their respective senior theses at Washington and Lee.

I would also like to thank the Washington and Lee Department of Geology in general for their support of me throughout my undergraduate education. The geology program at Washington and Lee is truly exceptional, and I am thankful to each of my professors, specifically Dr. Chris Connors, Dr. Paul Low, Dr. Lisa Greer, Dr. David Harbor, Dr. Jeff Rahl for helping me to grow as a scientist throughout my four years here at Washington and Lee. I would especially like to thank Dr. Paul Low for providing me with a fantastic research experience during my junior year, as well as Dr. Lisa Greer for serving as my undergraduate advisor. Thanks also to the Washington and Lee Department of Geology for their sponsorship of my attendance at the American Association of Petroleum Geologists Pacific Section Meeting in April 2013 in order to present a poster on my thesis research. Finally, I would like to acknowledge the R.E. Lee Summer Research Grant for their support of my research this summer, which was very valuable in allowing me to explore this project to a level of depth that would have been otherwise very difficult to accomplish during the academic year alone. Thanks also to Seismic Micro-Technology, Inc. and Midland Valley for providing an academic license of their software and technical support.

INTRODUCTION

Study Area: The National Petroleum Reserve in Alaska

The National Petroleum Reserve in Alaska (NPRA) (Figure 1) is a plot of land that was originally set aside by an Executive Order in 1923 for the Department of the Navy to evaluate the petroleum production potential in Arctic Alaska (Gryc, 1970). Responsibility for the region was transferred in 1977 through the National Petroleum Reserves Production Act (Public Law 94-258) to the Department of Interior, which further delegated exploration in the region to the United States Geological Survey (USGS), a bureau of the U.S. Department of Interior. Additionally the act commissioned two studies, designated as the 105b study and the 105c study, to explore the production potential and value of the NPRA lands, as well as the optimum production procedures for any petroleum there. This evaluation included a large amount of data collection over a span of 7 years from 1975-1982, resulting in the drilling of 28 exploratory wells, 10 test wells, and 23,632 line km of seismic data, including about 8,000 line km for the NPRA Regional Lines/R-Lines (Figure 2). The region encompasses approximately 95,000 km^2 of land, which though small relative to Alaska as a whole, makes up a very large region almost the size of the entire state of Virginia (see Figure 3) (Gryc, 1988).

Drilling to date in the region has not produced significant hydrocarbon discoveries and there has been no commercial drilling of wells within the NPRA, however the region is of recent interest due to the potential for leasing in the near future through a bill known as the National Petroleum Reserve Alaska Access Act (H.R. 2150), which was introduced to Congress in June of 2011. This bill would commission a new assessment by the USGS of potential fossil fuel resources within the NPRA and potentially initiate a leasing program for oil and gas exploration in the near future. The region is also of general exploration interest due to the presence of several large producing oil fields in the close vicinity, including Prudhoe Bay, Alpine Oil Field and Tarn Oil Field (Figure 1) (Montgomerey, 1998). Arctic Alaska is one of the leading sources of North American oil production, with several different source rocks and the presence of both structural and stratigraphic traps in various petroleum systems (Houseknecht and Bird, 2006). There have also been several publications suggesting that there may be large amounts of undiscovered oil, and especially gas in the Arctic Alaska, with estimates of up to 30 billion undiscovered, technically recoverable barrels of oil and 181 trillion cubic feet (TCF) of nonassociated gas (Bird and Houseknecht, 2011).

Motivation

Especially given the renewal of interest in hydrocarbon exploration in the National Petroleum Reserve, it is important to develop a regional understanding of the stratigraphy and structures in order to constrain the petroleum system elements and timing of events that can be used to characterize the prospects of a potential accumulation. These elements include the source, the reservoir, the seal, the trap and the charge, all of which can be better understood through modeling (Magoon and Dow, 1994). Regional modeling can, for example, be used to predict the source rock depositional environment, which may be used to predict rock type organic content, or the stratigraphic facies of the reservoir, for example shelf, deep water or slope, which can heavily influence the sand content of the rock.

Regional interpretation and modeling can also provide important insights into the general geologic framework of a region, which is also important from a geologic and scientific perspective. Regional interpretation of stratigraphy, for example, can demonstrate depositional trends through time, while structural interpretation can be used to better constrain the structural style of a region, for example the relationship between sequence boundaries and later thrusting. Previous studies have worked to generate large scale models of petroleum systems in this region (Schenk et al., 2012) though there has not been published regional interpretation and modeling at this level of detail that incorporates the structural complexity of the folding and faulting in the Brooks Range Foothills in a modern framework.

Sequence Stratigraphy

Sequence stratigraphy is a framework for describing the deposition of conformable successions of rock strata developed in the 1970s to describe chronostratigraphic sequences of rocks (Mitchum et al., 1977). While other methods of understanding the deposition of sedimentary rock packages tend to emphasize lithostratigraphic differences between strata, for example lithology or inferred depositional environment, the sequence stratigraphic approach argues for the use of chronostratigraphic horizons, or surfaces in time. This is very useful, first because lithostratigraphic properties can be somewhat subjective and can vary within a single depositional sequence, and also because the surfaces represent a point in time, and relative ages can be inferred from the relationships between different rock sequences (Mitchum et al., 1977). Sequences can then be further broken down into systems tracts, namely highstand systems tracts (HST), lowstand systems tracts (LST) and transgressive systems tracts (TST), which together make up the individual parts of a complete sequence (Catuneanu, 2006). Mapping of chronostratigraphic sequence boundaries can be especially useful in the interpretation of seismic data, as unconformable surfaces tend to produced relatively strong reflectors and discordant relationships between rock strata can often be easily identified in seismic survey lines and correlated across a seismic grid (Mitchum and Vail, 1977).

The geometries of deposited sequence are dependent on several different factors, primarily a result of the combination of eustatic sea level changes, tectonic subsidence, and the influx of sediment (Galloway, 1989) (Figure 4). High sediment influx, low subsidence and static sea levels, for example, tend to produce progradational clinoforms, while low sediment influx, significant tectonic subsidence and rising sea levels tend to produce transgression or retrogradation (Figure 5). While the specific geometry varies based on these depositional conditions, sequences nevertheless preserve a sense of the shelf slope geometry at time of deposition, which is consistent with modern observations of shelf slope geometries (Figure 6). The lithostratigraphic facies of a deposited rock also tends to vary based on depositional position within a sequence, with shelf facies, for example, tending to be dominated by shales or mudstones, while sands tend to be more prevalent in the shelf and deep water basin (Van Wagoner et al., 1988).

Mitchum and Vail (1977) also provide a detailed framework for identifying sequence boundaries, which proves very applicable to sequence stratigraphic interpretation in seismic data. As sequences are by definition bounded by an unconformity surface, identifying these gaps in the rock record resulting from, for example, a period of erosion or non-deposition are the key to recognizing sequence boundaries in data. These hiatal surfaces are characterized into groups based on the position of the termination relative to the rock package. First there are the unconformity surfaces at the top of a package of rock, which are further subdivided into erosional truncation and toplap, the former being an erosional surface at the top of a rock package, while the later describes where strata are cut-off updip at the top of the sequence by an erosional or nondepositional surface. The other group, discordant relationships at the base of a rock package, are subdivided into downlap and onlap, the former being an initially dipping layer terminating downdip against another surface, while the latter describes the termination of a rock layer, initially horizontal or inclined, against another surface in the updip direction (Mitchum et al., 1977) (Figure 7). These unconformity surfaces are in contrast to conformable rock strata with concordant boundaries, which represent continuous deposition rather than a depositional hiatus.

Fault-Related Folding

Fault-related folding is a theory for understanding the relationships between faulting and associated folding that can result from a variety of factors related to the growth or initiation of a fault. The main three types of fault-related folds are fault-bend folds, fault-propagation folds and detachment folds (Figure 8). Fault-bend folds are folds in a rock that result from movement along a bend in a fault, for example where a ramp meets a detachment, fault-propagation folds are folds that develop due to the growth of a fault at its tip, resulting from an actively propagating fault, and finally detachment folds are folds that result from displacement along a detachment fault with incompetent thickening in the core of the fold (Shaw et al., 2005).

Additionally, faults often form near to one another, especially in orogenic wedges, where thrust faults tend to step away from the interior of the mountain range through time, which can result in imbricated fault systems (Figure 9). Certain assumptions, such as the conservation of line length and layer thickness, allow the shapes of fault-related folds to be related to the geometry of the fault of interest in terms of the cutoff angle (θ) and interlimb angle (γ) (Suppe, 1983). These relationships can be very effectively applied to real-world fault-related folds to better understand the structural style of a region, and have been very useful in the interpretation of faulting and folding in seismic sections where these geometries are visible in cross-section (Shaw et al., 2005; Chen et al., 2005).

GEOLOGY OF THE STUDY AREA

Overview

The study area (the National Petroleum Reserve in Alaska) is located in northwestern Arctic Alaska, which is situated on what is known as the Arctic Alaskan microplate (Hubbard et al., 1987). The region has undergone a complex tectonic history, including several distinct orogenic events and significant anticlockwise rotation relative to the North American craton (Embry, 1990). The Brooks Range orogeny was initiated in the Jurassic, with sediments from the North filling the accommodation space in the foreland to form the Kingak shale during this time (Martin, 1970; Houseknecht and Bird, 2004). The Arctic microplate then rotated counter-clockwise into its current position and the Colville Basin was formed as a result of loading from the Brooks Range and rifting in the Beaufort. The Torok and Nanushuk were then deposited in the Aptian to Cenomanian, predominantly from sediments coming off the Chukotka Belt, as well as the Brooks Range, which were then deposited into shelf, slope and basin floor depositional environments (Houseknecht et al., 2009). Arctic Alaska has been divided into several physiographic provinces, including the Arctic Coastal Plain, the Northern Foothills, the Southern Foothills and the Brooks Range, all of which make up parts of the NPRA (Gryc, 1970) (Figure 10).

Shublik Formation

The Shublik Formation is a member of a Carboniferous to Lower Cretaceous package of rocks known as the Ellesmerian sequence (Parrish et al., 2001), consisting of rock ranging in composition from limestone and calcareous shale to siltstones and sandstone, as well as some phosphatic layers (Jones and Speers, 1976). Deposition of the Shublik Formation likely occurred relatively slowly in a low-energy marine environment at water depths of about 200-1000 feet, with relatively restricted circulation but sufficient nutrient levels to allow for abundant fossils (Detterman, 1970). The Shublik Formation generally ranges in thickness from about 90 to 510 feet and is continuous across the NPRA and most of the North Slope, except for some regions in northeastern Alaska and near Point Barrow. Deposition of the Shublik Formation occurred on the gently sloping shelf created by the underlying Sadlerochit Group with a sediment source located to the North providing mud to silt sized sediment, as well as some sand (Bird, 1987). The Shublik Formation is the dominant source rock for many petroleum systems in the North Slope, with geochemical analysis suggesting an organic carbon content averaging about 1.7 wt

% and a majority of the formation situated in the catagenic or metagenic stages for petroleum generation based on vitrinite reflectance data (Peters et al., 2006; Magoon and Bird, 1987).

Kingak and Pebble Shales

The Kingak Shale is a rock unit consisting largely of marine shale with some interbedded siltstone and sandstone that overlies the Shublik Formation (Houseknecht and Bird, 2004). The Kingak Shale ranges in thickness from 0 feet in the Northeast where it has been eroded away to up to 3,450 feet in the South, and is likely a contributing source rock for oil in the North Slope with an organic carbon content ranging from 0.5 to 2.0 wt % and a mixture of marine and terrestrial kerogen (Magoon and Bird, 1987; Houseknecht and Bird, 2011). The Kingak Shale is Jurassic to Lower Cretaceous in age, and is bounded by strong seismic reflectors that represent the Triassic Shublik and the Cretaceous Pebble Shale (Bird, 1987). Interpretation of seismic data from the NPRA shows a pattern of soutward downlapping clinoforms (Bird, 1987; Houseknecht and Bird, 2004), which were interpreted in much of the NPRA by a previous Washington and Lee Honors Thesis by Natalie Stier (2012). The Pebble Shale is a marine shale with interbedded sandstones that overlies the Lower Cretaceous Unconformity (LCU) surface (Schenk and Bird, 1993). The unit is about 160 to 520 feet in thickness, with a radioactive shale layer in approximately the top 100 feet of the unit, which is designated as the gamma ray zone (GRZ) due to the peak that it produces in the gamma ray curve. The Pebble Shale is another potential source rock with a relatively high average organic carbon content of 2.4 wt %, though the unit may be immature in much of the NPRA (Magoon and Bird, 1987).

Torok and Nanushuk Formations

The Aptian-Cenomanian aged Torok Formation and time equivalent deltaic Nanushuk Formation consist of moderate- to deep-water shales, siltstones and sandstones (Weimer, 1987). The slope and deep-water facies were likely deposited at depths of at least 1,000 feet and formation as a whole ranges in thickness from 1,200 feet to up to 20,000 feet in the Colville trough (Bird, 1987). The organic carbon content of the Torok is relatively low, averaging 1.2 wt %, and the Torok trends towards terrestrial (type III) kerogen, though the thermal maturity as per the vitrinite reflectance suggests that it is mature enough in some locations to generate hydrocarbons, though it is likely dominated by gas production along with some potential for oil (Magoon and Bird, 1987). The Torok Formation is the fine-grained marine slope and basin floor facies that is age equivalent to the Nanushuk Formation, which is composed primarily of shallow marine sandstone (Bird, 1987). The Torok and the Nanushuk have been identified as deposited through several phases of deposition, including regression, transgression, aggradation and progradation (Houseknecht and Schenk, 2001), with the later producing significant eastward migration of the Torok shelf margin.

METHODS

Data

The evaluation of petroleum potential in the National Petroleum Reserve in Alaska produced large amounts of public domain data from the USGS, from which a subset of seismic lines and wells were selected for analysis and interpretation for this study (Miller et al., 2000). The project contains over 200,000 line kilometers of 2D seismic data, and 746 wells, with over

5,000 line km of seismic data interpreted within the NPRA and a subset of 272 wells used for formation top correlations and the generation of the velocity model (Figure 12). Formation tops from wells demark lithostratigraphic unit tops from Ken Bird of the US Geological Survey, and were correlated to the seismic data for stratigraphic interpretation. Time to depth functions for several wells were also generated previously by another Washington and Lee thesis (Stier, 2012).

Stratigraphic Interpretation

Seismic reflectors are the product of impedence contrasts between rock layers (Badley, 1985) (Figure 13), which makes seismic imaging a valuable tool for mapping rock layers and the unconformity surfaces that bound stratigraphic sequences. Seismic interpretation is especially considered to be a reliable indicator of paleotopographic surfaces for the Albian Torok Formation and Nanushuk Group due to minimal tectonic deformation in the Coastal Plain after the Cretaceous (Tetzlaff and Harbaugh, 2011). Lithostratigraphic formation tops that were previously picked by the USGS through well data were used to correlate formation tops to the seismic data (Figure 14). The horizons were then mapped across each of the lines to generate an internally consistent interpretation with reliable ties between seismic line intersections (Figure 15). The Shublik Formation top and the main sequences of the Kingak Shale were interpreted in a previous study of the region (Stier, 2012), and these horizons were incorporated into subsequent modeling work presented here. This study also contributes the mapping of a Pebble Shale formation top across the NPRA, along with the Torok Formation, and

Nanushuk groups, which were further divided into several sequences, which were identified based on the framework laid out by Mitchum and Vail (1977).

Sequences in the Torok and Nanushuk are identified in this project based on downlap observed through cutoffs in the seismic data (Figure 7). The Torok Formation and the Nanushuk Group were not differentiated for the purposes of this mapping, as the distinction tends to rely on lithostratigraphic distinctions between the two rock units, while sequence stratigraphic mapping relies on chronostratigraphic surfaces. These lithostratigraphic differences involve the composition and grain size of the deposited rock, with the label of Nanushuk generally being used to describe the shelf facies, which are predominantly sands, and Torok being used to describe the slope facies, which are dominated by shales. The Torok/Nanushuk was then subdivided into eleven mapped sequences (Figure 15), which may not account for all sequences within this section but is sufficient to identify the important depositional trends. The geometries of the sequences indicate that they are progradational clinoforms, which suggests relatively high sediment influx in relation to the magnitude of relative sea level change. Progradation of the Torok and Nanushuk occurs in an East to West orientation, in contrast to Kingak progradation, which was largely in a North to South orientation (Houseknecht and Bird, 2008; Stier, 2012).

Mapping of the Torok and Nanushuk across the NPRA allows for a clearer understanding of the change in position of the shelf margin through time. By identifying the break between the shelf and the slope in 2D lines as well as in grids of the horizons across the NPRA, the shelf margin for each identified sequence was mapped in space to show the relative positions of the shelf margin between sequences. Consistent with progradational deposition, the Torok/Nanushuk shelf margins steps eastward between sequences, which is easily observed through isochron maps between Torok horizons, which clearly highlight the thick package of sediment represented by the slope sediments (Figures 16-18). These isochron maps were generated by gridding of the mapped horizons at a 5 km grid spacing to generate a structure contour map (Figure 19), and performing simple math between two horizons to measure the thickness of each sequence. There is also some complexity in the geometry of the shelf margin, with the margin tending to curve towards the East near the southern quarter of the NPRA (Figure 20). These findings of the general position and trends in the shelf margin through time are consistent with previous studies of the region (Houseknecht et al., 2009).

Structural Interpretation

Structures of the NPRA were interpreted using a fault-related folding framework, which is generally very appropriate for the contractional structures observed in this region. Previous structural interpretation was done for much of the Brooks Range foothills-related deformation in the Kingak shale strata, especially involving the Carbon Creek anticline (Moore and Potter, 2003; Stier, 2012). Previous work found the region of the Brooks Range foothills to be dominated by thin-skinned deformation with displacement resolved along a master detachment in the lower Kingak sequences and Shublik (Moore et al., 2004). The structures interpreted in this study are consistent with and make use of these findings, additionally contributing to the structural interpretation of the younger strata, particularly the Torok/Nanushuk horizons.

Faulting in the Torok and Nanushuk horizons is dominated by thrust faulting and detachment faulting, with weaker detachments forming in some of the younger strata. Faulting appears to step up from the lower detachment observed in the Kingak into Torok detachments towards the North, which tend to discretely step up with increasing distance away from the Brooks Range foothills (Figure 21). Fault-related folding is common in conjunction with faulting, especially with fault-bend folding occurring at anticlinal and synclinal bends occurring between a ramp into a detachment horizon and detachment folding occurring above a detachment that is consuming slip due to incompetence in the overlying rock layers.

Structrual style is heavily influenced by the relationship between the shelf-slope geometry against the primary direction of contraction. For faulting in the Torok horizons, contraction is largely oriented in a North-South direction, while primary stratigraphic thickening due to clinoformal geometries occurs locally in an East-West orientation. This is a challenge for structural interpretation in that rules such as conservation of layer thickness do not always apply, as thickening occurs in the slope facies (Figure 22). This interplay also exerts an influence on the formation of detachments in these upper horizons, with upper detachments tending to form in the Torok slope facies (Figure 23). Slope deposition tends to be composed of weaker shales rather than sandstones (Catuneanu, 2006), which tend to be more resistant to deformation, so this occurrence makes sense from a lithologic standpoint.

Velocity Modeling and Depth Conversion

While the horizons and faults mapped across the NPRA are a useful first-step in understanding the geological history and modern architecture of this region, the seismic data is recorded in time on the vertical access, meaning that the horizons and faults are also mapped in time rather than depth. Depth horizons and faults are essential to the generation of a useful 3D model, so all horizons were depth converted using the Dynamic Depth Conversion tool available in the SMT Kingdom software suite (see Appendix A). The process makes use of Time to Depth functions, which were previously generated to display formation tops on the seismic data (Stier, 2012), as well as the mapped horizon positions. Ties between the two are then used to create a velocity model, in which velocity is predicted for a 3D region of interest. This velocity model was then used to convert time horizons into depth (Figure 24) based on the simple relationship between velocity, distance and time.

3D Model Building

The regional interpretation of horizons and faults across the NPRA was then used to create 3D surfaces for each of the horizons using a gridding algorithm in the SMT Kingdom software package. A 3D model was first generated from the interpreted depth-converted horizons within the NPRA bounds (Figure 25). Grids of each of the horizons were then generated with a 5 km cell size using a convex hull of horizon data, which were then loaded into the 3D modeling environment Midland Valley Move (Figure 26). 3D modeling allows for the visualization of the horizon lines and surfaces in 3D space, which is very useful for the understanding of geologic structures and depositional systems, which by nature are in 3D space.

The complete 3D model shows a carefully constructed interpretation of the modern positions of the rock strata in the NPRA from the Shublik up to the Torok. Individual packages of rocks can also be examined in the 3D environment, showing for example, the North-South progradation of Kingak clinoforms onto the top of the Shublik Formation (Figure 27) and the East-West progradation of Torok/Nanushuk clinoforms onto the Pebble Shale drape surface (Figure 28). As surfaces show the present day positions of rock strata, some of the upper sequences of the Torok are not present in the central part of the NPRA, as shown in the gaps in the model (Figure 28), resulting from post-depositional erosion of these layers.

DISCUSSION

Progradation of Torok Clinoforms

Stratigraphic interpretation of the Torok and Nanushuk clinoforms shows clear eastward progradation of the sequences through time. Accomodation space for the Torok and Nanushuk was generated from the space created by the Kingak ultimate shelf margin (Houseknecht and Bird, 2006), as well as the foreland basin resulting from Tectonic loading to the south from the ancestral Brooks Range (Nunn et al., 1987). The Torok is deposited over the Pebble Shale/Gamma Ray Zone (GRZ) drape layer, which resulted from a continuous sediment drape across the region due to a sea level high (Figure 28- A). Progradation then continues eastward with large clinoform sequences filling the accommodation space generated by the Kingak shelf margin and the foreland of the ancestral Brooks Range. These large clinoform sequences suggest relatively high sediment influx and low tectonic subsidence during the time of deposition. Top Torok layers continue this pattern of depositon, though erosion has taken off much of these upper Torok layers in the central NPRA due to slight uplift.

Structural Style

Previous structural interpretation in the Kingak Shale of this region has shown thrust faulting near the foothills of the western Brooks Range, transferring displacement along a master detachment located in a weak shale section composed of compressed Shublik, Kingak Shale and Pebble Shale (Stier, 2012). Faulting in the upper strata, which consist largely of the Torok Formation and Nanushuk Group, makes use of some relatively smaller upper detachments, which step up towards the North (Figure 21). Structural interpretation is made somewhat more complicated by the localized tectonic thickening in the Torok horizons that occurs in some sequences near the deformed Foothills region. Strike lines clearly show this stratigraphic thickening that results from the transition from the thinning shelf facies into the thicker slope facies, and dip lines show the detachment folding and resulting tectonic thickening (Figures 22 and 23). This thickening exerts some control on the faulting in the region, with detachments tending to form in the weaker slope facies (Figure 21 and Figure 22).

CONCLUSIONS

Sequence Stratigraphic interpretation of the rock strata of the National Petroleum Reserve in Alaska show significant clinoform progradation in the Torok and Nanushuk sequences, suggesting high sediment supply at the time of deposition. The shelf margin generally progrades eastward through time, crossing most of the NPRA (Figure 20). The shelf margin also shows some complexity in its geometry with some bending towards the East near the base of the NPRA, especially for the top Torok sequences, which is likely the result of primary deposition rather than structural deformation. Structural interpretation is consistent with typical fold and thrust belt deformation. Fault-related folding is commonly observed, especially fault-bend folds associated with transitions between thrust faults and detachment faults. Detachments tend to be localized in weaker shale layers, with the lower detachment occurring in a condensed shale section composed of the Shublik Formation, the Kingak Shale and the Pebble Shale. Upper detachments are commonly observed in the Torok slope facies, also represented a more shale dominated lithology, resulting in a stepping up of the detachment as deformation moves northward.

Future Work

Future work in this region could involve restoration of 2D cross sections and 3D models. This would involve the undoing of structural deformation, specifically faulting, folding and the flexural response to loading; the backstripping of depositional sequences; and the decompaction of rock strata to account for burial compaction. This model could also be used in the future for basin modeling work, to for example understand the thermal maturity of these rocks or potential migration routes. Additionally, future work could involve the connection of the interpretation here to interpretations in adjacent regions of Arctic Alaska, such as the Chukchi and the Alaska State Lands in order to generate a larger regional interpretation of this area.

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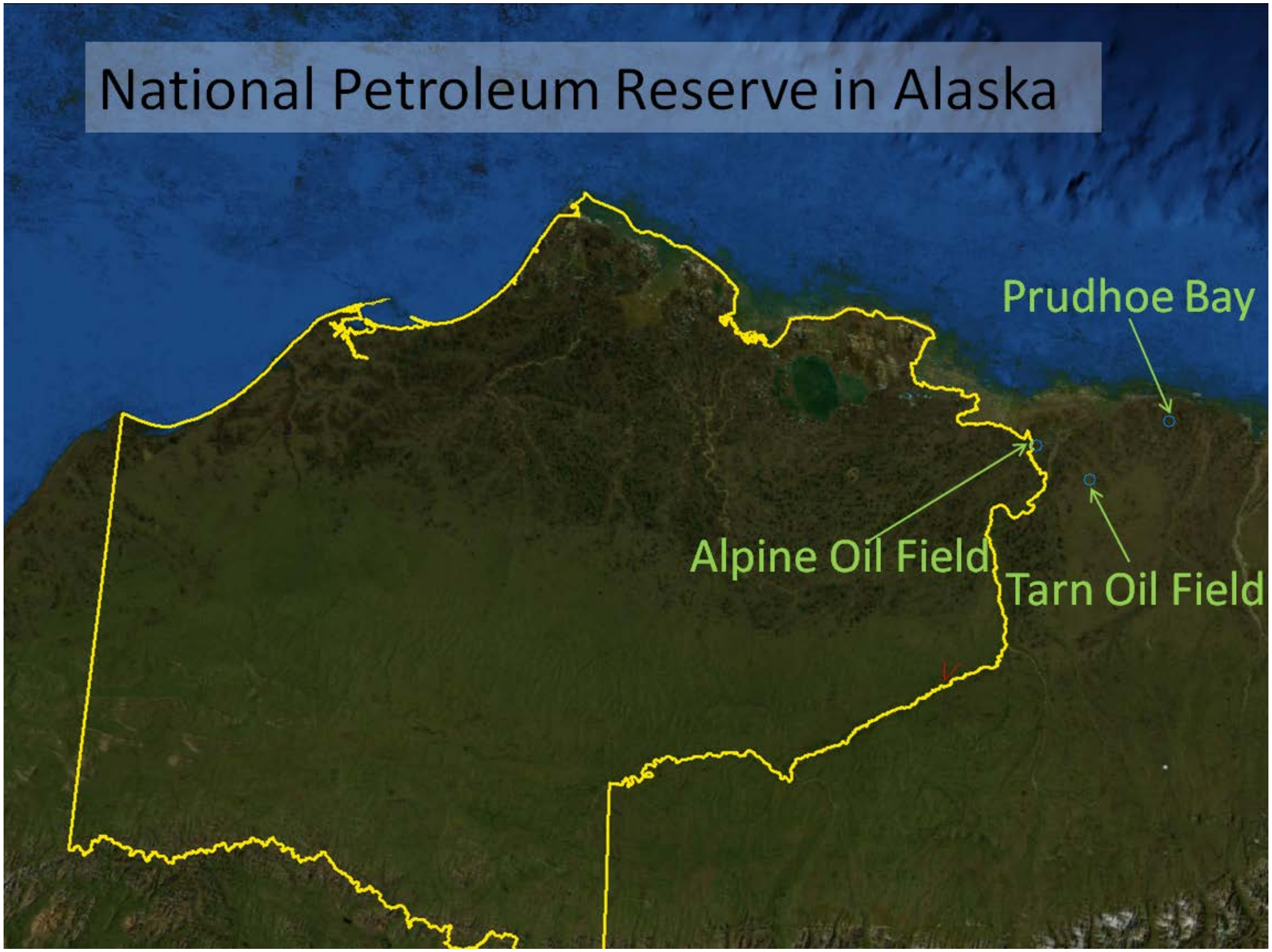


Figure 1. The boundaries of the National Petroleum Reserve in Alaska in yellow overlain on a Blue Marble image. Three major producing oil fields in the region are highlighted by blue circles.

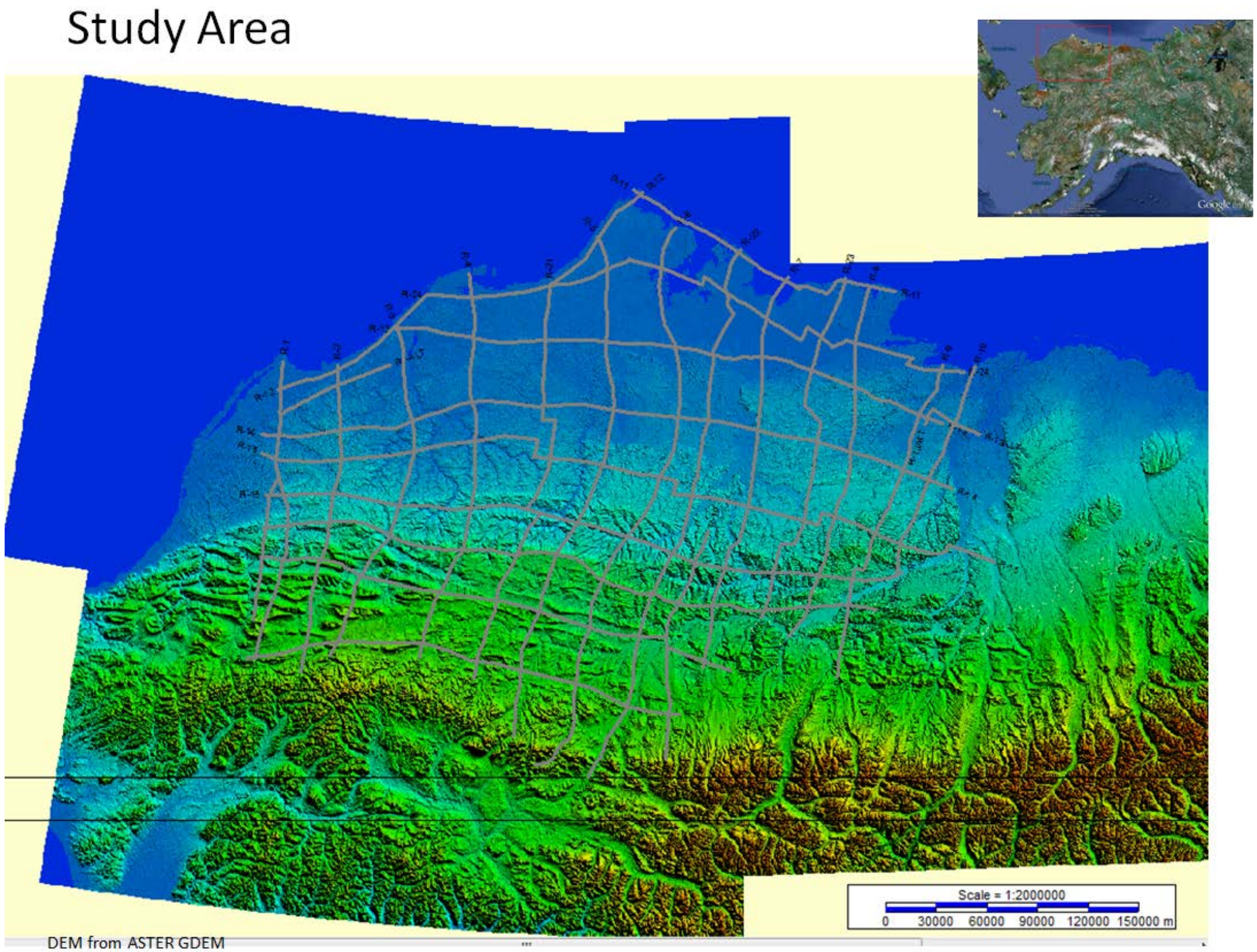
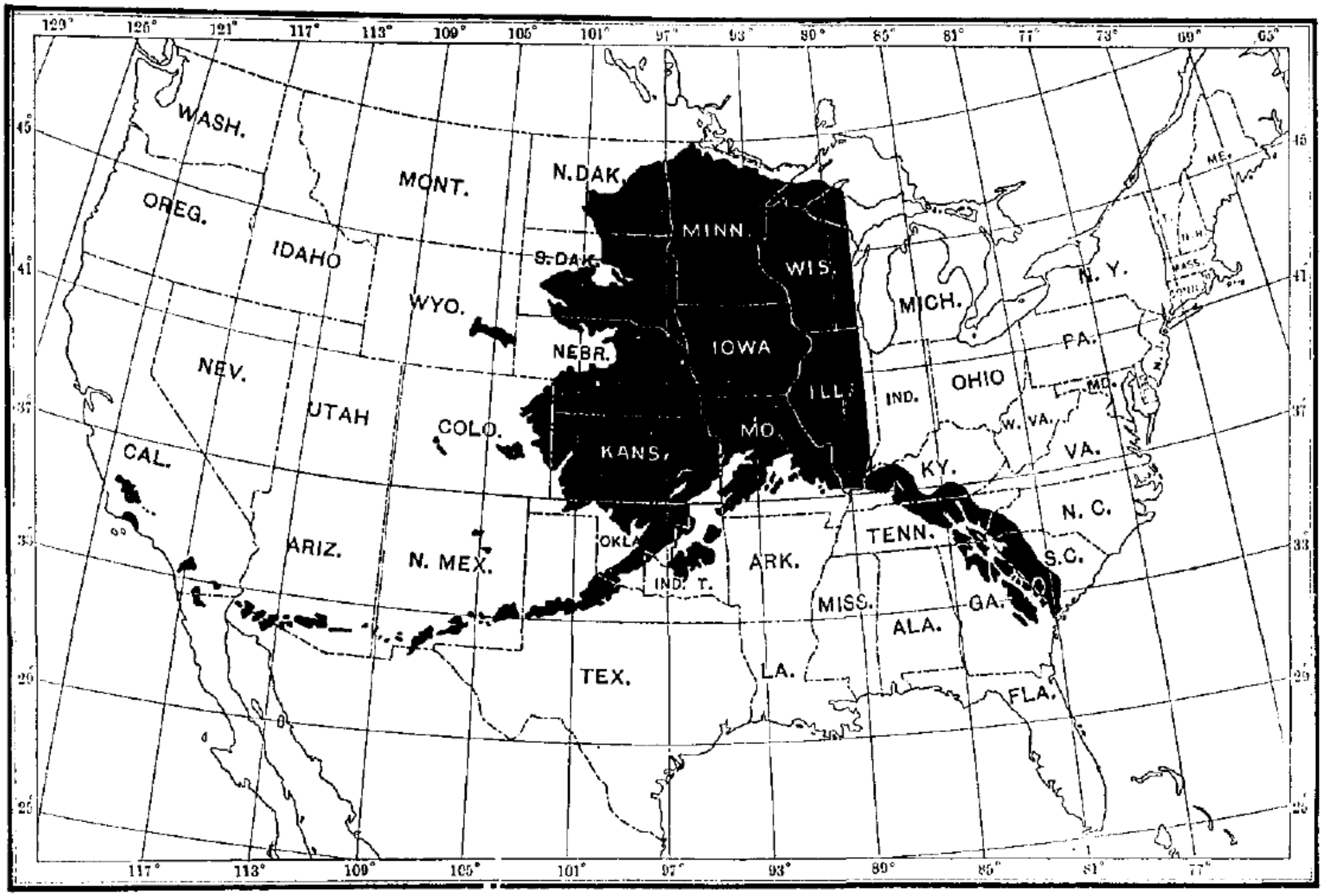


Figure 2. The NPRA Regional Lines (R-Lines) over an ASTER Global Digital Elevation model, with inset showing position of region relative to surrounding region in Google Earth.



From A. H. Brooks, 1906

Figure 3. Size of Alaska relative to the continental United States for scale. From Gryc, 1970

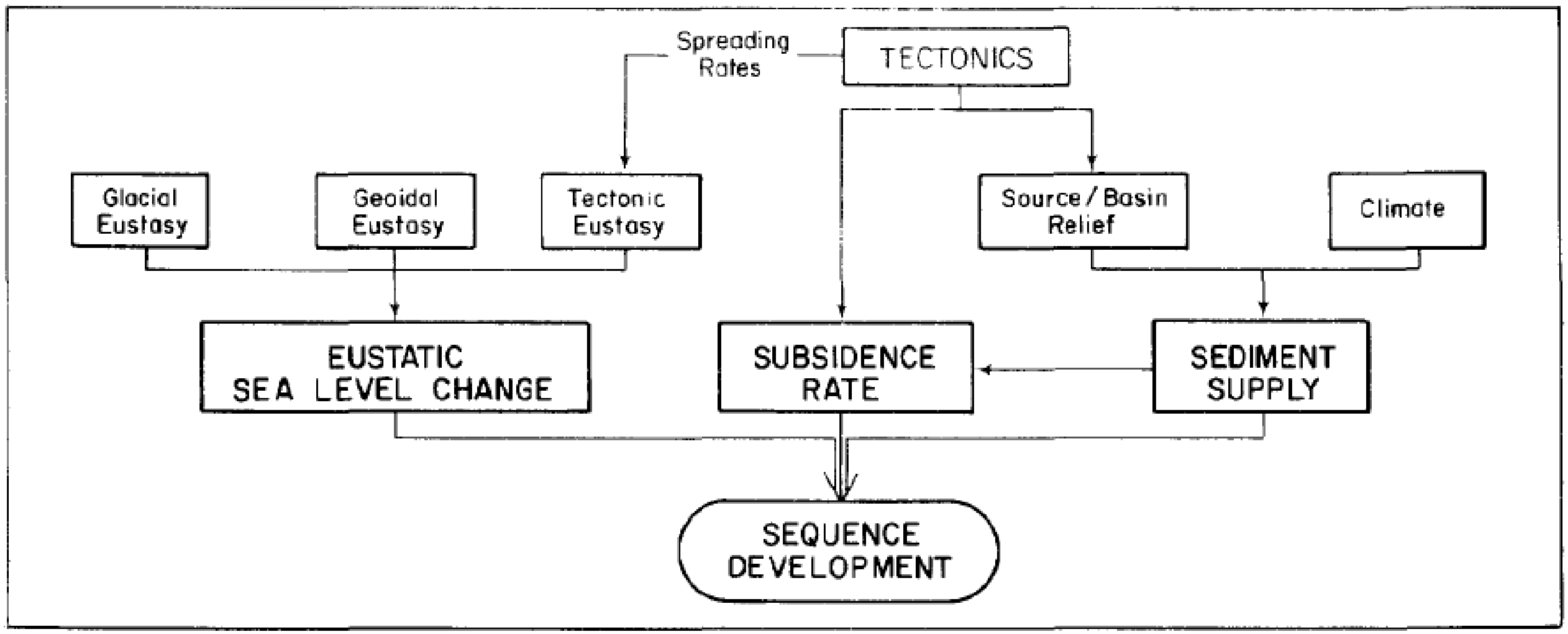


Figure 4. The various factors, and combinations thereof, that go into the development of a depositional sequence. From Galloway, 1989.

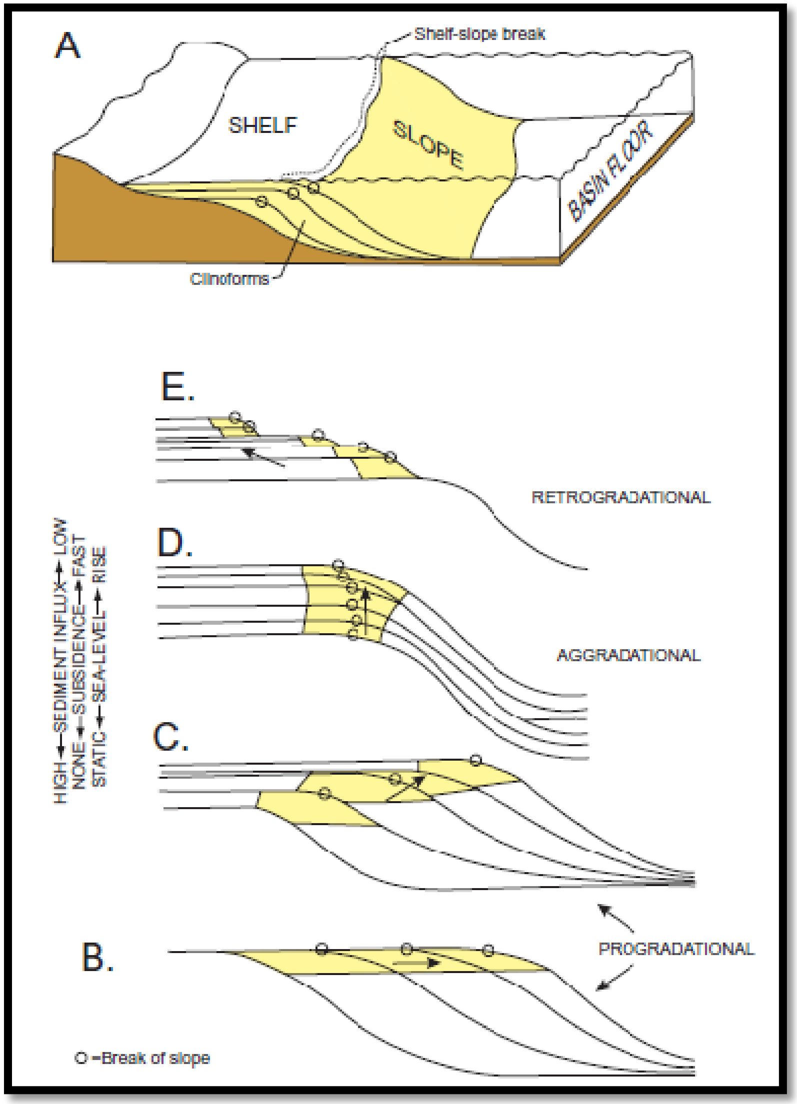


Figure 5. Modified from Galloway (1989) and from Emery and Myers (1996).

Figure 6. Modern shelf-slope geometry observed through seismic data off the coast of Alaska with transition from left to right throught the shelf to shelf-slope break to slope to the deep water basin. Position of seismic line relative to the NPRA displayed in red in the lower Blue Marble image.

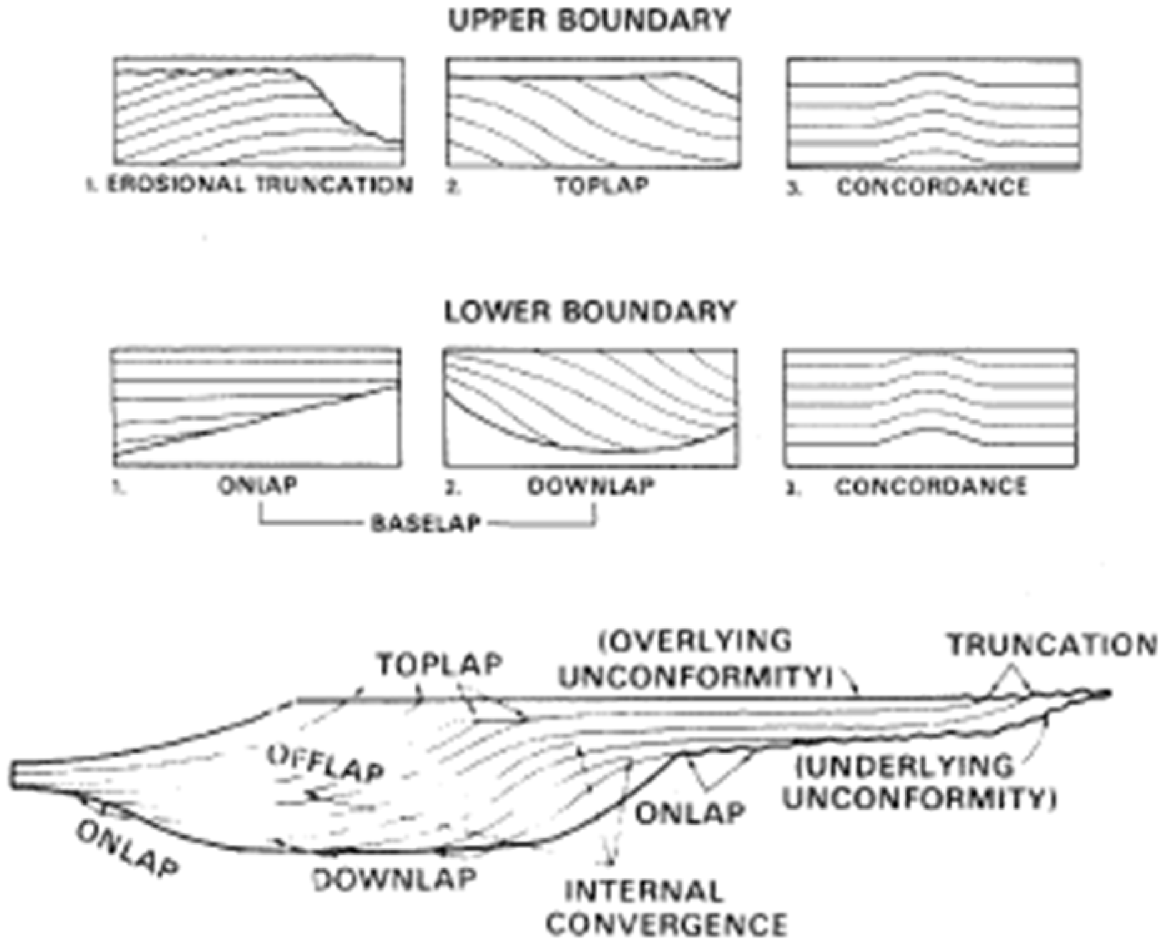


Figure 7. Modified from Mitchum et al., 1977.

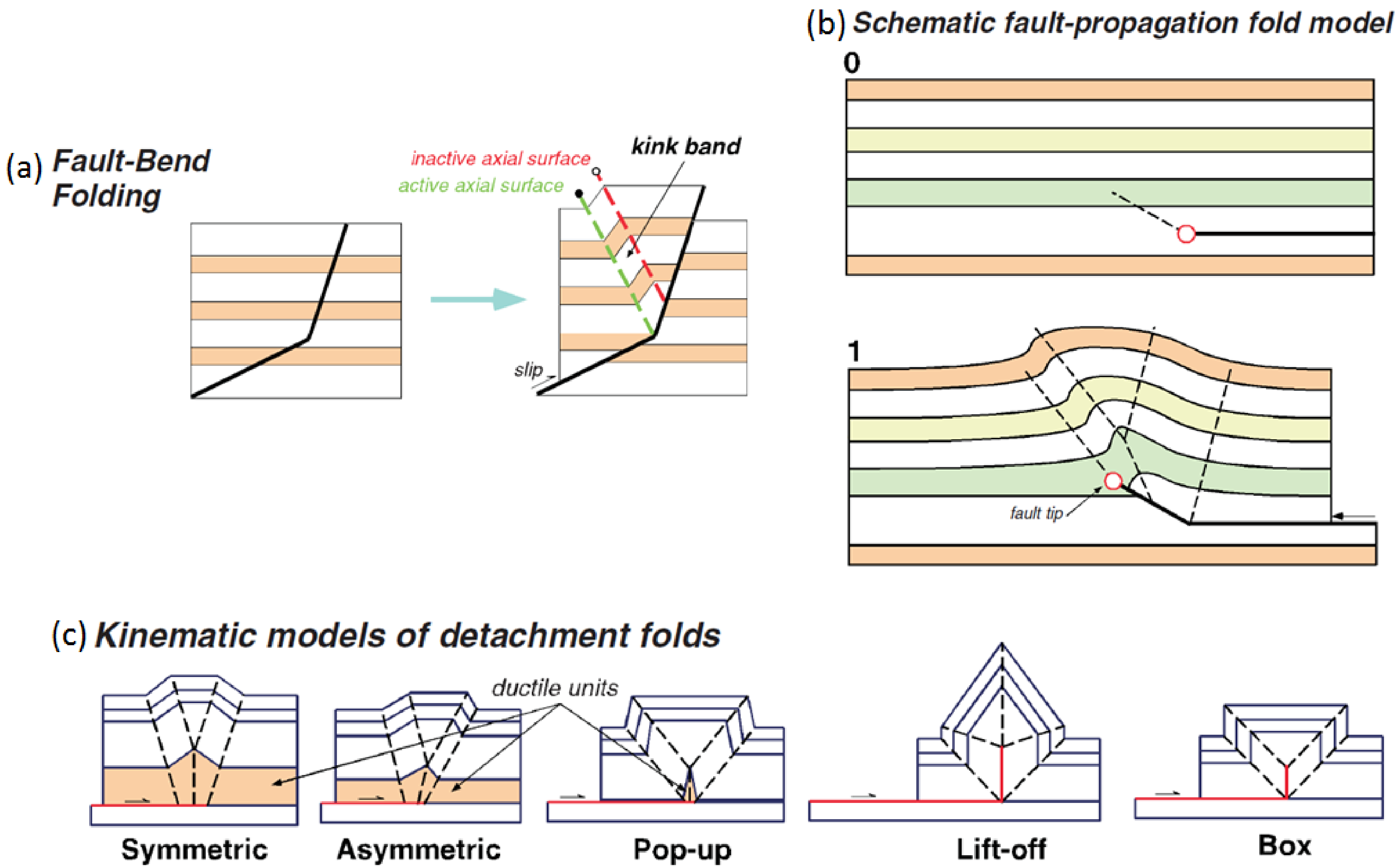


Figure 8. Conceptual sketches of the three classifications of fault-related folding for (a) fault-bend folds; (b) fault-propogation folds; and (c) detachement folds. From Shaw et al., 2005.

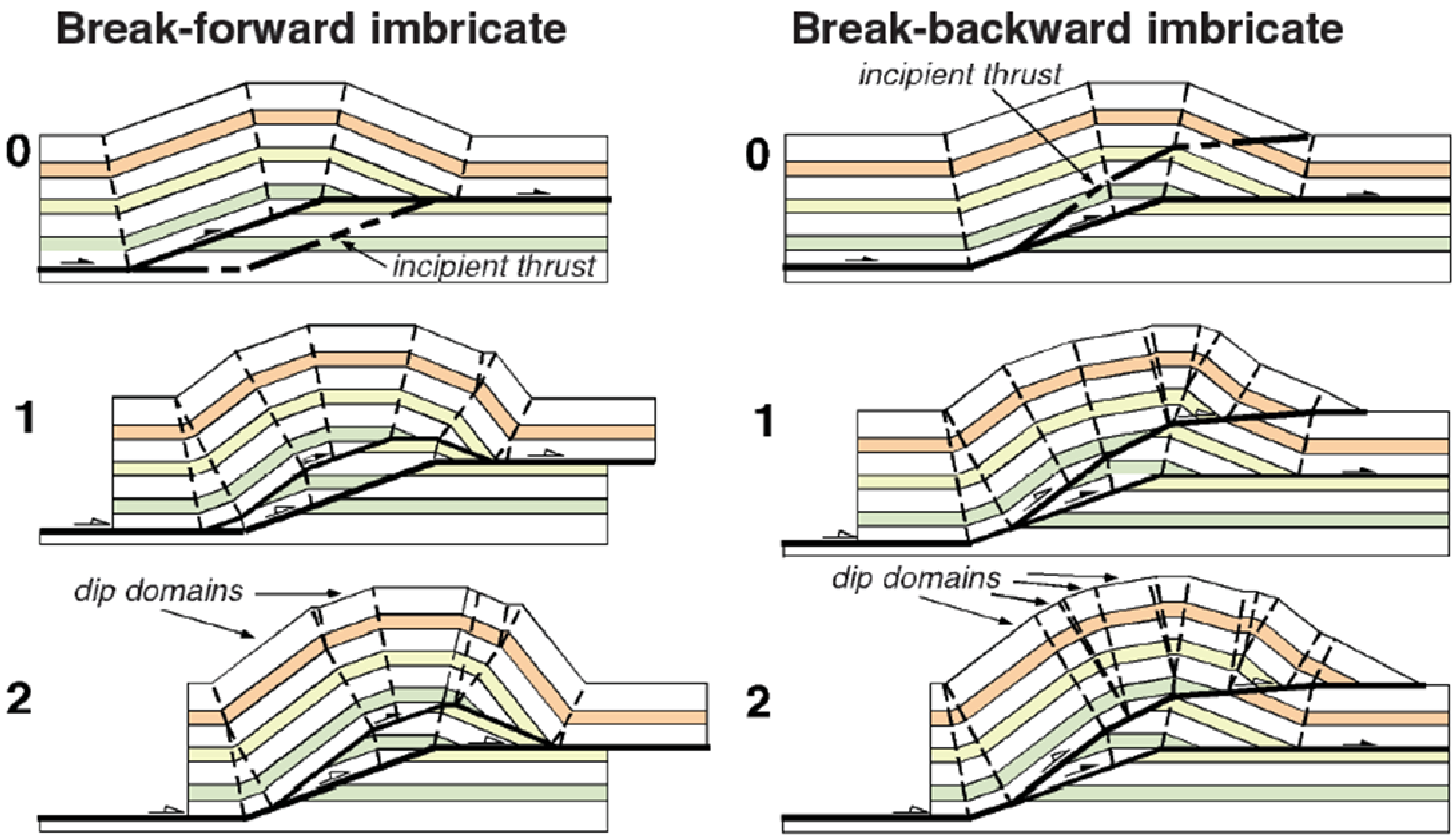


Figure 9. Kinematic models of break-forward and break-backward imbricate systems with time advancing from an initial state 0 to a final state 2. From Shaw et al., 2005.

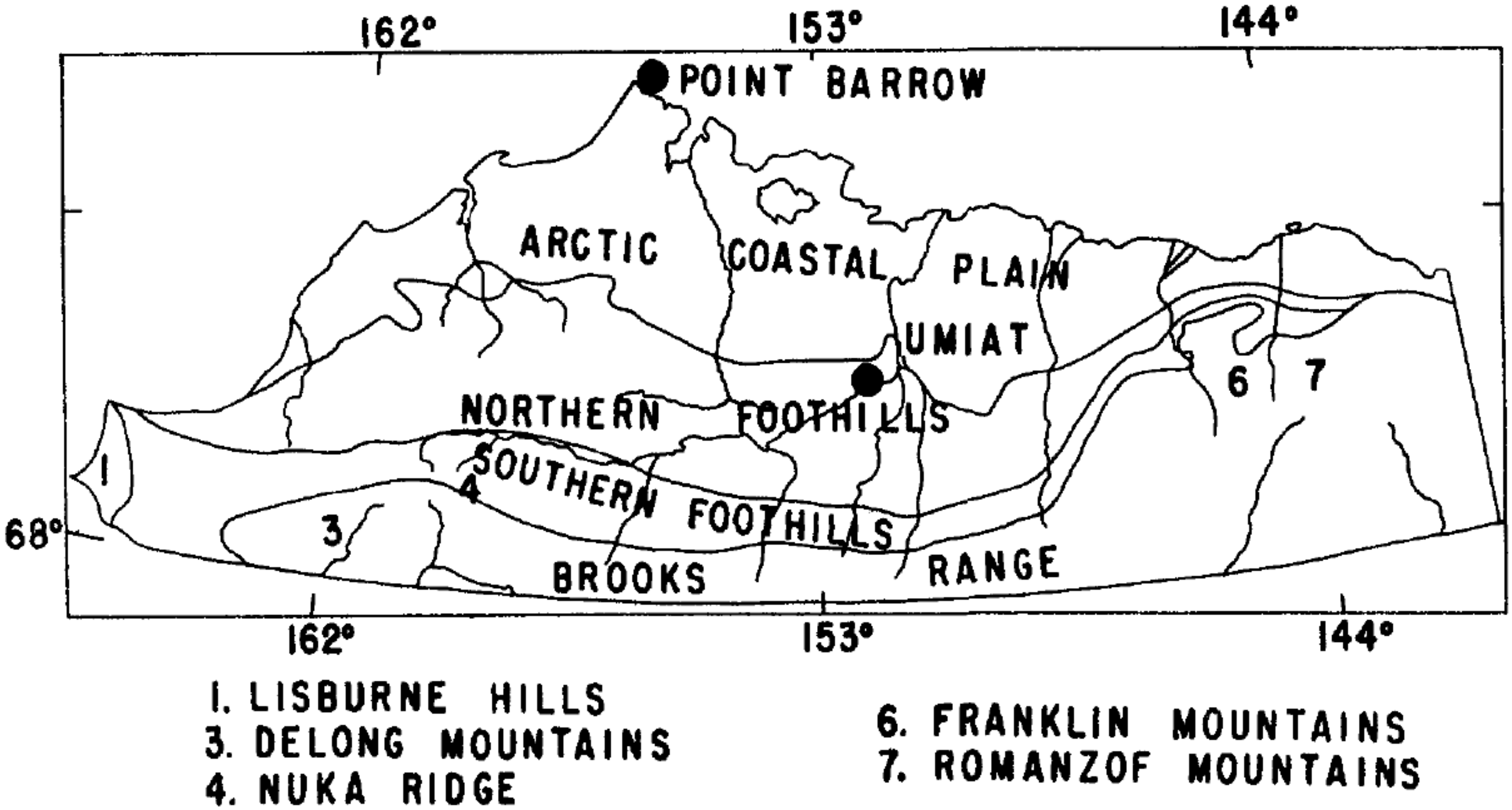


Figure 10. The physiographic provinces of Arctic Alaska. The National Petroleum Reserve in Alaskan extends from the Arctic Coastal Plain in the North to the Brooks Range and Brooks Range Foothills in the South. From Gryc, 1970.

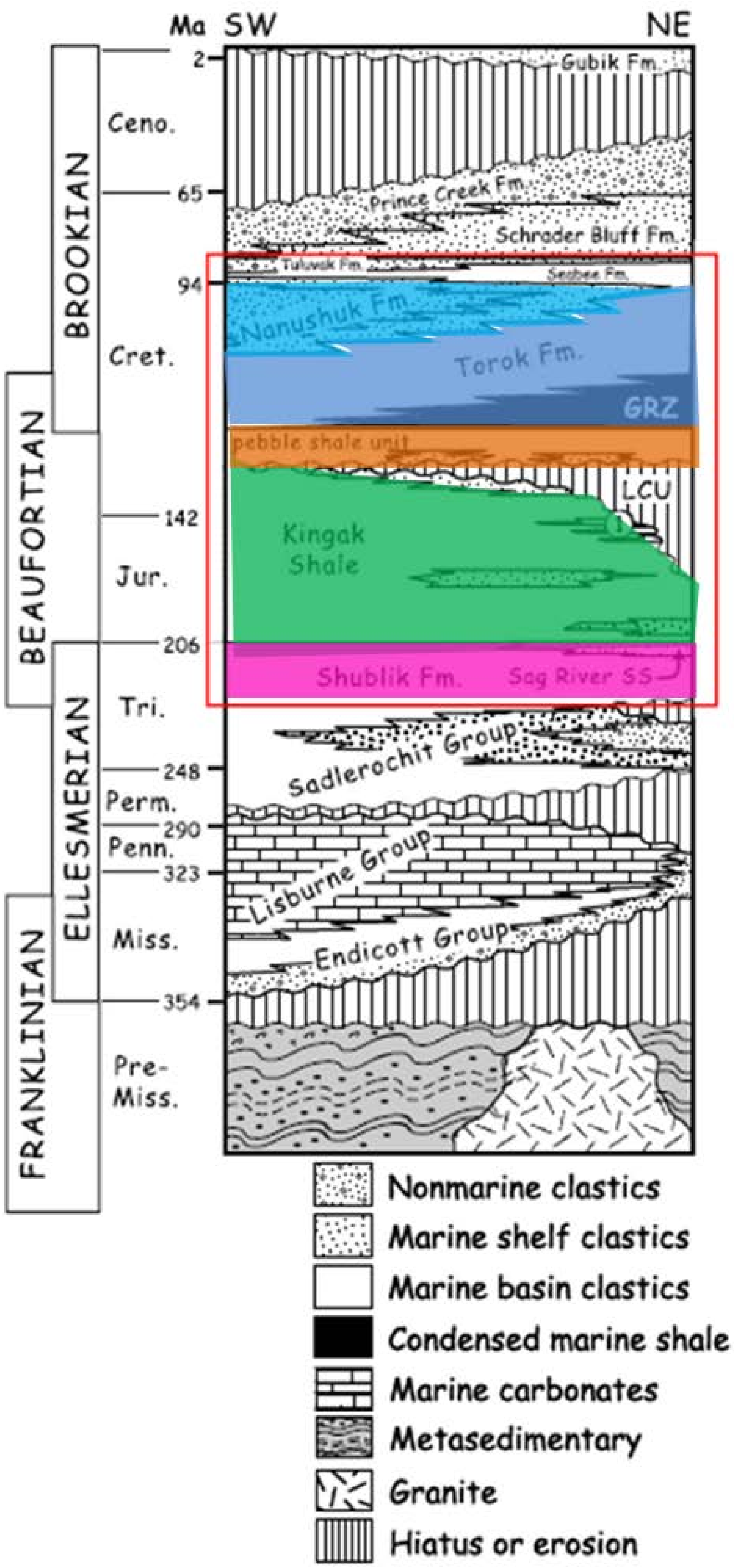


Figure 11. Stratigraphic column of the North Slope with units of interest highlighted in the red frame. Modified from Stier, 2012; Houseknecht and Bird, 2004.

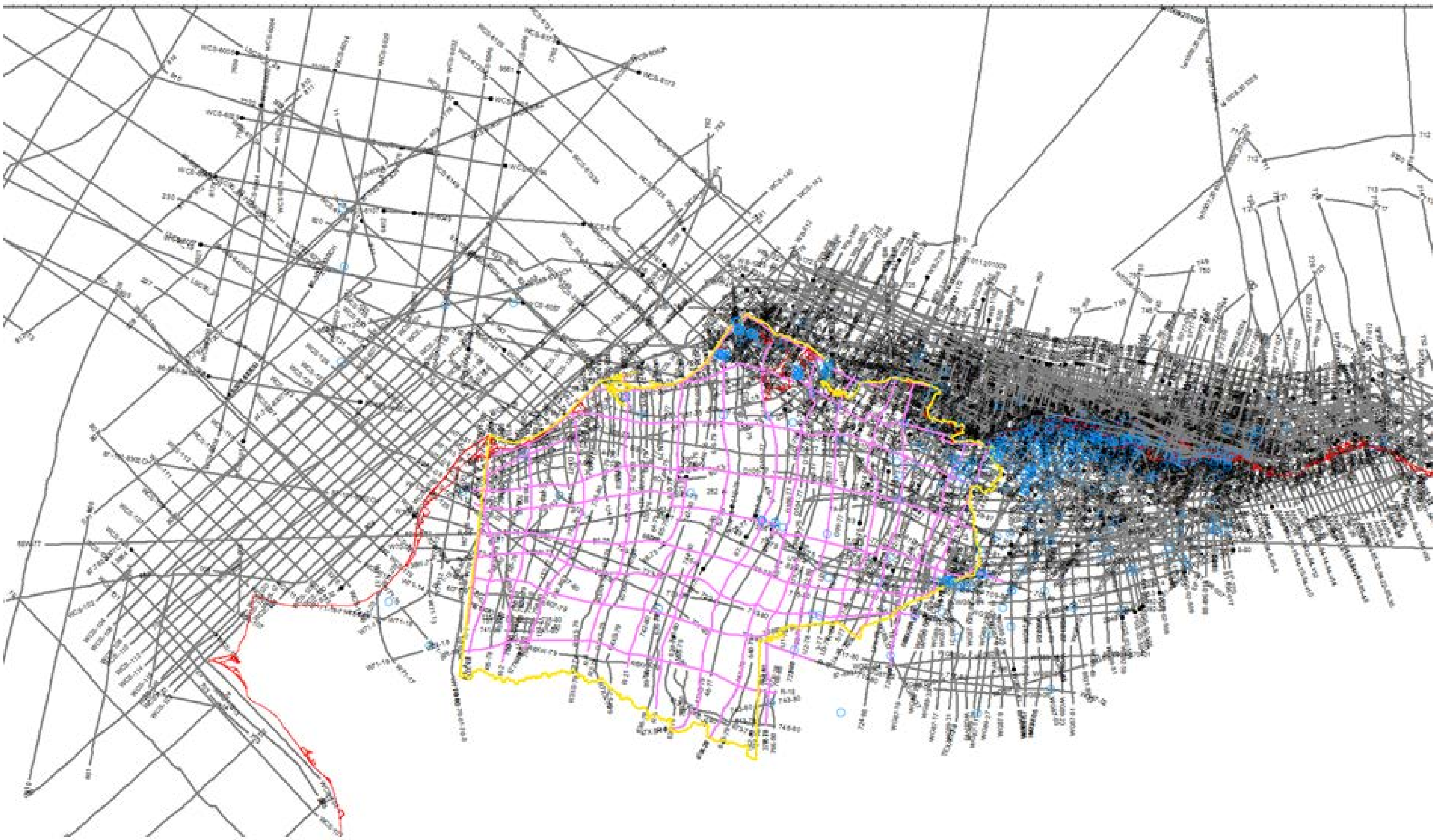


Figure 12. Project data available for this project, with NPRA R-Lines highlighted in pink, the Alaskan coastline shown in red, the NPRA bounds shown in yellow and the available well data displayed in blue.

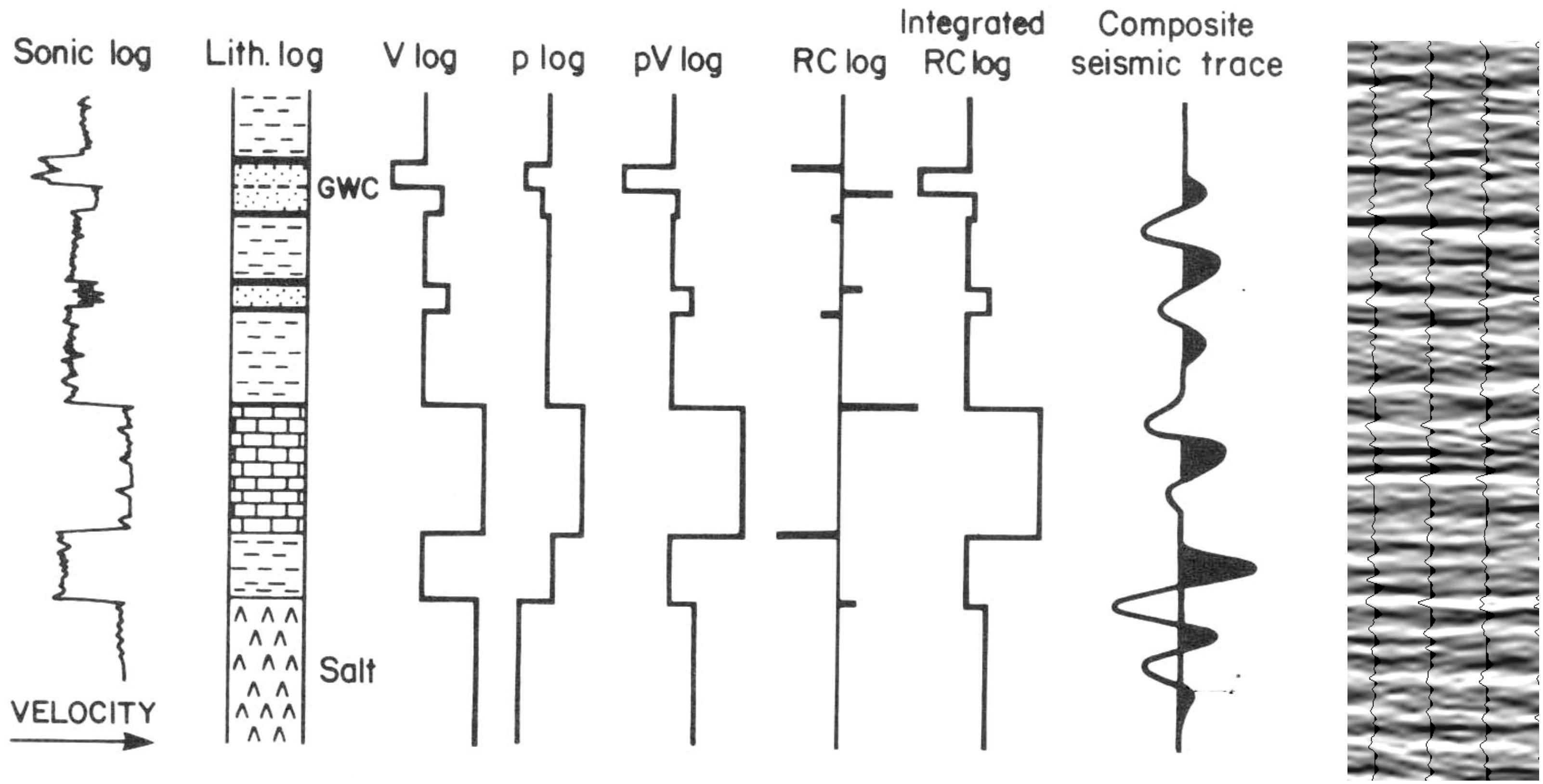
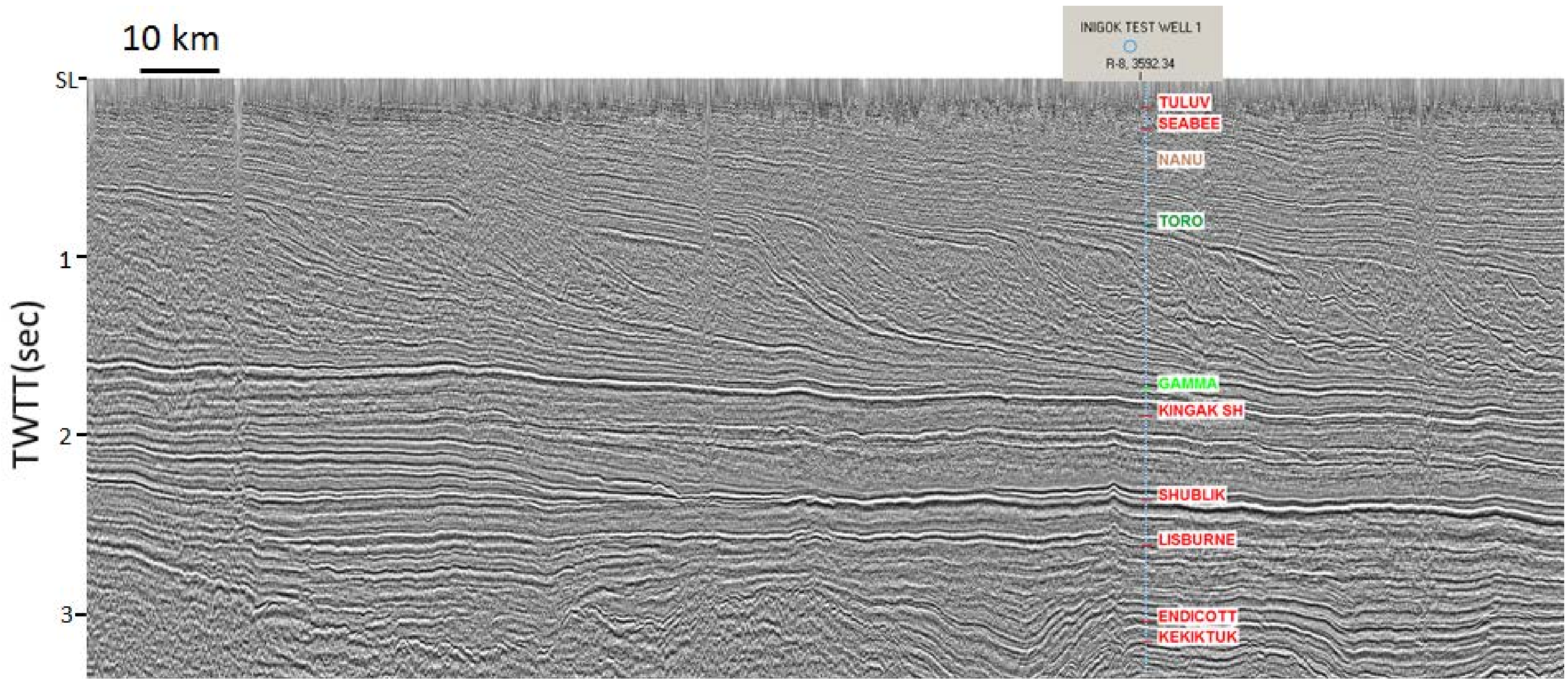
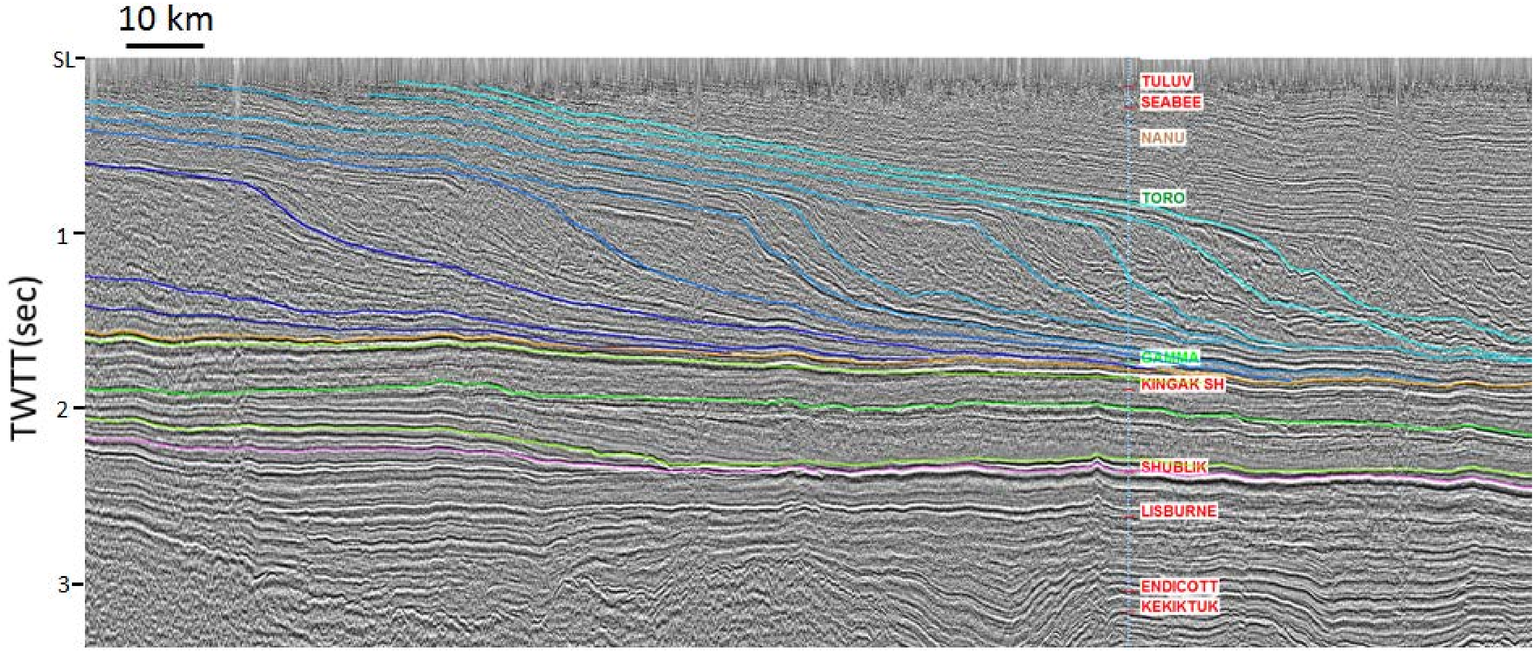


Figure 13. The various types of log data, along with a composite seismic trace. Composite seismic traces along a line can be used to create a 2D seismic image, as shown in the far right. Modified from Badley, 1985.



NPRA Line R-14

Figure 14. Seismic line R-14 with USGS picked tops shown from the Inigok Test Well 1.



NPRA Line R-14

Figure 15. Seismic line R-14 with USGS tops correlated to mapped horizons with Torok horizons shown in blue, Pebble shale in orange, Kingak in green and Shublik in pink.

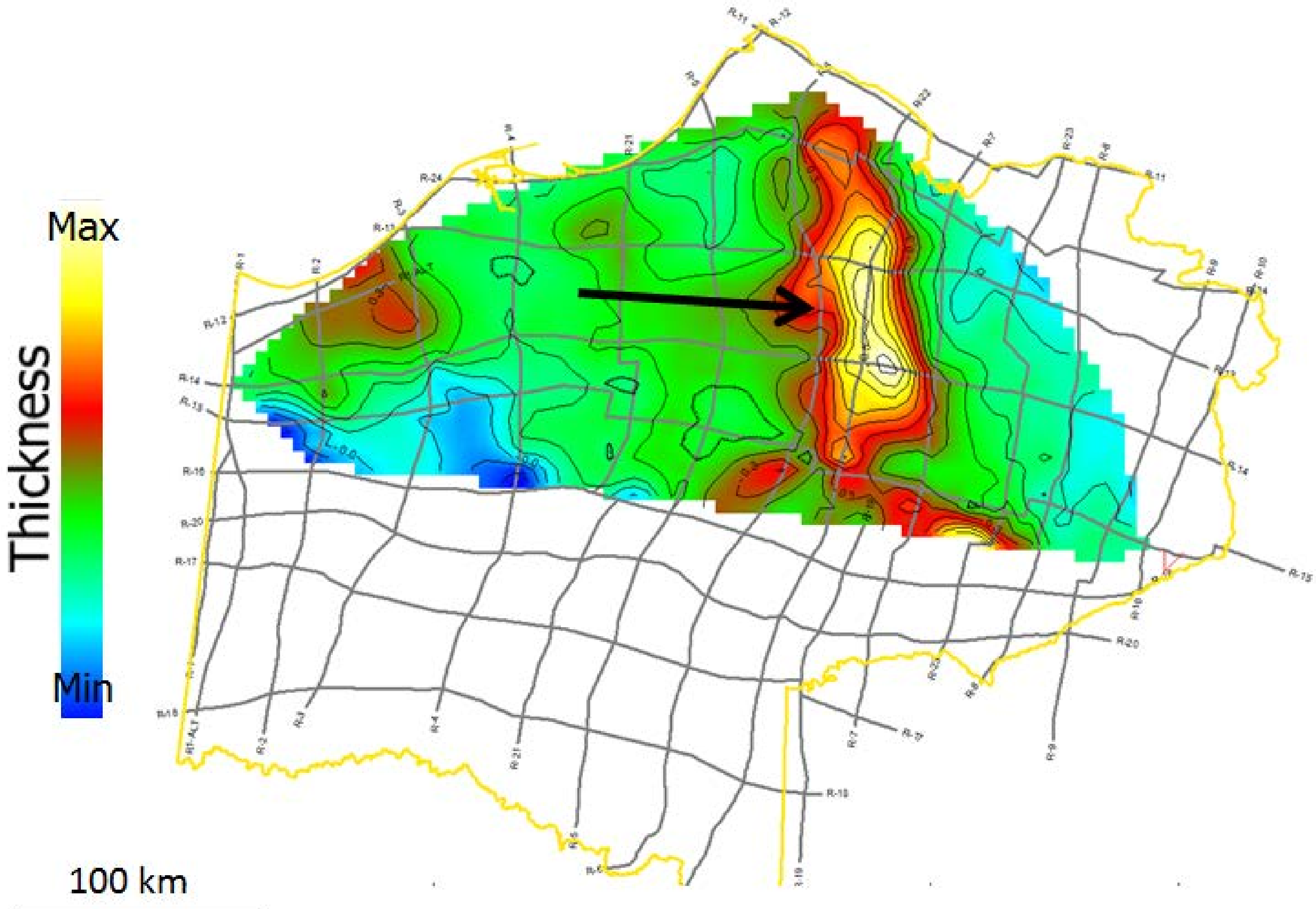


Figure 16. Isochron map between Torok sequences T3 and T4 with shelf margin highlighted by arrow.

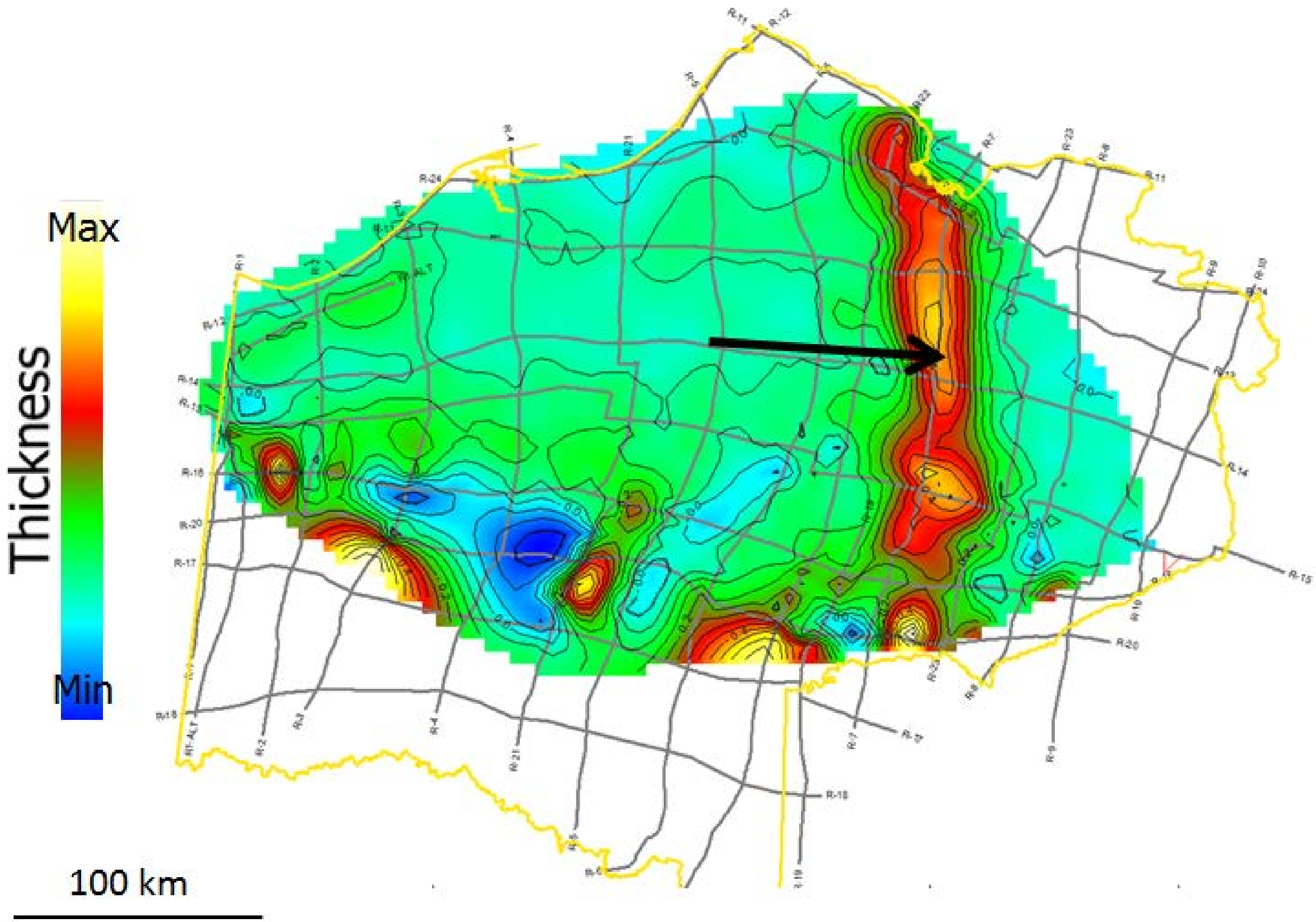


Figure 17. Isochron map between Torok sequences T2 and T3 with shelf margin highlighted by arrow.

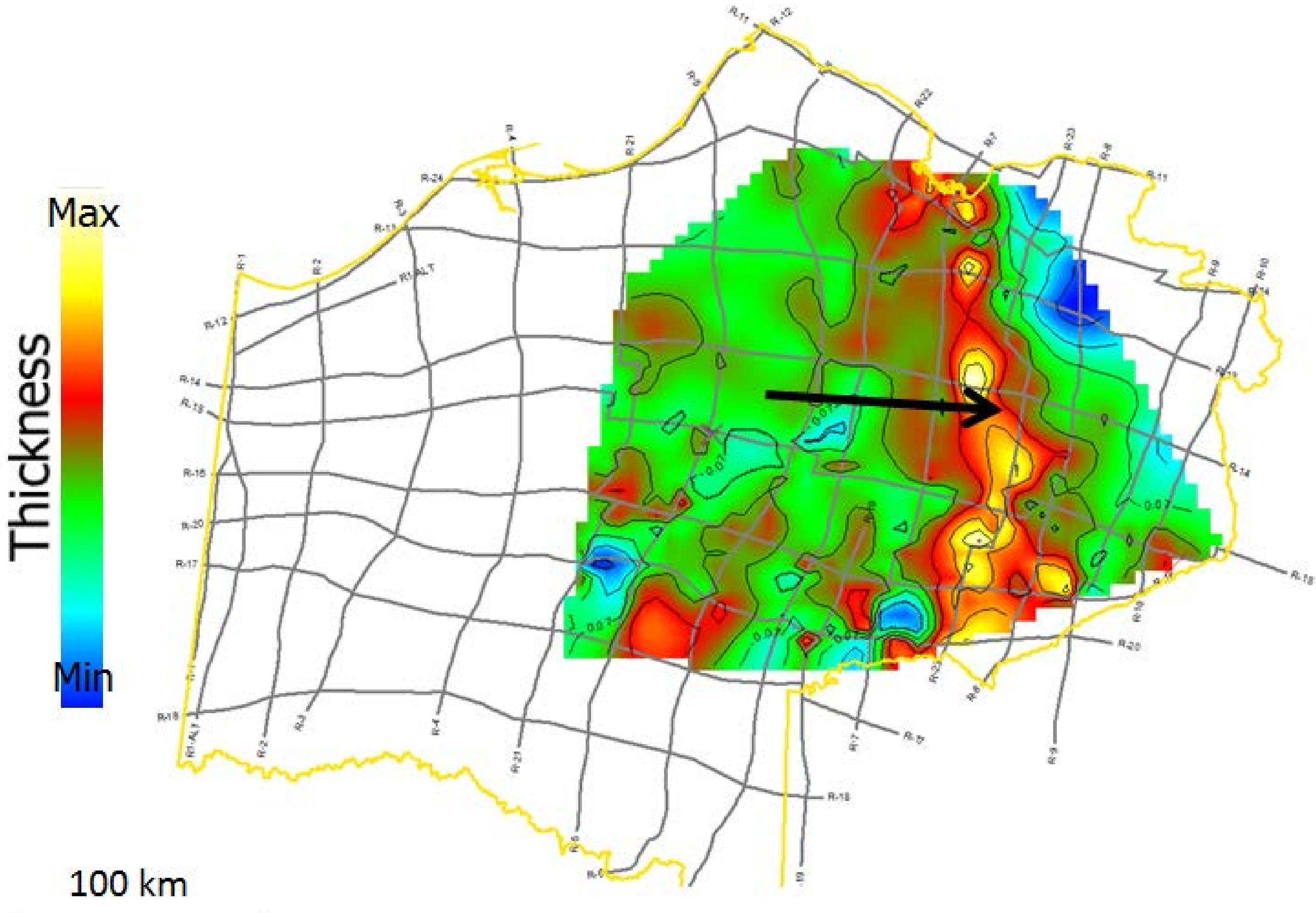


Figure 18. Isochron map between Torok sequences T1 and T2 with shelf margin highlighted by arrow.

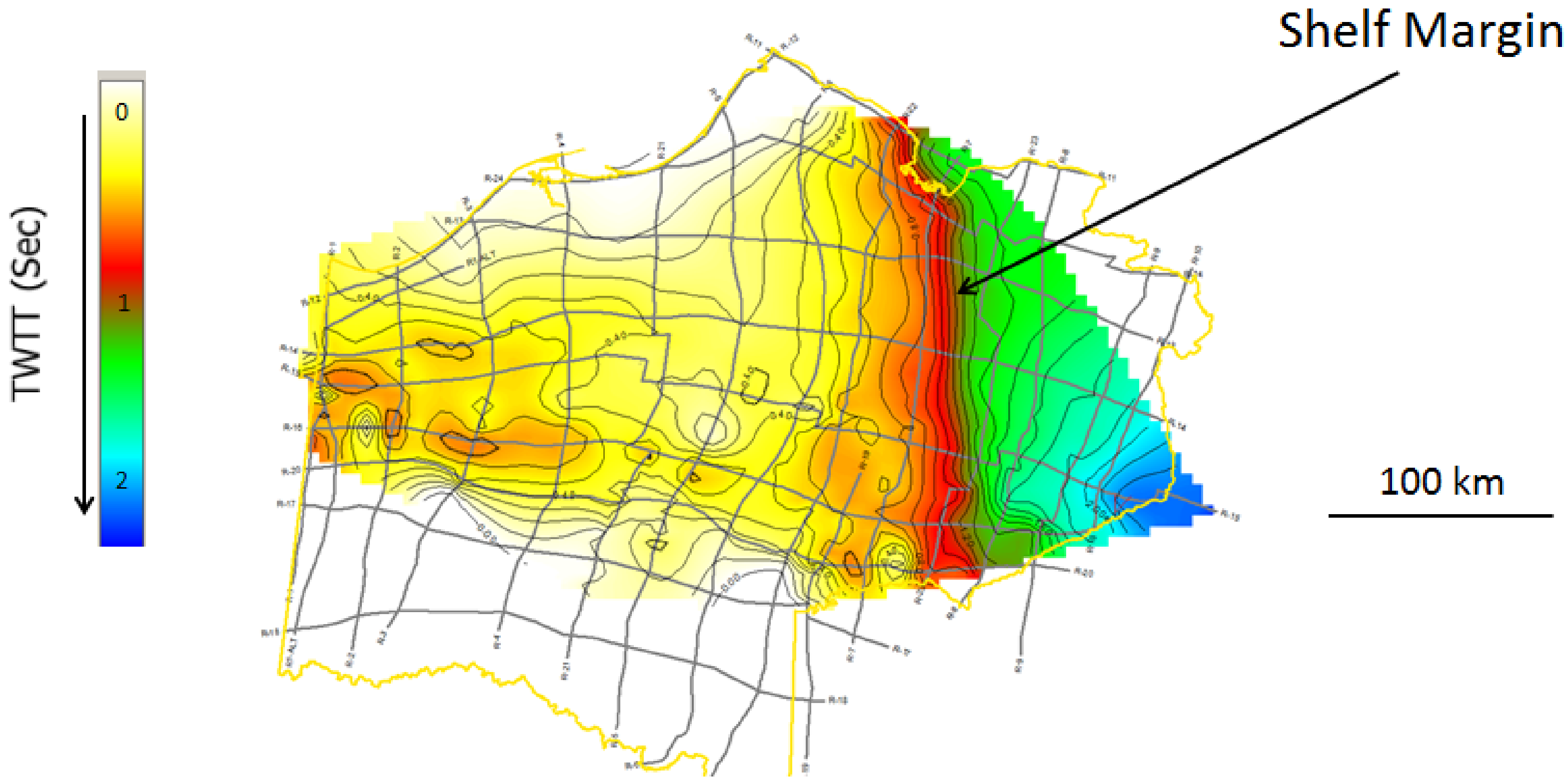


Figure 19. Structure contour map of Torok 2 sequence top with 0.1 sec contours shown in black.

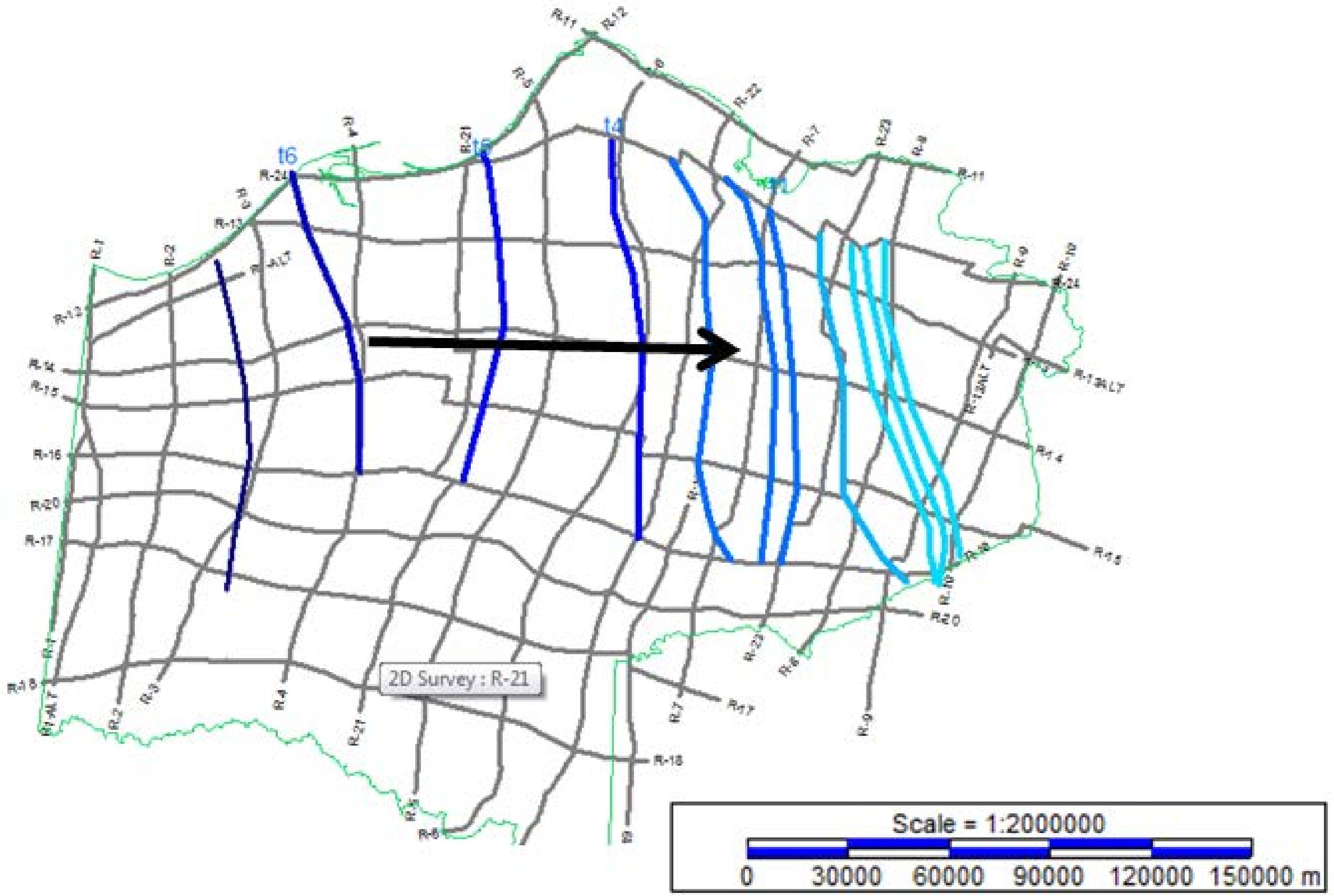


Figure 20. Torok margin through time with East-West progradation through time apparent through the eastward shift in the position of the shelf margin.

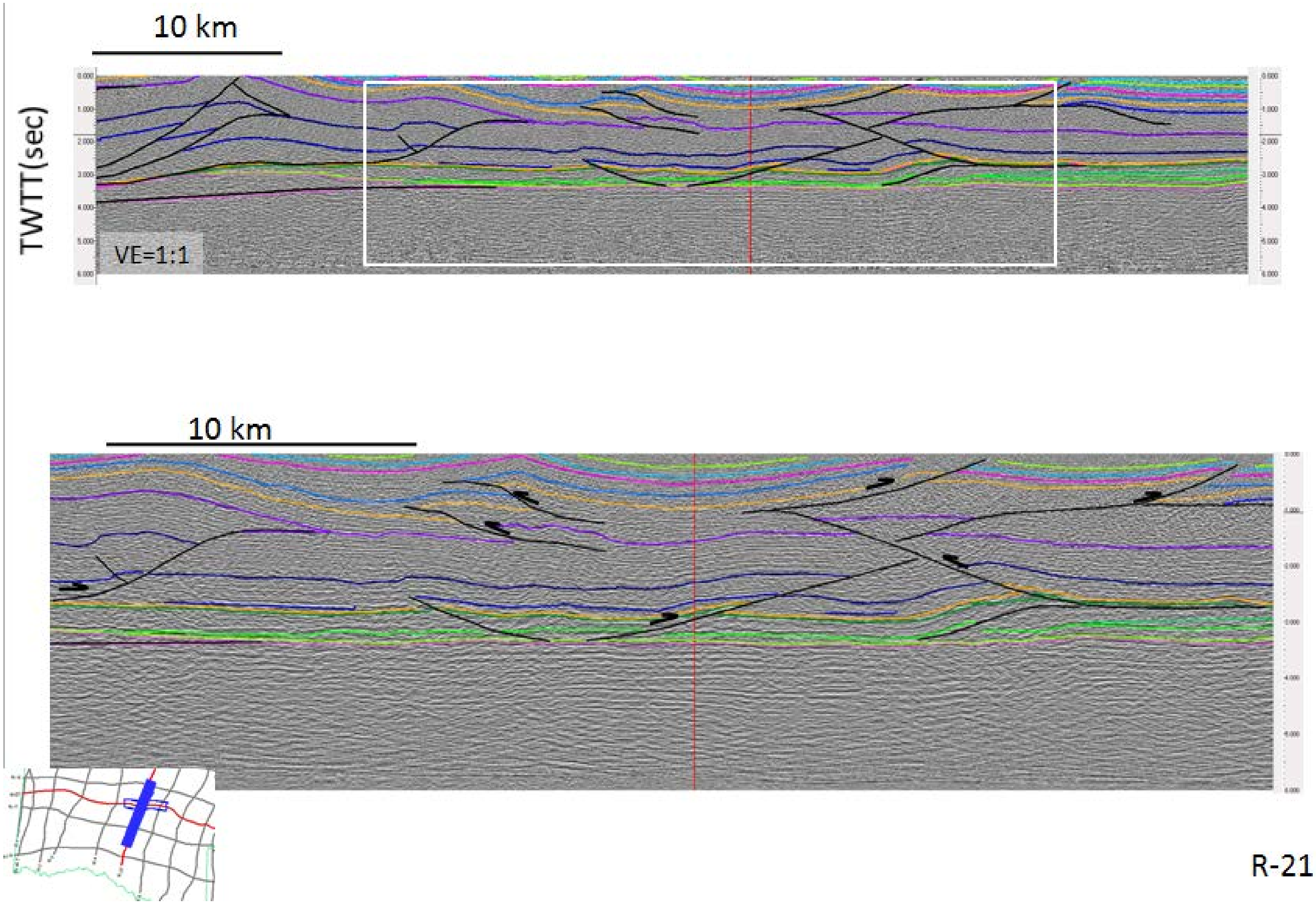


Figure 21. Structural interpretation of seismic line R-21 with faults shown in black.

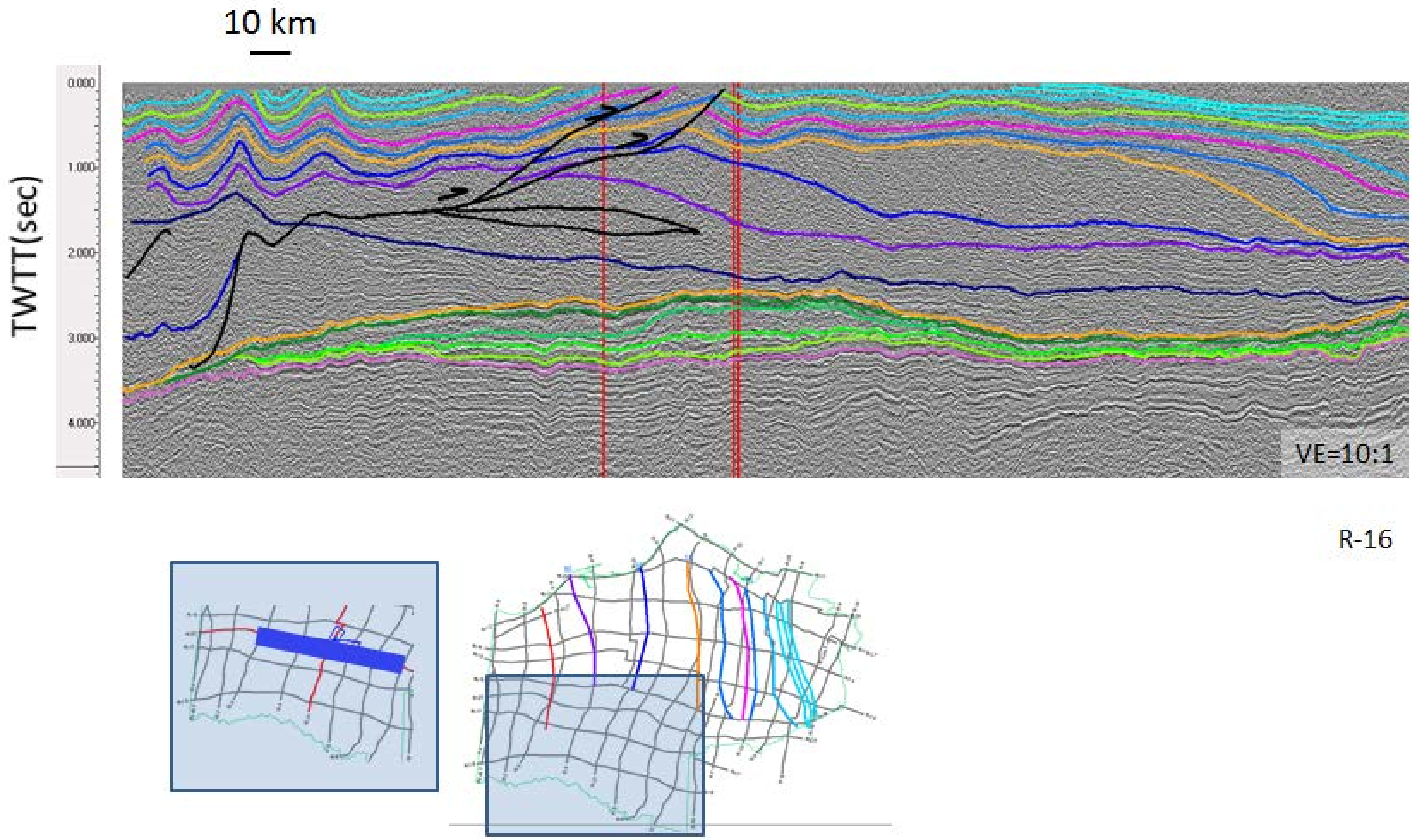


Figure 22. Structural interpretation of a seismic strike line,R-16, with faults shown in black and line intersections shown in red. Insets below show position of line and position in space relative to Torok shelf margin. Note that thickening occurs in the purple horizon, which represents the slope facies in this section.

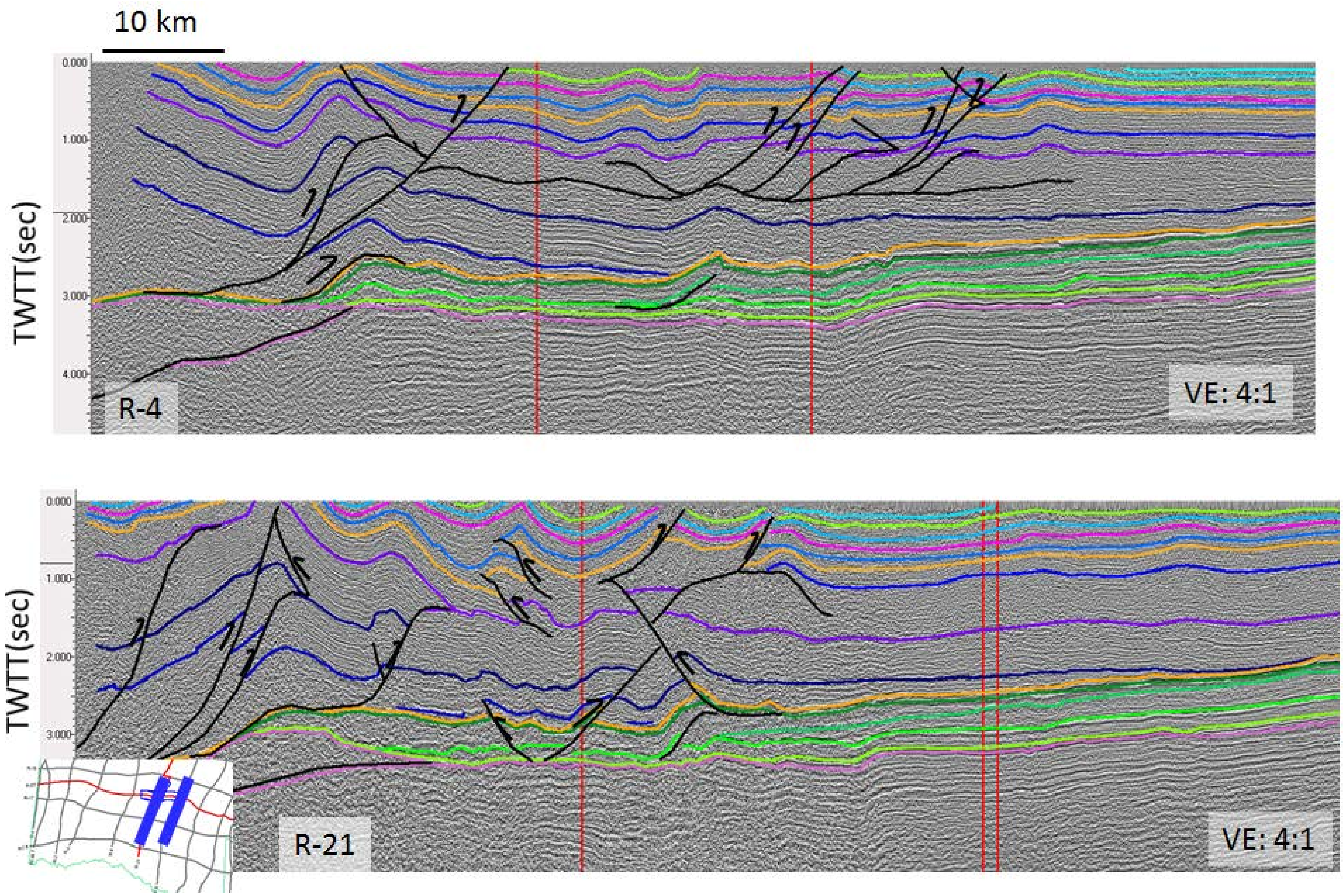


Figure 23. Structural interpretation of two seismic dip lines, R-21 (below) and R-4 (top), with faults shown in black and line intersections shown in red.

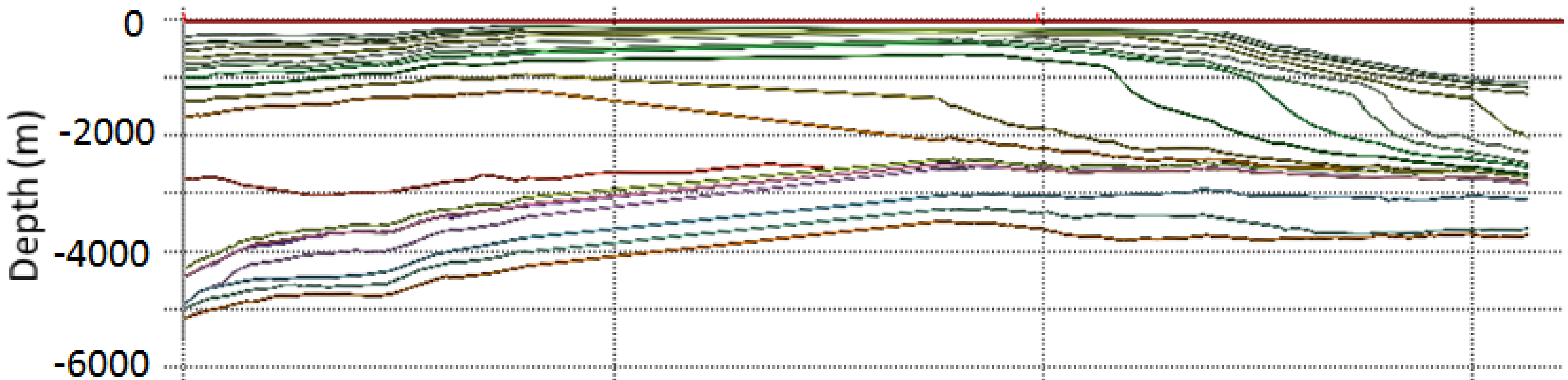


Figure 24. Horizons interpreted on seismic line R-14 after depth conversion. Note that vertical axis units are in meters.

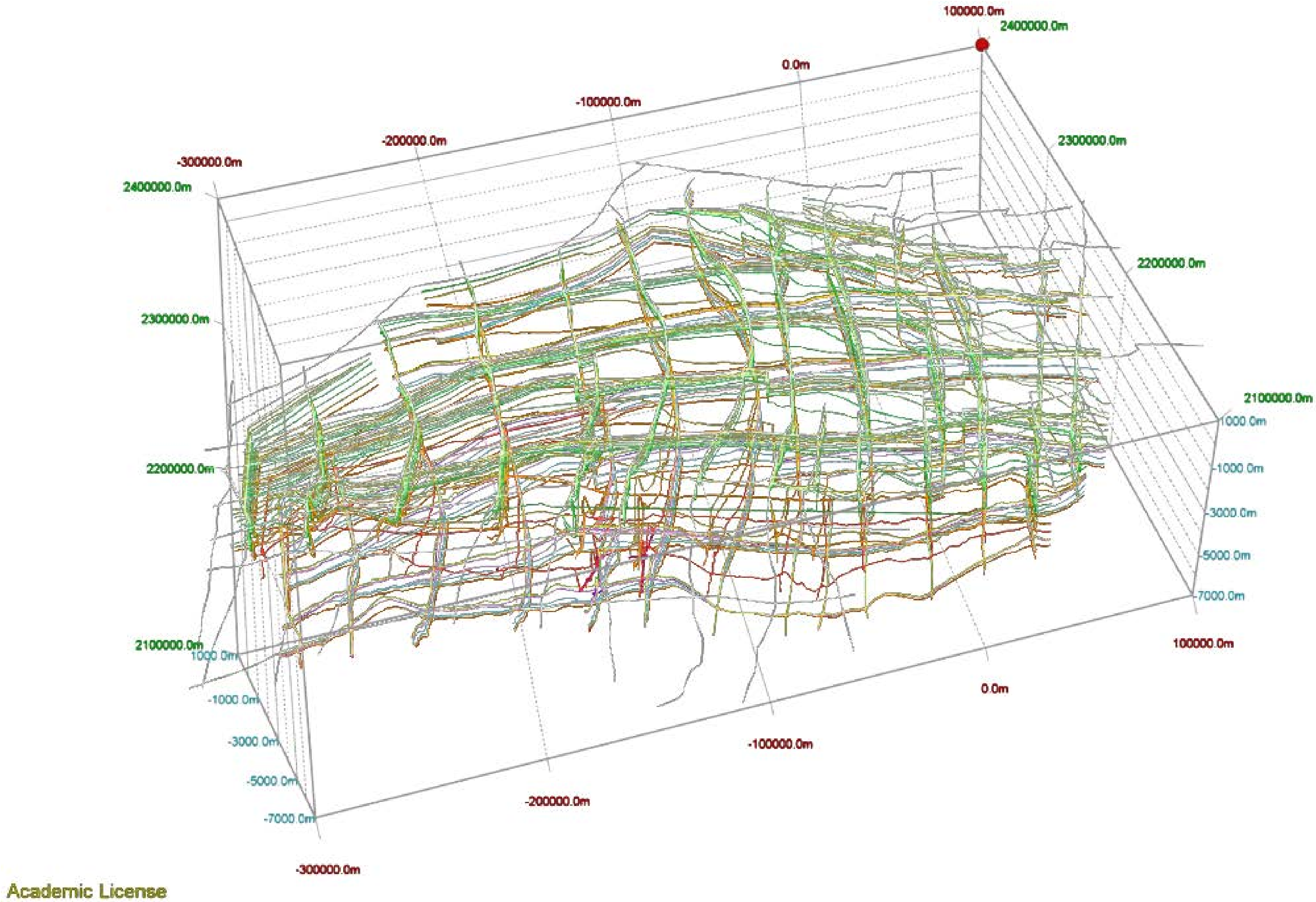


Figure 25. All interpreted horizons from NPRA post-depth conversion, shown in 3D environment.

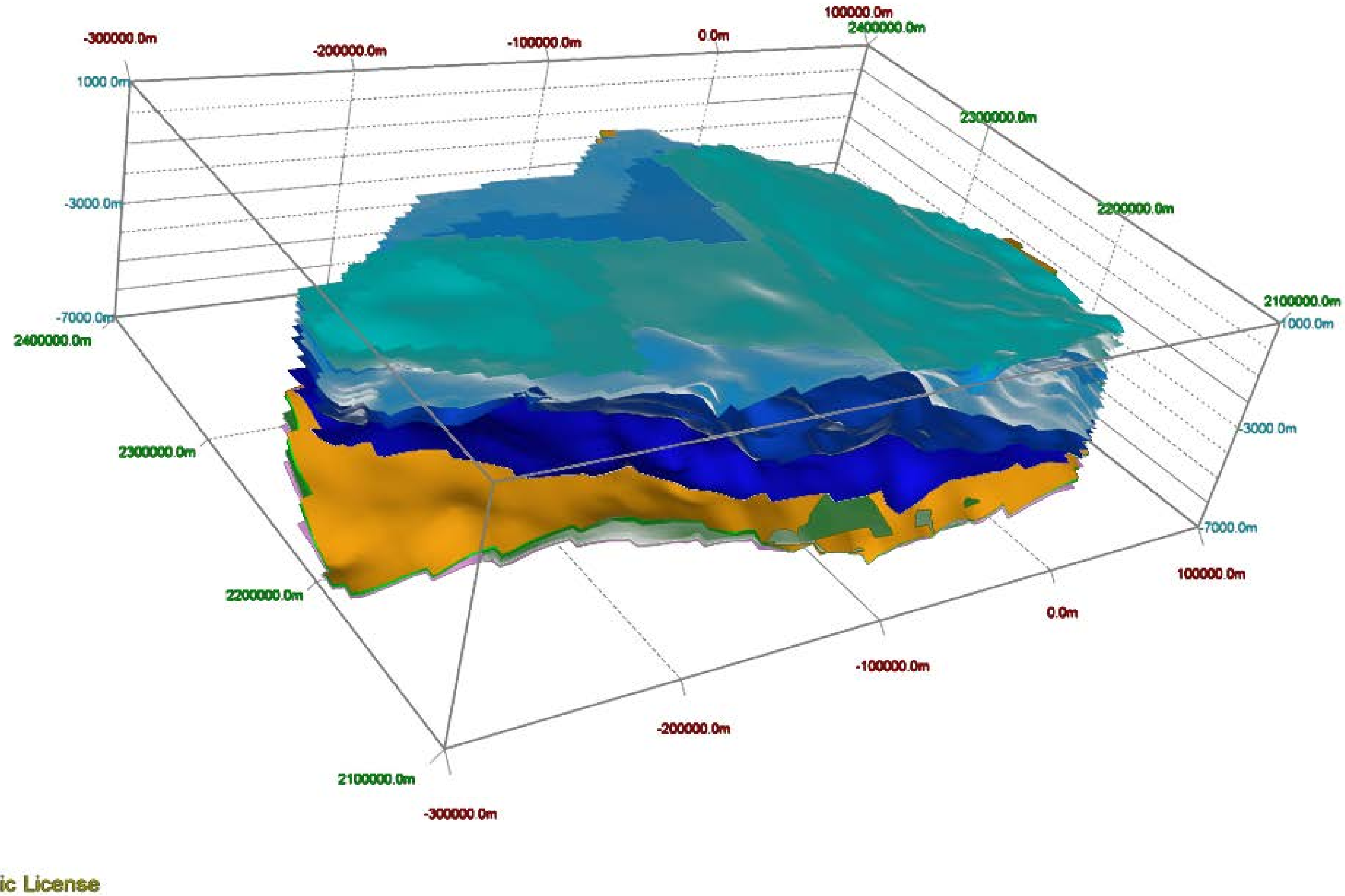


Figure 26. 3D model of horizons within the NPRA using depth-converted grids of mapped horizon data. Shublik horizons in pink, KIngak in green, Pebble Shale in orange, and Torok in blue.

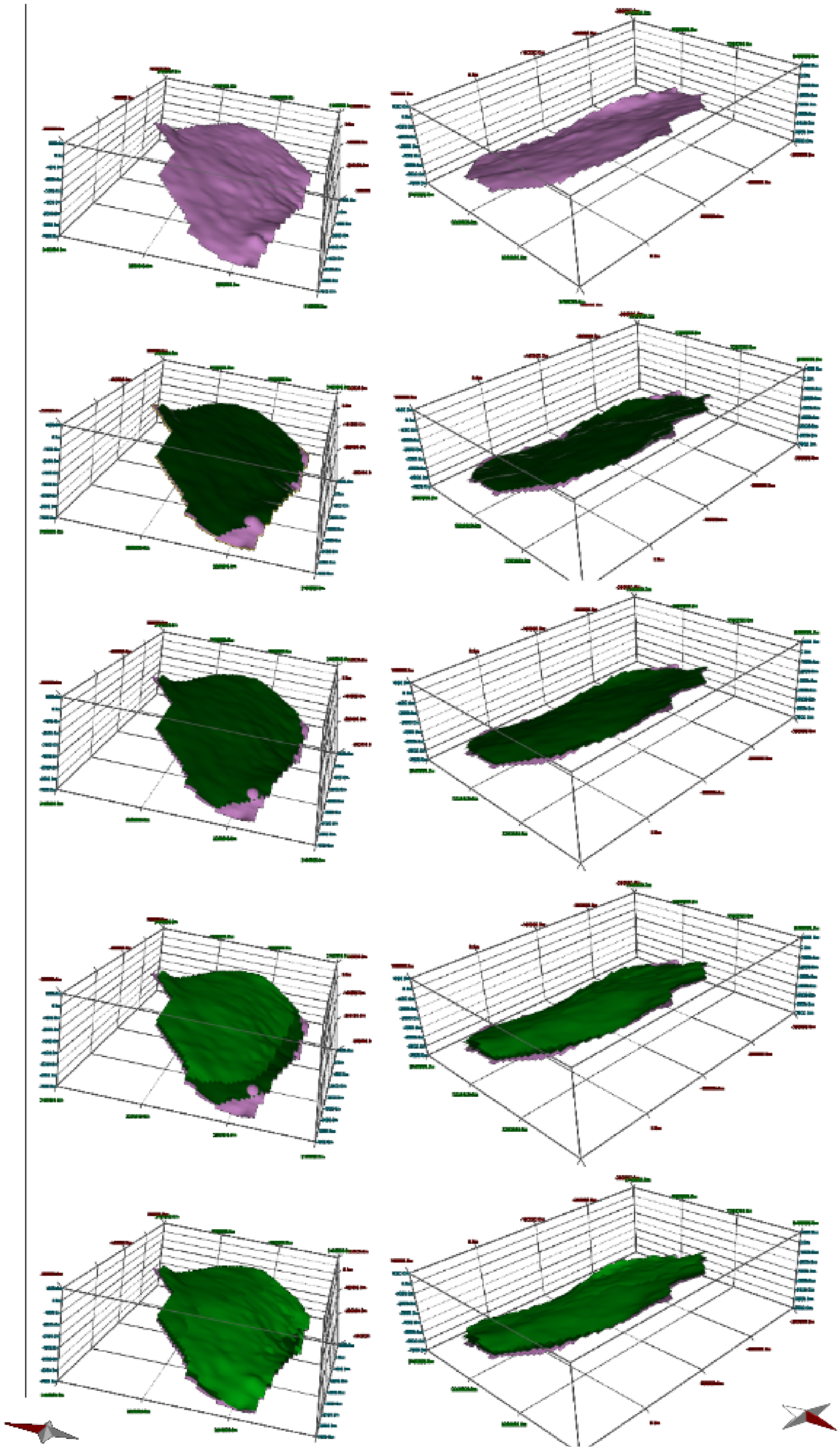


Figure 27. Kingak sequence tops in green shown through time from oldest (top) to youngest (bottom) as deposited over Shublik top in pink. Images of the left are oriented with North to the left, while images on the left are oriented with North towards the bottom right.

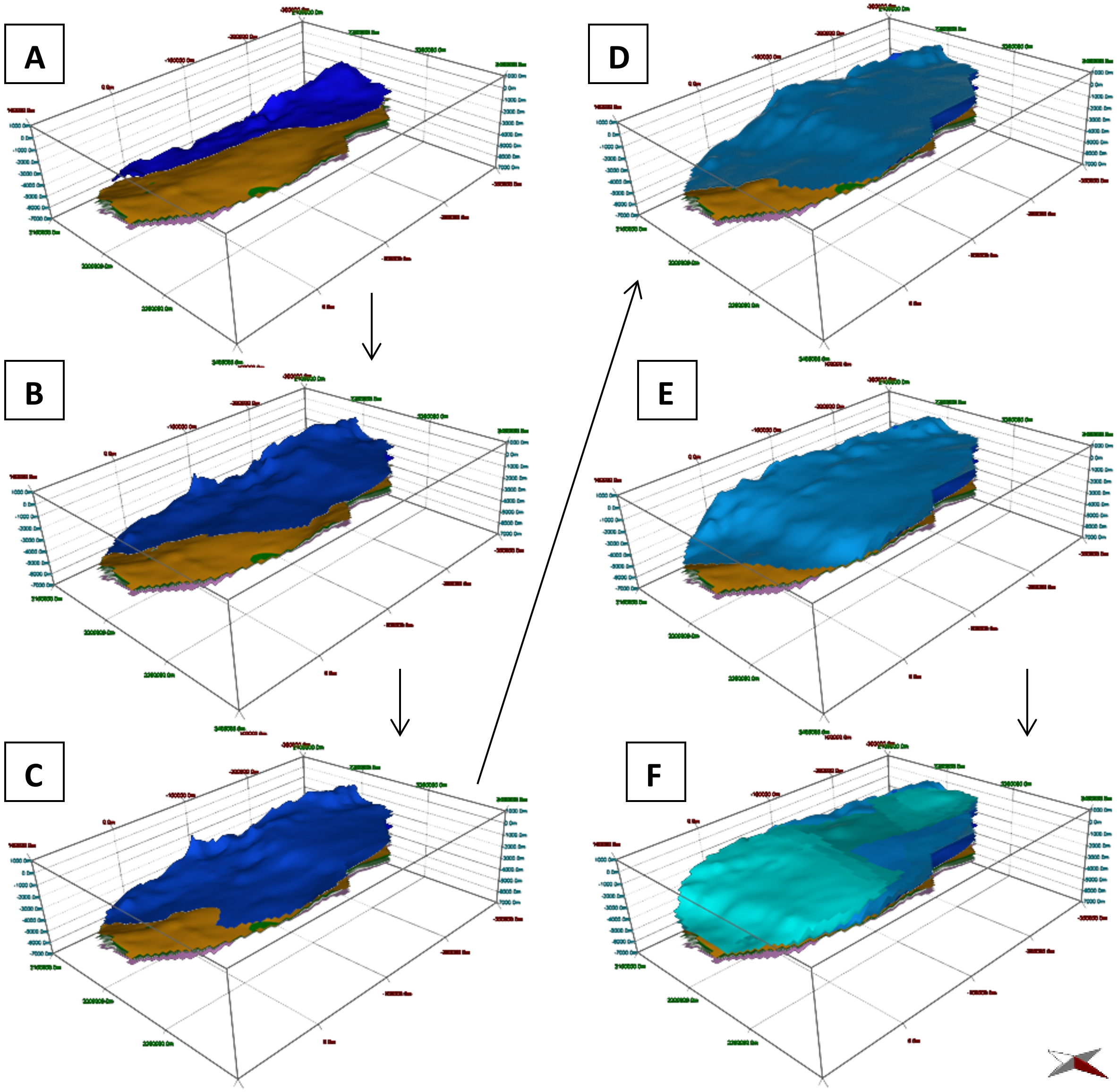


Figure 28. Torok sequence tops in blue shown through time from youngest (top left) to oldest (bottom right) as deposited over the Pebble shale drape surface in orange. Images are oriented with North towards the bottom right.

APPENDIX A

Dynamic Depth Conversion

Dynamic Depth Conversion is a process for converting horizons and faults from time to depth using the SMT Kingdom software package 8.8 and later. In order to convert horizons to depth, a velocity model must first be generated. This is done by providing directions for which horizons in the seismic data correspond to which formation tops, then generating velocities using T-D functions from the wells. Therefore, before creating the velocity model, the wells and horizons that are to be used to generate the velocity model must be activated. Note that these selections can be later changed by reselecting the desired horizons and/or wells and updating the model using the double arrows button (Update Velocity Model) (Figure A-1).

In order to create the velocity model, time and depth data must be loaded into the Model Definition. This is done by selected the desired horizons in the Time category and selected the associated tops from the well data in the Depth category. The depth data associated with a given time horizon must be in the same row in order to correlate the depth data to the time data. When this data is entered into the velocity model, the 'Enable Velocity Model' button can be selected to create the model, which will turn the button from red to green, indicating that the model is active. Changes to the horizons are well-data can be incorporated into the model by using the 'Update Velocity Model' tool (Figure A-1).

While the model is active, horizons and faults can be converted to depth using the Actions panel (double chevron button). For example, to convert a horizon from time to depth, select 'Extract time or depth data type' from the Horizons category (Figure A-2), then selecting the desired horizon in the Horizons box and 'Convert Time to Depth' in the Data types to extract box. Select the forward arrow into the Selected combinations box and click apply to depth convert the selected horizon. This may be done for a maximum of two horizons at a time and must be reconverted if the velocity model is changed.

The velocity model works by generating a 3D volume of velocity data for the region of interest. This is done by relating the velocity values from the T-D functions to the horizons, which then creates a velocity surface (Figure A-4 and A-5). Interpolation and extrapolation between and beyond these surfaces creates a velocity model that can be used to depth convert horizons and/or faults.

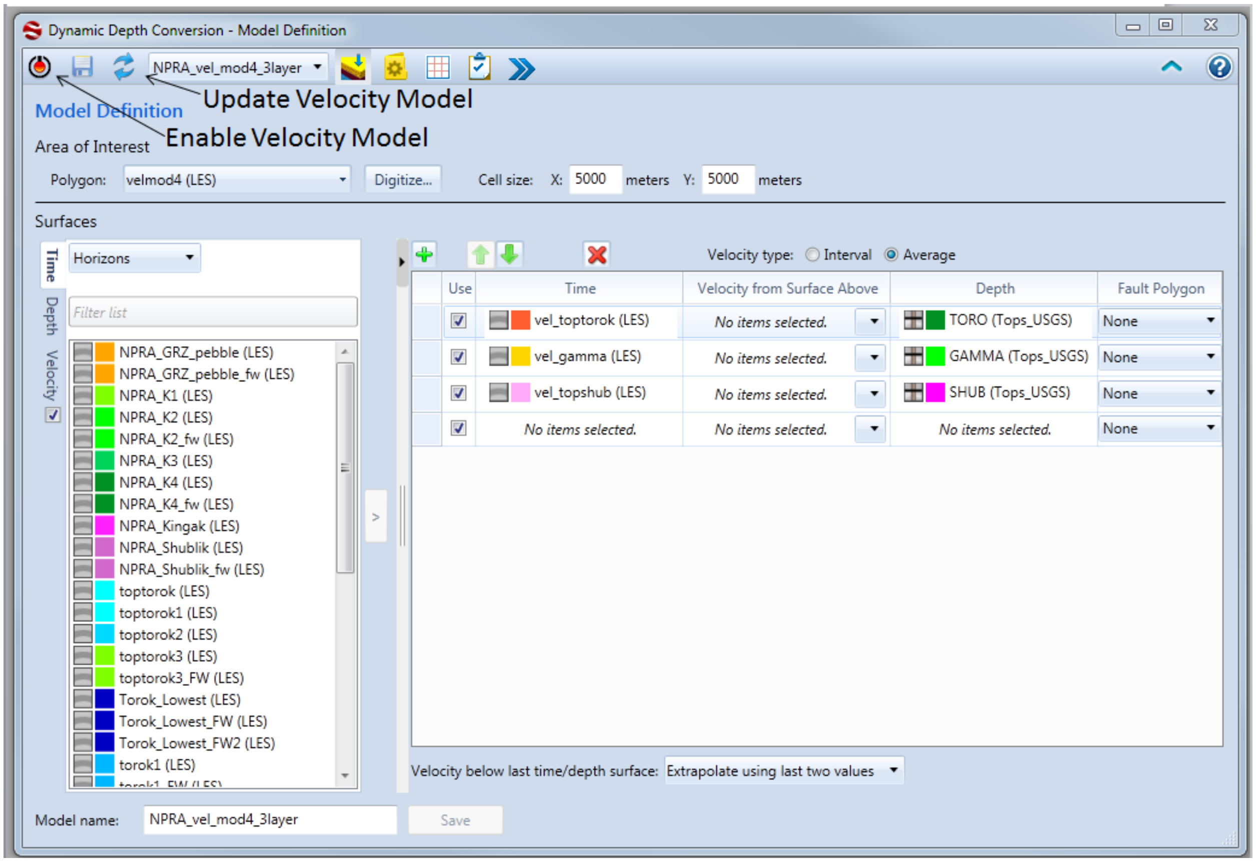


Figure A-1. Dynamic Depth Conversion control panel with 'Enable Velocity Model' and 'Update Velocity Model' tools distinguished at the top.

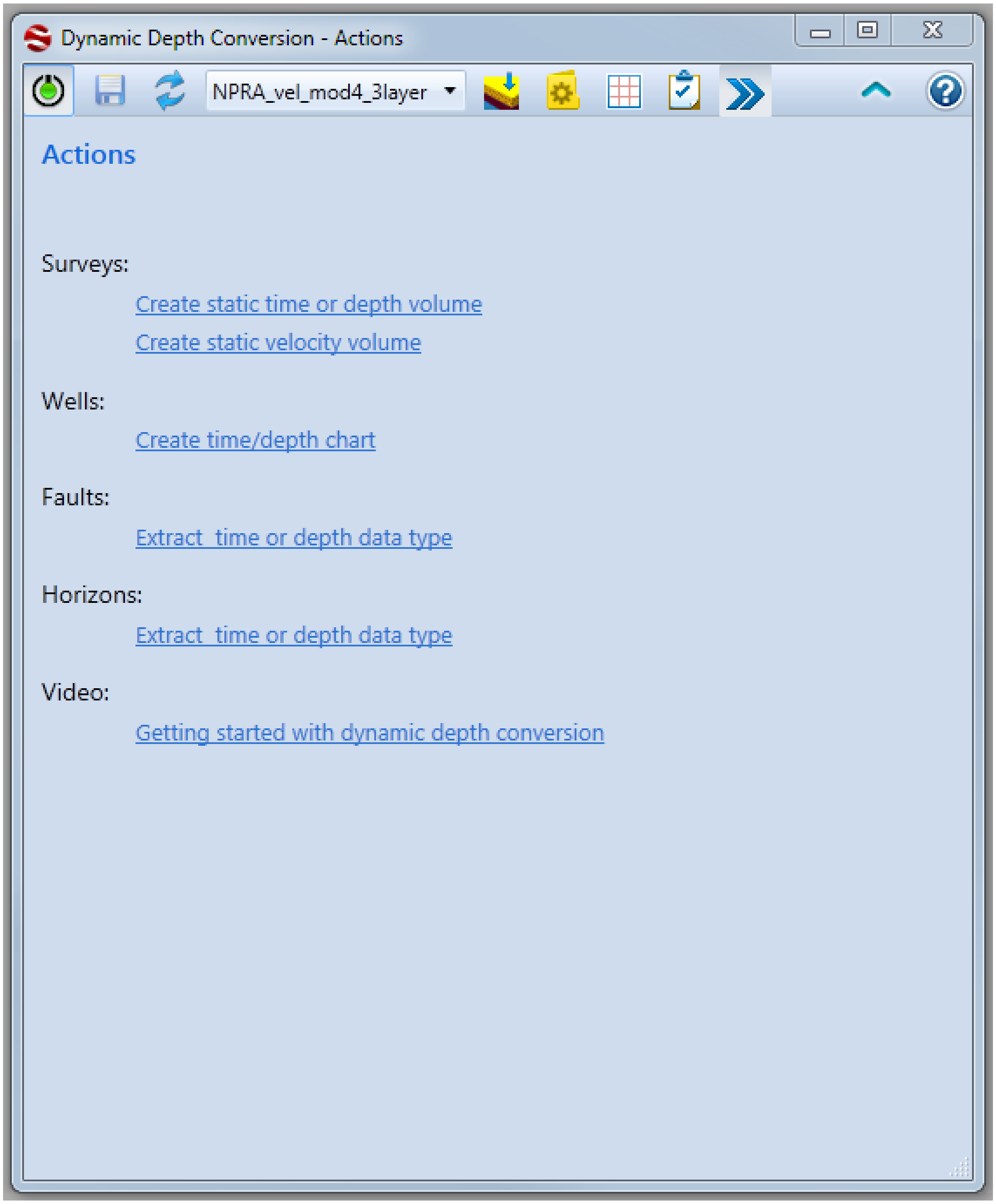


Figure A-2. The Actions tab for Dynamic Depth Conversion.

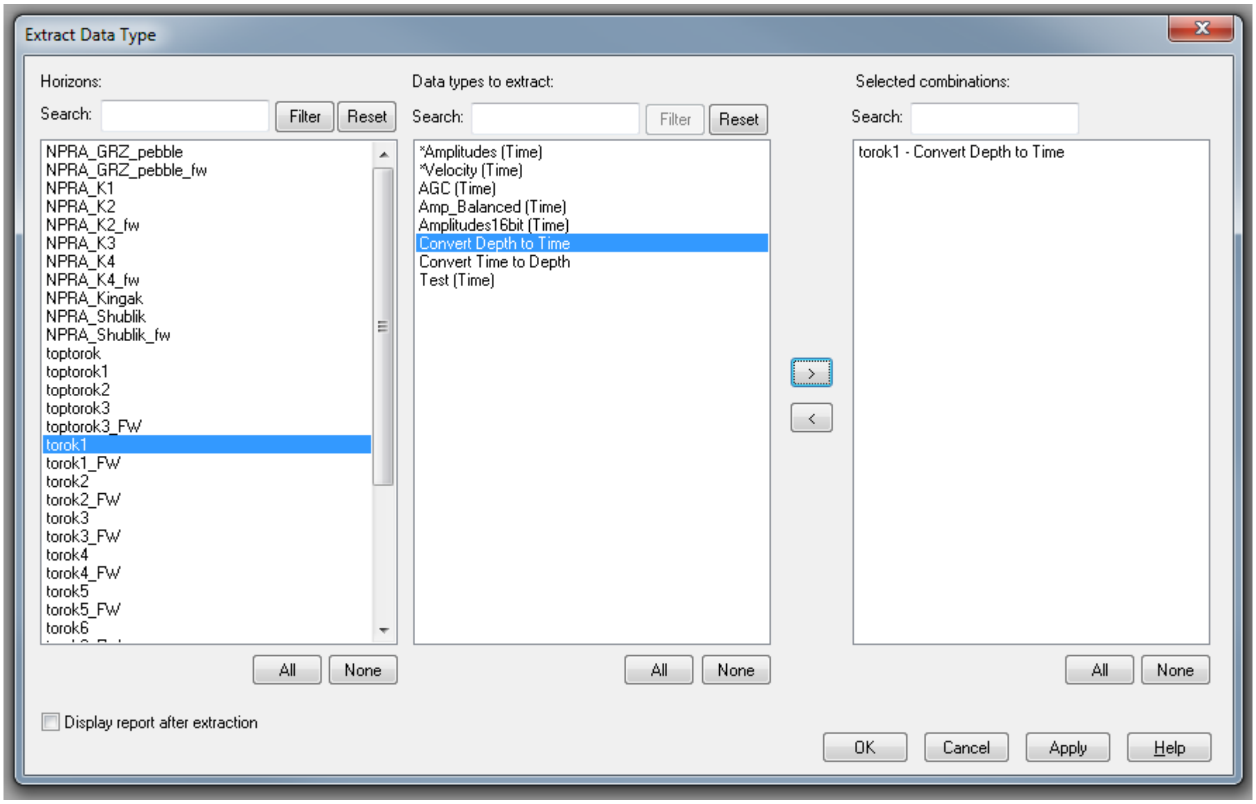


Figure A-3. Extract Data Type tab used for depth conversion of horizons.

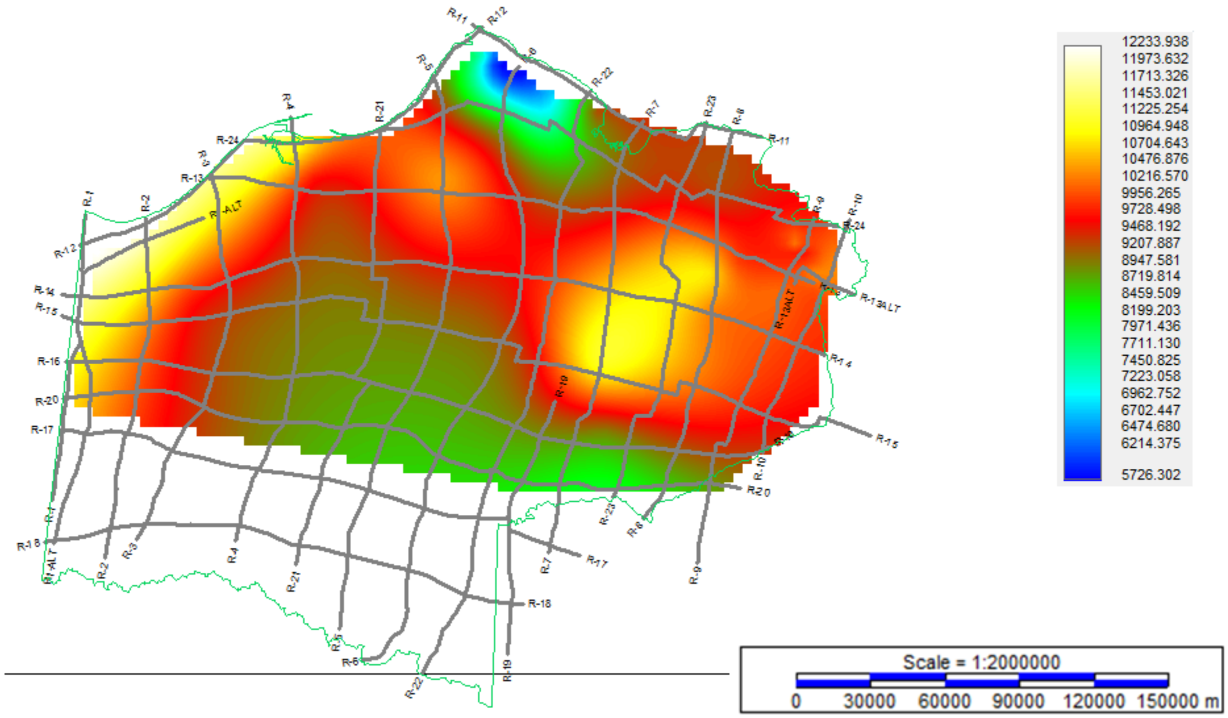


Figure A-4. Sample velocity horizon for the Torok layer in the Dynamic Depth Conversion model.

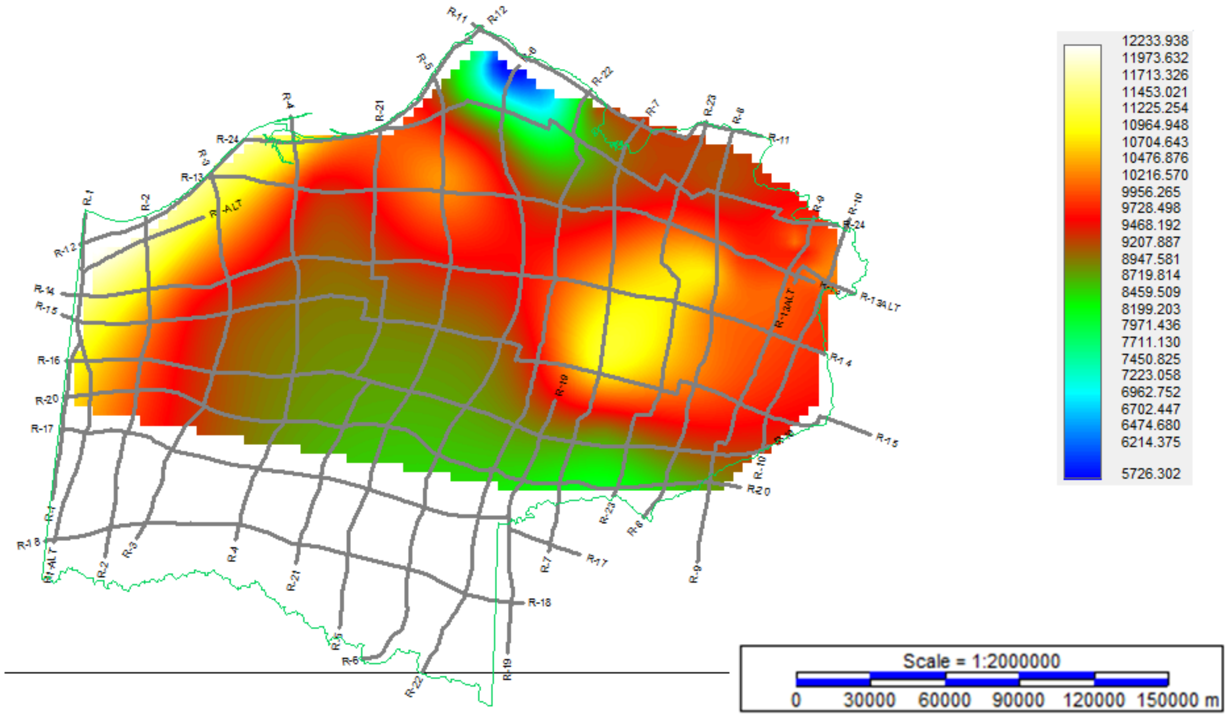


Figure A-5. Sample velocity horizon for the Shublik layer in the Dynamic Depth Conversion model.