`

APTIAN/ALBIAN SEDIMENT VOLUME AND ACCUMULATION RATES, ALASKA NORTH SLOPE AND BEAUFORT SHELF, FROM SEQUENCE STRATIGRAPHIC INTERPRETATION AND MODELING

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ABSTRACT

We present a regional sequence-stratigraphic interpretation of the Torok-Nanushuk clinothem in the National Petroleum Reserve of Alaska (NPRA), Alaskan state lands and Beaufort shelf using 2-D seismic reflection data, augmented by surface and well data. We take into account the adjacent geology in a consistent regional context. This interpretation refines previous interpretation of the Aptian-Cenomanian clinothem. From this interpretation, we created a 3D model which includes nineteen individual sequences, each representing approximately 1 Ma of sedimentation. We calculated sediment accumulation volumes and rates for the Torok-Nanushuk system represented in the study area. Our bulk estimates of volume in the study area is more than than 638,660 km^3 deposited over 20 million years, or an average of 0.08 km per million year. This is a minimum rate for the total Torok-Nanushuk sequence in Arctic Alaska, as we do not take into account erosion or decompaction.

Along the southwestern edge of the Coleville basin, the Torok Formation onlaps the Lower Cretaceous Mount Kelly Graywacke and interfingers Fortress Mountain Formations. Onshore, the Torok-Nanushuk clinothem downlap onto a relict shelf margin which was later draped by a marine transgressive unit, the Hauterivian-Aptian pebble shale unit and gamma ray zone. Offshore, the Torok-Nanushuk clinothem downlap onto a lower Cretaceous unconformity. The ultimate shelf margin occurs just east of the Coleville River, where it is terminated by a lowstand sequence boundary.

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Introduction

More than 40% of the total undiscovered oil and gas resource potential within the United States is in Alaska (Bird, 2001). This is mostly concentrated in northern Alaska, where two of North America's major petroleum provinces hold reserves of approximately 20 billion barrels of oil (Hubbard et al., 1987). The discovery of the Prudhoe Bay field in 1967 brought about much interest in Arctic Alaskan geology. Despite the region's abundant resource potential, the region remains relatively unexplored because of the harsh and remote Arctic environment.

Arctic Alaska, the northern terminus of the American Cordillera, was assembled through the accretion of a number of paleoterranes (Bird, 2001). Episodes of rifting, orogenic activity, and the emplacement of exotic terranes developed a geologically complex region, with several depocenters that have experienced numerous deformation events. Within the stratigraphic section of this region, there are several source rocks and potential reservoir rocks. Although there is a lot of research concerning Arctic Alaska's petroleum potential, the rich tectonic history is yet to be fully resolved.

Motivation

This paper aims to refine the current understanding of the stratigraphic and tectonic development of the Coleville basin in northern Alaska from Cretaceous Aptian to Albian time, which constrains sedimentation volume and timing across the Coleville basin. One of these horizons is currently being pursued as a reservoir in a play on the North Slope, and discerning sedimentation rates and volumes has major implications for understanding the thermal maturation history of the reservoir (Bailey, 2016). In order to create this project, we utilized geophysical and log data that was provided to us by the United States Geological Survey.

Overview of the Study Area

The 400,000 square kilometer area of Arctic Alaska borders Canada to the east, the Chukchi and Beaufort seas to the west and north, and the Yukon Flats and Koyukuk basin to the south (Moore et al., 1994). Moore et al., (1994) define three physiographic provinces in northern Alaska: the Brooks Range, the Arctic Foothills, and the Coastal Plain (Figure 1). The Brooks Range, an east-trending mountain belt, is the structural continuation of the Rocky Mountains in Alaska. North of the Brooks Range rest the Arctic Foothills, a sequence of rolling hills, mesas, and east-trending ridges that decrease in elevation northward, grading into the Coastal plain, or the Coleville Basin (Bird and Molenaar, 1992). The Barrow Arch separates the Coleville trough and the Beaufort Sea continental margin (Coakley, 1991).

Our study area encompasses approximately 169,125 km^2, including the entirety of the National Petroleum Reserve of Alaska (NPRA), and parts of the offshore Beaufort Shelf and the Alaskan state lands (Figure 2).

Geology of the Study Area

Tectonic History

The North American Cordillera, following along the west coast of North America, is considered to be the result of progressive accretion of allochtonous terranes associated with subduction (Miller et al., 2011; Strauss et al., 2013). The pericratonic Arctic Alaska terrane, due to its stratigraphic resemblance with the Chukotka peninsula of the Russian Far East, is thought to have been analogous with the Chukotka until the Cretaceous, when these terranes were rotated into their current positions (Embry, 2000; Miller et al., 2006). In its current position in the Arctic realm, the Arctic Alaska terrane, together with the Insular and Farewell terranes, developed successive Paleozoic and Mesozoic arcs and basins. (Colpron et al., 2007). These basins are the focus of this study.

The Late Proterozoic breakup of Rhodinia created a passive margin on the western side of Laurentia. Thick carbonate-shelf to deep-marine-slope deposits, which constitute the Franklinian acoustic basement rocks of the Arctic Alaska terrane, accumulated on the passive continental margin until the Devonian (Figure 3; Moore et al., 1994).

Onset of convergence in the middle-Paleozoic transformed the Laurentian passive margin into a subduction zone (Moore et al., 1994). The Late Devonian to Mississippian aged Ellesmerian orogeny emplaced an exotic terrane of unknown origin onto the northern edge of the continent (Embry, 1988). This deposited a Devonian foreland clastic wedge, similar to that of the Canadian Arctic Islands and northern Yukon territory (Gottlieb et al., 2014). Uplift and erosional unroofing caused by the Ellesmerian orogeny shed siliclastic sediment westward across the carbonate shelf, depositing a synorogenic clastic wedge, the Endicott Group (Mull et al., 1972; Gottlieb et al., 2014). Uplift in this orogeny also produced a pre-Mississippian angular unconformity, which involves deformed pre-Devonian and Devonian strata (Moore et al., 1994). The Ellesmerian orogeny deposited a clastic wedge, which is dated as young as early Mississippian (Gottlieb et al., 2014). Small latest Mississippian and Pennsylvanian accumulations of arkosic sandstone in the De Long Mountains subterrane suggest a granitic source not found in the Arctic Alaska subterrane (Gottlieb et al., 2014). Mayfield et al. (1988) hypothesize a southern paleohighland, Nukaland, which sourced the granite and opposed the southern facing continental margin.

Latest Devonian to Middle Permian rifting generated a southward facing passive margin that endured until the Jurassic. Clastic deposition of the Endicott Group ceased in the Late Mississippian, and carbonate-platform rocks of the Lisburne group blanketed both margins of the epicontinetal basin (Moore et al., 1994). Carbonate deposition continued until middle Pennsylvanian time (Bird and Molenaar, 1992).

Uplift in the northern highlands in Latest Permian time eroded and deposited transgressive siliciclastic deposits to alluvial-fan deposits of the Sadlerochit Group across the subsiding Lisburne carbonate platform (Bird, 2001). The Sadlerochit Group gradually thins northward, as it inherited irregular basin topography (Bird, 2001). The Shublik Formation, an organic-rich shale, siltstone, and limestone, was deposited over the Sadlerochit Group during a period of marine transgression. The depositional environment of the Shublik was oxygen-depleted and episodically upwelled, creating ideal conditions for the Shublik as a generous source rock (Moore et al., 1994).

The Canadian basin opened by counterclockwise rotation of the Arctic Alaska plate about a pole near the Mackenzie Delta (Embry, 2000). Episodes of failed Jurassic and successful Cretaceous rifting of the Canadian Basin are recorded in the Beaufortian sequence, a synrift megasequence (Figure 3). The primary stratigraphic unit of the megasequence, the southward-offlapping Jurassic-Lower Cretaceous Kingak Shale unit, thins southward, culminating in a relict shelf margin (Houseknecht and Bird, 2004). This unit is further cut down to the north by the Lower Cretaceous Unconformity (LCU), a breakup unconformity that formed as a response to regional uplift of the Barrow arch (Grantz and May, 1982).

Synchronous with the rifting of the Canadian Basin to the north, subduction beneath the Koyukuk Arc closed the Angayucham ocean, colliding the Angayucham terrane with the Arctic Alaska terrane. This series of events resulted in the diachronous Brookian orogeny (Moore et al., 1994). Contemporaneous to the onset of the Brookian orogeny, the western Chukotka terrane collided with the western edge of the Arctic Alaska terrane (Miller et al., 2006). Synorogenic sediment from the Chukotka collision filled the Coleville basin, from the west to the east, recorded by the Torok-Nanushuk formations (Houseknecht et al., 2009). Late Brookian tectonism uplifted the Brooks Range. Consequent erosional unroofing shed huge volumes of clastic debris northward into the Colville basin and southward into the Koyukuk basin (Moore et al., 1994). Late Cretaceous to Tertiary north-vergent thrusting resulted in northward prograding sediments of the Coleville Group (Figure 3; Moore et al., 2004).

The Brooks Range developed in two phases (Moore et al., 2004). In the first stage, arc-continental collisions deformed the Ellesmerian and Beaufortian strata from approximately 160-120 Ma (Moore et al., 2004). The deformation exploited the weaker layers into detachments, imbricating the stronger stratigraphic layers. The second stage occurred 60 Ma, reactivated at 45 Ma and continues into the present (Moore et al., 2004). Thrusting in the late Early Cretaceous occurred above a deep detachment that ramped up onto the Kingak Shale (Stier et al., 2014). This period of thick-skinned thrusting formed crustal scale duplexes in the Brooks Range and deposition of sediment in the north.

Aptian-Cenomanian clinothem

As mentioned above, the Coleville basin formed in response to tectonic loading by the uplift of Brooks Range and Herald Arch (Bird and Molenaar, 1992; Moore et al., 1994). Progressive filling of the Coleville foreland basin by eastward prograding Brookian strata in mostly Aptian to Albian time was sourced from the southwest, where the Chukotka terrane collided with the Siberian terrane (Figure 3; Miller et al., 2006; Houseknecht et al., 2009). Brookian strata are considered to be a typical flysch to molasses sequence, with the distal Torok prodelta shale and thinly bedded turbidites as the flysch and the overlying neritic Nanushuk deposits as the mollasse (Figure 3; Mull, 1985). These sediments were most likely deposited at depths ranging from 700 to 1400 m (Bird and Molenaar, 1992). The Hue Shale represents the distal facies, and is expressed seismically as bottomset reflectors (Houseknecht et al., 2009). These formations are expressed in seismic as offlapping reflectors (Kerr, 1985).

Total sediment thickness

In the Coleville basin, the total volume of the sediments younger than the Franklinian basement is greater than 12 km^3 in some depocenters (Saltus et al., 2003). The major depocenters in this study area are the onshore Coleville trough and the Beaufort Sea continental margin.

METHODS

Data

To interpret the subsurface of the study area, we used over 100,000 line km of 2D seismic data provided to us by the USGS. Some of the data is available to the public as part of the USGS's efforts to evaluate the petroleum potential of Arctic Alaska. Part of the dataset is proprietary industry seismic data, which while not shown in this report, was used in this interpretation.

We completed our interpretation using IHS Kingdom® Suite. We augmented our seismic interpretation by lithostratigraphic picks and surface maps. Dr. Kenneth J. Bird from the U.S. Geological Survey picked lithostratigraphic formation tops in the 272 wells within our study area. Natalie Stier '12 generated time to depth functions of several onshore wells (Stier, 2012).

Previous work

Our work is based off of previous Washington and Lee University undergraduate theses that focused on interpreting several onshore areas on the North Slope (Frierson, 2011; Stockmeyer, 2011; Stier, 2012; Schultz, 2013). This thesis extends and refines their interpretations, particularly offshore onto the Beaufort shelf and into the state lands east of the NPRA (Figure 2). We specifically focused on refining the interpretation of the Mount Kelly Graywacke, which is concentrated in the southwestern region of the study area. We tied our interpretation of the Mount Kelly Graywacke to surface data (Figure 4, 5).

Sequence stratigraphy

Sequence stratigraphers study the sedimentary response to changes in accommodation space and sedimentation rates (Catuneanu, 2006). Sequence stratigraphy incorporates principles from many geologic sub-fields, including sedimentology, stratigraphy, geophysics, geomorphology, isotope geochemistry and basin analysis (Catuneanu, 2006). In order to understand the development of the Coleville basin throughout time, we applied principles of sequence stratigraphy to our interpretation.

In order to fully understand this method, it is crucial to define the main constituents of the sedimentary record as described by sequence stratigraphy. The units of sequence stratigraphy are independent of scale, age, thickness, and lateral extent, and can therefore be used to describe strata at a broad range of scales (Galloway, 1989). Depositional facies are units of rock that record depositional environments (Galloway, 1989). A series of laterally correlative depositional systems form a systems tract (Brown and Fisher, 1977).

Systems tracts record shoreline shifts at each particular stage of basin fill. Multiple conformable and genetically related systems tracts, bounded by unconformities or correlative conformities, are considered a sequence (Mitchum, 1977). Unconformable boundaries signify changes in the depositional history of the basin. Changes in depositional trends of a basin are caused by erosion, sedimentation rates and base level changes (Catuneanu, 2006). Base level is the equipotential line where sedimentation and erosion are in equilibrium. Base level fall indicates a sequence boundary and regression of the basal surface, where as base level rise is expressed as a maximum flooding surface.

Seismic relationships between beds can be mapped to show changes in depositional systems (Figure 6). Truncated strata are eroded by a sequence boundary. Toplap describes strata that terminate against an overlying surface, usually signifying sediment starvation. Offlaping strata terminate deeper in the basin. Onlapping strata end against other surfaces. Downlapping strata terminate against strata that are down dip (Catuneanu, 2006).

Catuneanu (2002) developed a nomenclature for describing systems tracts (Figure 7). Systems tracts are used to determine sea level rise, fall and sedimentation patterns. Base level fall and forced regression describe a *falling-stage systems tract*. In a falling-stage systems tract, there is a high rate of progradation. Base level rise produces a *highstand systems tract*, characterized by a low rate of progradation and shoreline regression. Rising sea and base level and high sedimentation rates create a *lowstand systems tract*. A *transgressive systems tract* is created by base level rise at the shoreline and transgression.

Sequence stratigraphic interpretation

We used lithostratigraphic formation tops in order to correlate our subsurface interpretation to well data (Figure 8). We mapped horizons continuously, with the objective that the horizons would tie at seismic intersections and well formation tops. We verified and refined previous interpretations of the Basement, Shublik Formation, Kingak Shale, Pebble Shale formation, Torok and Nanushuk formations where necessary (Stier, 2012; Schultz, 2013). We extended all of these horizons to the north into the offshore Beaufort shelf and to the east into the state lands.

We utilized principles of sequence stratigraphy in order to interpret and characterize nineteen Aptian-Cenomanian clinothem, a significant though not every clinoform of the Torok-Nanushuk clinothem. We based eleven of the clinothem off of work by Lauren Schultz (2013). This group represents an estimated 20 million years. Each sequence was mapped on a strong peak reflector, which in seismic corresponds to a strong impedence contrast between rock layers (Badley, 1985). These horizons are expressed as offlapping reflectors in seismic data (Kerr, 1985). Sequences downlap onto the Hauterivian-Aptian pebble shale unit and gamma ray zone (Figure 8). Where the Pebble Shale Unit is missin, the sequences downlap onto the Lower Cretaceous unconformity. The Torok-Nanushuk clinothem constitute several stages of deposition, but all continue progradation from west to east across the Coleville basin, suggesting that there was a relatively large sediment influx (Houseknecht and Bird, 2009).

Model boundaries

We defined our model boundaries based off of the known extent of the Torok-Nanushuk clinothem (Figure 2). The model limit to the west is the western boundary of the NPRA. The Torok-Nanushuk clinothem extend farther west of this boundary. The southwestern limit to the model is the Aptian to Albian Fortress Mountain formation and Mount Kelly Graywacke, which the Torok formation onlaps (Mull, 1985, Moore et al., 2015). The eastern limit of our model is the ultimate shelf margin, studied by a previous Washington and Lee University undergraduate thesis (Frierson, 2011). At the ultimate shelf margin, deposition of the Torok Nanushuk formation ceased due to a major sea level transgression that deposited the Turonian-Coniacian Seabee and Tuluvak Formations (Houseknecht et al., 2005). The northern limit is a Cenozoic growth normal fault system that involved Torok-Nanushuk strata. The extent of the clinothem cannot be reliably mapped past these faults (Grantz, 1982).

Depth conversion

Seismic data is recorded in two way travel time on the vertical axis. Thus, the horizons and faults within the study area are mapped in time. In order to create a 3D model of the area, it was essential to convert the horizons from time to depth.

We incorporated information from the sonic drilling logs of nineteen onshore and offshore wells within our study area. Using measured depth and time information from the sonic drilling logs, we were able to convert the seismic data from time to depth (Stier, 2012; Frierson, 2011; Stockmeyer, 2011). We completed this math on the horizons within Paradigm® GOCAD® (Figure 9).

Model building

We exported twenty-two interpreted horizons from IHS Kingdom® Suite. It was necessary to decimate the horizons by a sampling rate of 10 in order to import them into Paradigm® GOCAD®. We preformed decimation within MATLAB®. Once imported into GOCAD®, we converted the horizon curves into depth by the computational tool within GOCAD®. Once converted into depth, we drew polygons around the horizons in order to define the limits of the surface. We created surfaces from the polygons. We constrained surfaces with horizon curves and polygon borders (Figure 10). Surface editing muted artifacts that were generated during model building.

The 3D model allows for the visualization of the rock horizons as surfaces in their modern day positions (Figure 11). The surfaces within the model do not account for the entire package of rock, because as of present day, significant portions of the rock strata have been eroded. The full extent of the west-to-east progradation of the Torok-Nanushuk clinothem from Aptian to Albian time is well visualized within the model (Figure 12).

Volume estimates

We extracted volume estimates from the 3D model. In order to account for the sections of the rock that was eroded to the present day, we attached the horizons to the present-day topographic surface (Figure 13). This constitutes the minimal volume estimate for these horizons.

In order to compute the volume of the horizons, we created SGrids (Stratigraphic 3D grids) for each horizon within GOCAD®. The SGrids were bounded between the surface of interest with topography, and the pebble shale unit (Figure 14). Each SGrid represents the entirety of the Torok-Nanushuk clinothem for each given time. From the SGrid, we extracted the volumes of the entire region.

DISCUSSION

Total volume and sedimentation rate estimates

Our bulk minimum volume estimate for the entire Torok/Nanushuk package within our 395,845 km^2 study area is 638,660 km^3 (D. Houseknecht, personal communication, 2016). Assuming a time of twenty million years, this bulk volume estimate corresponds to a mean sedimentation rate of 0.08m/1000yr. This is an underestimate because it does not take into account erosion and compaction. Total sedimentation increases linearly throughout time. In order to get a finer resolution on the sedimentation rates, we generated volume estimates for six different horizons within the model. According to Schwab (1986), sedimentation rates for foreland basin molasse deposits ranges from 0.1 to 0.4m/1000yr. Our estimates reveal that the sedimentation rates across the Coleville basin are on the lower end for sedimentation rates in foreland basins.

West-to-east progadation from shelf margins and 3D modelling

Within HIS Kingdom Suite®, we mapped the shelf-slope break of each horizon in order to create a shelf margin map (Figure 15). It is apparent from the shelf margin map that from Aptian to Albian time, the sequences prograded from west to east. As the horizons prograded offshore to the Beaufort shelf, the progradation shifts northwestward. West-to-eastward progradation is demonstrated in the 3D model (Figure 12).

The Jurassic-Lower Cretaceous Kingak Shale, a series of southward offlapping depositional sequences that fashion a relict, southward-sloping shelf margin that has more than 1 km of relief, creating accommodation space for the Aptian-Cenomanian clinothem. During a marine transgression, the Hauterivian-Aptian pebble shale unit and gamma ray zone was draped over the shelf margin. Offshore, the pebble shale unit is not present, exposing the lower Cretaceous unconformity. Onshore, the Torok-Nanushuk clinothem downlap onto the Hauterivian-Aptian pebble shale. The sequences offshore on the Beaufort shelf downlap onto the lower Cretaceous unconformity.

Sourced from the Chukotka highland uplift to the west, the Torok-Nanushuk clinothem prograde across the Coleville basin from west to east throughout Aptian to Albian time, filling the accommodation space left behind by the relict Kingak shelf margin and the foreland basin of the ancestral Brooks Range and Chukotka uplift. The accommodation space decrease laterally away from the axis of the Coleville Basin, (Figure 16) (Houseknecht et al., 2009). The reduction of accommodation space changes geometry of the sequences (Catuneanu, 2006). As the sequences prograde offshore onto the Beaufort shelf, the accommodation increases significantly. Offshore, the sequences are more condensed and less defined.

FUTURE WORK

Arctic Alaska is one of geology's remaining frontiers, and many first order geologic issues remain unresolved. Opportunities for future work include structural balancing and restoration of previously generated interpretations in order to verify interpretation, extending the horizons onto the Beaufort shelf and into Prudhoe Bay, and refining our interpretation of the southeastern corner of the NPRA. Further interpretation of onshore Alaska will develop our understanding of the geology of the region, allowing for us to eventually create an earth model of onshore Alaska.

The model and our sediment accumulation estimates could be refined by generating a depth conversion model that takes into account vertical velocity variation and by 3D backstripping the model in order to account for the full section of sediment that was laid down before it compacted and subsided.

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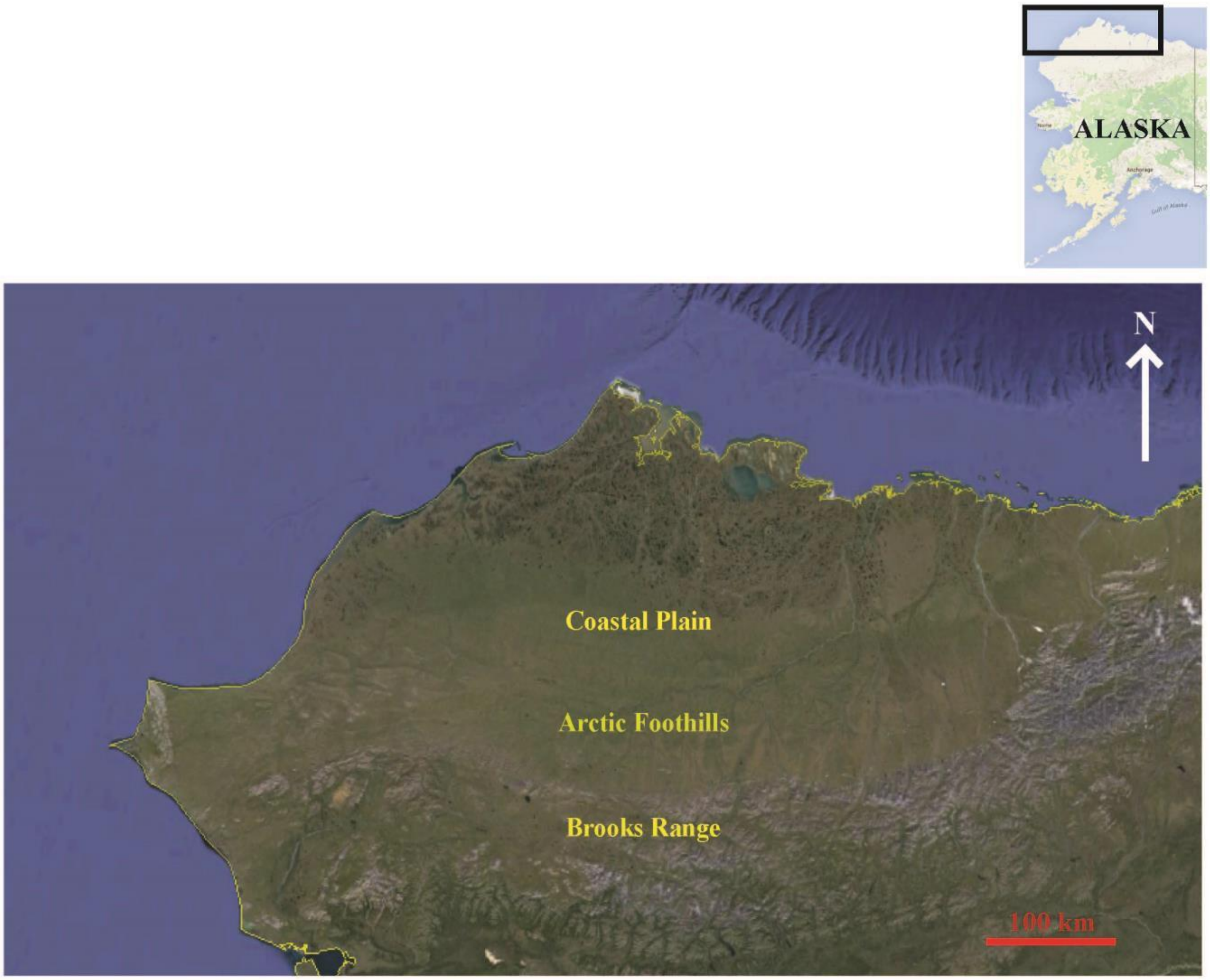

Figure 1: Google Earth image showing the physiographic provinces of Arctic Alaska: the Brooks Range, the Arctic Foothills, and the Coastal Plain. Inset is a Google Maps image of Alaska.

Figure 2: Extent of the study area, showing the seismic data used in the project. National Petroleum Reserve of Alaska (NPRA) is highlighted in gold. Inset is a Google Maps image of Alaska.

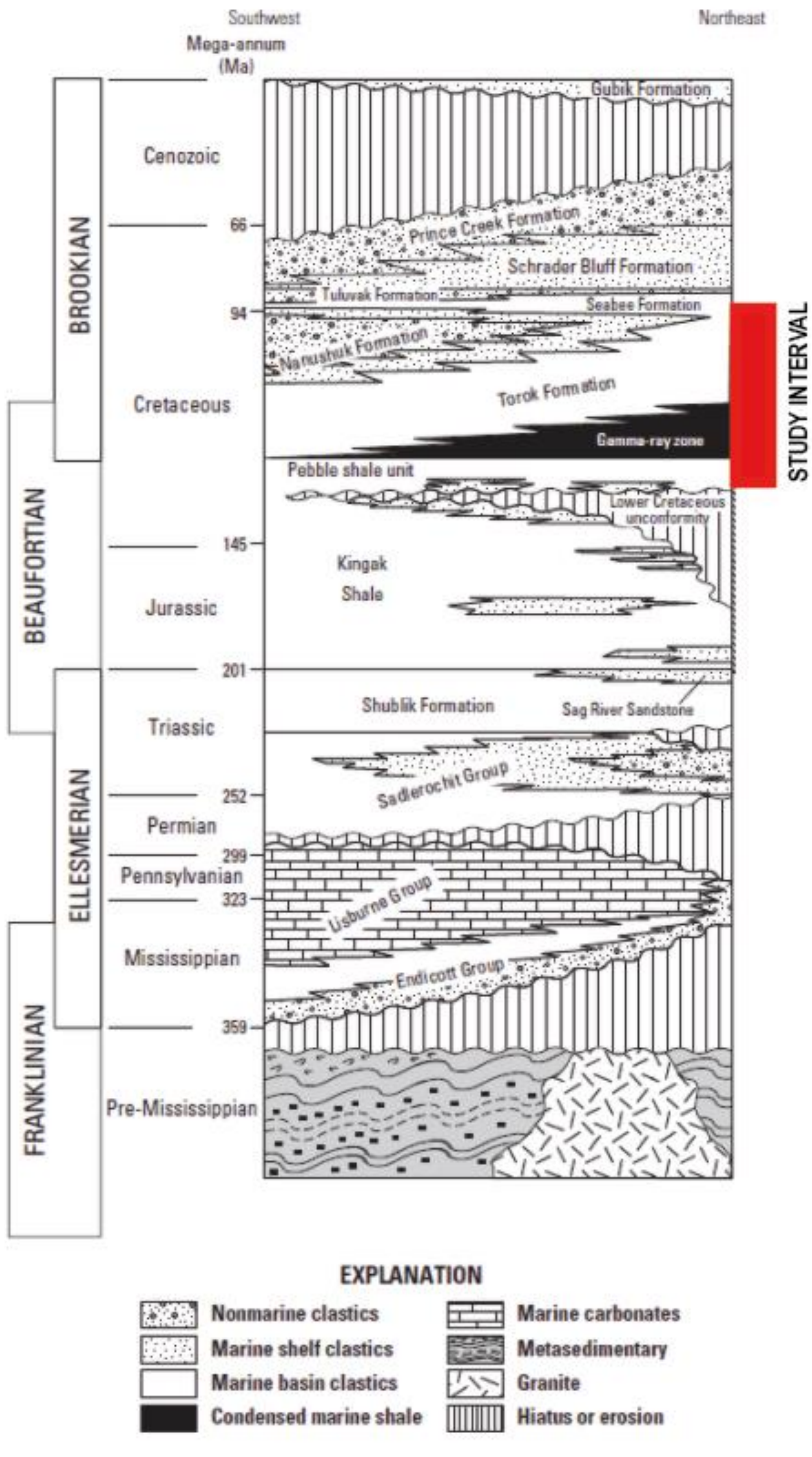

Figure 3: Chronostratigraphy of the North Slope. Franklinian, Ellesmerian, Beaufortian, and Brookian tectonostratigraphic megasequences are highlighted (modified from Houseknecht and Bird, 2004).

Figure 4: Base map showing the surface expression of the Mount Kelly Greywacke (brown). Inset is a Google Maps image of Alaska.

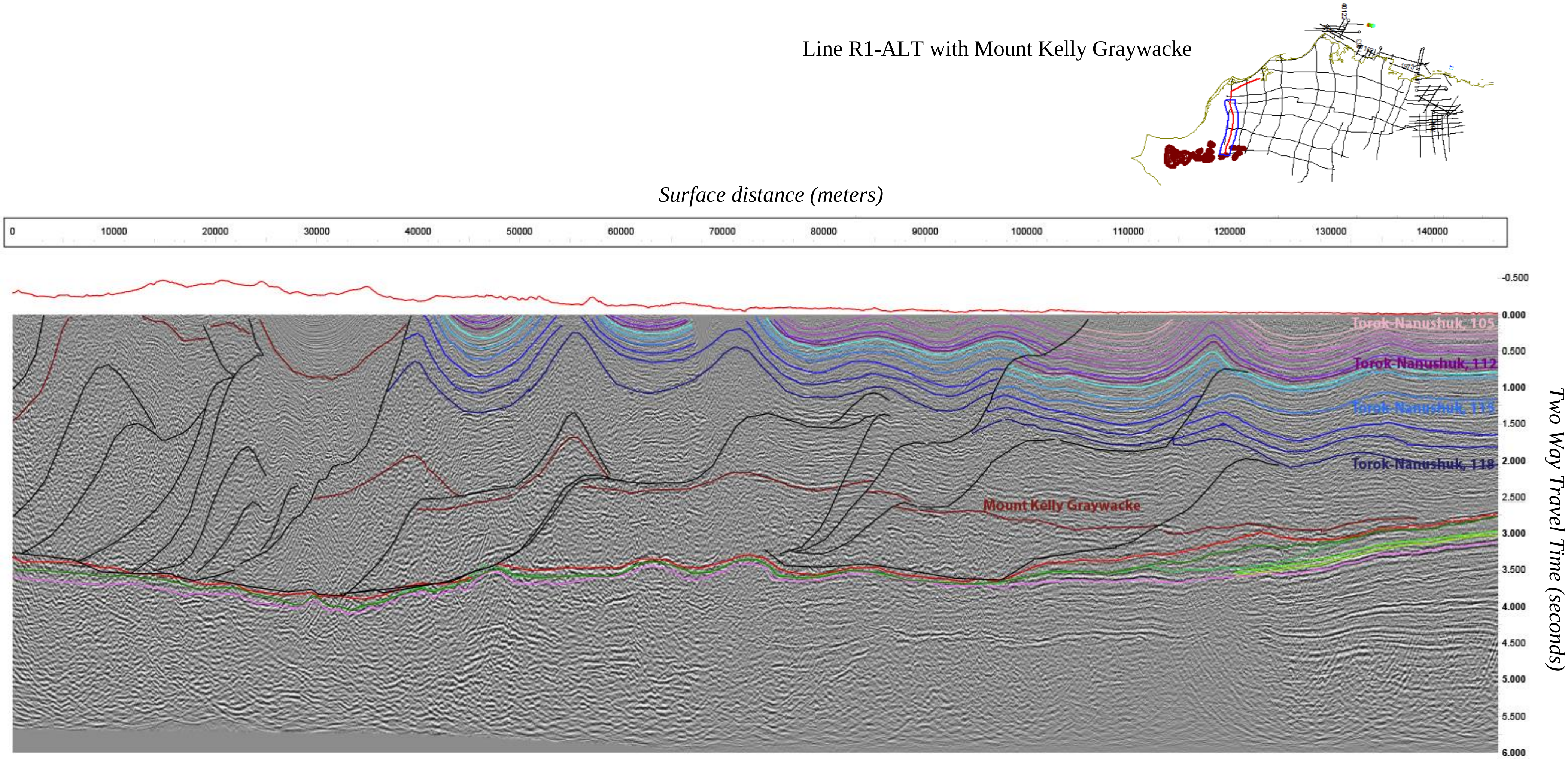

Figure 5: Interpretation of the Mount Kelly Graywacke in brown. Black lines represent faults. Our interpretation is tied to surface map data. 2:1 vertical exaggeration.

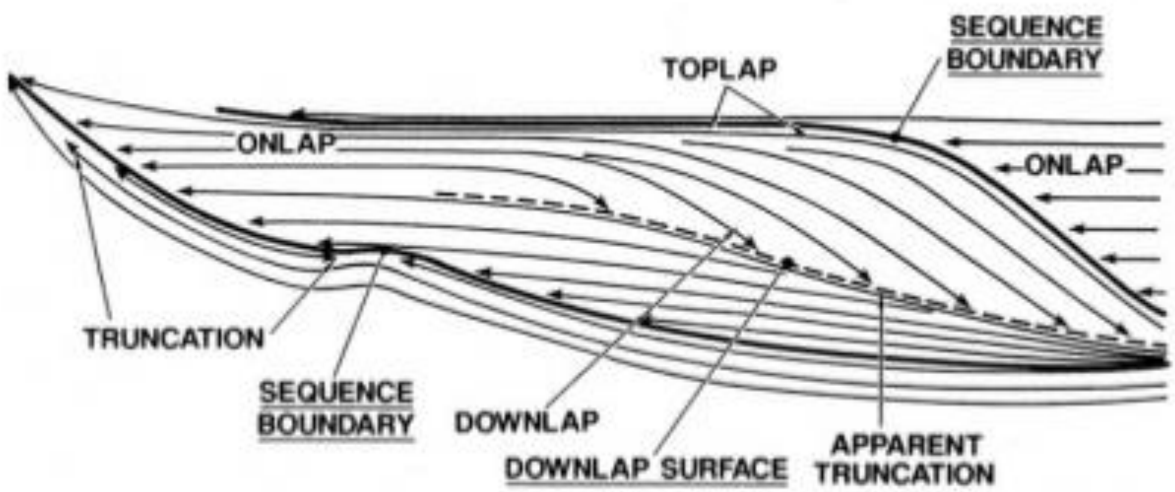

Figure 6: Description of possible relationships between surface boundaries, truncation, toplap, offlap, and downlap, originally described by Vail (1987).

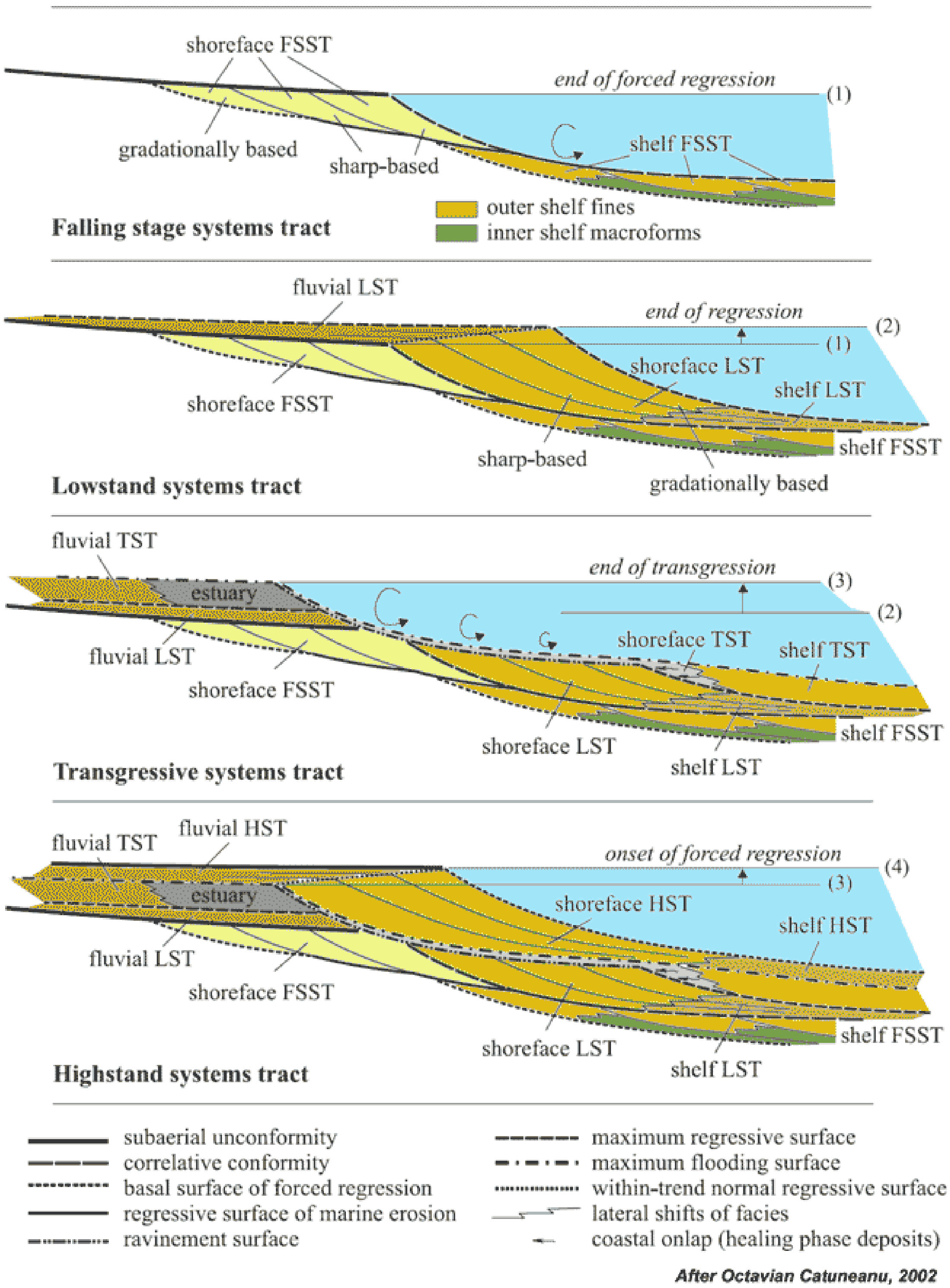

Figure 7: Regional architecture of systems tracts as described by Catuneanu (2002).

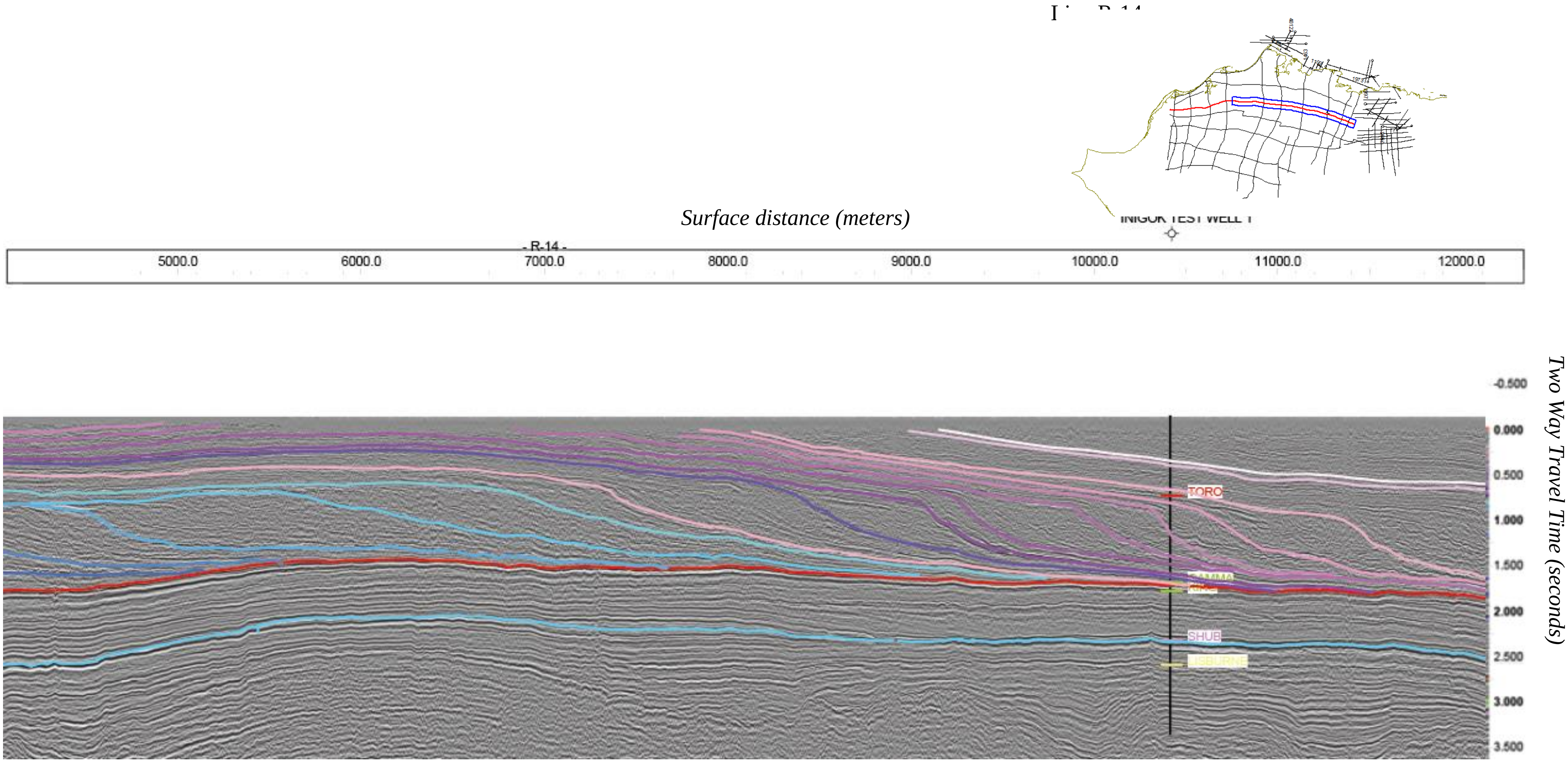

Figure 8: The Pebble Shale, Shublik Formation, and Torok Formations tied to U.S. Geological Survey picks in the Inigok Test Well. 2:1 vertical exaggeration.

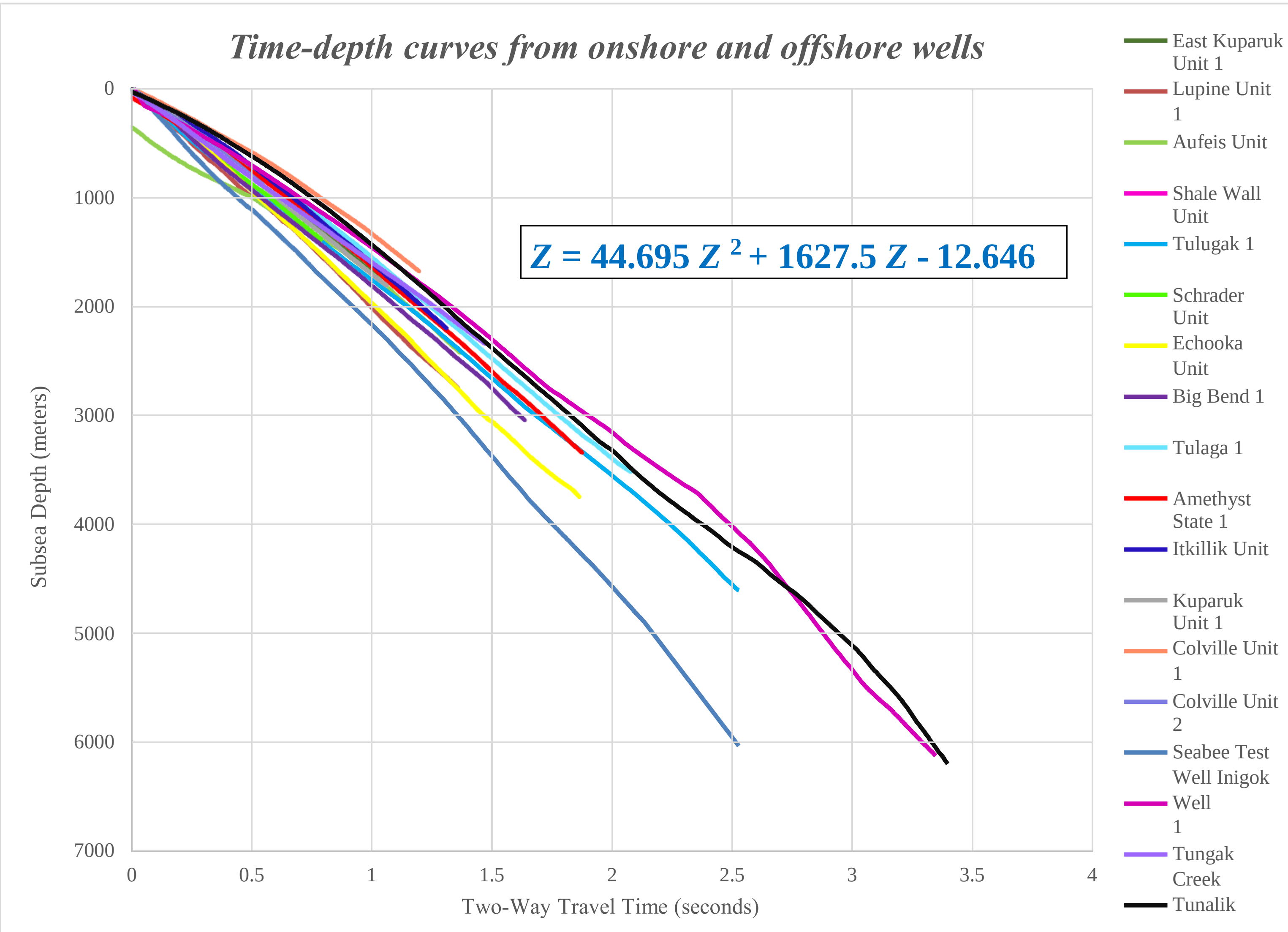

Figure 9: Depth as a function of average seismic reflection time for onshore wells, North Slope and State Lands. Polynomial function was generated as a mean of these curves and used to convert time to depth in meters.

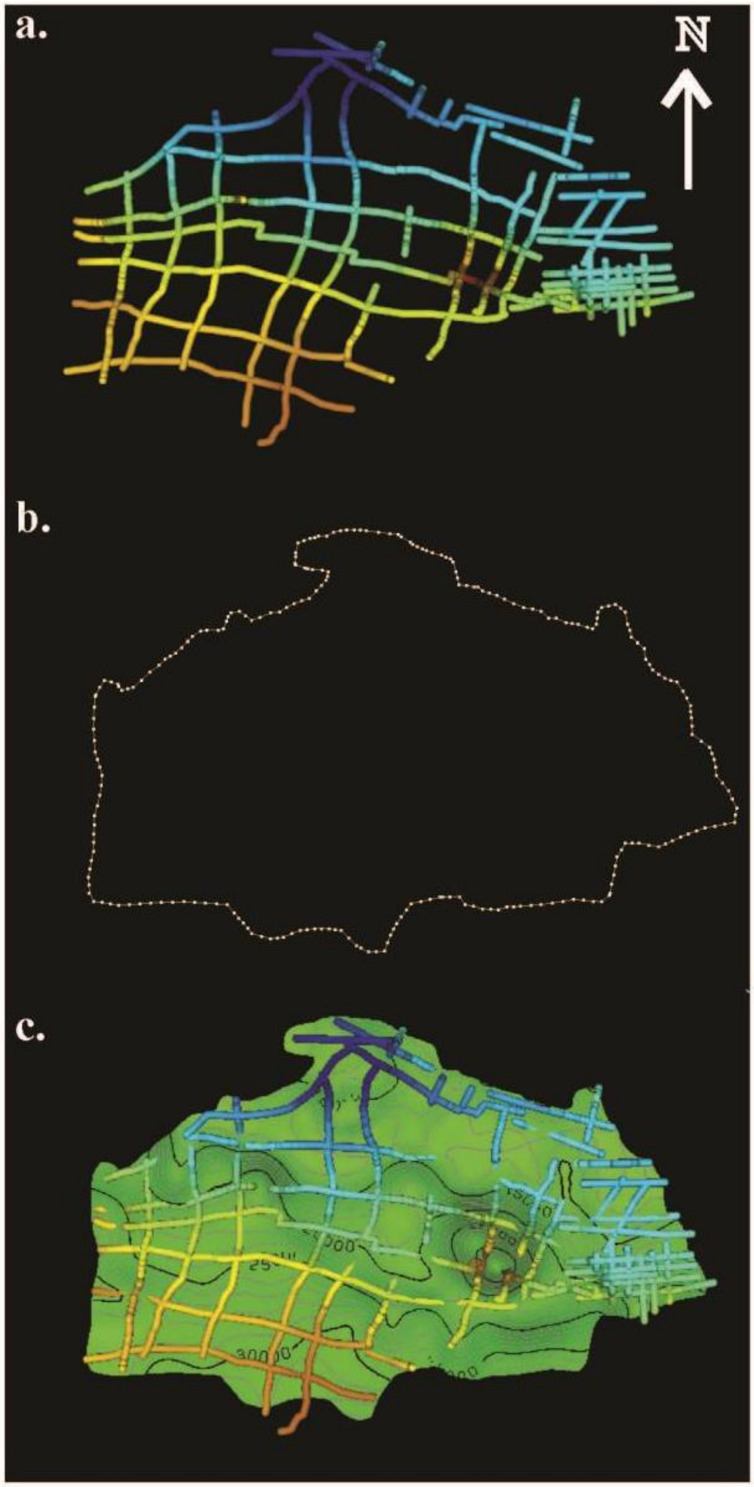

Figure 10: Steps to generating a 3D surface in GOCAD®: *a. Decimated horizons curves were brought into GOCAD®, b. polygons were drawn around the horizon curves, c. surfaces were generated from the polygons, constrained to horizon curves and polygon borders.* 5x vertical exaggeration.

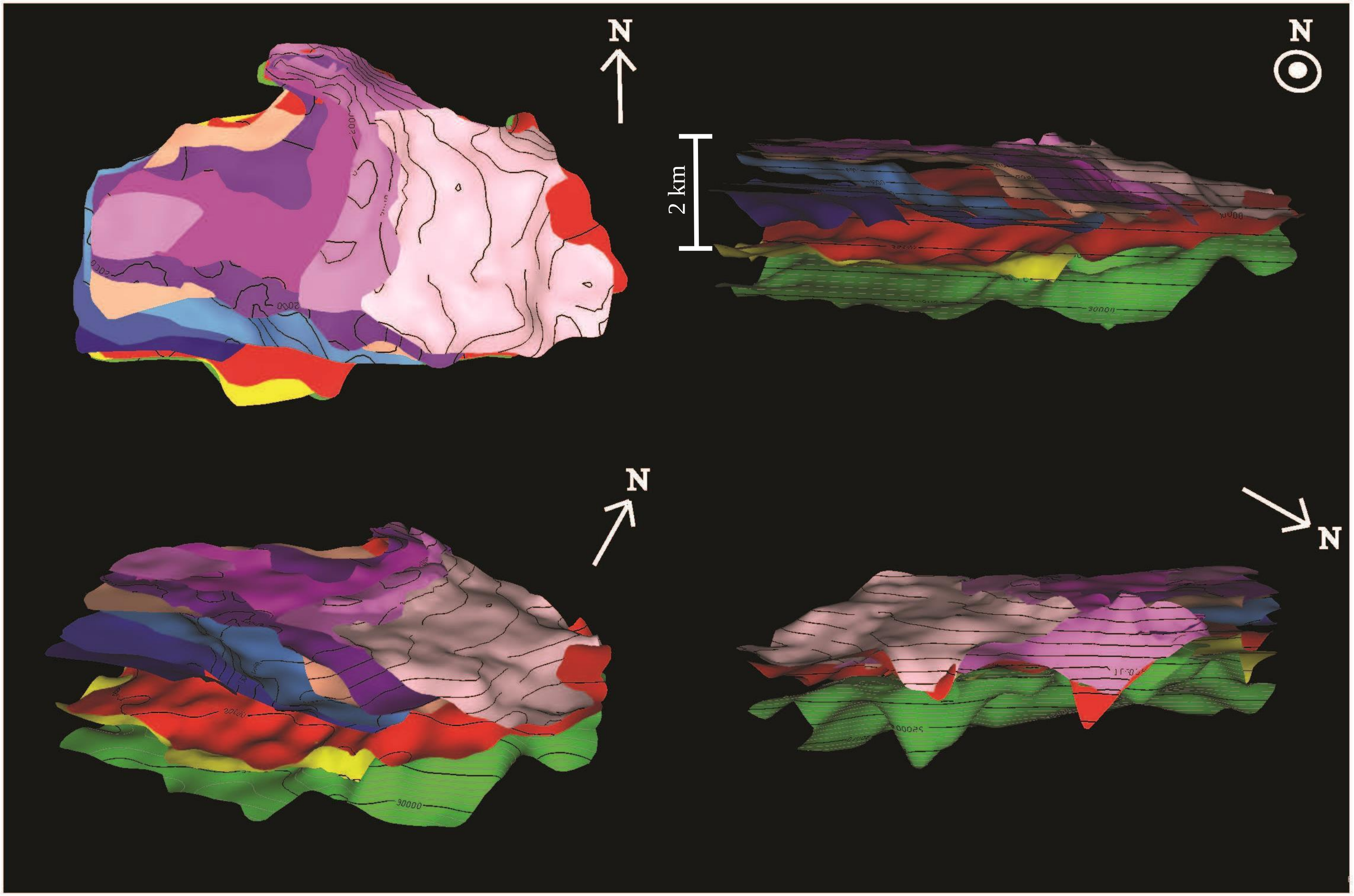

Figure 11: 3D model of the rock horizons shown in their modern day positions. Model is shown at different angles in order to visualize the horizons from different perspectives. Images from GOCAD®. 5x vertical exaggeration.

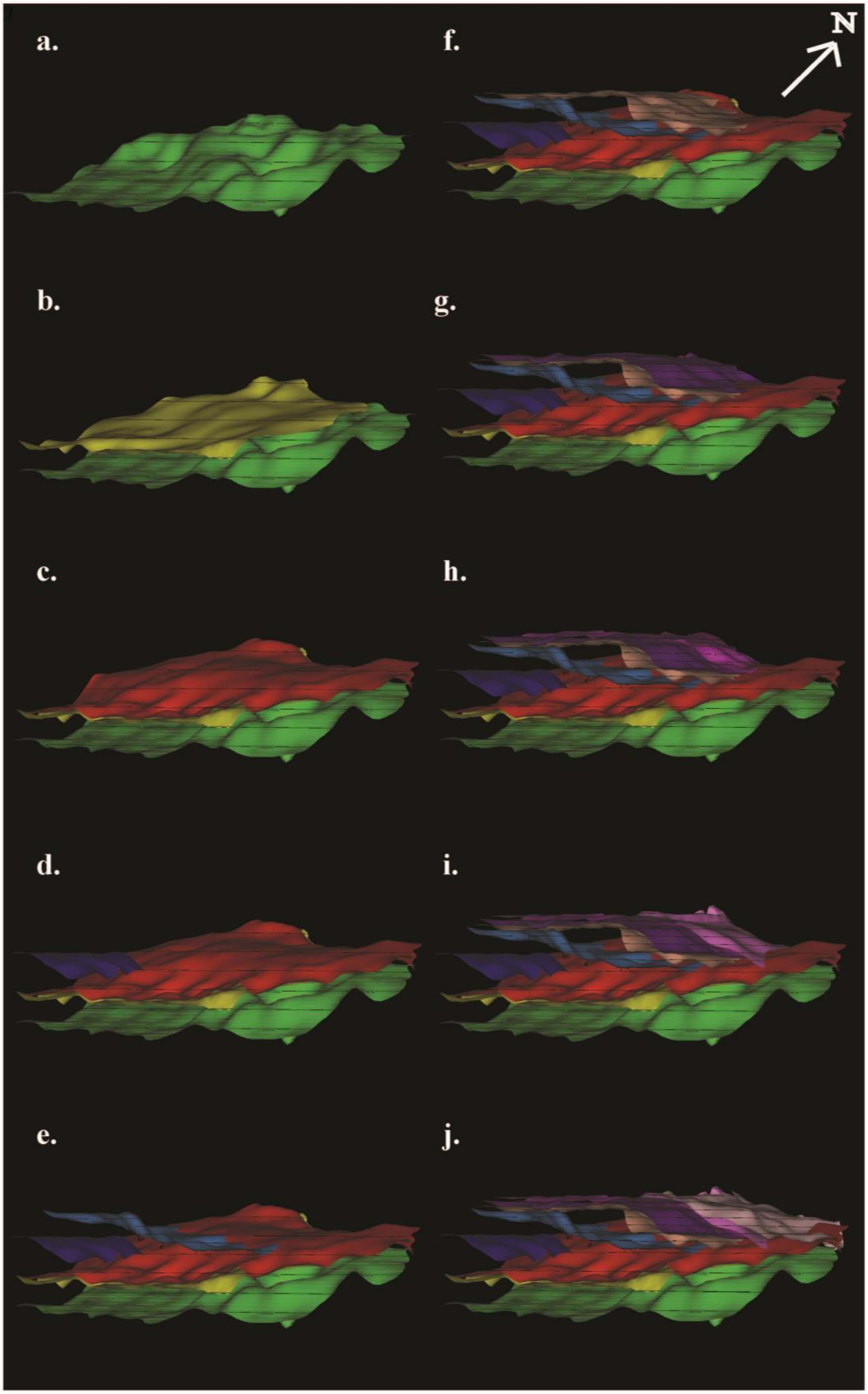

Figure 12: West to east progradation across the Coleville basin, as shown by the 3D model in GOCAD®, *a. Franklinian basement, b. Shublik formation, c. Pebble Shale Unit, d-j. Torok Nanushuk clinothem deposited west to east throughout time*. Images from GOCAD®. 5x vertical exaggeration.

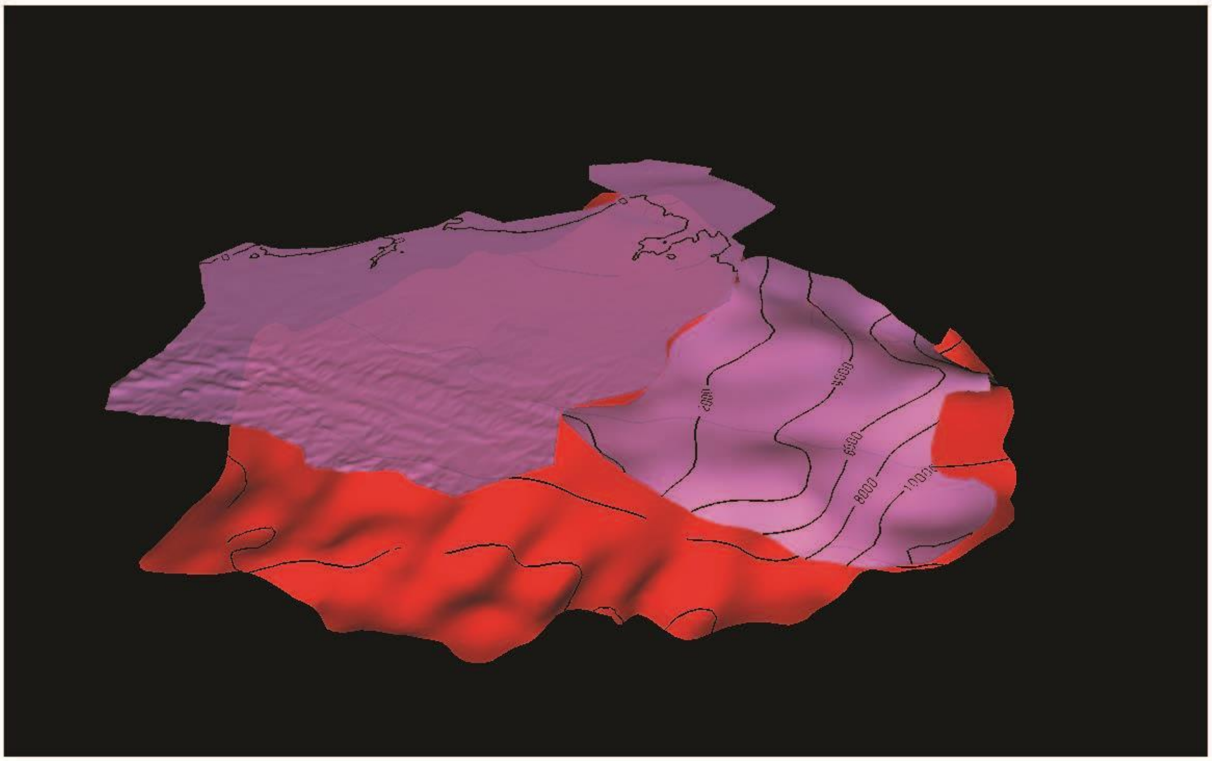

Figure 13: Surface attached to topographic surface downlapping onto the Pebble Shale Unit. Image from GOCAD®. 5x vertical exaggeration.

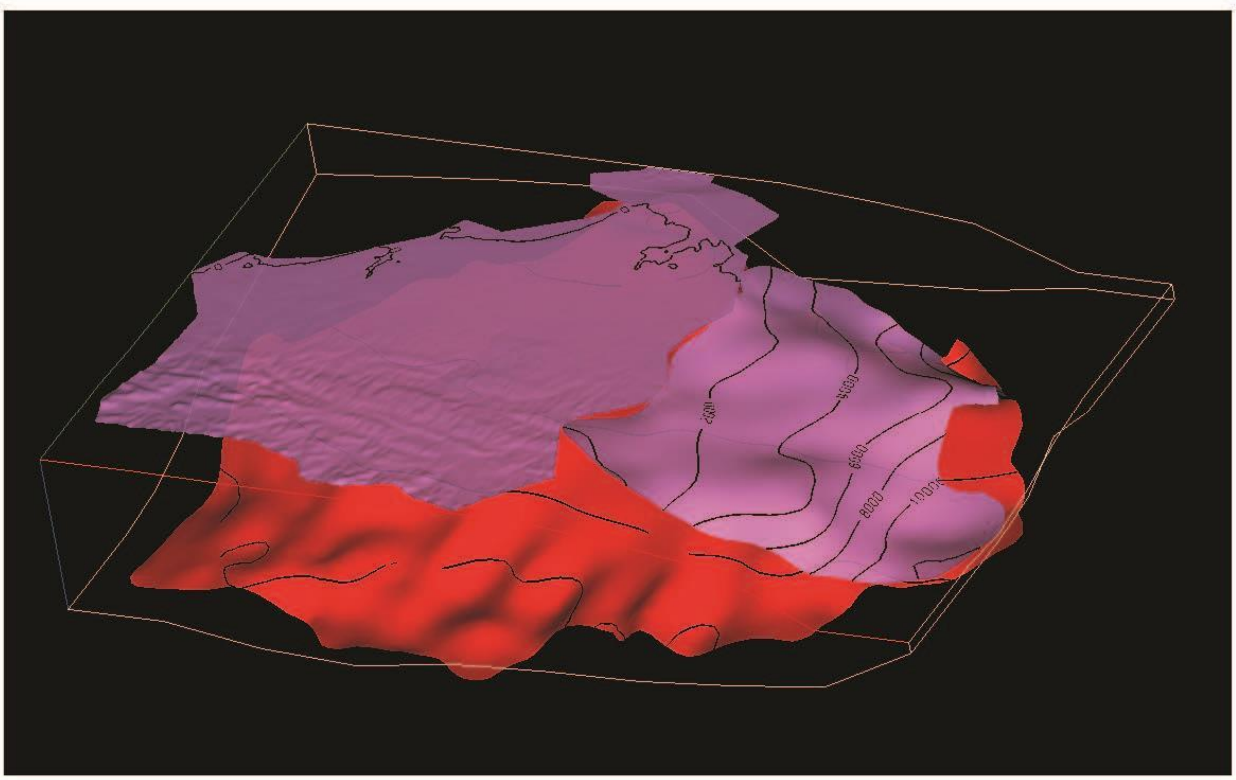

Figure 14: Shape is the SGrid (stratigraphic 3D grid) generated for a surface attached to the topographic surface and the Pebble Shale Unit. Image from GOCAD®. 5x vertical exaggeration.

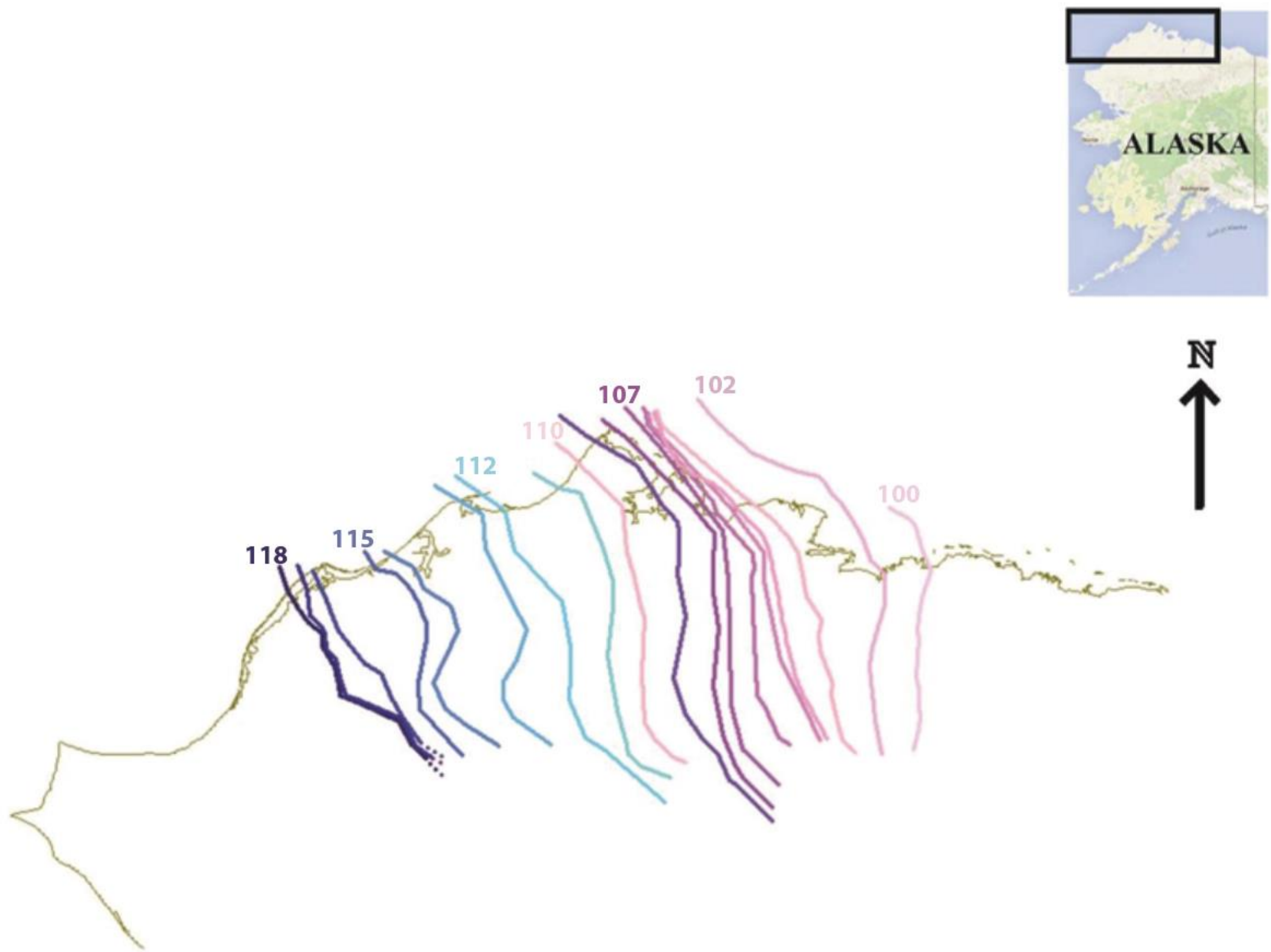

Figure 15: Torok-Nanushuk shelf margin map, showing west to eastward progradation. Modern day coastlines in yellow. Inset from Google Maps.

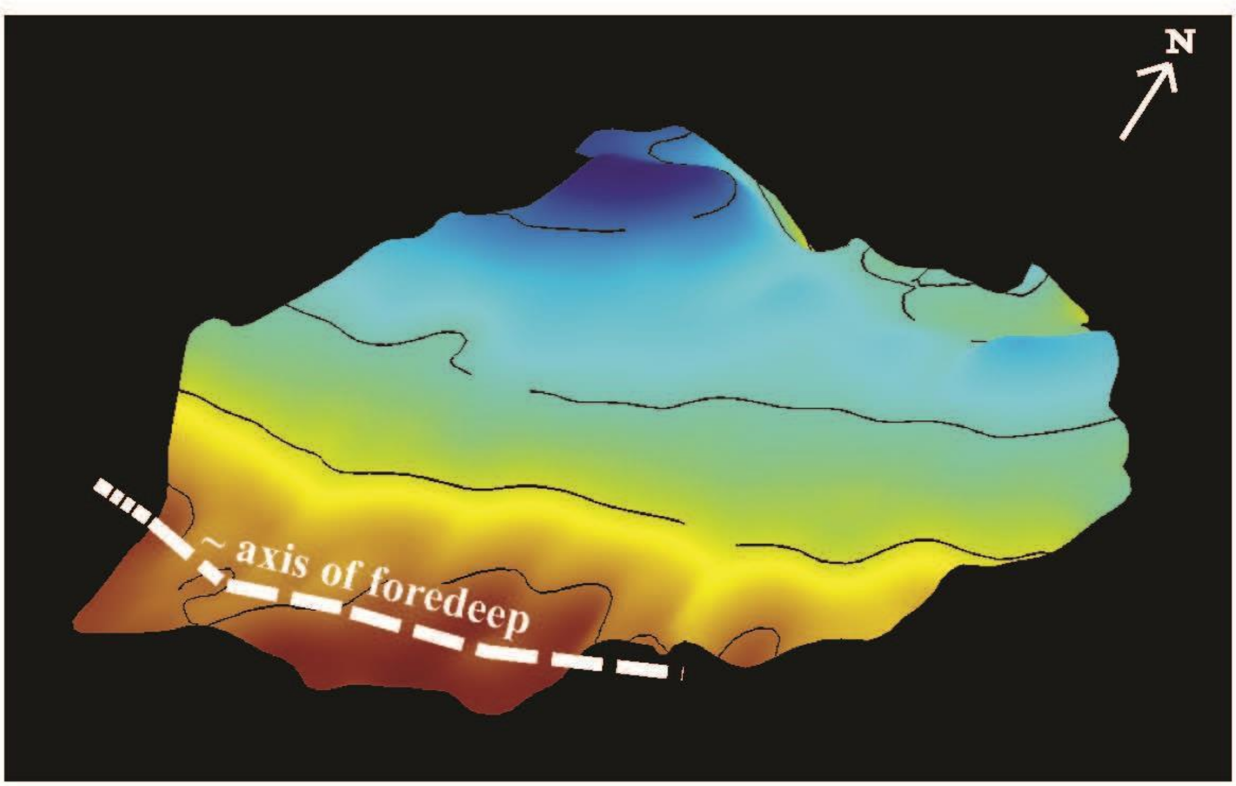

Figure 16: Pebble Shale Unit, the downlapping surface for the clinothem. Approximate axis of the foredeep highlighted. The accommodation space lessens as the distance from the axis increases. Image from GOCAD®. 5x vertical exaggeration.