Click to view animation of Reconstruction of Brookian Overburden (14.6 MB)
Click to view animation of Maturation of Triassic Shublik Formation (8.06 MB)
Click to view animation of Accumulations from Source Rocks Through Time (12.01 MB)

Timing of Petroleum System Events Controls Accumulations on the North Slope, Alaska*

Kenneth Peters[1], Oliver Schenk[2], and Kenneth Bird[3]

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Abstract

The Alaska North Slope is estimated to contain most of the undiscovered oil and gas in the circum-Arctic. Results from a calibrated 3D basin and petroleum system model for this region demonstrate the importance of the relative timing of trap formation and expulsion from the source rock. Petroleum system event charts for four examples from the model in the foothills of the Brooks Range, Prudhoe Bay, Mukluk, and the Barrow Peninsula show how the relative timing of these events impacts risk.

The event chart for a location in the foothills of the Brooks Range shows significant risk for accumulation in stratigraphic traps because they formed at about the same time as expulsion from the Triassic Shublik Formation source rock. Risk is also high for accumulations in structural traps formed after expulsion, because they can be filled only by remigration from older stratigraphic traps.

At Prudhoe Bay, trap formation preceded expulsion, resulting in a major accumulation. Biomarkers show that Prudhoe Bay Field contains mixed oil from the Triassic Shublik Formation and Cretaceous Hue-gamma ray zone (Hue-GRZ) with lesser input from the Jurassic Kingak Shale. These results are consistent with the 3D model, where the Shublik and Kingak source rocks started to expel petroleum during the Cretaceous, while the Hue-GRZ contributed later.

Debate persists over the reasons for failure of the Mukluk wildcat well. At the time of drilling, the Mukluk structure was estimated to contain 1.5 billion bbl of recoverable oil in a structural-stratigraphic trap, although subsurface imaging was uncertain due to difficulty in assessing seismic velocities through permafrost. Drill cuttings showed extensive oil stain in the target formation. The 3D model shows that petroleum accumulated, but spilled from the structure to the southeast through the Kuparuk C-D interval toward the Kuparuk River Field during Tertiary tilting.

Preliminary 3D simulations predicted a large petroleum accumulation on the Barrow Peninsula, although only a few small gas fields are known (S. Barrow, E. Barrow, Sikulik) near the Avak structure, which resulted from a middle-late Turonian meteorite impact. Our revised 3D model accounts for the effects of the meteorite impact on temperature and permeability of the target rocks. The model predicts a large accumulation prior to impact, but predicted present-day accumulations occur only to the west, south, and east of the Avak structure, in agreement with known accumulations.

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Peters K.E., L.S. Ramos, J.E. Zumberge, Z.C. Valin, C.R. Scotese, and D.L. Gautier, 2007, Circum-Arctic petroleum systems identified using decision-tree chemometrics: AAPG Bulletin, v. 91, p. 877-913.

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AAPG International Conference & Exhibition
Calgary, Alberta; September 12-15, 2010
Theme XV 9:05 am Wednesday

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K.E. Peters[1], O. Schenk[1], K.J. Bird[2]

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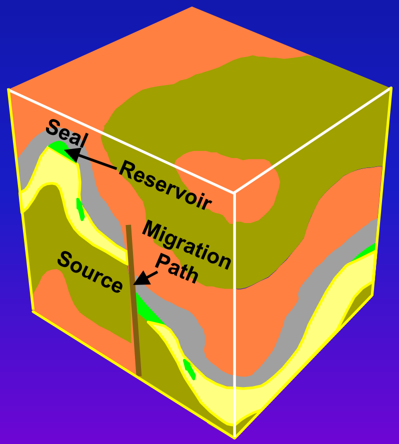
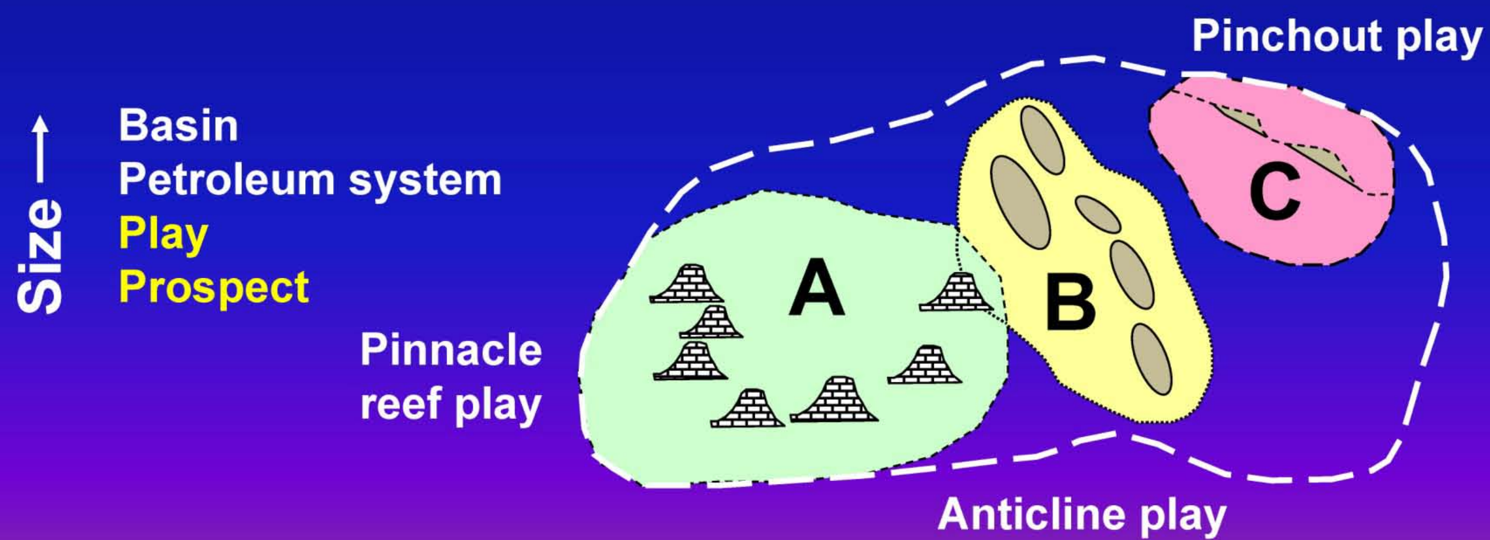
Purpose of the Presentation

- **Differentiate *static* 'play fairway' maps from *dynamic* basin and petroleum system models**
- **Provide four examples showing the importance of the timing of petroleum system events:**
  - ✓ **Prudhoe Bay**
  - ✓ **Foothills of the Brooks Range**
  - ✓ **Mukluk offshore wildcat well**
  - ✓ **Barrow Peninsula**



‘Play Fairway Maps’ Are Present-Day Snapshots That Neglect Event Timing

- **Prospect** - a potential trap that must be drilled to determine whether it is commercial.
- **Play** - fields and prospects having similar geology (e.g., reservoir, cap rock, trap type). Plays use discovered accumulations to risk undiscovered accumulations.



Notes by Presenter: Prospects disappear when drilled because they are either dry holes or discoveries.

What is a Petroleum System?

- four essential elements and two processes and all related petroleum that originated from one pod of active source rock

- Source rock
- Reservoir rock
- Seal rock
- Overburden rock

Essential Elements

- Trap Formation
- Generation-Migration-Accumulation

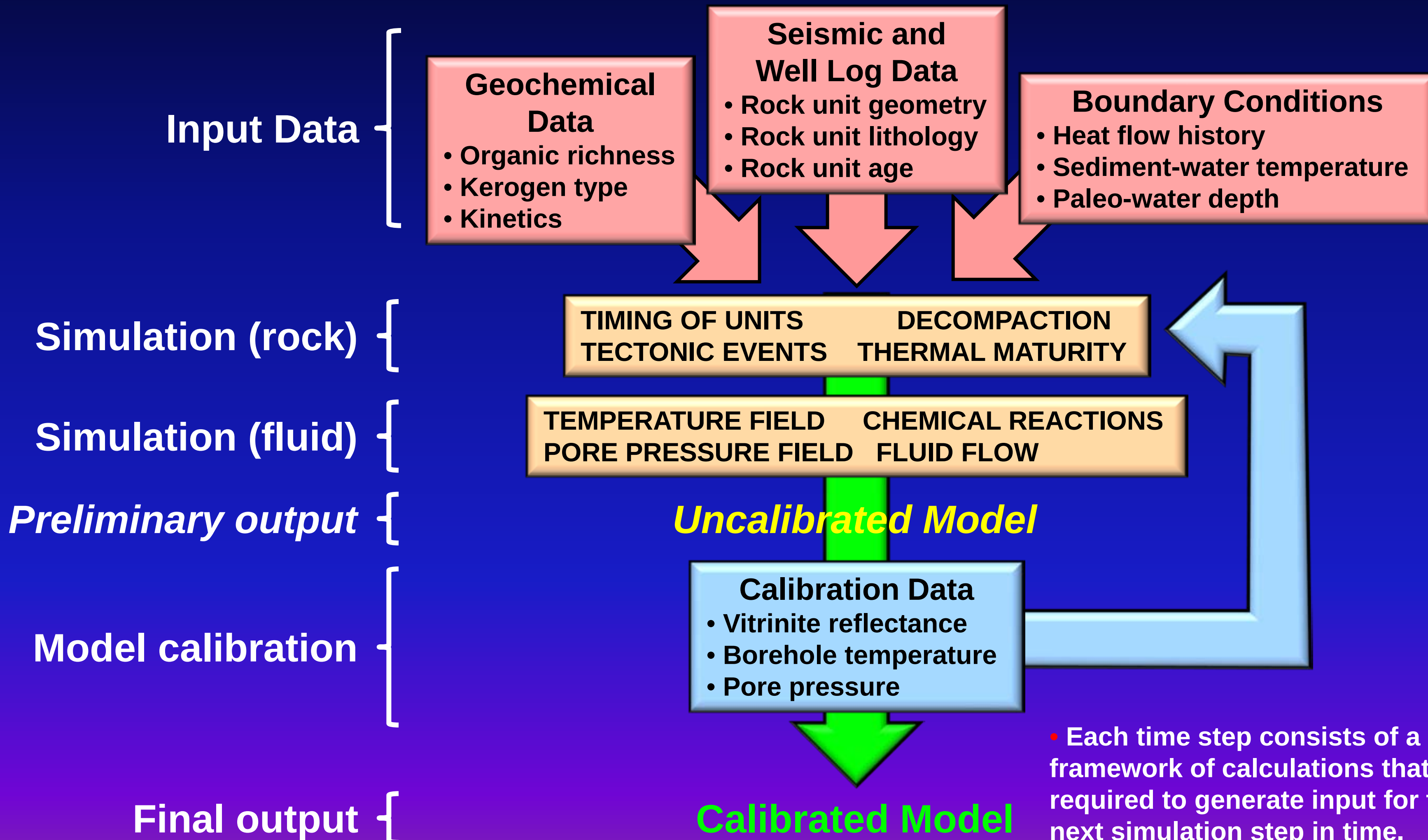
Processes

Magoon and Dow (1994)

What is Basin and Petroleum System Modeling (BSPM)?

- Basin modeling reconstructs the burial and temperature histories of the rocks
- Petroleum system modeling reconstructs the generation-migration-accumulation of oil and gas
- The term “basin modeling” is commonly used to include both of the above
- 1D, 2D, 3D models simulate geologic processes through time starting with deposition of the oldest layer; calculations are updated at each time step

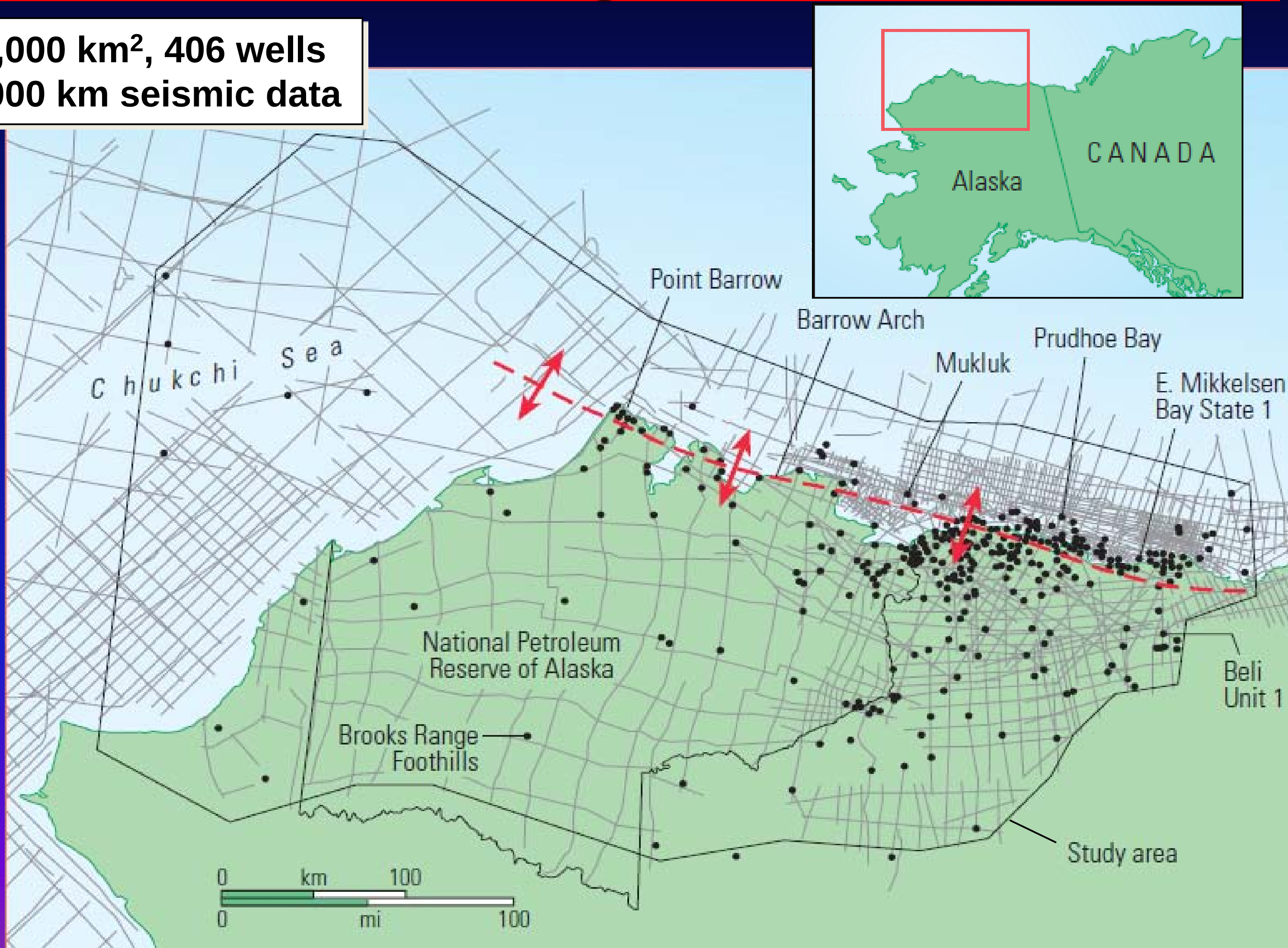
BPSM Workflow: Input, Simulation of Time Steps, Calibration of Output, Predictions



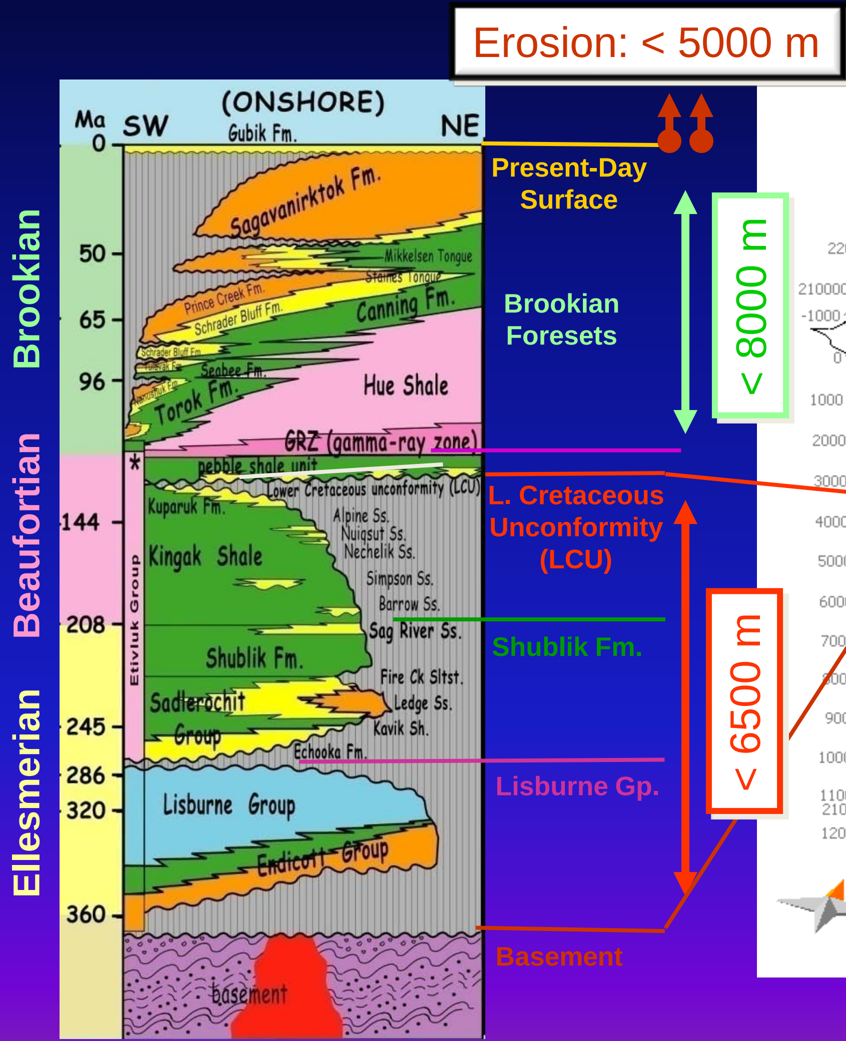
- Each time step consists of a framework of calculations that are required to generate input for the next simulation step in time.

Seismic Data Were Used to Create Subsurface Maps of Rock Units

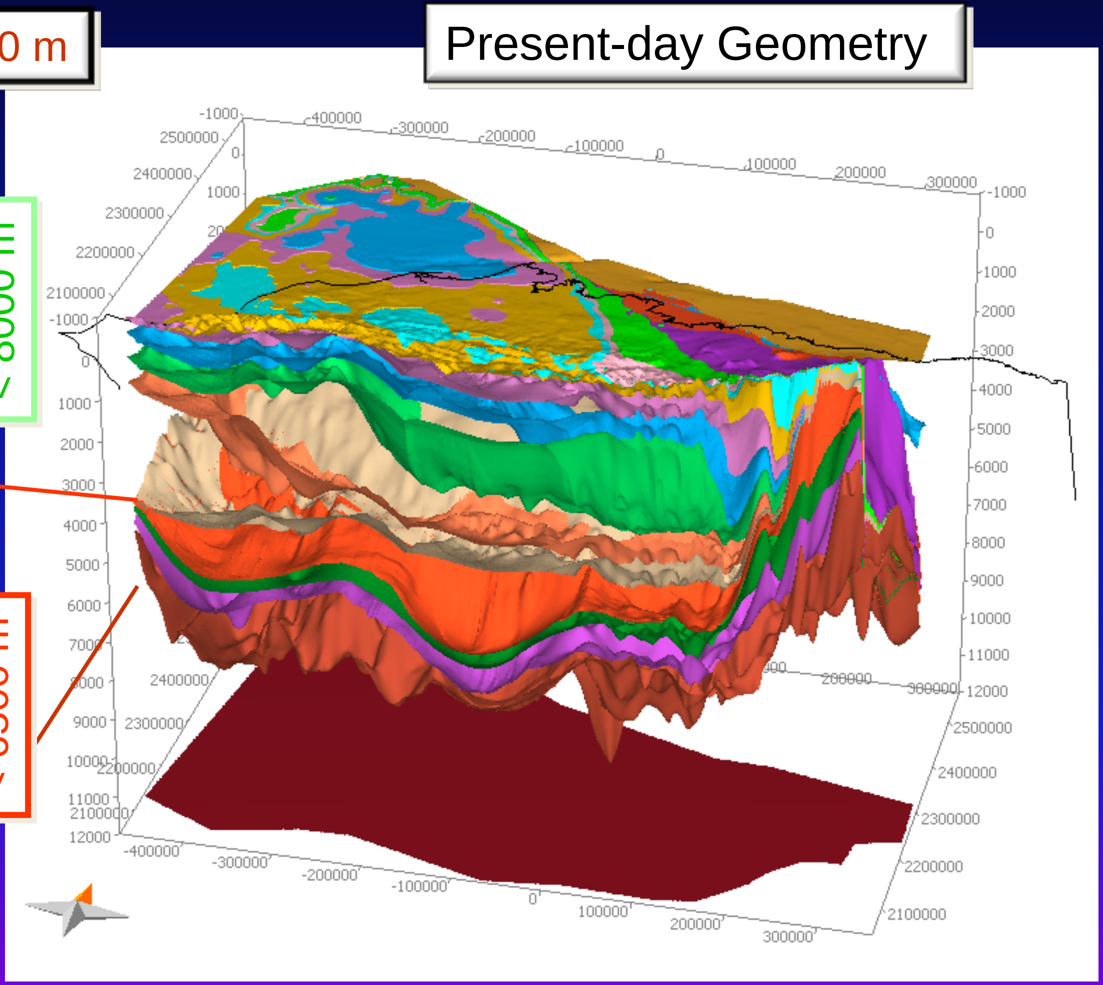
275,000 km², 406 wells
48,000 km seismic data



North Slope Model Includes Detailed Stratigraphy and Subsurface Maps



Houseknecht and Bird (2005)



Notes by Presenter (for previous slide):

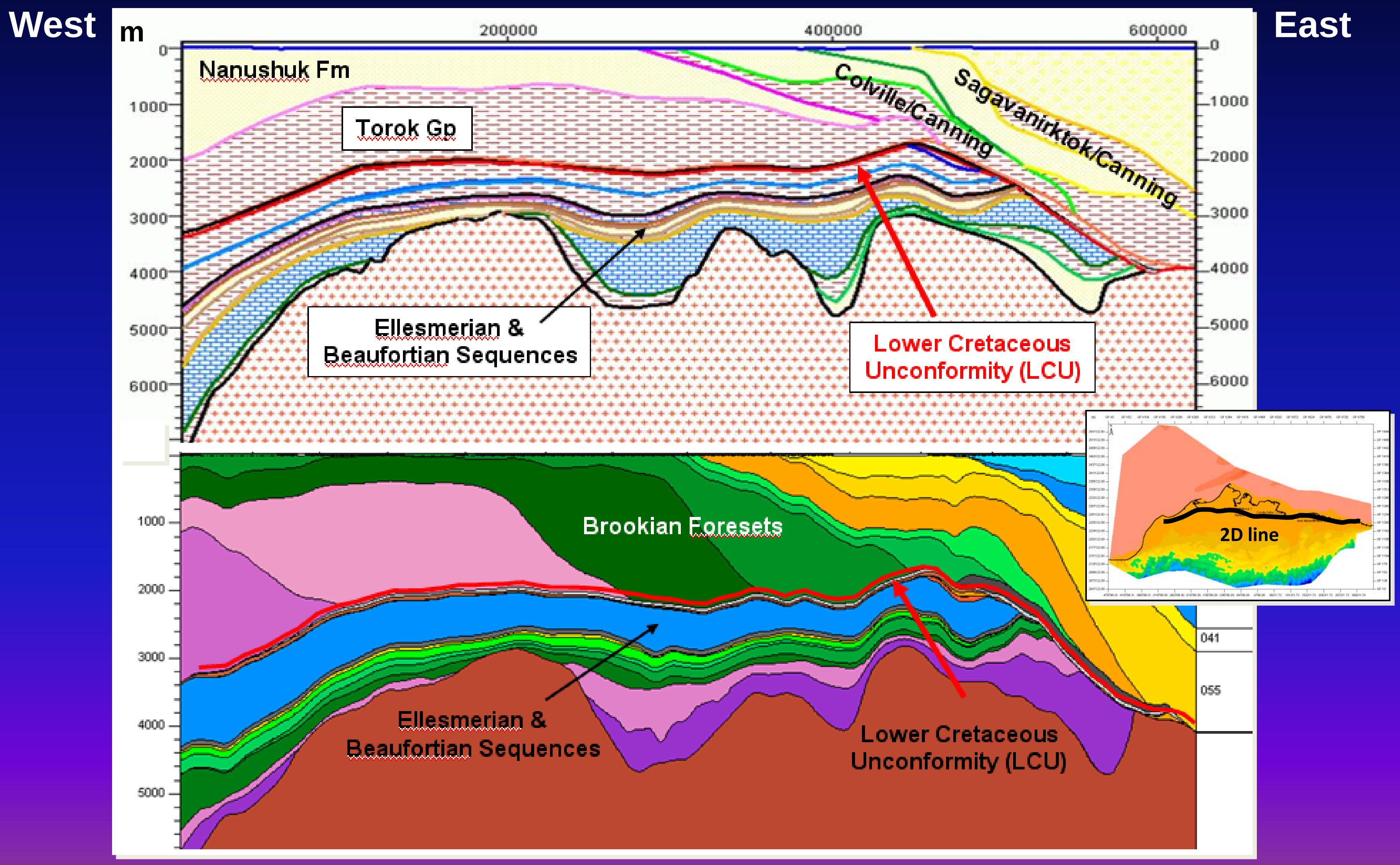
The 3D model is based on layered surfaces derived from well and seismic data that were input using Zmap (seismic 3D maps) and Arc/Info (foresets). Rather than using a stratigraphic subdivision of the Brookian sequences, timelines of prograding foresets were mapped to allow for a time-transgressive change of geometry: 5 structure maps; 35 + 9 Brookian and Jurassic

Reconstructed lost overburden reaches up to ~4000 m in the western part of the section. This lost section controls the burial depth and thermal maturity of the source rock and geometry of the migration paths. The Molenaar et al. 2D cross section was used to reconstruct the shape, current thickness, and eroded thickness of the prograding foresets in the Brookian section. The pre-erosional thickness (maximum burial depth) was determined using a linear extrapolation of measured Ro on semi-log scale for each well.

The eroded thickness reaches up to 4000 m in the far west of the study area. The values were derived again from well data, in this case VR data that was extrapolated beyond what was measured at the surface. The extrapolation of these values resulted in what you can see here. There are other studies based on AFT and compaction curves that come up with different, mostly less erosion values. The actual erosion remains to be discussed.

Click to View Notes by Presenter

Brookian Foresets: Chronostratigraphic Rather Than Lithologic Units

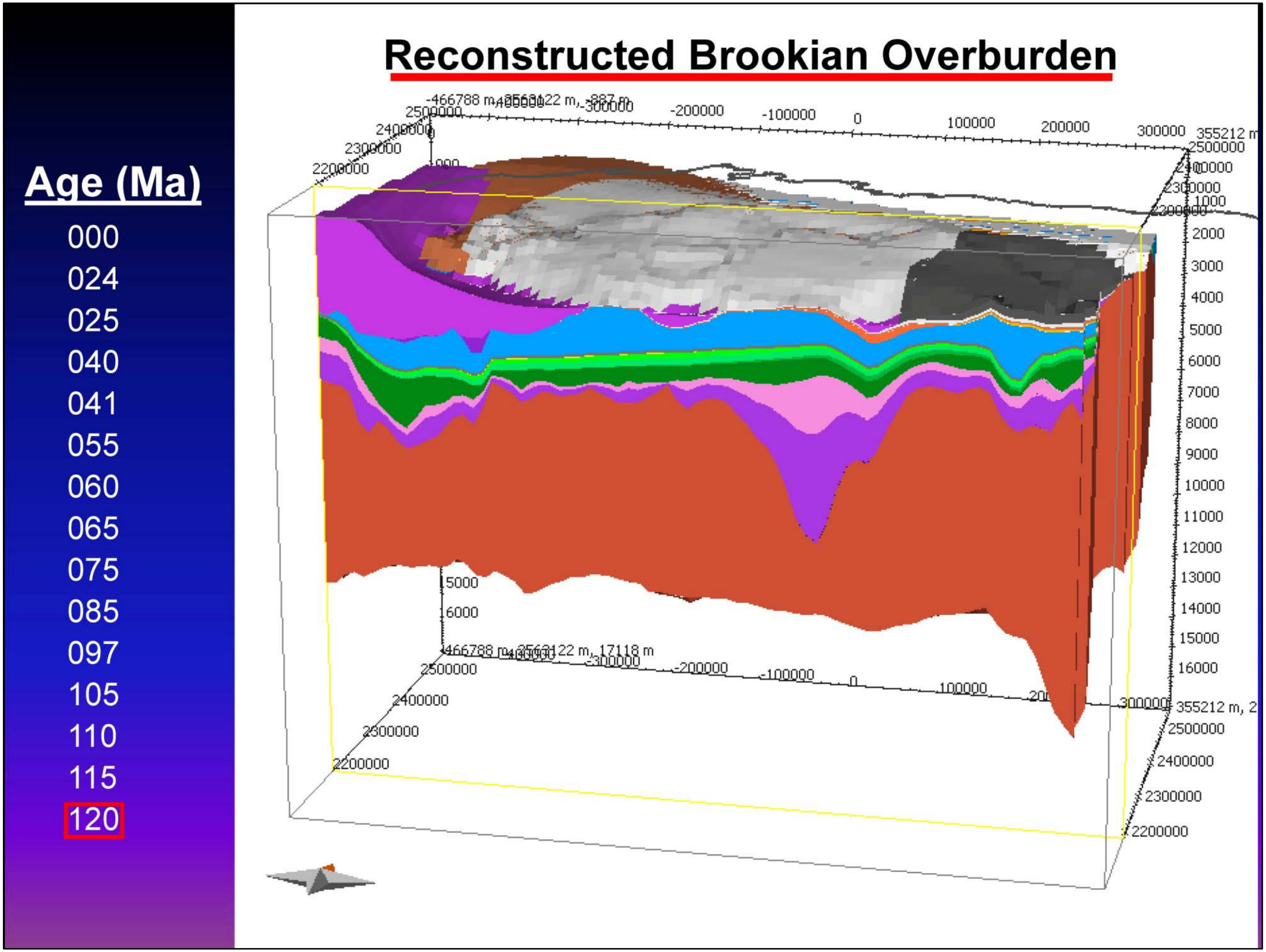


Notes by Presenter (for previous slide):

Geologic layers used for numerical modeling are described as chronostratigraphic rather than lithologic units in so much as each layer combines time-equivalent units into a single layer bearing the name of the dominant member.

The overlying Brookian Sequence with a total thickness of up to 8,000 m was deposited during Late Cretaceous and Cenozoic time in a prograding foreland basin predominantly from WSW to ENE (Bird, 2001). The reconstruction of this paleo-geometry—diachronous deposition, facies variation, and thickness distribution as well as variations in paleo-basin geometry—was one key element of this study. The designation of depocenters through time had a major impact on the timing of maturity, generation, and migration of hydrocarbons. These time-transgressive deposits were reconstructed by using timelines rather than formations. They were mapped from surface traces and shelf edges. The effects of multiple Tertiary erosion events were also taken into account.

Contour maps of original TOC (TOC_o) and HI (HI_o) for source rocks were taken from Peters et al. (2006) and extrapolated to the limits of the present study. Thermally immature source rock samples were analyzed using the new ‘Phase Kinetics’ procedure developed and calibrated for PVT-controlled prediction of petroleum phases and properties, such as API and GOR (di Primio and Horsfield, 2006). The results of the analyses were assigned to the respective source rocks. Source rock tracking helped to calibrate the model according to the existing mixed accumulations.



Notes by Presenter: Location of the North Slope and the study area within the North Slope. The area covers large parts of the NPRA and some ANWR/1002 Area. The southern boundary is the Brooks range. Show position of 2D Section

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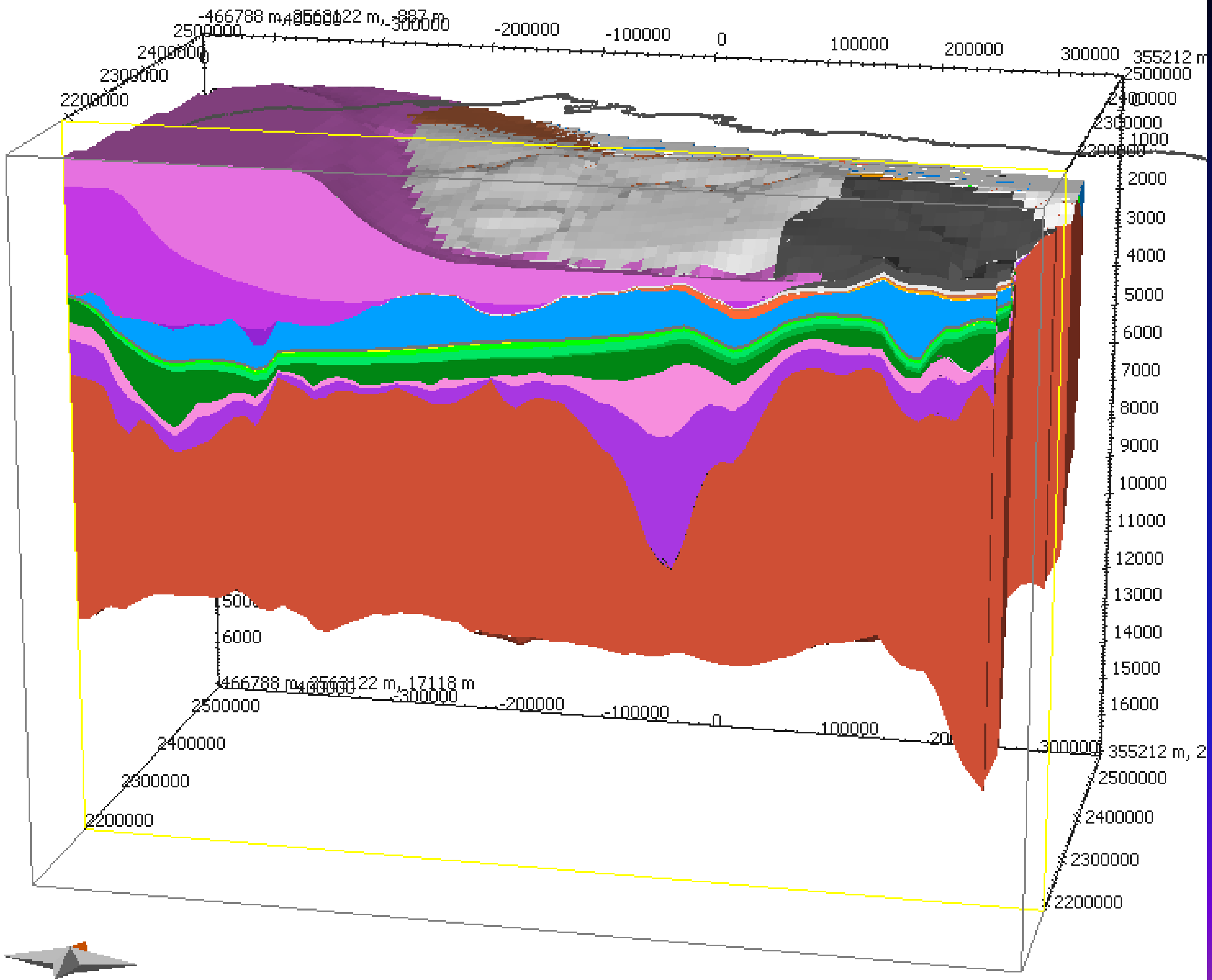

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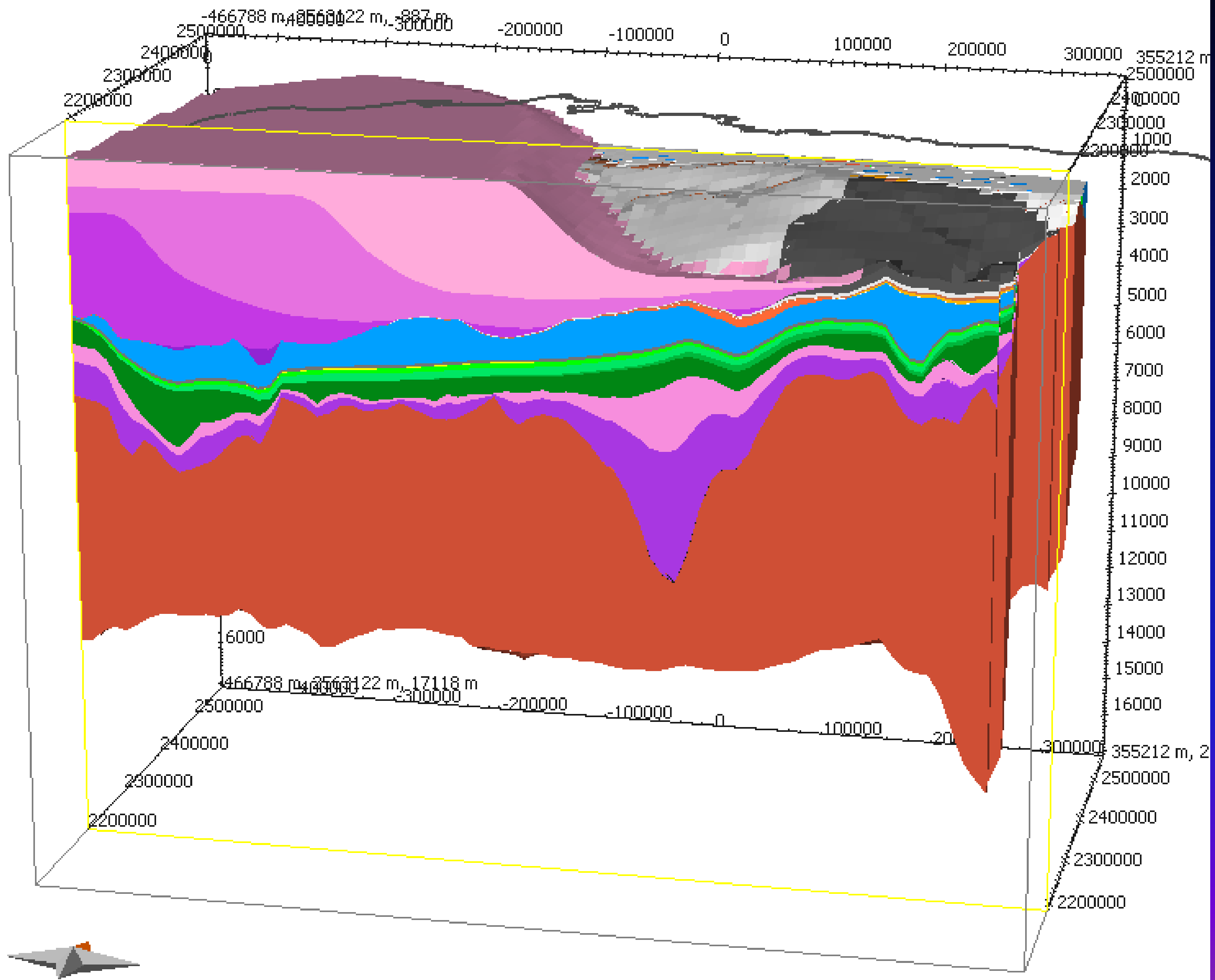

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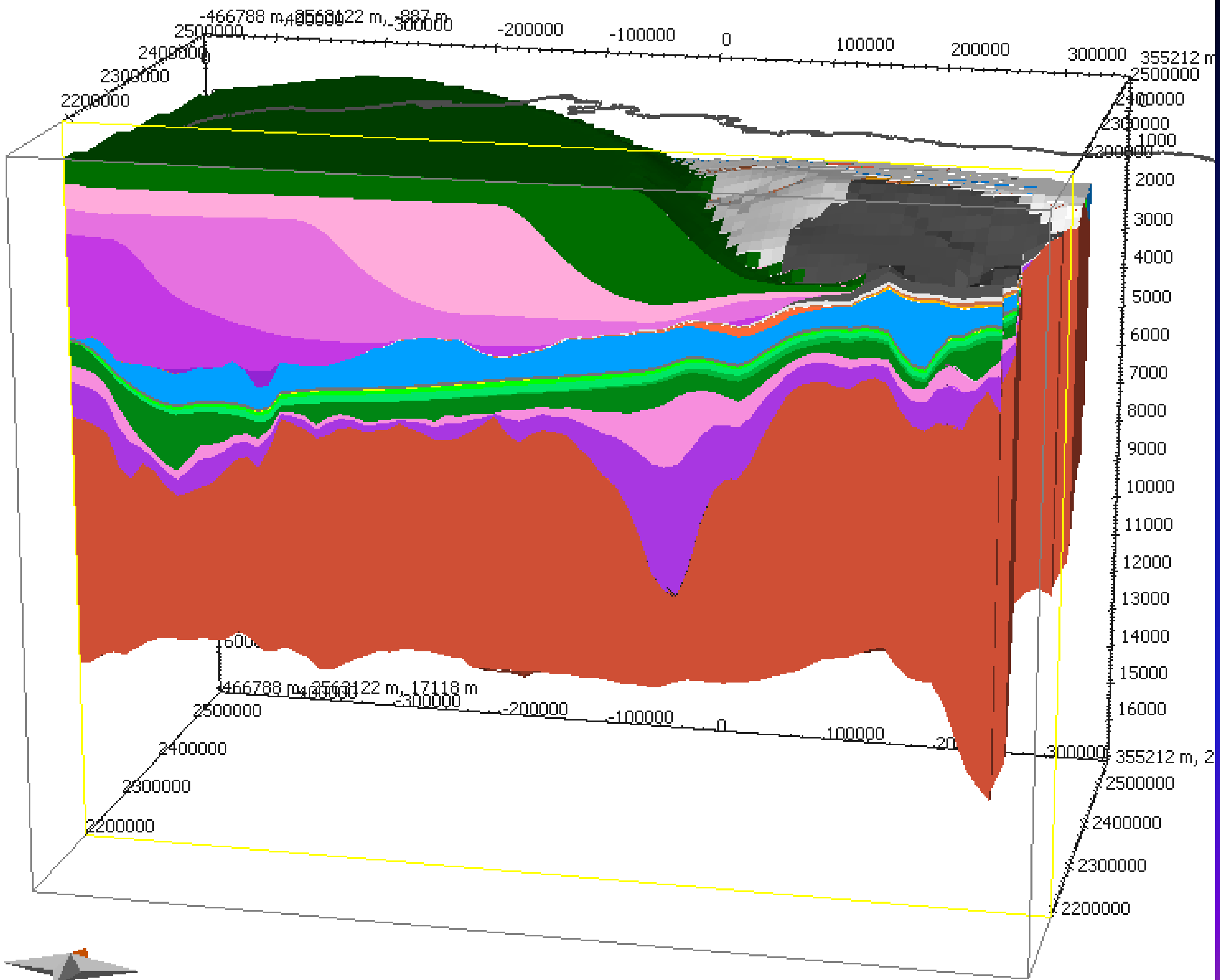

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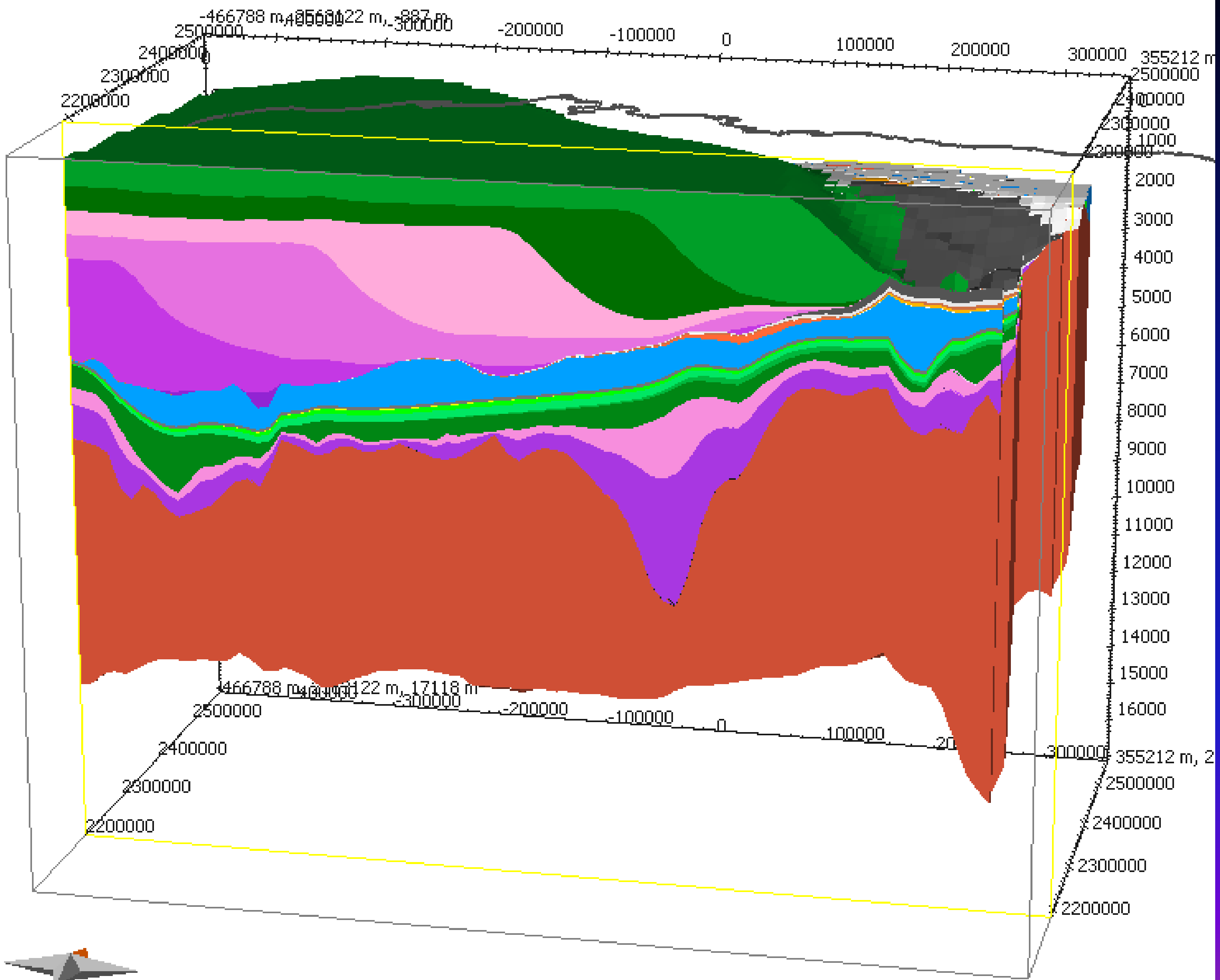

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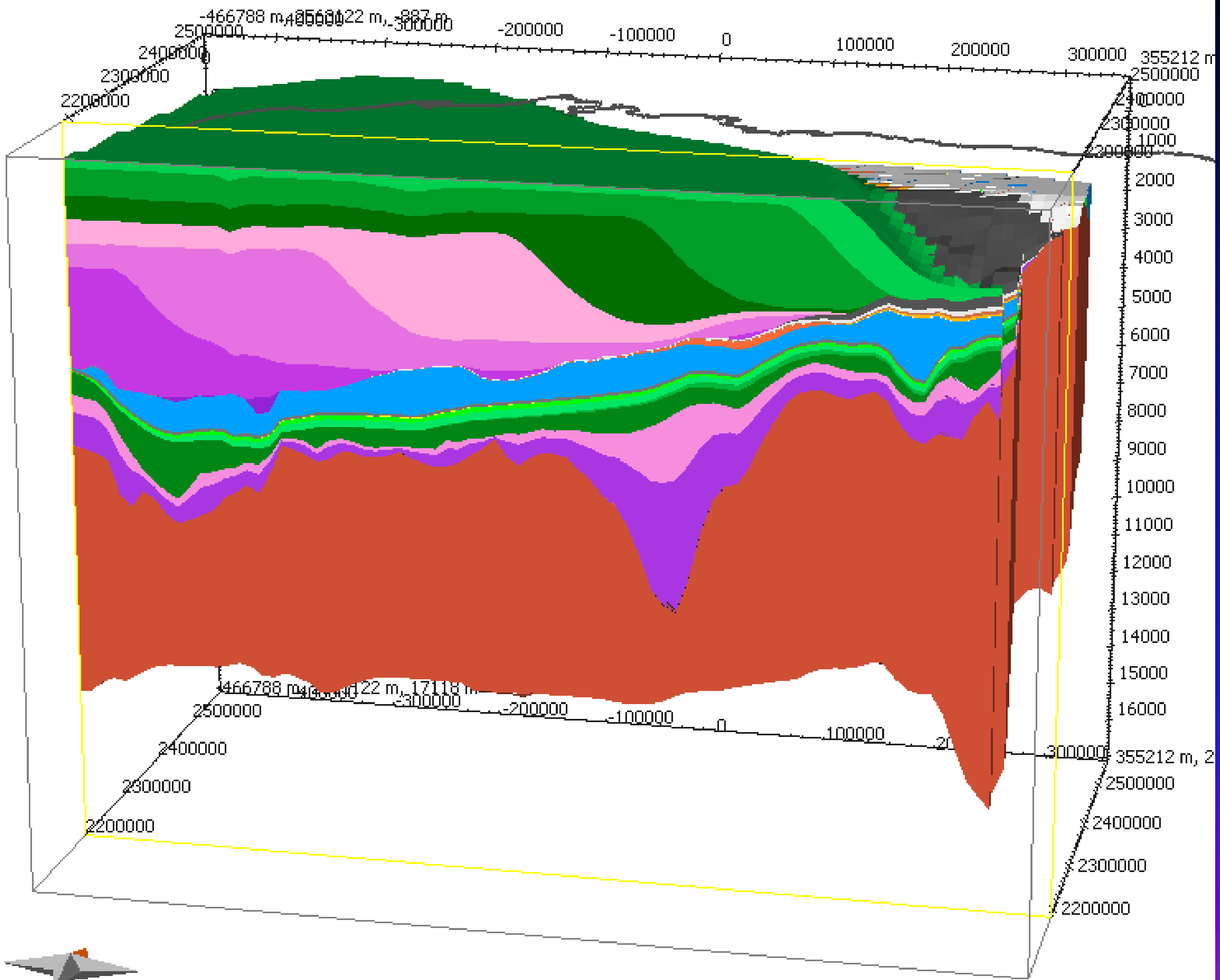

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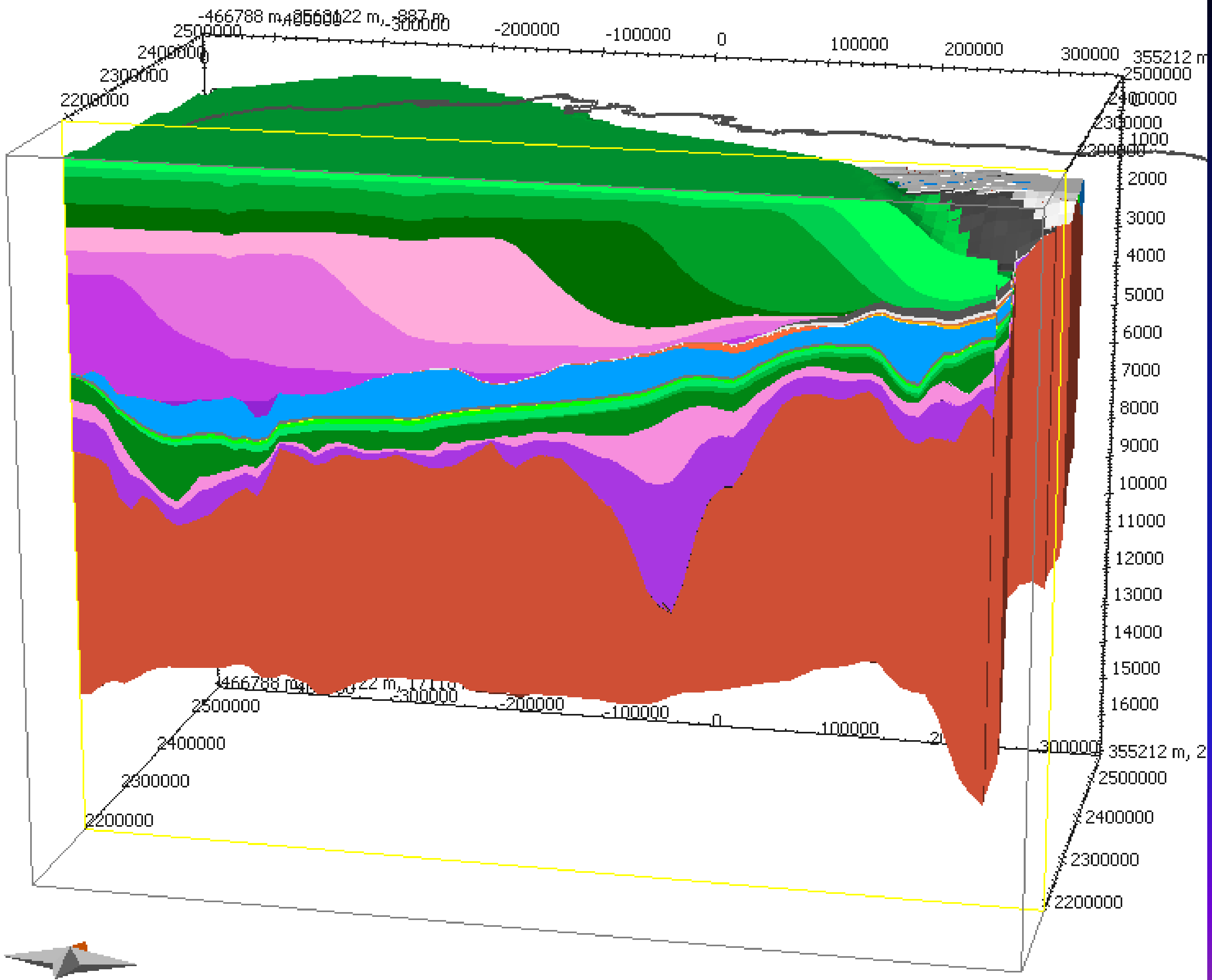

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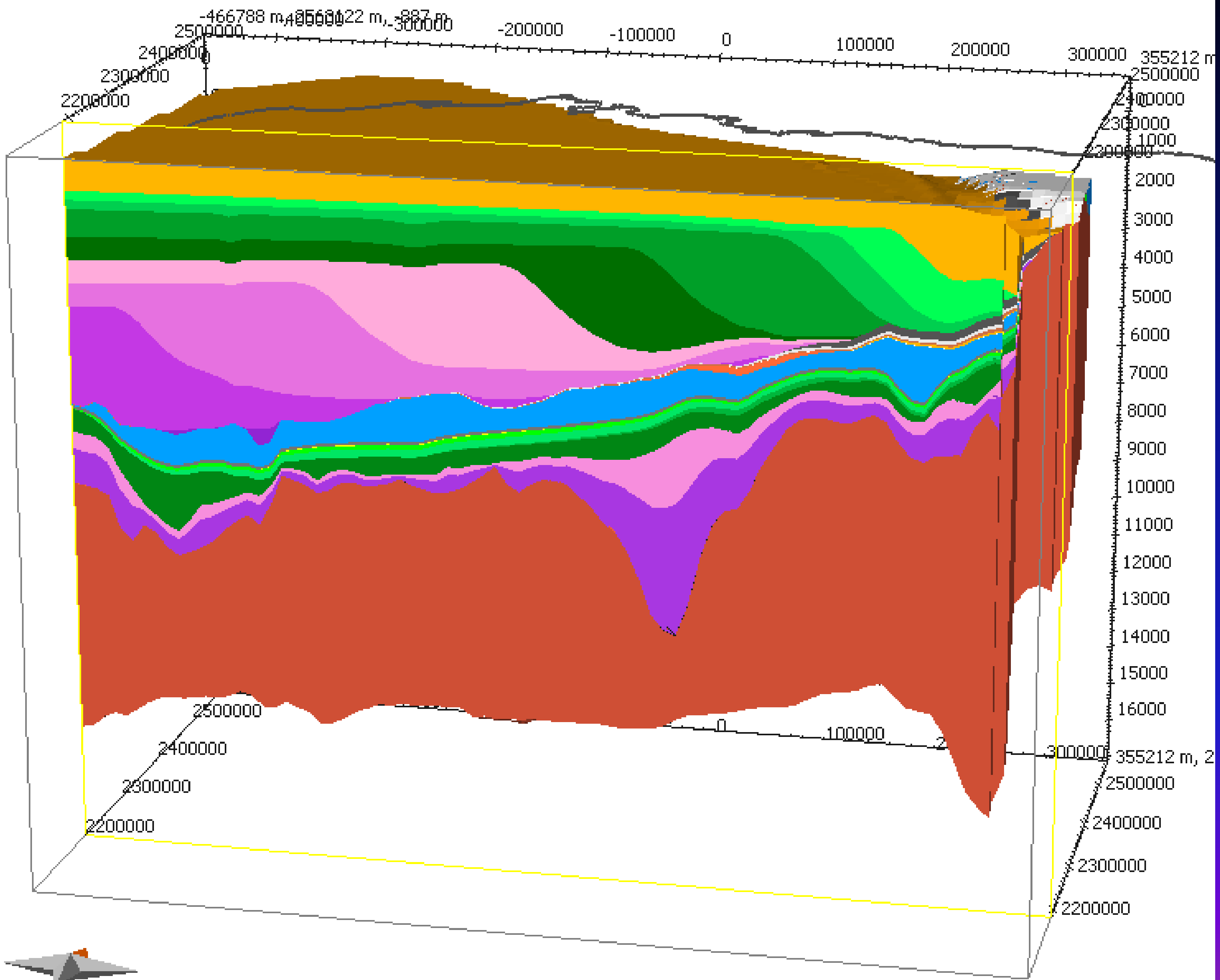

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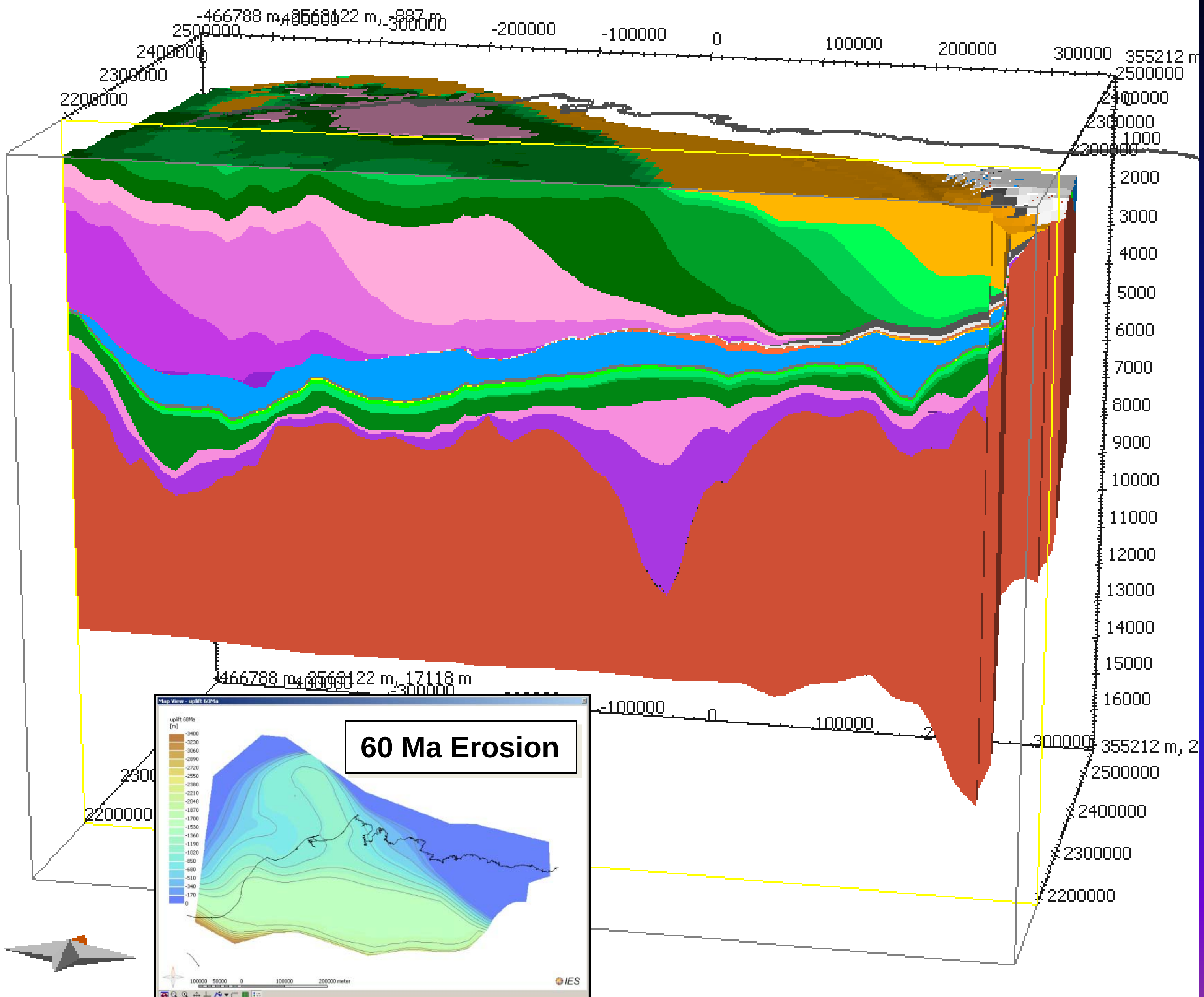

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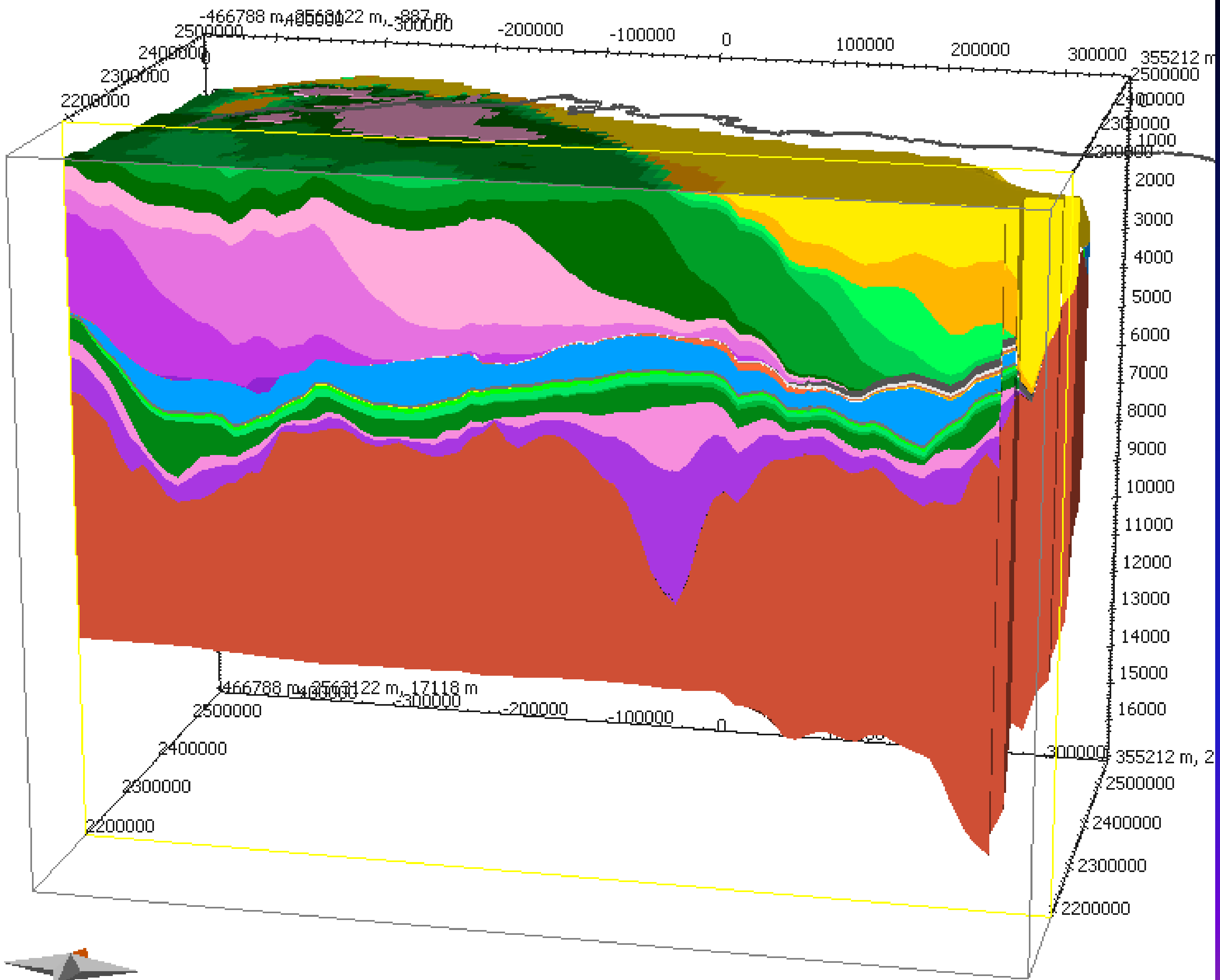

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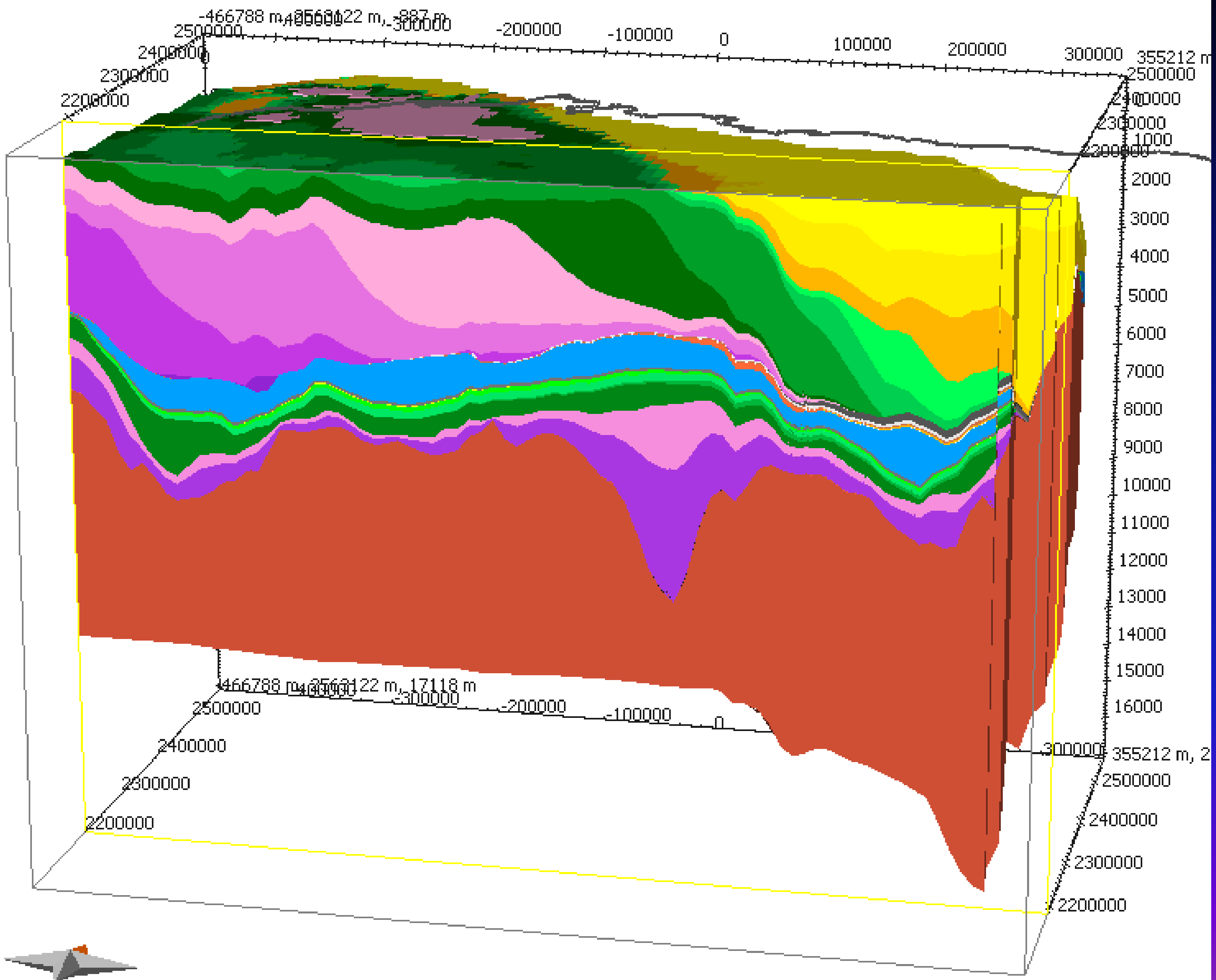

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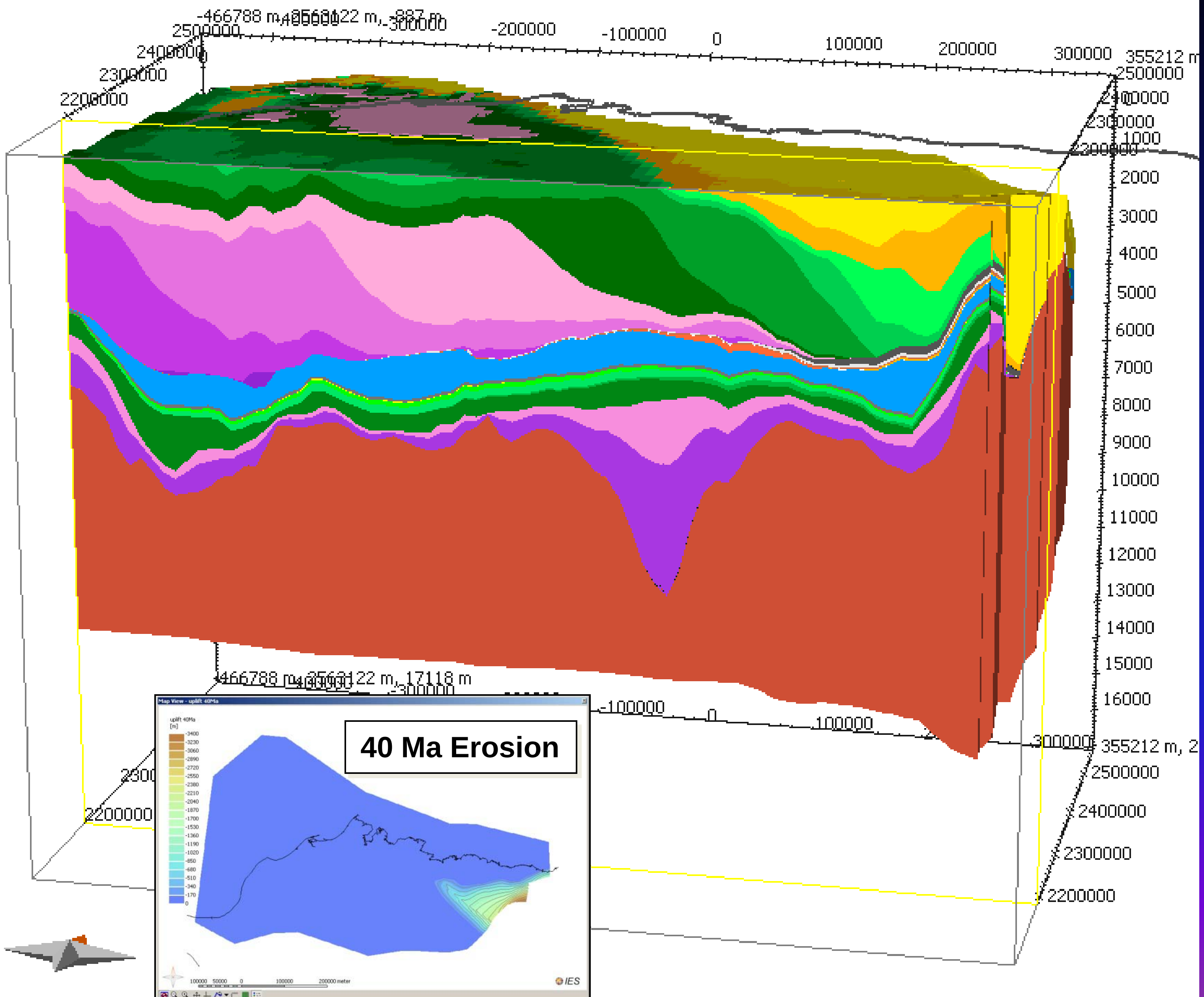

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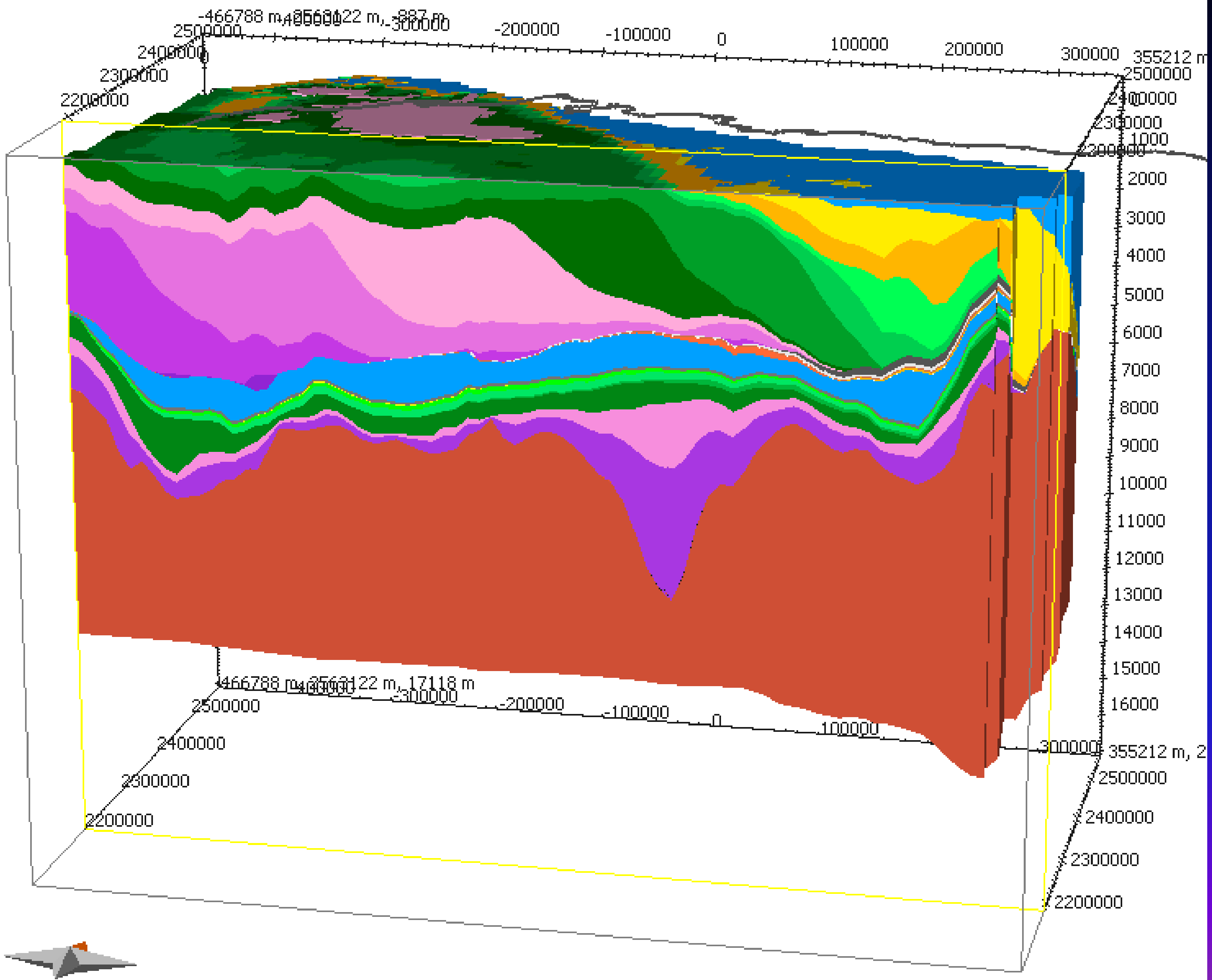

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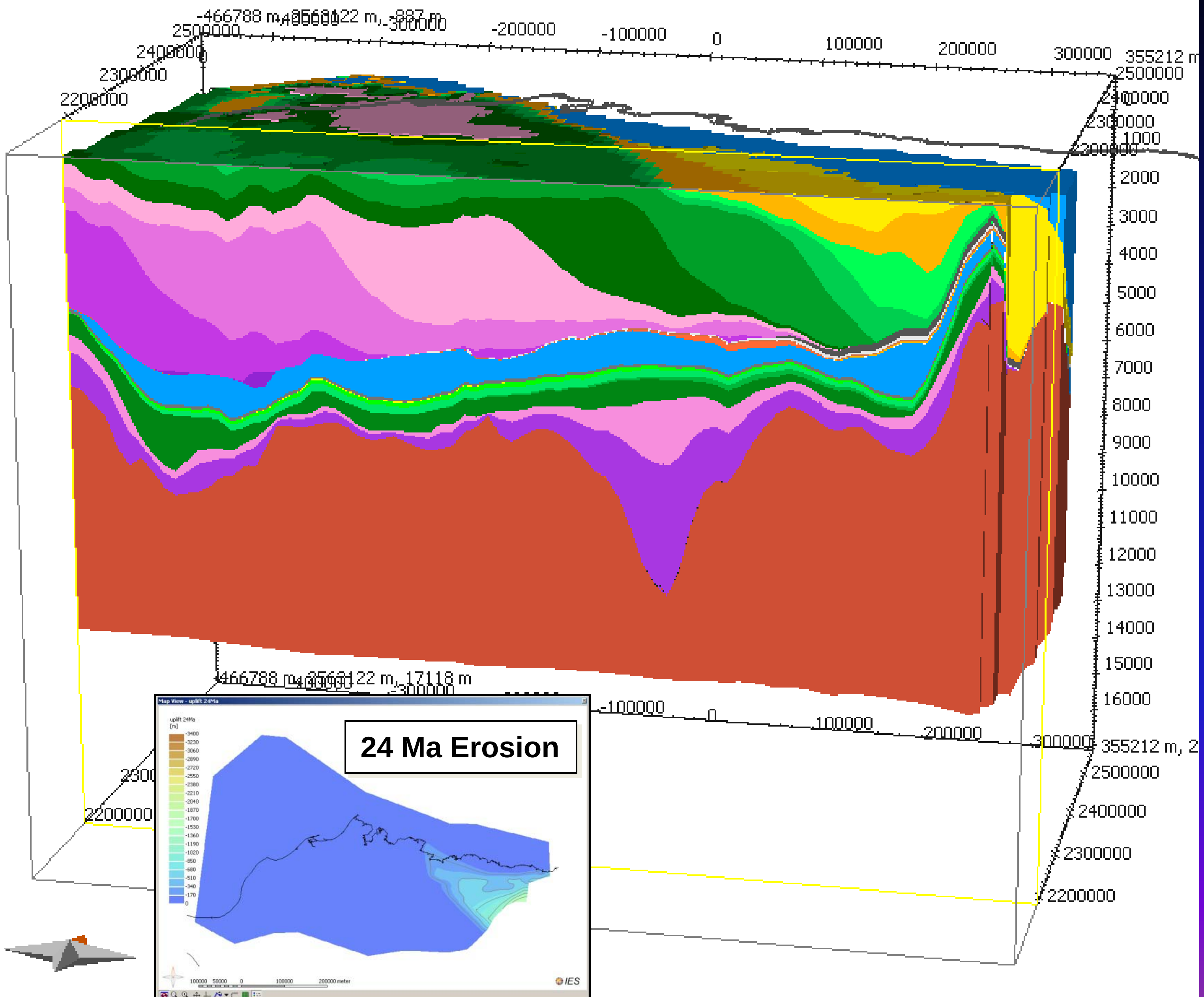

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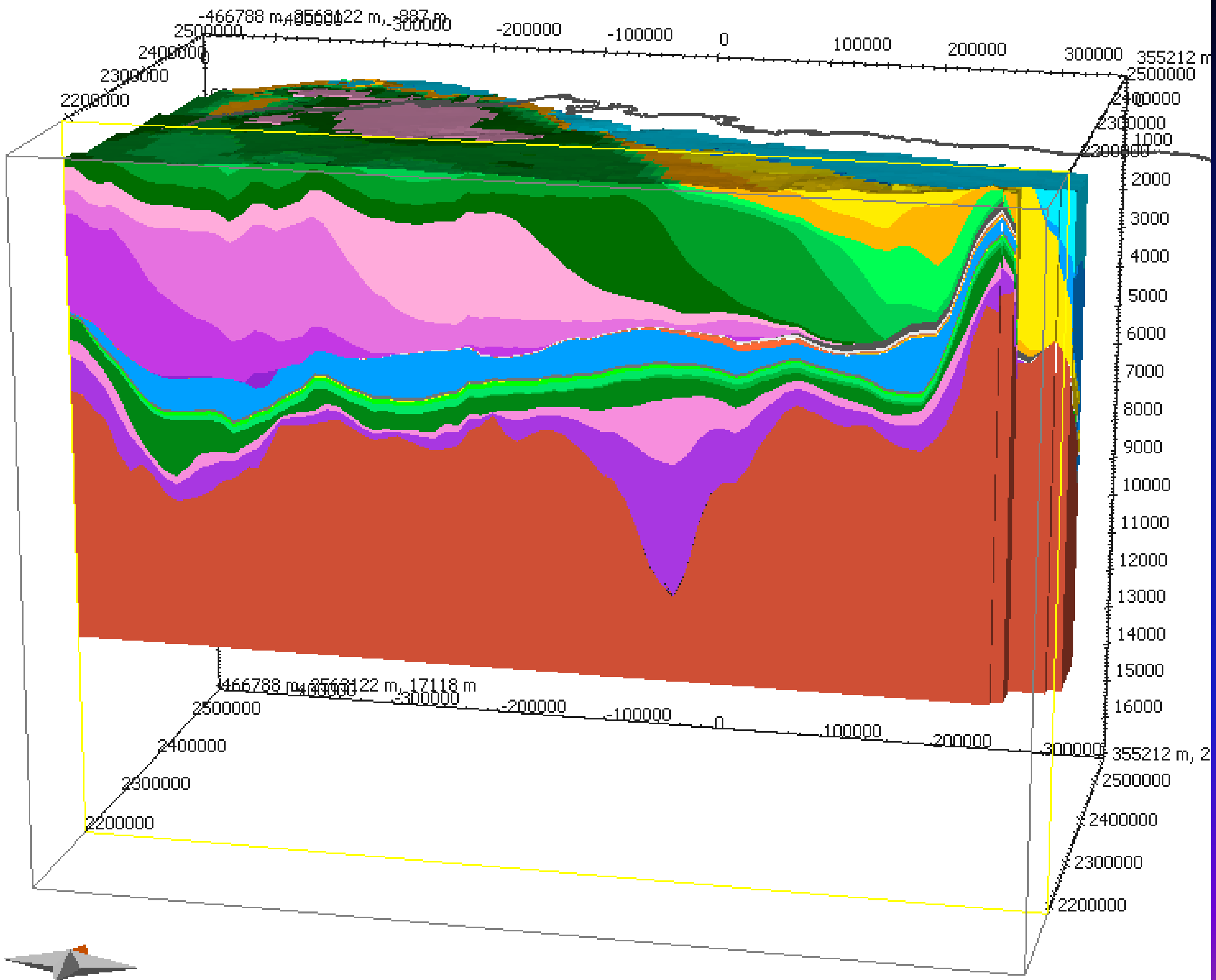
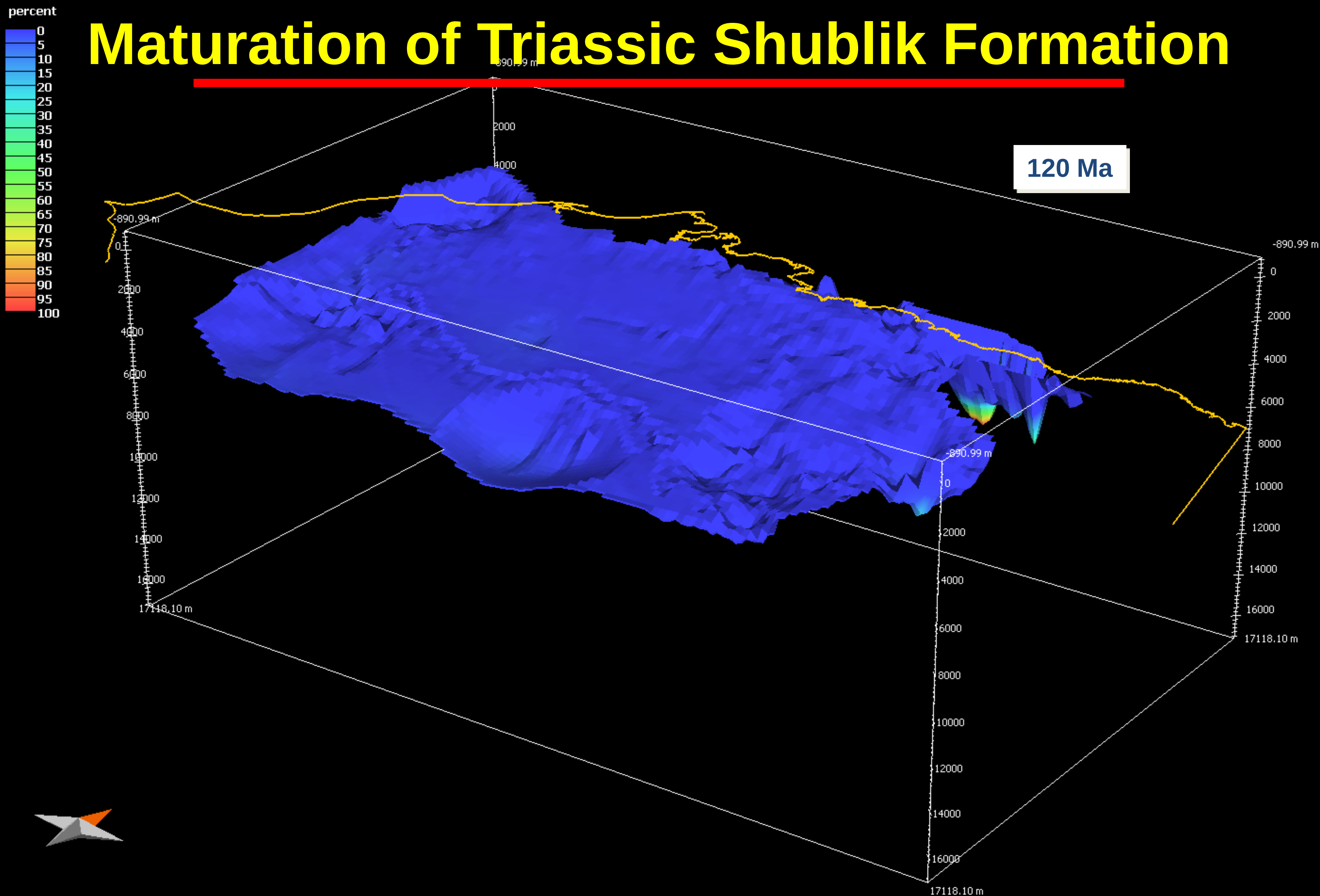
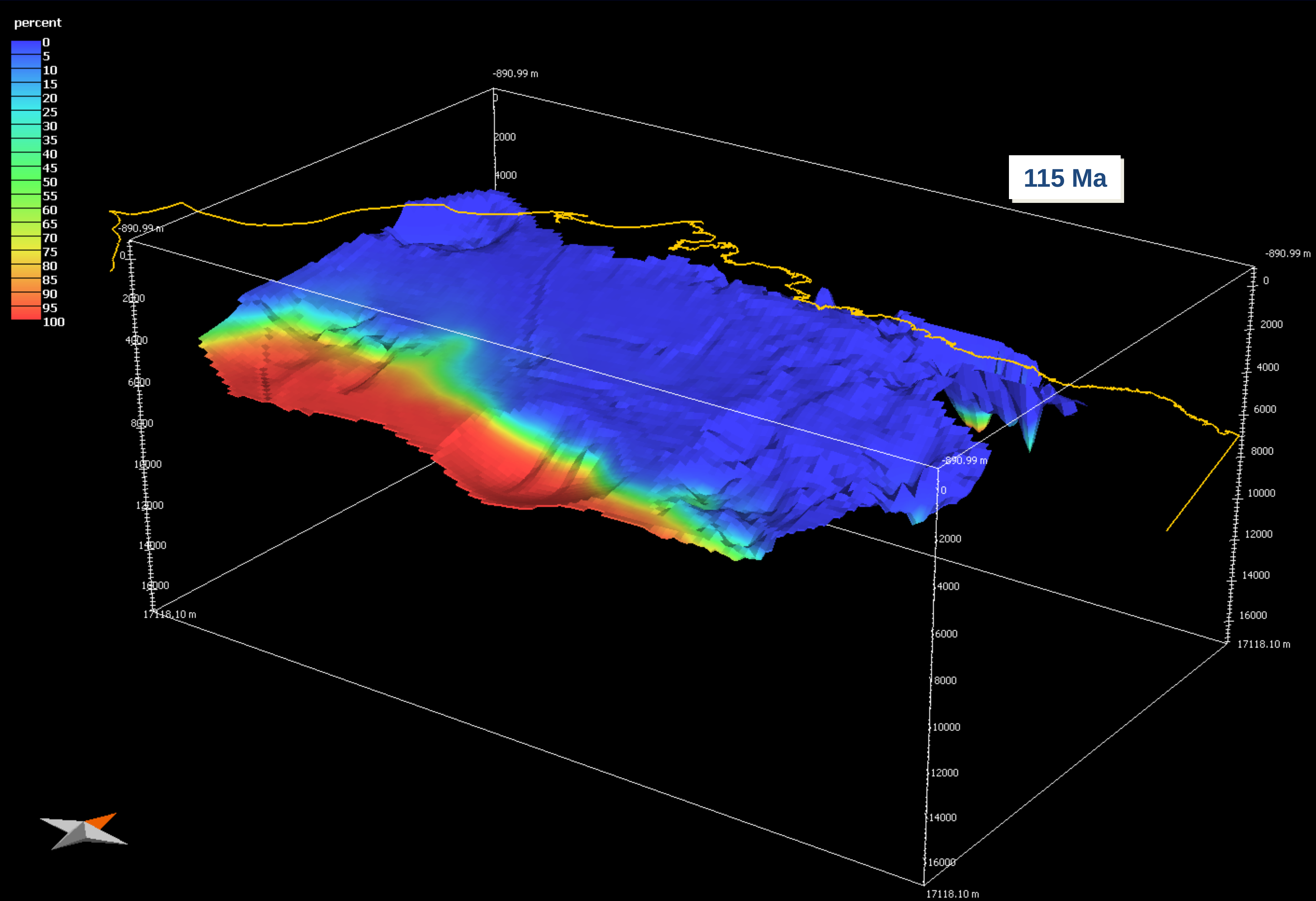


Transformation Ratios Increase With Maturation of Triassic Shublik Formation

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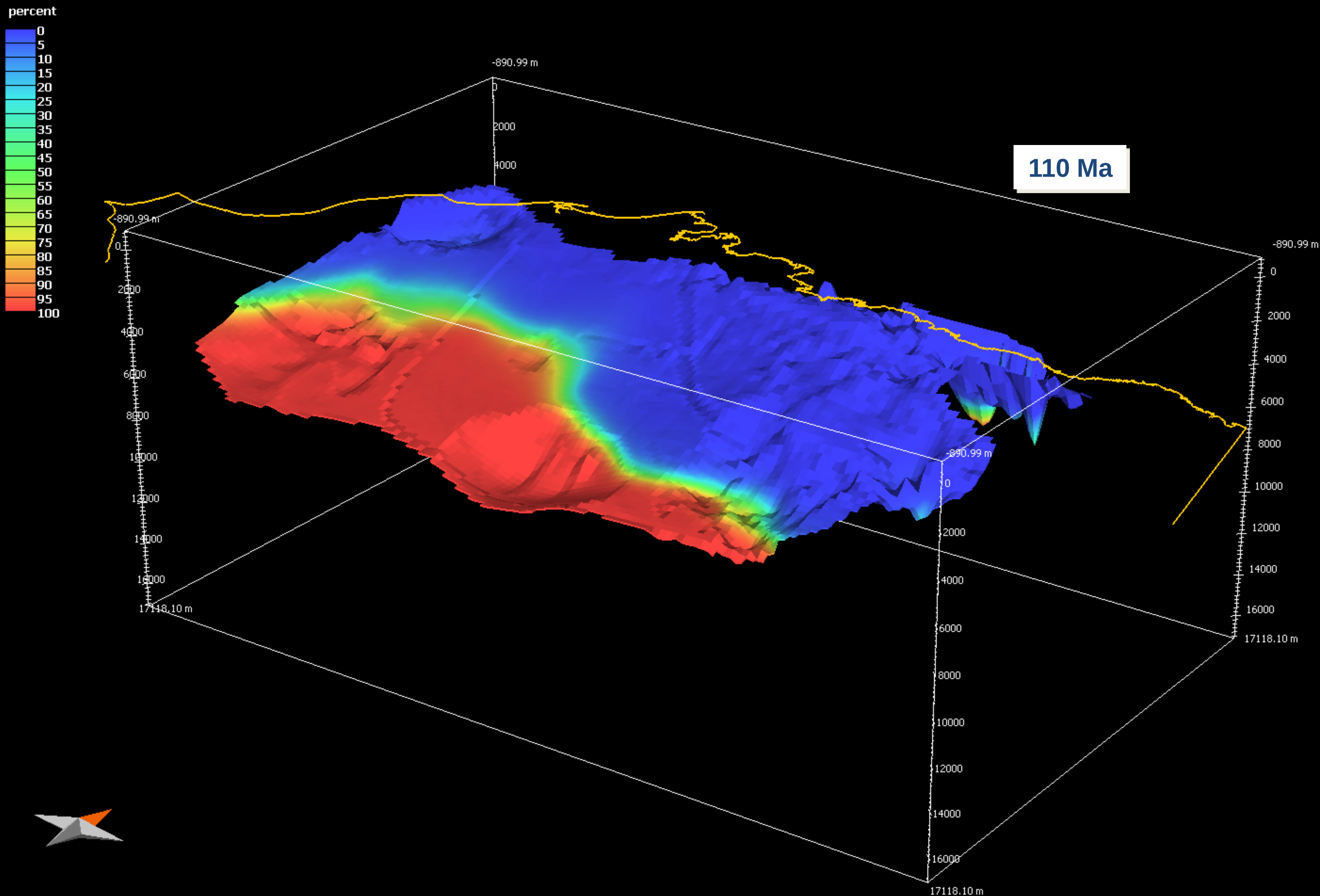
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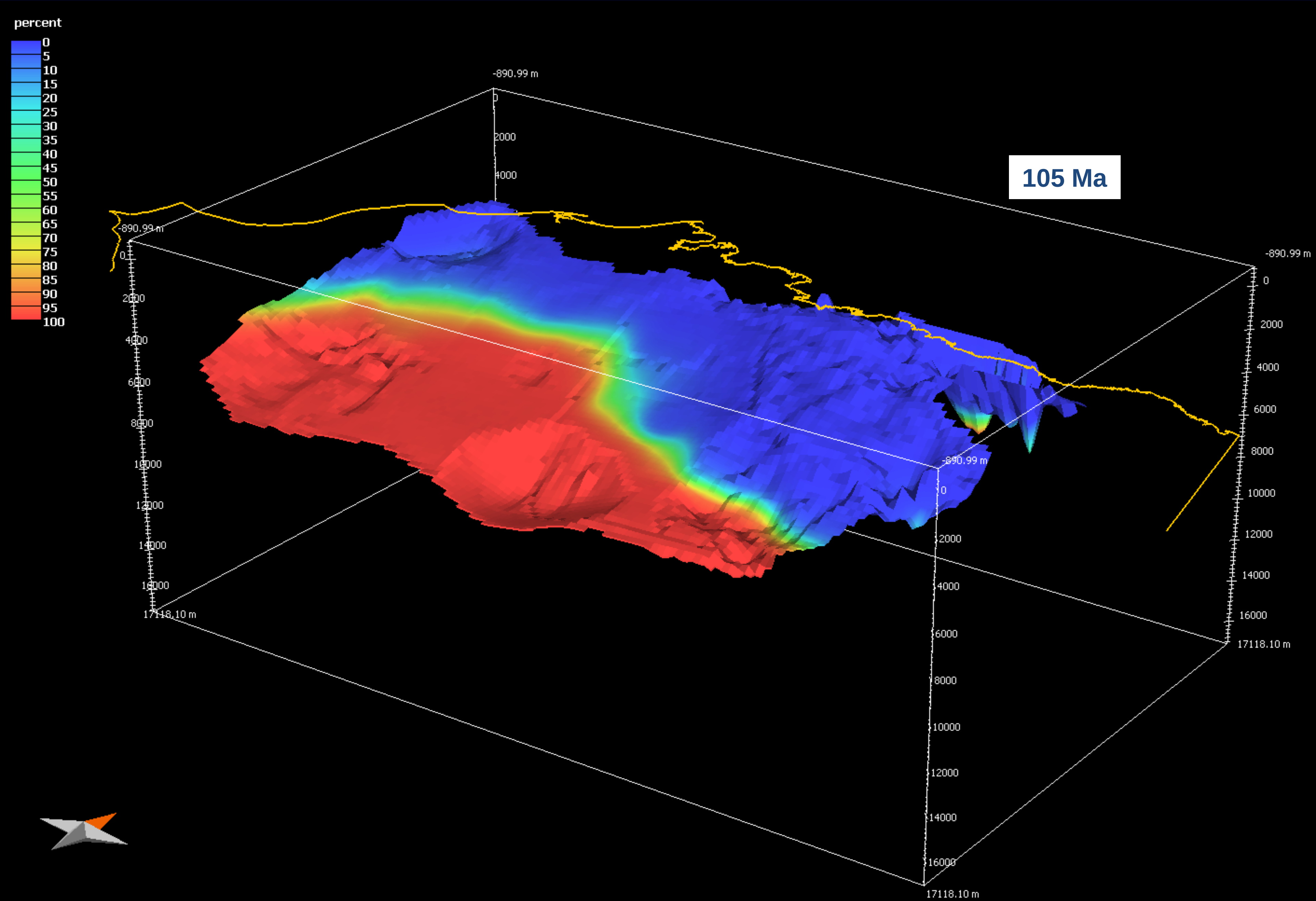
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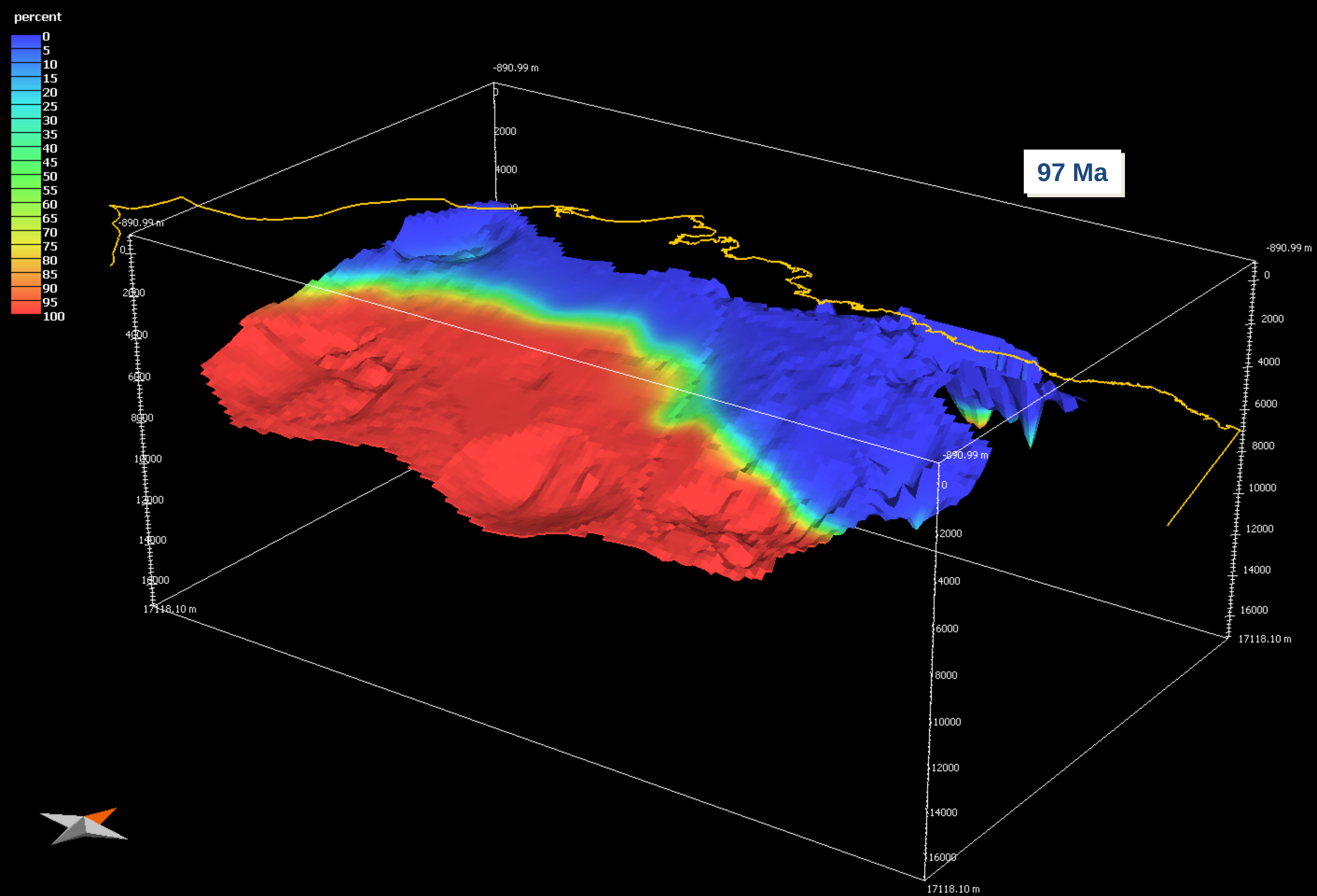

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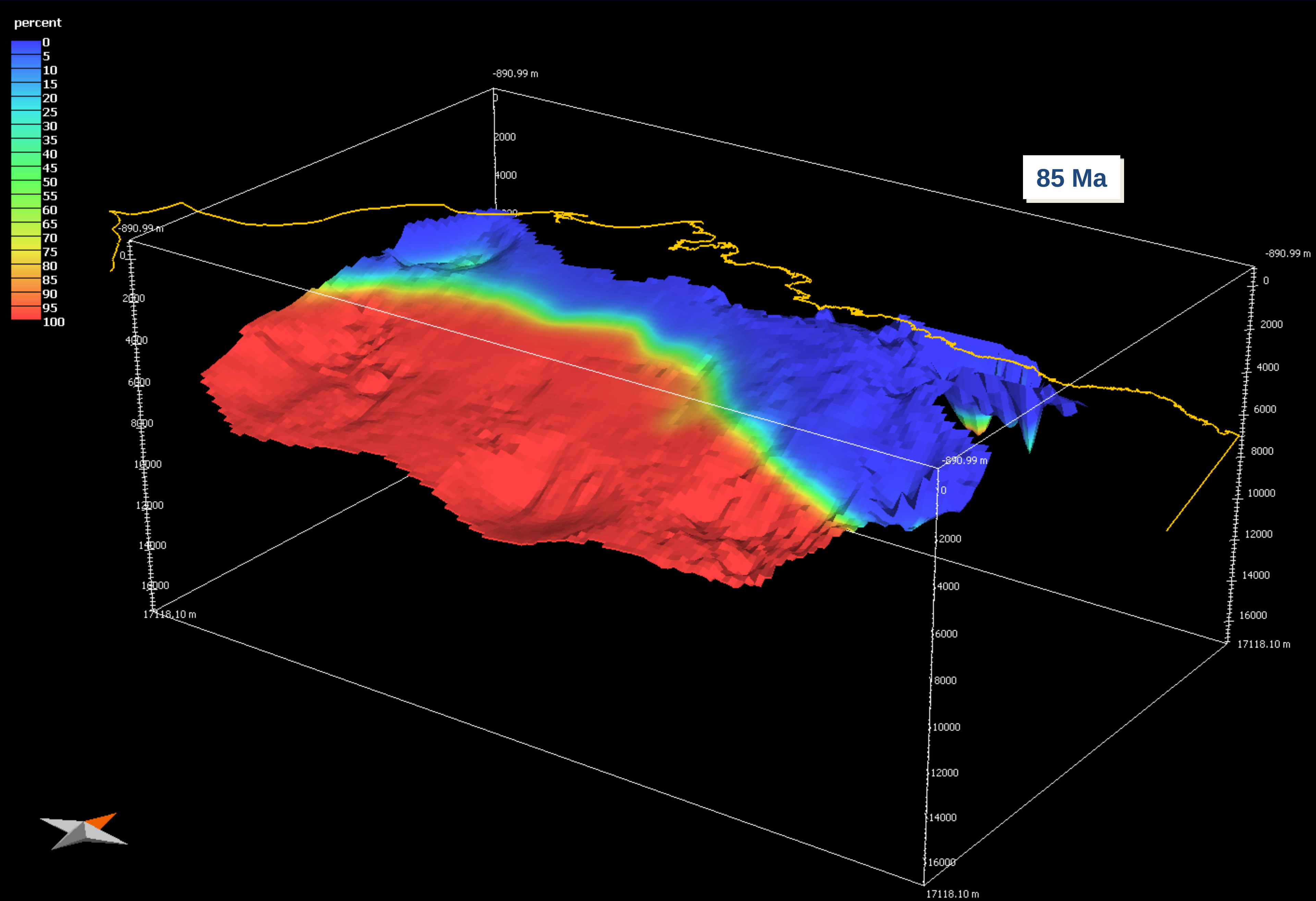
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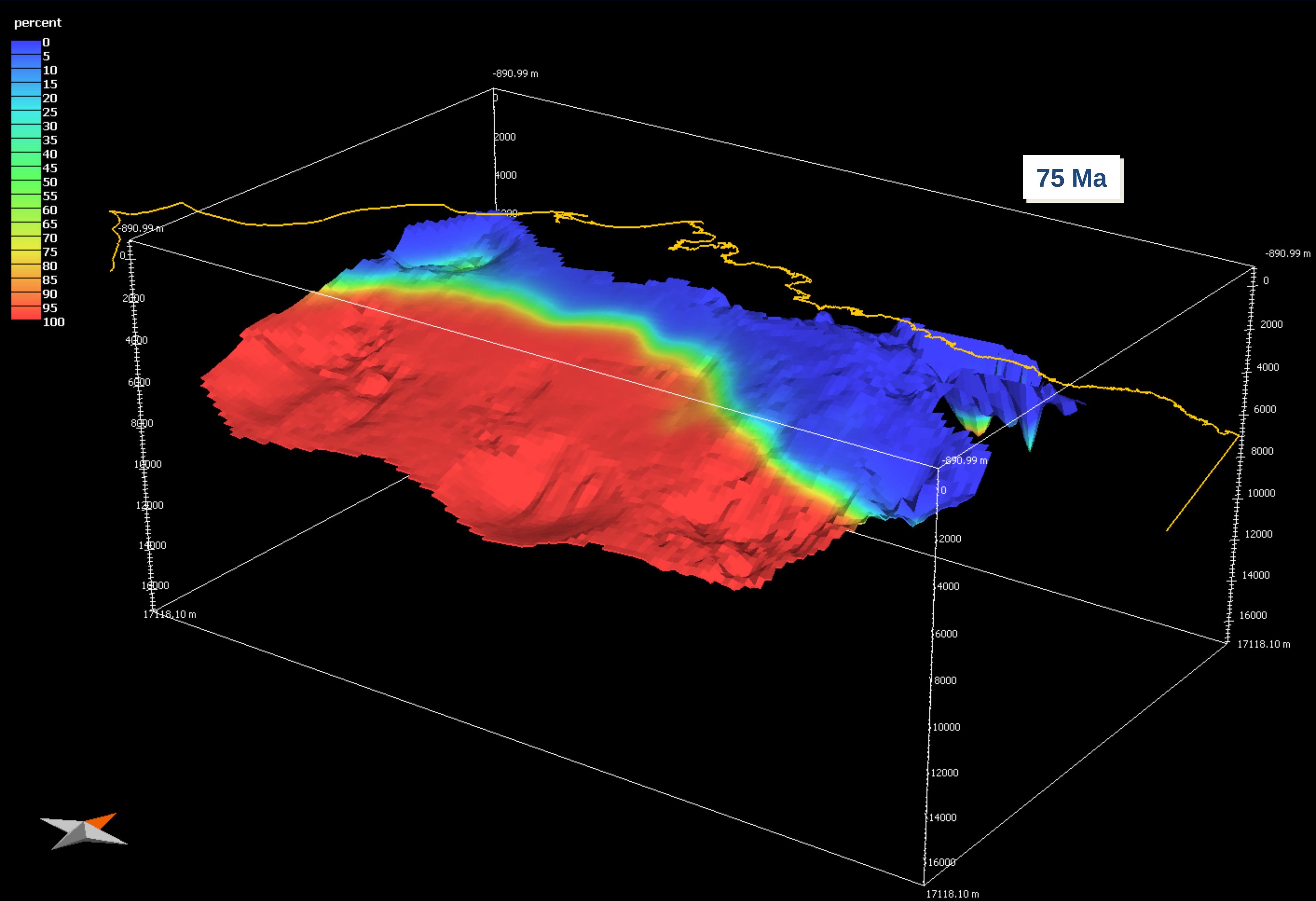

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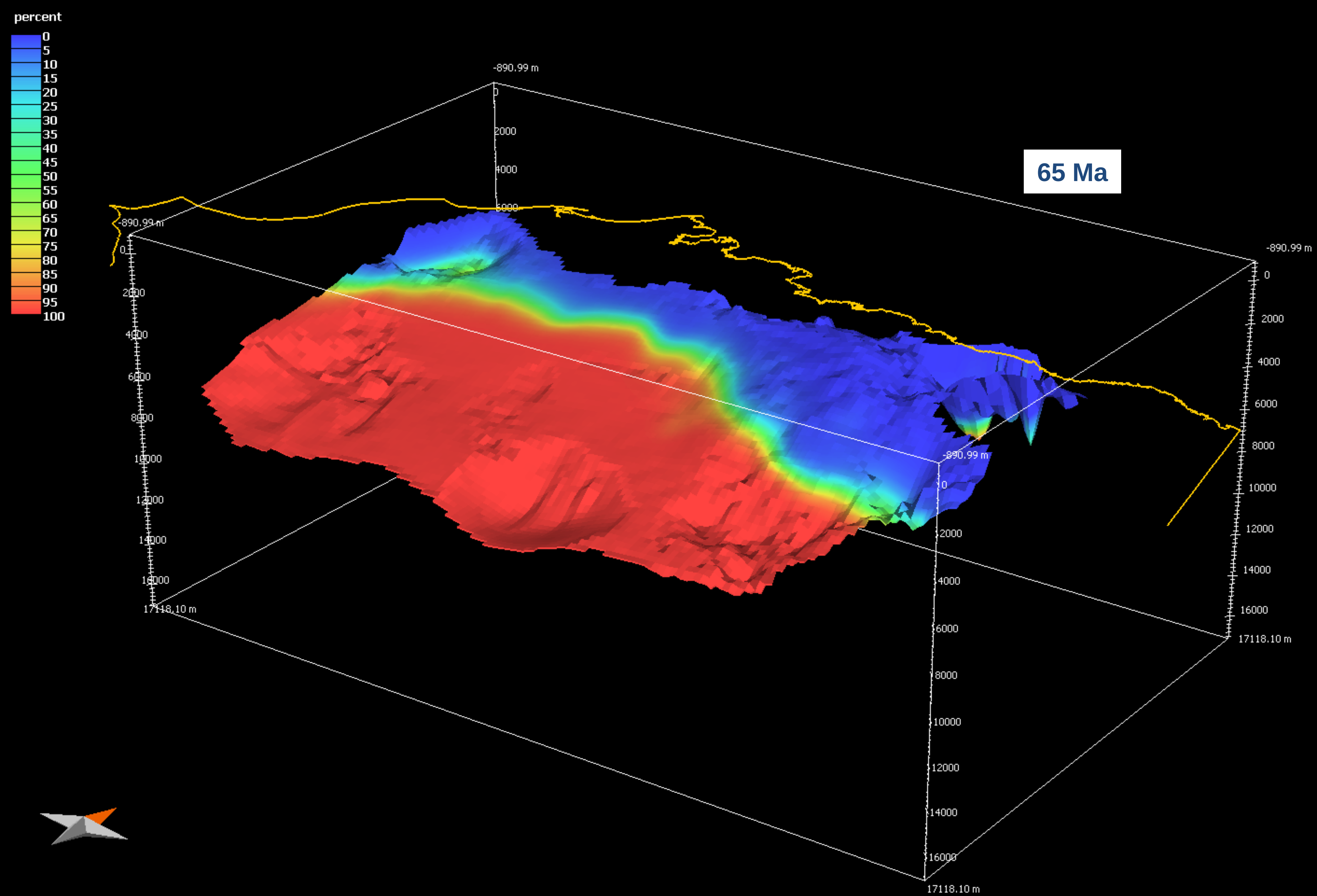

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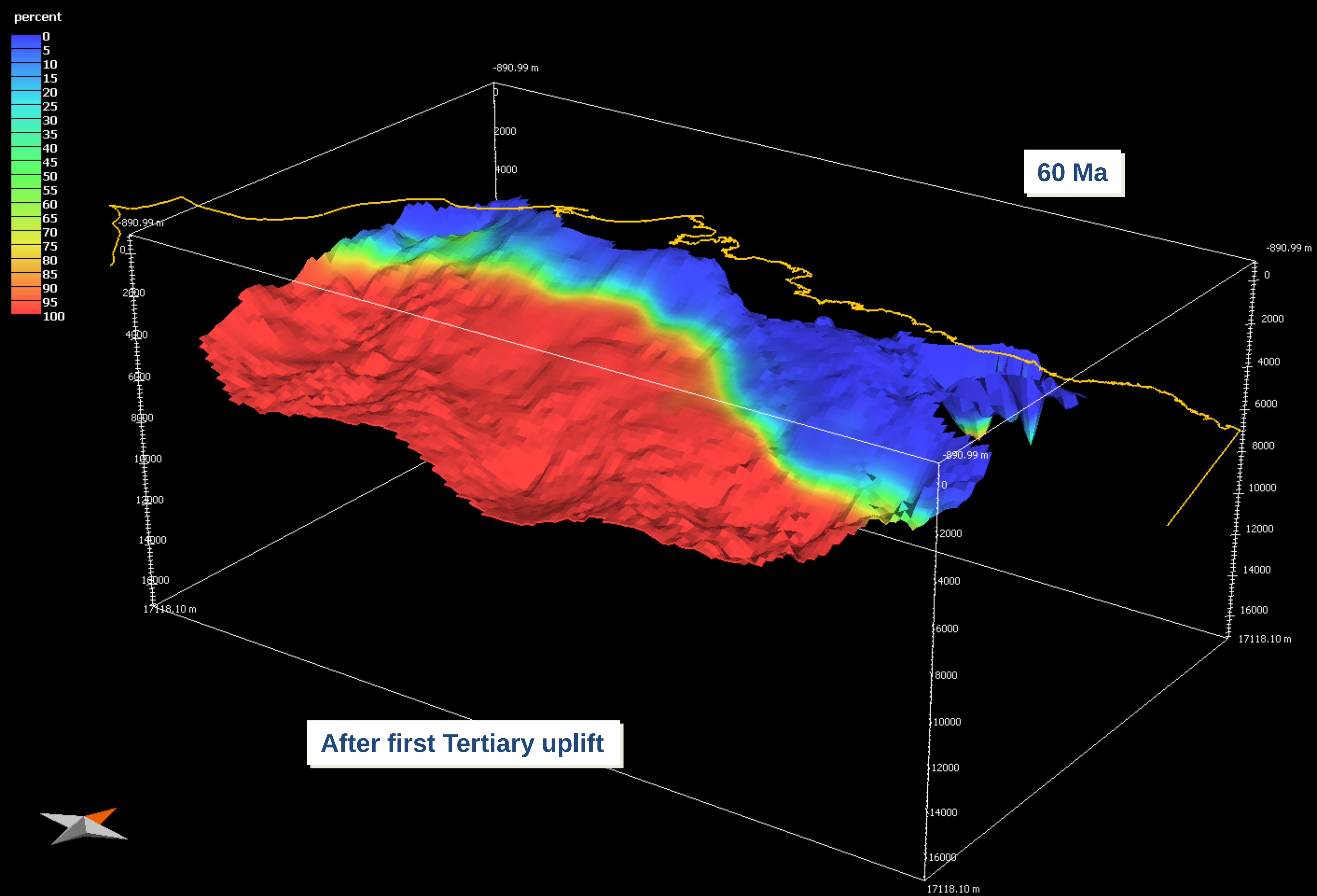
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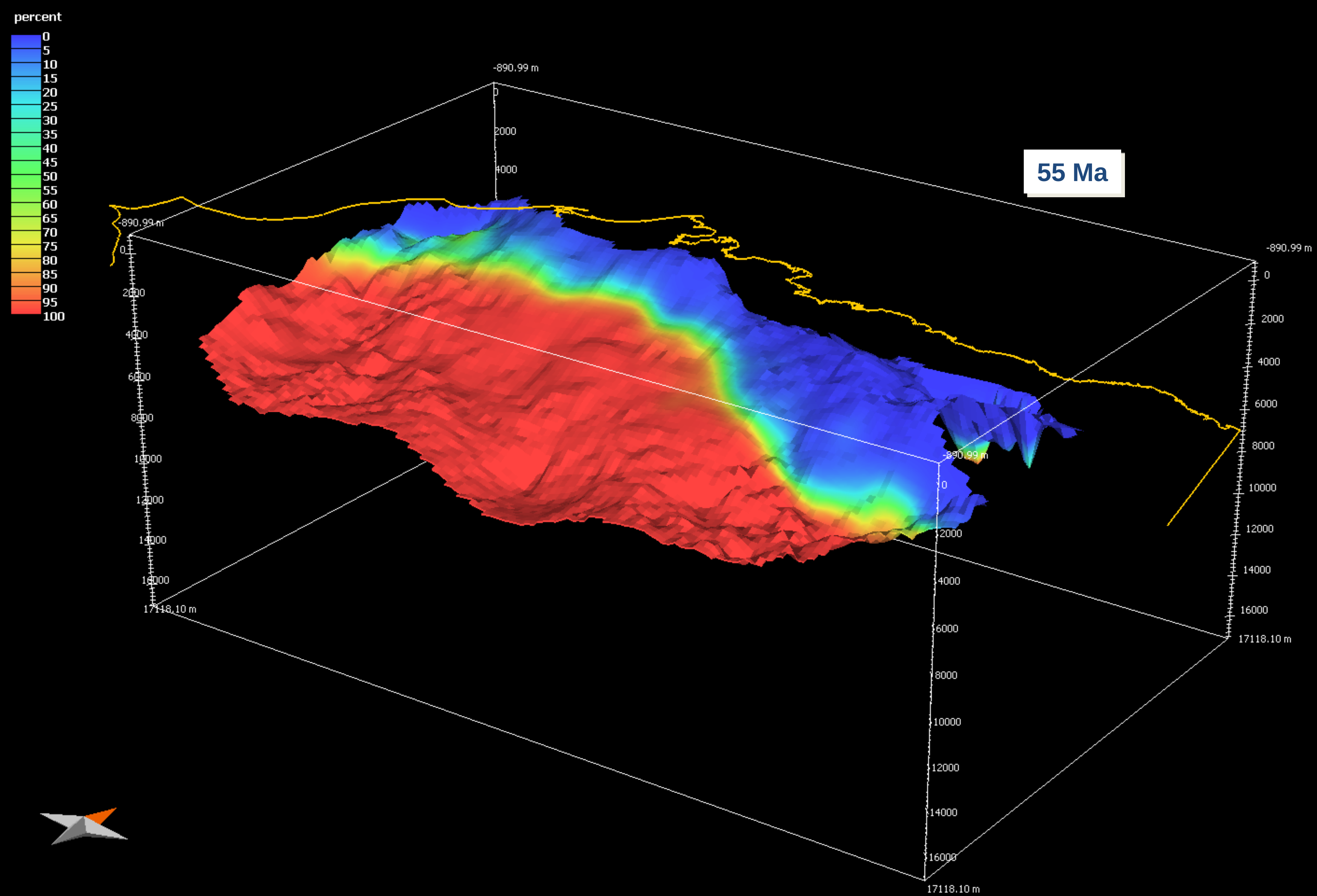

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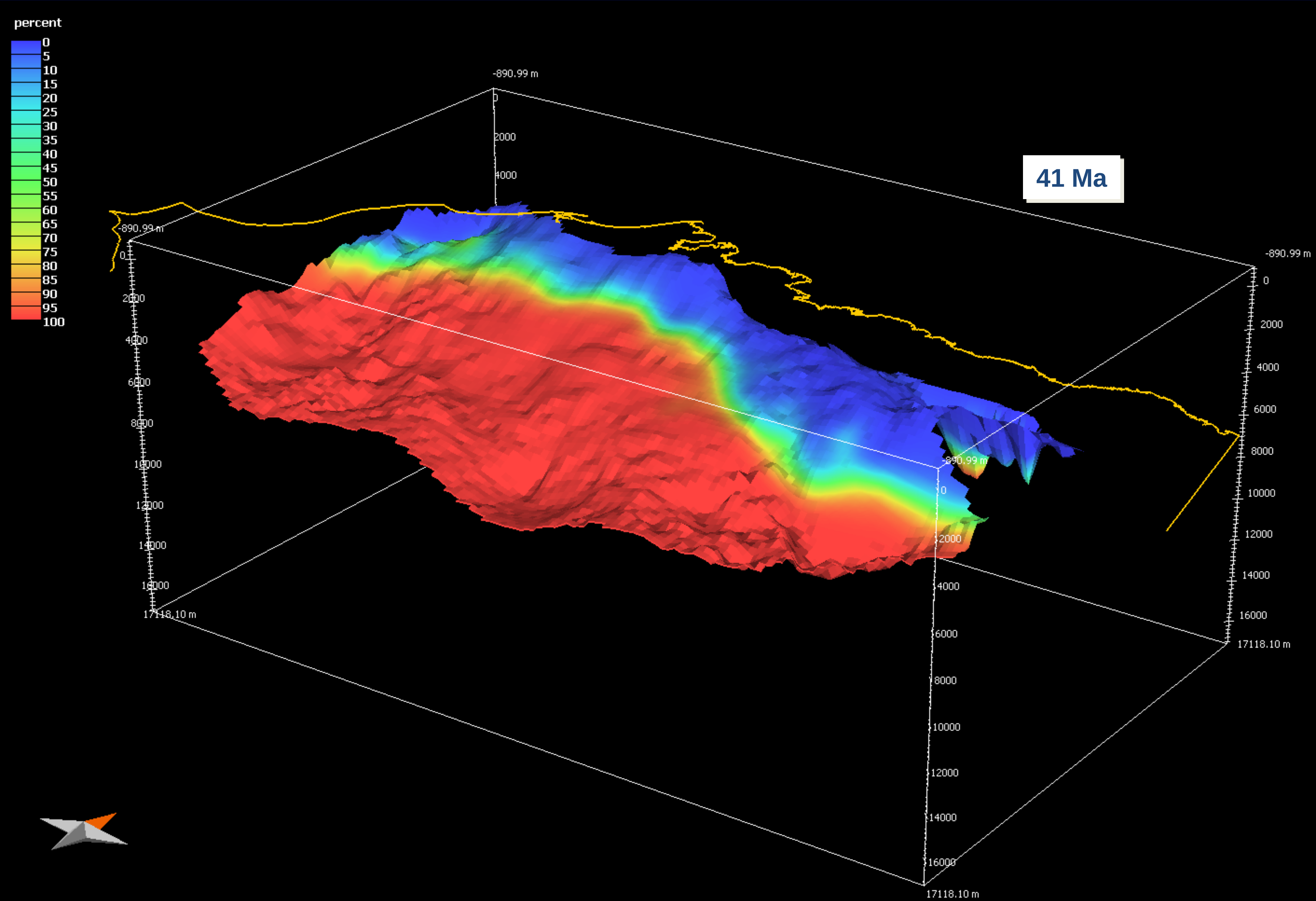

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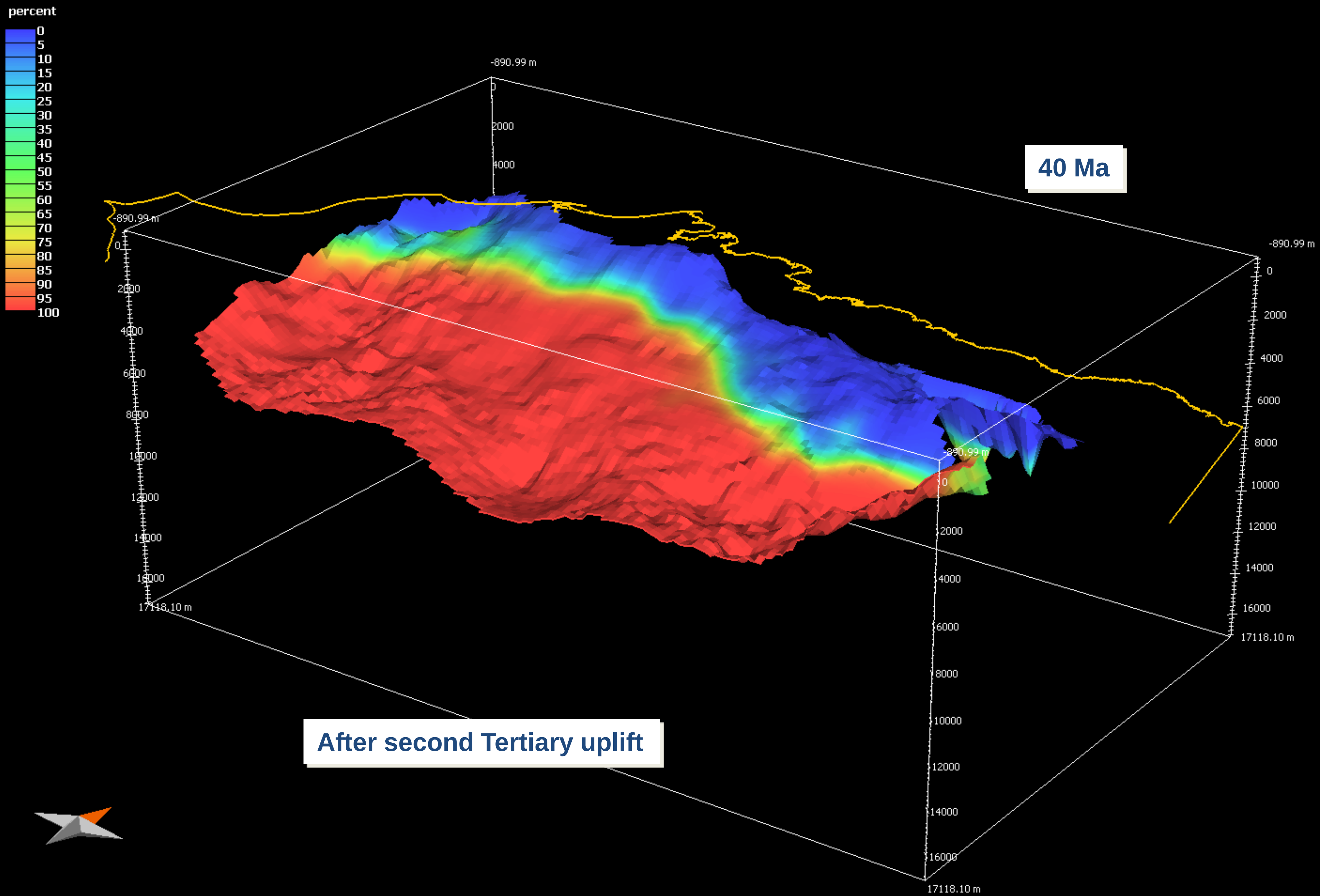

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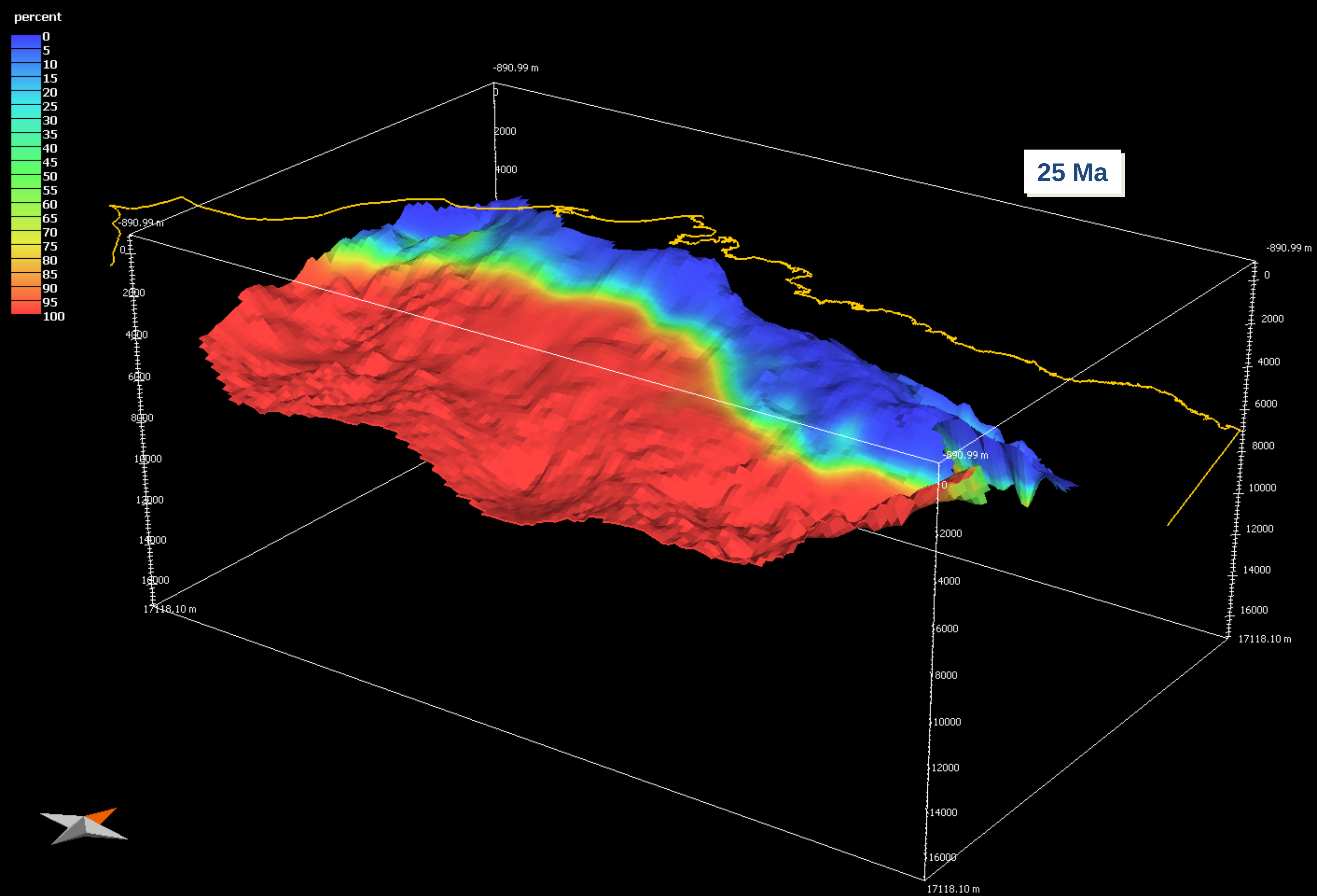
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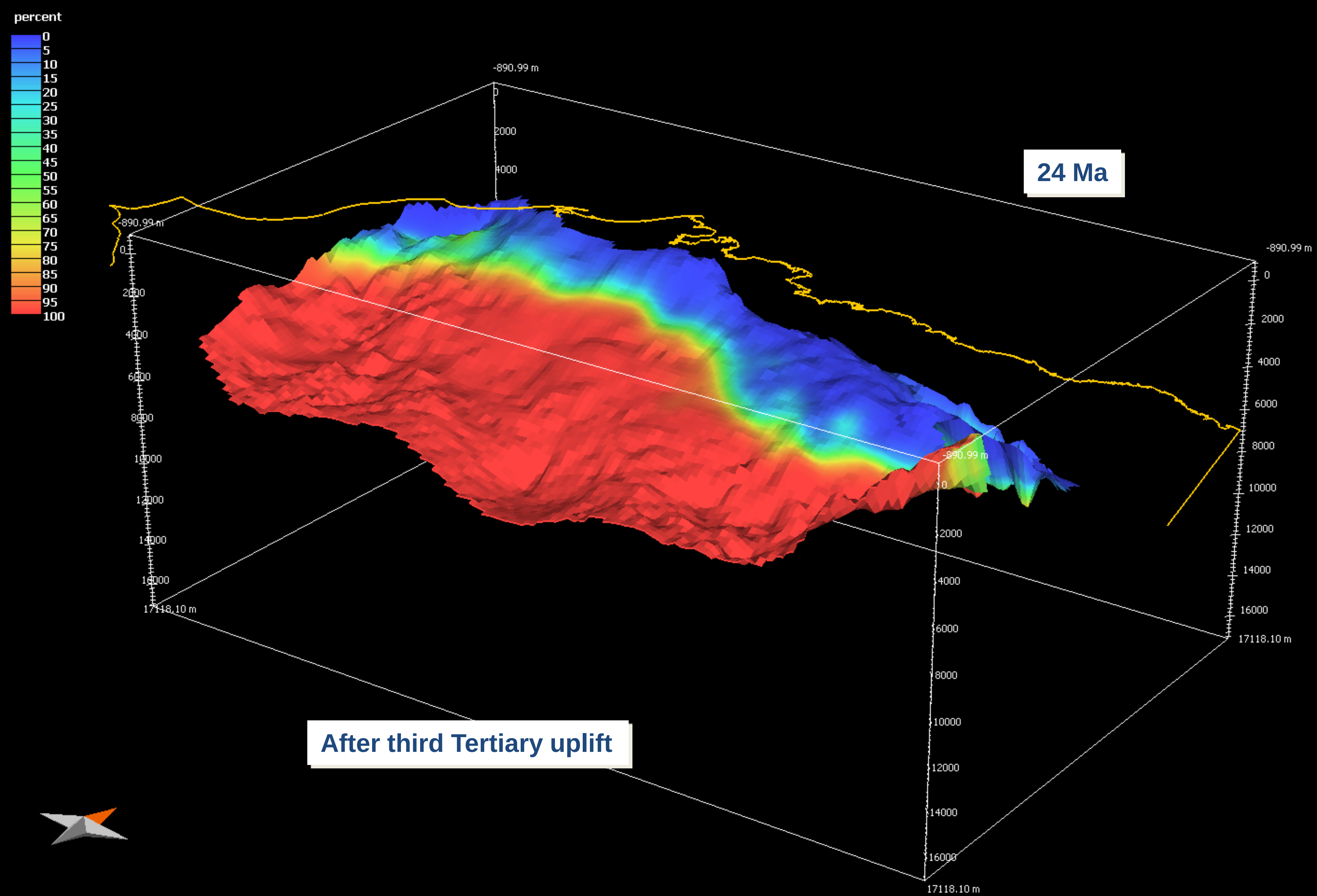
75
80
85
90
95
100
25 Ma
-890.99 m
17118.10 m



percent
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40
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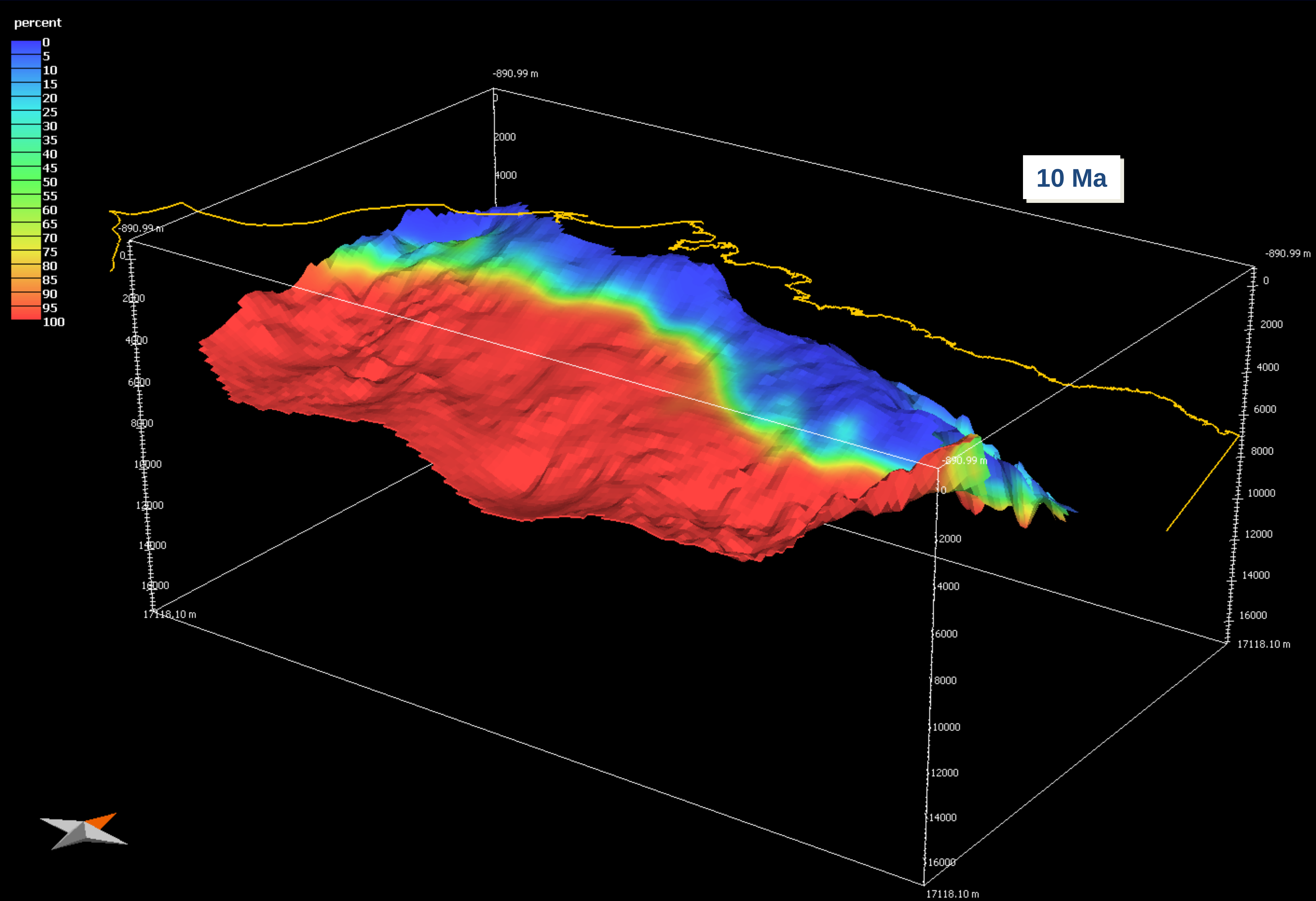
85
90
95
100
-890.99 m
17118.10 m
24 Ma
After third Tertiary uplift



percent
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10 Ma
-890.99 m
0
2000
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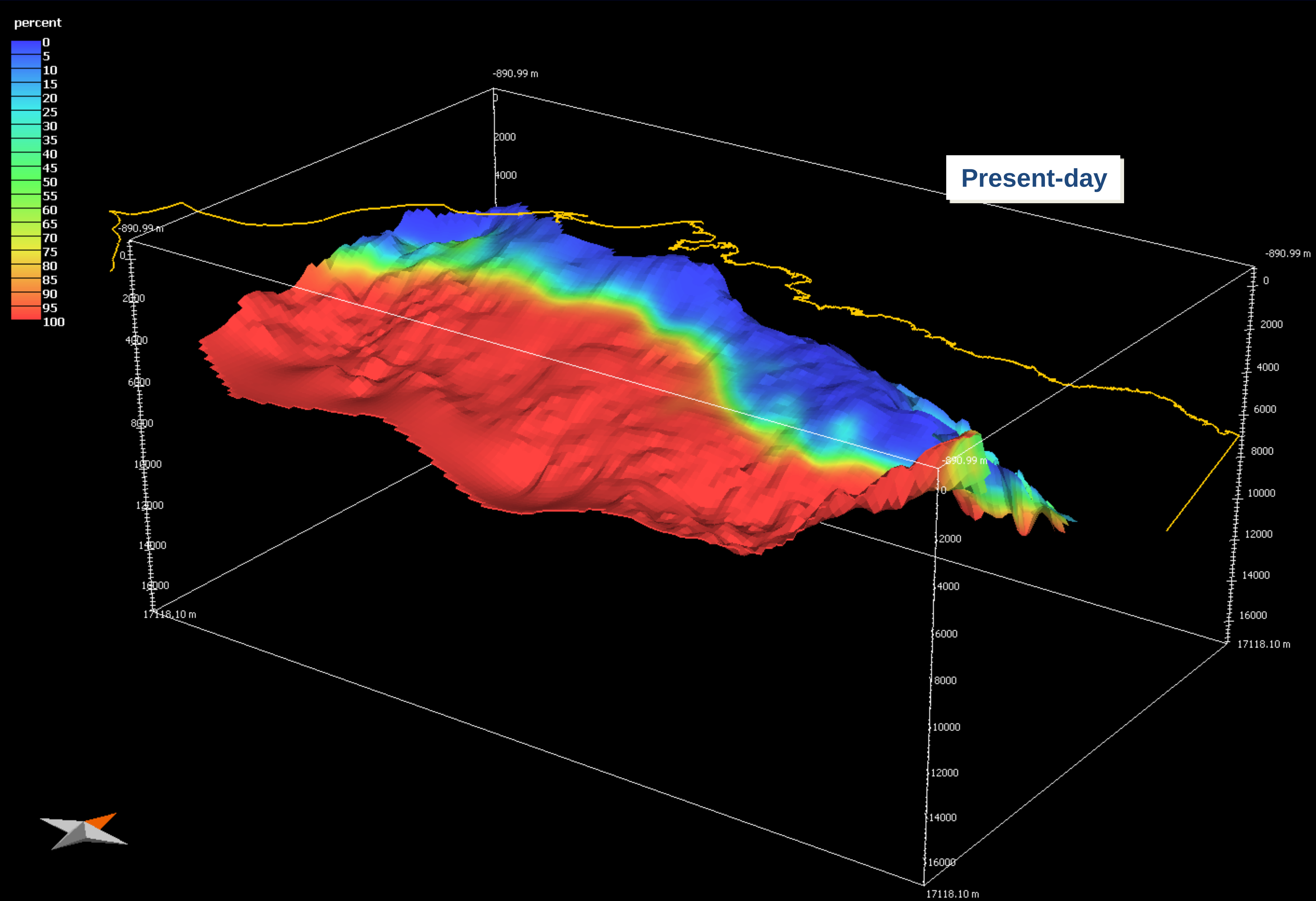
12000
14000
16000
17118.10 m


percent
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50
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65
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75
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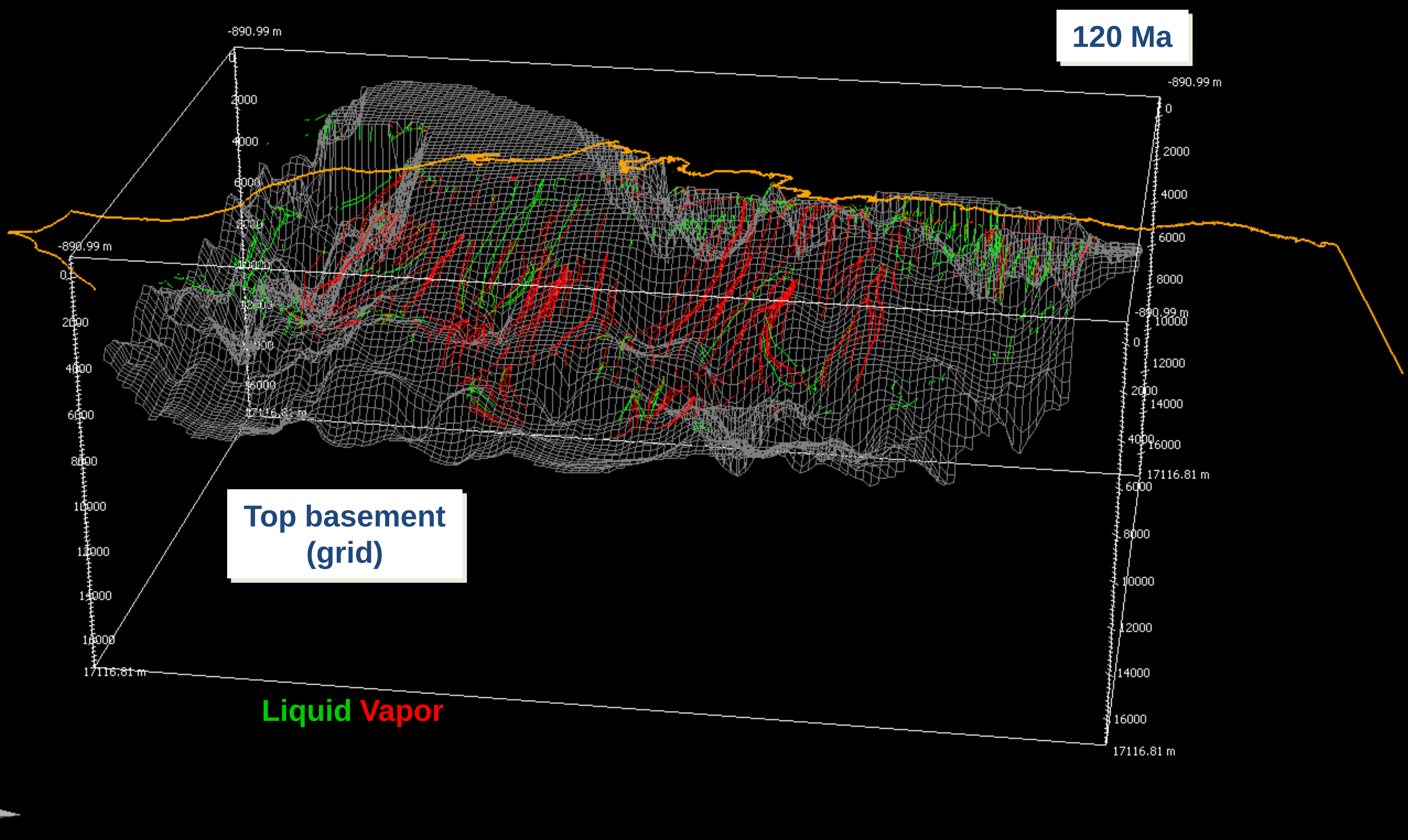
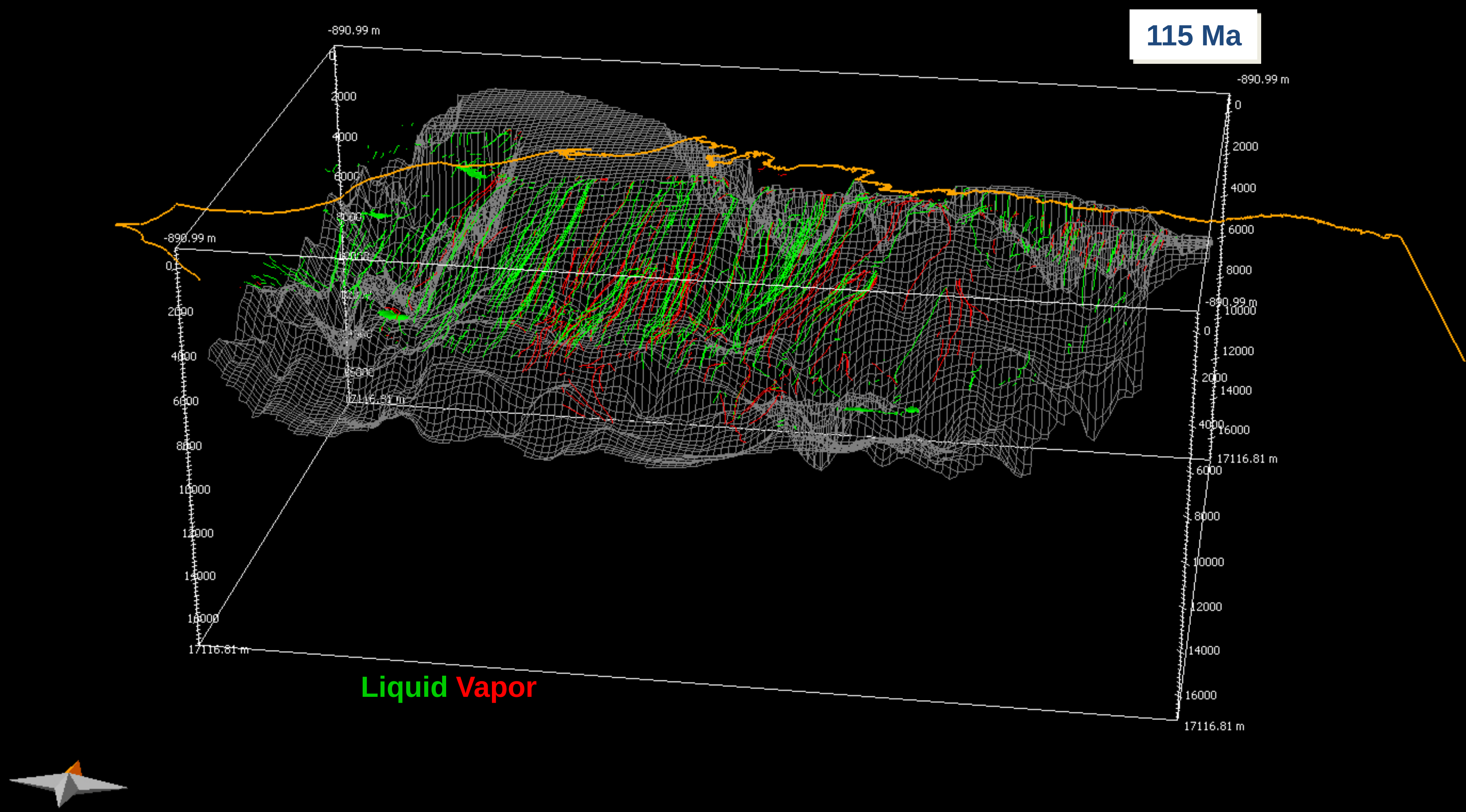
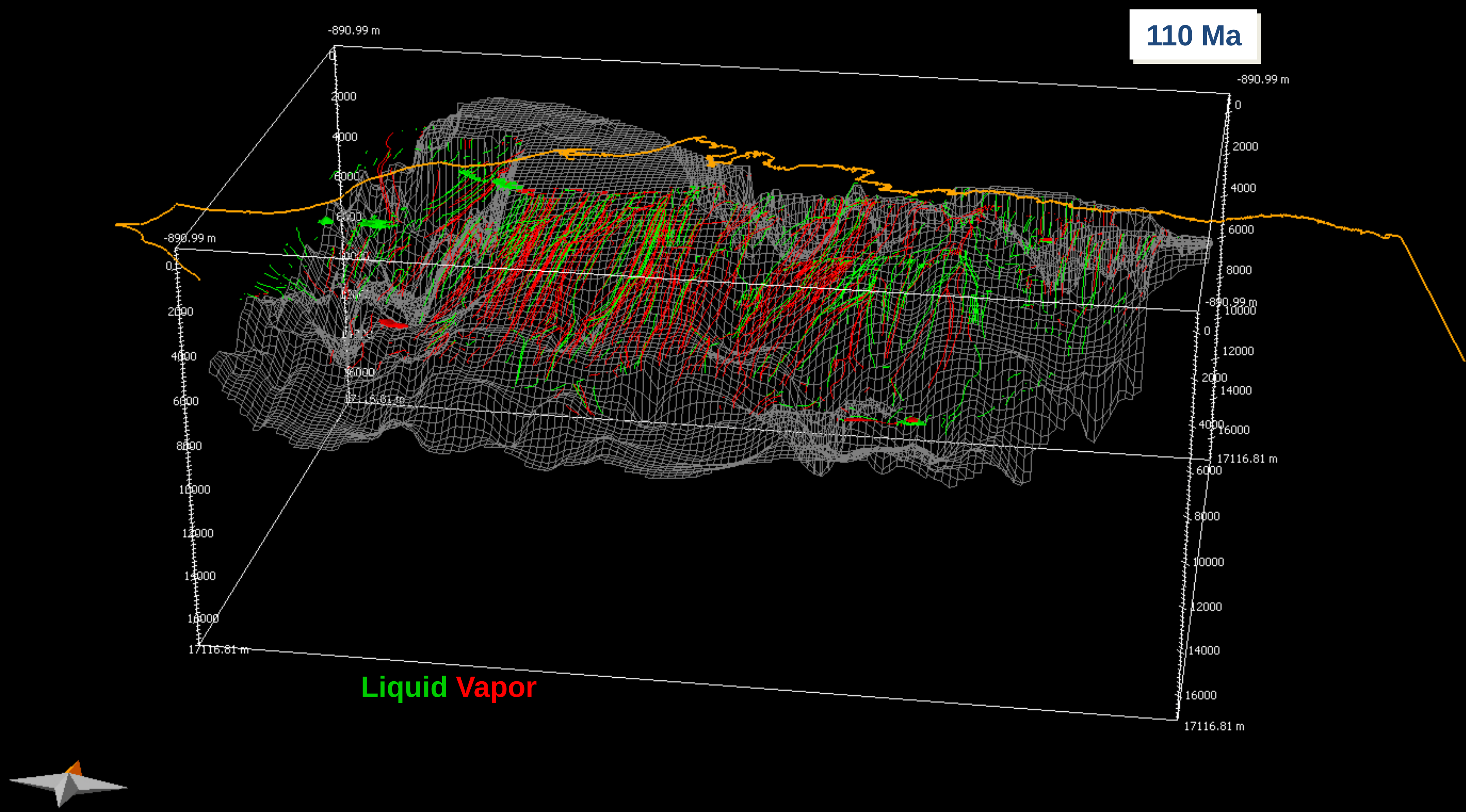
85
90
95
100
Present-day
-890.99 m
17118.10 m

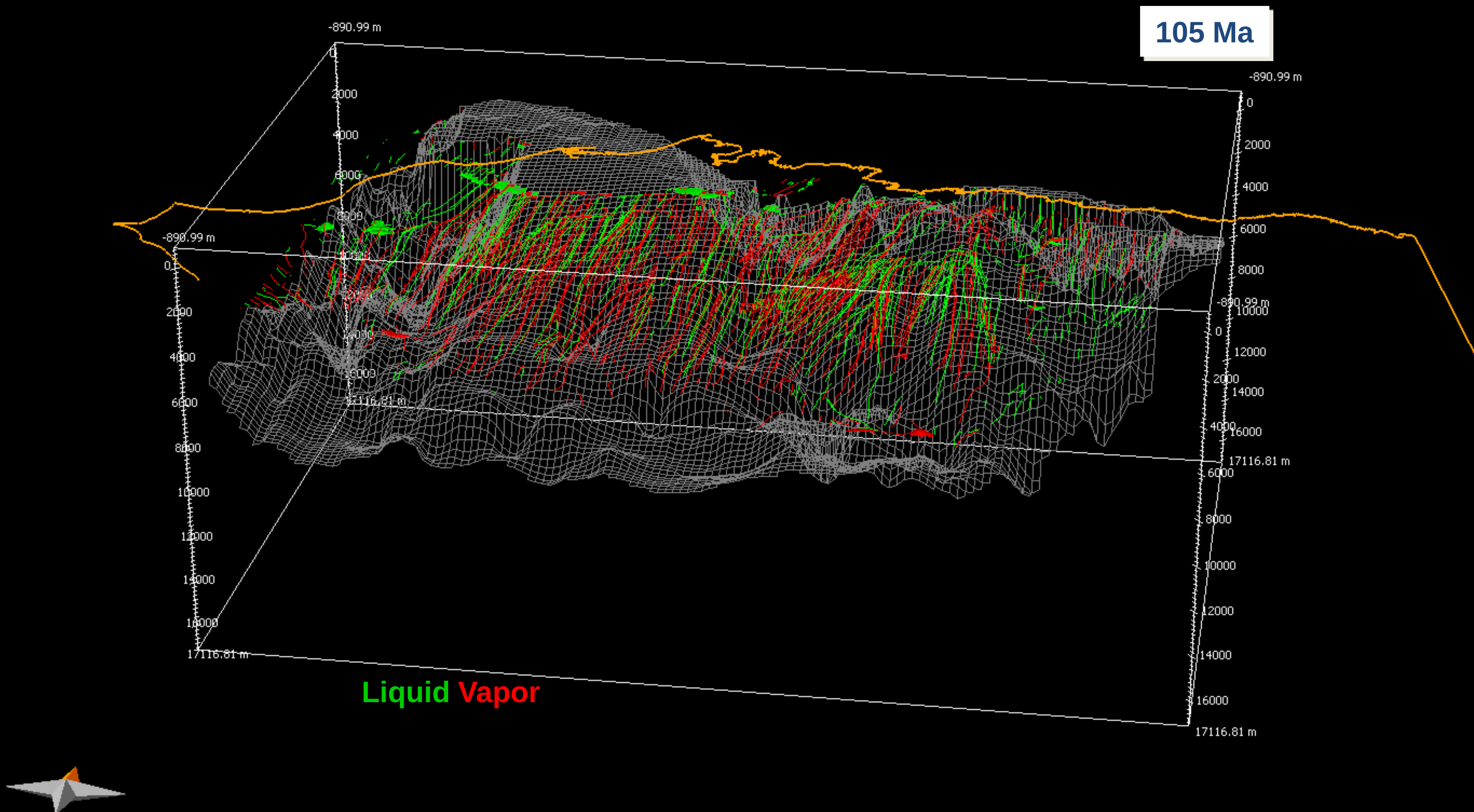
Accumulations Originate from Multiple Source Rocks Through Time

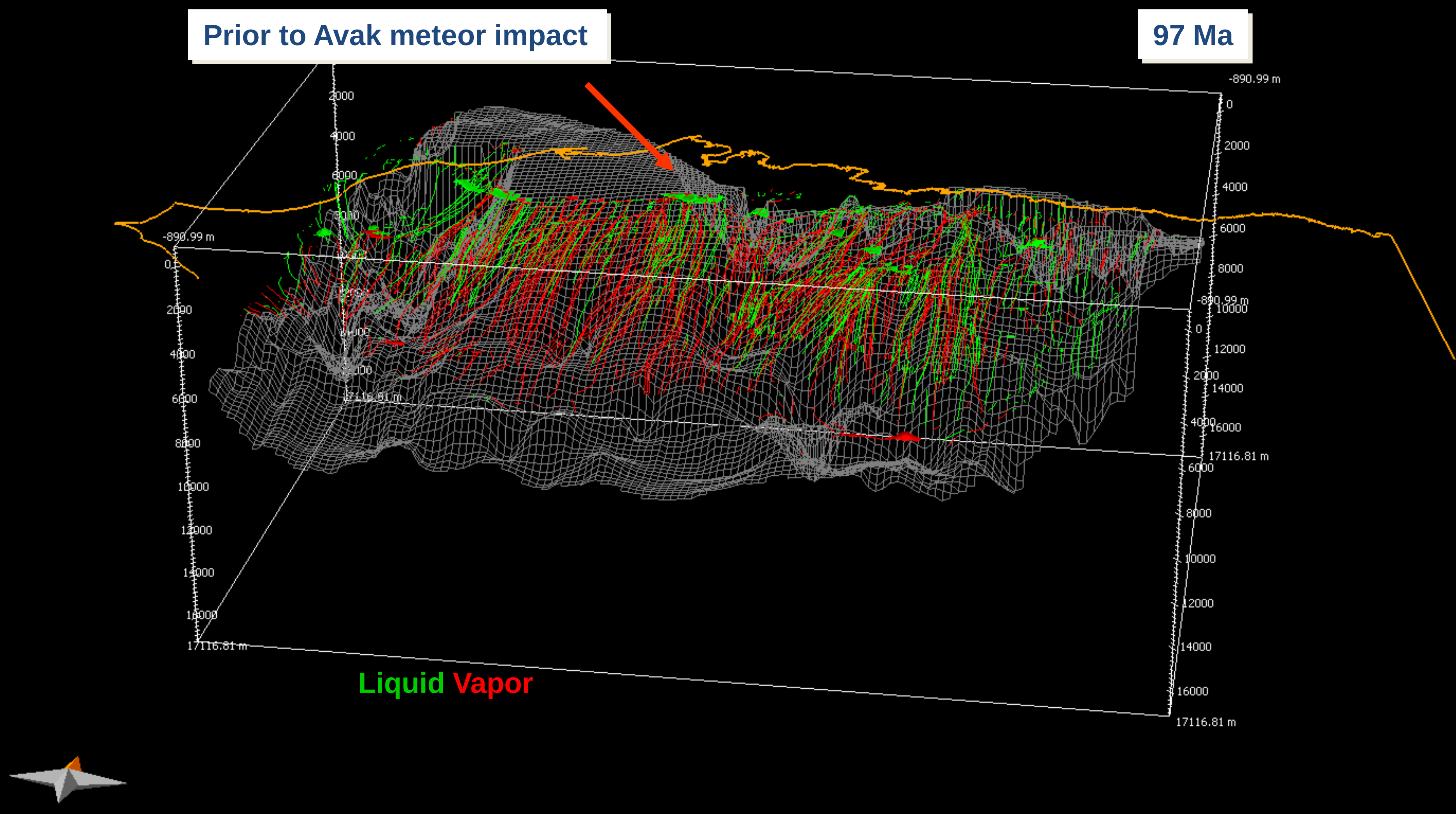




115 Ma
Liquid Vapor
-890.99 m
17116.81 m

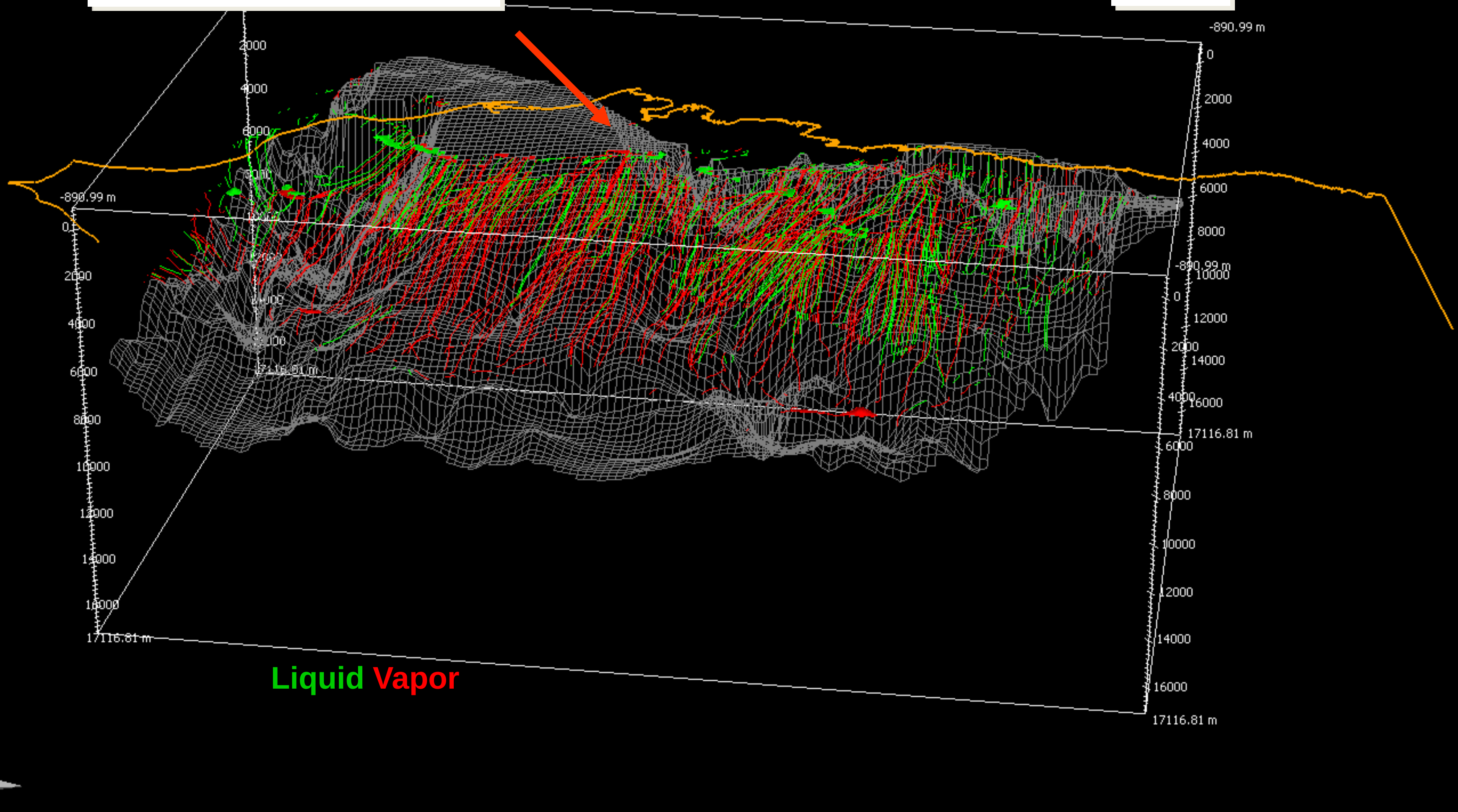

110 Ma
Liquid Vapor

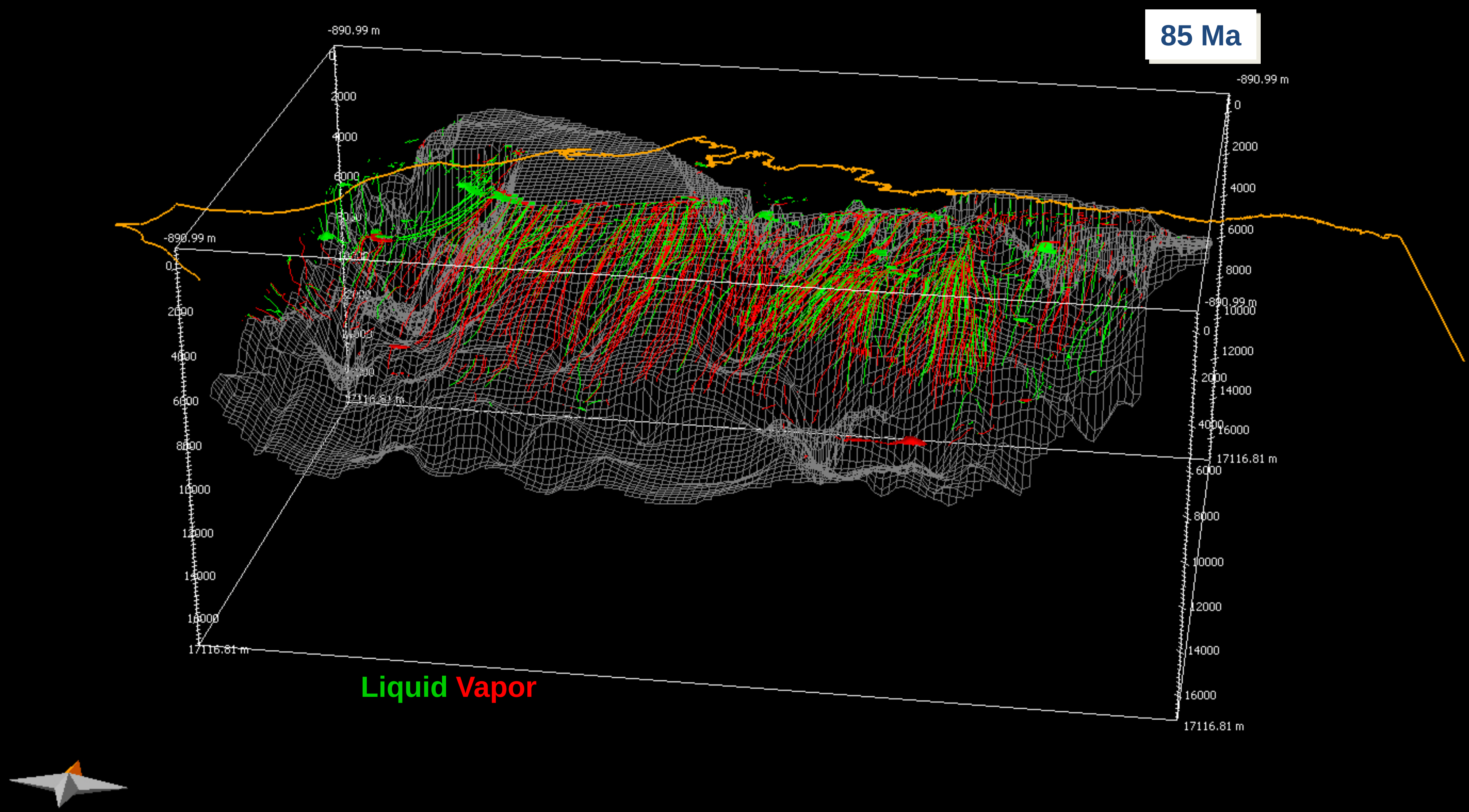

105 Ma
-890.99 m
17116.81 m
0
2000
4000
6000
8000
10000
12000
14000
16000
Liquid Vapor

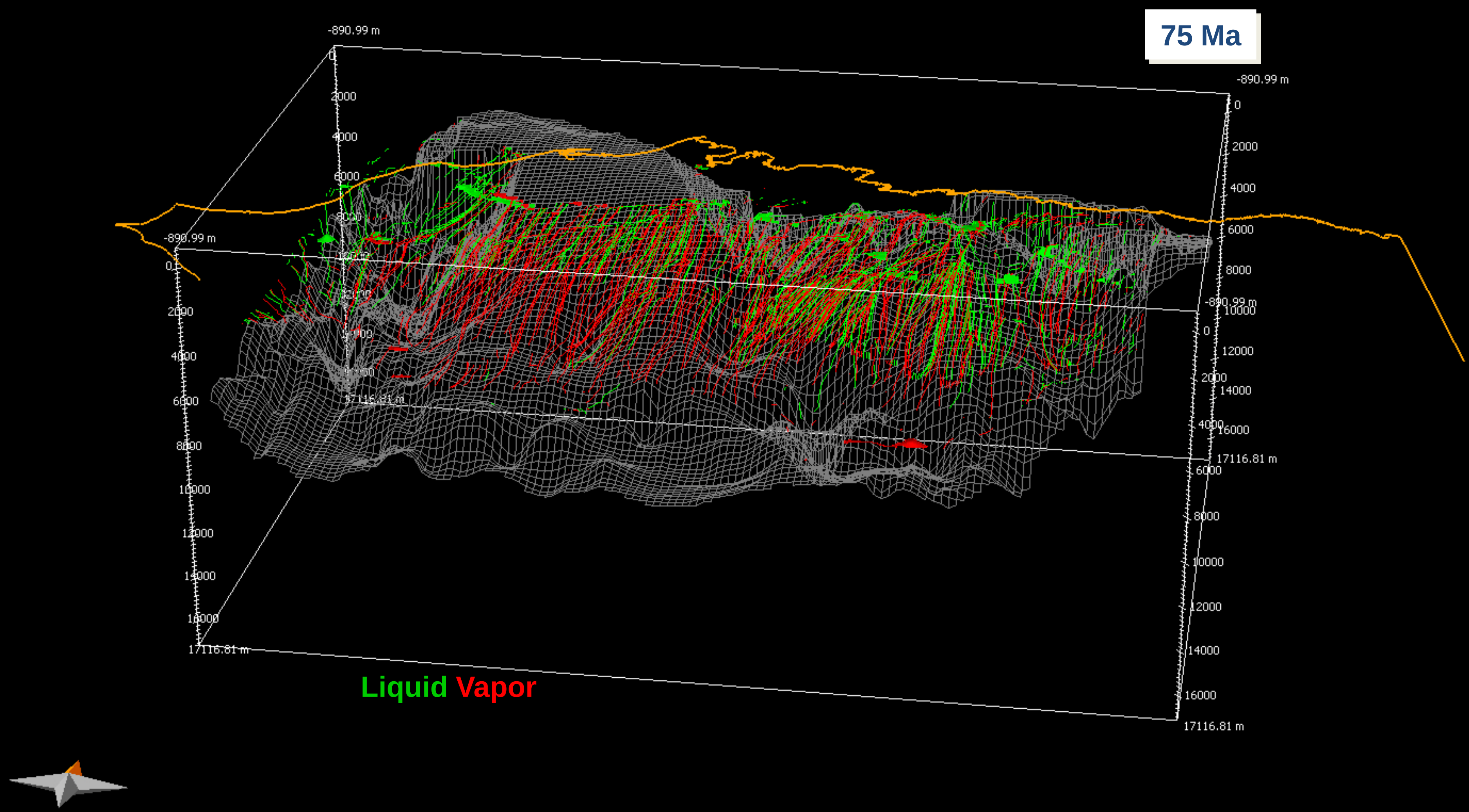

Prior to Avak meteor impact
97 Ma
Liquid Vapor

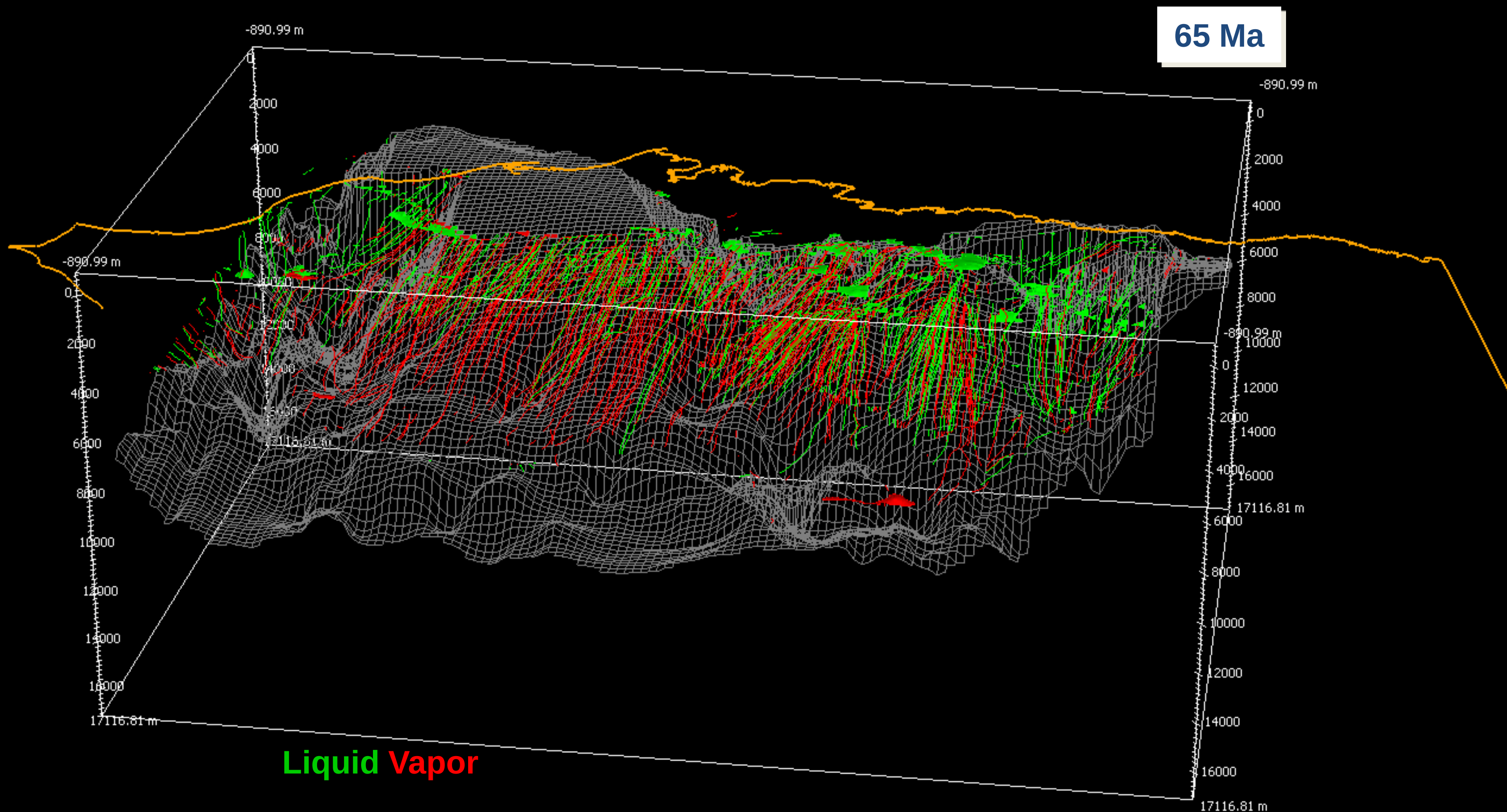
After Avak meteor impact

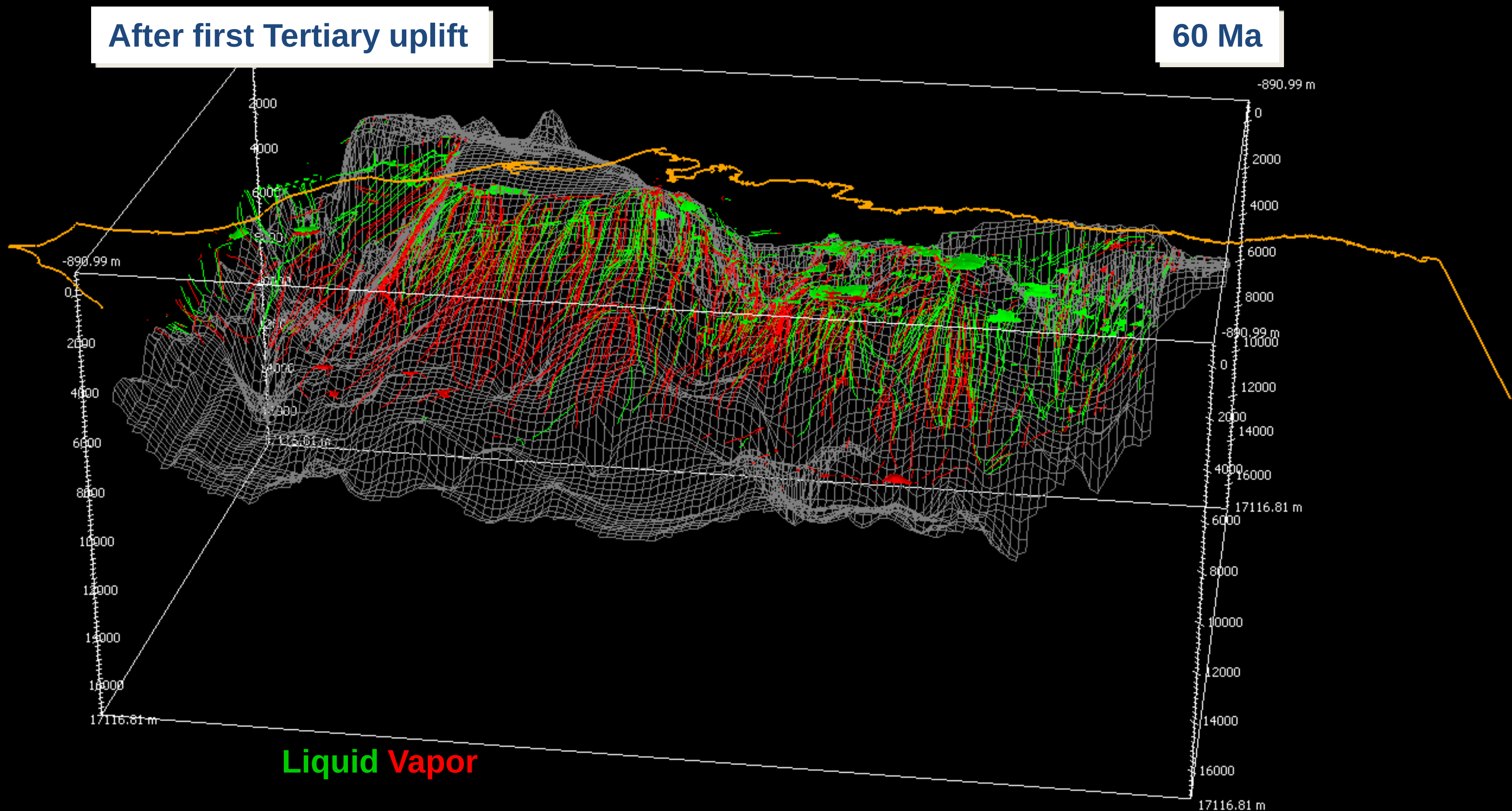
96 Ma

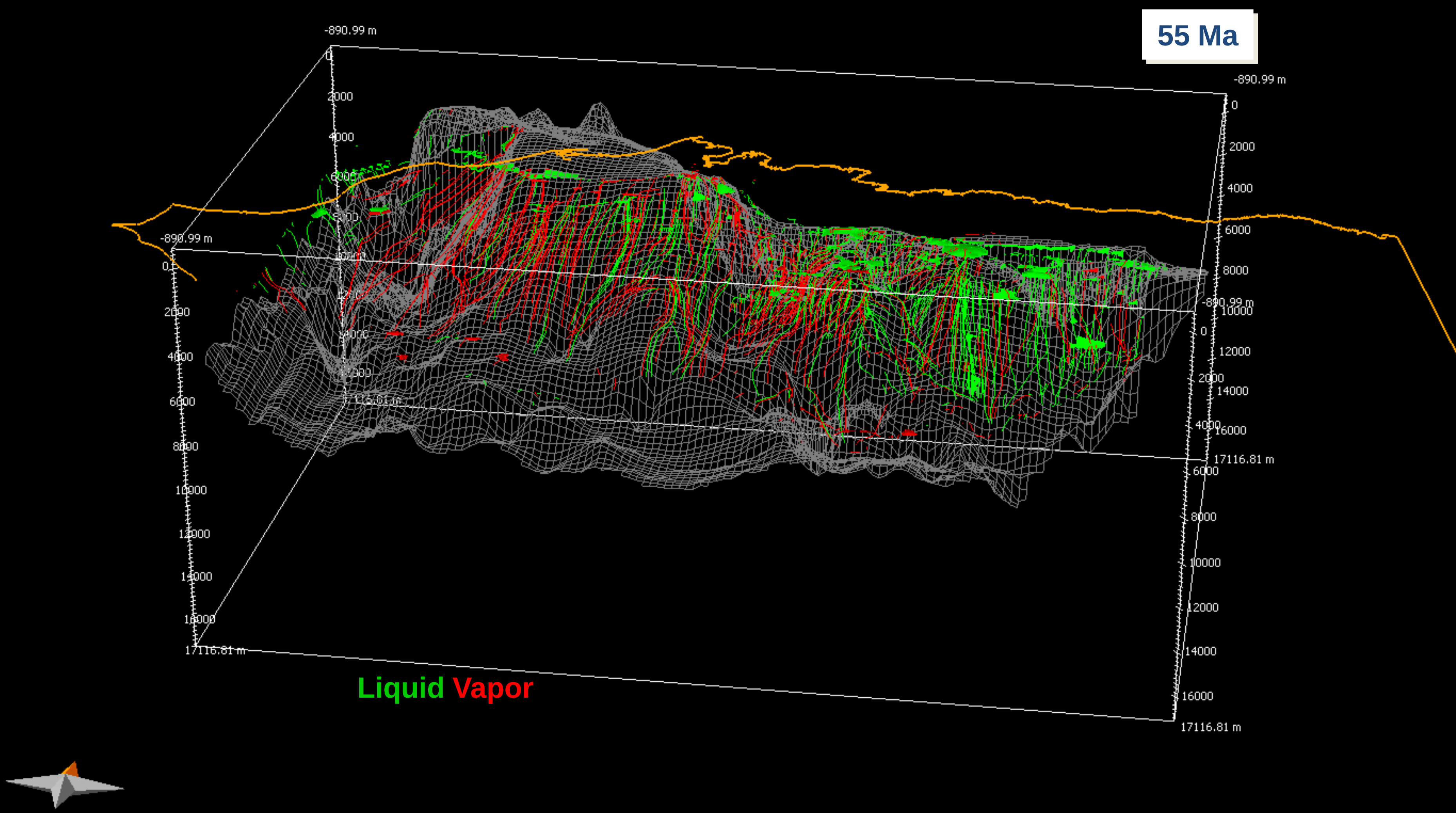


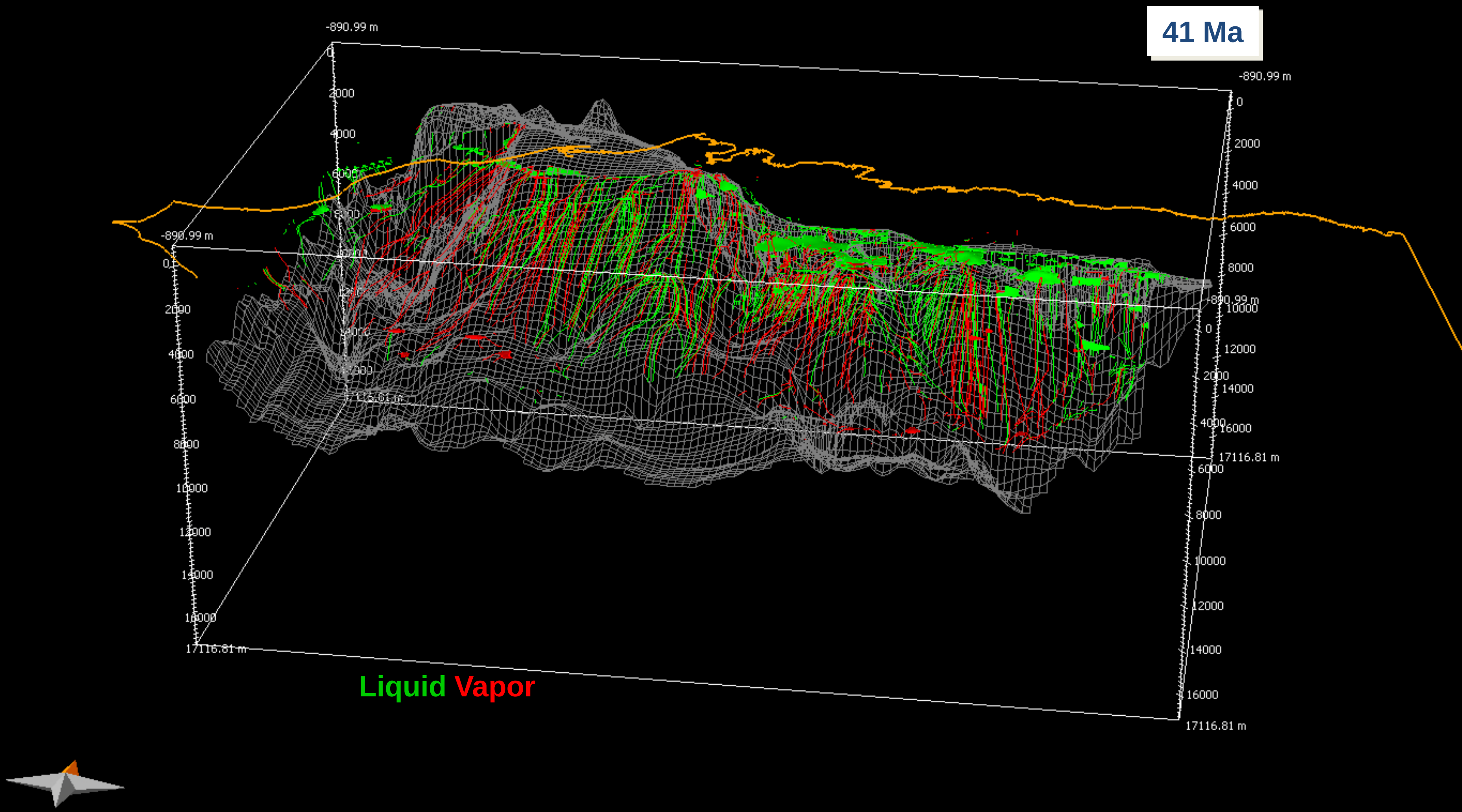

85 Ma
-890.99 m
17116.81 m
Liquid Vapor


75 Ma
-890.99 m
17116.81 m
Liquid Vapor


65 Ma
-890.99 m
17116.81 m
0
2000
4000
6000
8000
10000
12000
14000
16000
Liquid Vapor

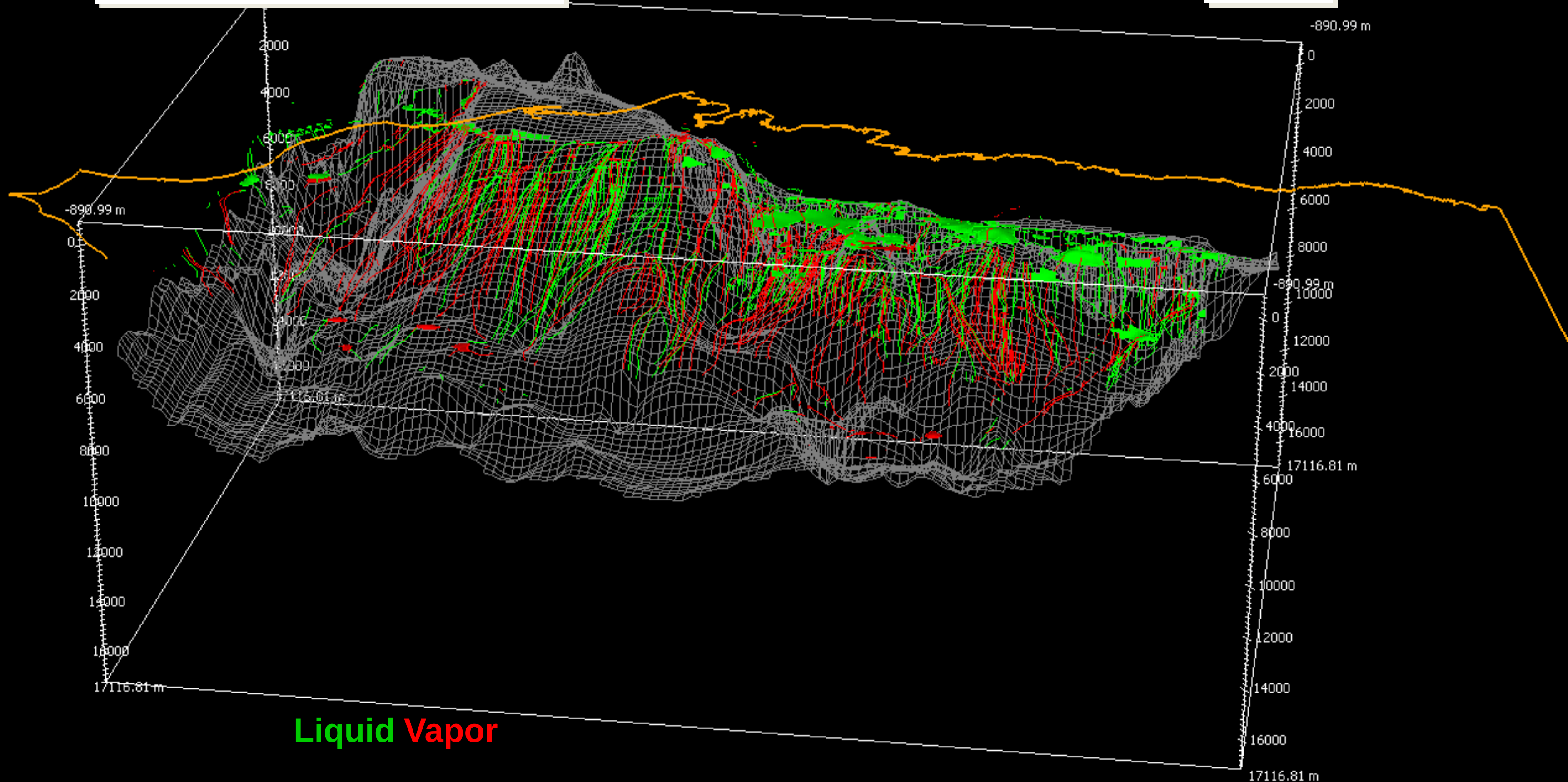

After first Tertiary uplift
60 Ma
Liquid
Vapor
-890.99 m
17116.81 m

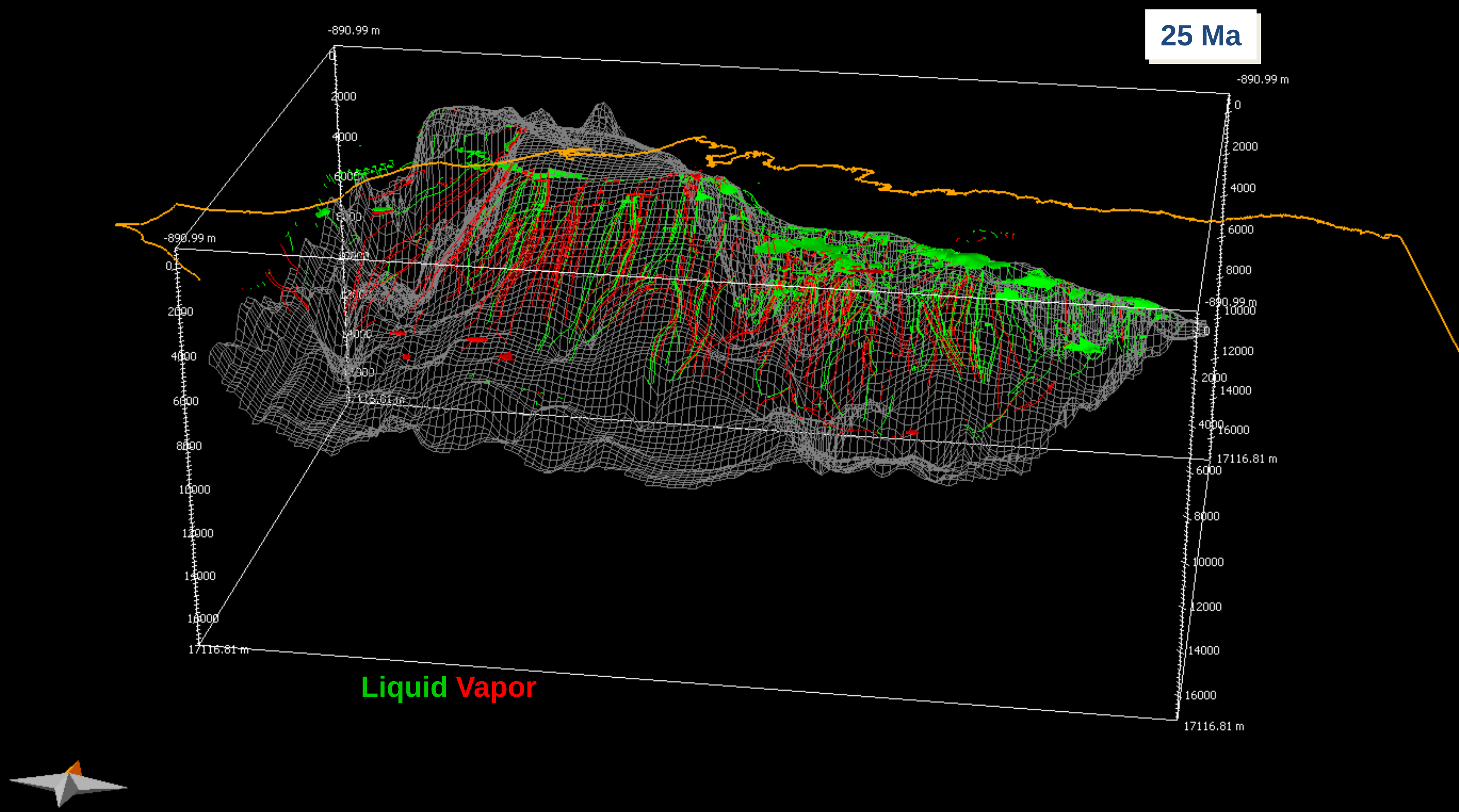

55 Ma
Liquid Vapor
-890.99 m
17116.81 m
0
2000
4000
6000
8000
10000
12000
14000
16000


41 Ma
-890.99 m
0
2000
4000
6000
8000
10000
12000
14000
16000
17116.81 m
Liquid
Vapor

After second Tertiary uplift

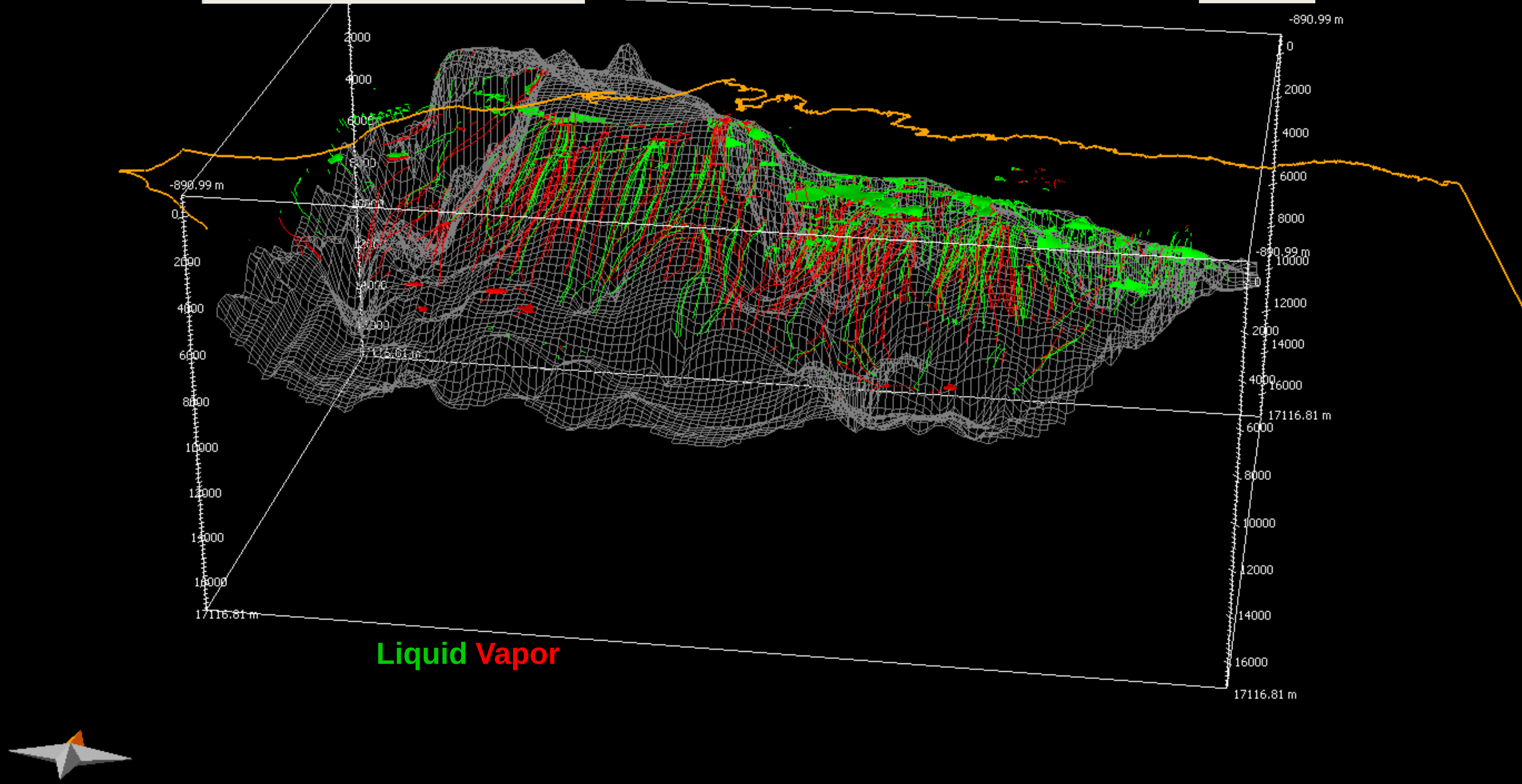
40 Ma

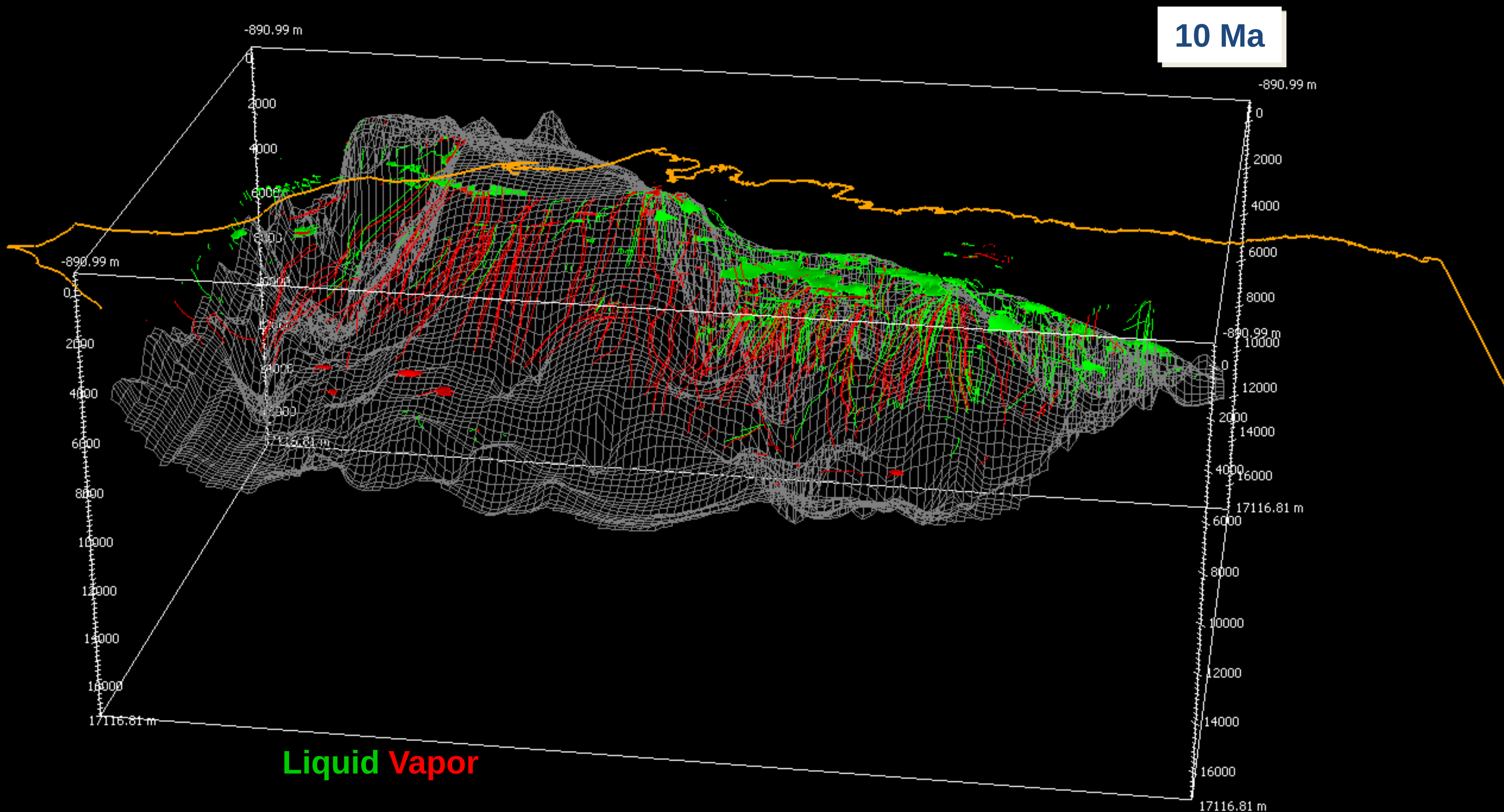


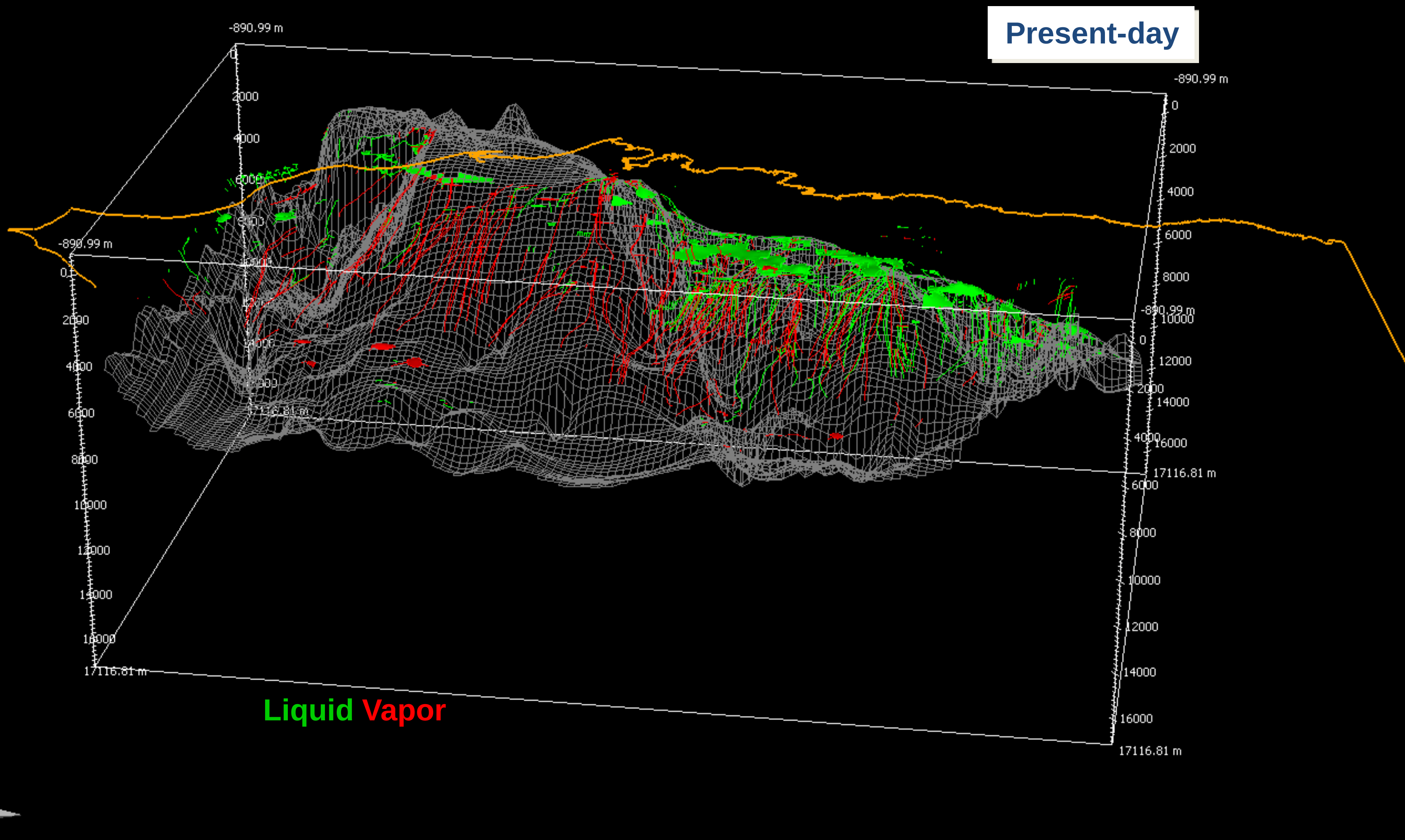

25 Ma
-890.99 m
17116.81 m
0
2000
4000
6000
8000
10000
12000
14000
16000
Liquid Vapor

After third Tertiary uplift

24 Ma

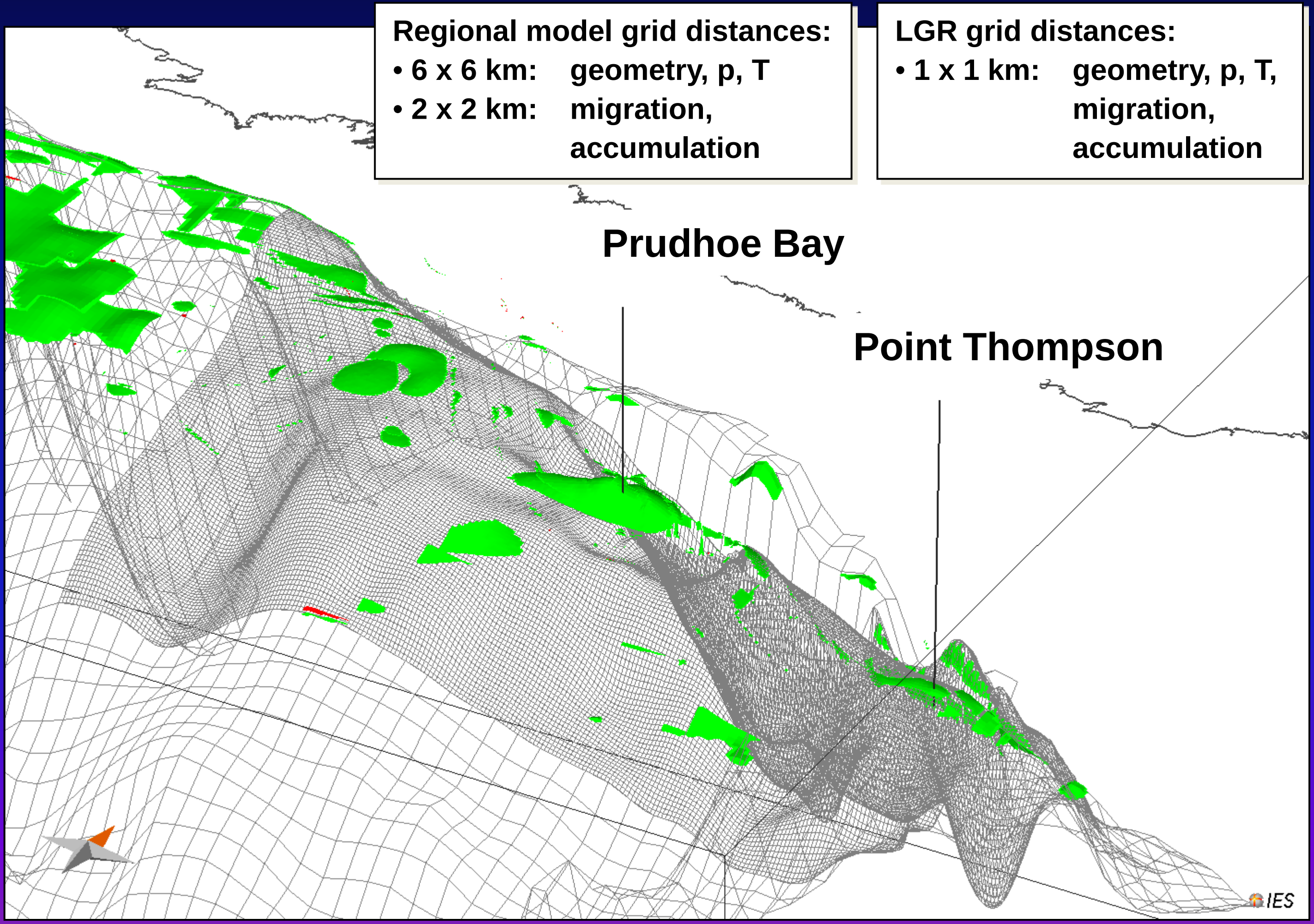



10 Ma
-890.99 m
17116.81 m
0
2000
4000
6000
8000
10000
12000
14000
16000
Liquid Vapor

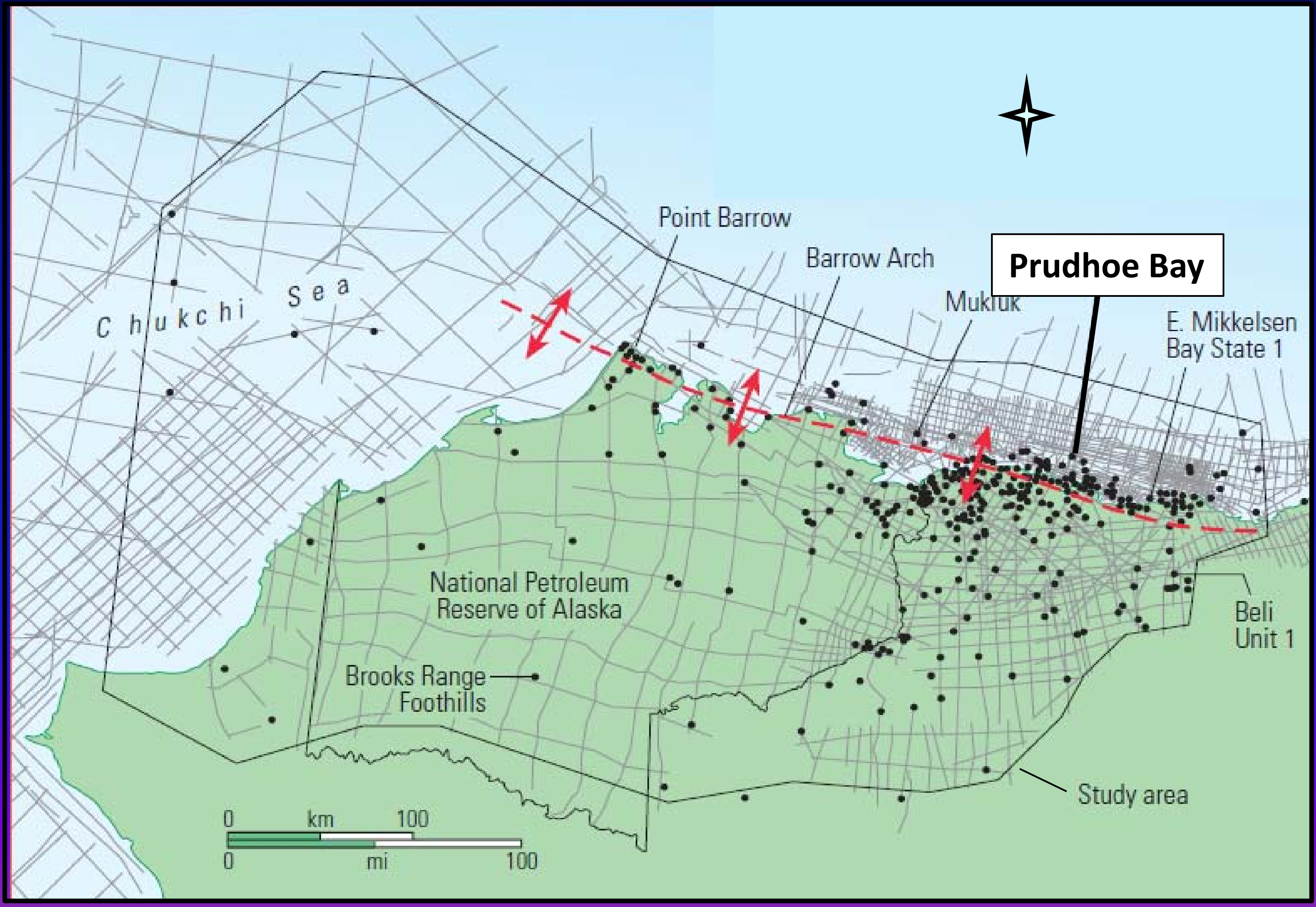


Present-day
-890.99 m
17116.81 m
Liquid Vapor

Local Grid Refinement (LGR) Allows Higher Spatial Resolution

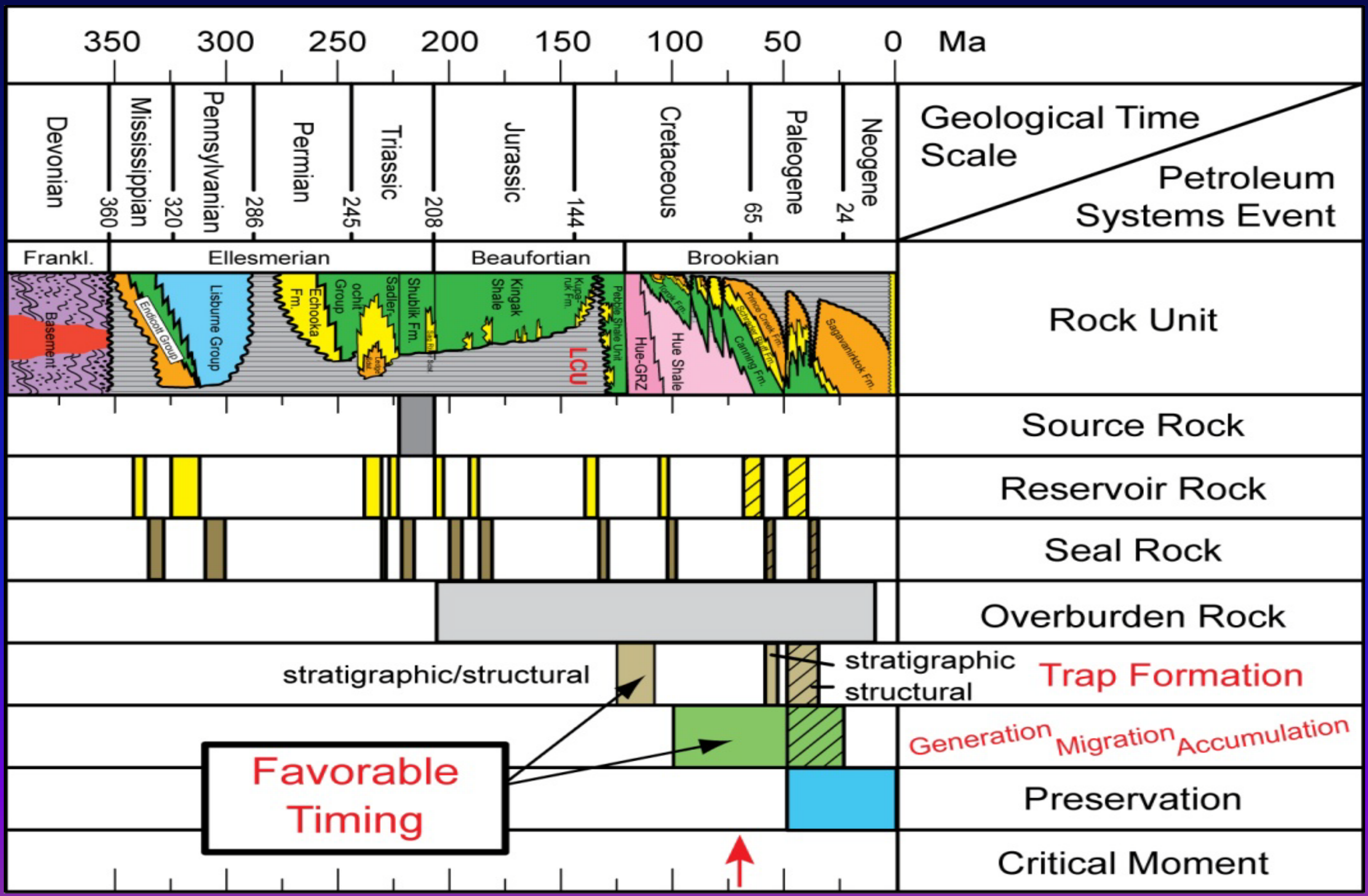


Prudhoe Bay: Event Timing Favors Accumulation of Shublik Oil and Gas



Click to View Notes by Presenter

Prudhoe Bay: Event Timing Favors Accumulation of Shublik Oil and Gas



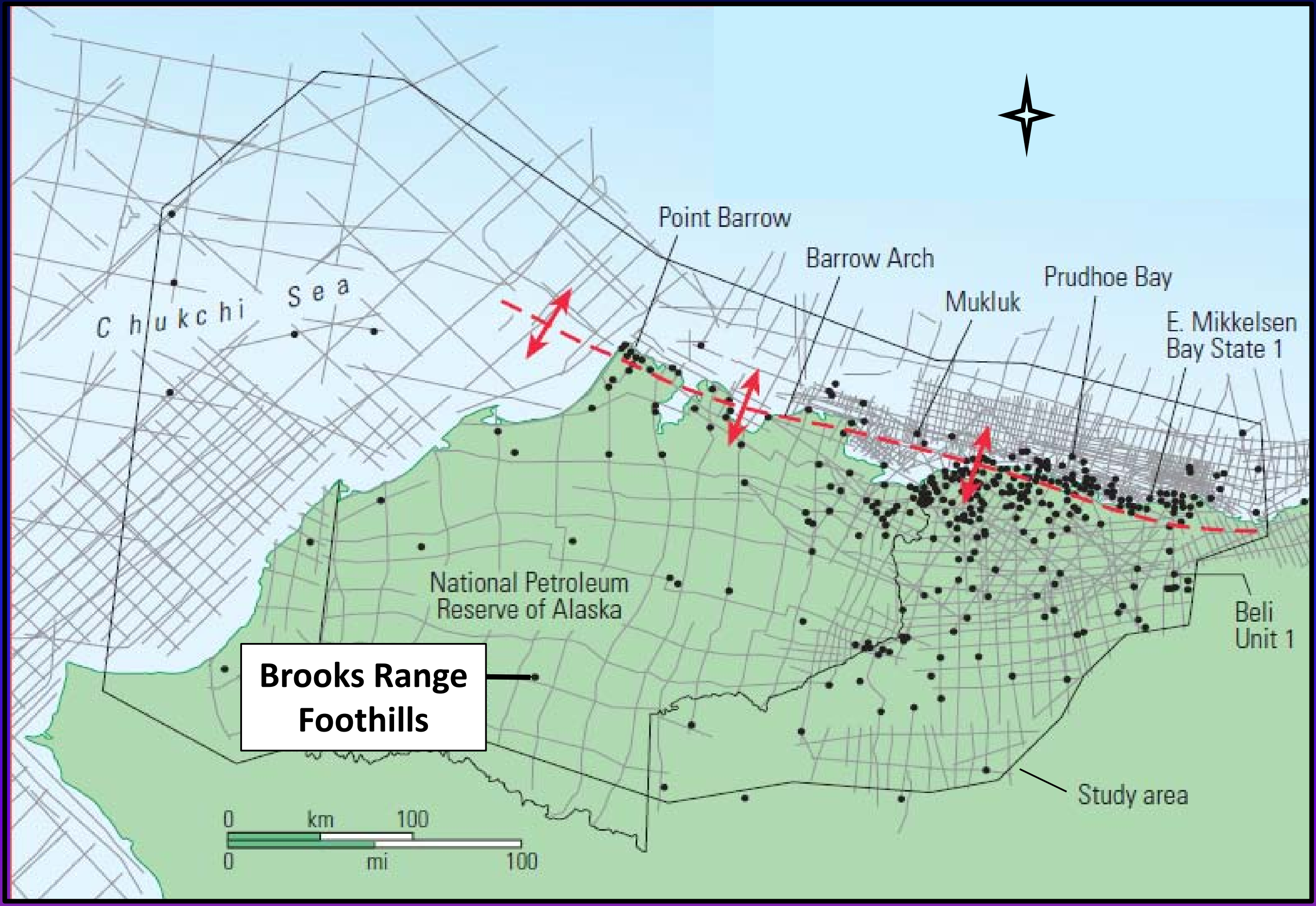
Notes by Presenter (for previous slide):

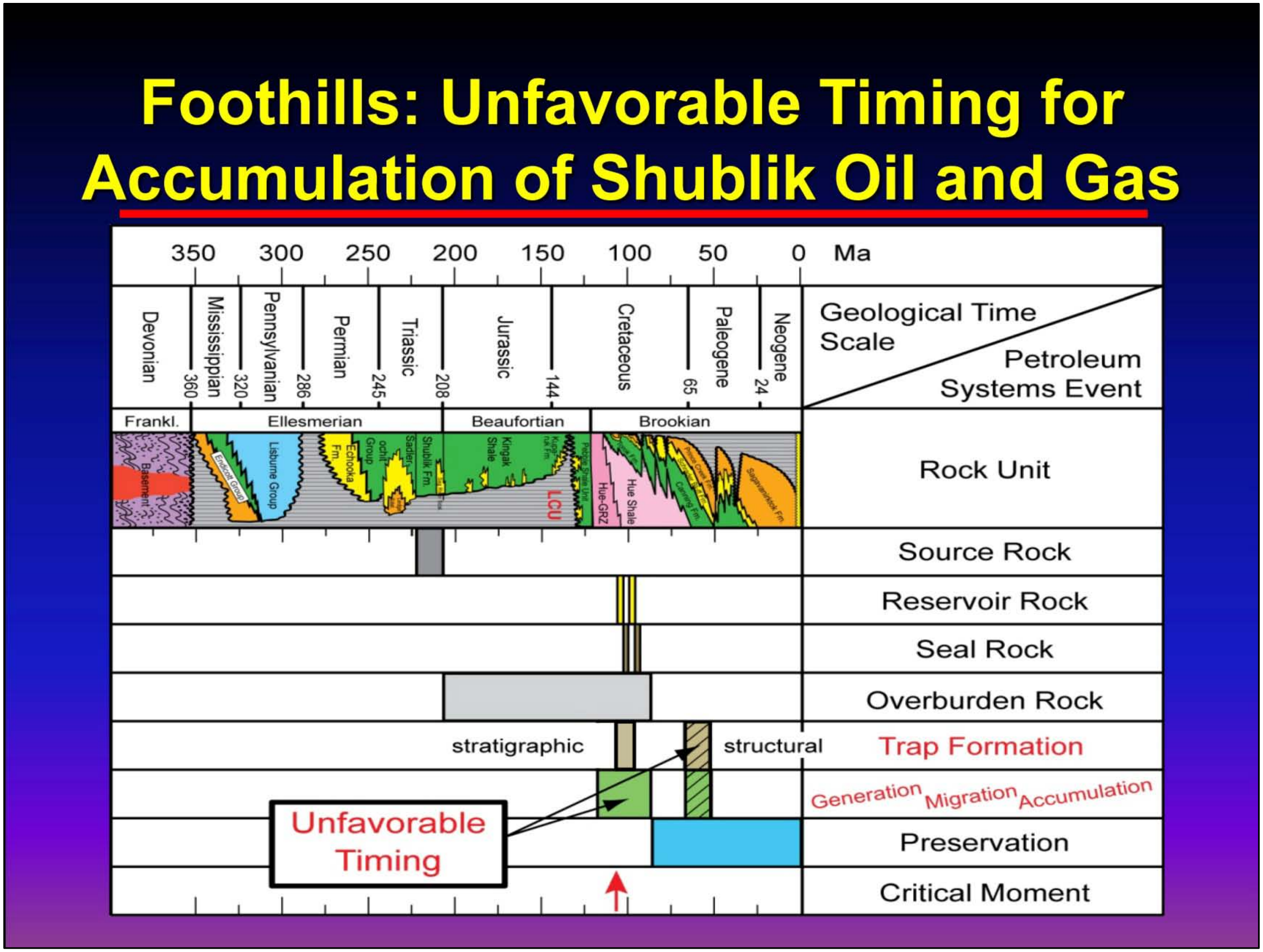
Hatchured pattern indicates estimated time of eastward tilting of earlier trapped petroleum to traps in younger (early Tertiary) reservoirs.

Timing of generation and expulsion were obtained from the model, but information on trap formation, reservoir rocks, and migration pathways are based on other data.

At Prudhoe Bay, trap formation preceded expulsion, resulting in a major accumulation. Biomarkers show that Prudhoe Bay field contains mixed oil from the Triassic Shublik Formation and Cretaceous Hue Shale with lesser input from the Jurassic Kingak Shale (Peters et al., 2008). These results are consistent with the 3D model (Figure 3): the Shublik and Kingak source rocks started to expel hydrocarbons during the Cretaceous mainly in the Colville Basin which migrate northward to the Barrow Arch. During Tertiary time burial is mainly restricted to the northeastern part of the study area and associated tilting and subsidence results in hydrocarbon generation from the Hue Shale. These hydrocarbons expelled downwards into a zone which is related to the Lower Cretaceous Unconformity (LCU) along which they migrate toward the Barrow Arch and leads to late-stage contribution of Hue oil at Prudhoe Bay.

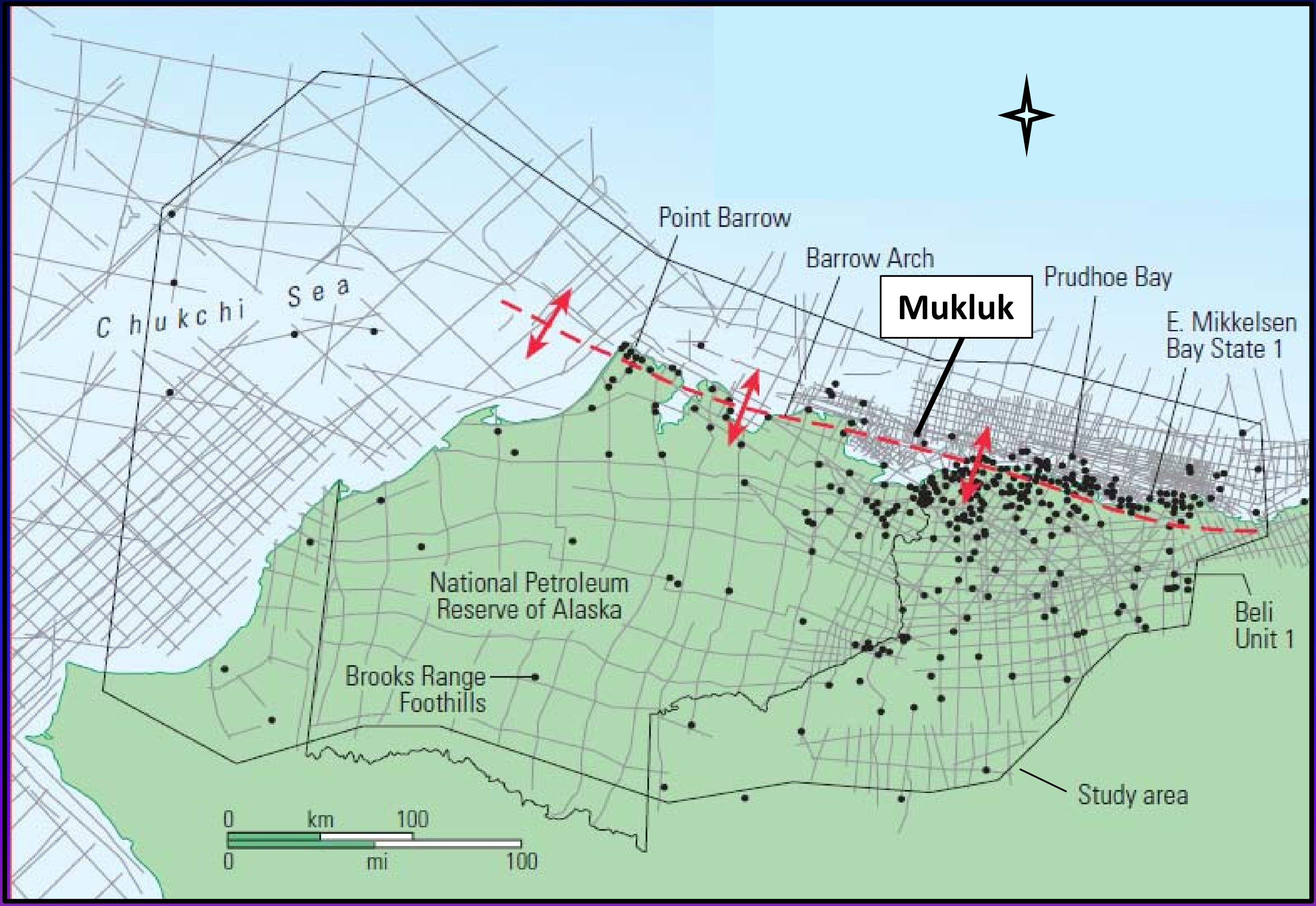
Foothills: Unfavorable Timing for Accumulation of Shublik Oil and Gas

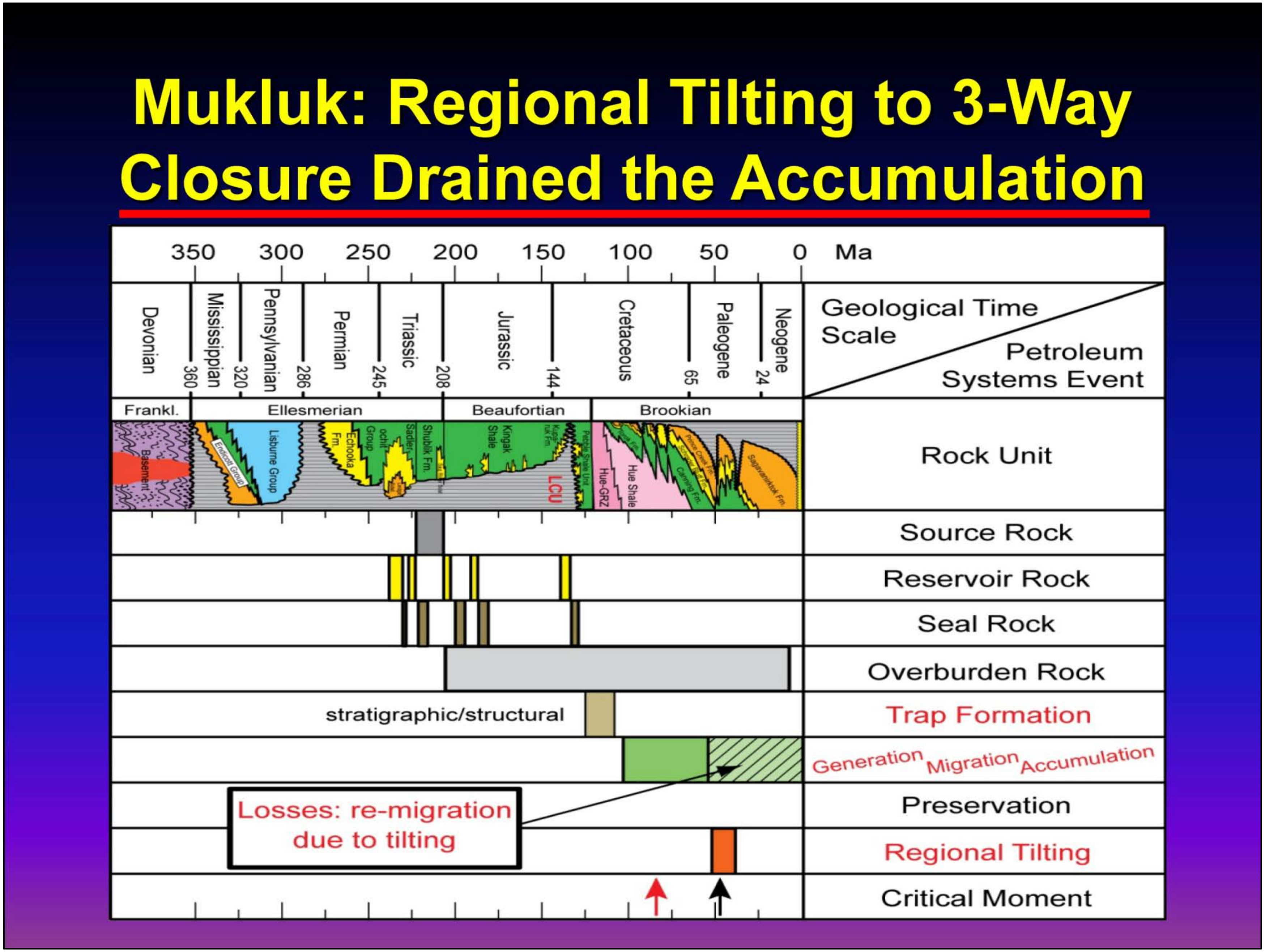




Notes by Presenter: Hatchured pattern indicates estimated time of eastward tilting of earlier trapped petroleum to traps in younger (early Tertiary) reservoirs. Preliminary 3D simulations predicted a large petroleum accumulation on the Barrow Peninsula, although only a few small gas fields are known (S. Barrow, E. Barrow, Sikulik) near the Avak structure, which resulted from a middle-late Turonian meteor impact. Our revised 3D model accounts for the effects of the meteor impact on temperature and permeability of the target rocks. The model predicts a large accumulation prior to impact, but predicted present-day accumulations occur only to the west, south, and east of the Avak structure, in agreement with known accumulations

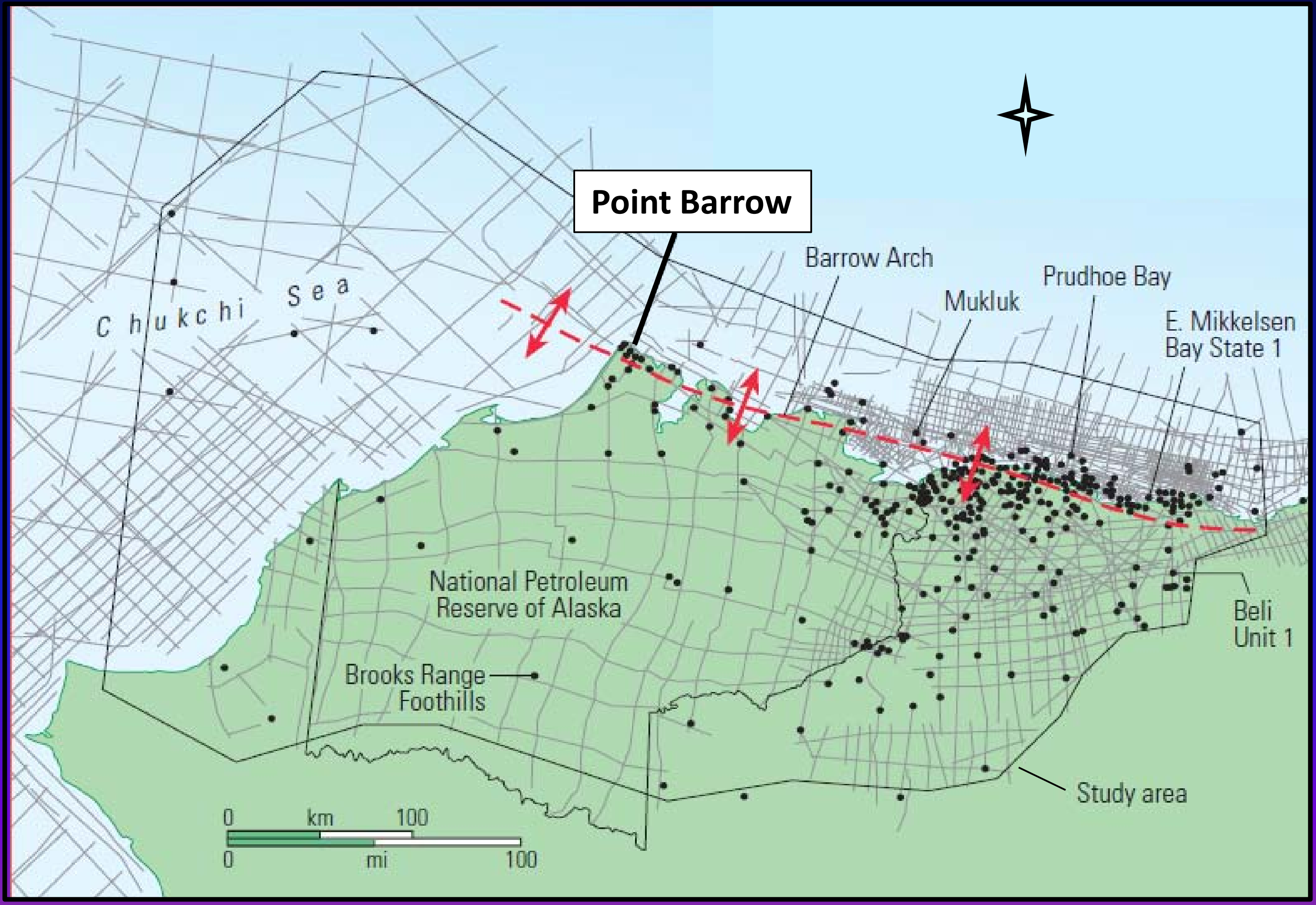
Mukluk: Regional Tilting to 3-Way Closure Drained the Accumulation



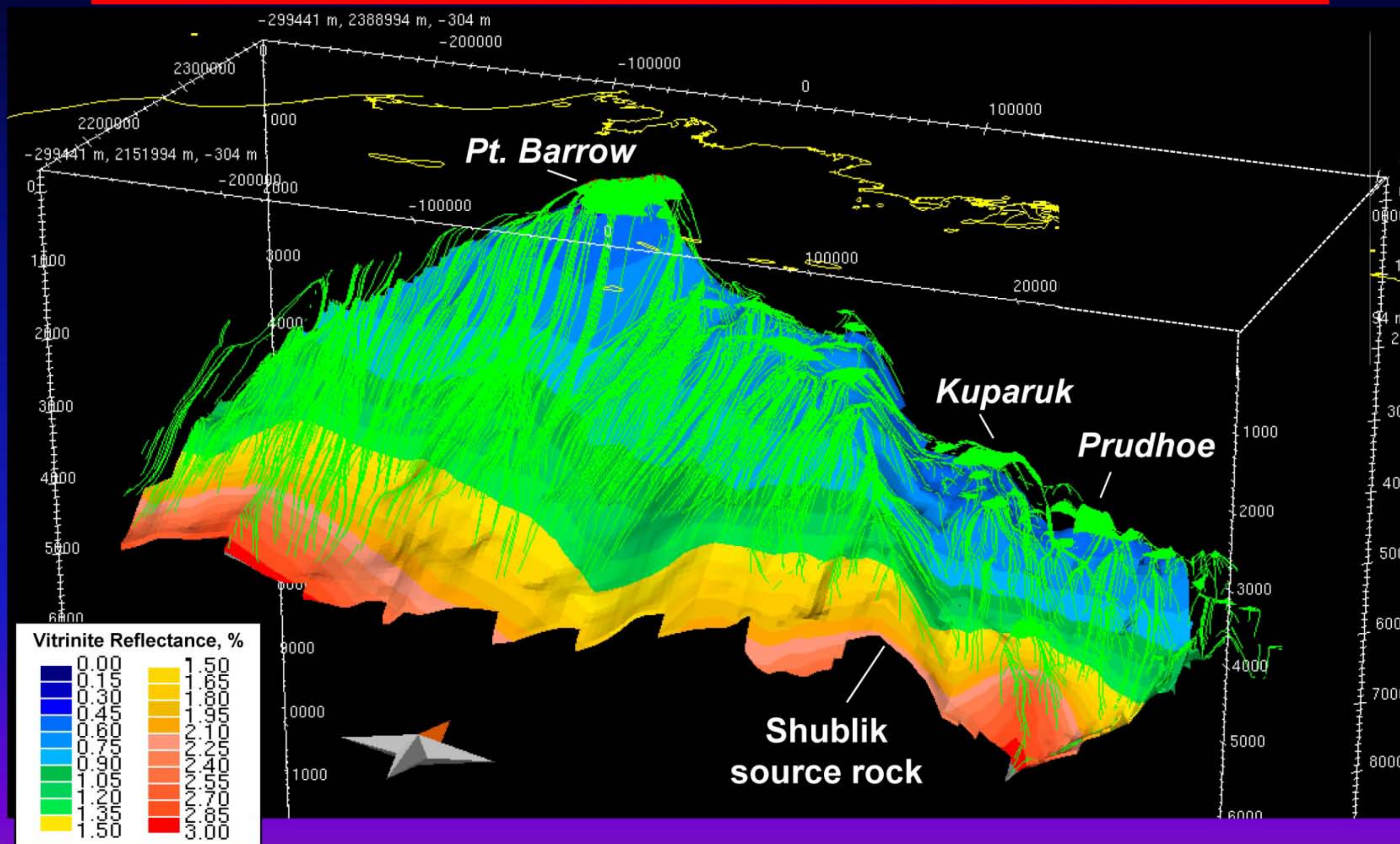


Notes by Presenter: Hatchured pattern indicates estimated time of eastward tilting of earlier trapped petroleum to traps in younger (early Tertiary) reservoirs.

Point Barrow: Unusual Event Destroyed a Large Accumulation

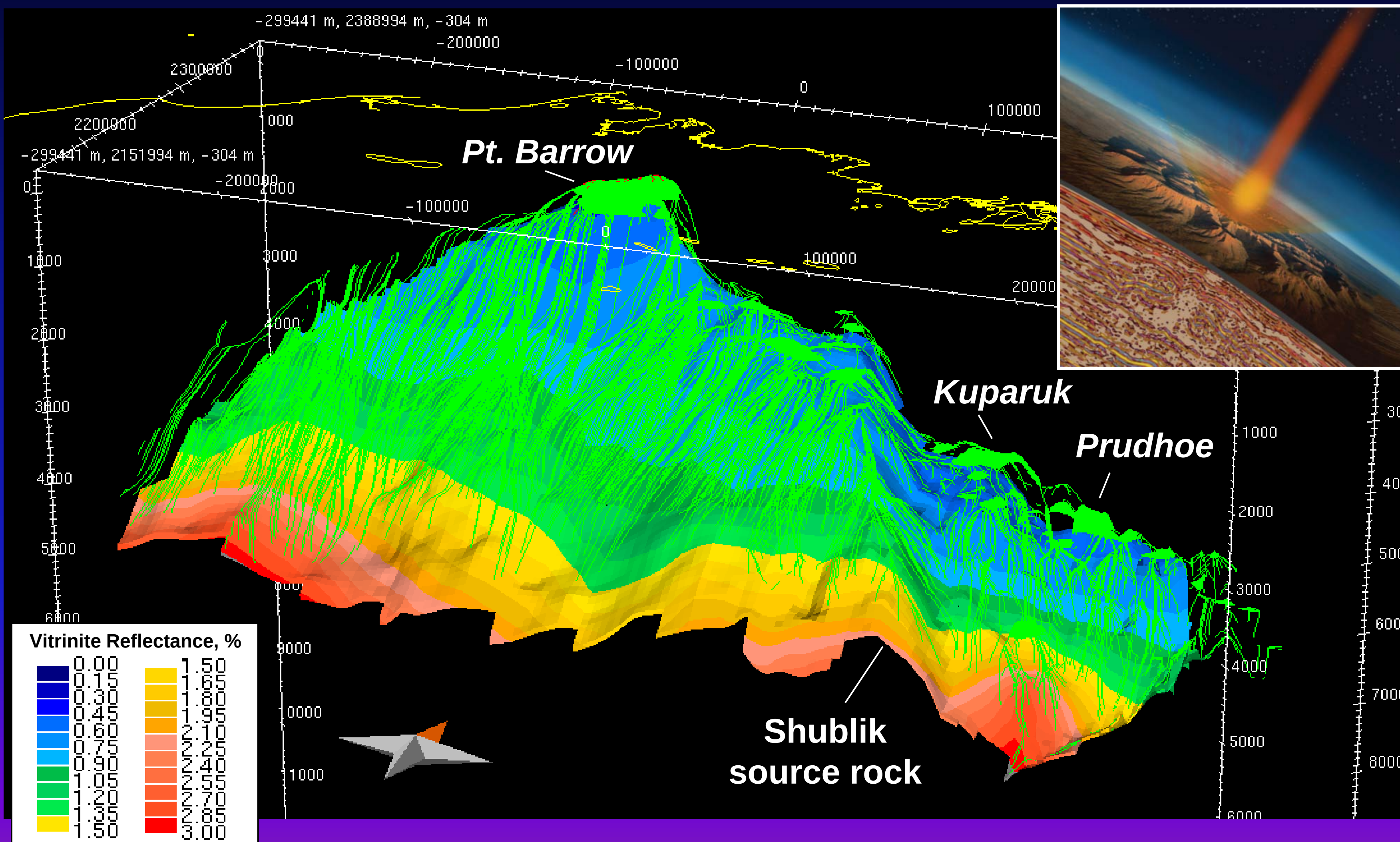


Early Model Predicts Large Present-Day Oil Accumulation at Point Barrow

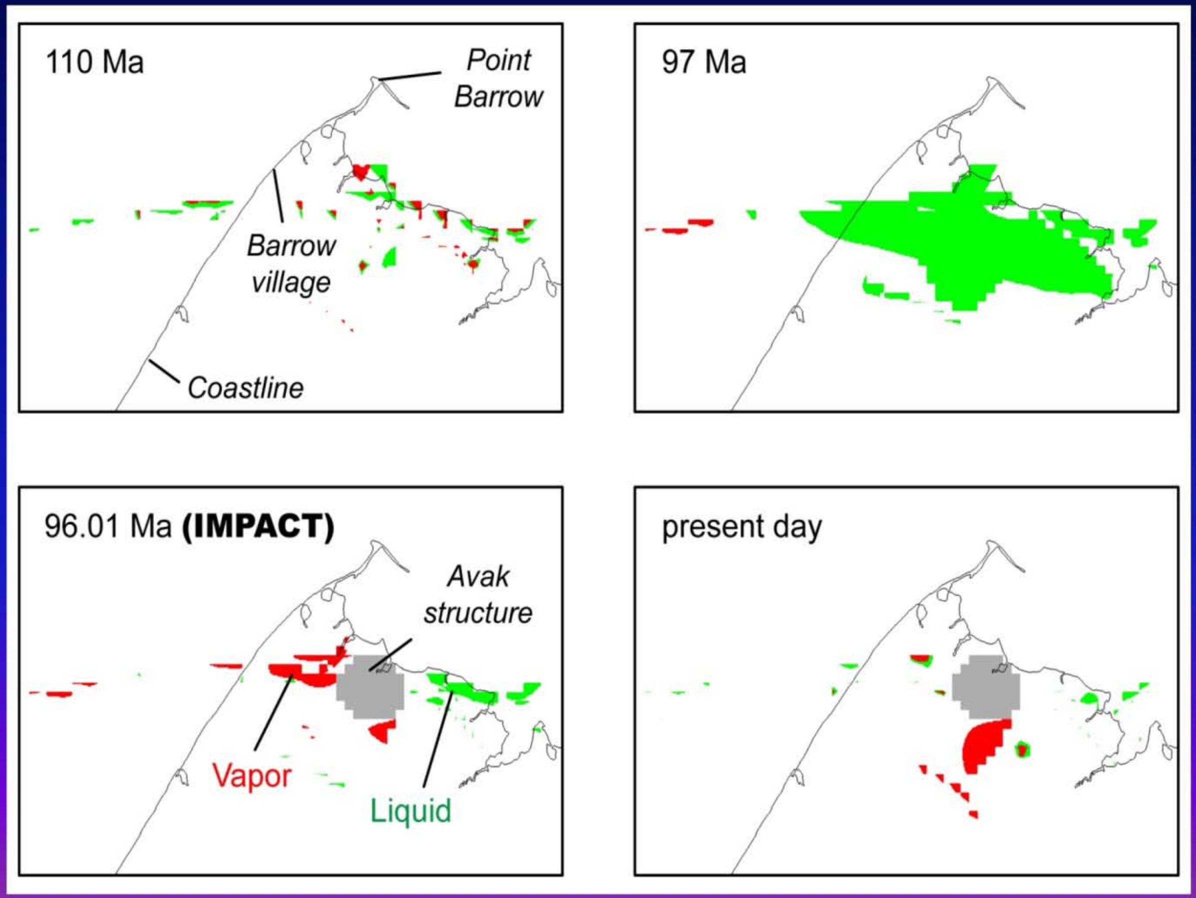


Notes by Presenter: Most petroleum flows today along migration pathways from south to north. Spill pathways and secondary migration pathways caused by geometry changes resulting from the prograding Brookian foresets run perpendicular to the major direction of migration. The model predicts 52 billion barrels of liquid petroleum with little vapor, mainly originating from the Shublik Formation source rock. Large predicted accumulation at Point Barrow (which is mostly just stained now) may have leaked due to the Avak impact event (well developed in Torok, but age could be 2-100 Ma). Small accumulations at Barrow are partly in upturned crater rim sediments.

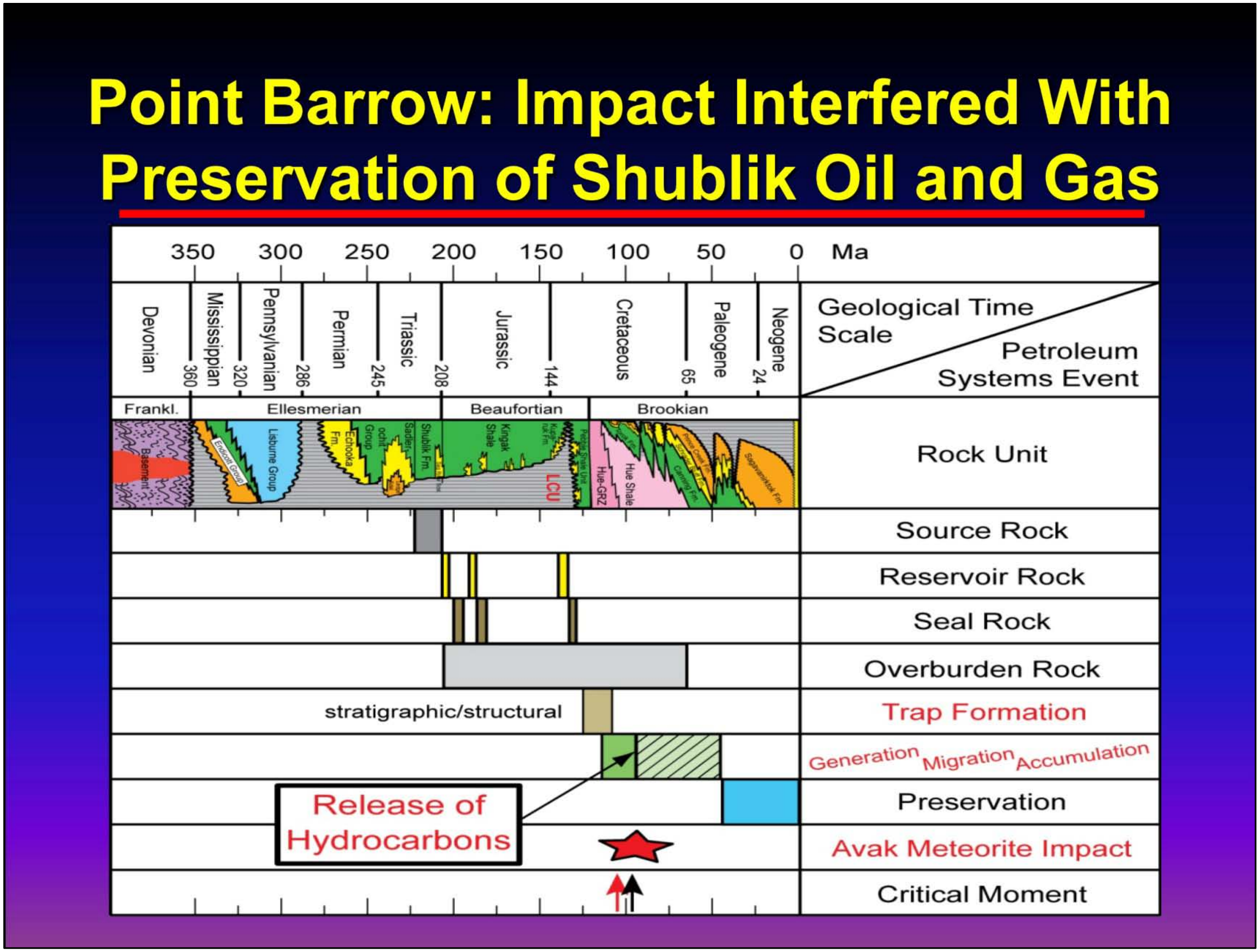
Avak Meteor Impact ~96 Ma Destroyed the Accumulation at Point Barrow



Point Barrow: Avak Meteor Impact Destroyed a Large Accumulation



Notes by Presenter: Model results including the Avak meteorite impact. Simulation of hydrocarbon maturation, migration, and accumulation through time on the Barrow Peninsula shows a large accumulation at 97 Ma. At about 96 Ma, the impact occurred, producing a circular, crater-like damage (gray), effectively increasing the permeability and temperature. After the impact, the large liquid accumulation disappeared. At present day, our model shows several vapor accumulation near the impact structure.



Notes by Presenter: Hatchured pattern indicates estimated time of eastward tilting of earlier trapped petroleum to traps in younger (early Tertiary) reservoirs. Preliminary 3D simulations predicted a large petroleum accumulation on the Barrow Peninsula, although only a few small gas fields are known (S. Barrow, E. Barrow, Sikulik) near the Avak structure, which resulted from a middle-late Turonian meteor impact. Our revised 3D model accounts for the effects of the meteor impact on temperature and permeability of the target rocks. The model predicts a large accumulation prior to impact, but predicted present-day accumulations occur only to the west, south, and east of the Avak structure, in agreement with known accumulations.

Conclusions: Timing of Events

- **Play fairway maps are *static* snapshots that fail to account for timing of petroleum system events.**
- **BPSM is *dynamic* and explains why traps are barren or filled with oil and gas.**
- **Petroleum system event charts are powerful tools to identify exploration risk.**

AAPG International Conference & Exhibition
Calgary, Alberta; September 12-15, 2010
Theme XV 9:05 am Wednesday

References

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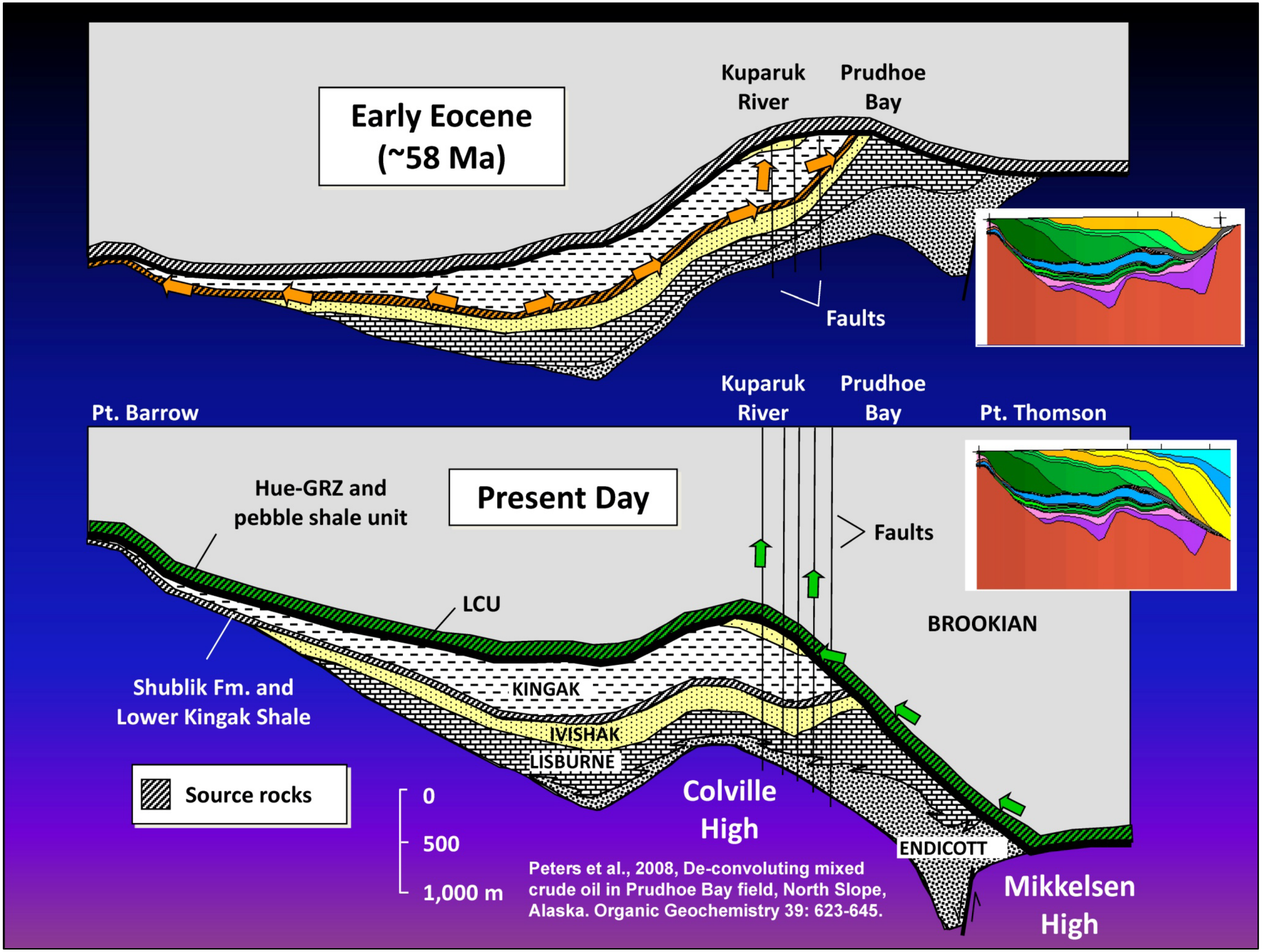
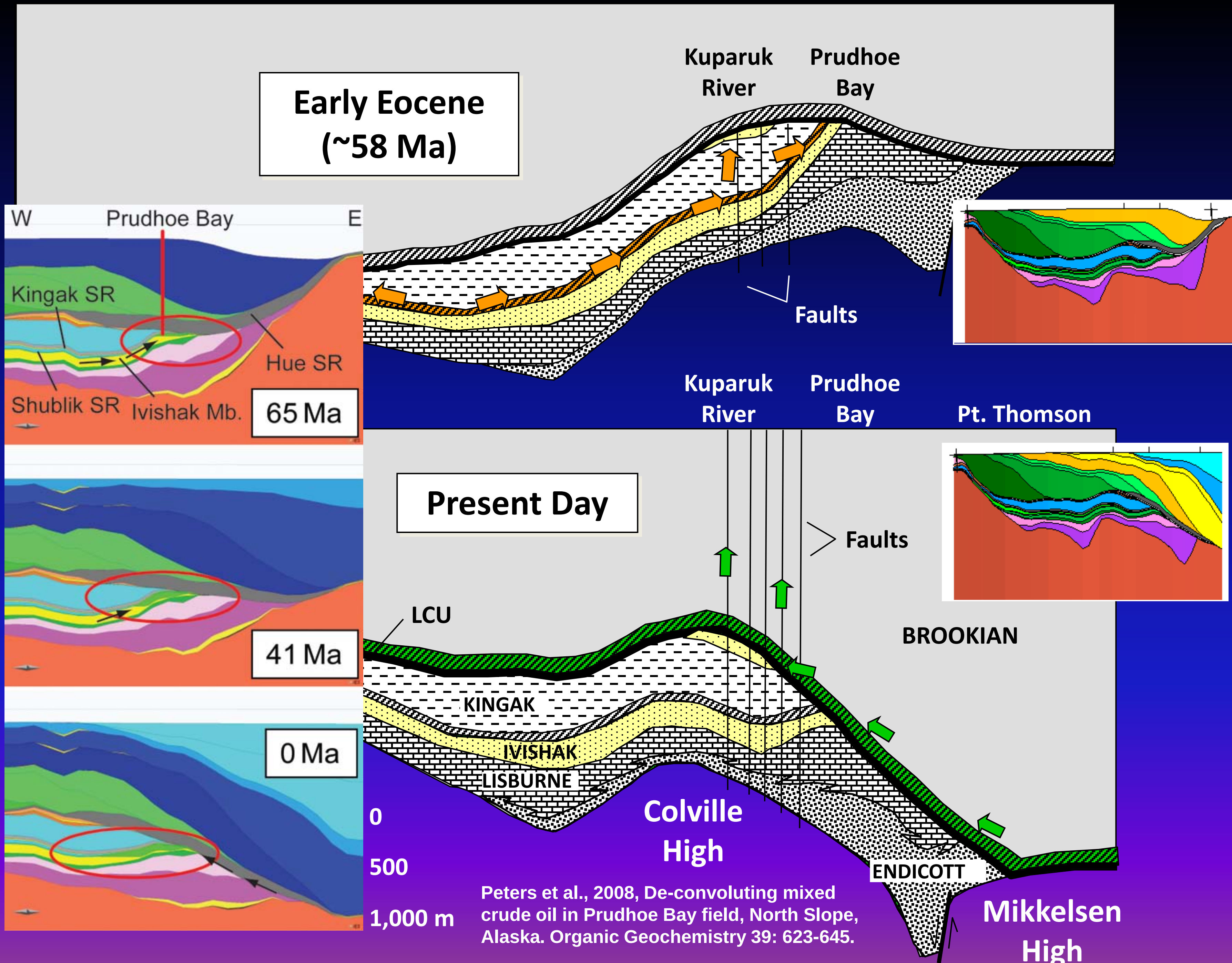
- Magoon, L.B. and W.G. Dow, 1994. The Petroleum System – From Source to Trap. AAPG Memoir 60, 655 p.
- Peters, K.E., ed., 2009. Basin and Petroleum System Modeling. AAPG Getting Started Series No. 16, AAPG/Datapages, Tulsa, OK.
- Peters, K.E., L.S. Ramos, J.S. Zumberge, Z.C. Valin, and K.J. Bird, 2008. De-convoluting mixed crude oil in Prudhoe Bay field, North Slope, Alaska. Organic Geochemistry 39: 623-645.
- Peters K.E., L.B. Magoon, K.J. Bird, Z.C. Valin, and M.A. Keller, 2006, North Slope, Alaska: source rock distribution, richness, thermal maturity, and petroleum charge. AAPG Bulletin 90, 261-292.
- Peters K.E., L.S. Ramos, J.E. Zumberge, Z.C. Valin, C.R. Scotese, and D.L. Gautier, 2007, Circum-Arctic petroleum systems identified using decision-tree chemometrics. AAPG Bulletin 91: 877-913.

Notes by Presenter: Petroleum was expelled from deeply buried Shublik Formation in the southwestern part of the study area beginning about 110-115 Ma. Migration was primarily northward. The onset of deposition of Brookian foresets at about 110 Ma induced west-east trending geometry changes. Subsidence in the western part of the study area drove accumulated petroleum toward the east. Pools formed on highs in the Prudhoe Bay and Simpson Peninsula areas and continued to receive petroleum charge from the south as well. These accumulations were much larger 30-40 Ma than today. After about 30-40 Ma, subsidence in the east reversed migration patterns, causing re-migration of petroleum from east to west mainly along the Barrow Arch.



Notes by Presenter: Late Generated Hue-GRZ Oil Mixed With In-Place Shublik Oil at Prudhoe Bay.


Early Eocene (~58 Ma)
Kuparuk River
Prudhoe Bay
Faults
W
Prudhoe Bay
E
Kingak SR
Hue SR
Shublik SR
Ivishak Mb.
65 Ma
41 Ma
0 Ma
Kuparuk River
Prudhoe Bay
Pt. Thomson
Present Day
Faults
LCU
BROOKIAN
KINGAK
IVISHAK
LISBURNE
Colville High
ENDICOTT
Mikkelsen High
0
500
1,000 m
Peters et al., 2008, De-convoluting mixed crude oil in Prudhoe Bay field, North Slope, Alaska. Organic Geochemistry 39: 623-645.

Geochemistry Supports Model Results Indicating Mixed Oil Along Barrow Arch

Peters et al., 2008, De-convoluting mixed crude oil in Prudhoe Bay field, North Slope, Alaska. Organic Geochemistry 39: 623-645.