Evolution of Structures above a Salt Diapir - Case Study from the Arabian Gulf Region*

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Abstract

We employ volumetric, geomechanically-based structural restoration methods to obtain insights into the development of structures within the sedimentary cover above an interpreted salt body in the Arabian Gulf region. The study area is a hydrocarbon-bearing dome that owes its structural uplift to a combination of salt and regional tectonics. We investigate the stratigraphic section from Permian to Tertiary and concentrate on: 1) the evolution of the dome structure, 2) the patterns and displacement history of faults in the dome, and 3) strain patterns from both folding and faulting at reservoirs through geological time. The study utilizes 3-D seismic reflection and well data to model subsurface horizons and associated structures. The 3-D model was divided into several mechanical units obtained from an existing 1D geomechanical model developed for the area. The restoration technique allows us to simultaneously restore each mechanical unit to a pre-deformation (unfolded and unfaulted) configuration with limited boundary conditions.

Analysis of the dome and fault growth suggests two stages of faulting, and a stage of folding that produced a gentle dome structure. Normal faulting was developed within the Paleozoic section, followed by fault reactivations and development of new normal faults within the overlying Jurassic and Cretaceous strata. Analysis of the structure indicates a slow uplift we associate with salt movement in Early Jurassic with increasing rates of uplift in the Late Cretaceous and Early Tertiary concomitant with the Zagros orogeny. The non-radial patterns of the faults and graben systems, and the relative timing of faulting and folding, suggest that the structure is a reactive diapir. Within the Jurassic reservoirs, the strain patterns calculated for pre Tertiary structural growth indicate larger strains around faults, and relatively lesser strains in areas only flexed by dome development. However, we find that the uplift during Late Cretaceous and Early Tertiary results in increased flexure/fold related strains within the Jurassic reservoirs.

This provides a model to predict a relative timeframe for fault and flexure-associated fractures, as well as the locations of these fracture systems. The information from the restoration model improves our understanding about the structural history and strain patterns within the reservoirs, and can be integrated with further subsurface data for reservoir development.

Selected References

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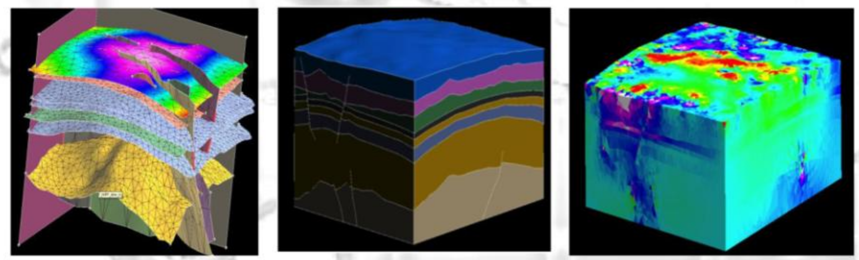
STRUCTURAL GEOLOGY AND EARTH RESOURCES

Saudi Aramco

EVOLUTION OF STRUCTURES ABOVE A SALT DOME

Case Study from the Arabian Gulf Region



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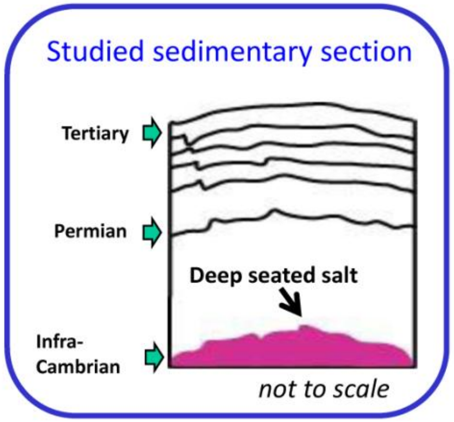
Presenter's notes: A case study presentation on the evolution of structures in sedimentary strata above salt body. The area is a hydrocarbon field in the Arabian Gulf Region.

Objectives

➔ Model subsurface structures from 3D reflection seismic and well data.

➔ Perform 3D geomechanics-based structural restorations covering the sedimentary section from upper Permian to Tertiary to gain insights into the:

- **Structural growth of the dome**
- **Geometry of faults and their displacements**
- **Growth mechanism**
- **Strain patterns at reservoirs**



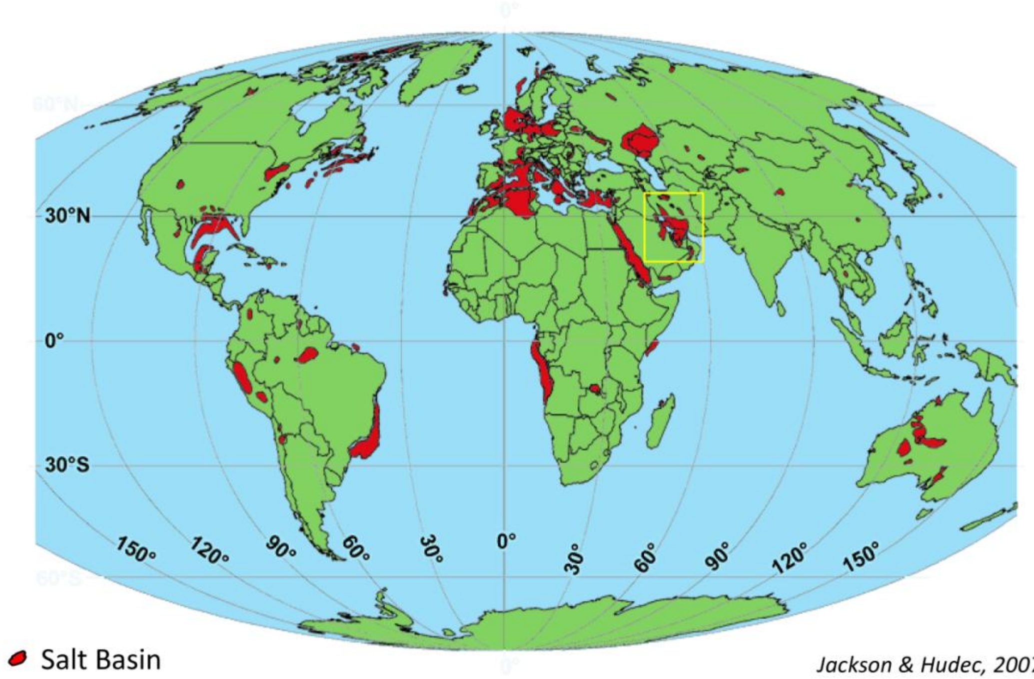
Presenter's notes: The figure shows the section of interest. Our 3D model includes the structures in the sedimentary section from Permian to Tertiary. The section below Permian is not included in the 3D model for the lack of well data and the poor quality of seismic reflectivity. Therefore, we don't know about the nature (i.e., geometry and mechanics) of the structures developed in immediate contact with the salt body.

Outlines

1) **Background**
2) **Methods**
3) **Results**
4) **Conclusions**

Presenter's notes: The second objective was to perform new methods of structural restorations in the section of interest.resenter's notes: The first objective of our study was to model the subsurface structures from 3D seismic and well data. This figure shows our section of interest. We modeled the structures in the sedimentary section from Permian to Tertiary. This is where we have a number of oil and gas reservoirs. We didn't model the deeper section, because of the lack of well data and the poor quality of seismic reflectivity. So until now, we don't know about the nature of structures in immediate contact with the salt.

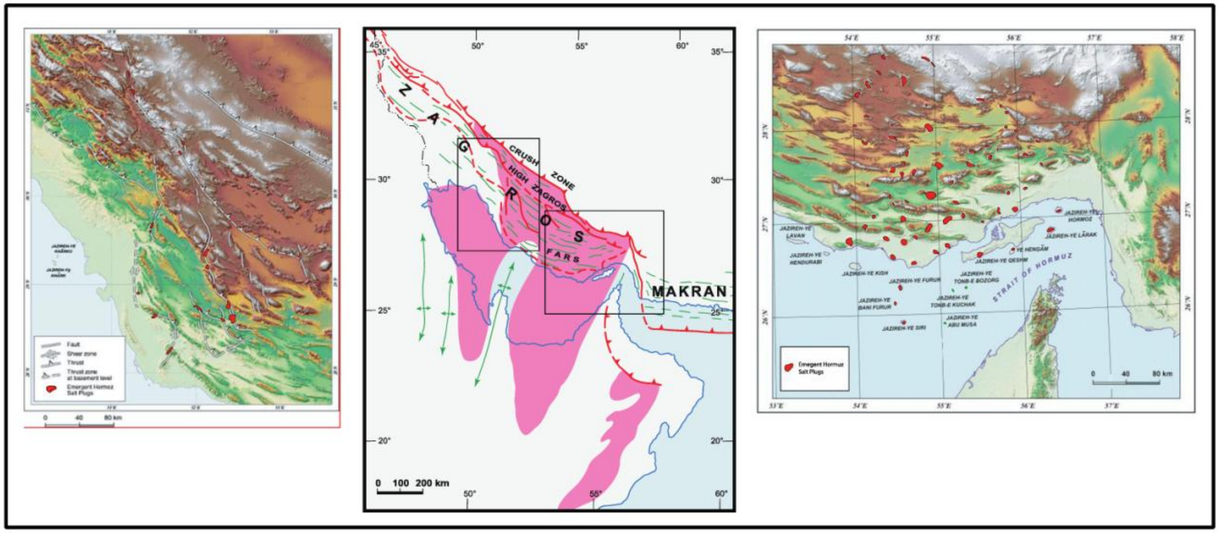
Global Salt Tectonics



Jackson & Hudec, 2007

Presenter's notes: The Gulf region is one of the world's recognized salt tectonic regimes. Approximately 160 Hormuz salt diapirs have extruded in the Zagros Mountains and their foreland, and about 20 of the islands in the Southern Gulf owe their existence to the Hormuz salt (Kent, 1958, 1979, 1987; Player, 1969; Edgell, 1996; Talbot 1998). The extent of the salt in the Zagros and the Arabian Gulf regions is deduced from emergent diapirs, where the depositional salt thickness is large enough to develop salt ridges, pillows and diapirs (Callot et al, 2007).

Salt Plugs in the Arabian Gulf Region

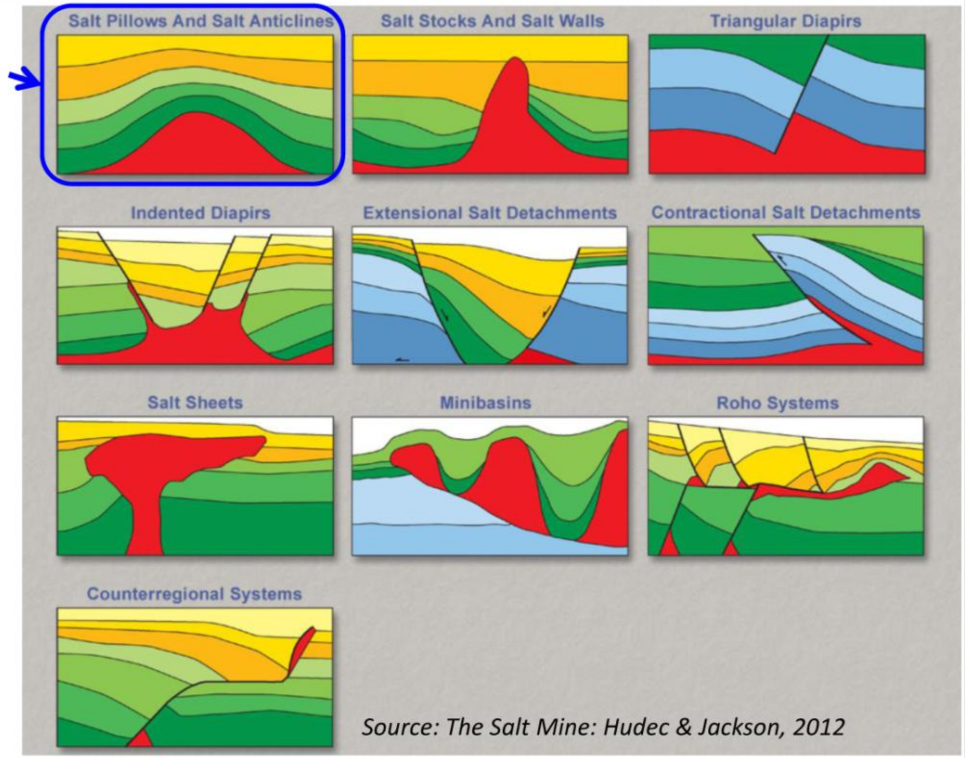


Callot et al, 2007

Presenter's notes: This map shows the distribution of salt in Eastern Arabia. The study area is located on the western periphery of the north basin of the Arabian Gulf, where structural growth of some domes is attributed to deep-seated salt diaprisim interpreted on the basis structural geometry and strong negative gravity anomalies (e.g., Powers et al., 1966, e.g., Edgell, 1991). The salt is believed to be part of the infraCambrian Hormuz Salt, which is found in great parts of the eastern area of the Phanerozoic sequence of the Arabian Plate (e.g., Edgell, 1991, Beydoun, 1991, Weijermars, R. 1999).

Salt Structure Style of the Area

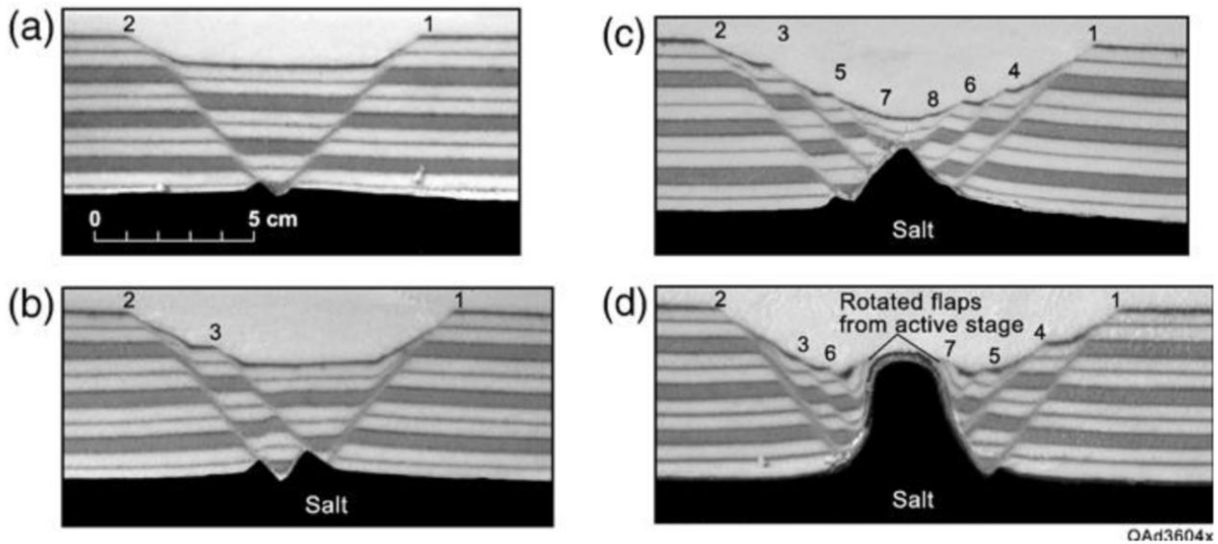
The study area was interpreted as a salt-cored structure based on gravity anomaly (Power, 1966), and dome structural style (Edgell, 1991, 1996)



Source: The Salt Mine: Hudec & Jackson, 2012

Presenter's notes: The mapped subsurface formations of the study area are gently-folded and appear to be originally developed by an active salt pillow, but the faults are more complex. Although the salt is not piercing, the rock formations are faulted. One large graben formed in the late growth of the structures due to apparently dominating reactive diaprisim.

Mechanism of Reactive Diapirism



Vendevilleand Jackson, 1992

Presenter's notes: In reactive diaprisim, the diapir forms in reaction to regional extension, causing the sedimentary cover of the diapir to be stretched and to subside below the regional level (Vendeville and Jackson, 1992).

Workflow & Methods

- Modeling horizons and faults
  - From 3D seismic & well data

- Building geomechanical layers
  - Young's moduli, Poisson's ratios & Lamé parameters (guided by1D mechanical earth model of one vertical well)

- Building 3D mesh (finite element model)

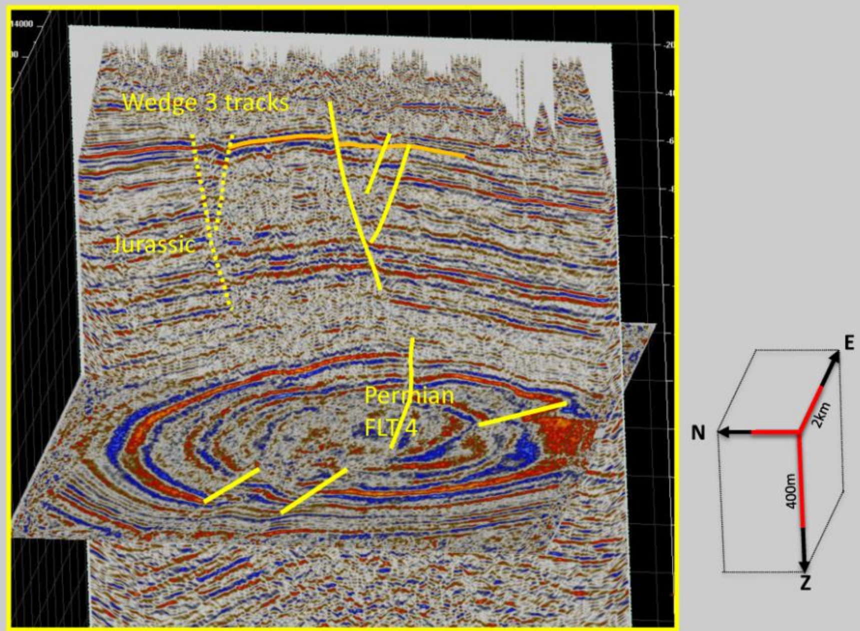
- Performing 3D srtructural restorations

- Analyzing sequential growth of the dome, fault displacements & strain patterns at reservoir

Using FEM-based 3D structural restoration plugin (gOcad)

Workflow & Methods

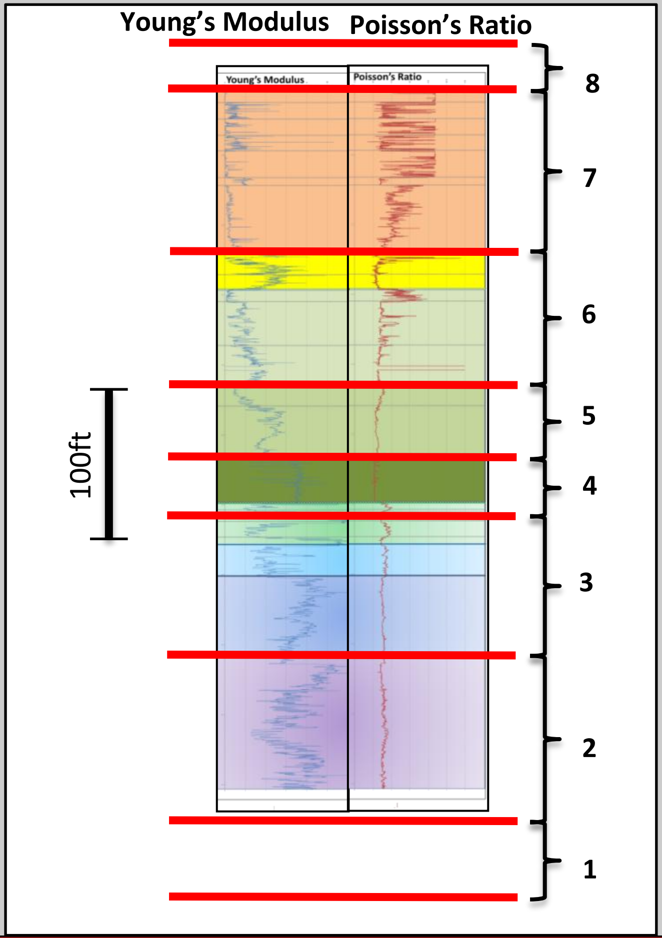
- Modeling horizons and faults
  - From 3D seismic & well data

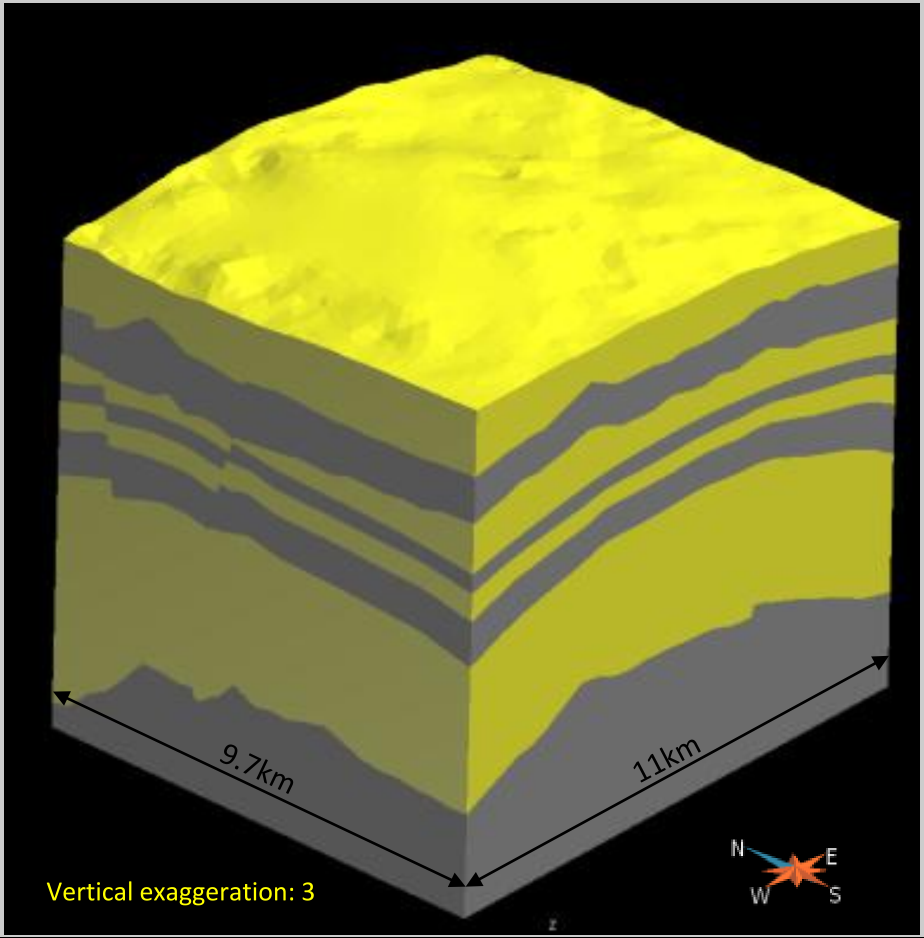


Presenter's notes: This figure gives combining view for a seismic section and a seismic horizon from the 3D seismic reflection. It displays some of the structural elements (faults and dome structure).

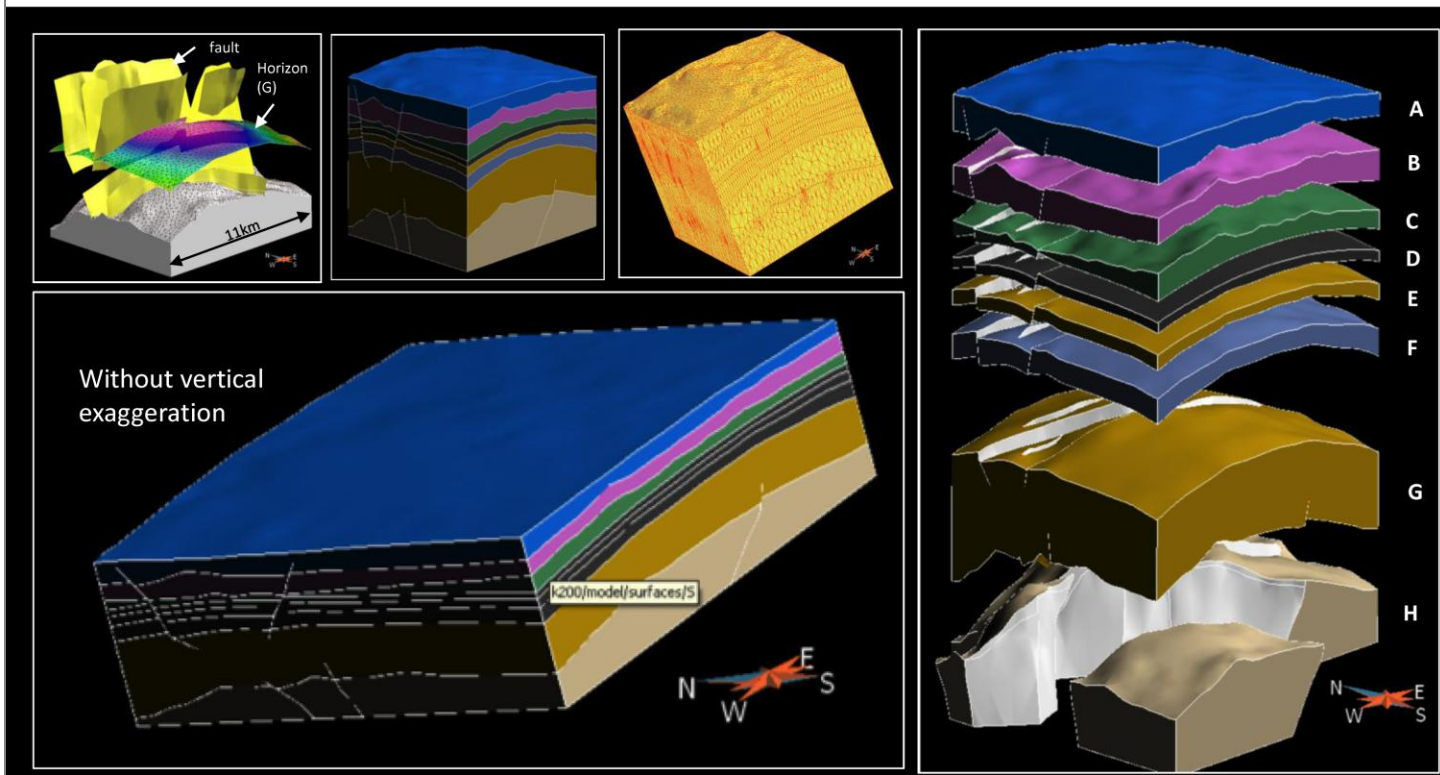
Workflow & Methods

- Building Geomechanical Layers
  - Young's moduli, Poisson's Ratios & Lamé parameters (guided by1D Mechanical Earth Model)





Workflow & Methods

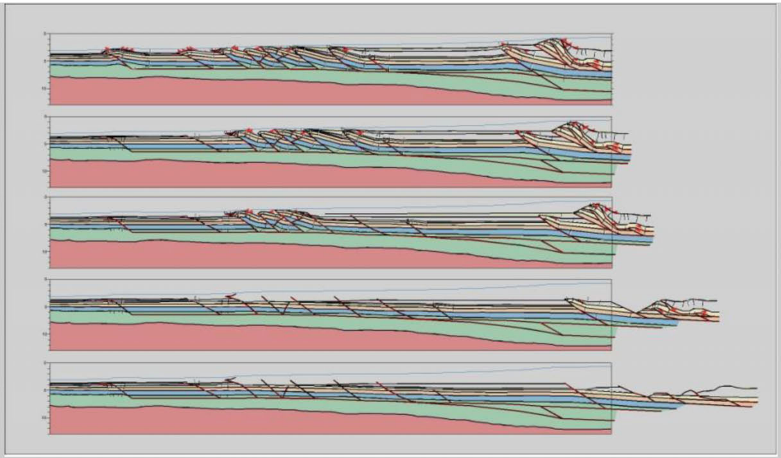


Presenter's notes: Different views for the triangulated 3D model

Workflow & Methods

- Performing 3D structural restorations

Classic Palinspastic Restoration



Current methods of structural restoration are based on geometric & kinematic techniques that …

have proven useful in validating structural interpretations and defining trap geometries,

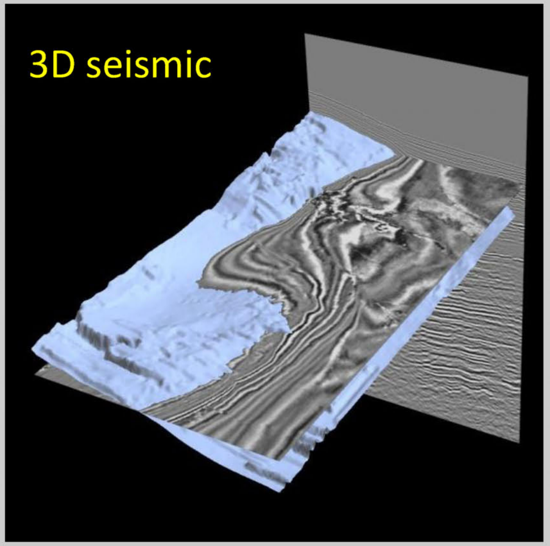
… *but have generally proven to be poor at* predicting reservoir strains, because they are:

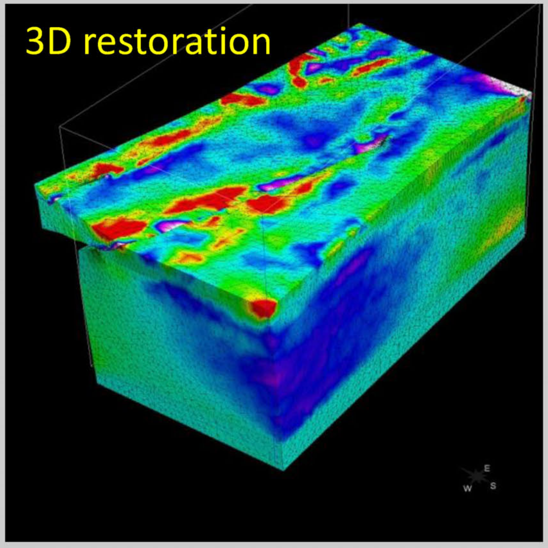
- **solely geometric & kinematic, and don't consider stress and rock mechanics;**
- **do not incorporate the effects of variable rock strengths, caused by differences in lithology, which can dramatically influence strain intensity and distribution;**
- **cannot address inherently 3D aspects of deformation, such as strike- or oblique-slip faulting & salt domes**

Workflow & Methods

- Performing 3D structural restorations

As an alternative, we use a new physics-based approach to performing 3D (Volumetric) structural restorations, that can:

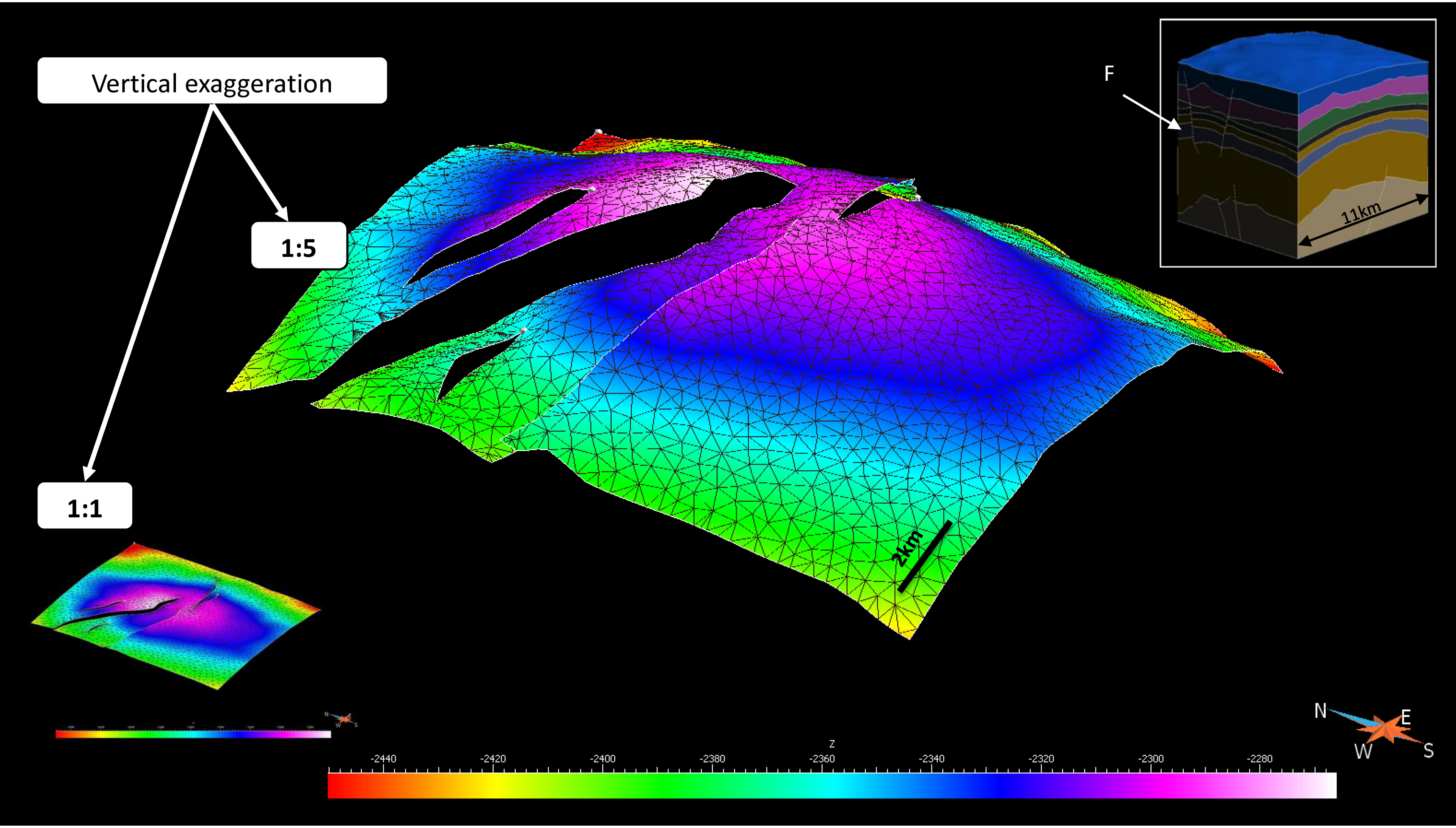




Shaw, 2009

- **make direct use of 3D seismic constraints on structure.**
- **incorporate rock strengths and fully 3D aspects of deformation**
- **yield more accurate strain predictions, which can be used to constrain reservoir segmentation and natural fracture patterns.**

Sequential Restorations of the Reservoir (Unit “F”)

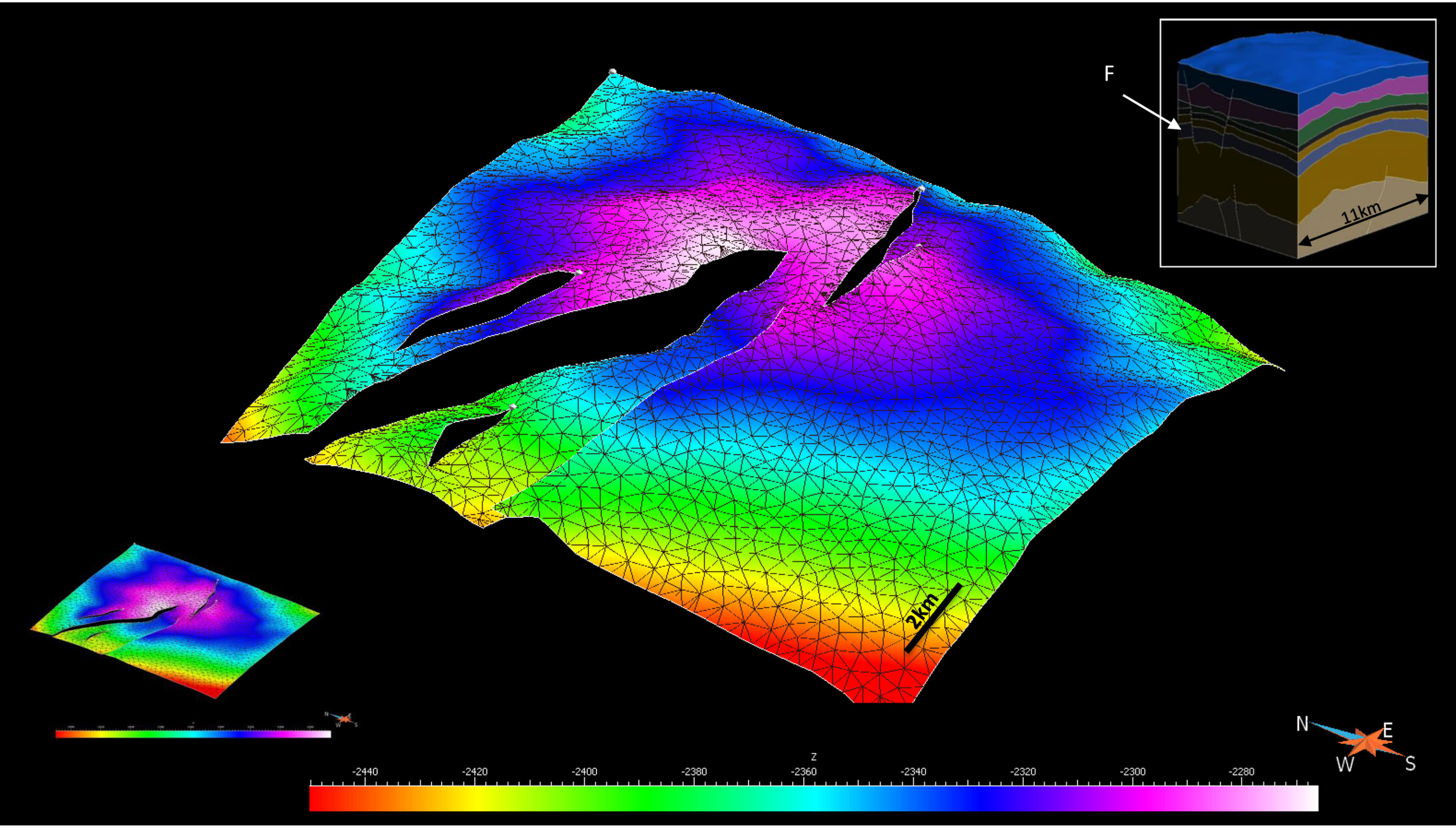


Presenter's notes for previous slide:

In the process of sequential restorations, we start restoring the top unit to a flat datum, which resembles the formation geometry at its deposition time. Then, we continue restoring other units until the bottom (but in this presentation display, we show the backstripping until the deposition time of Unit F, see the figure in the upper right of the slide).

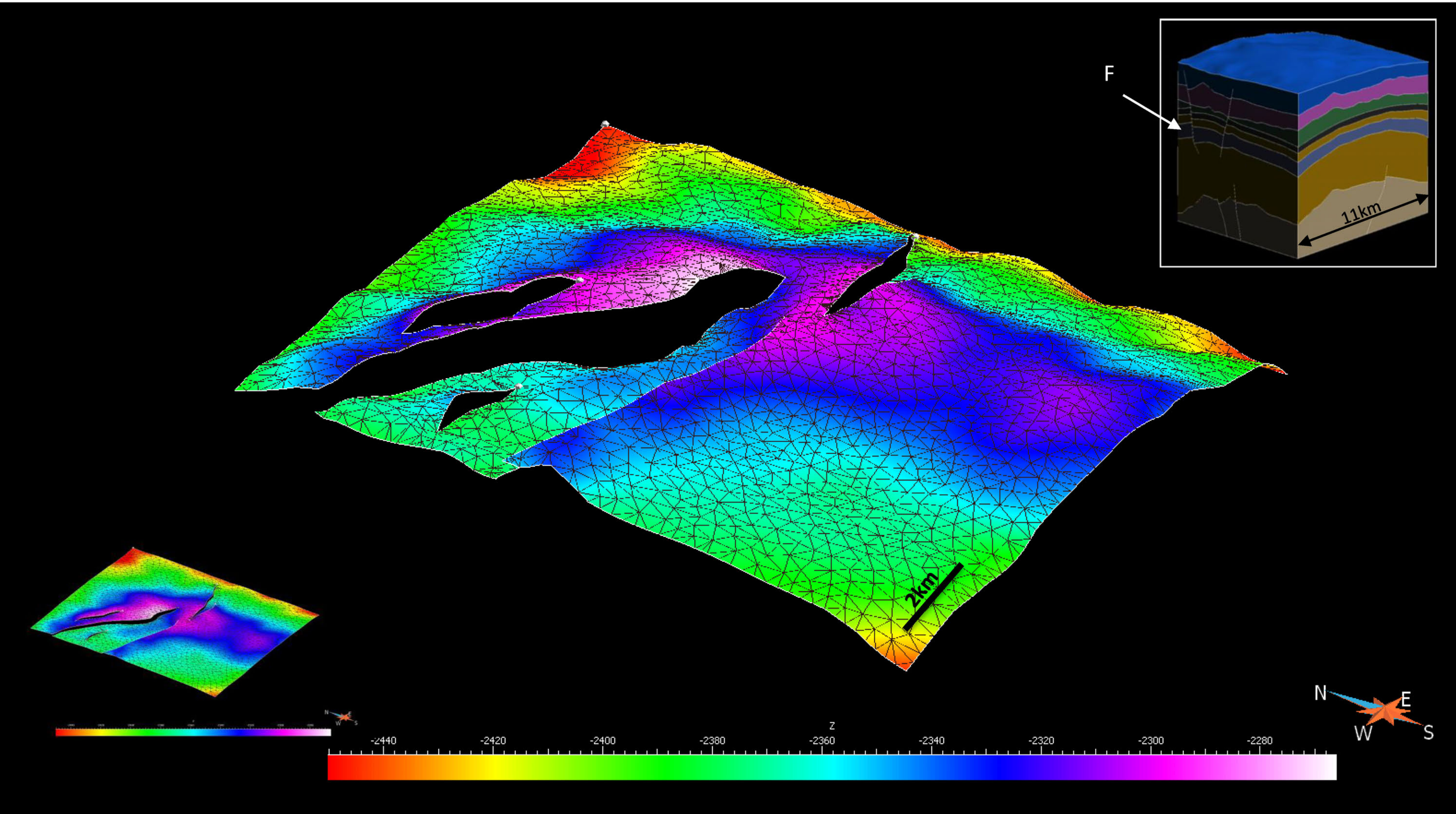
The two figures in the slide show the present-day structure of Unit F. The small figure is without vertical exaggeration. The below bar shows the geologic time. Next slides show the restored structures of Unit F at different geologic time intervals extracted from relative age of the overlaying restored units in the 3D model. Essentially, we only show an extracted horizon from the top of the 3D model of Unit F, which is computed from the displacement vectors of the sequential restorations.

Sequential Restorations of the Reservoir (Unit "F")



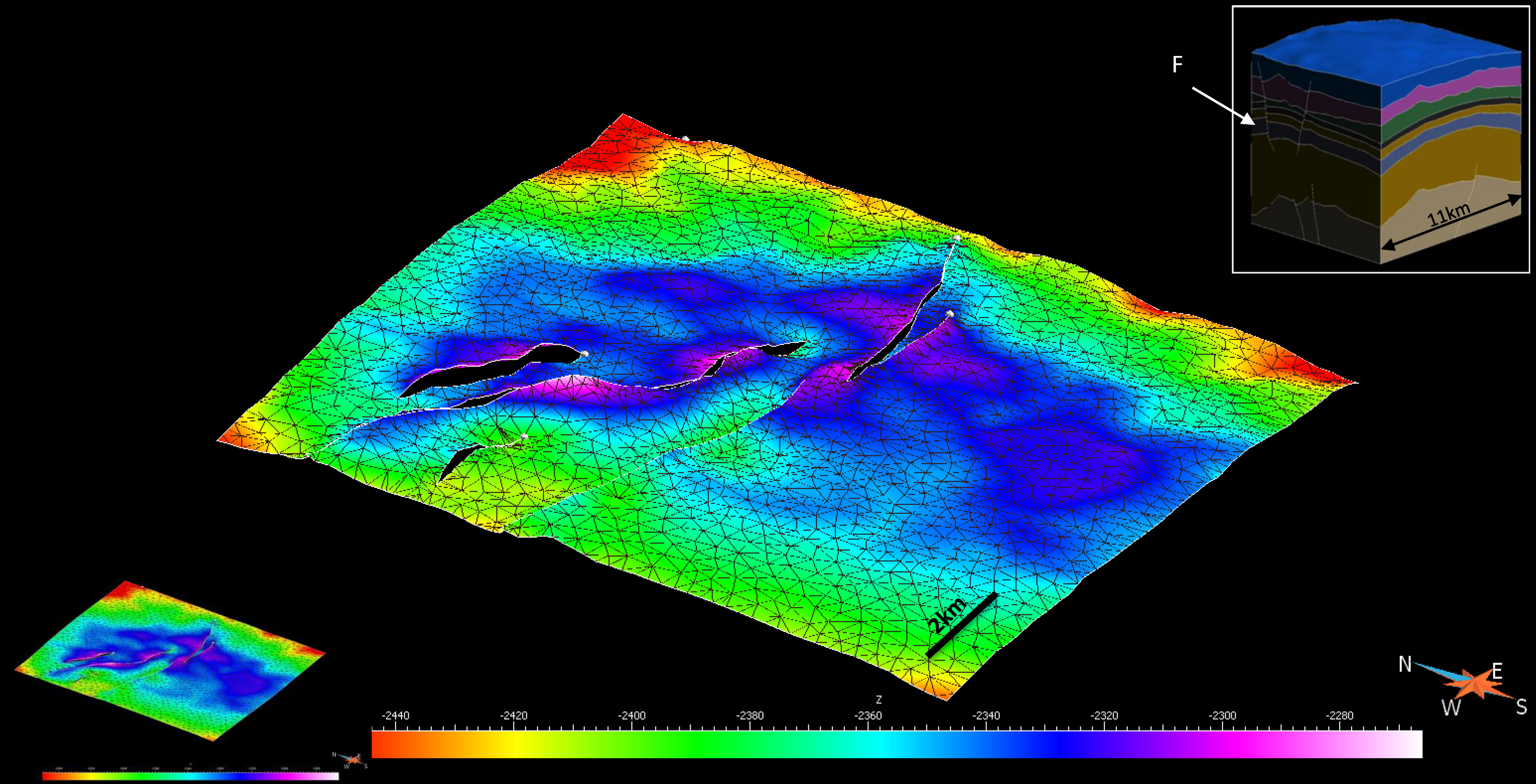
Late Cretaceous
~89my

Sequential Restorations of the Reservoir (Unit "F")

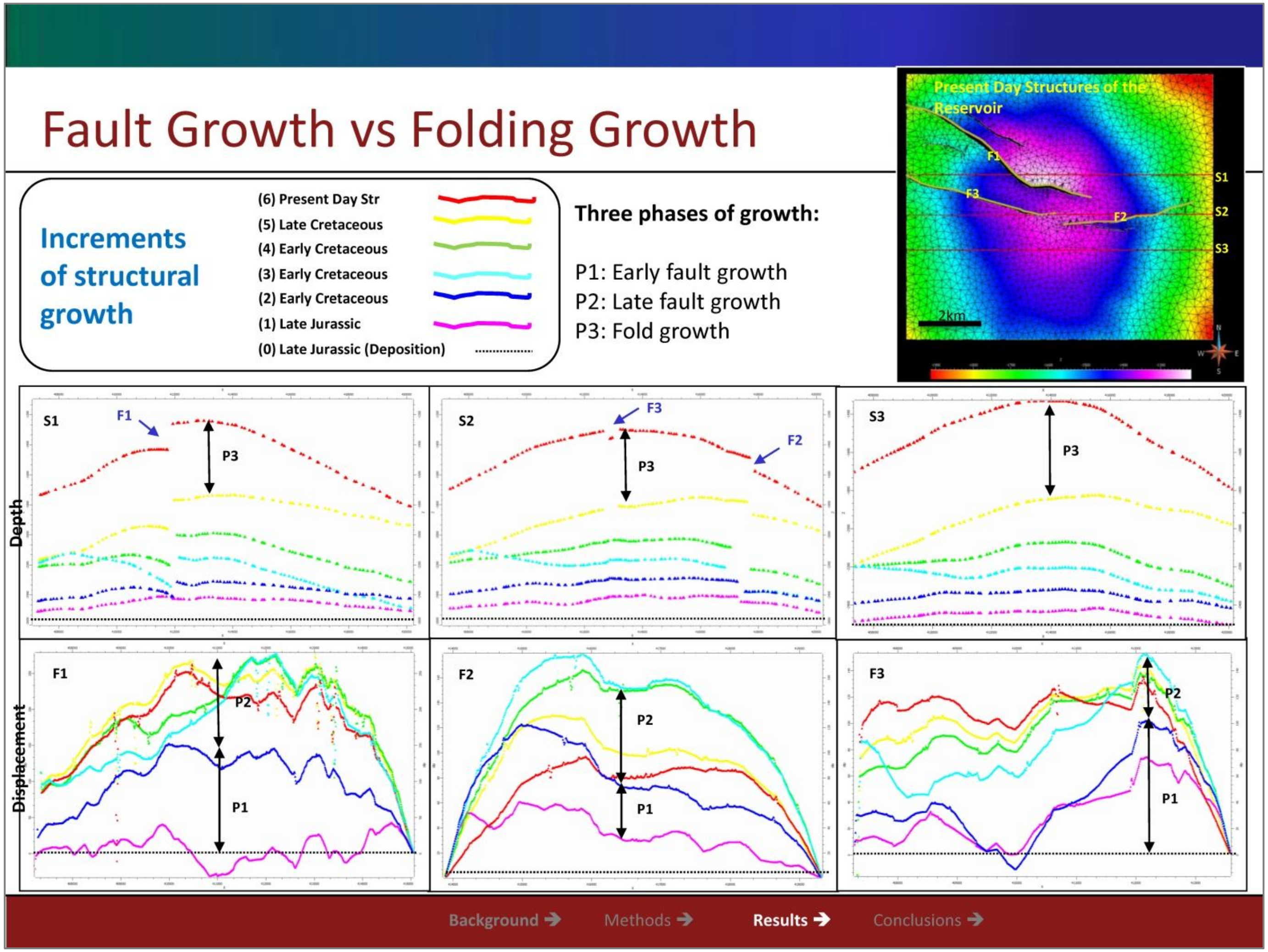


Early Cretaceous
~112my

Sequential Restorations of the Reservoir (Unit "F")



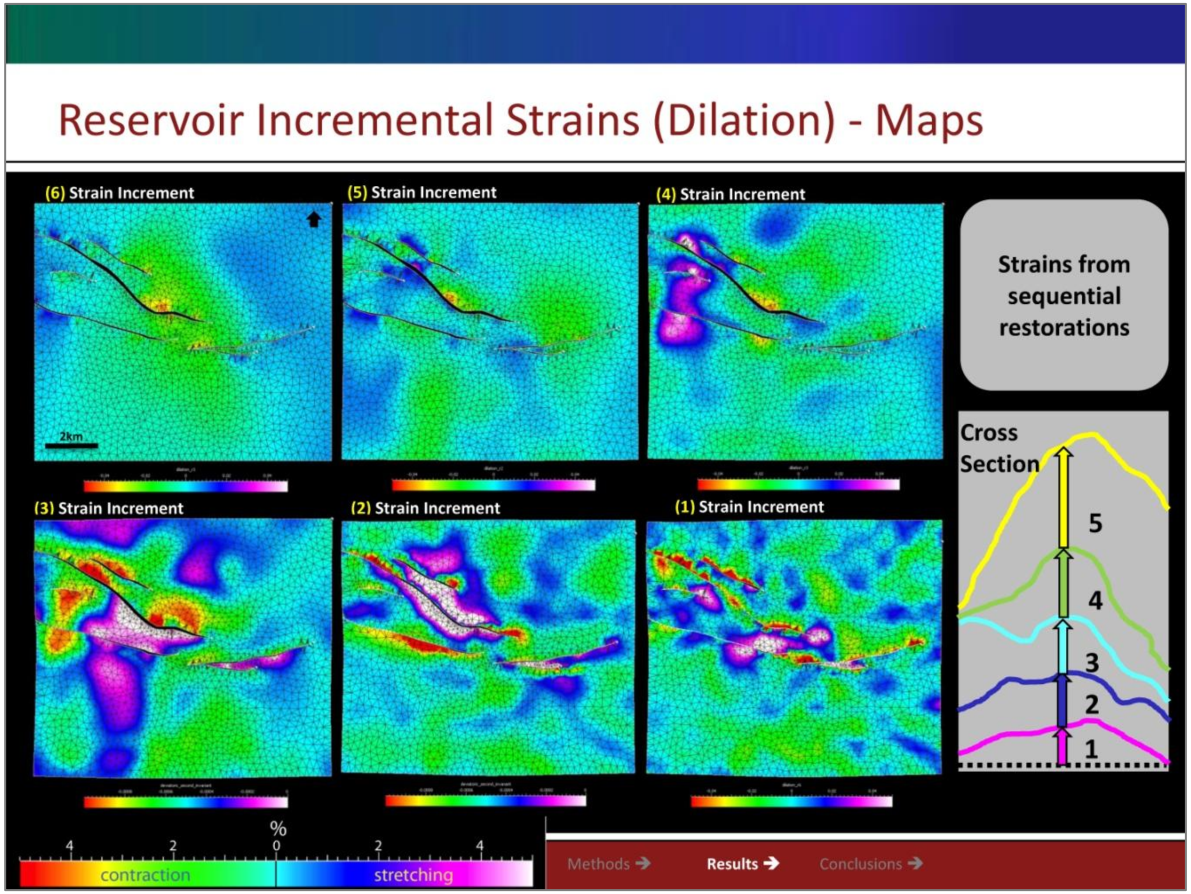
Late Jurassic
~141my



Presenter's notes: In this slide, we show a map for the top of Unit F (upper right). We also show three cross sections, named here S1, S2, & S3. The cross sections display the dome growth from the restoration steps we preformed, and presented in the animation slides (13-17). *Presenter's notes continued on next slide.*

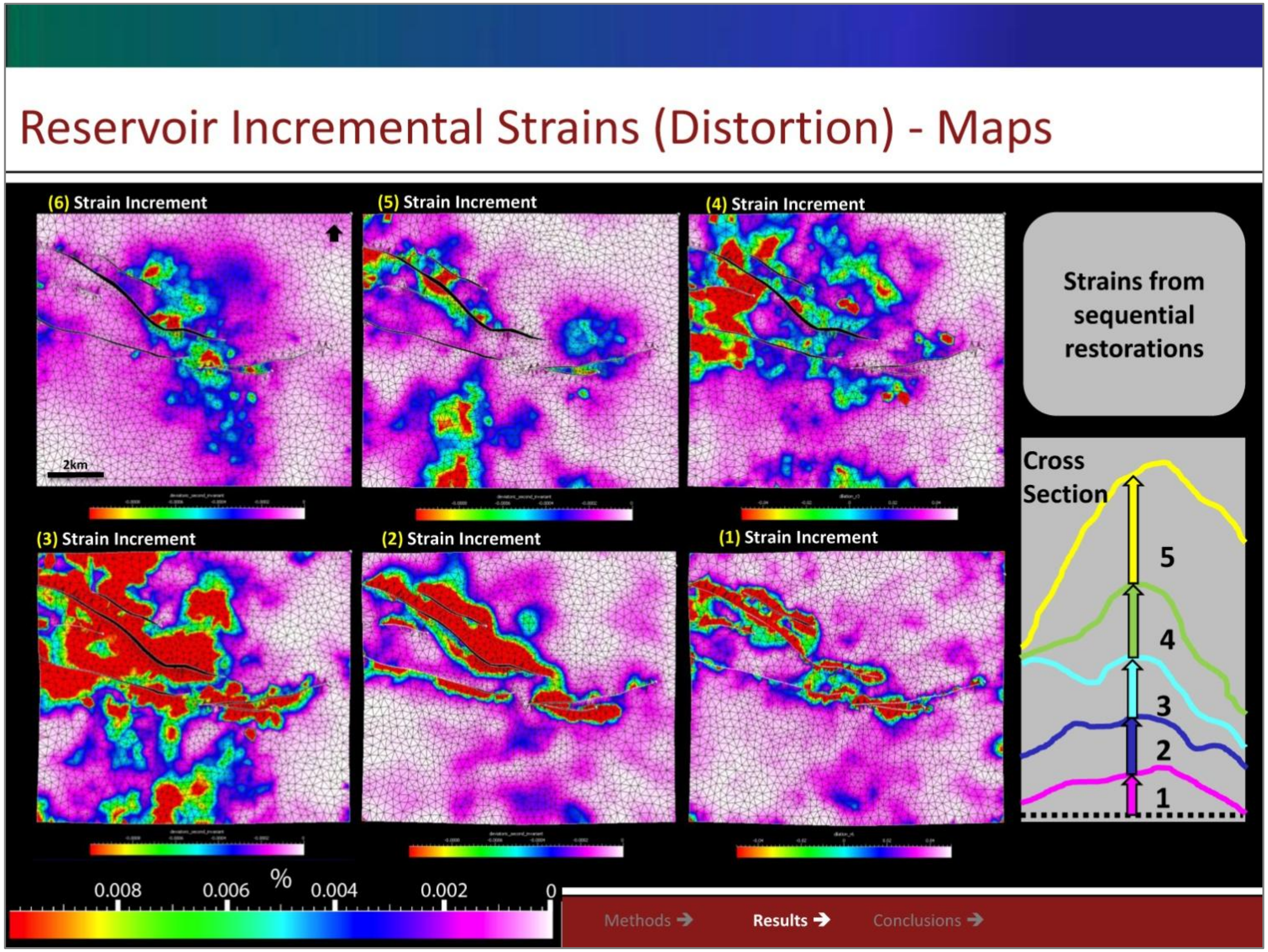
Presenter's notes continued from previous slide:

Starting with the first section (S1), we show how the reservoir evolved through geologic time. The profiles are given different colors to highlight the relative geologic time. Here, we are not interested in depth values (Y-axis, left) but interested in the amplitude of the profile (which is the difference in depth between the center and flank of the dome). The depth values can only be taken qualitatively as they correspond to thickness of strata, restoration datums and possible regional uplift/subsidence. But, we are interested in the curve amplitudes, which displays the sequential development of the dome through geologic time.
In the cross section (S1, S2, & S3), we see the influence of faults on horizon geometry in early stages of deformation. We don’t see much clear influence from the dome development until the period from late Cretaceous to present day. The growth of the faults is different and very intriguing in terms of timing and unpredictable displacements. We extracted the fault displacement vectors from fault restoration steps. We computed for the restored distance along the faultslip plane from each restoration step and we generated profiles for magnitude of displacements (in Y-axis) and project them against fault path in the map view. The simple takeaway of this demonstration is that folding (doming) was not the driving mechanism for faulting at this particular section (from Jurassic
to present day).



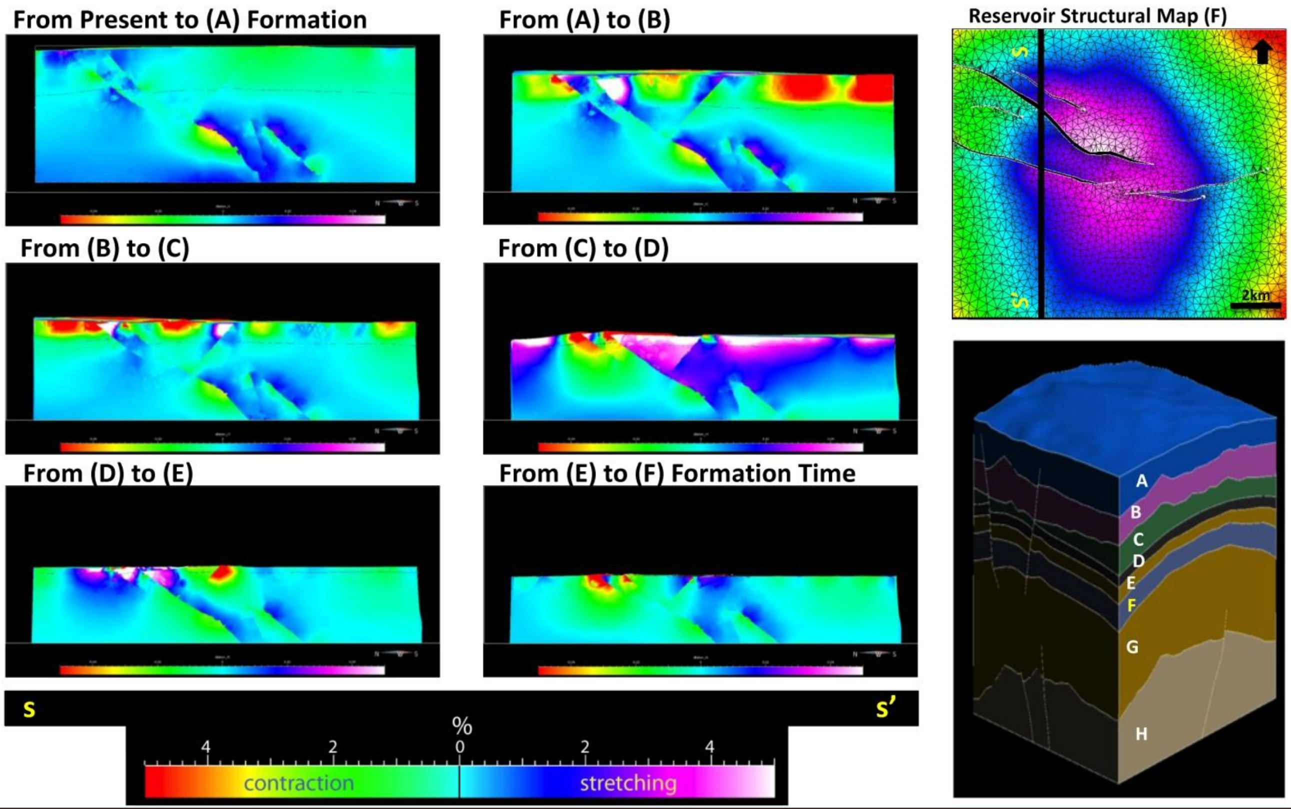
Presenter's notes: The maps show strains from the top of Unit F. Maps are extracted from the 3D strain developed from restoration increments.

The strain (dilation or change in volume) is greatly concentrated in the faulted zones. The strains reflect the great displacements of some faults at certain periods. The analysis also confirms the dome related strain (Strain increment (6)). The maps also show some elevated flexure related strains due to fault displacements.



Presenter's notes: The strain (distortion or change in shape) confirm the great magnitude of fault development compared to dome development. It also show a pronounced strain for a dome became slight elliptical with a major axis appear perpendicular to the compression trend of the Zagros orogeny. This indicates that the salt original dome was compressed to some elliptical shape in Later time of the structural evolution.

Strain Model from Seq. Restorations – X-Section



Presenter's notes: Different views for the 3D strain model (cross sections).

Conclusions

➔ The structural growth of the dome mostly took place during Late Cretaceous and Early Tertiary.

➔ The fault displacements mostly took place before the dome development.

➔ The relative time of faulting & folding, and the faulting pattern indicate that the growth mechanism is due to a reactive diaprisim.

➔ The model suggests that fault-associated strains are stronger than dome-associated strains.

➔ Strain analysis from 3D restored model can be integrated with reservoir dynamic data for future field development (e.g. to compare density of fractured areas with strain patterns).

Acknowledgment

➔ The authors would like to thank the management of the Reservoir Characterization Department (RCD) of Saudi Aramco for funding this study, and for giving the authors the permission to present results. Special thanks go to Aus Al-Tawil, Abdullah Al-Shamsi and Jamil Al-Hajhog.

➔ The authors also thank many contributors from the RCD (especially Mohammed Raji Yaacob)

➔ The presenter (MM Al-Fahmi) would like to thank the Structural Geology Group of Harvard University for hosting him during the course of this study.