Playing It Forward – Modelling the Evolution of Deepwater Subsalt Fields on Passive Margins Using 2-D Finite Element Models*

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Abstract

Over the past decade, reservoir development has benefited from advanced 3D finite-element geomechanical models that aim to reproduce the present day state of stress as observed in drilling data. These allow prediction of highly variable stress states resulting from complex structural-stratigraphic architecture, salt bodies, and pore pressure depletion over field life. Most model inputs are relatively well-constrained, including structural framework mapped from seismic reflection data; mechanical properties measured in logs and core; 3D distribution of overburden pore pressure derived from seismic velocity transforms; and 4D reservoir pressures from reservoir simulators. Results are compared to measured field data, such as LOTs and minifrac. If there are mismatches, the input parameters can be adjusted and the model iterated until an acceptable solution is found. One key parameter that remains relatively unknown, however, is the initial regional stress, a boundary condition commonly applied as a ratio of vertical to horizontal stress (Ko). Ko is influenced by the structural history, varies spatially, and is difficult to measure in the field, therefore it is challenging to define as an input parameter. To place better constraints on the present day Ko for our field scale 3D models, we built a 2D forward model to characterize the complete evolutionary history of the structure and the change in regional boundary stress through time. To do this, we developed a basin-scale model that attempted to replicate regional restorations of the Gulf of Mexico Atwater fold belt, including the evolution from a Jurassic salt basin to a down-dip fold belt, as regional progradation drove deformation basinward. The model incorporated a flexural isostatic response to constrain the influence of basement relief on halostatic pressure and a fully coupled thermal solution field, including mantle heat flow into the base of the model and radiogenic heat production within the basement and overlying sediment wedge, to constrain the appropriate flow viscosity of salt. After 65 Myr of runtime, the final geometry resembles the present day structure. Longer run times and reduced frictional parameters allowed us to model allochthonous salt breakthrough and generate stresses comparable to 3D models in the area. This suggests we have developed the capability to start predicting stresses ahead of the drill bit, which will help to evaluate risk in future exploration prospects.

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Mohamed, F., G. Akinniranye, Z.C. Kong, S. Chakraborty, C. Walker, V. Singh, and M. Albertin, 2016, Drilling and 4D Seismic Calibrated Geomechanical Model – Enabling Extended Reach Drilling Well Design in Complex Sub-Salt GOM Play: SEG International Exposition and 87th Annual Meeting Technical Program Expanded Abstracts, p. 5418.

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AAPG April 2017

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Playing It Forward

Modelling the evolution of deepwater subsalt fields

Introduction

- using forward models to calibrate static models
- resolving uncertainty in K_0 parameter

Modeling approach

- introduction to ELFEN software
- modeling set up
- addition of isostasy

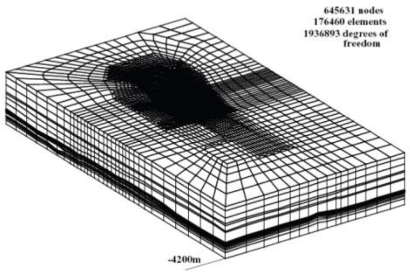
Results

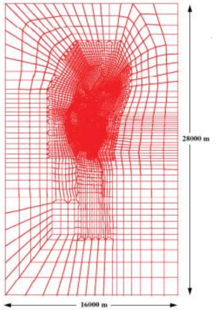
- example runs
- parameter study
- comparison with real structures

Playing It Forward

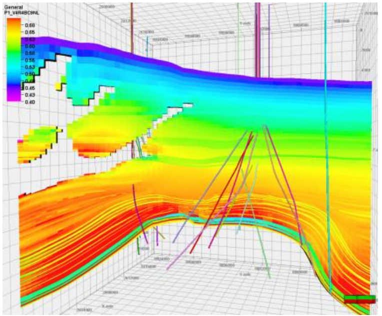
Statement of problem

4D Geomechanical models are increasingly being used in deepwater oil fields to predict subsurface stresses for drilling, completion, and production-related compaction





e.g. Kristiansen & Plischke, 2010, SPE 13 1505-MS



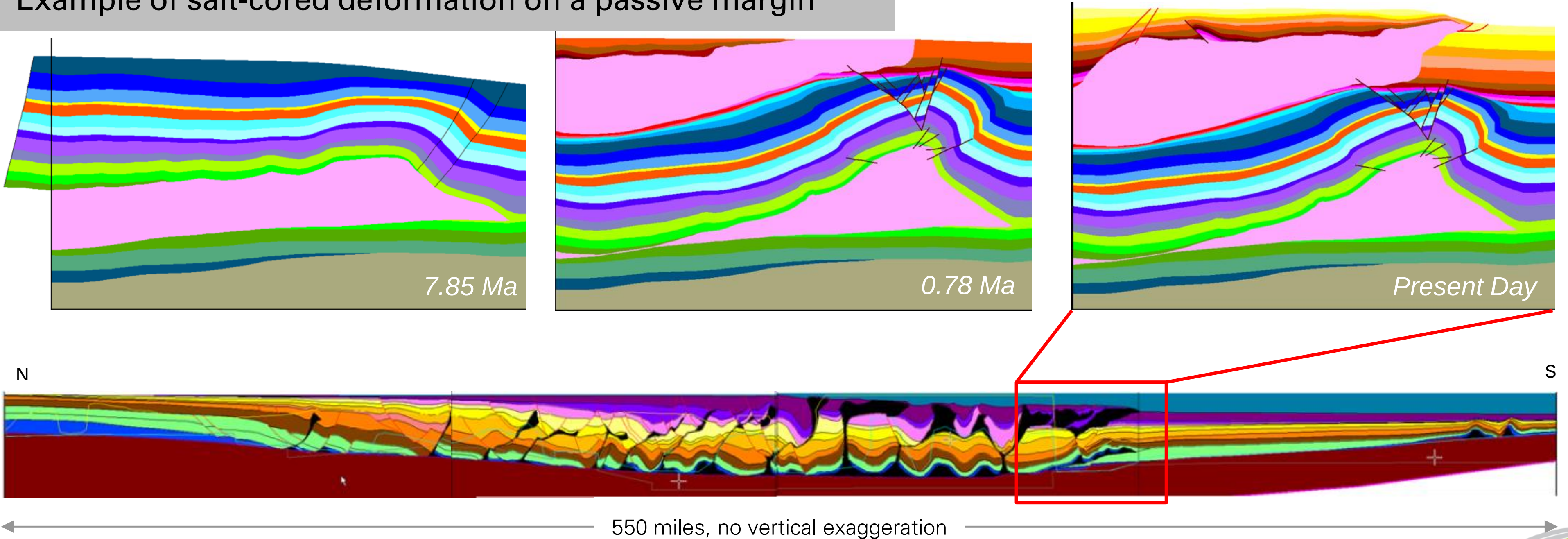
e.g. Mohamed et al., 2016, SEG

1) **Construct geometry**
   - Basement-to-seafloor, internally-consistent fault and horizon framework
   - Horizons include major lithologic and pore pressure boundaries
2) **Fill geometry with properties**
   - Material properties from well logs and geomechanical tests on core plugs (Density, Porosity, Young's Modulus, Poisson's ratio)
   - 3D shale pore pressure volume (basement-to-seafloor) for shale derived from seismic velocity model
   - 4D reservoir pore pressure volume from the reservoir model
3) **Build element mesh**
   - Mesh resolution should be specific to questions the model will address (i.e. reservoir, overburden, etc.)
4) **Set initial conditions**
   - Boundary conditions, estimate of vertical to horizontal stress K_0
5) **Run simulation and calibrate results**
   - Calibrate model against field data; LOTs, PITs, FITs, loss events, break outs, mini fracs, 1D PPFG predictions etc.
6) **Iterate to improve match with field observations**
   - Change estimate of initial stresses

Problem with static models of subsurface stress

Present day stresses represent accretion of deformation through structural evolution

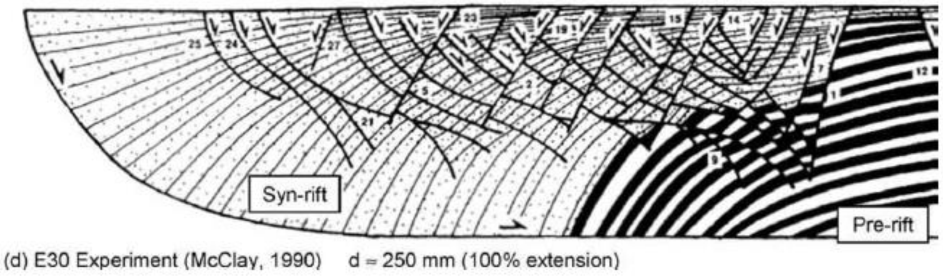
Example of salt-cored deformation on a passive margin



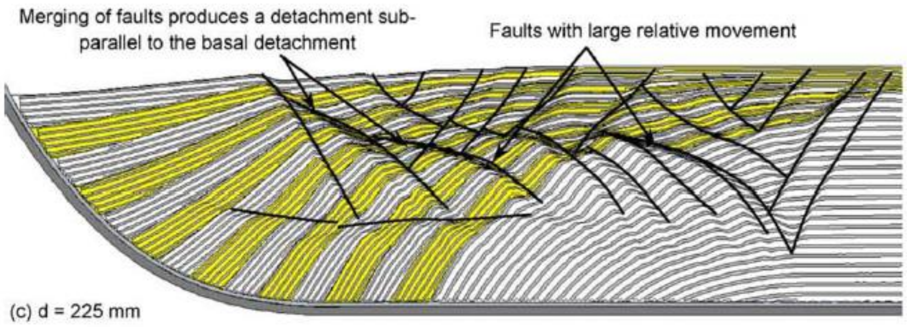
Need to zoom out to capture boundary effects ...which means modeling the entire passive margin

Rockfield Software

ELFEN Finite Element code allows tracking of large deformations

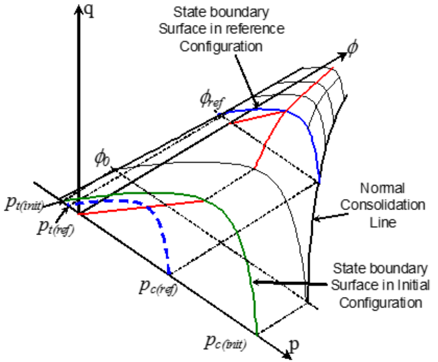


Analogue modelling of extension over a listric detachment



ELFEN simulation of extension over a listric detachment

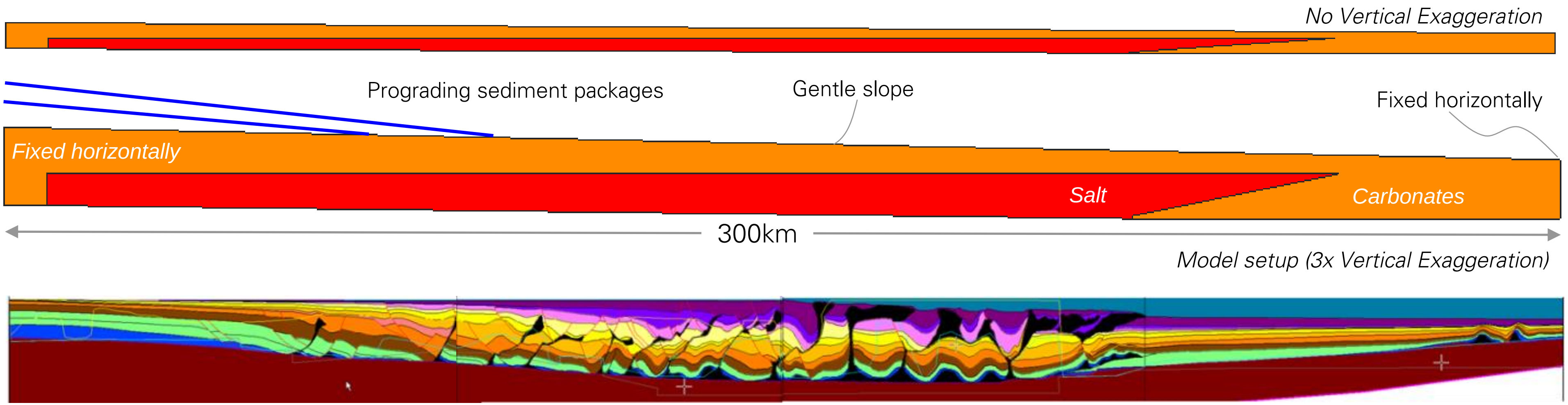
SR3 yield surface represented in 3D p′-q-porosity space



- ***ELFEN FM*** is Rockfield's in-house geomechanical forward modelling code.
- The computational framework is based on an adaptive, finite-strain, finite element formulation with robust automated remeshing techniques
- This allows extremely large deformations crucial for representing multiple deforming layers and including depositional and erosional processes.
- The software features advanced constitutive models for representing salt and clastic sediments.
- 'Basal profiles' may be used to force the model into predefined shapes to mimic supplied restorations etc.

Model set up

Simple model of prograding sediment deposition on carbonates overlying salt

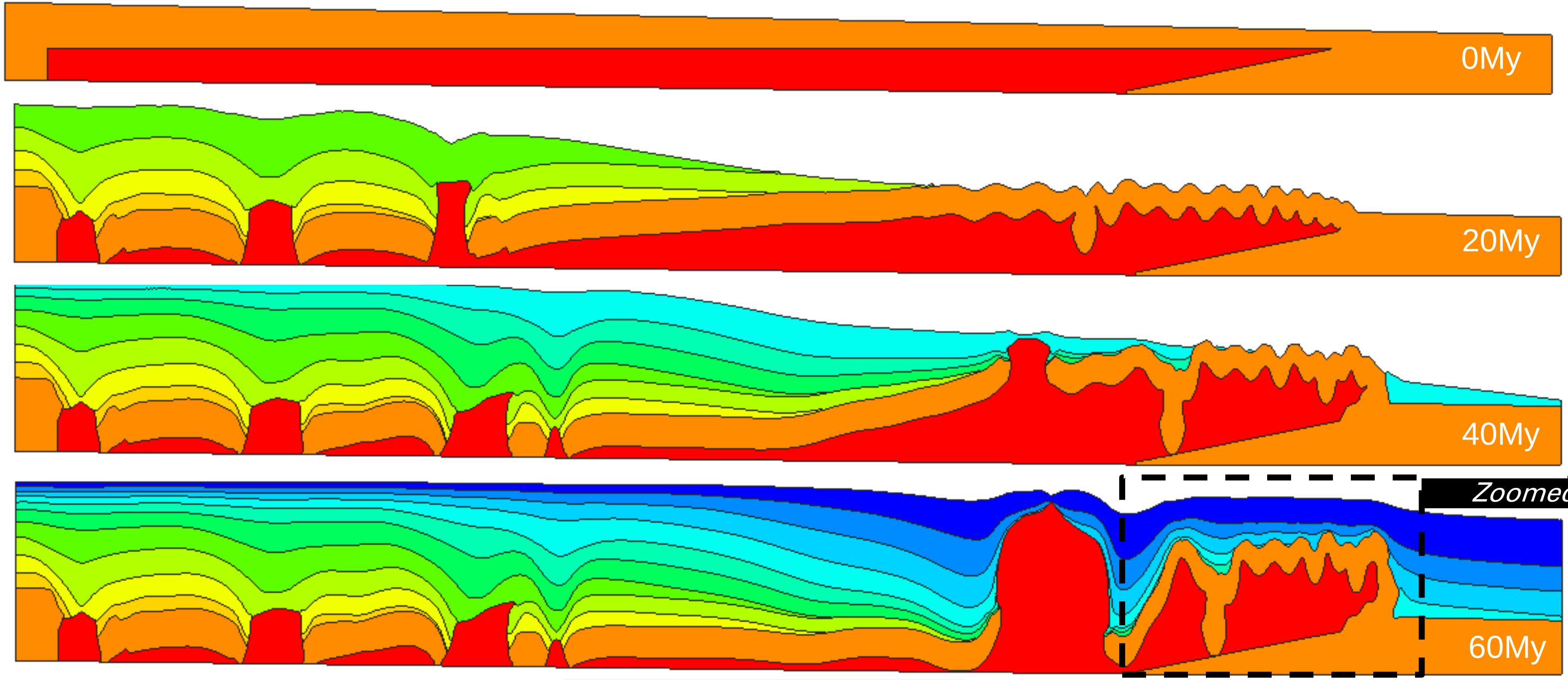


- Simple conceptual model is 'mechanical only' – at this stage a prescribed temperature gradient is used for the model.
- Pre-kinematic carbonates overlying a fairly thick salt layer of around 250km in length. Salt thickness is 2.5km in the landward region, and tapers at the margin toe to represent an earlier salt extrusion. Sediment thickness reduces from 3.5km in the updip region to 1.4km at the toe.
- The base of the model is inclined at approximately 0.5° to promote early gravity gliding and drainage of salt towards the toe.

Model test run

Simple model captures many features of salt movement on a passive margin

(3x Vertical Exaggeration)



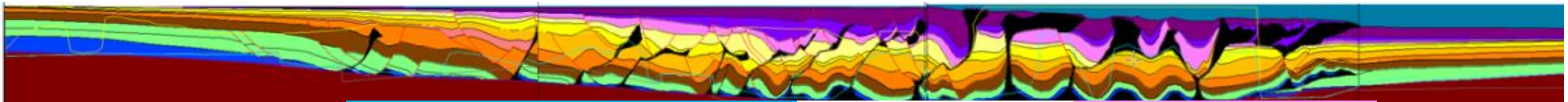
High amplitude folding at toe

Local extensional domains develop around diapirs

Zoomed section on next slide

Diapir starts growing; promotes (and is fed by) backlimb collapse

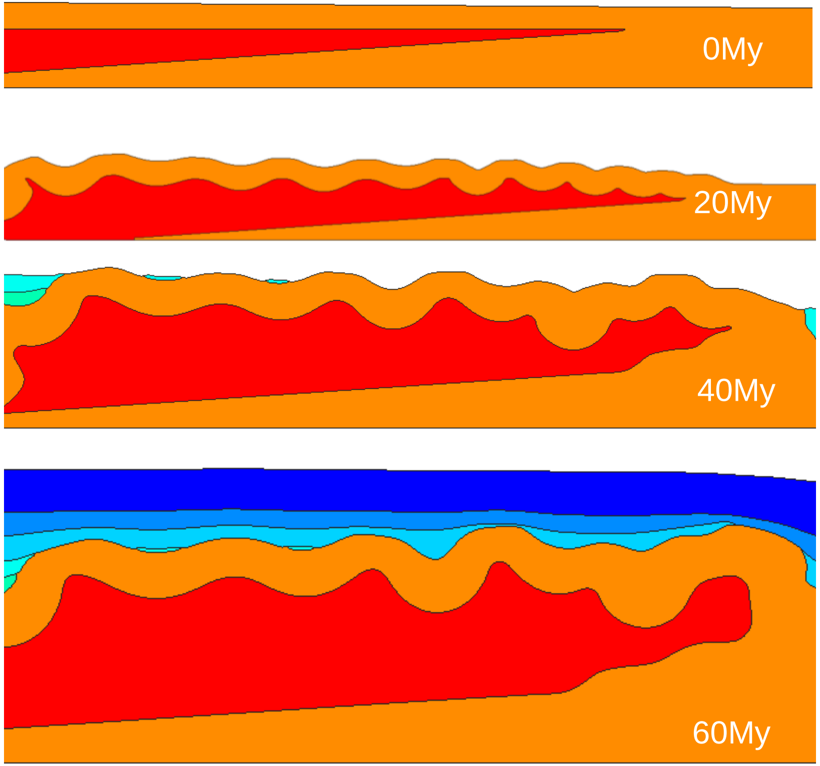
Extension	Translation	Compression
small buried salt walls and stocks	*no significant deformation*	*folding and large salt walls*



Extension	Translation	Compression

Evolution of model at various times

Model mimics geometrically derived restoration of GOM passive margin

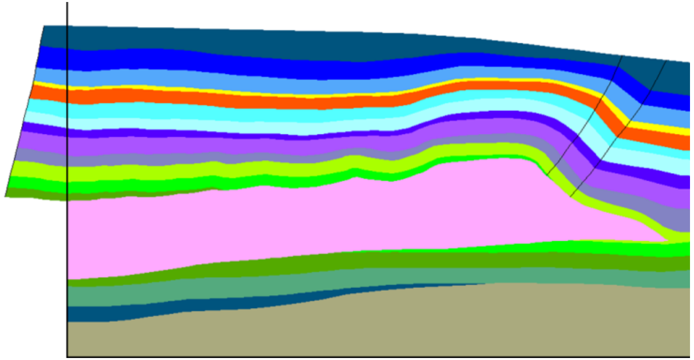


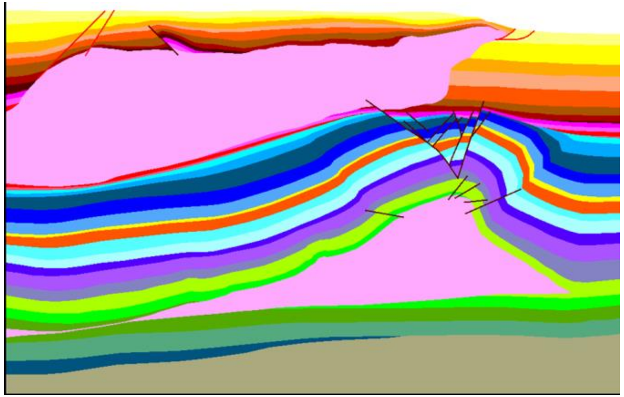
Initial configuration

Salt inflation and buckle fold belt

Extreme folding results in welding and 'buttress' effect

Salt deflation and backlimb collapse

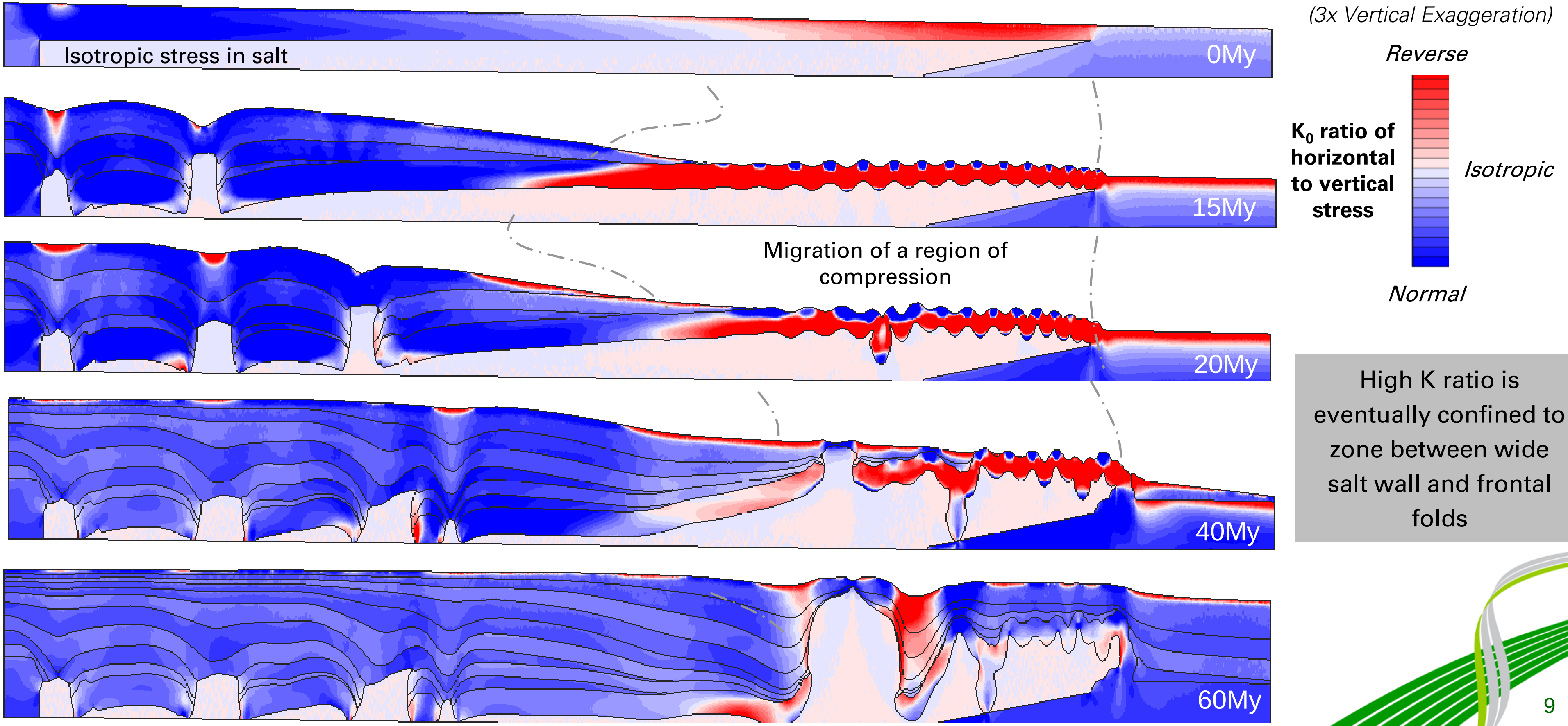




No Vertical Exaggeration

Evolution of stresses within the model

Broad region of compression develops early then focusses toward toe over time

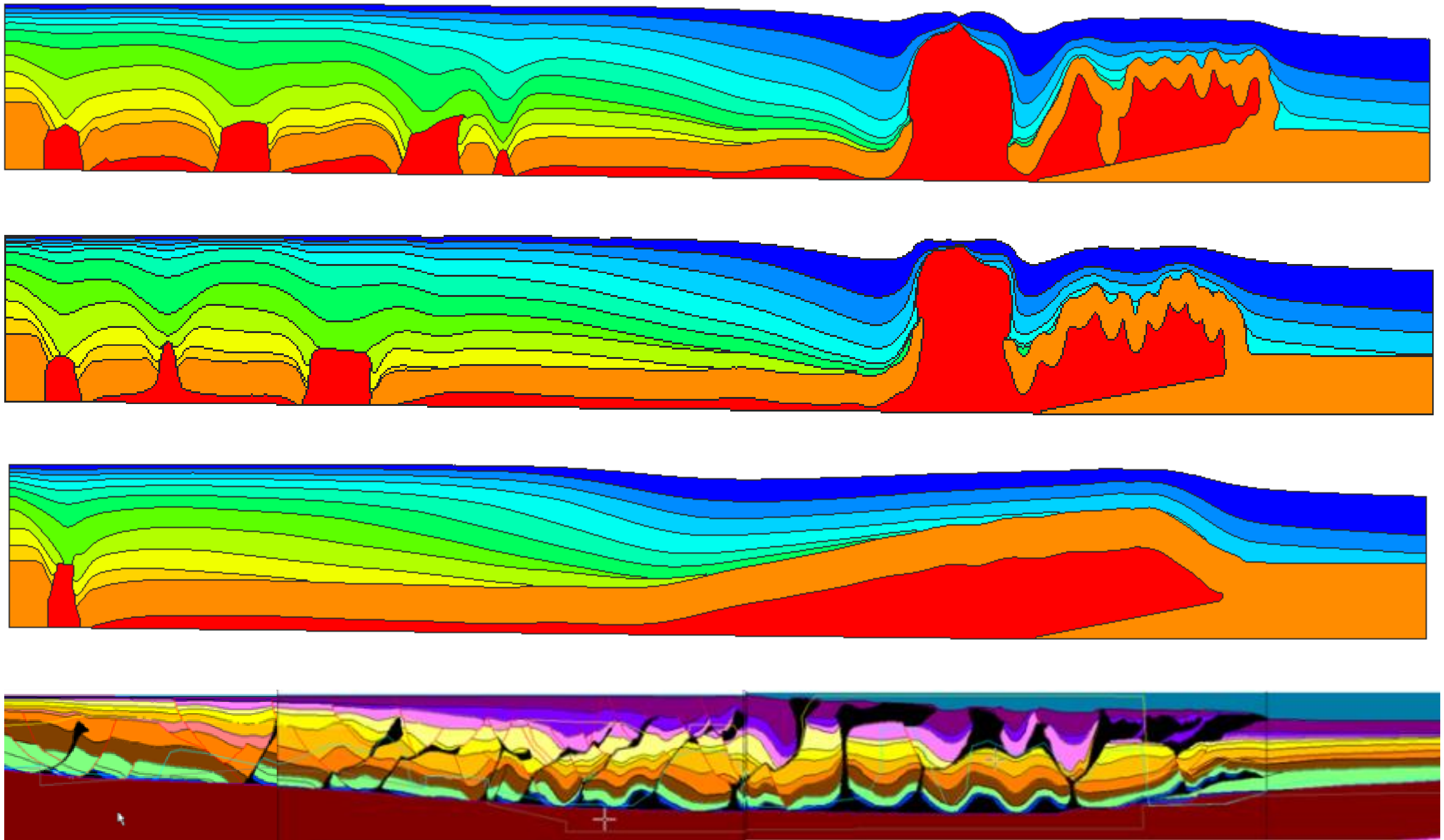


High K ratio is eventually confined to zone between wide salt wall and frontal folds

Sensitivity study

Changing the input parameters to more closely mimic the Gulf of Mexico reduces the geometric similarity

(3x Vertical Exaggeration)



Base case

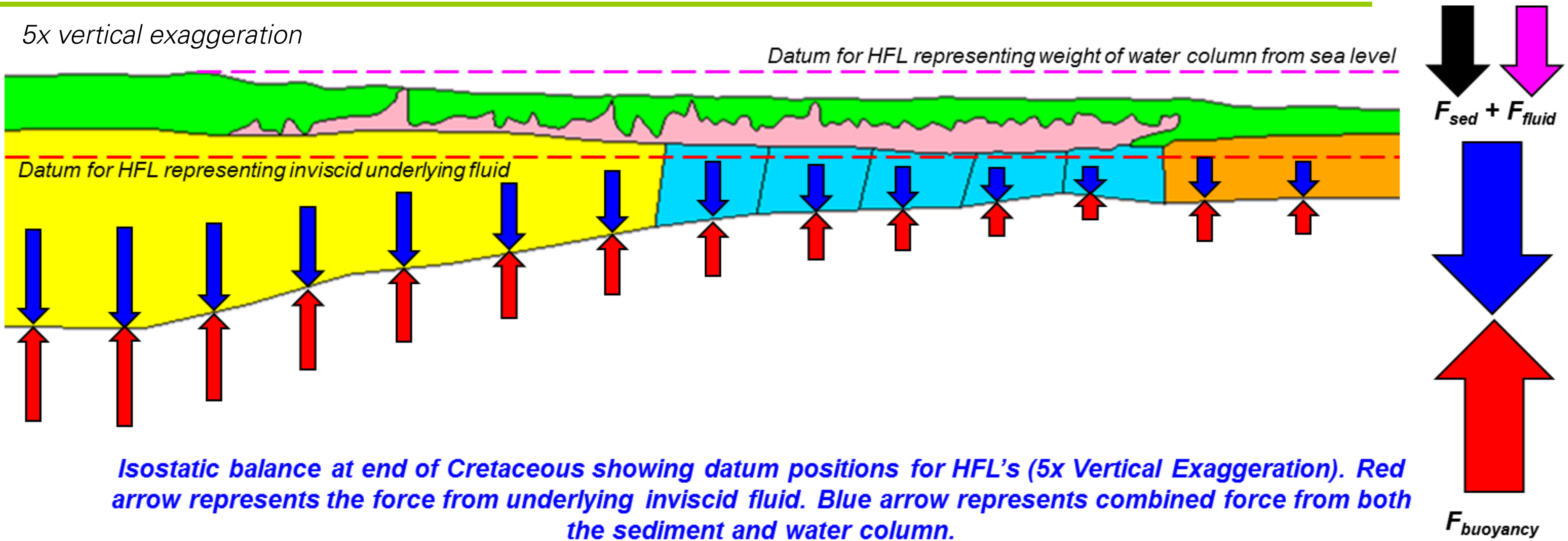
Sediment thickness at the toe x1.5

Sediment thickness at the toe x2
Deposition rates more similar to GOM

Incorporation of isostasy

Isostatic response modeled by application of a hydrostatic face load at the crust/mantle boundary, providing a buoyant response to the weight of sedimentation

5x vertical exaggeration

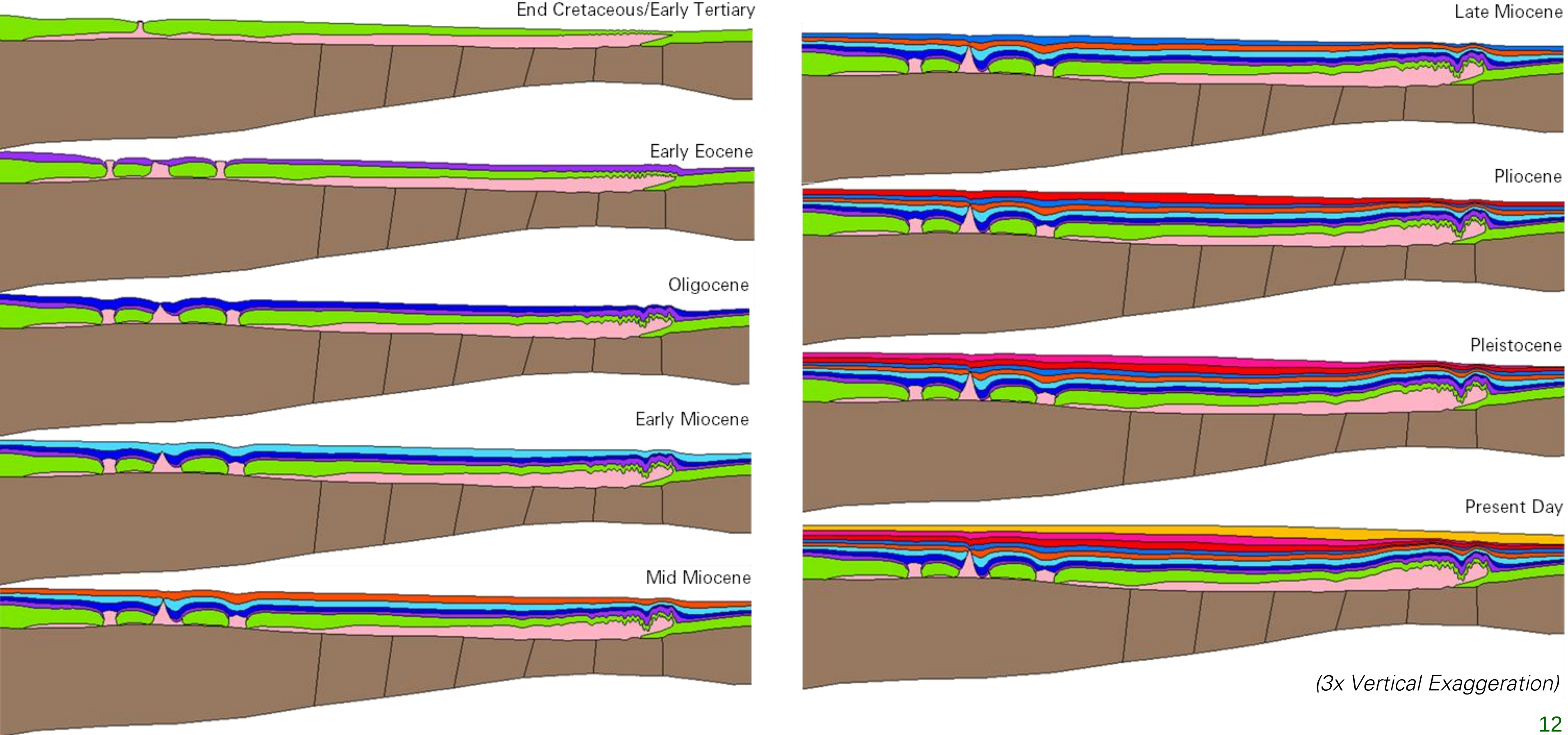


Isostatic balance at end of Cretaceous showing datum positions for HFL's (5x Vertical Exaggeration). Red arrow represents the force from underlying inviscid fluid. Blue arrow represents combined force from both the sediment and water column.

Thermal, radiogenic and elastic properties all specified for each layer

Full model run incorporating isostasy

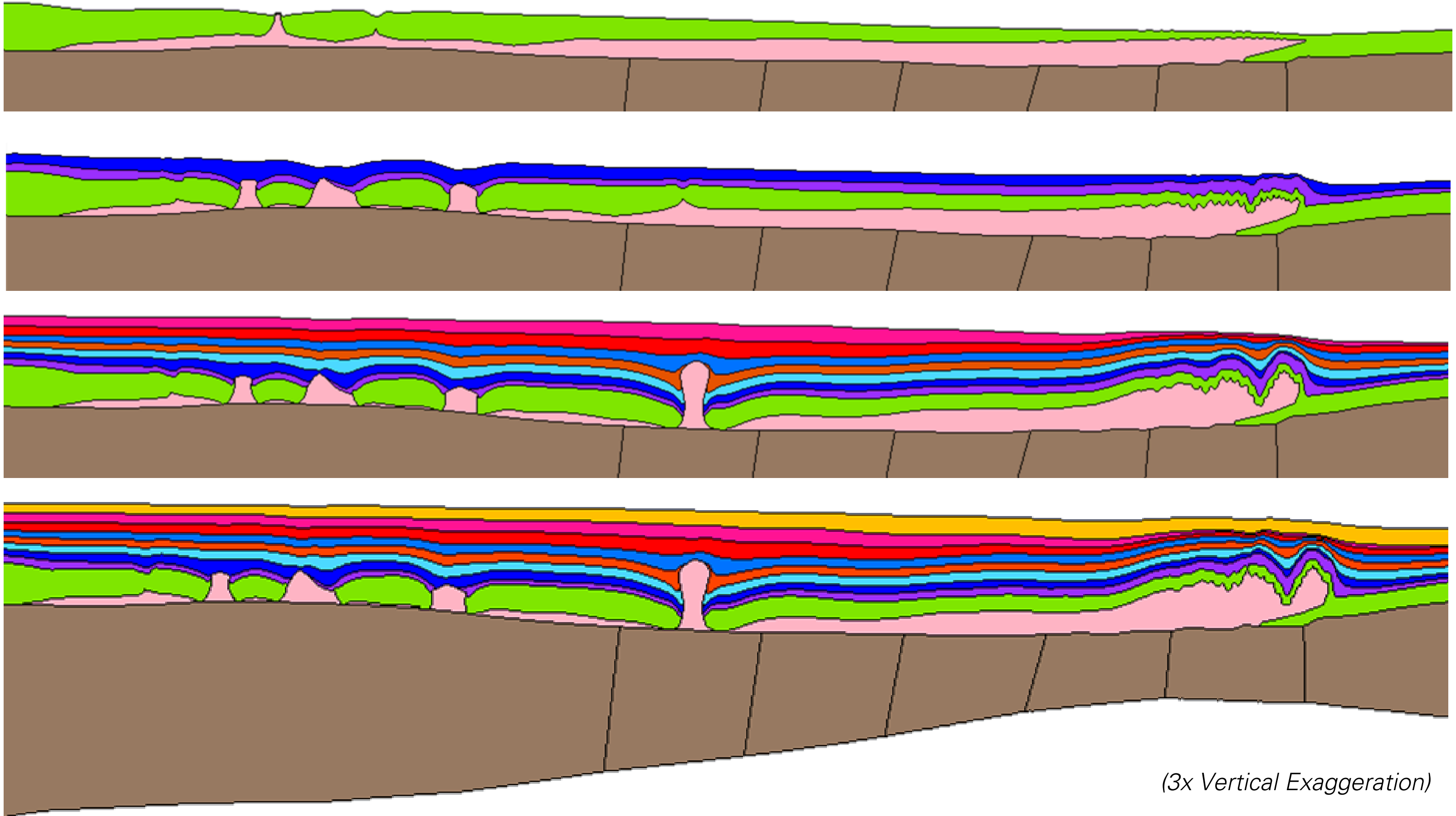
More accurate representation of basal geometry and sedimentation doesn't lead to the creation of a canopy, instead early fold belt gets frozen in place



(3x Vertical Exaggeration)

Full model run sensitivity – reduced frictional strength

Creates increased deformation and a noticeably wider extensional domain



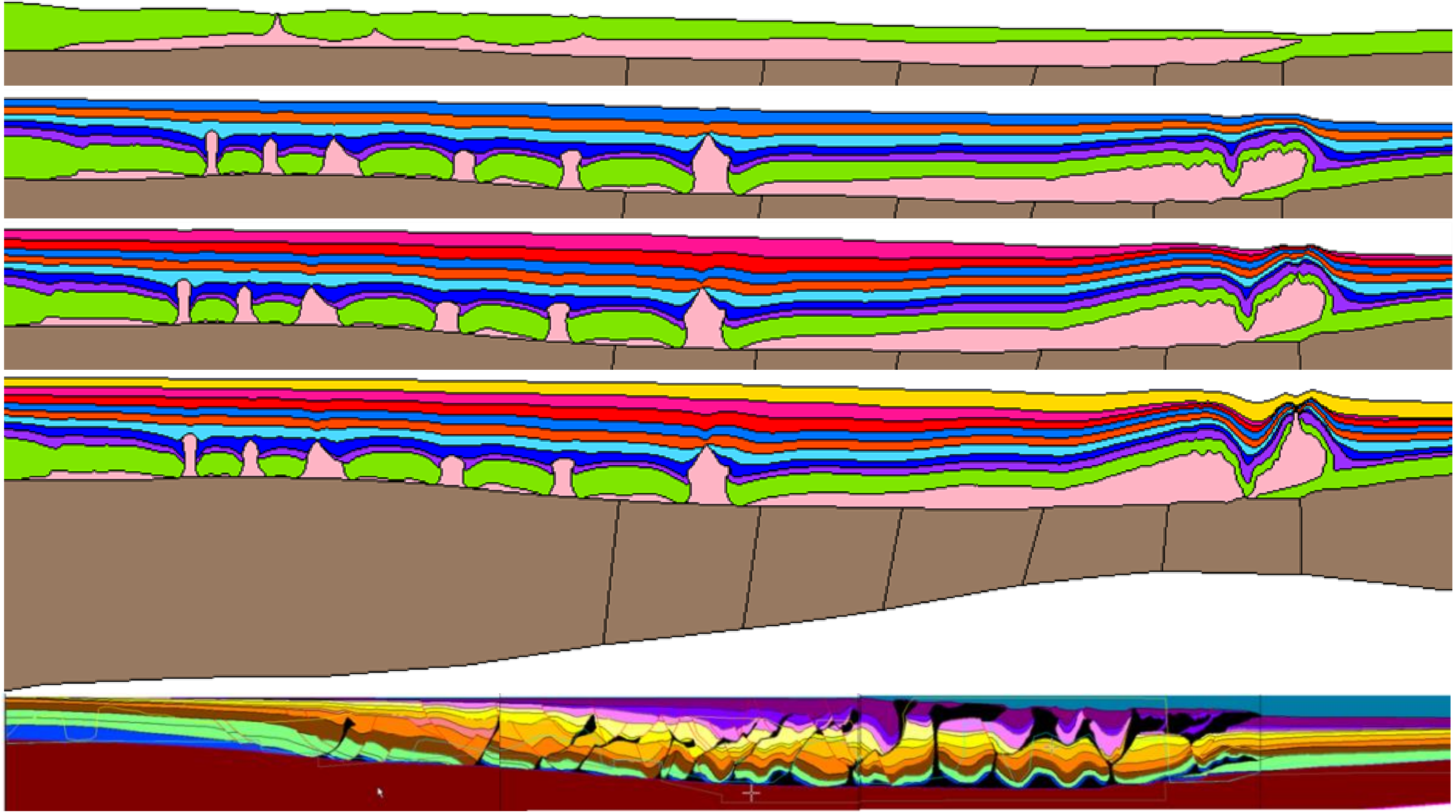
Increased deformation primarily in extensional domain

Noticeably wider extensional domain.

(3x Vertical Exaggeration)

Full model run sensitivity – significantly reduced frictional strength

Creates increased deformation in the contractional domain as well

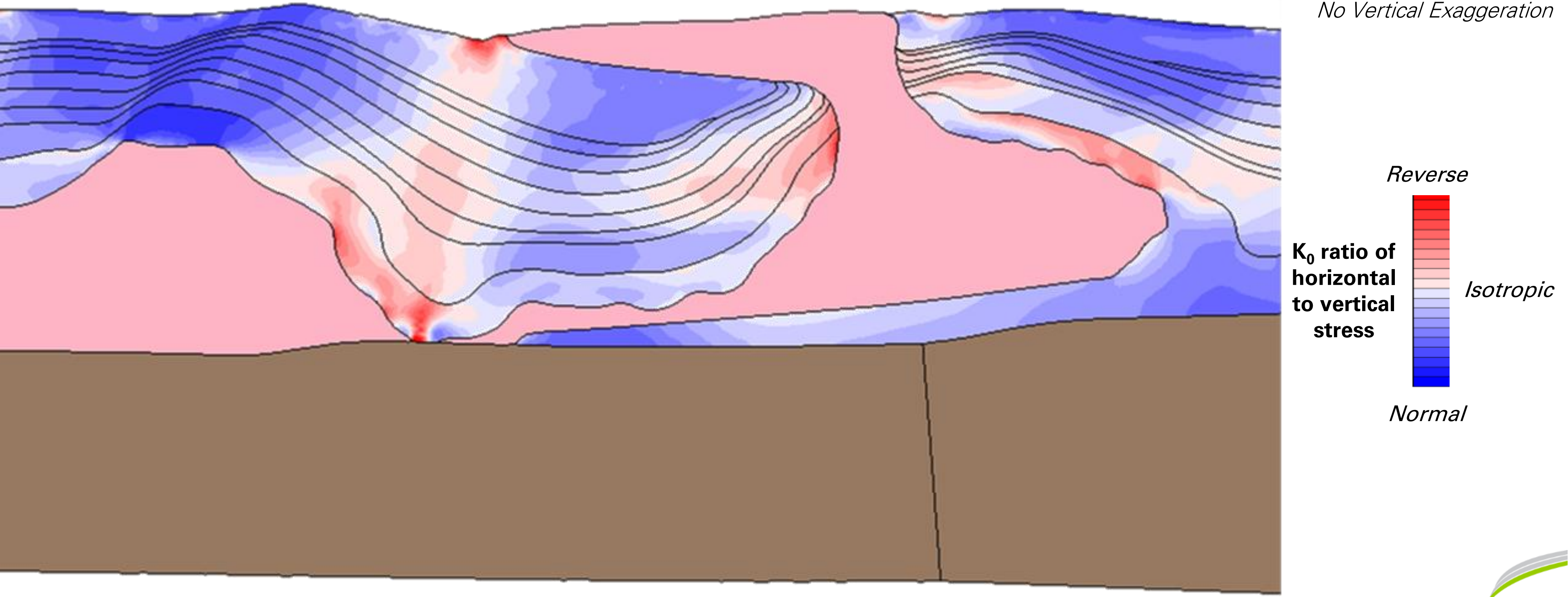


Diapirs now forming in the contractional domain as well as the extensional domain; close to breaking through and forming a canopy

Full model run sensitivity – significantly reduced frictional strength

With another 5 million years of model deformation, achieved canopy breakthrough

No Vertical Exaggeration

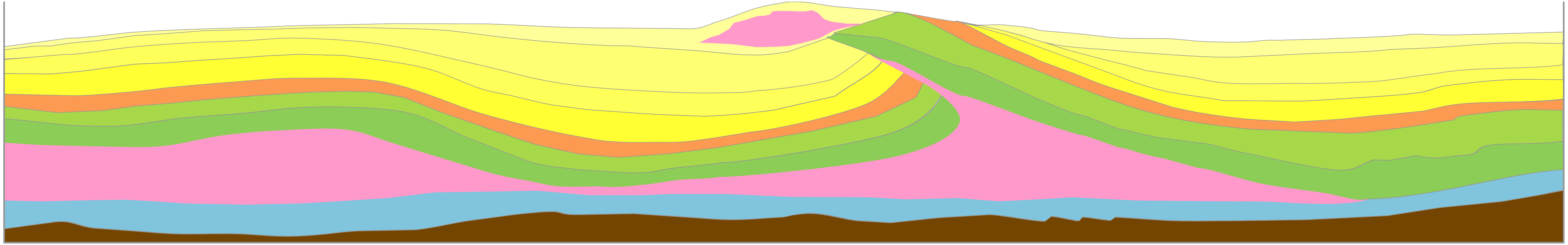


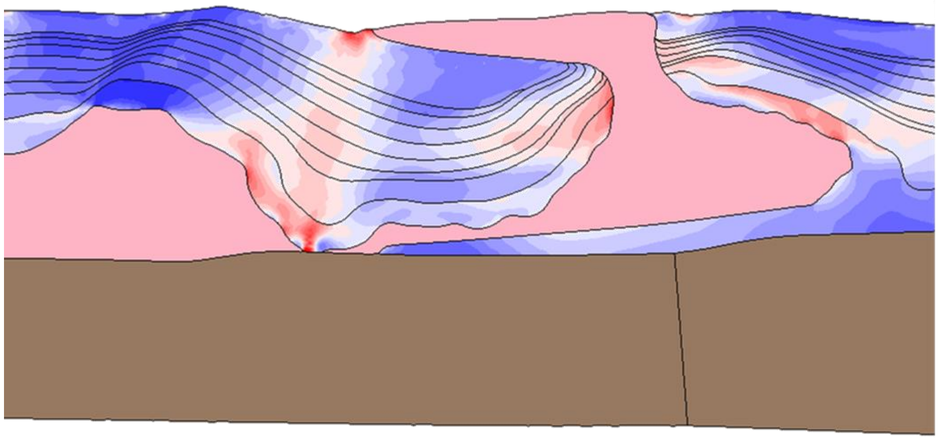
This begins to capture the spatial variations in K_0 around salt structures that we can use for input into our 3D static models.

Starting to create structures that resemble real geology

Line drawing of GOM structure restored to Plio-Pleistocene boundary

No Vertical Exaggeration

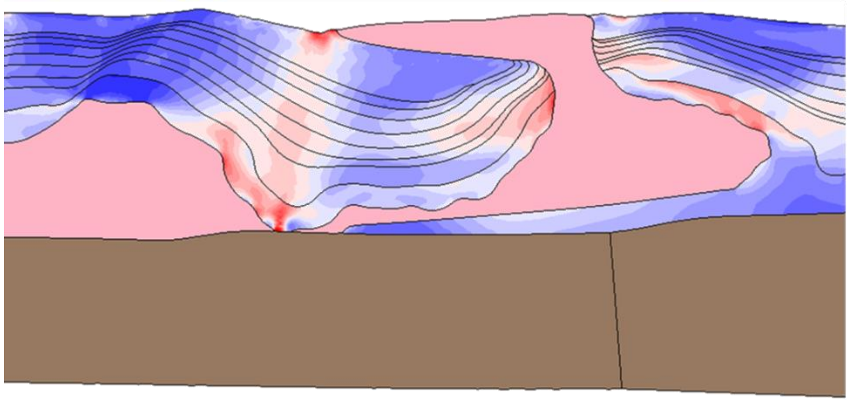


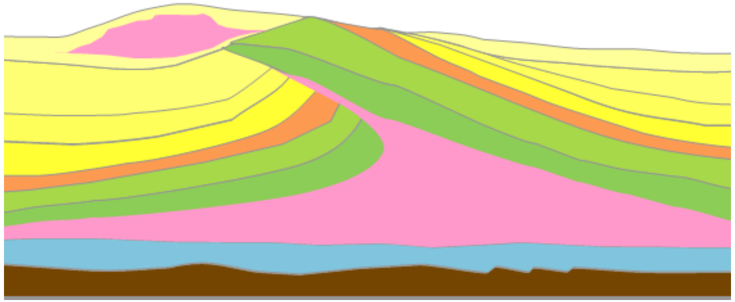


Allows us to identify regions in the 3D static model that may contain different K_0 ratios

Summary

- 4D Geomechanical models useful for 21st Century Reservoir Development
- Largest uncertainty lies in input parameters
- Forward models are a way to help predict input stresses if they can generate similar structures
- We have modeled salt movement under sedimentary deposition and isostatically-balanced subsidence
- Unable to create canopy breakthrough with standard properties
- Breakthrough achieved with significantly reduced frictional strength and additional time
- Created structures that resemble those observed today
- Can use the modeled stresses to inform the starting point for present day 4D Geomechanical model builds





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