Investigating the Controls of Salt Movement Using Finite Element Modelling*

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Abstract

2D geomechanical modelling is used to study the field-scale evolution of two geological scenarios incorporating salt structures: (1) salt sheet advance under compression, and (2) inflation of a toe fold. The models are constructed using the finite element method, and are validated against numerical, analogue, and geological examples. A full sensitivity analysis assesses how different parameters promote or inhibit salt movement.

An advancing salt sheet (1) is recreated with a ‘ramp-flat’ base salt geometry. Ramp development is favoured by high sedimentation rates, causing sheet inflation over peripheral buttressing strata. Wide flats develop beneath thick sheets, expressing significant forward motion that can cause overturning of peripheral strata and sub-salt shear zone development. Sheets with a thick initial overburden develop smoother base geometries, increasing interpretation complexity.

The basinward limit of salt on a margin experiencing compression (2) is a high strain environment subjected to considerable buttressing effects. High compression rates and overburden thicknesses favour development of a toe thrust, while high sedimentation rates and salt layer thicknesses favour a toe fold.

These results are demonstrated with reference to case studies, and we discuss their implication on salt flow mechanism predictions, stratal geometries, damage zone distributions and fracture orientations. The models developed here enable high-resolution, geologically realistic reconstructions of salt structures, and may guide interpretation in areas with sparse or poor seismic imaging.

References Cited

Argus Holdings Ltd, Automatic Grid and Mesh Generation. Website accesses January 28, 2018. http://www.argusone.com/MeshGeneration.html

Fossen, H., 2010, Structural Geology: Cambridge, Cambridge University, p. 480.

Hearon, T.E., M.G. Rowan, T.F., Lawton, P.T., Hannah, and K.A., Giles, 2015, Geology and tectonics of Neoproterozoic salt diapirs and salt sheets in the eastern Wilouran Ranges, South Austraila: Basin Research, v. 27/2, p. 183-207.

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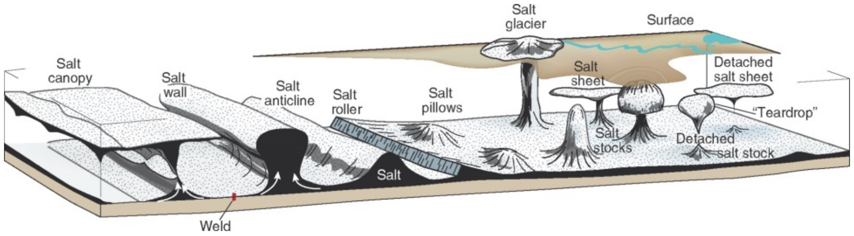
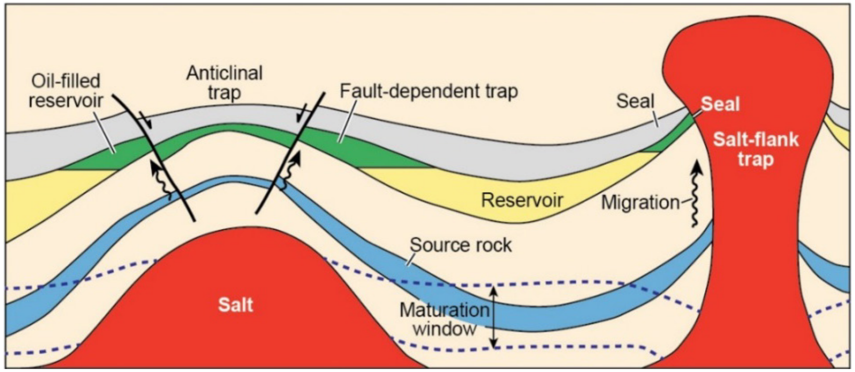
Understanding salt movement

- Salt impacts all elements of the petroleum system
- Effects of geological parameters on promoting/inhibiting salt movement receives little attention
- Scenarios incorporating salt structures
  - **(1) Salt sheet advance under compression**
  - **(2) Inflation of a toe fold**



A wide range of salt structure geometries can develop (Fossen, 2010)



Petroleum system elements associated with salt structures (Jackson and Hudec, 2015).

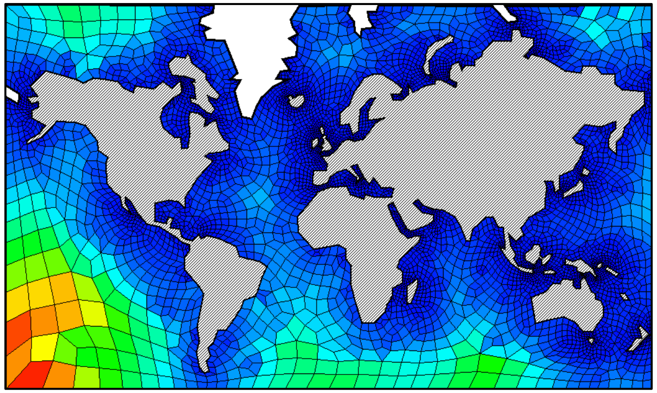
Presenter's notes:

- Salt is inherently complex – deforming as a viscous fluid under geological time-scales.
- It is critical therefore to gain significant insight into salt behaviour, and how salt structures develop, when attempting hydrocarbon exploration and reservoir management.
- And broadly, the presence of salt in a basin impacts all elements of the petroleum system
- Key drivers of salt movement are well understood – differential loading or displacement.
- However, the effects of geological parameters on promoting or inhibiting this flow receives little attention
- Understand these controls in 2 different geological scenarios incorporating salt structures
  - 1) Salt sheet advance under compression
  - 2) Inflation of a toe fold

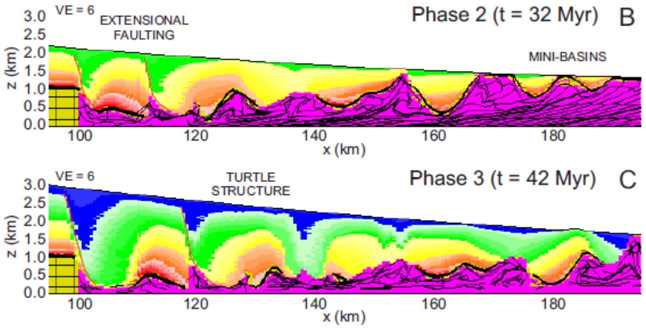
Finite element modelling

- 2D geomechanical models
- "Solve boundary problems for differential equations simulating rock deformation"
  - Realistic scaling and properties
  - Transient and time-dependent processes
- Approximate - 'finite elements'
- Elfen® software package

Limited development of field-scale models



Finite elements define a 'mesh', which define boundaries to areas with a similar solution (Argus Holdings).



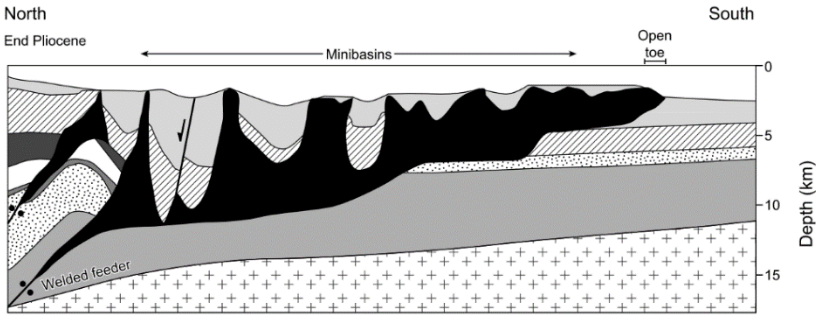
Passive margin numerical model (Ings et al., 2004).

Presenter's notes:

- With advancements in software and processing speed – gradually moving away from analogue (sandbox) experiments, and into the numerical realm.
- This study considers 2D geomechanical modelling, using the Elfen software package.
- Developed by Rockfield Global as part of a research consortium – in the effort to "simulate structural evolution in geological environments"
- Numerical: solving boundary conditions for differential equations that simulate rock deformation.
- Finite element: approximate solutions, breaks model down into smaller, simpler finite elements.
- Advantages: complex geometries; quick and accurate, geologically realistic scaling and materials, transient and time-dependent processes such as strain rate.
- Note: traditional research focused on passive-scale models; limited development of field-scale models

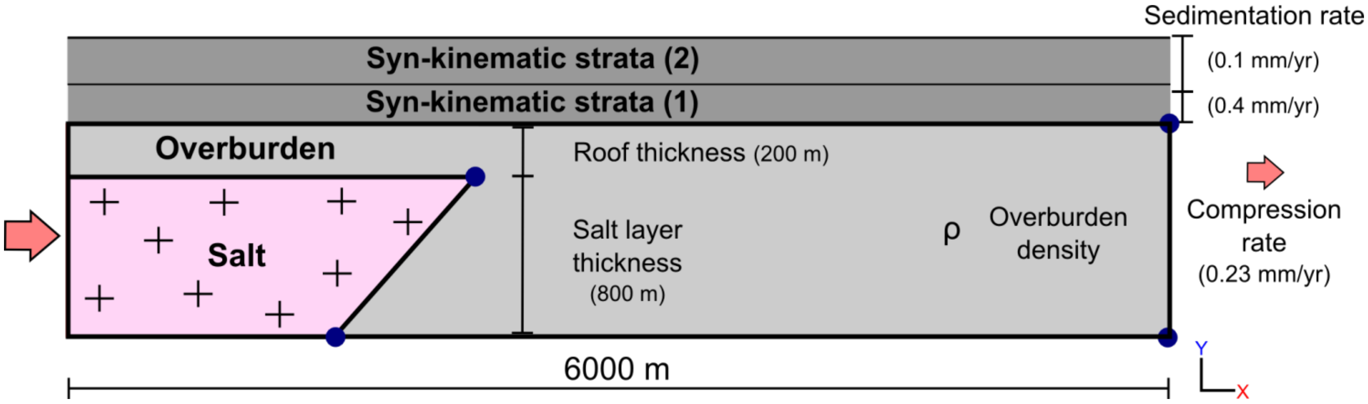
(1) Salt sheet advance under compression

- Salt sheets commonly exhibit a 'ramp-flat' base geometry
- Traditional interpretation: sedimentation vs. sheet advance rates *(e.g. Vendeville and Jackson, 1990).*
- Are there other controls?



'Ramp-flat' geometry beneath the Louann salt canopy, northern Gulf of Mexico (Hudec and Jackson, 2006).

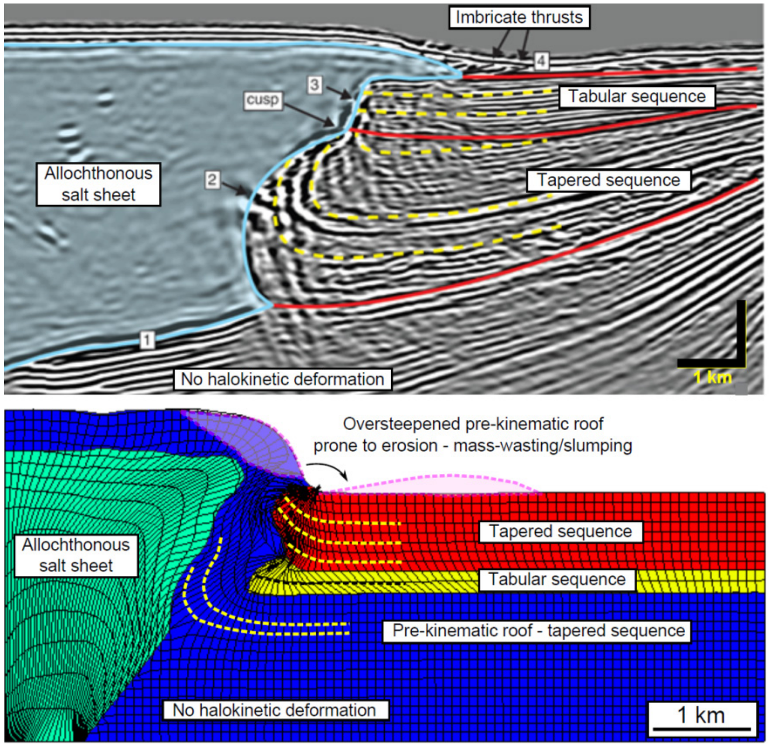
Sheet advance model design – values indicate model defaults



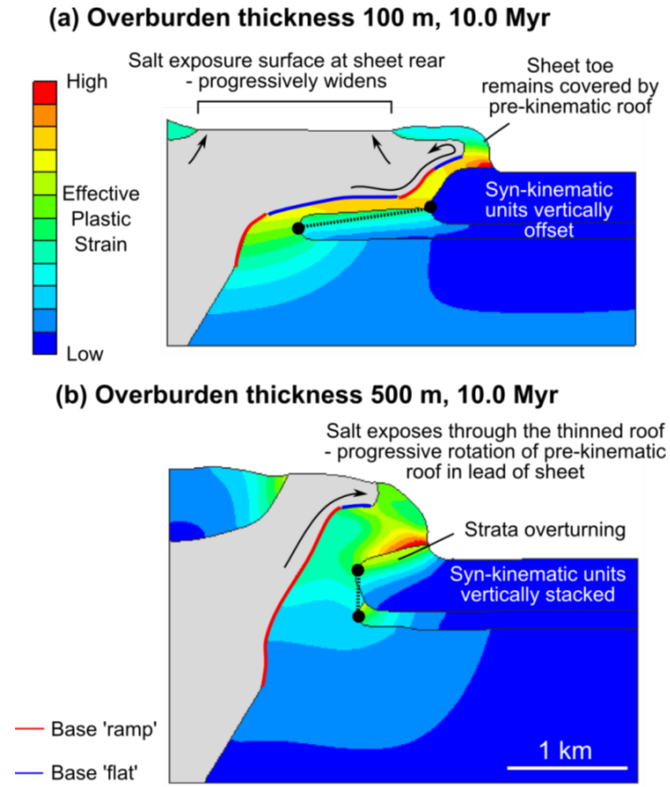
Presenter's notes:

- Salt sheets are prominent structures in many salt basins.
- In many cases, a 'ramp-flat' geometry is observed in their base, e.g. beneath Louann salt canopy, where the base salt progressively climbs up towards the outer-most zone defined by the famous Sigsbee Escarpment.
- Traditional views suggest that the shape of the base depends on the relative rates of sedimentation and sheet advance
- Aim to recreate this pattern by changing the sedimentation rate through time with a constant compression rate, are there other controls?

(1) Salt sheet advance under compression



Model comparison to a seismic example from the northern Gulf of Mexico using material grids (Hearon et al., 2015)

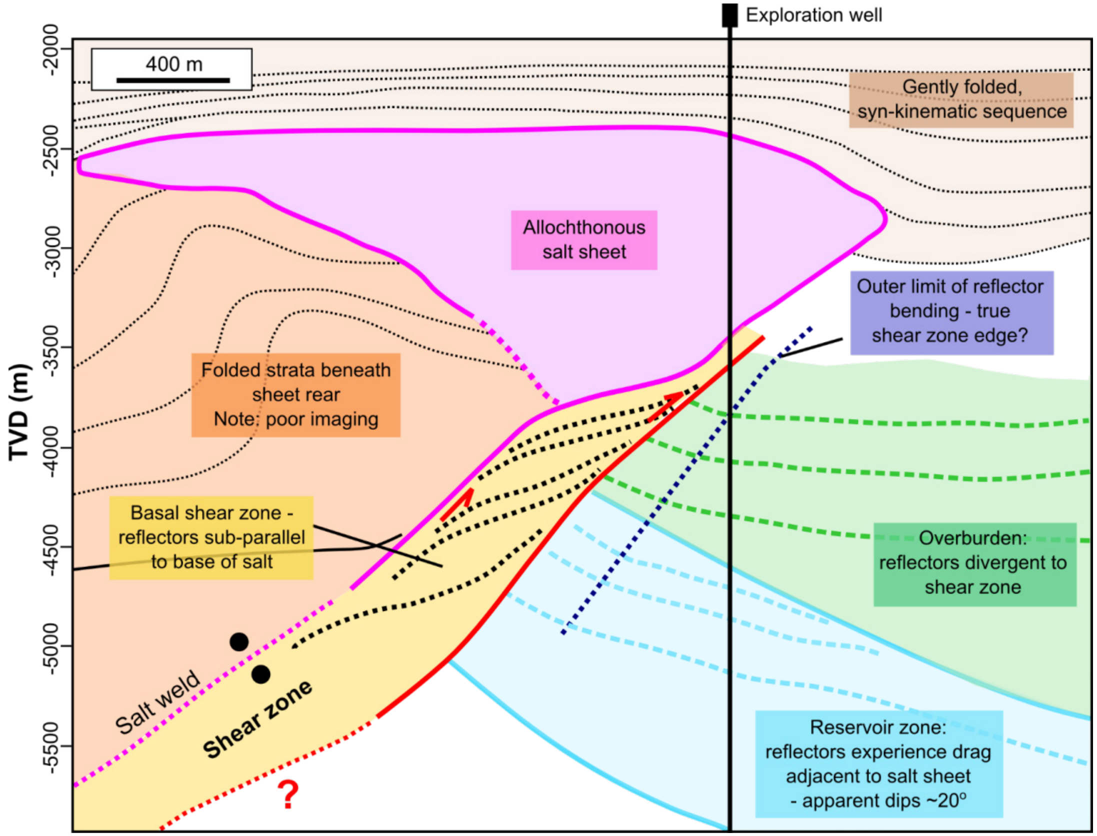


Model runs with varying initial overburden thickness

Presenter's notes

- On the left is an example of the model, compared with a seismic example from the northern Gulf of Mexico. Material grids overlying the model simulate rock deformation and flow contours.
- Similarity – ramps and flats (low and high angle geometries); significant tilting of the strata, and in some cases overturning e.g. the pre-kinematic roof, some cases no tilting
- In the model the roof oversteepens, which in reality would be prone to erosion and mass-wasting, which has not been captured.
- During deposition of the syn-kinematic units, this acts as a buttress to the sheet, causing it to inflate in its attempt to override over and developing a steep base geometry or ramp.
- Other parameters complicate the story (right) – thinner overburdens significant forward motion so wide flat, and conversely thicker overburden is difficult to stretch and therefore significant inflation with subtle base geometry changes. This is also critical for vertical reservoir connectivity, in thin overburden significant offsets!

Case Study: Prospect Typhon

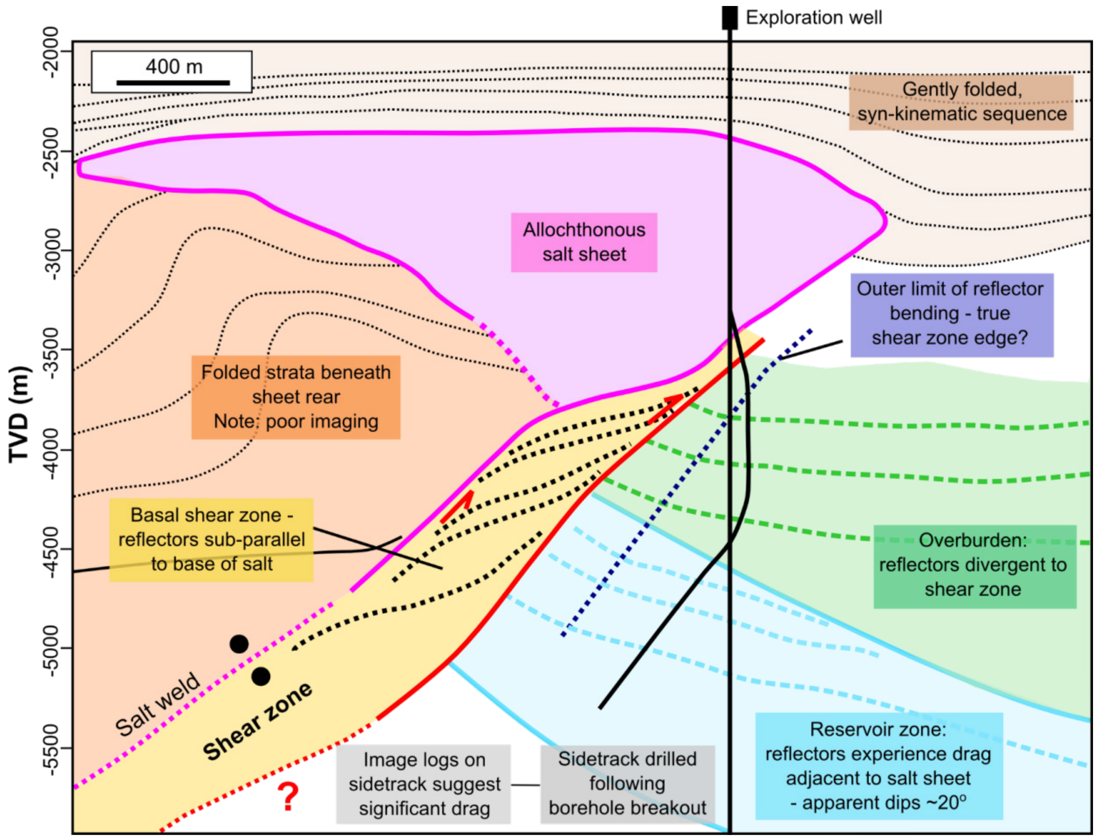


Prospect Typhon: a challenging sub-canopy target (modified from Von Nicolai, 2015).

Presenter's notes:

- The first case study I'm presenting is Prospect Typhon, a sub-canopy target penetrated with a vertical exploration well
- Seismic observations: the reservoir zone was not expected to have experienced significant deformation
- Sub-parallel reflectors to the sheet base suggested the presence of a shear zone (C-S shear fabric); however thought to be confined close to the sheet.
- Although some bending is observed further to the blue dotted line, this may just be a seismic artefact.
- Changes in resistivity measurements during drilling campaign indicate significant wellbore instability below the sheet; later confirmed by cavings found in mud returns.
- Explanation: high pore pressures due to HCs trapped in highly fractured material within basal shear zone.

Case Study: Prospect Typhon

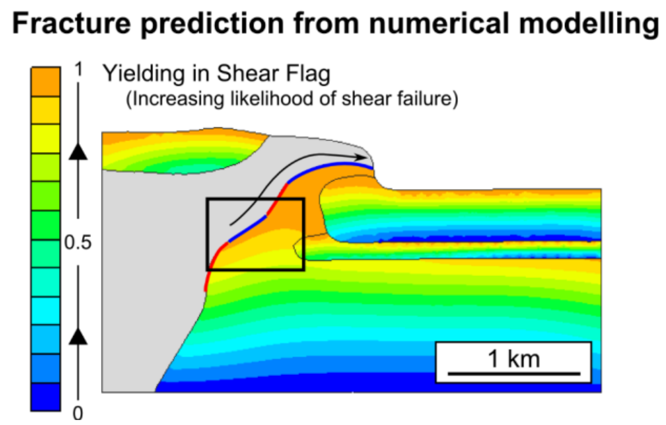


Prospect Typhon: a challenging sub-canopy target (modified from Von Nicolai, 2015).

Presenter's notes:

- Necessitated an operational sidetrack; accounting for cumulative non-productive time equivalent to $15 million

Case Study: Prospect Typhon

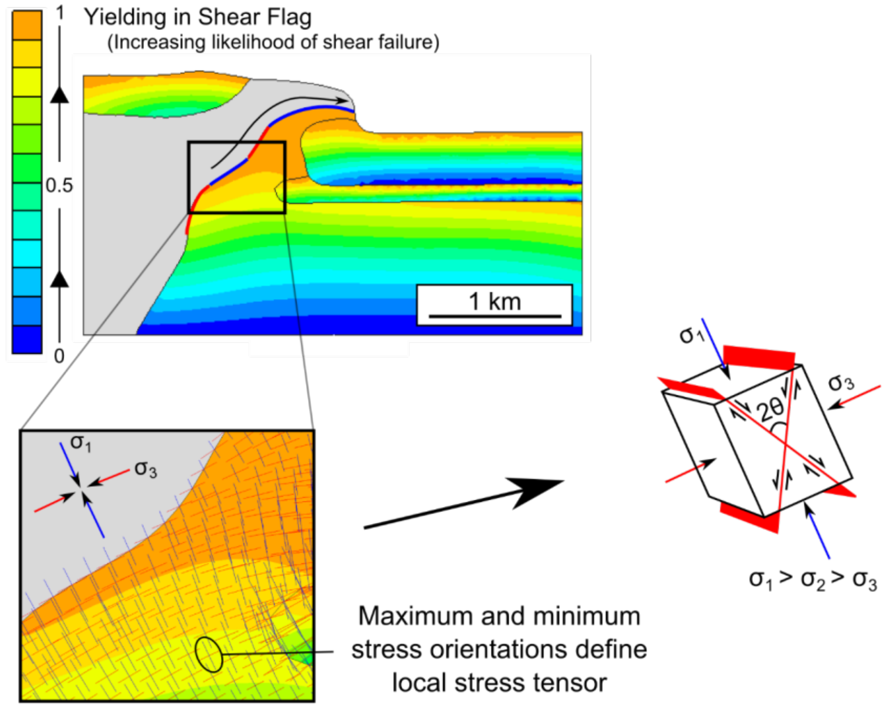


Presenter's notes:

- Significant drag and stratal steepening is predicted by various model variants, particularly during development of flats in the base salt trajectory subsequent to tilting during inflation e.g. overriding glacier
- Interpreted shear zone compares to a broad zone of predicted rock failure beneath the sheet.

Case Study: Prospect Typhon

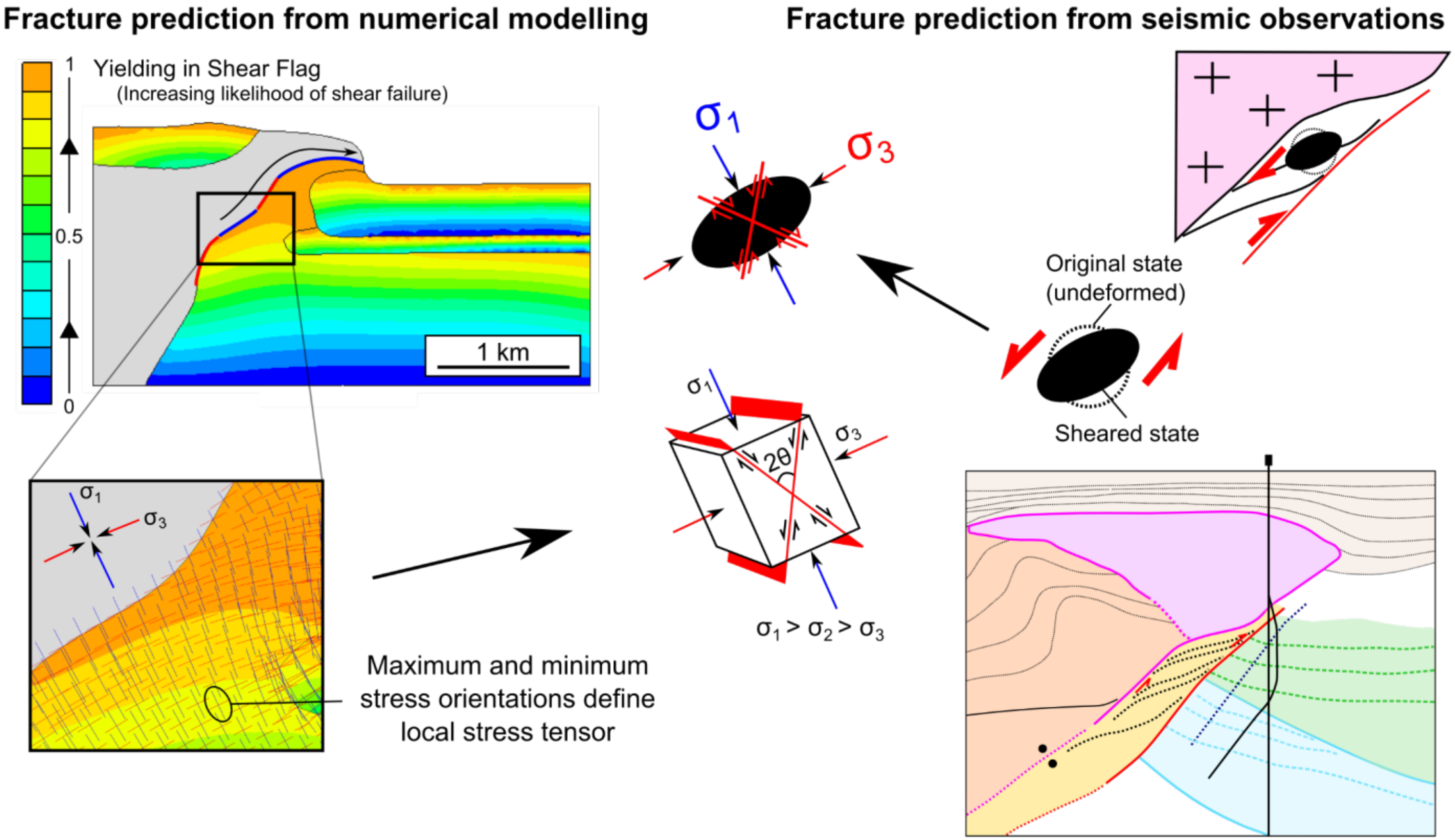
Fracture prediction from numerical modelling



Presenter's notes:

- Local stress tensors were analysed, and can predict fracture orientations.

Case Study: Prospect Typhon

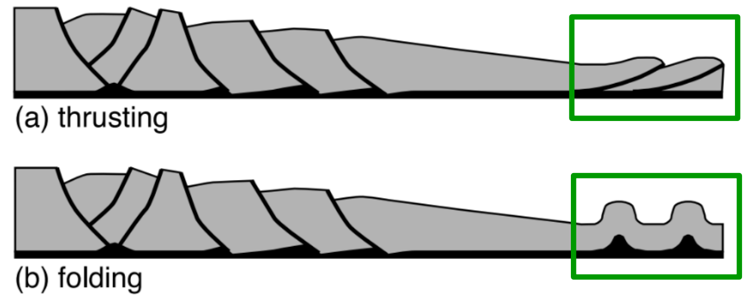


Presenter's notes:

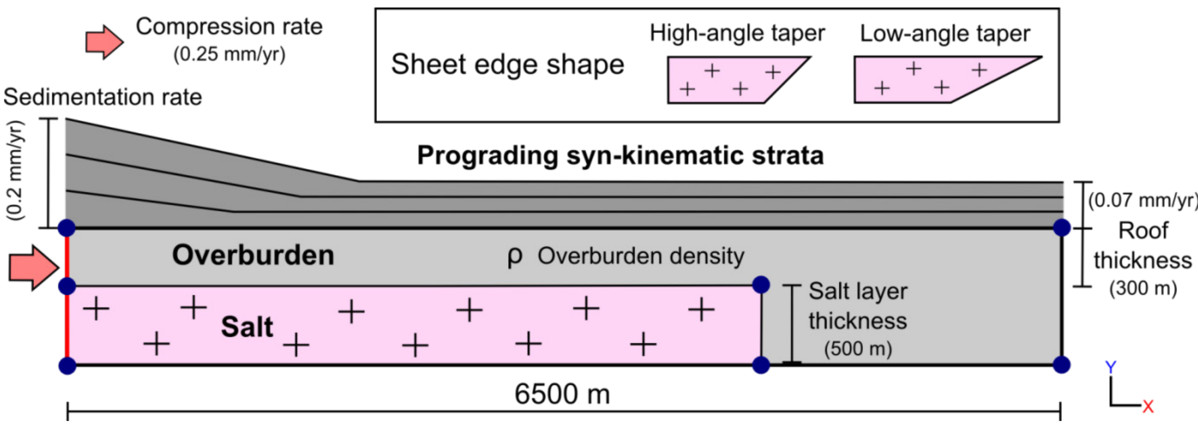
- Independently we took a close look at the shear zone to consider the local stress state. This can be achieved by considering the stress as an ellipse, and using the C-S shear orientations.
- The predicted shear fracture orientations match those from the model.
- The numerical models therefore predict the presence of a shear zone beneath a migrating salt sheet; and with consideration of the stratigraphy could predict the development of over-pressure.
- Could lead to the development of coupled mechanical-seepage models, which may quantify sub-canopy pore-pressures.

(2) Inflation of a toe fold

- Outer passive margins can experience compression linked to up-dip extension *(e.g. Peel et al., 1995)*
- Prograding depositional systems apply a differential load
- What controls structural style?



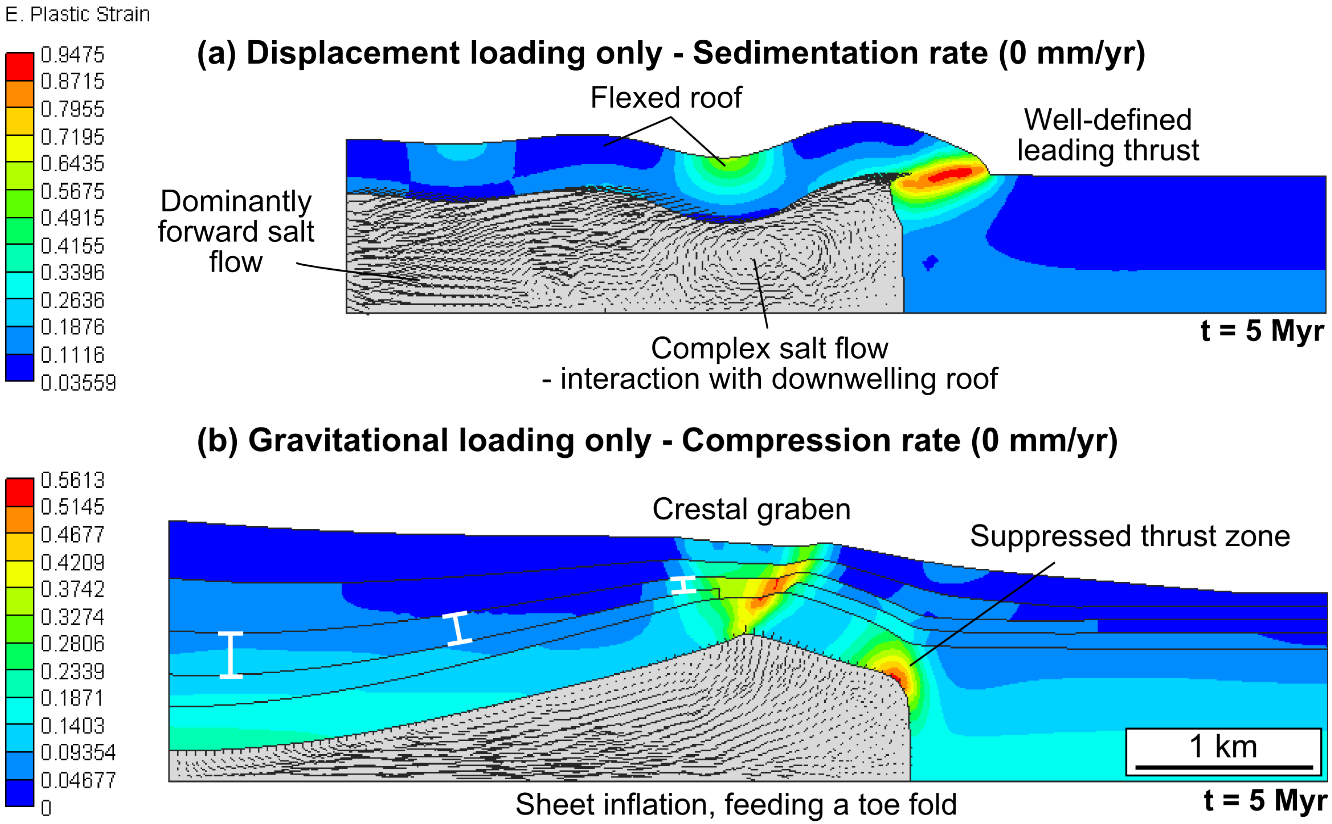
Different expressions of shortening at the distal toe of a deforming wedge (Rowan et al., 2004).



Outer passive margin model design – values indicate model defaults

Presenter's notes:
- The outer parts of many passive margins experience compression linked to up-dip extension – indicated in the final model by compression from the left
- These areas are becoming of particular interest in many mature areas
- Progradational depositional systems such as basin floor fans are common, loading and deforming an initial salt layer
- Evaluate the contribution of both differential and displacement loading – what controls the structural style at the toe of a passive margin
- Salt thickness is thought to be key – thicker salt, decoupled deformation, folding rather than faulting – other parameters will also be tested.

(2) Inflation of a toe fold

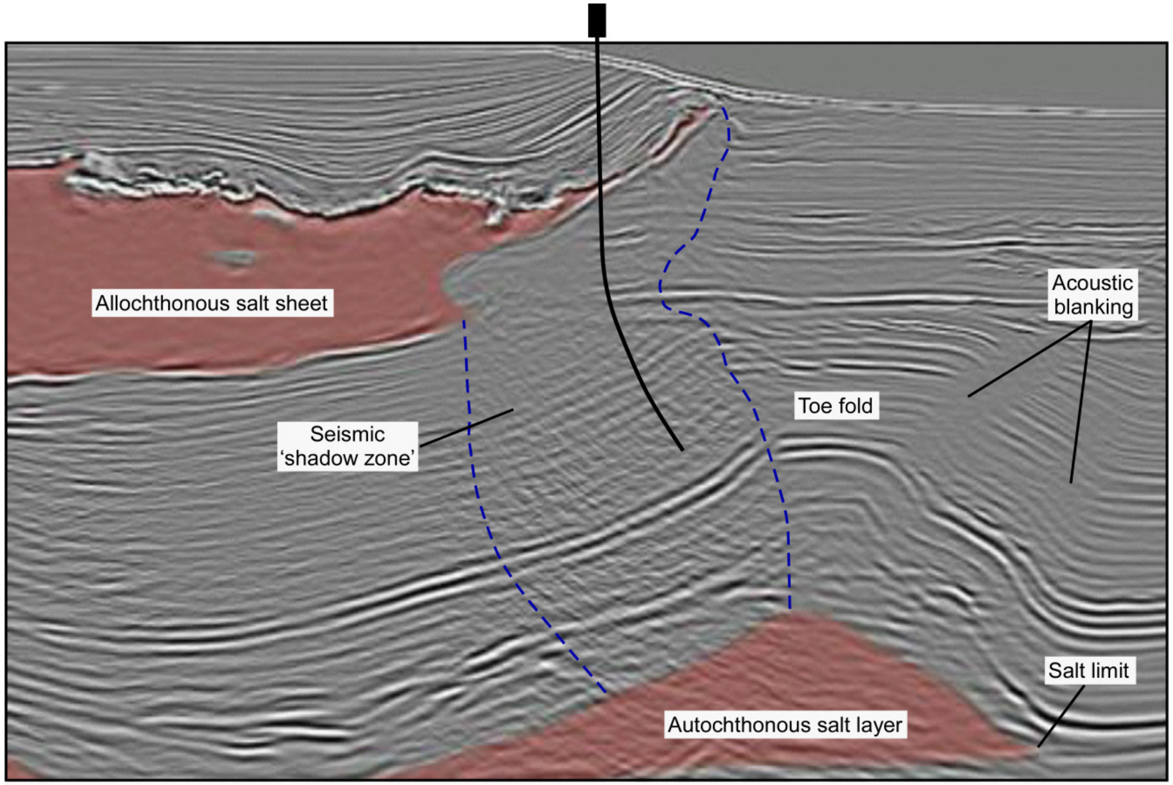


End-member model runs, comparing influence of displacement vs. gravitational loading on structural development.

Presenter's notes:

- These two model variants compare end-case scenarios: only compression; and only differential loading by a sediment wedge
- Contrasting structural development
- 1) Roof buckles into a series of low amplitude folds: this complicates salt flow vectors as the salt interacts with downwelling sections. Flow is dominantly forward, developing a well-defined thrust zone in the lead of the sheet.
- 2) Salt efficiently evacuates beneath the load, providing accommodation space for the development of a thick minibasin sequence. The sheet tends to inflate, feeding development of a toe fold which develops a crestal graben in response to layer-parallel bending and stretching. The thrust zone ahead of the sheet is suppressed, limiting high strain to a narrow zone close to the sheet front

Case Study: Prospect Altum

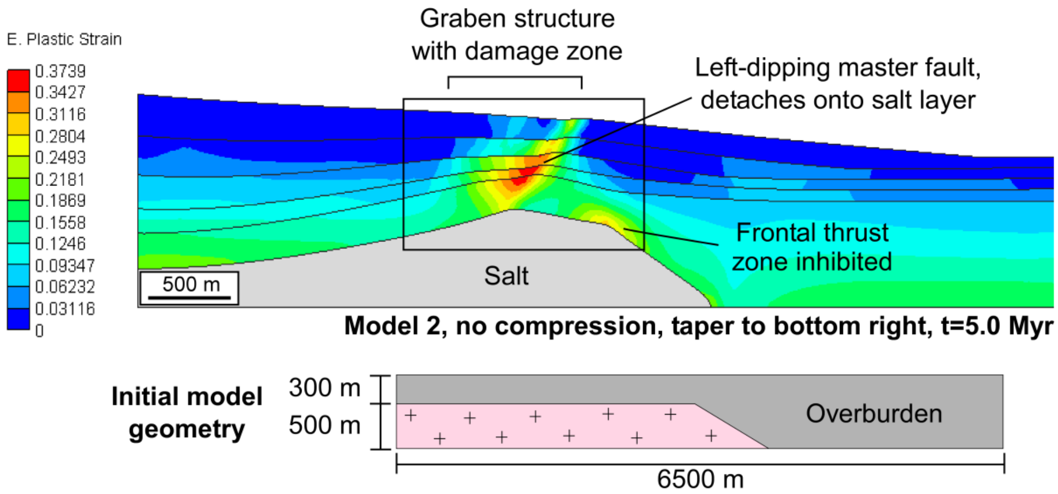


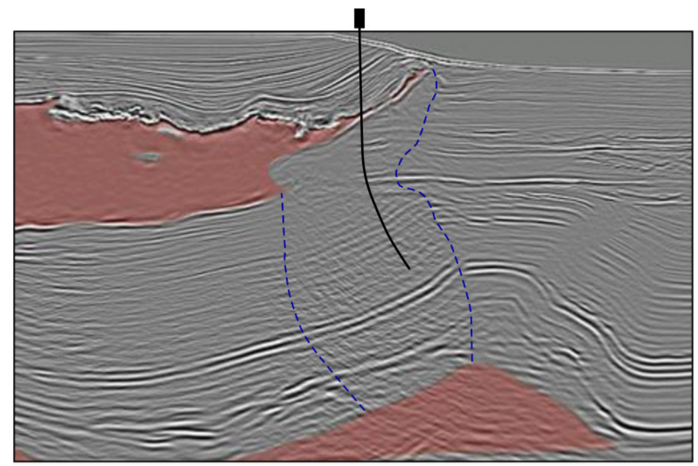
Prospect Altum: a faulted anticlinal trap above a toe fold (modified from Roberts et al., 2011).

Presenter's notes:

- My second case study is Prospect Altum, a sub-canopy target comprising a faulted, 4-way dip closure located above a salt-cored toe fold
- Until recently ~60% of the prospect lies within a seismic 'shadow zone' caused by sub-salt imaging issues
- Therefore the extent of prospect structural characterisation is significantly limited – what are the fault geometries/distribution?

Case Study: Prospect Altum

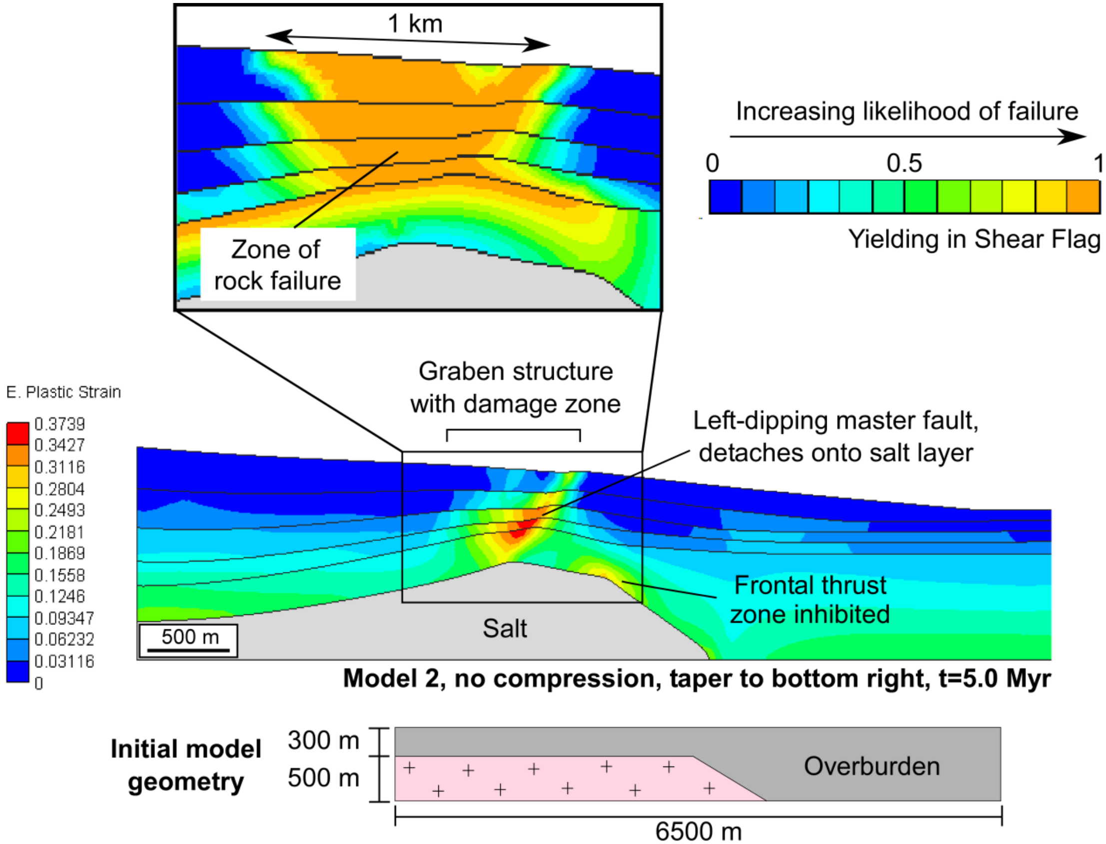


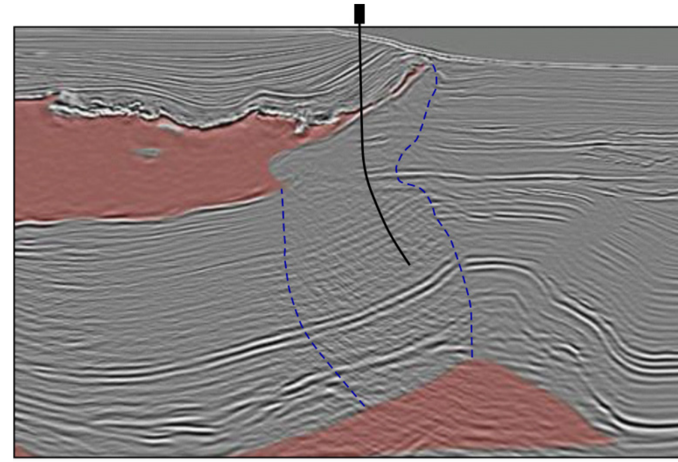


Presenter's notes:

- One model variant conforms with recent ideas of an asymmetric toe fold geometry – no displacement loading; crestal graben from layer-parallel extension
- This conforms with ideas that structures on the compressional toe of this passive margin form in response to relatively recent, rapid sediment loading

Case Study: Prospect Altum

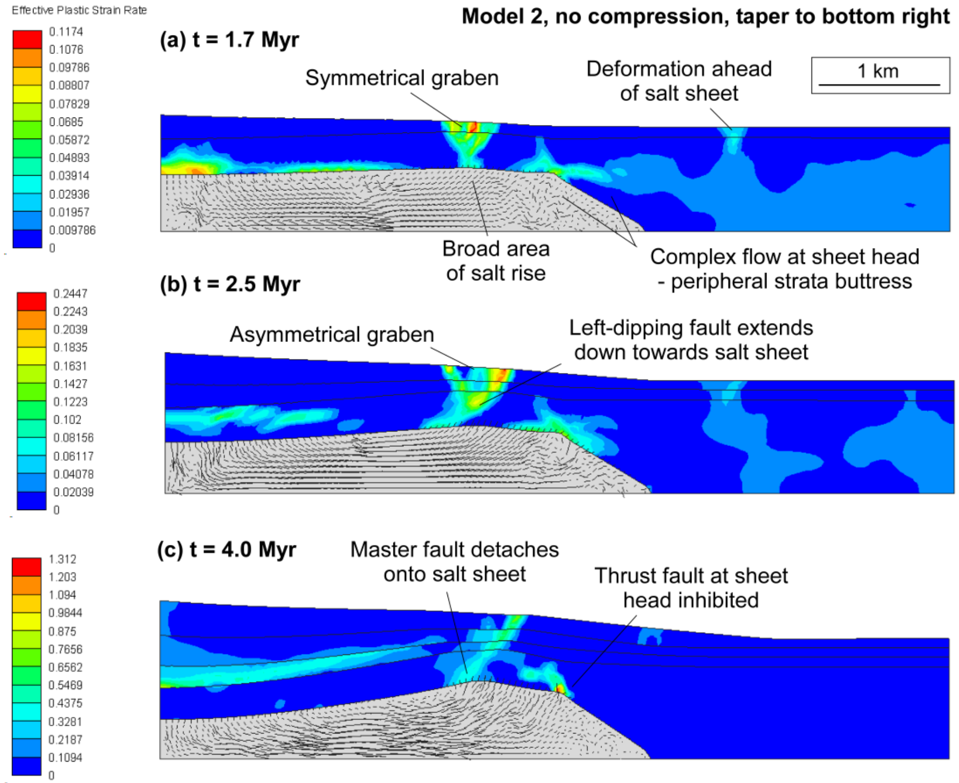


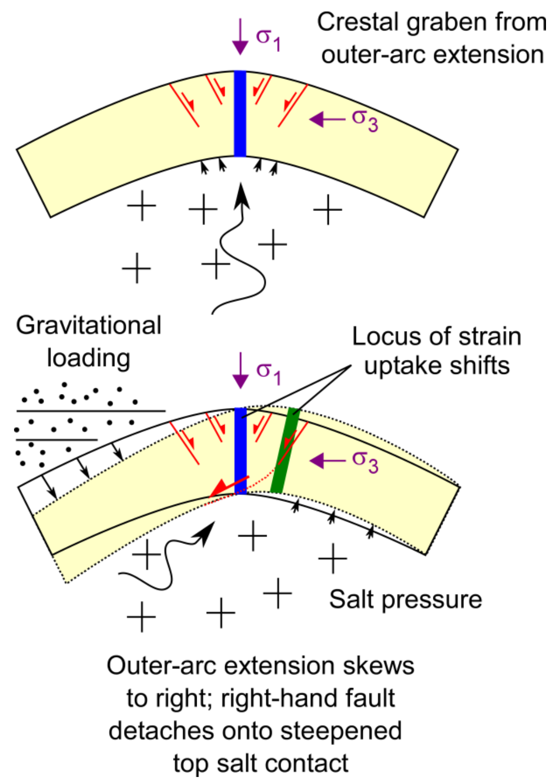


Presenter's notes:

- Using a Yielding in Shear Flag criteria, we can access the likelihood of rock failure, and therefore start to estimate and quantify damage distribution around this crestal graben

Case Study: Prospect Altum





Progressive model development, contoured by effective plastic strain rate.

Presenter's notes:

- Looking at model development through time can give us an idea of salt flow mechanisms and prospect development, which is summarised in the schematic on the right.
- Initially a symmetrical graben develops above a broad area of inflating salt, in response to initial loading. Flow at the head of the sheet is complex due to buttressing, creating a high strain area
- Progressive sediment loading in the sheet rear drives the salt forwards, which in turn creates more space for sediments to accumulate.
- The zone of salt rise progressively focuses into a smaller zone, reacting to space created beneath a master fault which develops and detaches down onto the salt sheet.
- The combination of forward and upward movement creates an asymmetry in salt pressure applied to the base of the fold, and the locus of strain uptake in the crestal graben shifts to the right
- Later focus on salt rise inhibits forward salt movement, and hence inhibits development of a toe thrust.

Summary and Implications

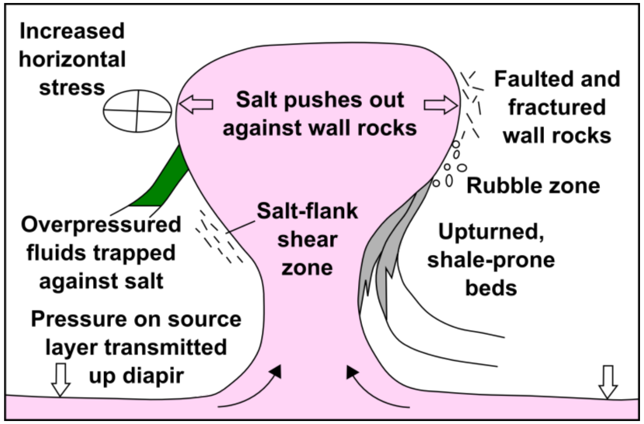
(1) Salt sheet advance under compression

- A thicker initial overburden hinders forward sheet movement and restricts salt exposure – additional control

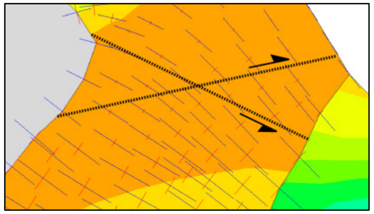
(2) Inflation of a toe fold

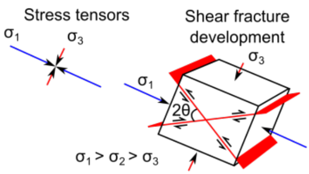
- Displacement loading encourages toe thrust development
- Gravitational loading encourages toe fold development

1. Damage distribution	Well positioning, migration pathways
2. Structure geometry	Trap style, size, and integrity
3. Stratal geometries	Reservoir distribution and quality, trap style
4. Salt flow mechanisms	Surface proximity, stress / loading patterns
5. Predictive tool	Damage / shear zones, fracture orientations



Common drilling problems experienced drilling around salt structures (Hudec, 2014).





Stress tensor analysis predicts fracture orientations.

Presenter's notes:
- A range of field-scale structures have been recreated and investigated; and have applied these to case study examples
- Model 1 –not simple story, other factors can complicate interpretation of the ramp-flat geometry, but has been recreated
- Model 2- thrust vs. fold depends on the compressional force driving vs. the resistance to inflation i.e. the overburden thickness
- Models have implications for E&P activities:
  - Damage distribution – to optimise well positioning
  - Structure geometry – understand your trap
  - Stratal geometries – predictive about stratigraphic response to salt movement
  - Salt flow mechanisms – reactive vs. active diapirism, Poisuielle vs. couette flow etc
  - Predictive tool – damage zones, fracture orientations

Questions?

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References

Argus Holdings Ltd, Automatic Grid and Mesh Generation, http://www.argusone.com/MeshGeneration.html (accessed September 8, 2016).

Fossen, H., 2010, Structural Geology: Cambridge, Cambridge University, pp. 480.

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