PS Fault Rock Prediction for Inverted Extensional Faults in Siliciclastic Sequences – Challenges, Methods and Risking for Hydrocarbon Exploration*

Stewart J. Smith[1] and Rob Knipe[1]

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[1]Rock Deformation Research Ltd, Leeds, United Kingdom (stewart@rdrgroup.co.uk)

Abstract

Prediction of fault rocks and their properties for normal faults in siliciclastic sequences is standard practice when assessing fault-controlled traps. Prediction methods such as the shale gouge ratio (SGR), for predicting the distribution of clays along a fault zone and the clay smear factor (CSF), for prediction of clay smear continuity and breakdown, are commonplace in fault seal workflows. However, for normal faults that have been subject to inversion the results from these predictive methods are not applicable. In this study, we review challenges faced in attempting prediction of fault properties for inverted normal faults. We present some new predictive methods and show how these can be incorporated into risking scenarios. Inverted fault systems can exhibit anticlinal growth above pre-existing normal faults and net extension is often still present at depth. The amplitude of the inversion anticlines can provide an indication of the pre-existing normal fault offsets at depth present before inversion. This can be used along with the final post inversion extensional throw to quantify the amount of initial normal offset and subsequent inversion that has occurred. Existing fault clay content prediction methods only account for initial extensional movement, while faults subjected to inversion will not only have a fault rock clay content associated with the initial normal offset, but will require additional prediction to account for the reverse movement that has occurred through later compression. We present several prediction methods that attempt to capture this behaviour and provide a fault clay prediction that can be incorporated into more familiar workflows associated with inversion. The methods include; a) Reverse offset deformation of the initial extensional fault rock clay contents, b) reverse faulting of the host rocks starting with the stratigraphic juxtapositions associated with the earlier extensional fault offsets, c) combinations of a) and b). The analysis demonstrates the potential errors that can be carried forward into reservoir fluid flow simulations of inverted faults if inversion is ignored and highlights the uncertainty ranges in the fault

rock property calculations related to the assumptions on the geological processes involved.

Fault Rock Prediction for Inverted Extensional Faults in Siliciclastic Sequences - Challenges, Methods and Risking for Hydrocarbon Exploration

Stewart Smith* and Rob Knipe
Rock Deformation Research Group, Leeds, UK
stewart@rdrgroup.co.uk

Introduction

The prediction of fault properties for normal faults within siliciclastic sequences is standard practice when assessing fault controlled traps. Estimates of fault rock clay content, and their distribution, through predication methods such as shale gouge ratio (SGR) and clay smear factor (CSF) are commonplace in fault seal workflows. However, incorrect application of these predictive methods to inverted extensional faults can lead to significant errors in the estimation of fault rock clay contents and subsequent fault property estimations such as permeability and threshold pressure.

In this contribution we present new predication methods that attempt to capture this behavior and provide a solution for assessing the fault clay prediction for inverted normal faults in a more familiar workflow. We aim to highlight the potential pitfalls and errors that can be carried forward into reservoir fluid flow simulations if fault inversion is unaccounted for and highlight the uncertainty ranges in fault rock property prediction and their relation to the geological process involved.

Aims

The main aims of this study are to:

1. Identify geological and geometrical indicators that can lead to identification of inverted normal faults within seismic data.
2. Highlight the impact inversion has on fault rock property prediction.
3. Provide predictive methods for estimating a inverted fault rock clay content.

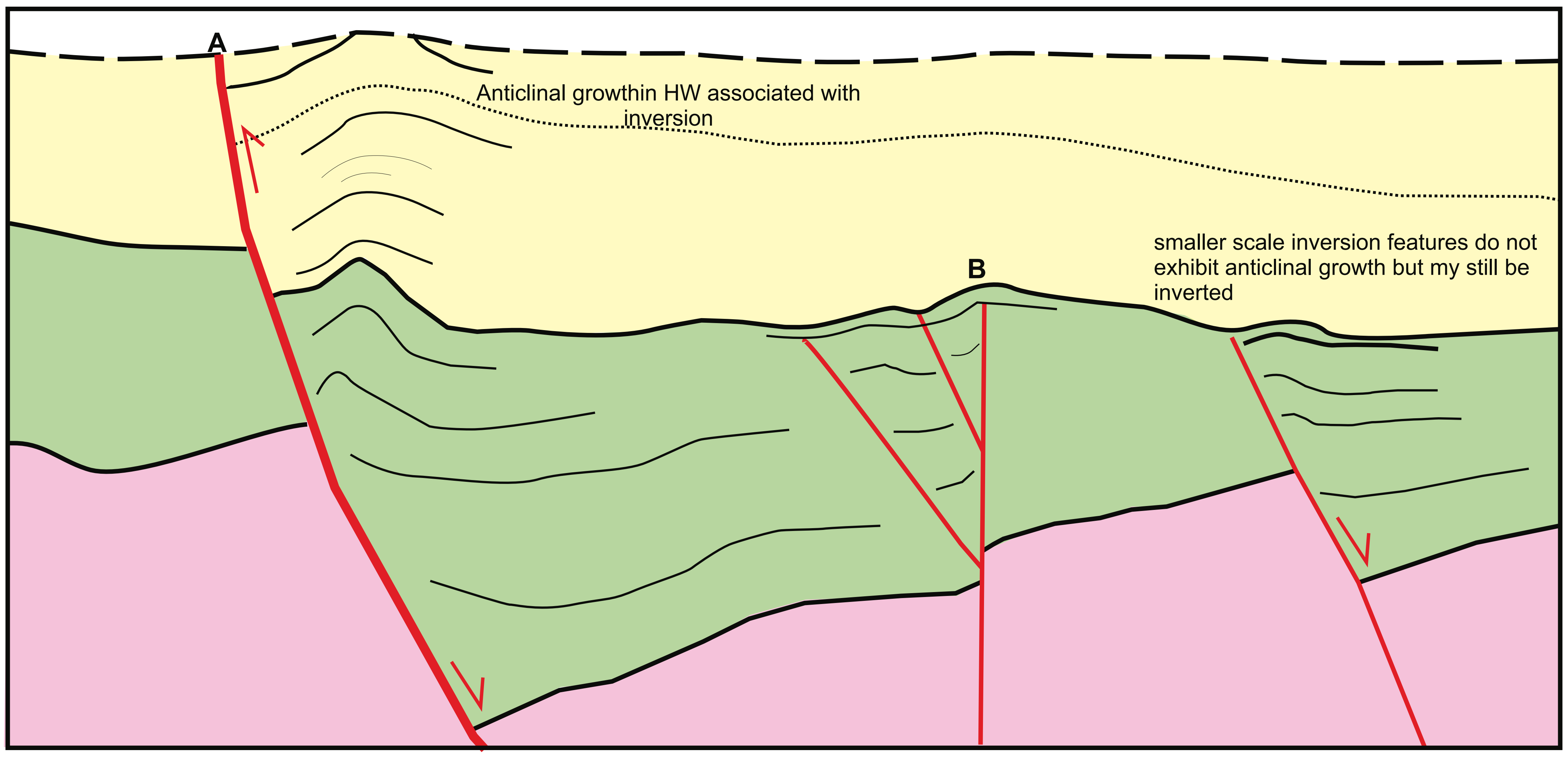


Figure 1. Schematic cross section illustrating geometric characteristics of large scale inversion. **A.** large scale normal fault that has been subjected to significant inversion. Note the upper horizons demonstrate typical anticlinal growth associated with inversion but still exhibit extensional offset. **B.** smaller scale inversion features
.

Inversion and fault rock prediction

- Structural inversion occurs when extensional structures are subjected to compressional tectonics, resulting in reverse fault movement.
- The resulting fault systems initially exhibit anticlinal growth *(fig 1 and 3)* within their upper portions with either; continued contraction of synrift sequences beyond the null point (full inversion) or cessation of contraction resulting in net extension at depth (partial inversion).
- In both instances this generates fault systems that have both normal and reverse movement.

Assumptions

- Fault inversion utilises pre-exisitng extensional fault rocks ie no secondary slip plane or shortcut faulting.
- Critical clay smear factor of 3 for smear development with smear breaking down at the centre point with no weighting applied.
- Study assesses the fault rock clay contents, not the fault rock petrophysical properties that depend on the geohistory and conditions of deformation.

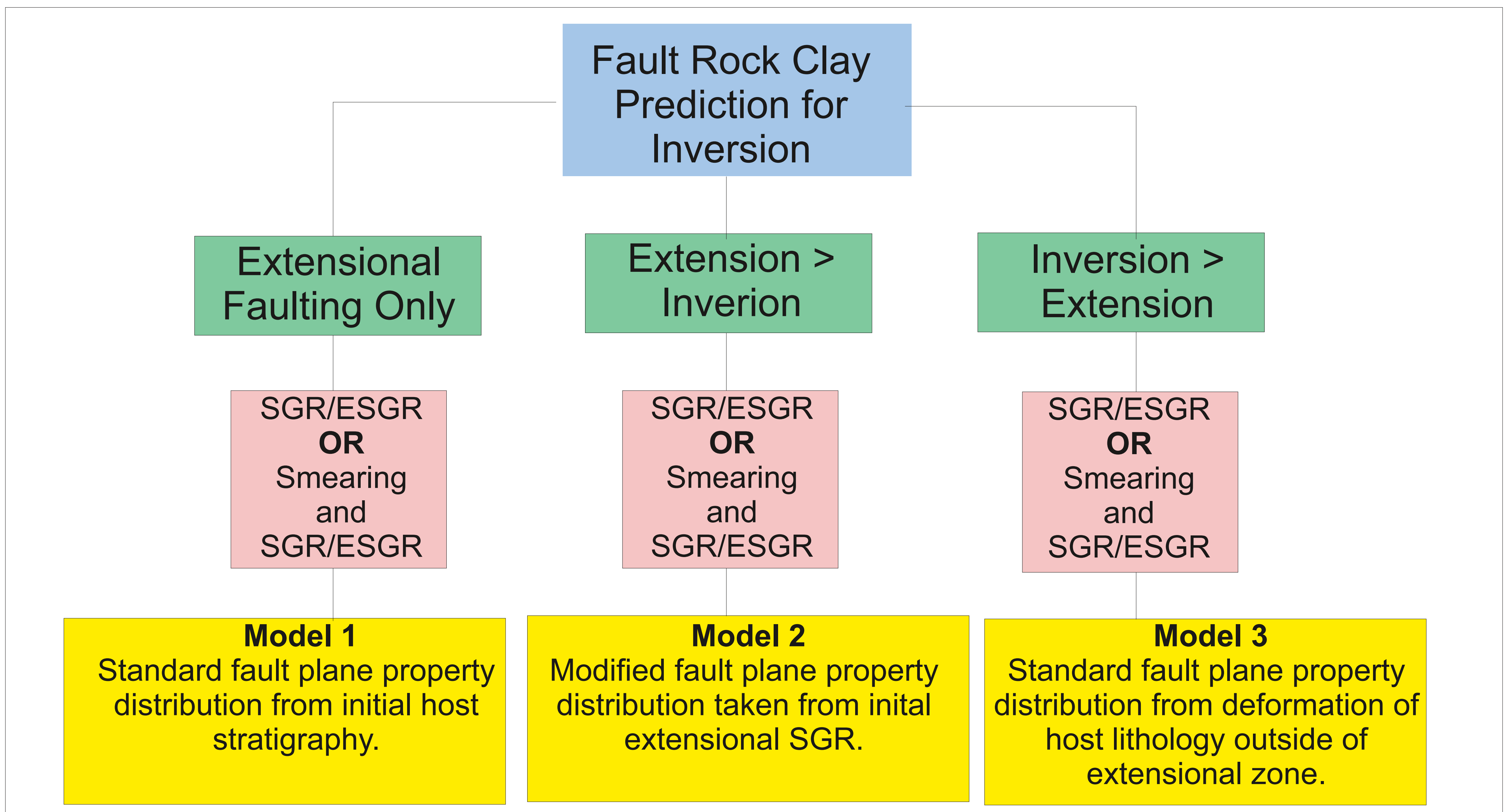
Key conclusions

- Several new conceptual methods have been produced in order to account for fault inversion when predicting fault rock clay contents.
- Applying these new methods to example cases has demonstrated the impact of not accounting for inversion and the potential errors in fault clay content estimates that can occur if only the finite extensional clay content estimates are made for inverted faults.
- Utilising the pre-exisitng fault rock as the stratigraphy for the inversion event for a defined inversion interval provides modified clay content estimates, that account for later reverse movement.
- If full inversion occurs and the fault becomes reverse in offset then a new clay prediction is required in addition to the inversion case due to new host stratigraphy being introduced to the fault rock that will be produced.
- Modified clay content values may be greater or less than the finite or maximum extensional throw clay content values. The maximum predicted fault clay content should be taken in all cases to ensure clay content is not under estimates for a finite throw value.

Estimation of fault rock clay contents

The basic principles of the SGR and CSF algorithms are essentially a function of throw vs clay content of the host stratigraphy, producing average (%) clay content or an indication of smear continuity for the slipped interval (Yielding et al., 1997 & Lindsay et a., 1993). When we take these concepts and try to apply them to extensional faults that have been inverted we come up against three key issues:

1. Existing fault clay content prediction methods only account for initial extensional movement.
2. Current mapped fault throw is not representative of the initial (pre-inversion) normal offset. Therefore fault clay content predictions will be inaccurate as the full throw range and subsequent cross fault juxtaposition relationships have not been accounted for.
3. If reverse movement has occurred on a pre-existing normal fault, what are the deformation mechanisms and how do they impact the prediction of fault clay content?



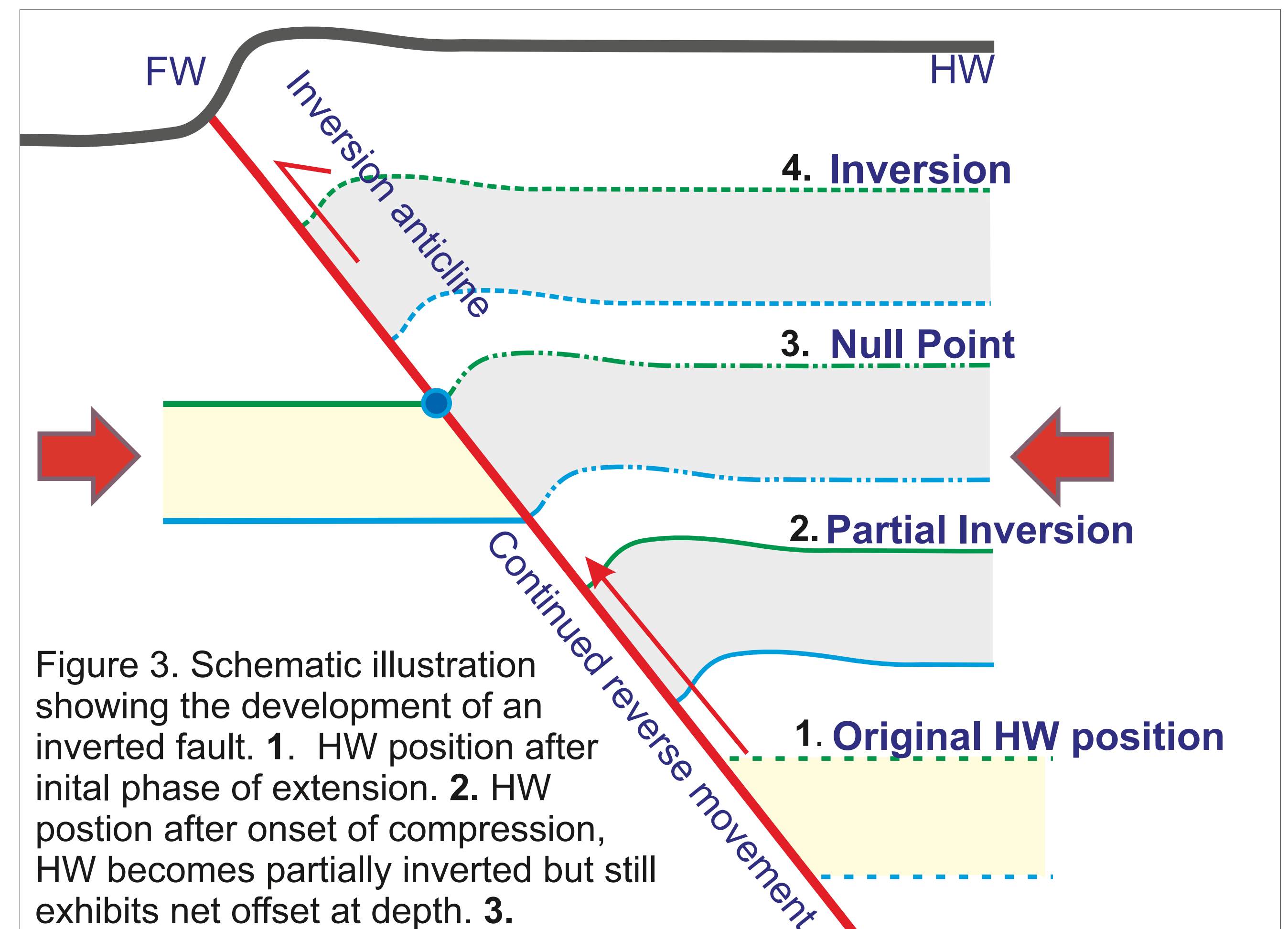
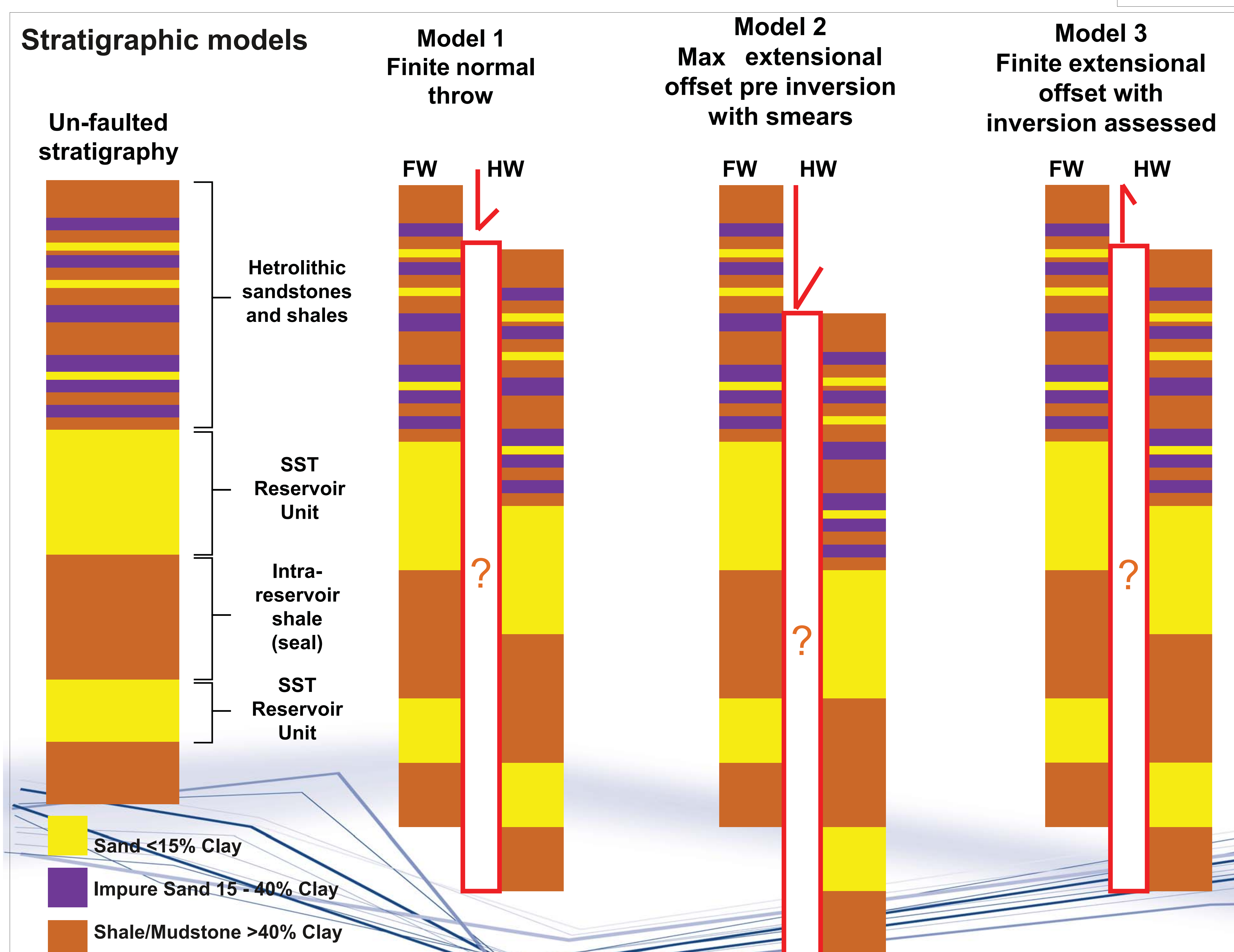


Figure 3. Schematic illustration showing the development of an inverted fault. **1.** HW position after inital phase of extension. **2.** HW postion after onset of compression, HW becomes partially inverted but still exhibits net offset at depth. **3.** continued compression inverted the HW to the null point. 4. further compression resulting in the developement of reverse offset geometry.



The stratigraphic models (left) show the stratigraphic stacking sequence that has been generated in order to investigate the different prediction methods.

The stacking sequence is made up of 2 main sandstone reservoir intervals assumed to be clean sandstone units with <15% clay content. The main reservoir unit is overlain by a package of hetroloithic lithology, with a range of clay contents. The 2 reservoir units are separated by a thick shale unit.

3 models will be investigated to demonstrate the variability in fault rock prediction for inverted faults.

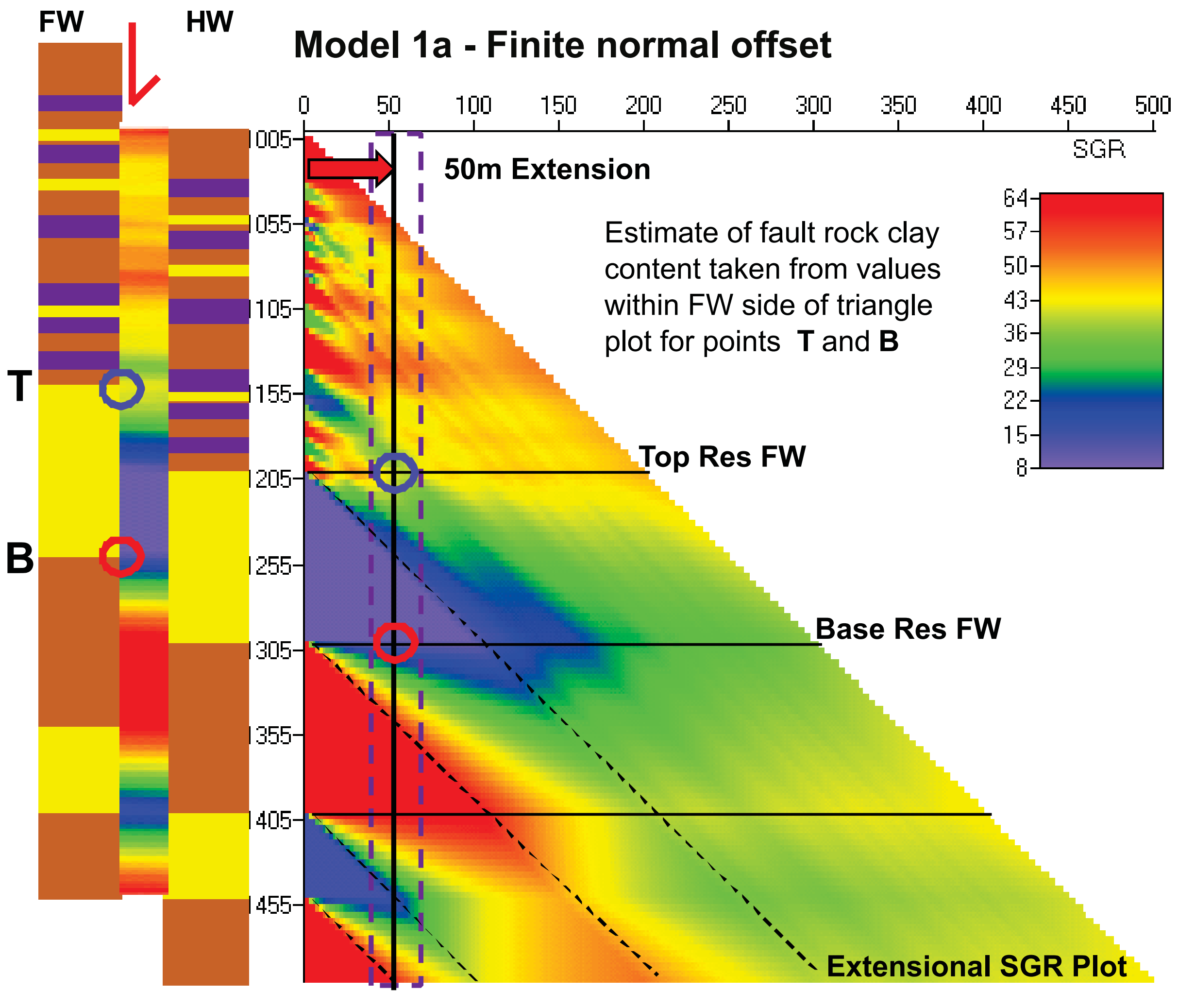
Model 1 - Finite normal throw. No inversion.

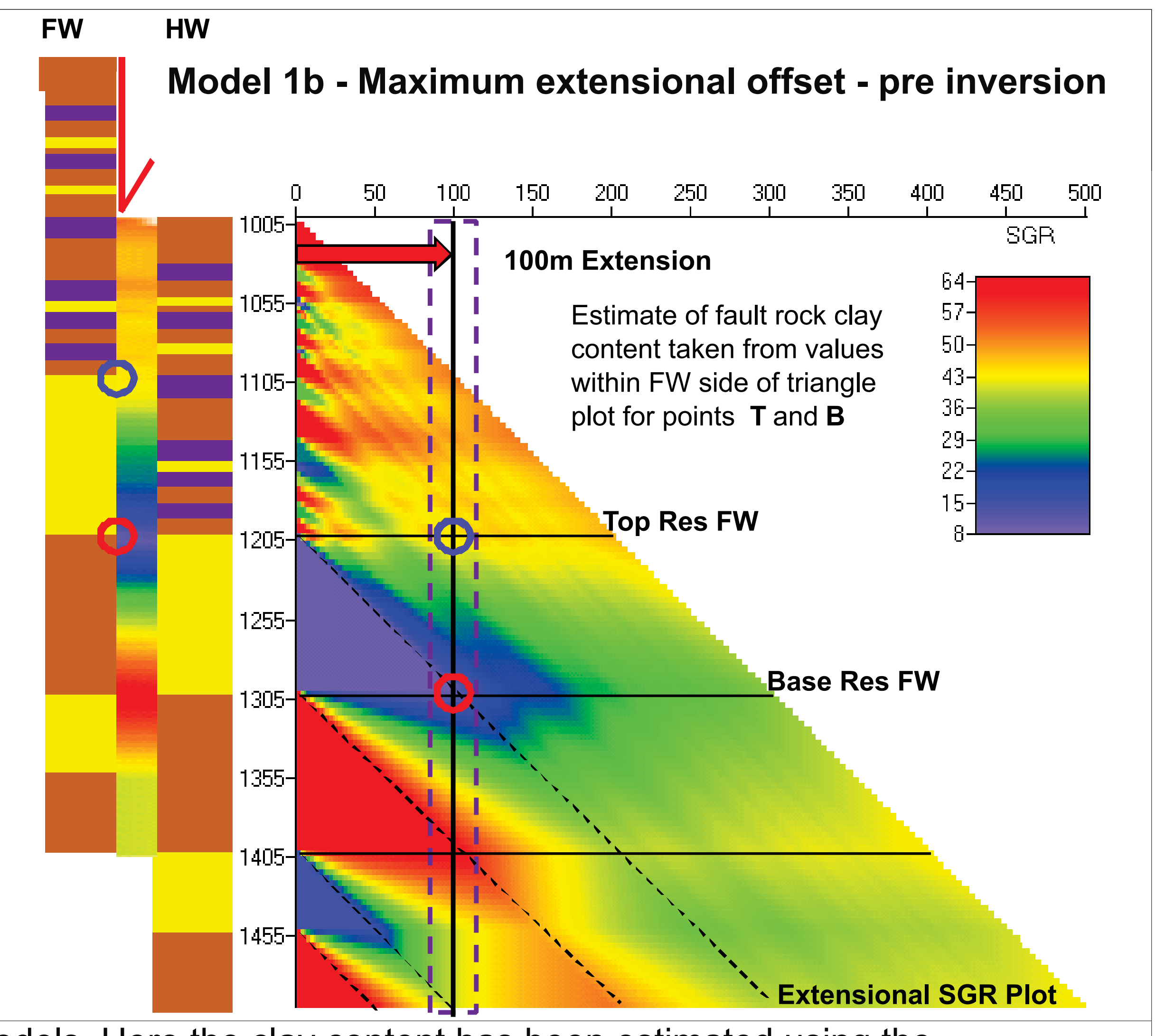
Model 2 - Max early extensional offset with smears and later, partial inversion.

Model 3 - Finite extensional offset with later inversion and reverse offset.

Model 1- Extensional offset

- This model considers the prediction of fault rock clay contents associated with purely extensional fault movement.
- The finite normal offset model considers the clay content for a normal fault throw of 50m that is not subjected to any further deformation.
- The maximum extension model also is also a purely extensional model however has a maximum throw of 100m.
- In both these models the standard SGR prediction methods have been used to estimate the fault rock clay content. In each the fault rock has been assessed for a footwall trap.





Shale gouge ratio triangle plots for both 50m and 100m normal offset models. Here the clay content has been estimated using the extensional triangle plot for SGR.

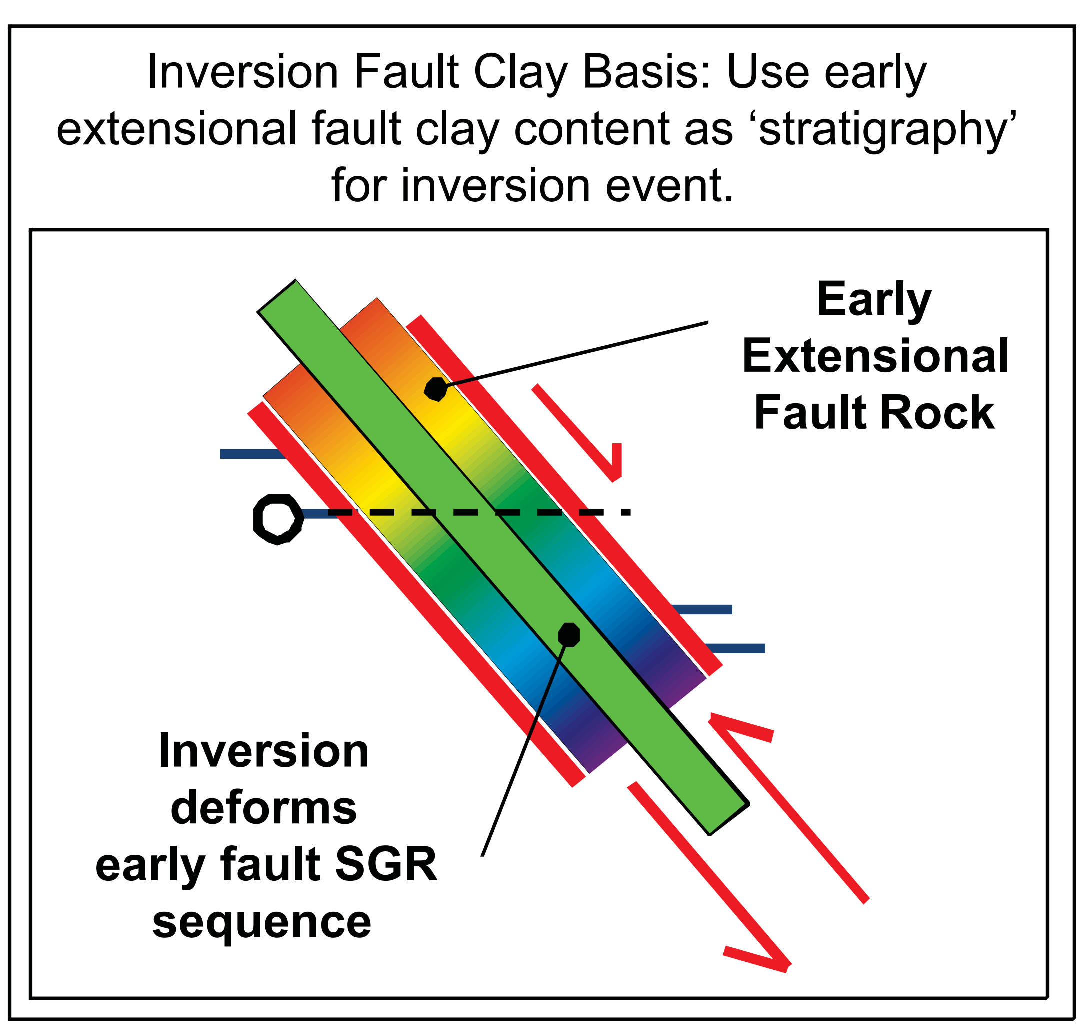
2 reference points have been used at the top and base of the main reservoir unit within the footwall. The values defined here will be used in comparsion with those estimated for the inversion and smearing models.

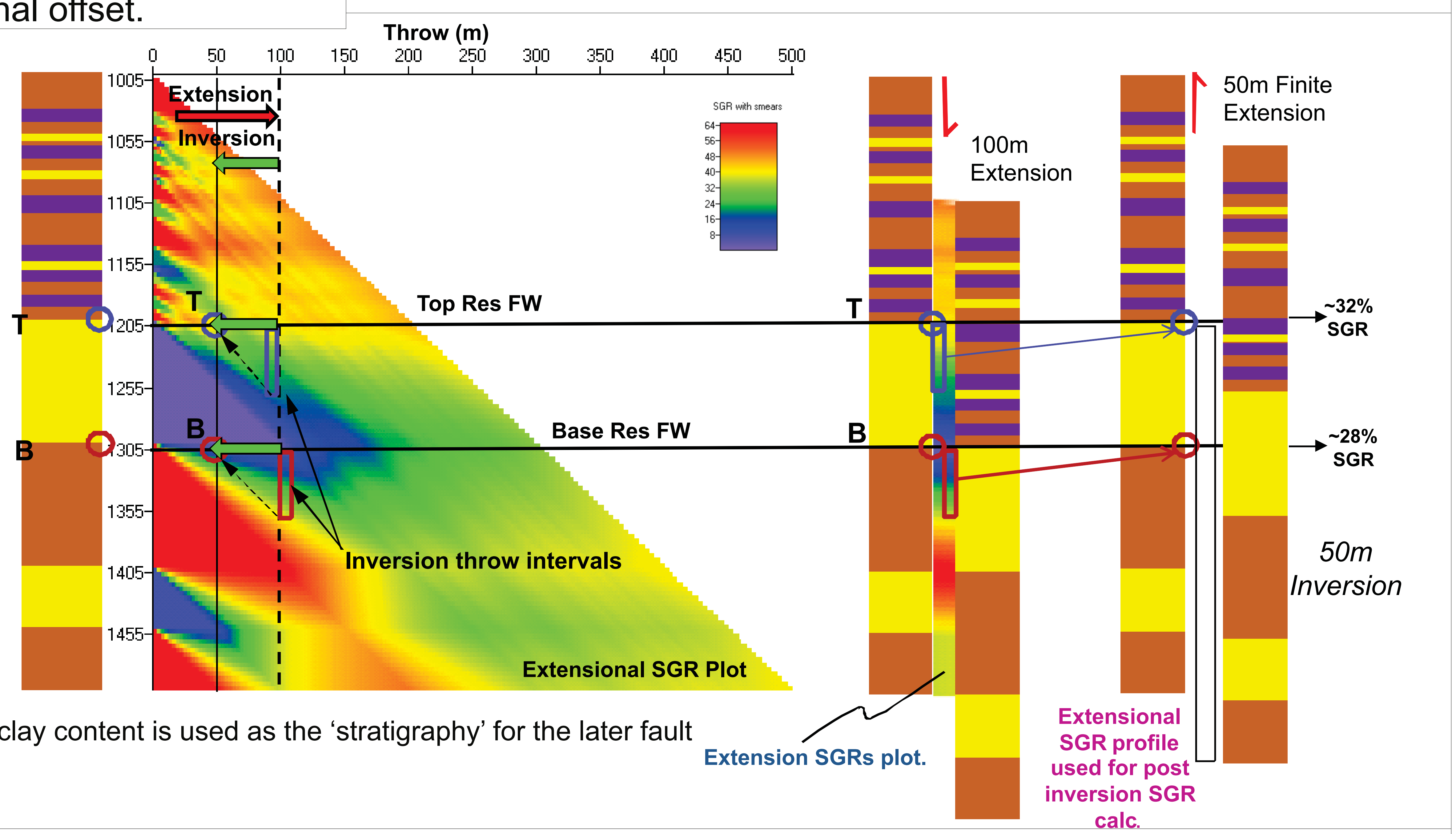
Model 2 Finite extensional offset with later inversion

- In this case the fault has under gone extensional offset as in model 2 (100m normal offset).
- The fault has then undergone further deformation through compression, resulting in fault inversion and a reduction in the net offset.
- The amount of inversion (50m) is still less than the initial extension therfore still exhibits an extensional offset.

Possible prediction Methods

1. Use SGR associated with maximum extensional faulting from host lithology.
2. Use clay content prediction associated with maximum extension as the basis for inverted fault rock prediction.
3. Use host lithologies to prediction clay content from reverse faulting, as new stratigraphy will be incoporated into the fault zone.



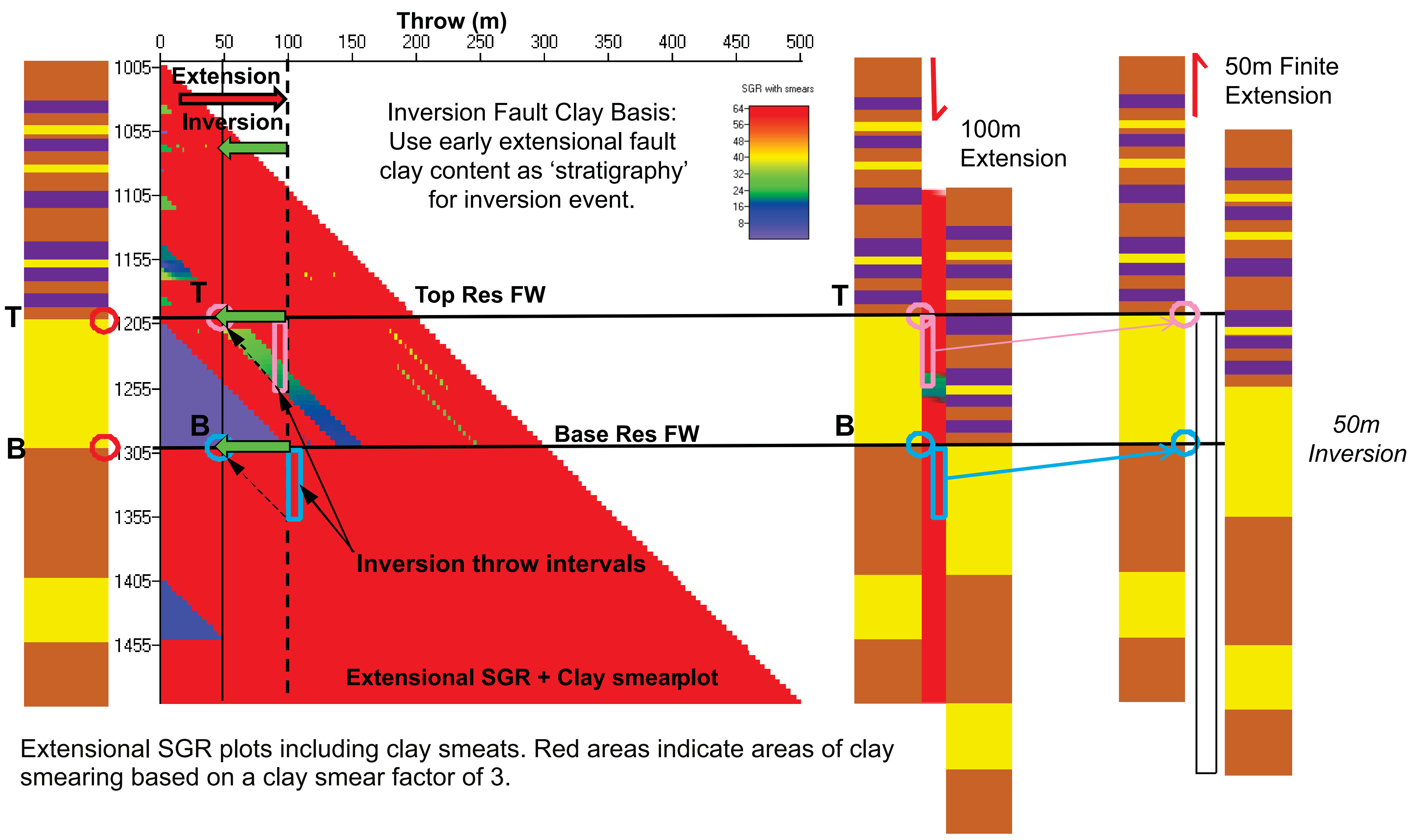


Inversion clay prediction where the early extensional fault clay content is used as the 'stratigraphy' for the later fault inversion.

- The method illustrated in the above figure generates a new clay content that will differ from the purely extensional prediction and provides a predictive model for the re-working of existing fault rock.
- This new clay content is an average of the initial extensional SGR, within the inversion throw interval, for a given point within the stratigraphy.
- The extensional SGR values within the inversion intervals are averaged to provide the inverted fault SGR, capturing the reverse movement past points T or B. The method utilises the existing fault rock prediction as the host for the later reverse fault movement and subsequent modification to the prediction.

Model 2 - Clay Smears

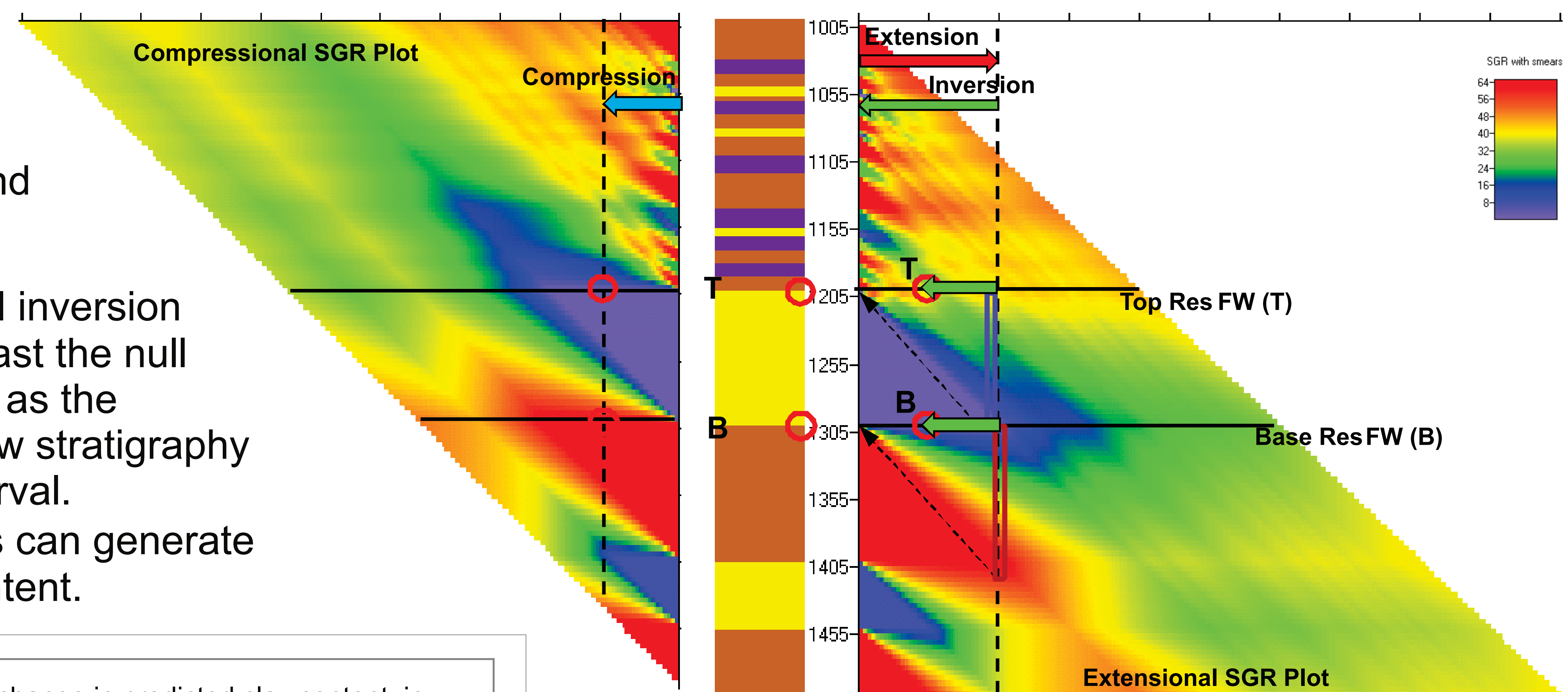
- In this case we have incorporated clay smears into the prediction. The triangle plot shows the clay smears generated for an extensional regime, utilising the same methodology as the SGR case.
- The model does not account for continued smearing of host units associated with reverse movement, only estimates of the clay content, from the inversion interval, as in the SGR case.
- The assumption of a central smear breakdown is also used, but we recognise that the breakdown of smears could be weighted to the FW or HW, generating different, lower SGR windows.



Extensional SGR plots including clay smeats. Red areas indicate areas of clay smearing based on a clay smear factor of 3.

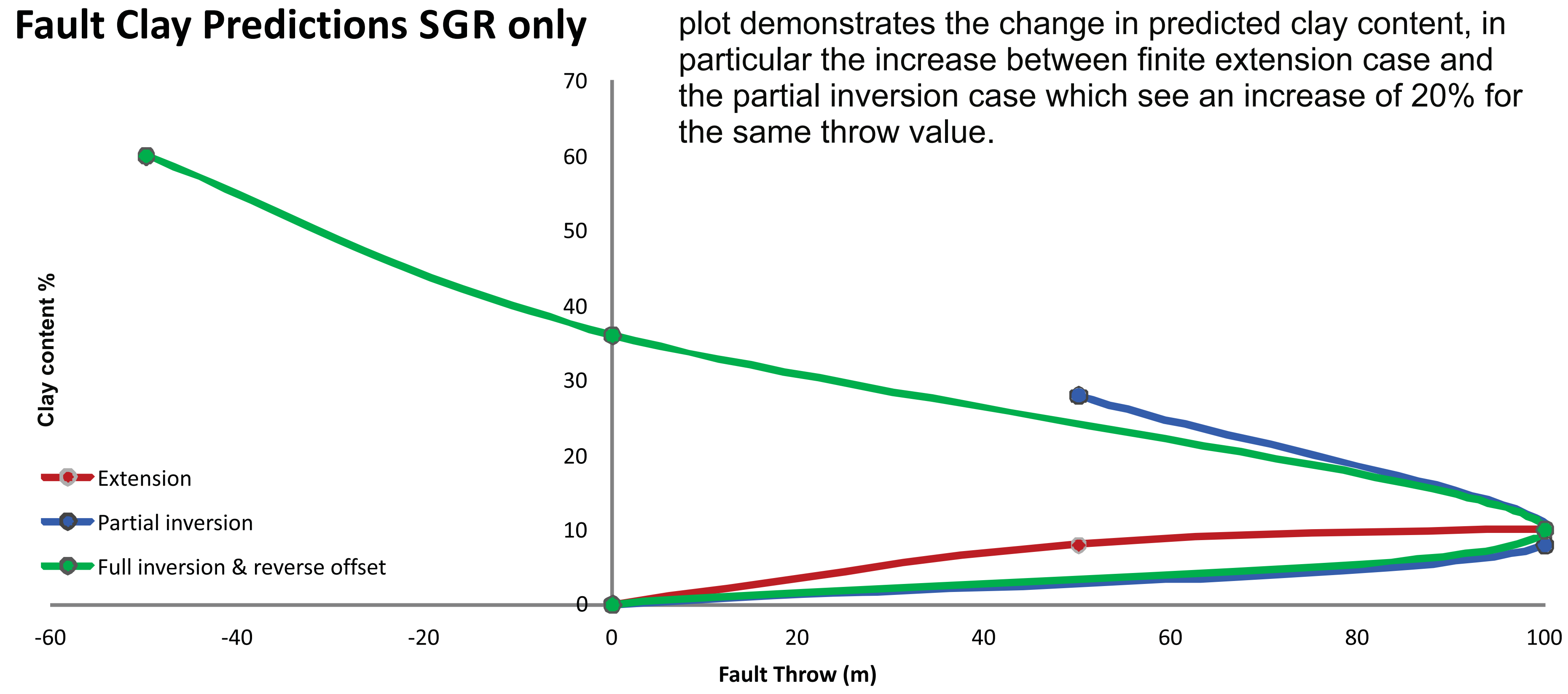
Model 3 - Full inversion & Reverse offset

- The combined triangle plot right shows the potential clay contents for both extensional and compressional fault movement.
- This model captures a case where continued inversion generates reverse offset as the HW moves past the null point. In this case the reverse plot is required as the inversion values are no longer relevant as new stratigraphy from the host is introduced to the slipped interval.
- Depending on the stratigraphic sequence this can generate significant differences in the preicted clay content.

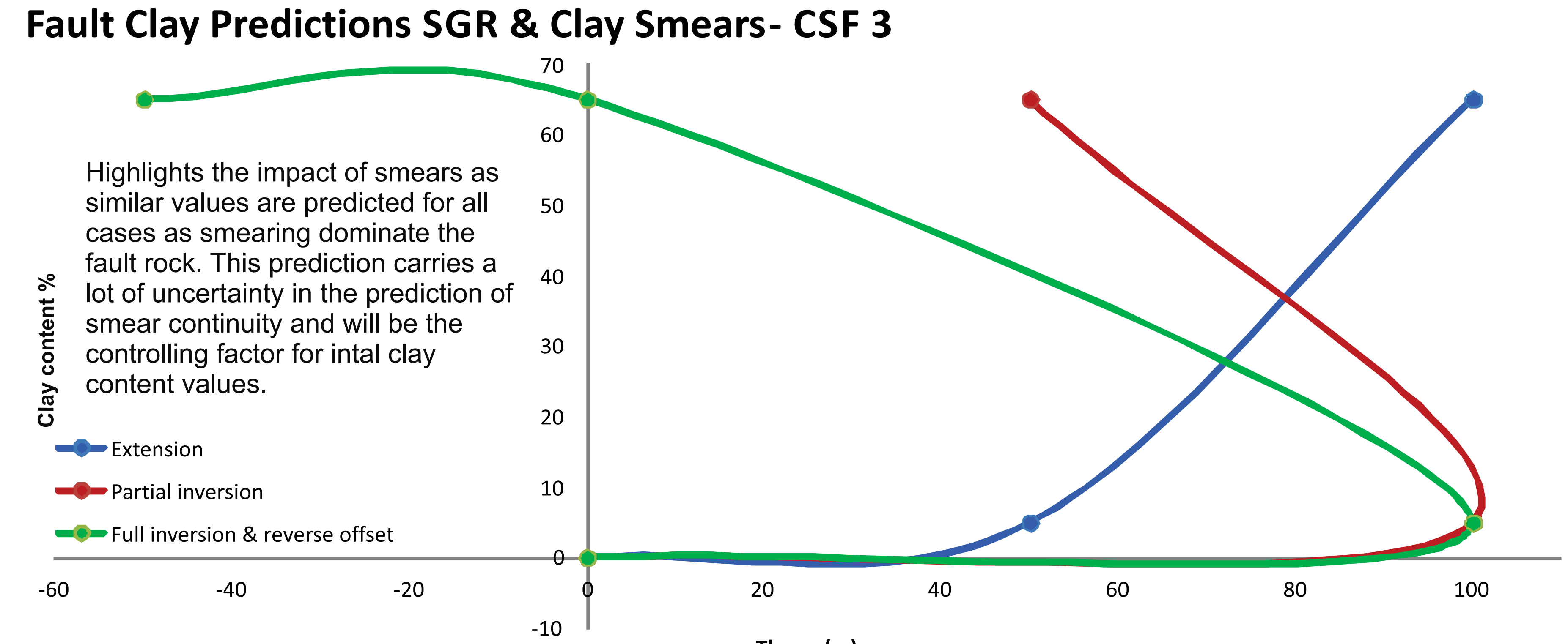


Fault Clay Predictions SGR only

plot demonstrates the change in predicted clay content, in particular the increase between finite extension case and the partial inversion case which see an increase of 20% for the same throw value.



Fault Clay Predictions SGR & Clay Smears- CSF 3



Plot of fault throw vs vs clay content % to demonstrate the evolution of fault rock clay content for the different models covered in this study. Note the SGR values for finite extension vs inversion and also the impact of smears on overall clay content.

Table (right) of clay contents (%) for the different models explored in this study.

	SGR		SGR + Smears	
Model	Top (T)	Base (B)	Top (T)	Base (B)
Extension only	40%	8%	65%	5%
Max extension	45%	10%	65%	65%
Partial inversion	45%	30%	65%	65%
Reverse offset	45%	60%	65%	65%

Conclusions

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