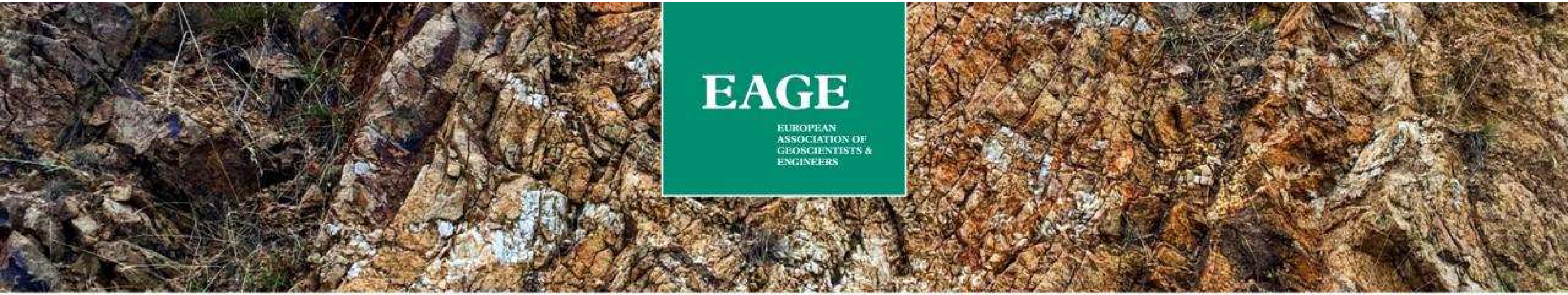

EAGE
EUROPEAN ASSOCIATION OF GEOSCIENTISTS & ENGINEERS

2nd EAGE Workshop on Fluid Flow in Faults and Fracture

15-16 AUGUST 2023 • CANBERRA, AUSTRALIA

Paper No 3

Modelling fluid flow in faults and fractures using calibrated models of multi pay faulted fields

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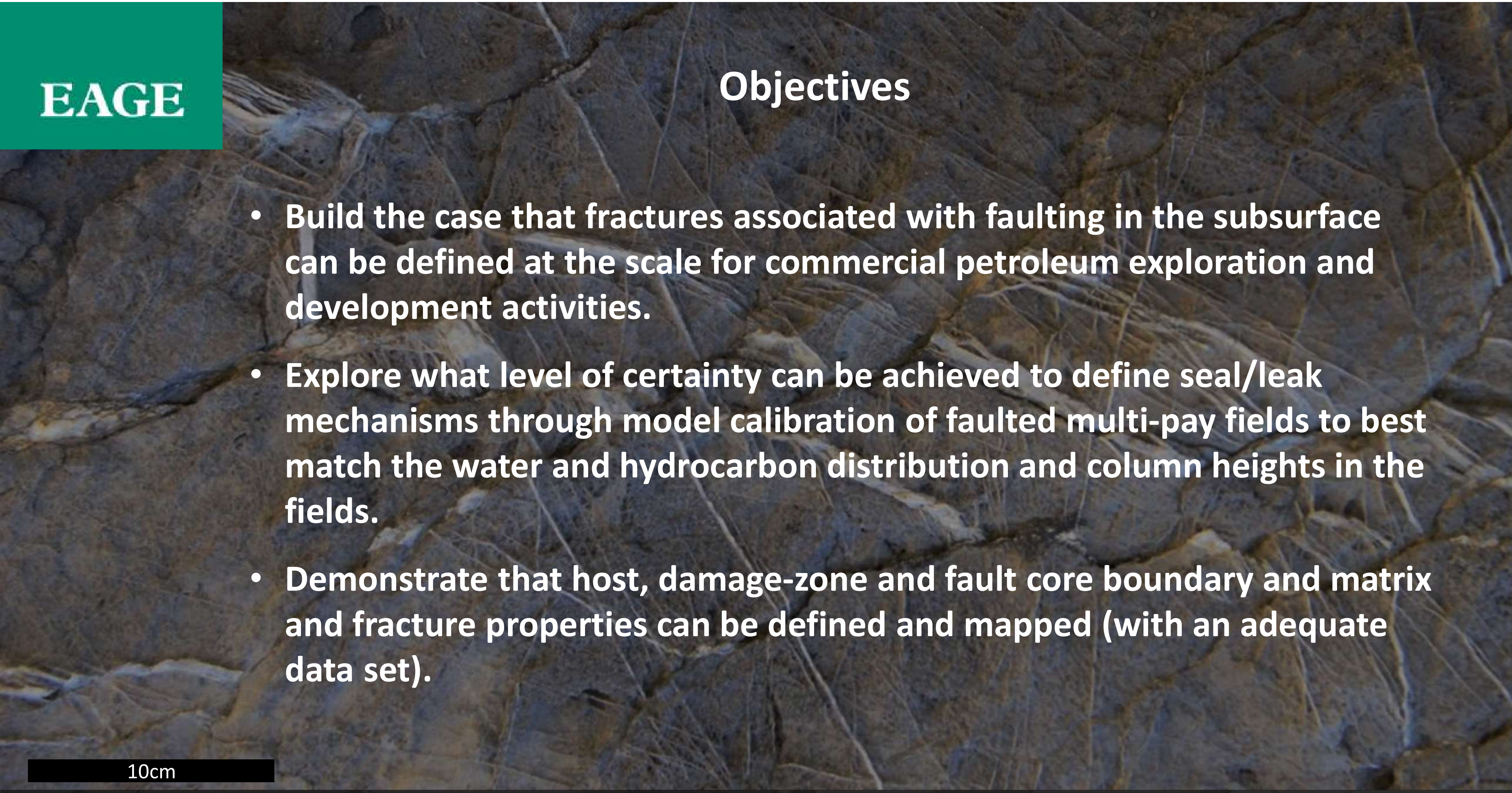
Objectives

- Build the case that fractures associated with faulting in the subsurface can be defined at the scale for commercial petroleum exploration and development activities.
- Explore what level of certainty can be achieved to define seal/leak mechanisms through model calibration of faulted multi-pay fields to best match the water and hydrocarbon distribution and column heights in the fields.
- Demonstrate that host, damage-zone and fault core boundary and matrix and fracture properties can be defined and mapped (with an adequate data set).



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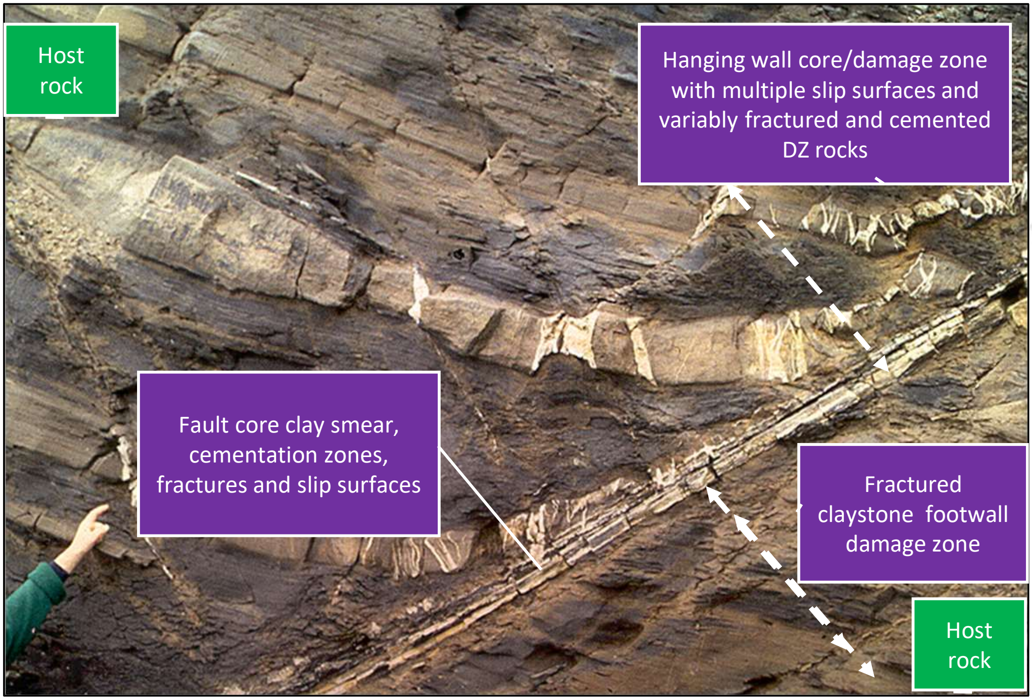
Method Overview

To address the fault seal problem, this method considers all components of fault development models, (Caine et al.,1996, Childs et al 2009)



Boundaries between core, damage zone and host rocks are often difficult to define. In addition boundaries between smear and gouge are transitional

We quantitatively differentiate between successful and failed seals;

- in juxtaposition
- in fault damage zones (DZ) (small faults and fractures)
- in fault rock (gouges, cataclasites and smears)
- and with consideration of through-going fault slip surfaces

Components of the method;

- **1 Seal quality algorithm (Seal Index)**

Used to identify brittle (potentially leaking) and ductile seals.

- **2 Empirical lithologic data**.

Effective intra-seal lithologic composition ranges differ between upthrown and downthrown faulted rocks

- **3 Permeability and threshold models of each host, damage-zone and fault rock component.**

Providing limits on hydrocarbon column heights.

All components are integrated into a 3D model where a range of possible fault sealing/leaking mechanisms are tested in calibration to faulted fields. No assumption on seal/leak mechanisms are made.

Calibration level and variance ranges are the basis for forward modelling.

1 Seal quality Index - differentiating plastic from brittle seals

Clay rocks with higher water content and/or higher organic matter content are relatively more plastic and less likely to fracture in or near fault zones.

How the Seal Index works

Track 4 shows ND with separation infilled green. Tracks 7 show Vclay.

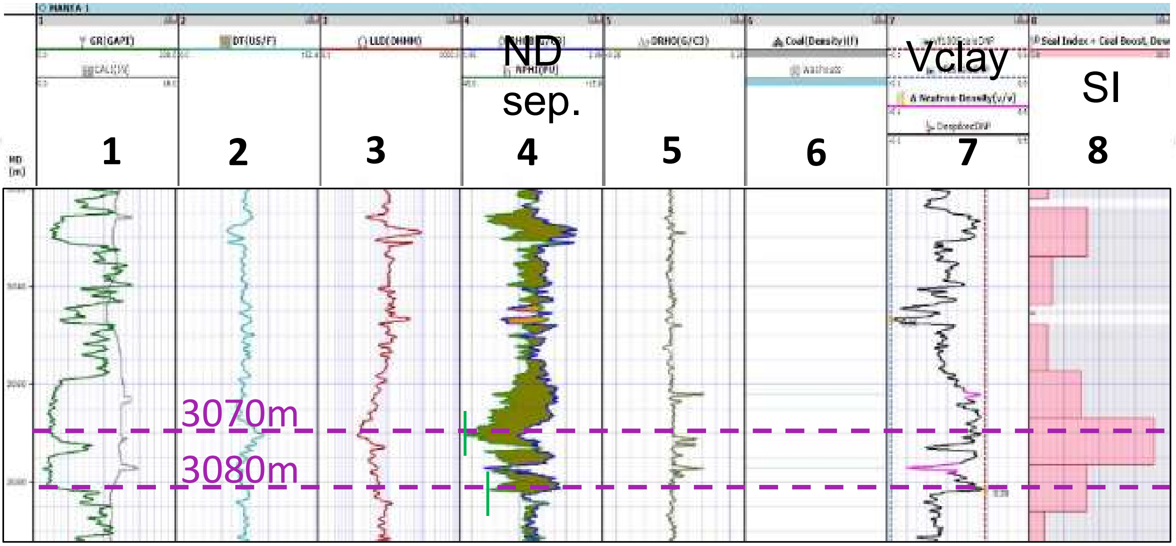
Track 8 Seal Index, shows at 3070m that the Seal Index is highest associated with the highest Neutron reading and a high ND separation (high volume of bound water).

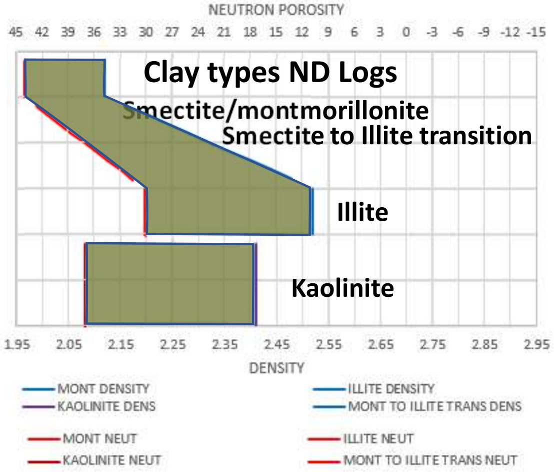
In contrast the 3080m point has the same Vclay, higher density & lower neutron and lower SI (a poorer quality seal).

The differentiated seals also have different physical properties eg Young's and Shear Modulus and Poisson's Ratio, which are consistent with SI variations.

A caution-when calibrating

N-D separation in seal quality and Vclay algorithms need to be calibrated to clay type, depth and temperature as clay types change and illitization modifies neutron and density log responses.





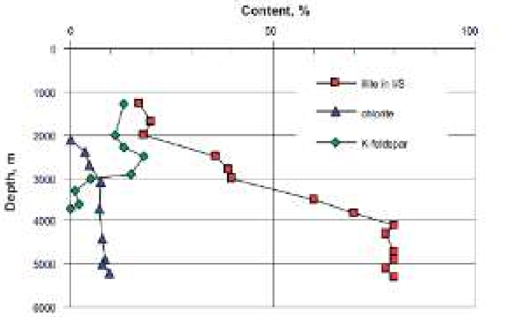
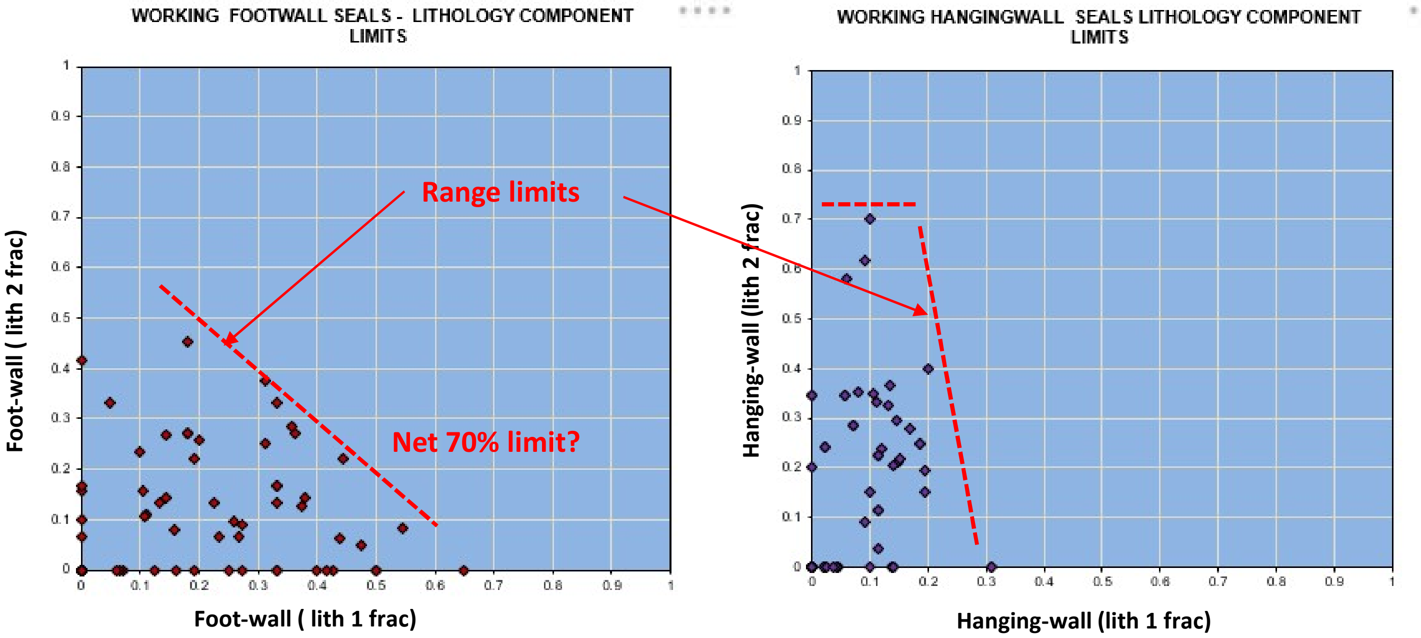


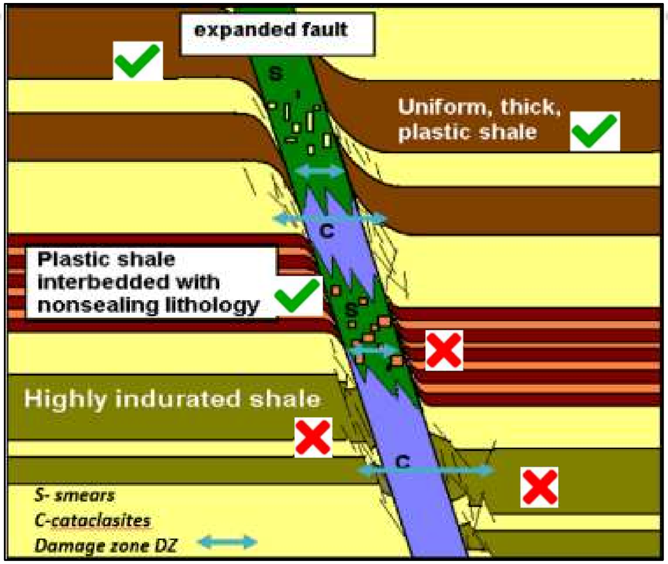
Figure 2-4. Depth-dependent changes in content of illite in smectite/illite in the <0.1 μm fraction, chlorite, and K-feldspar in the >2 μm fraction of argillaceous sediments of the early Tertiary Wilcox Group of the Gulf Coast (Hower 1981).

2 Empirical lithologic data

Hydrocarbon trapping, hanging-wall and foot-wall fault trap elements have different tolerance levels for each non-sealing lithology component (sand, carbonate, silt and coal).



<u>For two lithotypes</u>, intra-seal seal non sealing lithology component ranges from effective seals in foot and hanging walls (with well control both sides of fault)

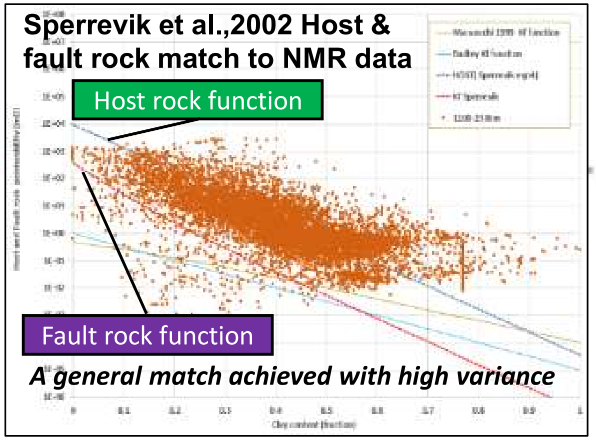


Diagrammatic illustration of variance in contingent seal responses in hanging and foot wall to faulting. Good seal ✓ *Failed seal* ✗

It is postulated that as hanging-wall damage zone rocks often show higher deformation, there is reduced tolerance to non-sealing lithology components in seals. Non-sealing lithology proportion also controls model effective smear extent.

Empirical non-sealing lithology limits are used as an independent differentiating criteria in complex lithology seal intervals.

3 Seal permeability modelling



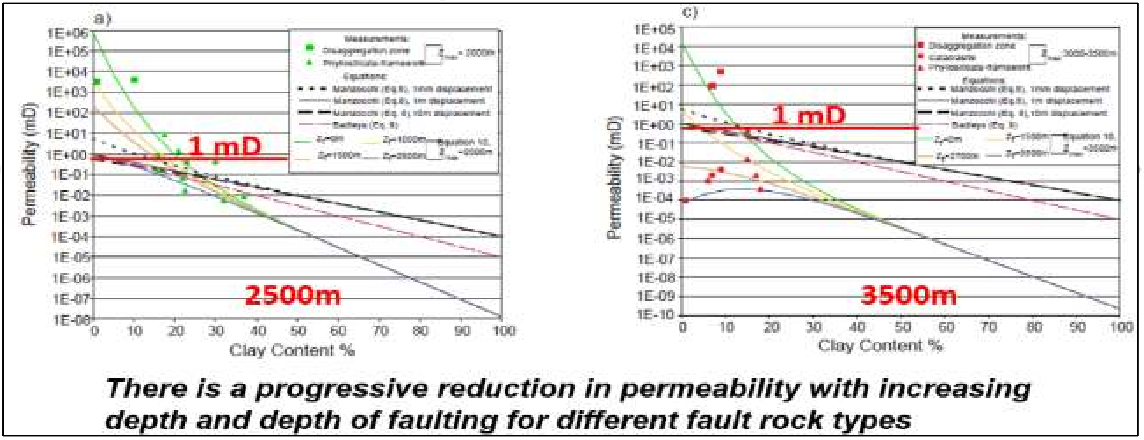
Sperrevik et al.,2002 Host & fault rock match to NMR data

Host rock function

Fault rock function

A general match achieved with high variance

Sperrevik et al.,2002



There is a progressive reduction in permeability with increasing depth and depth of faulting for different fault rock types

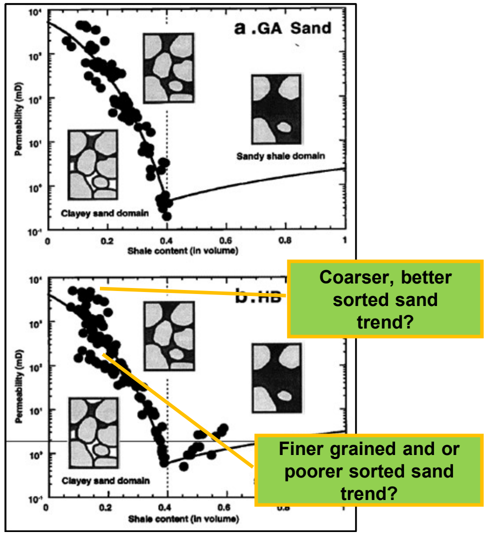
The permeability function developed is based on the models of Sperrevik et al.,2002, and Revil and Cathles,1999.

The Sperrevik et. al. model was the first to quantify the Vclay v permeability relationship with maximum burial depth for host and depth of faulting for fault rocks (data used- Vclay <40%).

Revil and Cathles,1999 demonstrated that in clayey sands, permeability reduces as Vclay increases up to about 0.4, at this point sand pore volume is theoretically filled with clay. At higher Vclay permeability increases.

Sands in a clay matrix both displace the permeable clay and cause stress concentration between grains in compaction reducing clay rock permeability. Both these factors reduce at higher Vclay.

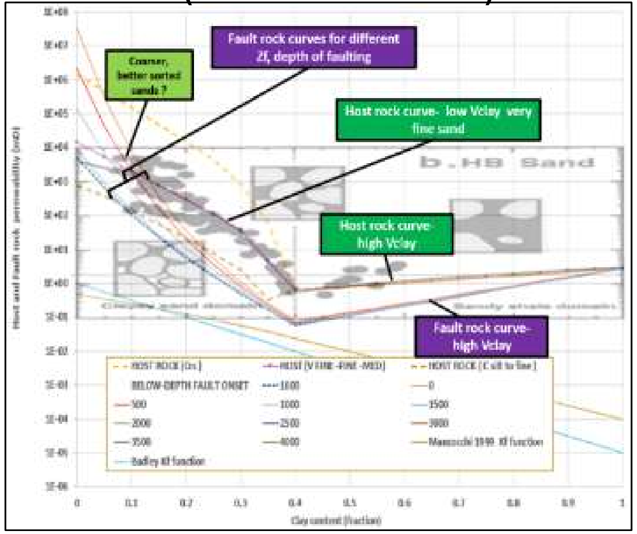
Revil and Cathles,1999



Coarser, better sorted sand trend?

Finer grained and or poorer sorted sand trend?

Quantiseal combined model (host and fault rock)



Coarser, better sorted sands ?

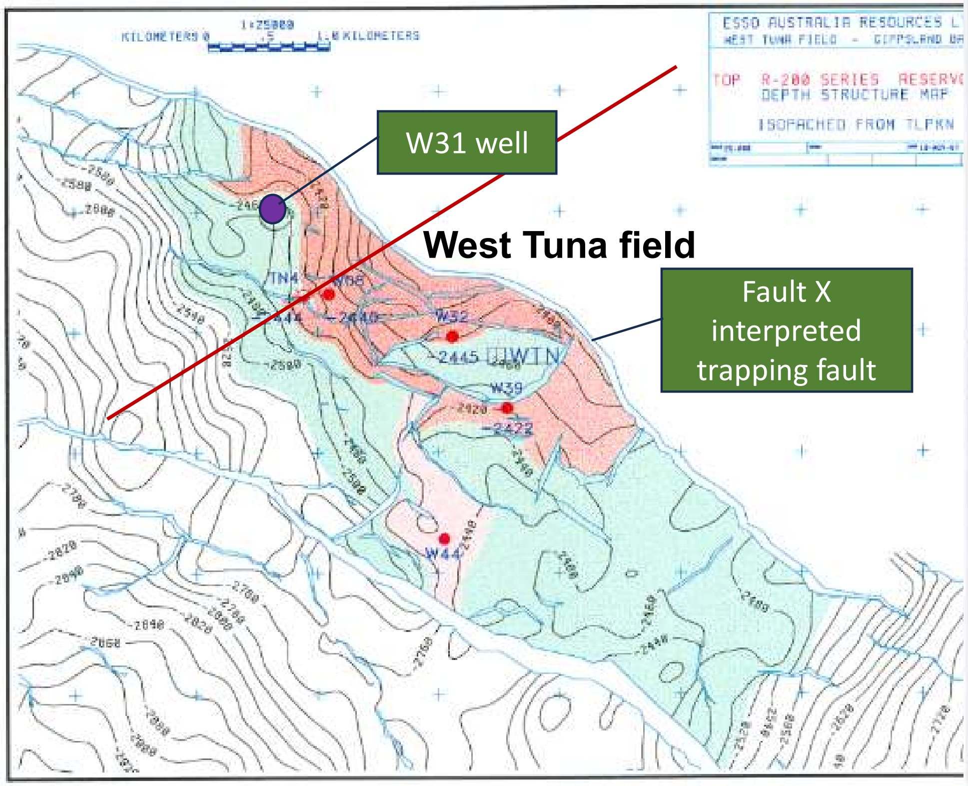
Fault rock curves for different Zf, depth of faulting

Host rock curve- low Vclay very fine sand

Host rock curve- high Vclay

Fault rock curve- high Vclay

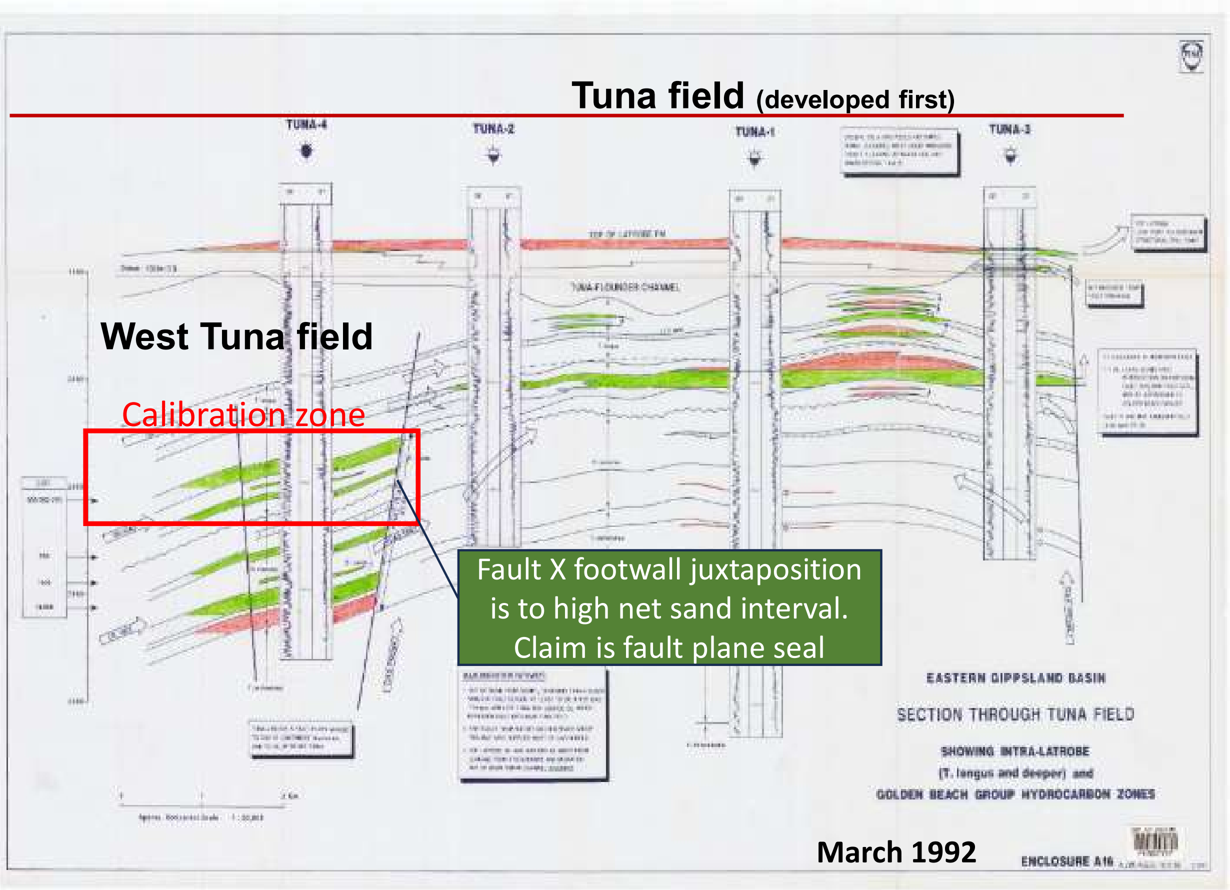
West Tuna field Seal model calibration example - setting



W31 well

West Tuna field

Fault X interpreted trapping fault



Tuna field (developed first)

West Tuna field

Calibration zone

Fault X footwall juxtaposition is to high net sand interval. Claim is fault plane seal

March 1992

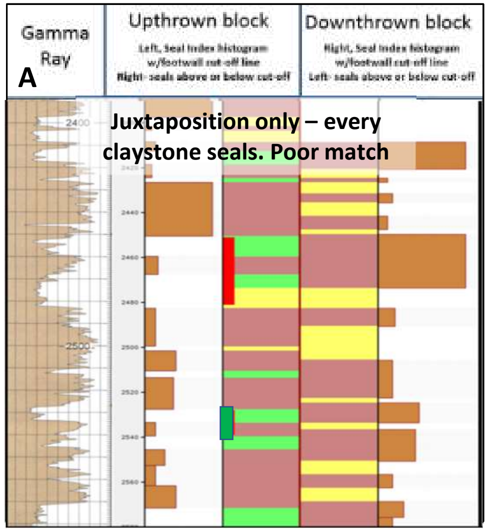
- Mapped as a downthrow trap against fault X with minor antithetic and radial faults.
- Fault X, footwall block (Tuna-2) is high net sand.
- Production draw-down on aquifer from Tuna impacts West Tuna evaluation pressures.

West Tuna field Seal model calibration example

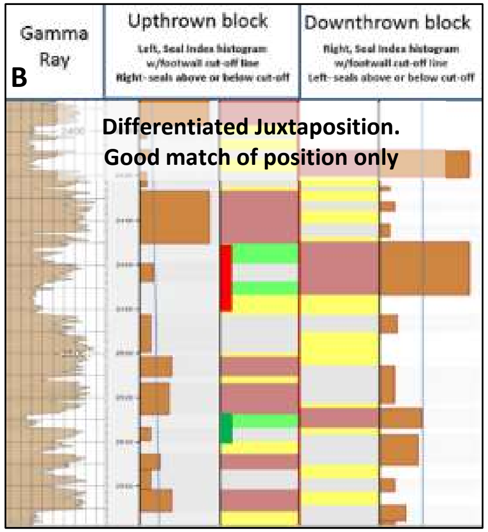
West Tuna W31 well, interbedded sands, coals and claystone. Fault throw range from seismic, pressure data confirms hydrocarbon columns & max stress is near horizontal.

Why is this happening?
Seal interval analysis shows that the poorer seals (lower Seal Index) have higher Young's Modulus and lower Poisson's Ratio values consistent with more brittle rocks, and higher fracture potential.

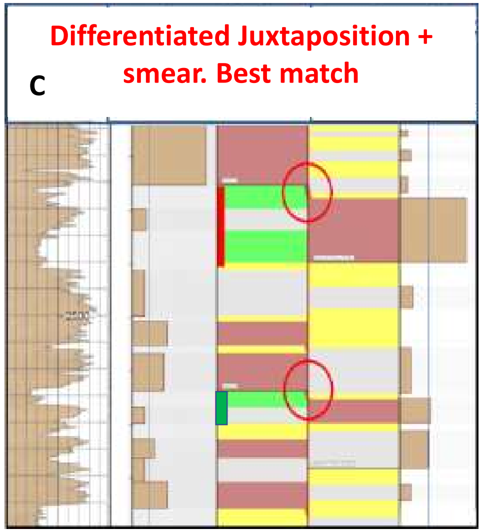
3 seal models tested



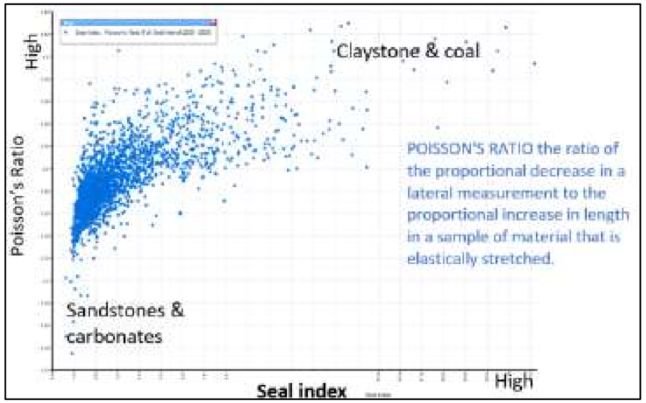
Juxtaposition only – every claystone seals. Poor match



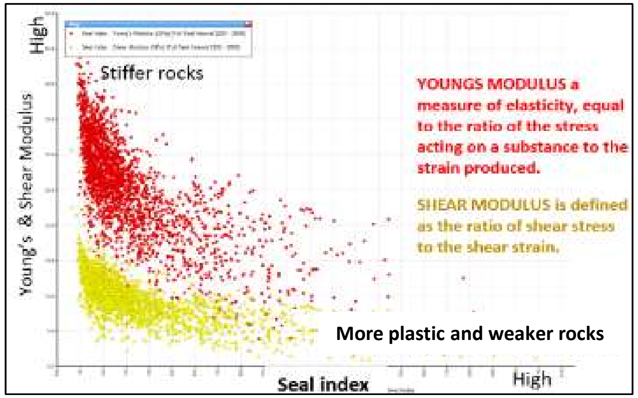
Differentiated Juxtaposition. Good match of position only



Differentiated Juxtaposition + smear. Best match



POISSON'S RATIO the ratio of the proportional decrease in a lateral measurement to the proportional increase in length in a sample of material that is elastically stretched.



YOUNGS MODULUS a measure of elasticity, equal to the ratio of the stress acting on a substance to the strain produced.

SHEAR MODULUS is defined as the ratio of shear stress to the shear strain.

The X axis shows the Seal Index value. A model hydrocarbon column (light green) is generated when seals are in a trapping configuration and seal index minimum values are exceeded (brown). Poor seals shown in grey fail to trap and are not barriers within hydrocarbon columns.

Fault throw, seal model, Seal Index cut off values etc. are changed until a geologically reasonable best fit is achieved.

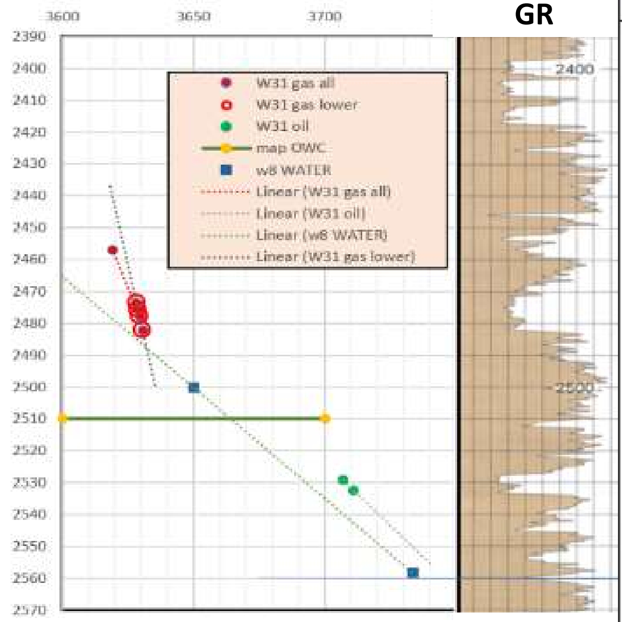
Differentiating brittleness is key to achieving good field calibration

West Tuna field Seal model calibration example

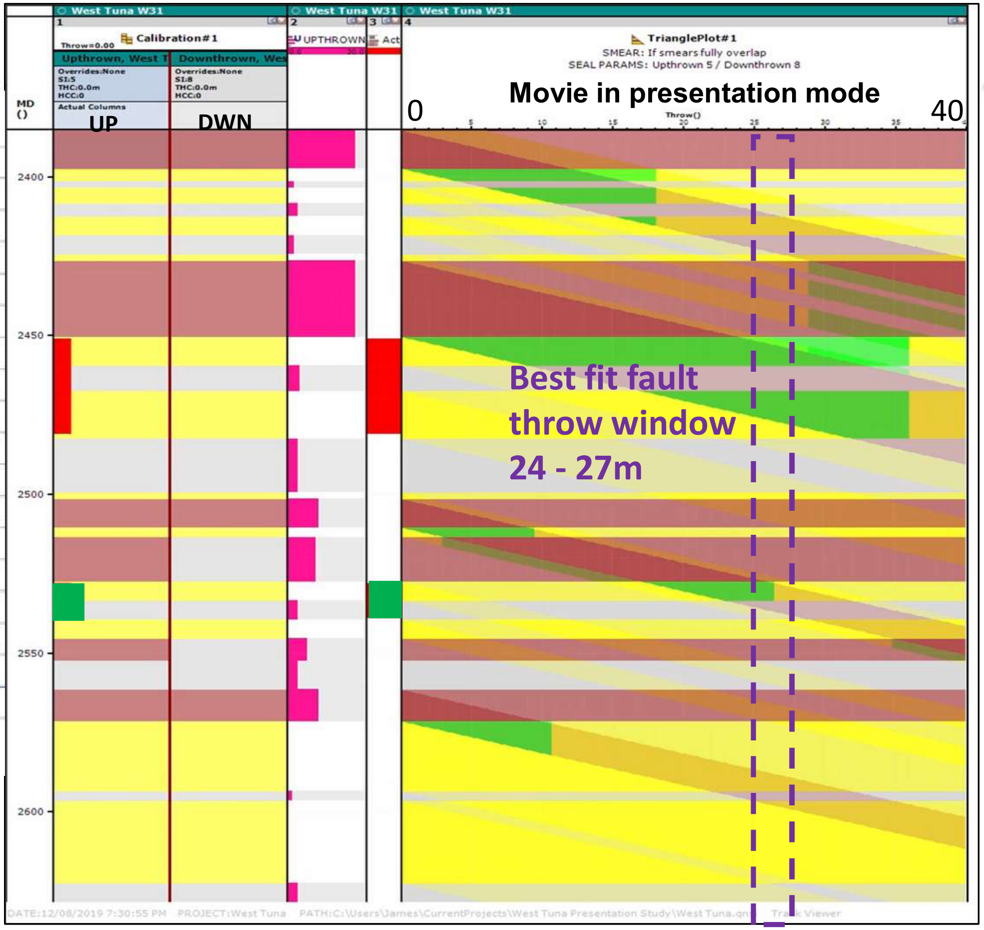
Differentiated juxtaposition + Smear model (best fit)

Testing variable fault throw

- Good quality seals are smear extended in this model with smear controlled by seal quality and the amount of non-sealing lithology components present.
- Seal Index cut-off values are higher in the downthrown block to get a calibration (same as other wells and supported by empirical data).
- Once model effective smear extent is reached a through going slip surface operates.
- Independent best fit fault throw a good match with estimated seismic fault throw



Calibrations on other W Tuna wells proves Fault X seal model is incorrect. Additional potential present.



Movie in presentation mode

Best fit fault throw window 24 - 27m

Differentiating brittleness and smear potential is key to achieving good field calibration

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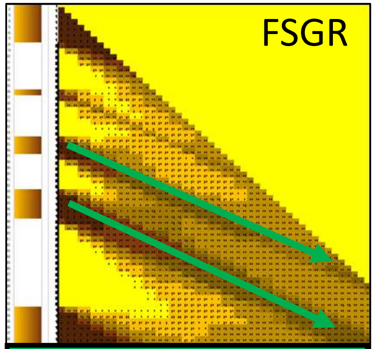
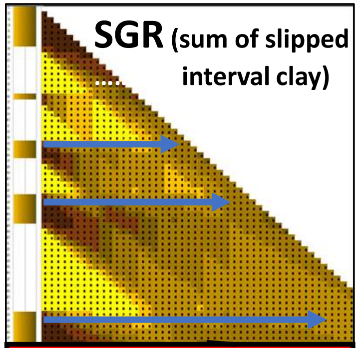
West Tuna field Seal model calibration example

Frictional Shale Gouge Ratio (FSGR) model

(N. Bozkurt Çiftçi et al 2013).

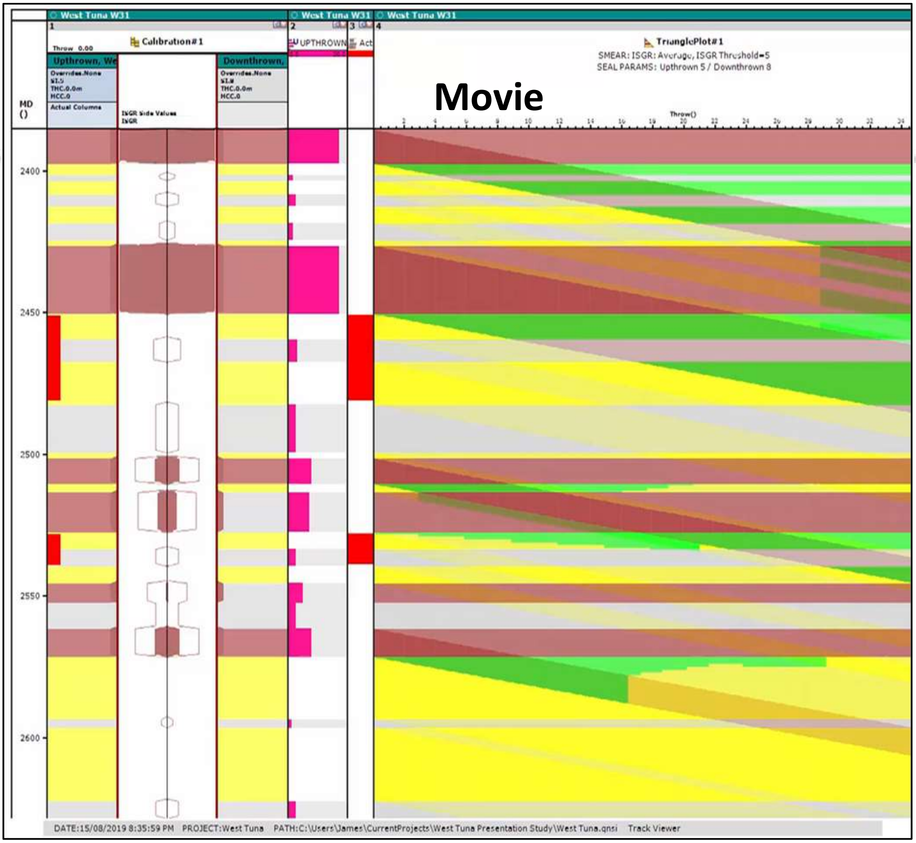


FSGR gouge moves down the fault plane at half the fault throw due to fault friction



SGR gouge stays at same depth point with increasing throw- Not possible!

- Gouge fault rock is preserved proportionally at roughly half the fault throw, as a result of fault zone friction.
- Effective FSGR gouge sealing quality is linked to effective host, foot and hanging-wall seal matrix Seal Index values with cut-off values established from multiple field calibrations.
- At a 41m throw there is a match of hydrocarbon positions but not column heights.
- There is also a poor match with the seismic estimate of fault throw (fault throw - 23 to 25m).



The FSGR model generates a differentiated and attenuated effective gouge consistent with fault development models

(<u>but is not a best fit model in this field</u>).

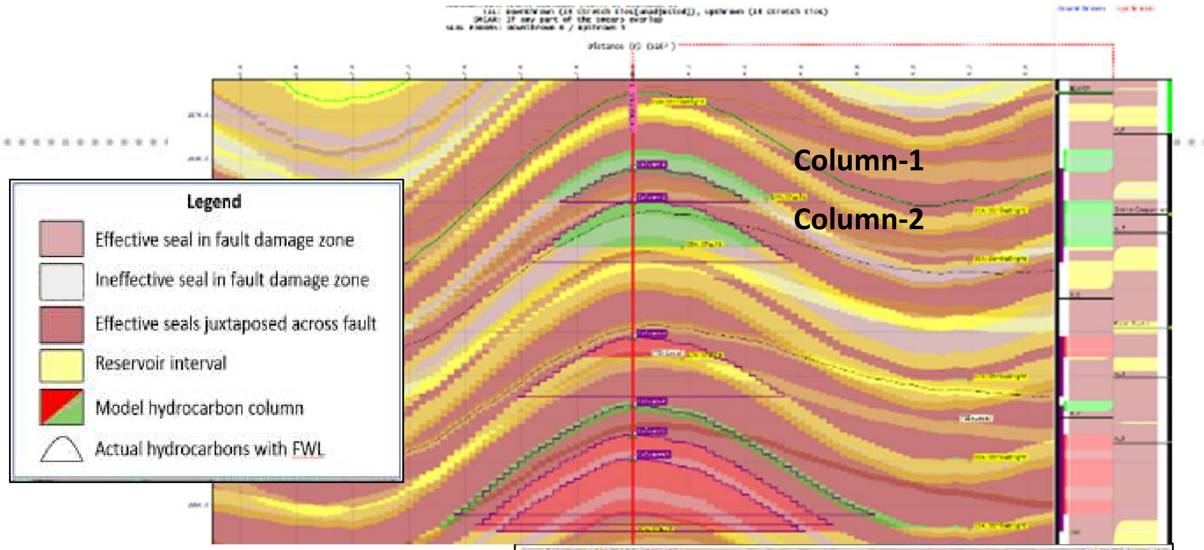
Manta field Seal model calibration example

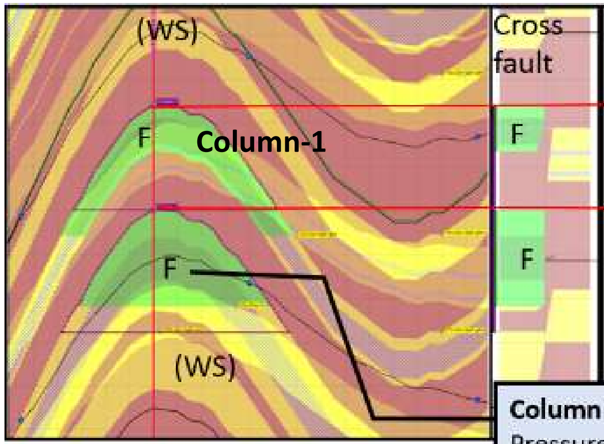
Wells used; down-thrown Manta-1, upthrown Chimaera-1

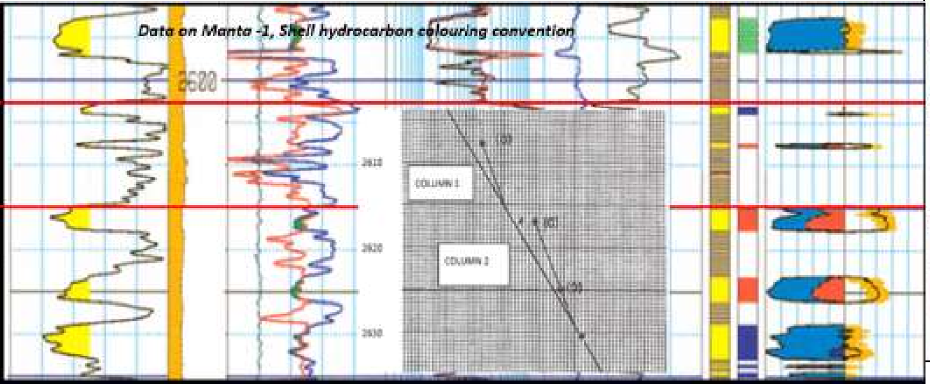
Grey shows seals with low seal index & higher fracture potential.

- do not form top or cross-fault seals or fault traps and
- show the same hydrocarbon pressure gradient across them (not a barrier in a geologic time frame)

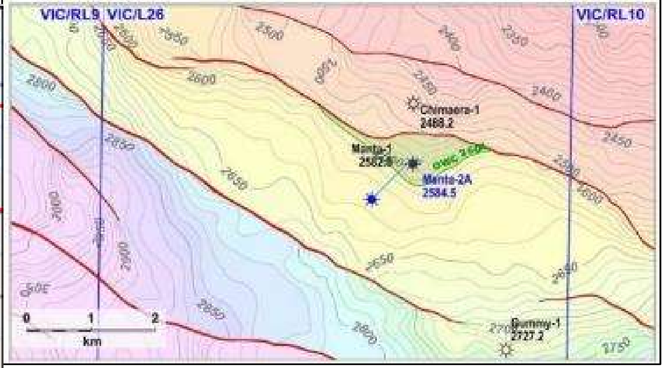
The best fit seal model is, differentiated seal plus smear, explains water sand distribution and hydrocarbon reservoir distribution and column heights.







Column -2 oil in two sands separated by poor failed damage zone seal (F grey). Pressure points in both sands lie on an oil gradient and prove linkage across failed seal. Effective seal, top and cross-fault (brown) is above top sand.



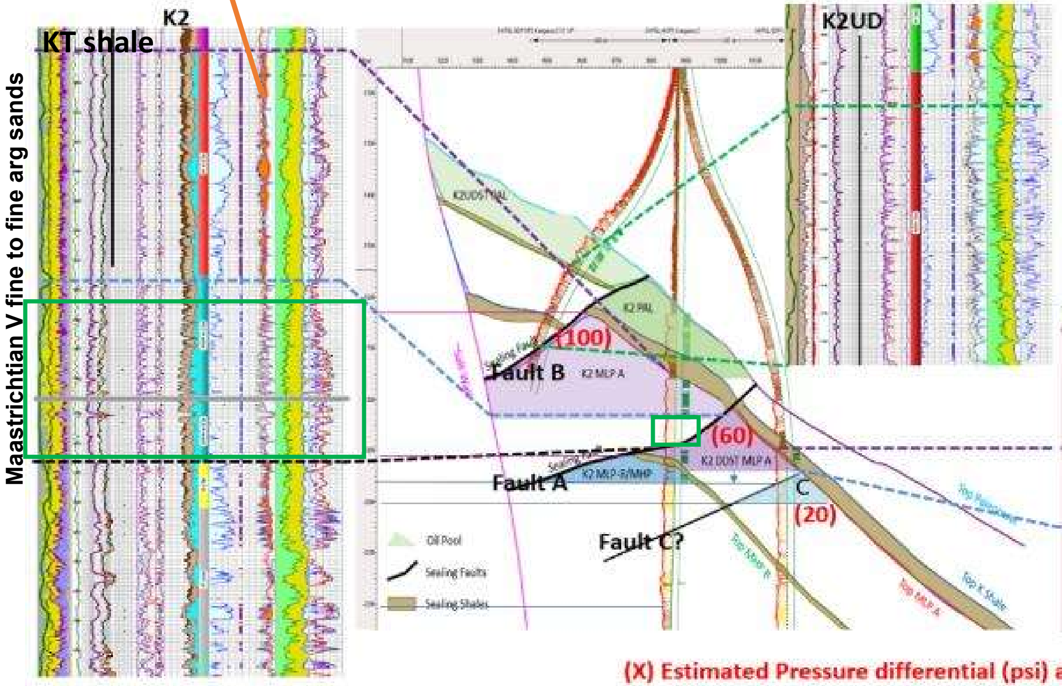
Same best fit seal model and cut off parameters for all 50 wells modelled in the Gippsland Basin

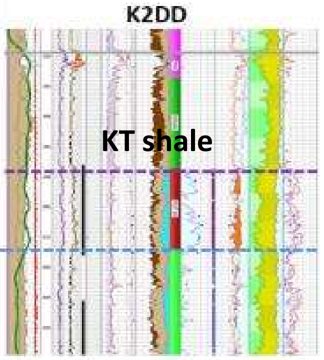
Kangaroo-2 well Santos Basin Brazil – other seal mechanisms - setting

- 8 separate oil columns
- Clay rock fault traps work only for thick top seal and KT shale

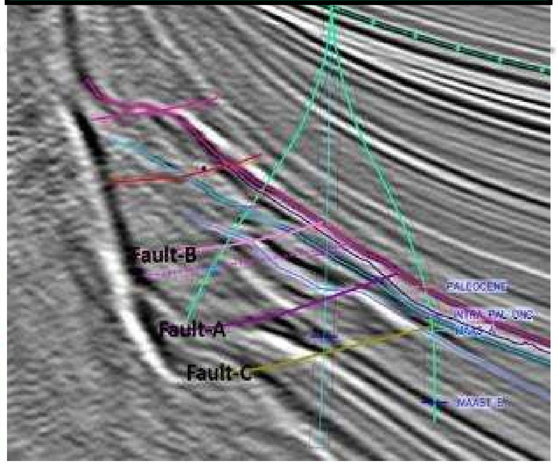
- **No hi Vclay cross fault seals for Faults A, B or C for the K2 Maastrichtian oil pools ??**

Oil zones shown in orange on all logs or green flags on section

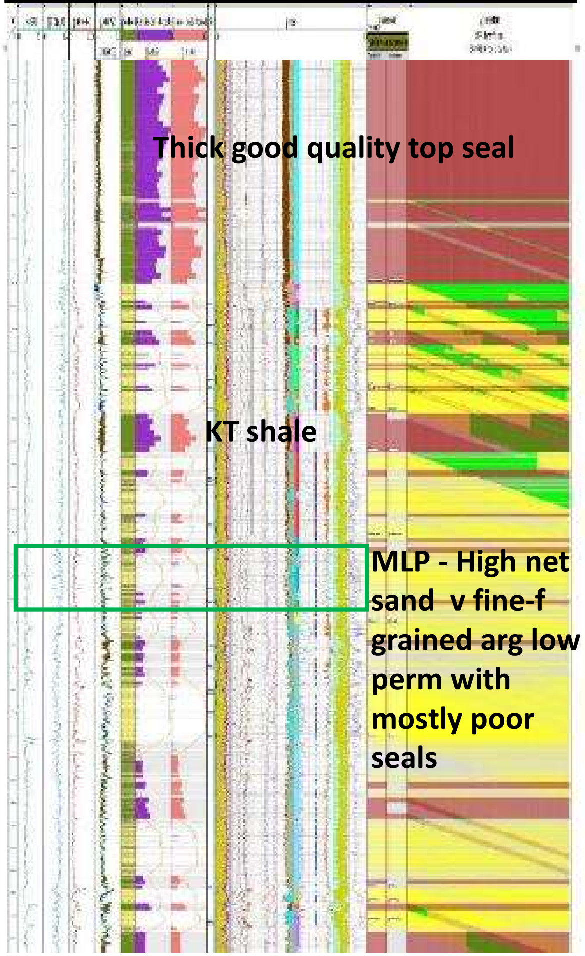




Salt flank field with rotated antithetic faults via addition salt uplift



Differentiated Fault Triangle -Poor fault seal potential below the KT shale



MLP - High net sand v fine-f grained arg low perm with mostly poor seals

(X) Estimated Pressure differential (psi) across barrier at trap crest

Other seal mechanisms need to be tested

Fault zone permeability modelling K-2 well Pal. oil bearing reservoirs and underlying KT shale

The permeability function, models clay rock permeability in host and fault rocks for any depth and depth of faulting for Vclay 0 to 1.0.

Function curves for host rocks change with grainsize, sorting and clay type.

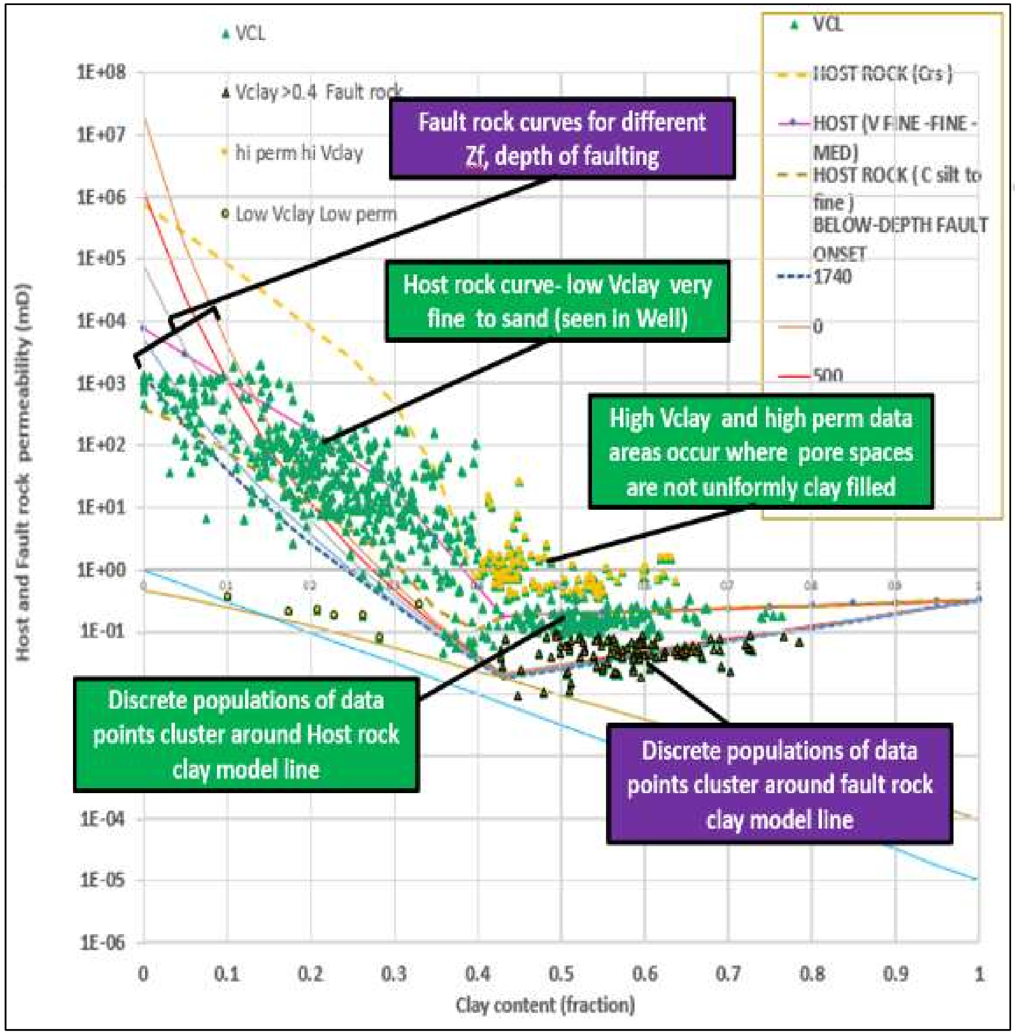
The model is overlain with NMR KSDR data, identifying distinct separate populations of high Vclay host and fault rock points. There is a very good model fit to NMR permeability data.

For low Vclay host rocks there is a good fit to the very fine to fine grained reservoir zones in this well.

No model depth adjustments were required. <u>Uplifted well models are depth adjusted as deepest permeability values are preserved</u>.

Host and fault rock points can be displayed in depth to define distribution and thickness of fault rock and damage zones in wells

Permeability data can then extrapolated across fault planes for seal and fluid flow modelling in matrix and fracture permeability systems



Fault rock curves for different Zf, depth of faulting

Host rock curve- low Vclay very fine to sand (seen in Well)

High Vclay and high perm data areas occur where pore spaces are not uniformly clay filled

Discrete populations of data points cluster around Host rock clay model line

Discrete populations of data points cluster around fault rock clay model line

Fault zone permeability modelling K-2 well Pal. oil bearing reservoirs and underlying KT shale

Shear zones are commonly identified in outcrop, often along clay rich bedding planes. In the subsurface, in-bed shear zones are very difficult to recognize seismically.

The permeability Vclay model can differentiate between sheared and unsheared higher Vclay rocks.

Well defined host rock and fault rock trends are seen here at higher Vclay values.

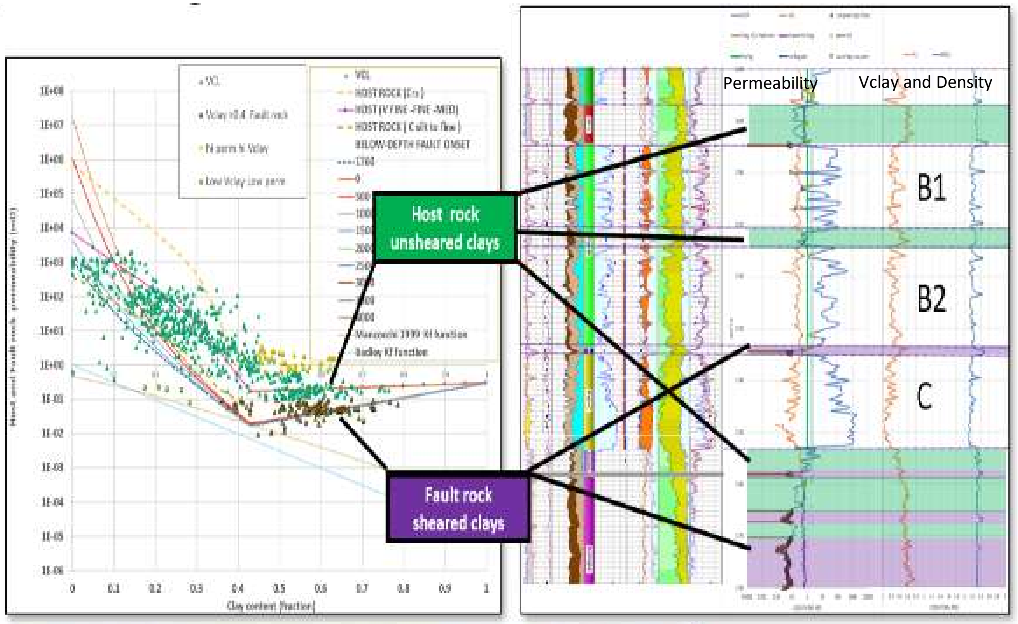
Top oil column C sheared clay (purple) is a pressure boundary between the C and B oil columns in a trap that dips at 30 degrees.

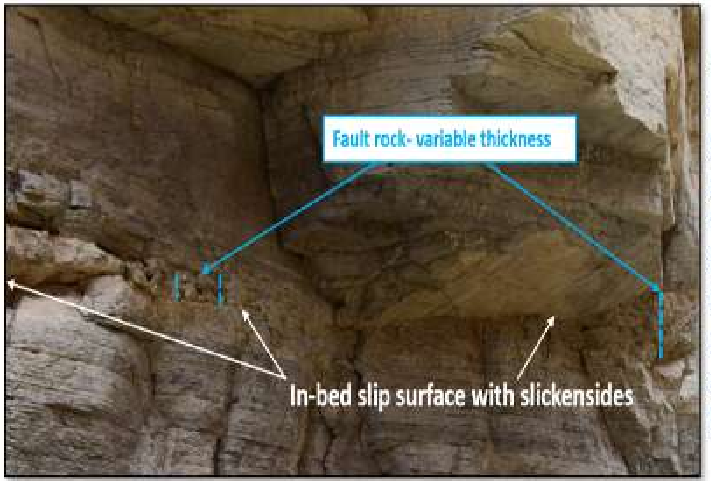
The lower thick shale has a number of shear zones (purple). There is no seismic or dipmeter evidence here for a normal fault.

It is postulated that as bed dip increased with structural growth, stress was relived through shearing in the weaker shale zones

Shear zone clays have lower permeability and significantly higher threshold pressures and as such can hold higher hydrocarbon columns

Shear zones Identified in the well





Being able to determine the orientation of low permeability barriers as parallel to (in-bed shears) or near perpendicular to bedding (faults), is very important in defining seal surfaces and building accurate exploration or fluid flow simulation models

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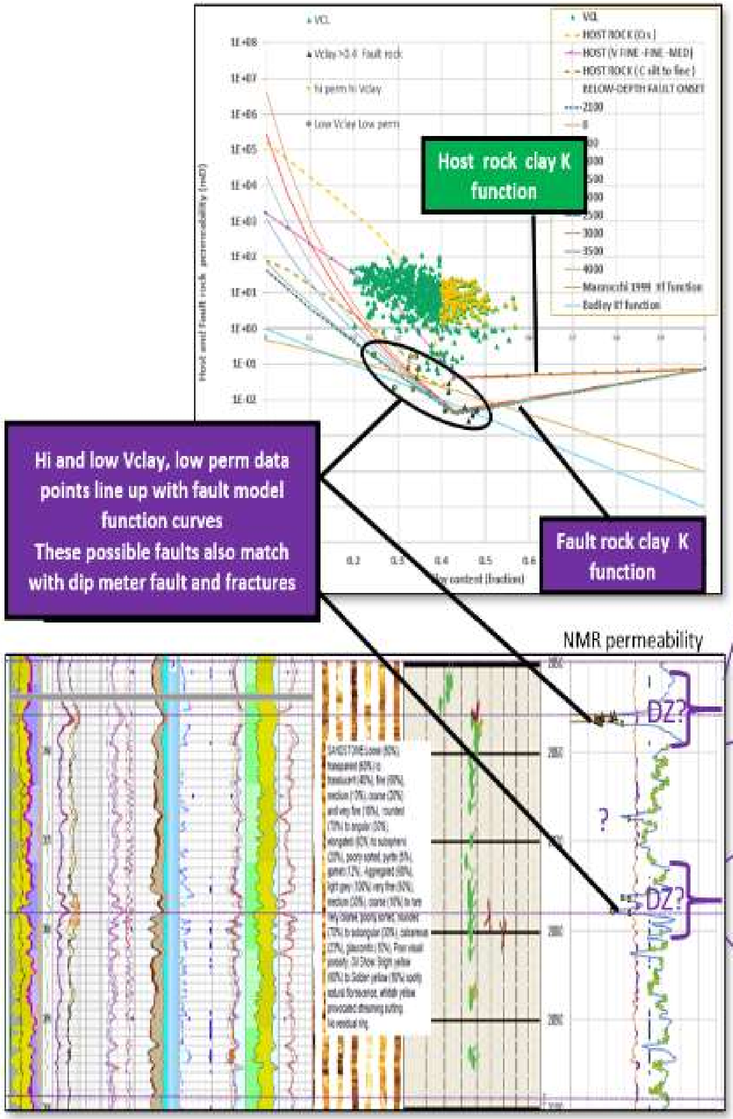
Fault zone permeability modelling K-2 well Maastrichtian section

- **The permeability model fits the NMR KSDR data, identifying fault cores and damage zones in the well.**
- Location, permeability and thickness of each fault rock component is defined in the well and fits with dipmeter.
- No empirically based fault core or damage zone thickness estimates are required if NMR data is available.
- Higher K, low Vclay coarse sands fit with coarse sand host model function (orange dashed line).

Data from this analysis is independent of, and calibrates very well with dipmeter data.

Using these models defines more precisely fault and host rock element positions, orientation, widths, and their properties in wells.



Host rock clay K function

Hi and low Vclay, low perm data points line up with fault model function curves
These possible faults also match with dip meter fault and fractures

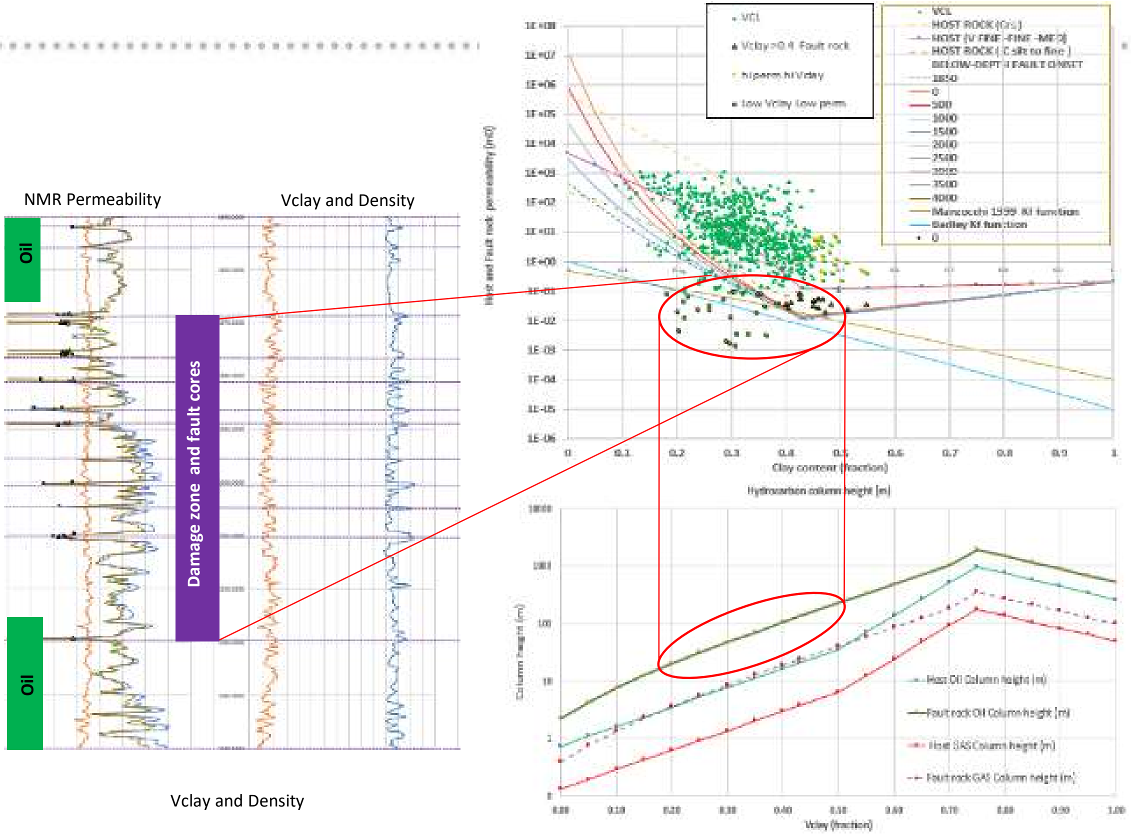
Fault rock clay K function

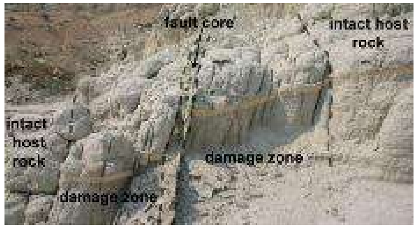
Seeing faulted rocks zone, internal architecture with variable clay content

Seeing internal architecture of the faults with two slip surfaces

Fault zone permeability modelling
K-2 well Maastrichtian section
Fault A model

- Fault A juxtaposes interbedded high net argillaceous silt to very fine sand and traps a 120m light oil column.
- Model fault rock for Vclay .2 to .5 traps up to a 200m light oil column.
- Damage zone with slip surfaces, carbonate richer cement fault cores and deformation bands developed over 60m interval provide the seal.





Permeability Model fit to data discriminates stratigraphic from structural elements – important for exploration of dynamic model build

Gular-1, Gippsland Basin fault seal observations

- Multiple crestal faults up to 20m throw at T2 level.
- Poor fault seal potential below Lakes Entrance Fm. seal

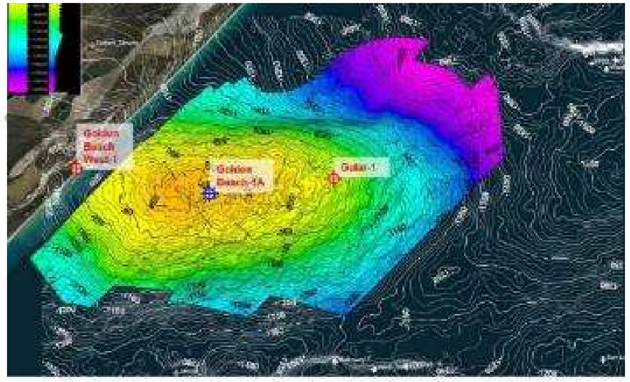
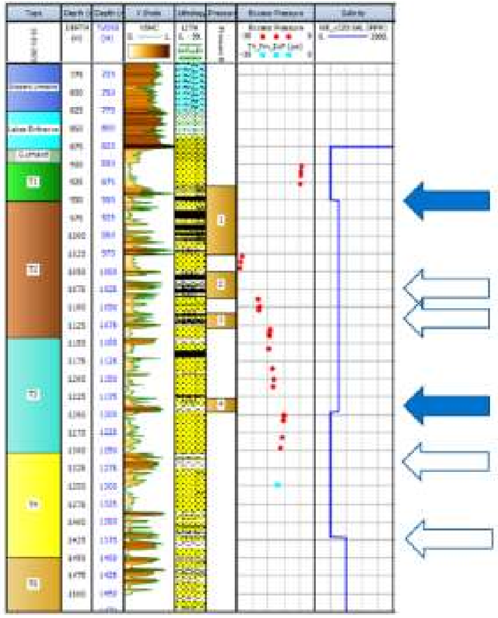


Figure 2: Gular-1 well location map and Pelican site topseal depth map.
The coloured area is from the GCN18A 3D survey, white contours are from older 3D surveys (2D surveys onshore/nearshore)



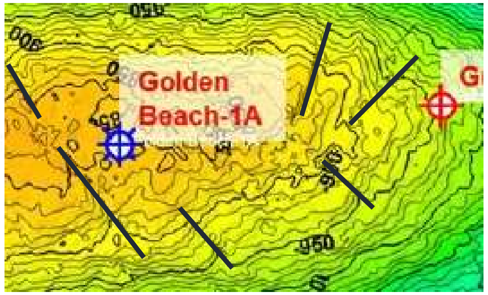
Top T2 pressure *and* salinity change

Lower T2 pressure changes only, Good MICP (65m CO_2)

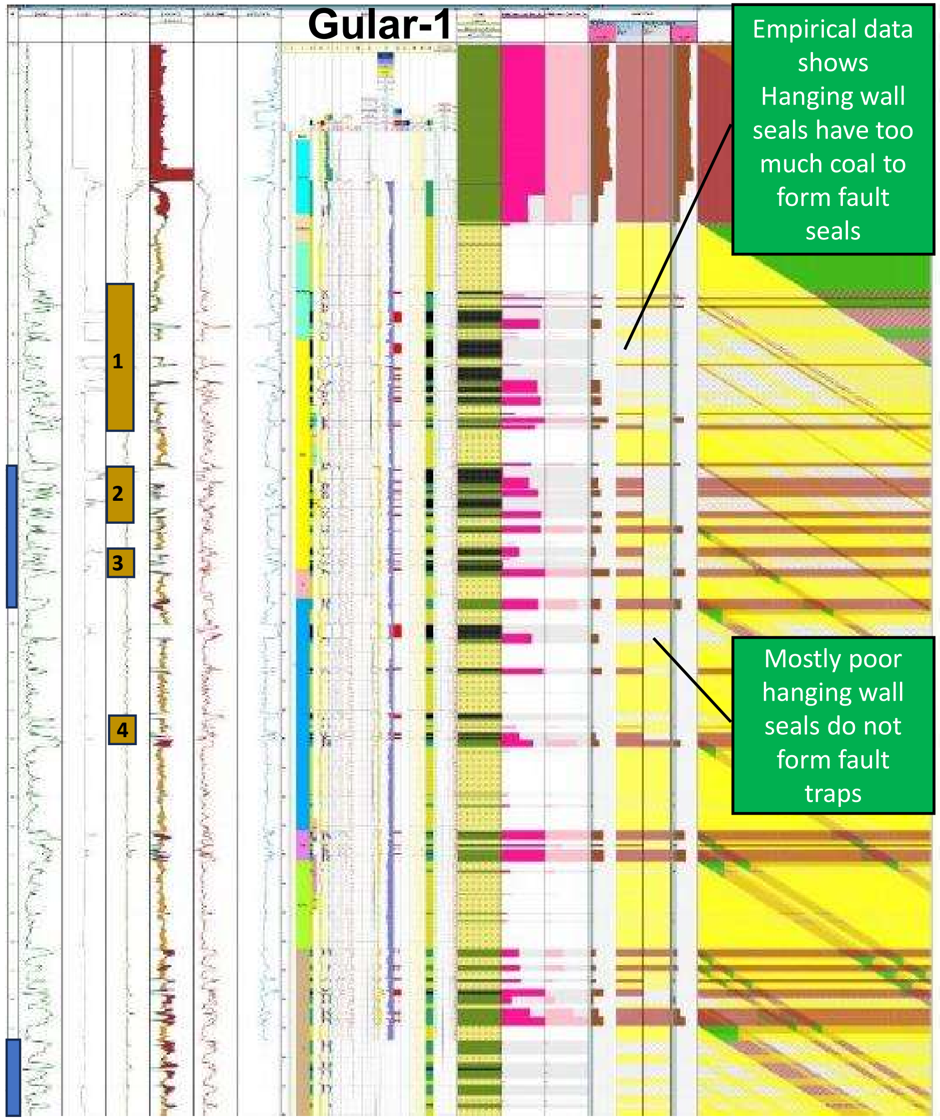
Mid T3 pressure *and* salinity change

Top T4 subtle pressure change, excellent MICP (330-490 m CO_2)

Base T4 salinity change, no pressure data



Model fault traps define trapping over a geologic time frame based field calibration



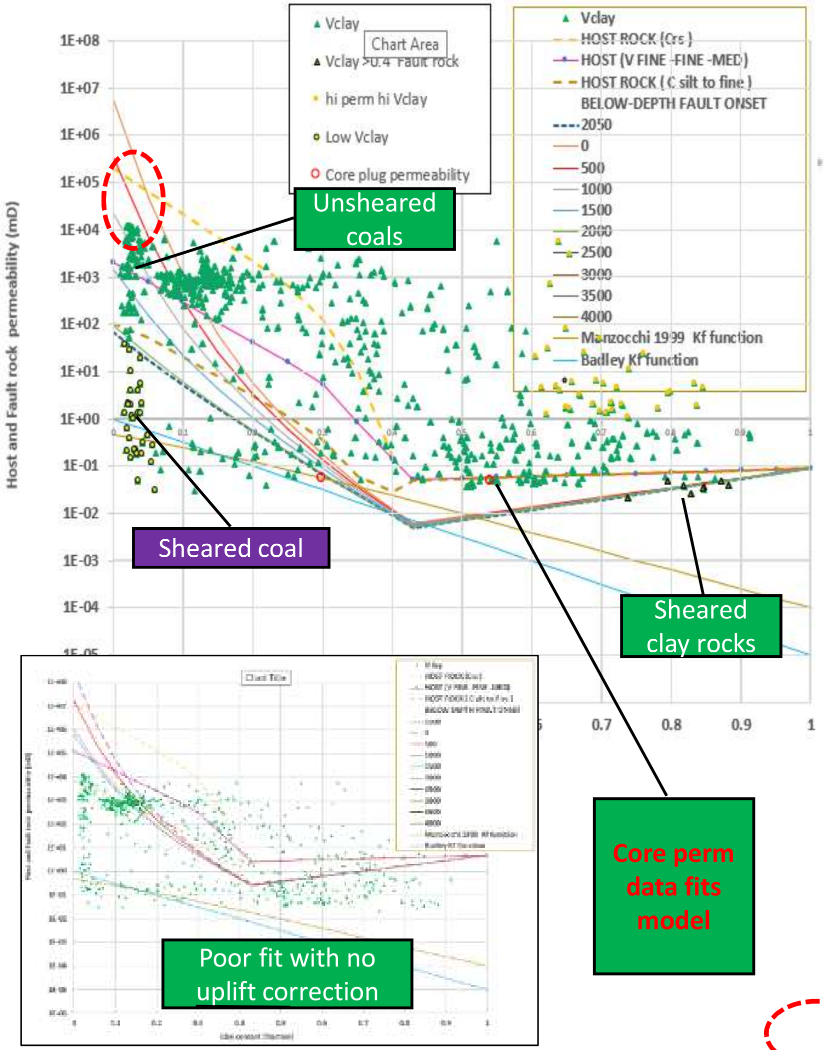
Empirical data shows Hanging wall seals have too much coal to form fault seals

Mostly poor hanging wall seals do not form fault traps

Gular-1, Gippsland Basin Permeability model

1100m model

Uplift to match model 950m



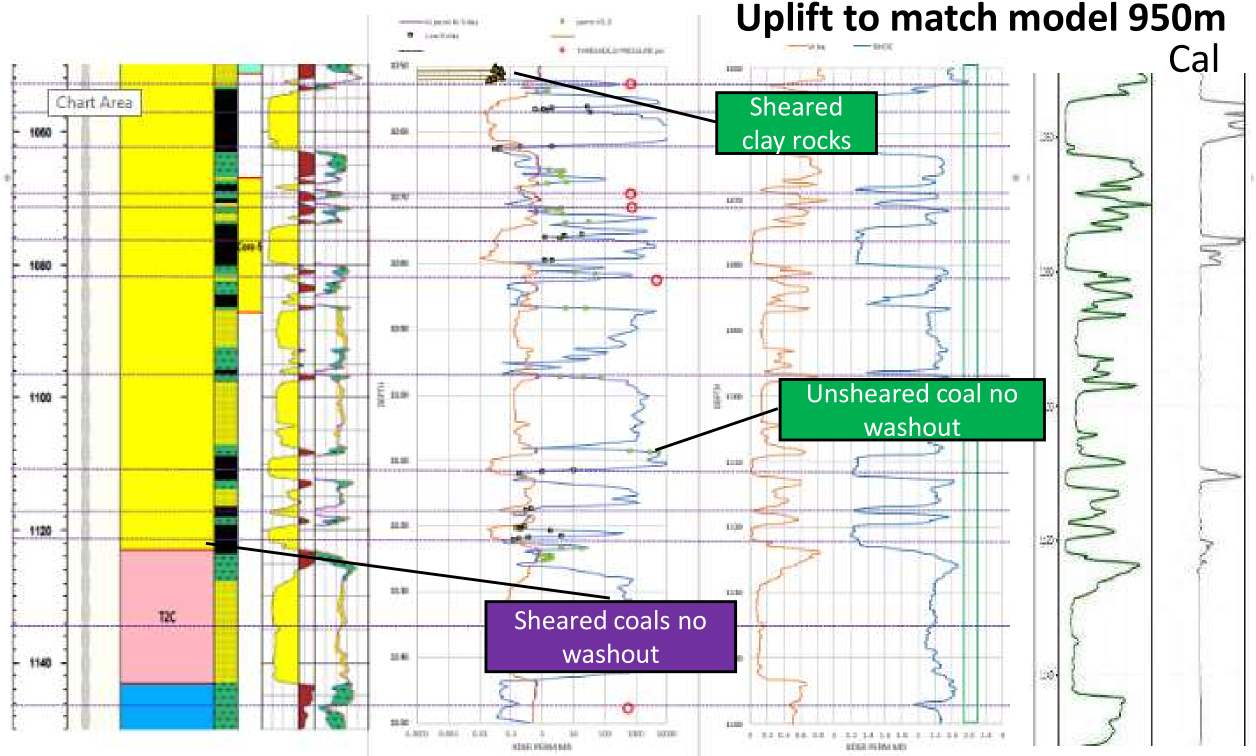
Unsheared coals

Sheared coal

Sheared clay rocks

Core perm data fits model

Poor fit with no uplift correction



Sheared clay rocks

Unsheared coal no washout

Sheared coals no washout

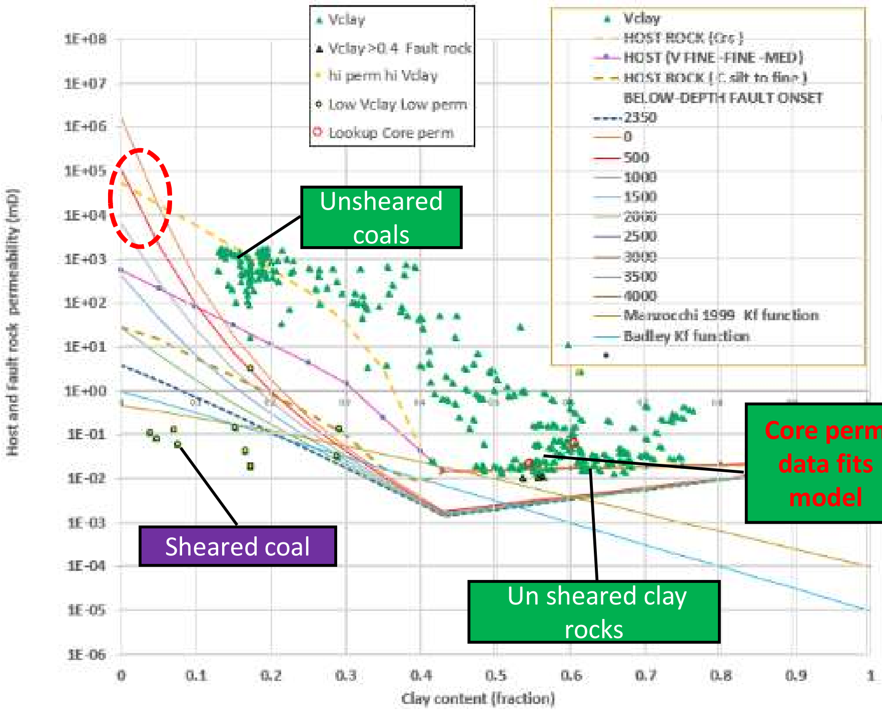
Uplift story

- Mid Miocene uplift event- major channeling with eroded thick Hapuku Subgroup clastics deposited offshore.
- Peak erosion, folding and faulting at shallower depths than present (less thickness of post Mid Miocene sediments)
- **As such, Low Vclay clastic fault rock likely faulted at shallow depths likely to be high perm and fractured (see red ellipse) in fault rock model.**

Gular-1, Gippsland Basin Permeability model

1500m model

Uplift to match model 850m

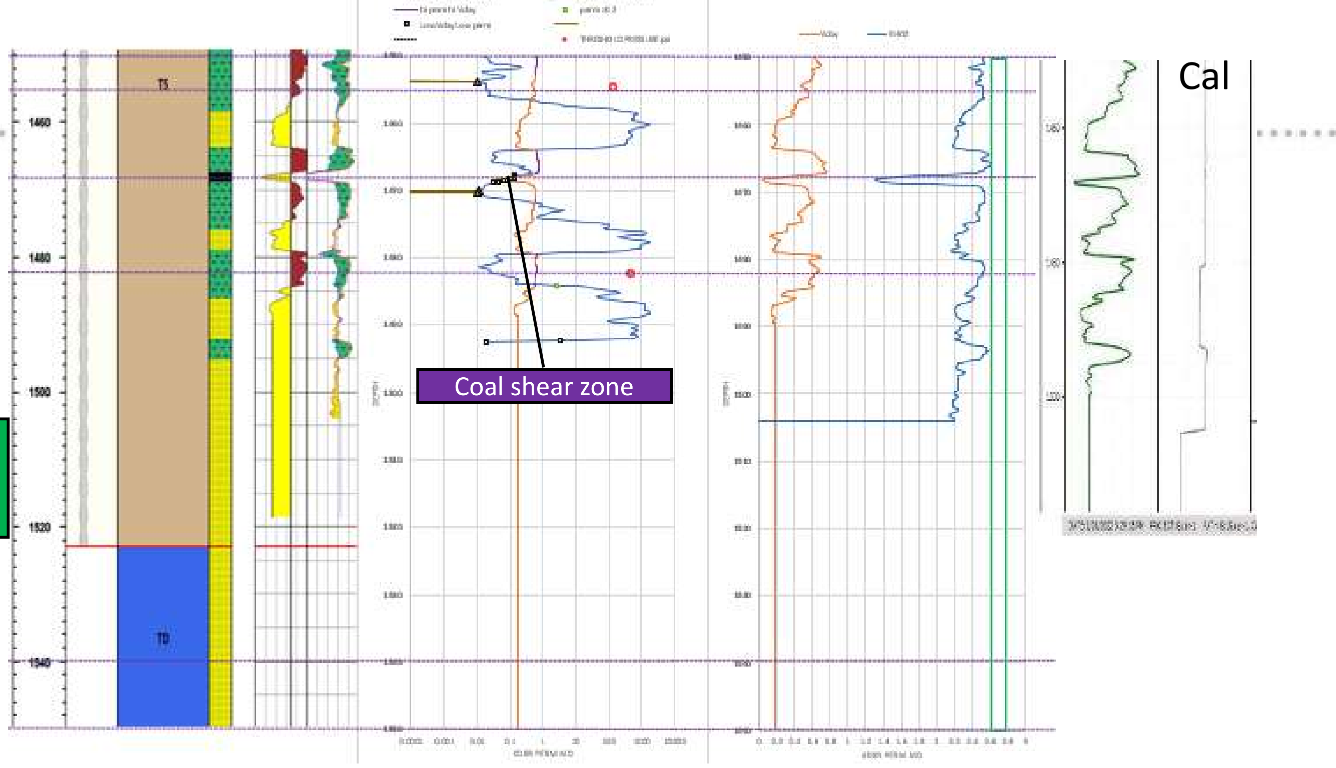


Unsheared coals

Sheared coal

Un sheared clay rocks

Core perm data fits model



Coal shear zone

Uplift story

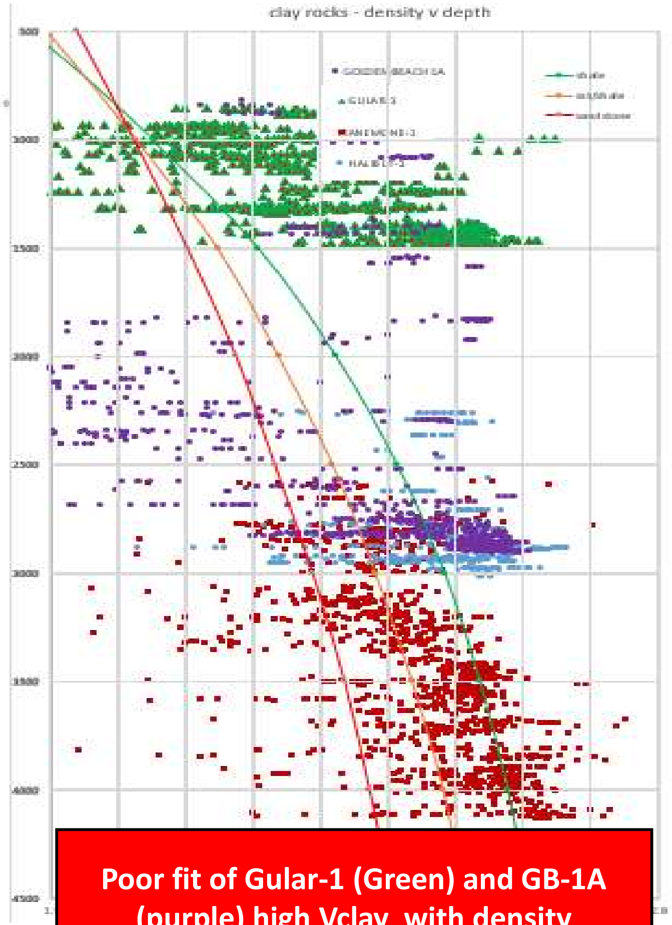
- Mid Miocene uplift event- major channeling with eroded thick Hapuku Subgroup clastics deposited offshore.
- Peak erosion, folding and faulting at shallower depths than present (less thickness of post Mid Miocene sediments)
- **As such, Low Vclay clastic fault rock likely faulted at shallow depths likely to be high perm and fractured (see red ellipse) in fault rock model.**

Gular-1, Gippsland Basin
Permeability model

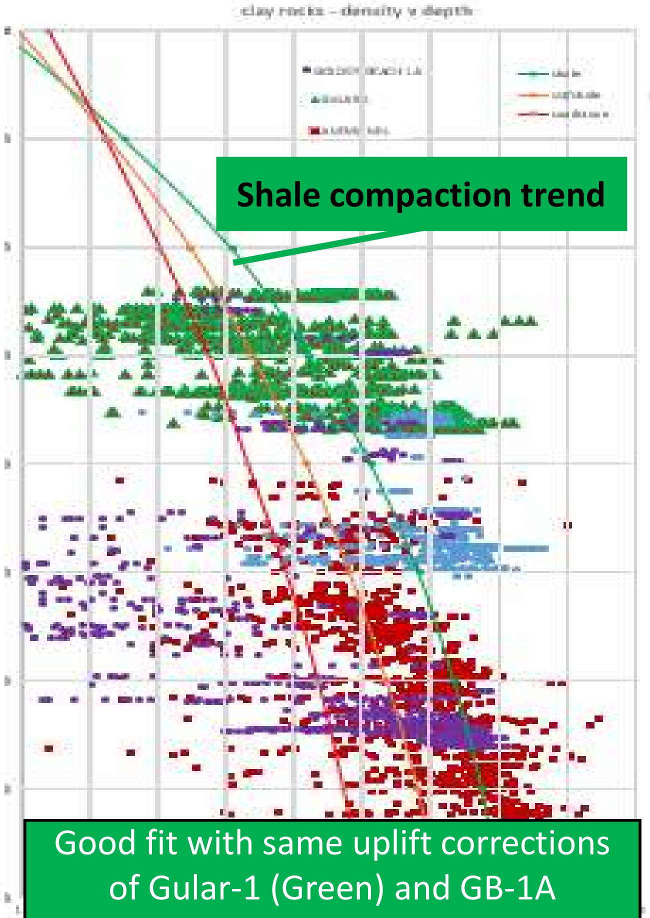
Function from- An investigation of salt tectonic structural styles in the Scotian Basin, offshore Atlantic   Albertz et al. TECTONICS, VOL. 29, TC4017, doi:10.1029/2009TC002539, 2010

Gular-1 Vclay v Perm uncorrected

Poor fit with no uplift correction



Poor fit of Gular-1 (Green) and GB-1A (purple) high Vclay with density functions



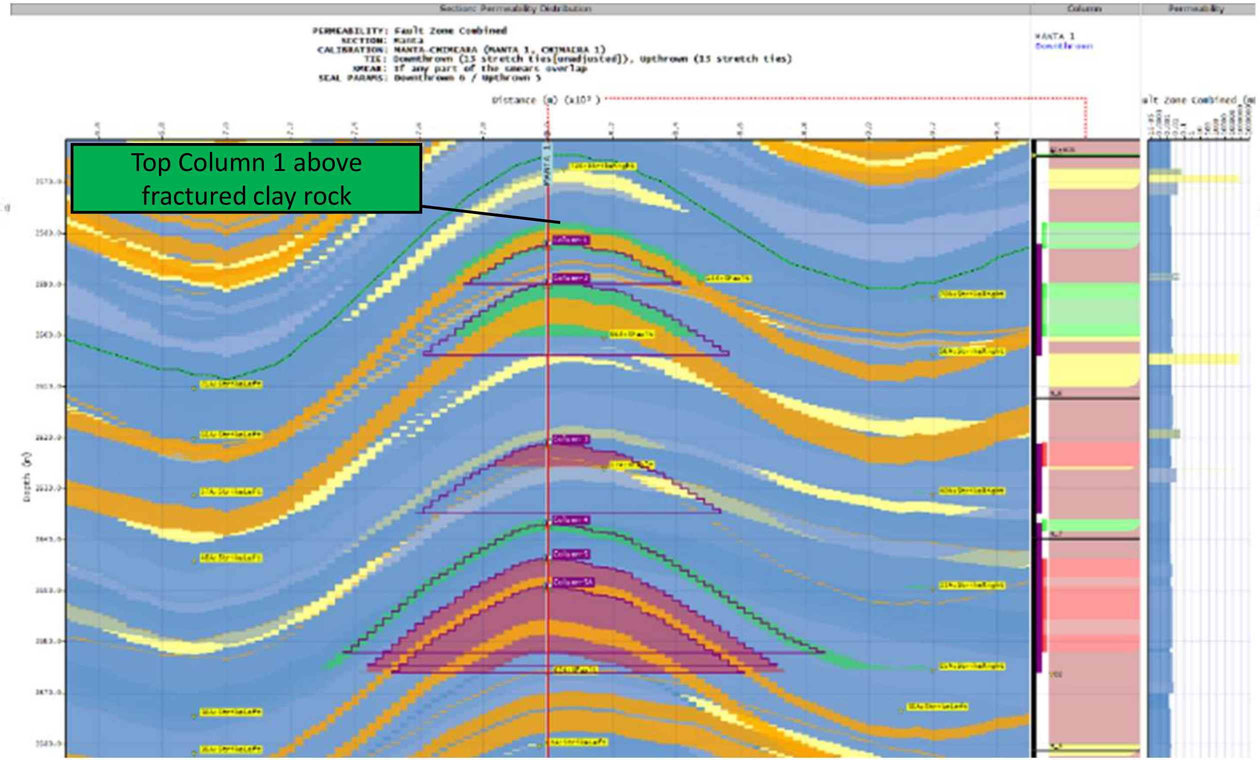
Shale compaction trend

Good fit with same uplift corrections of Gular-1 (Green) and GB-1A (purple) high Vclay with density functions

Uplift model supported by high GR density v depth curve matching

Conclusions

- **Built a case that fractures associated with faulting in the subsurface can be defined at the scale for commercial petroleum exploration and development activities with a quantified level of certainty by calibration to existing fields.**
- **Demonstrated that host, damage-zone and fault core boundary and matrix and fracture properties can be defined and mapped (with an adequate data set).**
- **Applicable to CCUS, Aquifer modelling and Hydrogen storage applications**
- **A strong quantified basis for developing static and dynamic models**



Top Column 1 above fractured clay rock

PERMEABILITY: Fault Zone Combined
SECTION: Manta
CALIBRATION: MANTA-CHIMICARA (MANTA 1, CHIMACRA 1)
TIE: Downthrown (13 stretch ties[unadjusted]), Upthrown (13 stretch ties)
SMEAR: If any part of the smears overlap
SEAL PARAMS: Downthrown 6 / Upthrown 5

- Manta field fault plane permeability model. Showing actual columns outlined predicted hydrocarbon columns red or green plus water sand distribution.
- Pale yellow shows fault plane higher perm windows.
- Orange shows fractured high Vclay intervals that are not sealing in a geological time frame and do not generate pressure barriers in hydrocarbon columns over geologic time.