Fault Triangle diagrams

Triangular fault juxtaposition diagrams (Knipe 1997) are frequently used in the oil and gas industry to quickly assess across-fault relationships and sealing capacity from a single well (e.g. Tozer & Borthwick 2010). In Move2016.2, Fault Triangle diagrams (Figure 1) can be created from the Fault Analysis module. In this Move Feature, the theory of Fault Triangle diagrams and the interpretation of these diagrams are described. A number of enhancements to the traditional Fault Triangle approach, which have been included within the tool, are then outlined and discussed. These enhancements improve visualization of the results and provide a more accurate representation of across-fault juxtapositions and sealing capacities.

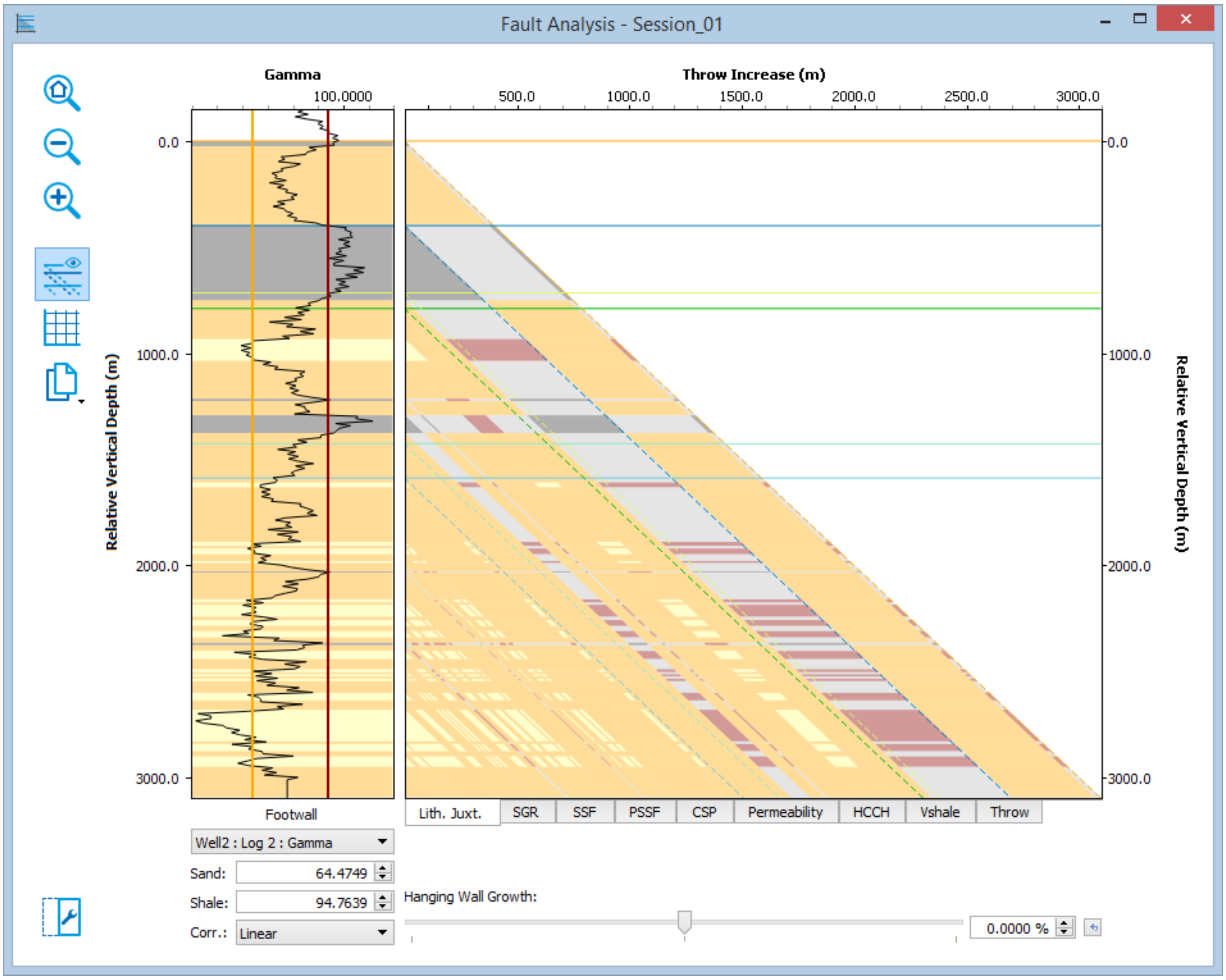

*Figure 1: The Fault Triangle window showing the lithological juxtaposition. The tool is launched by collecting a well into the **Fault Analysis** toolbox and clicking the **Fault Triangle button** on the **Seal Analysis** sheet.*

Interpreting Fault Triangle diagrams

Fault Triangle diagrams only require data from a single well. As a result of this limited data requirement, the diagrams are ideal for providing a first-pass look at potential across-fault juxtapositions and determining the range of possible sealing capacities of faults, particularly in regions of sparse or poor data.

The basic concept of the diagrams is that a 'layer-cake' stratigraphy defined by a well, is offset by a hypothetical fault (Figure 2a). The displacement of this fault increases linearly from zero to a maximum value, defined by the thickness of the 'layer-cake' stratigraphy (Figure 2b). Plotting the fault-horizon intersection lines (fault cut-off lines) on a 2D graph of the hypothetical fault forms the basis of the Fault Triangle diagram (Figure 2c). On these plots, the footwall cut-off lines are displayed as horizontal, solid lines and the hanging wall cut-offs are diagonal, dashed lines. The x-axis of the plot represents the vertical displacement of the fault (fault throw), while the y-axis corresponds to depth.

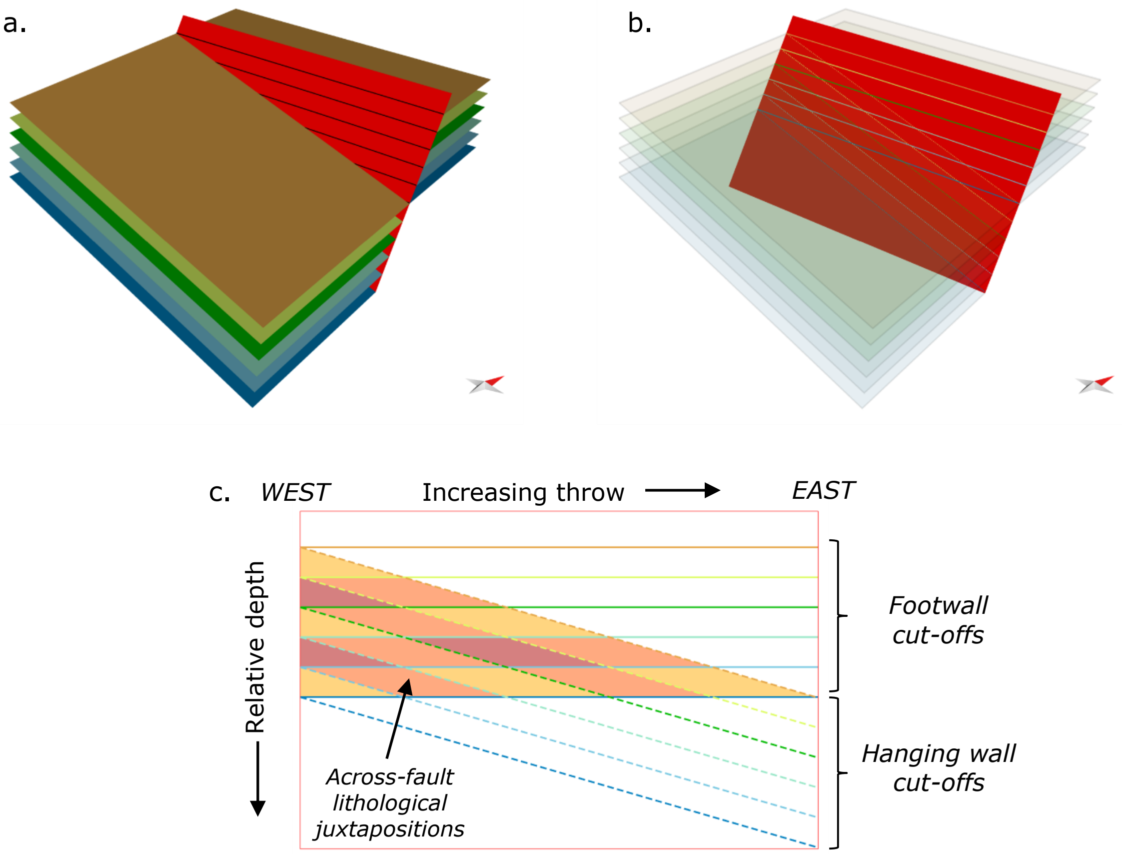

Figure 2: Illustration showing the construction of a Fault Triangle diagram from a hypothetical fault. (a) 3D representation of a 'layer-cake' stratigraphy offset by a hypothetical fault. (b) Fault cut-off lines from the horizon intersections with the hypothetical fault. (c) Side on view of the hypothetical fault (looking north) showing the footwall cut-off lines (horizontal, solid lines) and the hanging wall cut-off lines (diagonal, dashed lines); areas between the cut-off lines are colour-coded for across-fault lithological juxtaposition. The x-axis in this view is equivalent to the amount of throw and the y-axis equivalent to relative depth or distance down the fault.

The lithological juxtapositions generated for the hypothetical fault (Figure 3a) can be used to determine three fault sealing proxies (Figure 3b – d): Shale Gouge Ratio (SGR), Shale Smear Factor (SSF) and Clay Smear Potential (CSP) (Fulljames *et al.* 1997; Lindsay *et al.* 1993; Yielding *et al.* 1992). The calculations use the amount of shale in the stratigraphy based on Vshale values converted from gamma logs (Figure 3e), and the amount of throw (Figure 3f). Each of the fault seal proxies has a value, which marks the transition between sealing and leaking; for instance, SGR values >0.2 are typically assumed to seal (Childs *et al.* 2009).

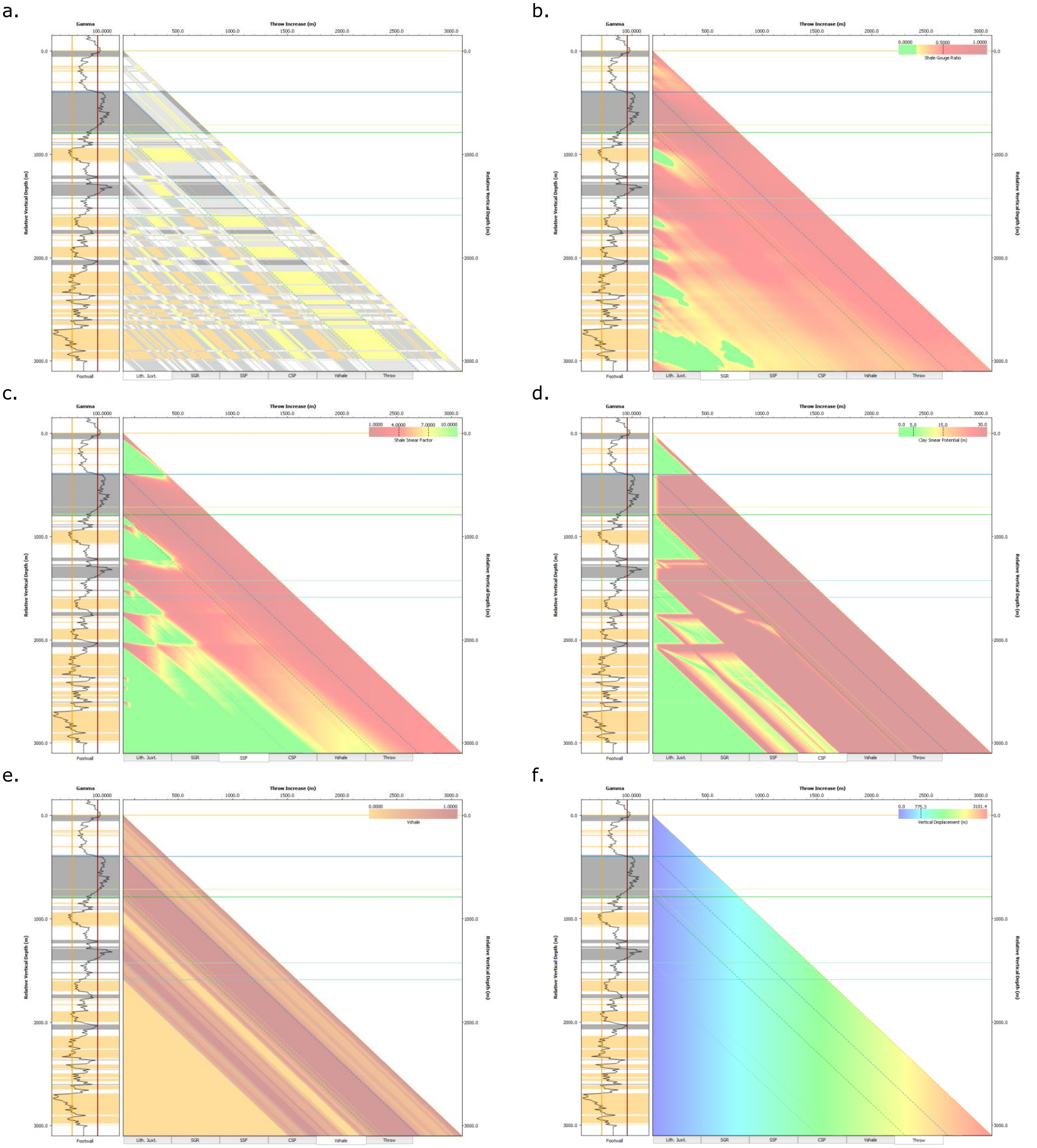

Figure 3: Fault Triangle diagrams colour mapped for: (a) Lithological juxtaposition; (b) Shale Gouge Ratio (SGR); (c) Shale Smear Factor (SSF); (d) Clay Smear Potential (CSP); (e) Vshale; (f) Fault Throw. These different plots are accessed using tabs along the bottom of the Fault Triangle diagram.

Rather than simply representing a single fault with variable displacement, Fault Triangle diagram can also be viewed as representing multiple faults covering the entire range of possible fault offsets that can be constrained from well data. In other words, a vertical line on the plot represents the expected across-fault juxtapositions down a fault with a particular amount of throw (black dashed line in Figure 4). To improve visualization, the across-fault juxtapositions down this fault can be displayed on a separate plot to the right-hand side of window. This separate plot is activated using the **Show Cross-Section** option in the **Display Settings** sheet. The corresponding fault throw position for this separate Cross-Section plot is illustrated on the main Fault Triangle diagram with a black dashed line, which can be dragged to vary the amount of fault throw. The SGR values down the fault are plotted as a black line on the separate Cross-Section plot (Figure 4). The ability for the user to vary the amount of fault throw whilst visualizing the lithological juxtaposition and the SGR, makes it very easy to determine the minimum throw required for a fault to seal.

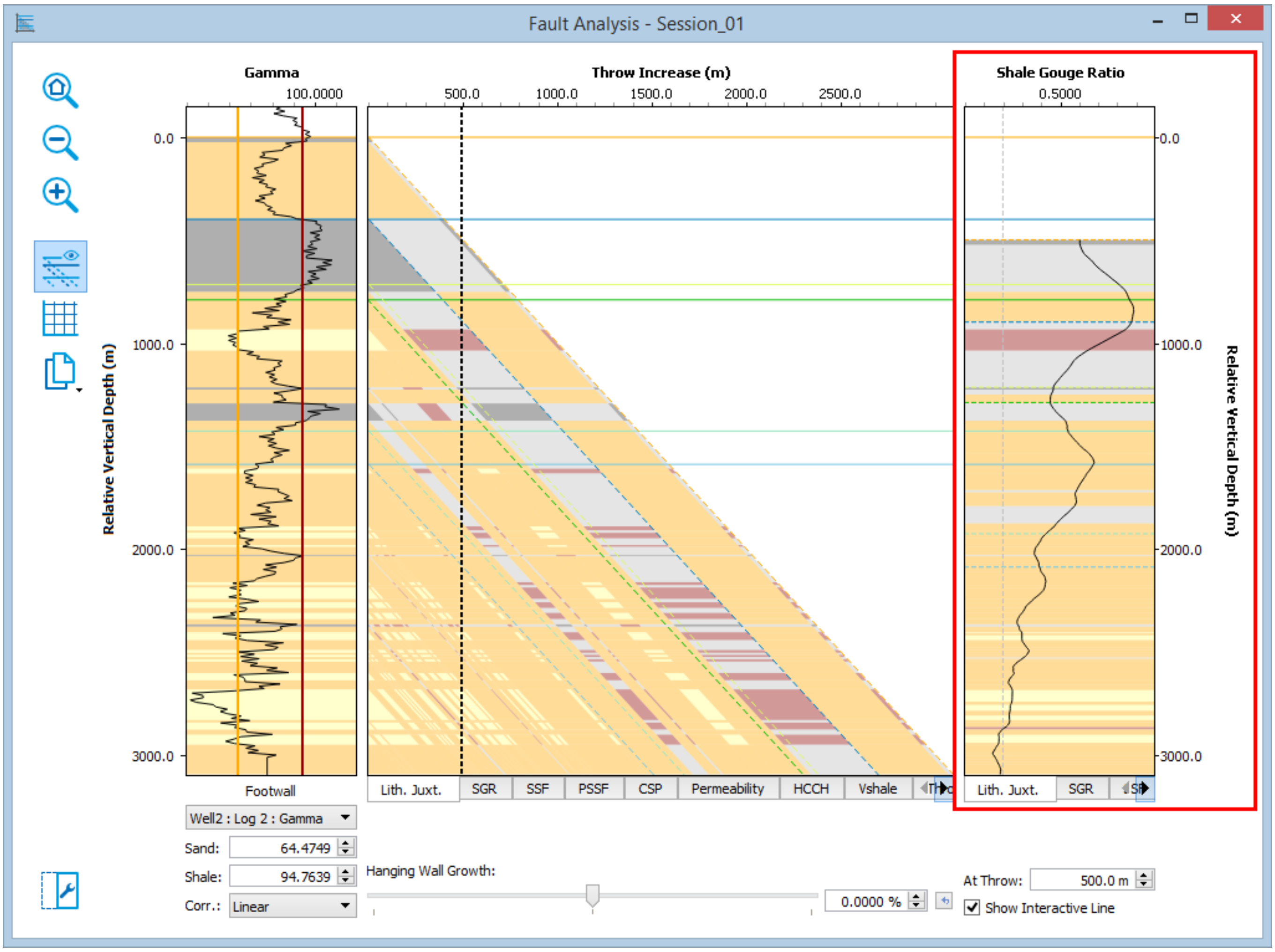

Figure 4: Fault Triangle window with the separate Cross-Section plot on the right-hand side highlighted with a red box; this plot corresponds to a fault with 500 m of throw (shown with the black dashed line). The Cross-Section plot significantly improves visualization in the Fault Triangle tool and makes it easier to quantitatively assess the fault sealing potential.

Incorporating across-fault thickness changes

The use of a single well as the input for traditional Fault Triangle diagrams requires that the thickness of sedimentary units remains constant across the faults. In the Fault Triangle tool in Move, this deficiency has been addressed with some simple modifications that are very straightforward and easy-to-use.

The first modification is the ability to include two wells in the Fault Triangle diagram; the hanging wall 'layer-cake' stratigraphy defined by one well is then moved past the stratigraphy defined by the second well (Figure 5). If data from two wells are available, the accuracy of the information obtained from the Fault Triangle diagram could be improved dramatically without making the tool difficult to use. Importantly, if two wells are not available, it may be possible to extract a pseudo-well from the existing stratigraphy of the region, and still utilise the two well option to provide a more accurate representation of across-fault juxtapositions and sealing capacities.

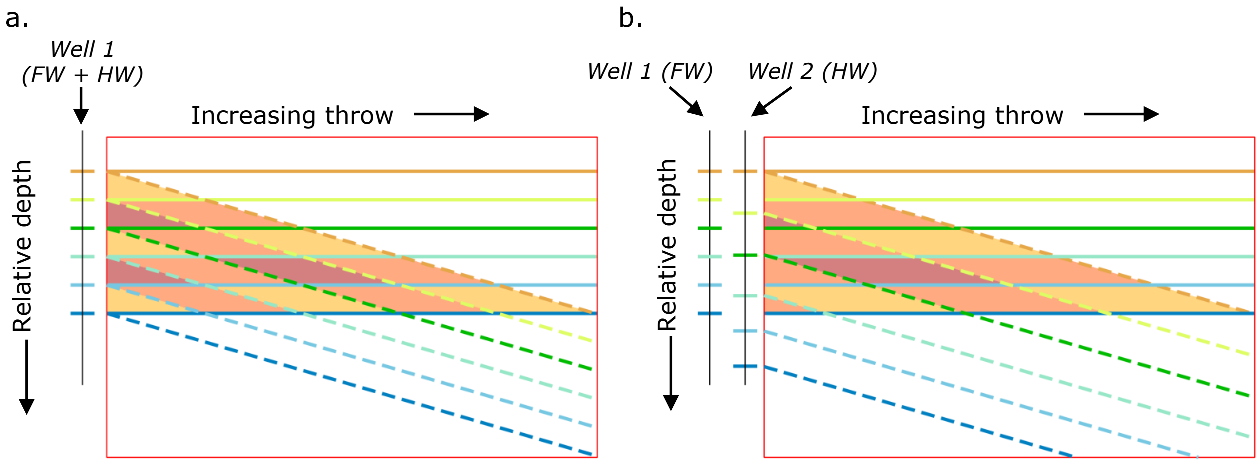

Figure 5: Illustration showing how two wells can be incorporated into a Fault Triangle diagram that is coloured according to the across-fault lithological juxtaposition. (a) Fault Triangle diagram where a single well is used to define the stratigraphy in both the footwall (FW) and the hanging wall (HW). (b) Fault Triangle diagram where a second well defines the stratigraphy in the hanging wall (HW); notice that on this plot the hanging wall cut-offs are offset at the left-hand side of diagram due to an across-fault change in thickness.

A second well can be added to the Fault Triangle diagram by toggling on the **Show Hanging Wall** option in the **Display Settings** sheet and selecting the corresponding well from the drop-down list below the well display plot, on the left-hand side of the window (highlighted with red box in Figure 6).

The second enhancement in the Fault Triangle tool in Move, compared to the traditional approach, is the ability to interactively adjust the amount of across-fault thickening. These across-fault thickness changes are incorporated using a slider, located below the main Fault Triangle diagram (highlighted with blue box in Figure 6). Typically, this slider can be used to quickly carry out sensitivity testing to establish the impact any across-fault thickness changes will have on fault sealing capacities. Significantly, this important enhancement need not require any additional data, and can be performed from a single well and a basic understanding of the timing of tectonic activity.

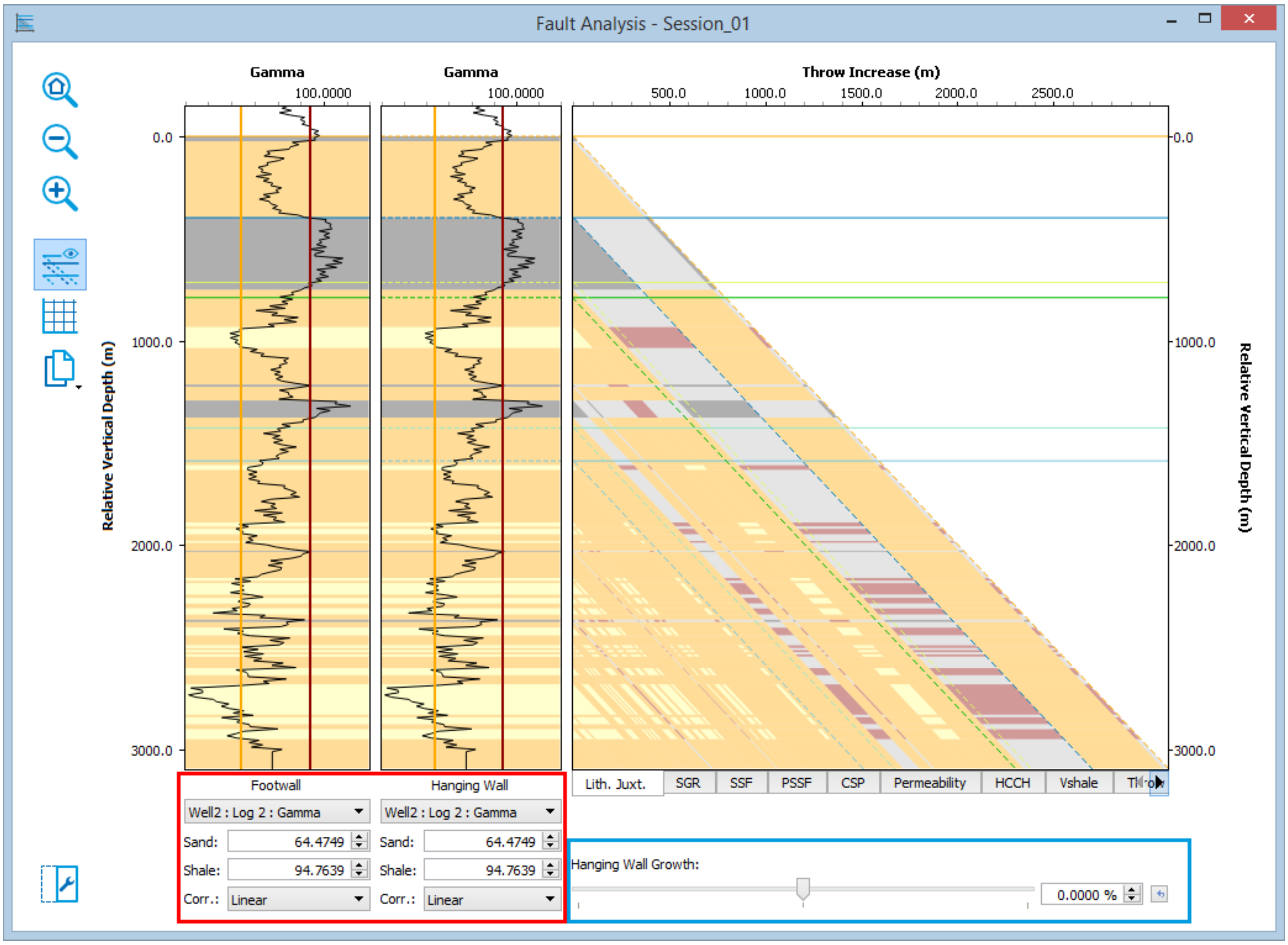

Figure 6: Fault Triangle window showing the lithological juxtaposition when two different wells are used to define the footwall and hanging wall stratigraphy. The different wells are defined using the drop-down list below the plots showing the well data on the left-hand side of the window (highlighted with red box). Across-fault thickness changes can also be incorporated using the slider below the Fault Triangle diagram (highlighted with blue box).

The ability to consider across-fault thickness changes can have a pronounced impact on the sealing capacity of faults. This is illustrated in an example below, where Fault Triangle diagrams have been generated with no across-fault thickening (Figure 7a) and with a 20% increase in the hanging wall thickness (Figure 7b). In this example, a 20% increase in hanging wall thickness is shown to reduce the minimum amount of fault throw required to have a complete sealing fault (SGR values >0.2) from ~930 m to 500 m; this could dramatically increase the number of possible fault-bounded hydrocarbon traps across an extensional basin.

a.

b.

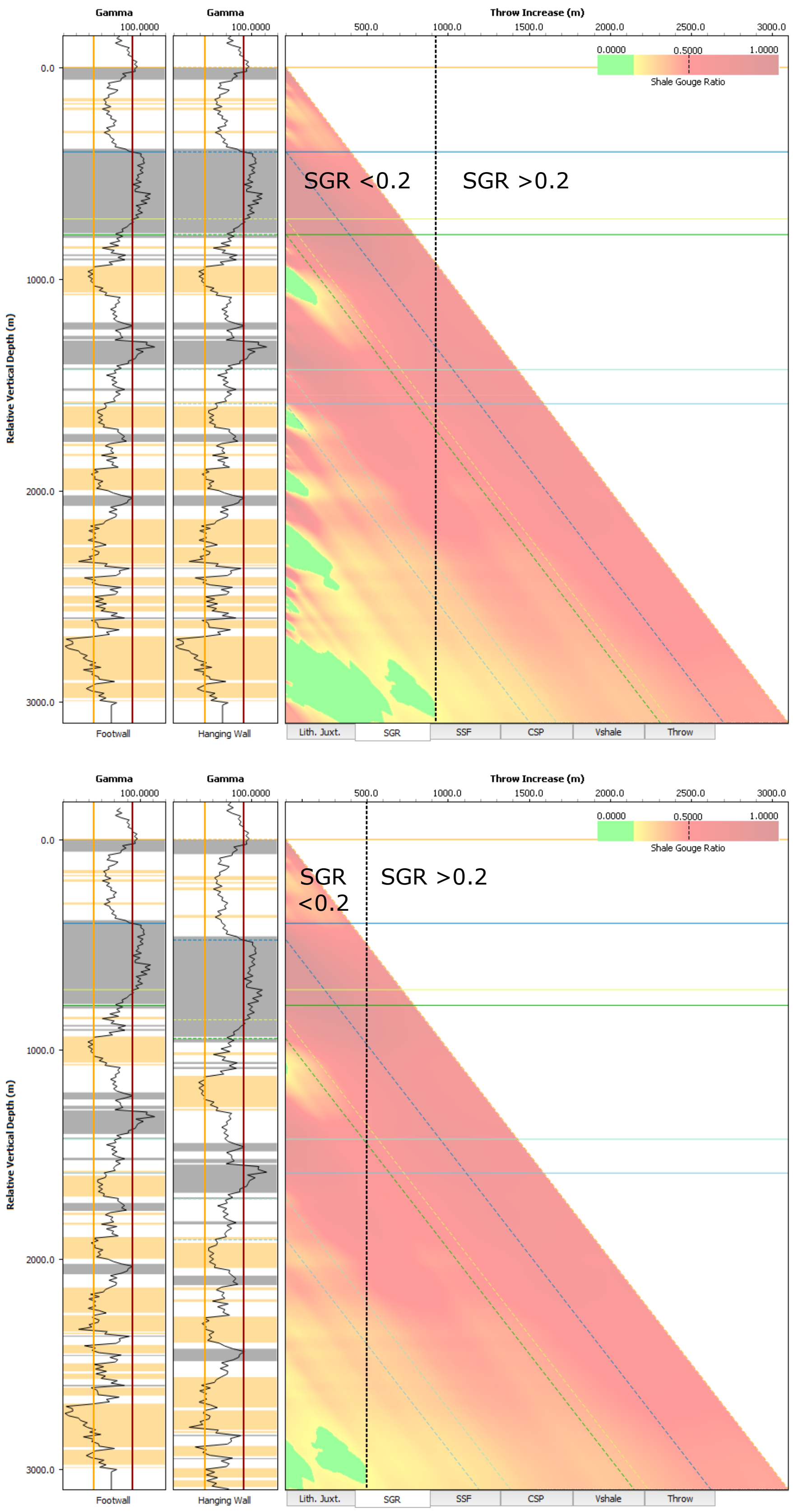

Figure 7: Fault Triangle diagrams showing differences in Shale Gouge Ratios (SGR) resulting from across-fault thickness changes. (a) SGR plot with no across-fault thickness change. (b) SGR plot with a 20% increase in the hanging wall thickness. Vertical black dashed line shows the amount of throw required for faults to have SGR values >0.2 and completely seal.

References

Childs, C., Sylta, Ø., Moriya, S., Morewood, N., Manzocchi, T., Walsh, J.J. & Hermanssen, D. 2009. Calibrating fault seal using a hydrocarbon migration model of the Oseberg Syd area, Viking Graben. *Marine and Petroleum Geology*, **26**, 764-774.

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Lindsay, N., Murphy, F., Walsh, J. & Watterson, J. 1993. Outcrop studies of shale smears on fault surfaces. *The geological modelling of hydrocarbon reservoirs and outcrop analogues*, 113-123.

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Yielding, G., Walsh, J. & Watterson, J. 1992. The prediction of small-scale faulting in reservoirs. *First break*, **10**, 449-449.

If you require any more information about Fault Triangle diagrams in Move, then please contact us by email: enquiries@mve.com or call: +44 (0)141 332 2681.