Fault seal analysis: sensitivity to modelling methods and uncertainty therein.

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A significant proportion of the world's conventional petroleum reservoirs occur in structural traps. Therefore, understanding the controls on structural geometry and fault seal are crucial steps in modelling/predicting hydrocarbon accumulation. One of the principal mechanisms by which faults are fluid-retaining is membrane seal; this is where smeared 'clay minerals' form impermeable barriers along structural planes. The following study shows that estimates of fault seal can be highly sensitive to the type of methods used to model the fault rock properties. Three methods were employed: B-Spline; SGS and a combined SGS+MPS method. The results suggest that, given the same structural model and well data, the pattern of fault seal integrity along the fault plane can vary considerably depending on the method used. Furthermore, stochastic methods (SGS and SGS+MPS) illustrate how uncertainty associated with the reservoir attributes (fault rock properties) propagate through to the final fault seal model. Therefore, uncertainties in fault seal estimates are fundamentally related to uncertainty in the faulted rock properties. The use of stochastic methods also helped illustrate the point that fault seal and reservoir properties are 'coupled' in an inverse sense so that fault seal will improve at the expense of reservoir quality.

Keywords: *geostatistics, T7, fault seal, sensitivity, uncertainty.*

Introduction

Phyllosilicate minerals, such as illite and muscovite, tend to deform along crystallographic fissile 'sheets' lending themselves to plasticity at a granular scale even under low differential stresses; the opposing mechanical end members being rigid minerals such as quartz or feldspar. The outcome of this 'plastic' behaviour is that phyllosilicate minerals can, and not withstanding that they have variable affinities (wettability: oil or water wet), form a barrier to fluid flow when smeared over structural planes. Estimates of phylloscilicate content is therefore important for many engineering fields.

The term shaliness is often used to denote the relative proportion of phyllosiciate minerals to total solid rock volume. Therefore, it follows that the relative degree of shaliness of different stratigraphic units will determine the degree, and extent, of shaliness within the fault 'plane' (i.e. between the faulted country rock complements: hangingwall and footwall planes), albeit modulated by the degree of movement along the structural plane. Perhaps the most widely applied method of modelling this smearing process, and its economic implications, is the shale gauge ratio (SGR: Yielding *et .al.*, 1997). The following study demonstrates that it is advisable not to treat the structural components, in terms of 'kinematical' arrangements, in isolation of the full geological characteristics of the country rock and visa-versa. In short, the sealing potential of a fault is not just a product of gross vertical changes in shaliness but also lateral variations in shaliness and whether these are discrete or continuous; the converse being that the nature of conducti across lateral units is a function of the mechanical environment and kinematic arrangement after faulting as well as sand body geometry.

The following study attempts to assess how modelling methods affects predicted fault seal integrity by holding all else constant (*i.e.* wells, structural model etc.) Admittedly, the geological model is contrived, so that while being derived from a real geological scenario, the reservoir property modelling is constrained by both real and simulated well data. Three modelling methods are used to assess the sensitivity of SGR patterns to modelling methods and associated uncertainty captured by stochastic methods.

It should be highlighted that the suggested workflows, from geocellular creation and property modelling right through to fault attribute modelling, took only an hour using a desktop PC with modest specifications. Therefore, the limitations often traditionally assumed as prohibitive, such as CPU constraints and time limitations, are now largely overcome by modern multithreaded G&G modelling software such as T7.

Methods

Geocellular model generation

A structural model was constructed after detailed interpretation of a 3D seismic volume (Fig. 1). Using the structural model shown in Figure 1, a corner point grid (CPG) was defined for the proposed reservoir; the reservoir interval is bound by the two modelled horizons. The geocellular model produced using the CPG had cellular dimensions of 300x300 with 30 layers, corresponding to model dimension of c. 15km x 13km x 900m. The models were then populated with reservoir properties using well data from both real and pseudo-wells.

Well data

Two well logs were used, lithofacies type and V-Shale. Three lithofacies were chosen based on a deltaic conceptual model: channel sand, levee silt/sand and interchannel shale. The channel sands represent the principal reservoir units, the levees marginal reservoir units and the interchannel non-reservoir.

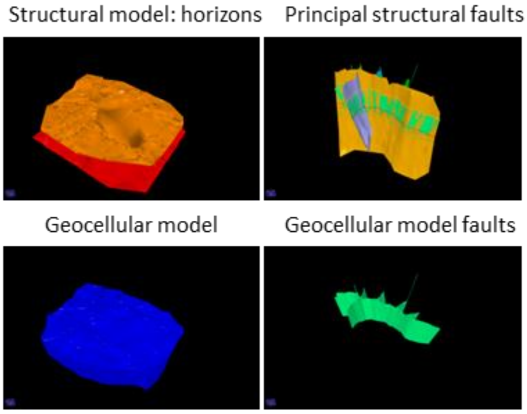


Figure 1. Principal components of the structural model and the derived geocellular model.

The lithofacies log was composed of a series discrete integer codes representing expected facies types (1=channel, 2=levee and 3=interchannel). The lithofacies codes are derived from the respective V-Shale values along the well path: <0.35 = channel; 0.35-0.50 = levee and >0.50 = interchannel.

A total of 20 wells including both vertical and deviated wells were used.

Reservoir properties

The geocellular grids were populated with reservoir properties using the well data. Control cells were determined from the well trajectory-cellular intersections; for the V-Shale attribute the well data was upscaled to cellular values using a simple arithmetic mean for the intersected portion of the well trajectory, the same approach was used for the lithofacies codes but the mode rather than arithmetic mean was used as the upscaling method. Once the geocellular models were populated with V-Shale values, the cellular fault attributes (such as the SGR) were synchronised for all the fault planes.

Fault attribute modelling workflows

In order to assess the relative sensitivity of the SGR results to modelling method, a number of strategies were employed, hereafter workflows. All the workflows follow a general form (Fig. 2): 1) Populate the geocellular models with reservoir properties (incl VShale); 2) assign VShale values to the FW and HW fault planes (VShale fault attribute); 3) determine throw from vertical offsets across the faults; and finally compute SGR and all derived attributes using a combination of 2 and 3. Steps 2 and 3 are fully automated, the step being commonly referred to as fault attribute synchronisation. The workflow names are inherited from the methods employed in step 1: B-Spline, SGS and SGS-MPS (i.e. B-Spline workflow, SGS-workflow and SGS-MPS workflow).

Property modelling methods

The first approach (B-Spline workflow) uses a simple deterministic approach were V-Shale was modelled on a layer-by-layer basis using a B-Spline (Figure 3). The second approach (SGS workflow) uses a stochastic method, stochastic Gaussian simulation (SGS). As a stochastic method SGS has the advantage of being able to produce many non-unique realisation (Fig. 4), which can be accrued for the purposes of uncertainty analysis via probabilistic methods. The SGS method employs a modified, sequential implementation of the 'kriging paradigm' and therefore requires variogram model definition (for a full description of SGS see Ch. 7, Duestch, 2002); the lateral and vertical variogram models are presented in Fig. 4.

The final approach (SGS-MPS workflow) has two steps: 1) produce a facies model and 2) model V-Shale on a facies-by-facies basis using the aforementioned SGS workflow. The facies modelling method employed multiple-point statsitics (MPS), a stochastic approach that produces a host of non-unique but equi-probable facies models (Fig. 5). These modelled scenarios are typically assessed in terms of connectivity and net:gross (Fig. 5) in order to capture associated uncertainty in both. In most instances one might be interested in a number of models (e.g. best, middle and worst connected), but for this study only one need be used; the focus of this study is not a comprehensive evaluation of reservoir attributes, but rather how different modelling approaches affect the outcome of SGR patterns on fault planes. The variograms for the different facies types are presented as part of an Appendix.

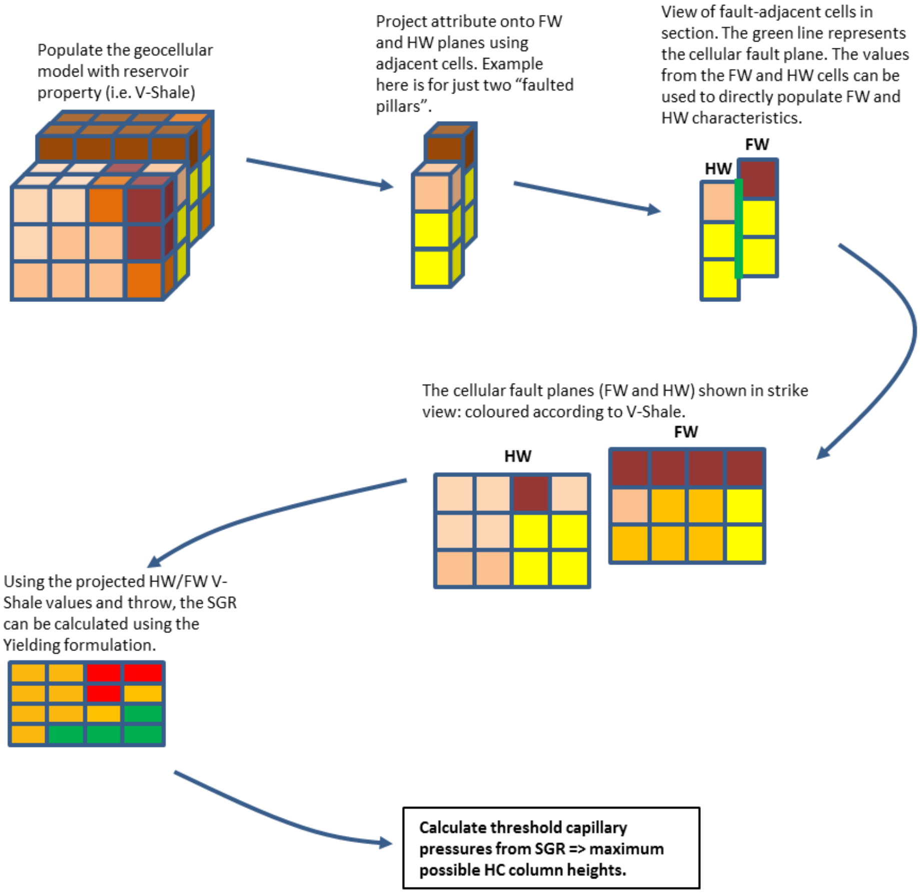


Figure 2. The generalised fault attribute modelling workflow. The entire workflow is automated, so once the model parameters are set the process.

Results

A cursory glance of the results from the three different workflows illustrates a number of clear differences between each technique (Fig. 6). Firstly, the B-Spline being a deterministic method provides only one VShale solution, and by extension, SGR model (Fig. 7), while the stochastic methods provide a series of probabilistic solutions; three are shown for each of the stochastic workflows and are derived from what are considered to represent the worst, best and middle reservoir cases (Figs. 7). Secondly, both the B-Spline and SGS workflows, both of which are global methods (*i.e.* they treat the reservoir as a single lithofacies), produce continuous (smooth) changes in the fault attribute values along the fault plane. In contrast, the SGS-MPS workflow, which typically creates discrete changes in reservoir VShale, produces discrete fault attribute patterns both in the lateral and vertical directions.

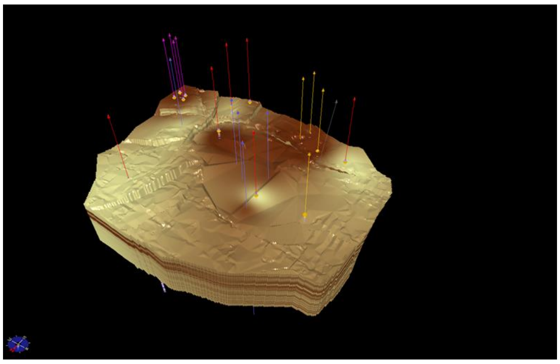


Figure 3. The B-Spline VShale reservoir property model. The wells have been included as a guide to their distribution and density. **The same wells are used for all other methods**.

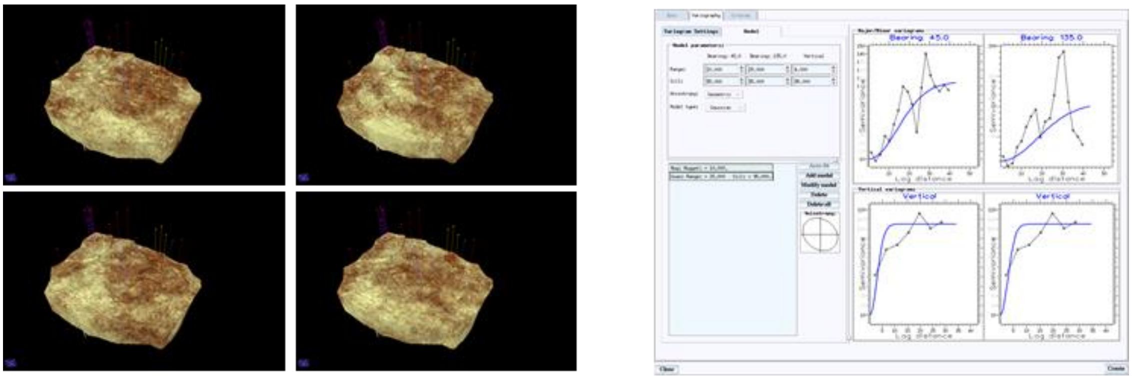
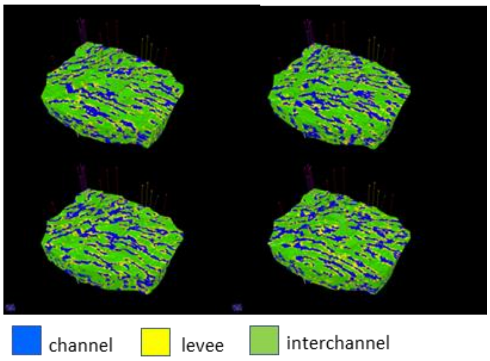


Figure 4. Four SGS realisations (from a possible 50) of modelled VShale. To the right, the experimental variograms and fitted models used for the SGS workflow. Note that the variography and SGS modelling was carried out in topological space to ensure depositional changes in V-Shale were preserved across faults.

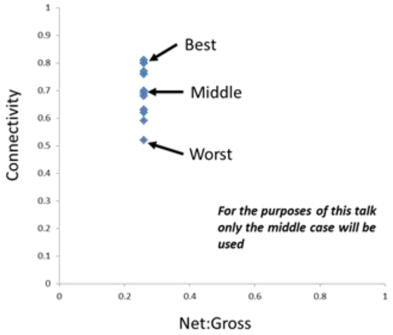
A) Modern depositional analogue

Conceptual facies model derived from the Lena Delta, Russia. Image reproduced from Wikipedia. Red square represents the scale of modelling.

B) Examples of simulated outputs



C) Results from suite of simulations



For the purposes of this talk only the middle case will be used

Figure 5. Summary of lithofacies modelling approach. A) The modern analogue used to inform the training image and conceptual model. B) Four MPS realisations (from a possible 50) lithofacies models. C) Connectivity vs Net:Gross plot for the 50 simulated models.

B-Spline workflow vs SGS workflow

Comparing results in a less generalised way, confirms the high sensitivity of the SGR fault attribute models to workflow. Comparisons between the outputs from the SGS workflow - using three main principal reservoir case scenarios (P10, P50 and P90; best, middle and worst respectively) and the B-Spline workflow (Fig. 6), shows that variability in SGR computed is less “laminated” using the SGS workflow. The reason for this lies in the nature of the VShale model, from which the SGR is partly derived. To expand, each SGS simulation (VShale simulation) is informed by the variogram models, therefore, the presence of “spatial autocorrelation” in the vertical direction (Fig. 4), will be expressed in each simulation and become compounded when all the solutions are treated using a summary statistic. In contrast, the B-Spline method was employed on a layer-by-layer basis. The projected VShale values on the respective FW and HW planes vary in accordance with the nature of the reservoir property model, which via the FW/HW VShale models, propagates through to the modelled SGR. It might follow then that that the B-Spline workflow is naïve in that it fails to capture real vertical trends in reservoir properties, but it is also important to acknowledge that stratification is very significant even when subtle. Furthermore, the fact that uncertainty beyond the lateral range of the variogram models is constant,

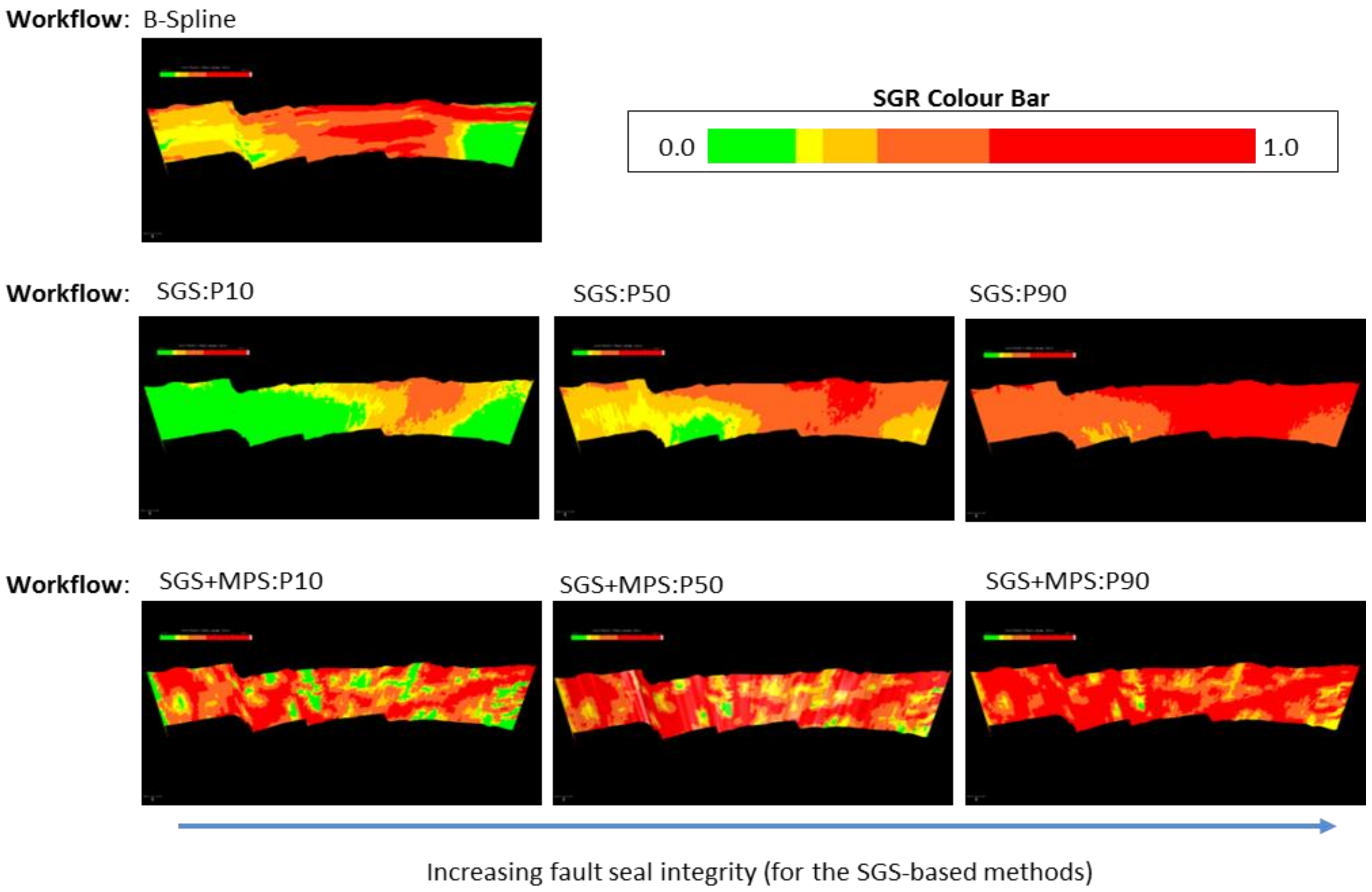


Figure 6. The SGR results for the main fault. Note the difference in SGR patterns between the three workflows. Most noteworthy, is the discrete lenticular nature of the SGS+MPS approach, highlighting the sensitivity of modelled SGR to reservoir architecture. The range of results for the stochastic methods (three cases are shown), also illustrates the need to appreciate the degree of uncertainty associated with reservoir VShale values and how these translate into fault attributes.

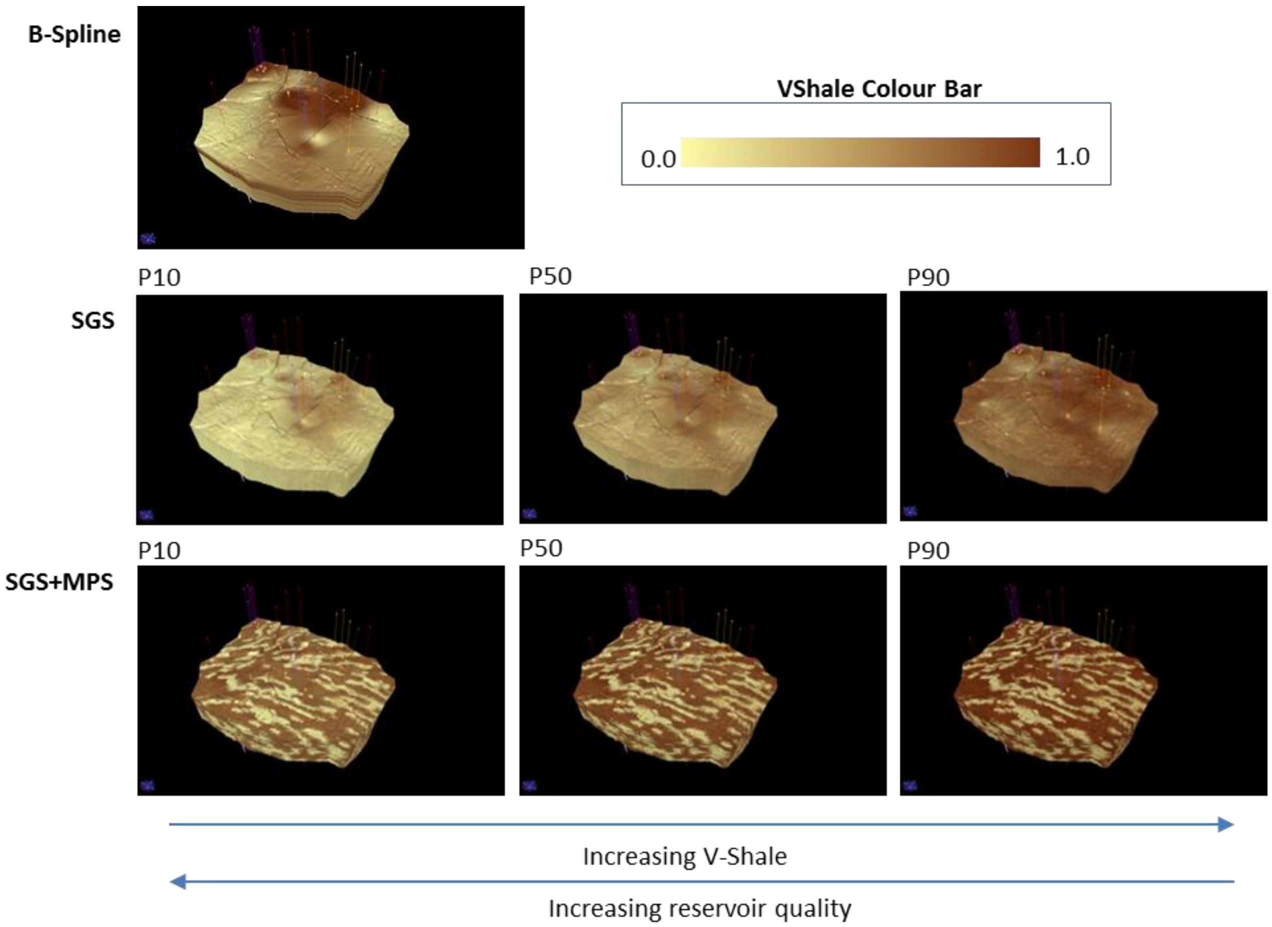


Figure 7. Summary diagram of the main findings of the VShale property modelling step. Three scenarios are selected from the SGS and SGS+MPS simulations. The choice of percentile cases (P10, P50 and P90) were chosen in order to capture both central tendency and end members implied from the range of uncertainty captured (per cell) by the suite of stochastic simulations.

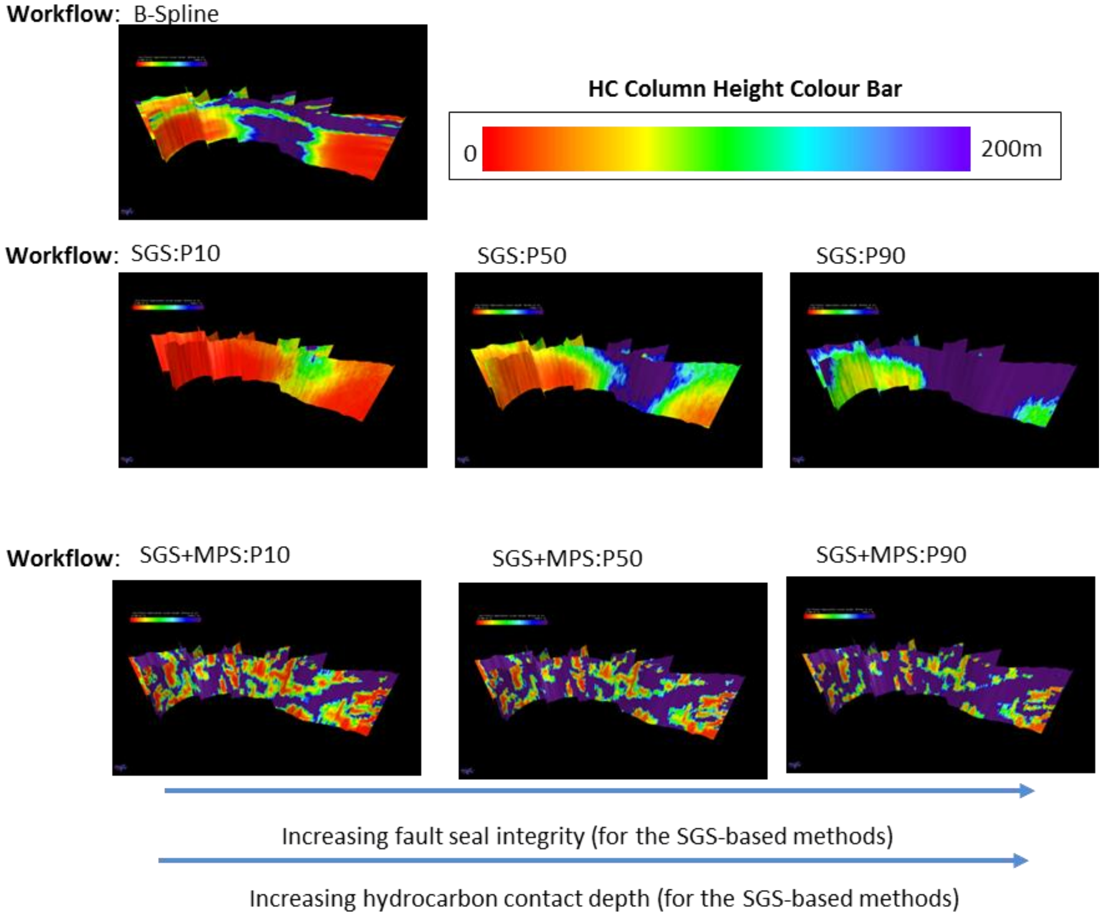


Figure 8. Overview of the hydrocarbon (HC) column heights computed via the SGR models, produced using the three different workflows, for all the cellular faults. Again one should note significant changes in the pattern of HC column height depending on the modelling method used and associated uncertainty as captured by the stochastic workflows. HC column heights are computed using the methods presented in Bretan *et al.* (2003)

means that the degree of smoothing beyond such distances from the control cells (wells), may lead to loss of vertical detail when using 3D geostatistical methods such as SGS. At this point it is also important to acknowledge that the SGR model derived from the middle SGS case and B-Spline workflow are quite similar, and that the SGS modelling method can be applied on a layer-by-layer basis. However, it also should be note that the SGS workflow highlights that there is a great degree of uncertainty pertaining to SGR along the fault when uncertainty in reservoir VShale are properly considered (i.e. wide range of SGR values between those derived from the P10, P50 and P90 case scenarios).

SGS-MPS workflow

As stated earlier, the SGS-MPS workflow produces very discrete patterns in SGR and by extension sealing potential. This is highlighted further when assessed in detail against the other two techniques (Fig. 6). This has significant implications for fault sealing potential and hydrocarbon column height. For example, given a simple two-way enclosure (single fault and top seal) were the closing fault is the one presented in Figs. 6. One can see that the B-Spline and SGS workflows suggest that the faults will seal due to the high lateral continuity in SGR along the top of the fault, and therefore, should theoretically support hydrocolumn columns; hydrocarbon accumulates down to the structural spill-point (modelled H/W contact superimposed on the faults). This is very unlikely when changes in reservoir lithofacies are accounted for via the SGS-MPS workflow. For all reservoir cases (P10, P50 and P90), the SGS-MPS workflow produces discrete lateral changes in SGR and sealing potential. As a result, the faults are less likely to be sealing and will leak before accumulations reach any structural spill-point. In short, one would not expect significant accumulations for the given trap, if there is significant internal reservoir heterogeneity as found in a fluvial system.

SGR uncertainty analysis

What should be clear from the above work is that SGR responds to changes in modelled reservoir VShale. This may seem intuitive, but is often overlooked during routine structural analysis of trap viability. What should be clear is that the P10 VShale case (for both the SGS and SGS-MPS methods) correspond to typically the lowest SGR values and lowest sealing potential along the fault while the P90 cases, representing the poorest reservoir properties, produce the highest SGR values and therefore greatest sealing potential (Gigs. 6 and 7). In short, there is typically an inverse relationship between reservoir quality and sealing potential when the entire reservoir system is treated holistically and can be considered “coupled” in an inverse sense.

To quote from the introduction:

“…it follows that the relative degree of shaliness of different stratigraphic units will determine the degree, and extent, of shaliness within the fault ‘plane’…”

Therefore, to model uncertainty in SGR one most account for uncertainty in the reservoir first.

Economic considerations

It should be obvious from the above discussion, that the any sensitivity of SGR to modelling workflow has significant economic implications. Figure 8 reflects this, here one can see that the lateral discontinuity in HC column height derived from the SGS+MPS workflow is much higher than the other two methods, cementing the finding that hydrocarbon accumulation can be less likely if reservoir properties respect – discrete - internal reservoir heterogeneities.

Conclusion

The results from the current study highlights the sensitivity of SGR models, and derived attributes, to the type of modelling workflow employed in generating the FW and HW VShale models. Furthermore, it might be possible to assess fault seal uncertainty, and the magnitude of that uncertainty, using a range of potential VShale reservoir scenarios derived via probabilistic methods. This was done successfully using the T7 software.

What should also be clear is that fault seal integrity does increase at the expense of reservoir quality. Therefore, there can exist, an inverse coupled relationship between reservoir quality and fault seal integrity. Taken together, it should be clear that treating the reservoir and fault attributes as disparate issues is likely to lead to grave inaccuracies even when the models may appear precise (i.e. significant level of detail).

References:

Bretan P., Yielding G. and Jones H. (2003). Using calibrated shale gouge ratio to estimate hydrocarbon column heights. AAPG Bulletin, 87, 397-413.

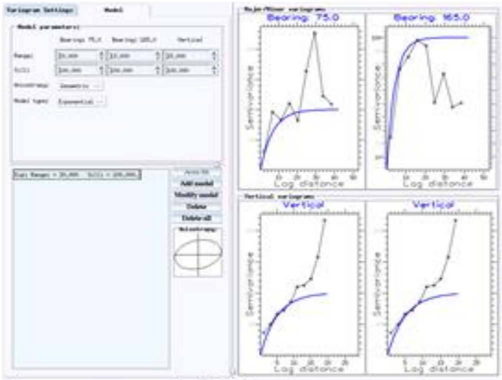
Deutsch, C.V. (2002). Geostatistical reservoir modelling, Oxford University Press, Oxford.

Yielding G., Freeman B. and Needham T. (1997). Quantitative Fault Seal Prediction. AAPG Bulletin, 81, 897-917.

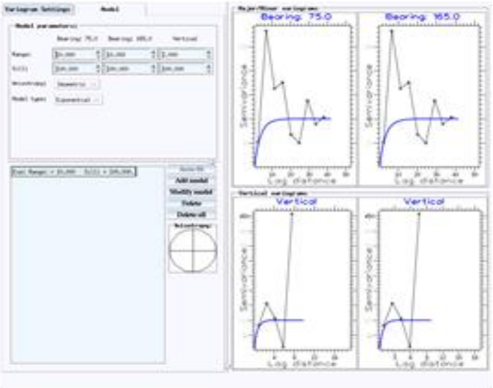
APPENDIX

Variogram models derived for the VShale attribute for each lithofacies type modelled.

Channel Sands



Levee sands/silts



Interchannel Shales