Chris Cubitt, Barbara Stummer, Wilfried Gruber, Robert Rieger and Reinhard Lind, HOT Engineering, Austria, present clastic reservoir characterisation from the core shed, logging truck and vibroseis to a simulation model.

IN CHARACTER

Fundamental to reservoir understanding and, ultimately hydrocarbon recoverability, is the analysis and interpretation of the producing rocks. Such an old fashioned idea has found considerable traction in the last 10 years with the rise of static and dynamic modelling, demanding an ever more accurate picture of reservoirs. Such a notion demands two things: that the reservoir data used is reliable and plentiful enough to garner an accurate rendering of a reservoir and that the description and interpretation of the collected data is pragmatically carried out and reliable. The following article will attempt to outline a workflow that addresses these notions (Figure 1).

The reservoir characterisation strategies presented in this article have been successfully employed by the HOT Engineering consulting group over the last few years, enabling geoscientists and engineers to convert disparate, often incomplete and highly varied reservoir data acquired in the core shed, on the seismic shoot, in the logging truck and on the rig, into consistent and workable geo-static and dynamic models.

Core shed: rock-based characterisation and integration

Reservoir understanding does not of course begin in the core shed. The basis of hydrocarbon reservoir investigation begins with petrophysical determinations (pay analysis)

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and stratigraphic correlation, whereby the liberal use of biostratigraphic data goes a long way in 'nailing down' most problem well to well correlations. Following standard sequence stratigraphic ideals (i.e., flooding to flooding surface correlation) and a check of corresponding seismic picks and clinoform intersections (erosion, top, bottom and onlap), a reservoir correlation 'skeleton' can be quickly constructed. This reservoir (and non-reservoir) 'skeleton' becomes the basis of reservoir characterisation with log, core and seismic data filling in the gaps of understanding.

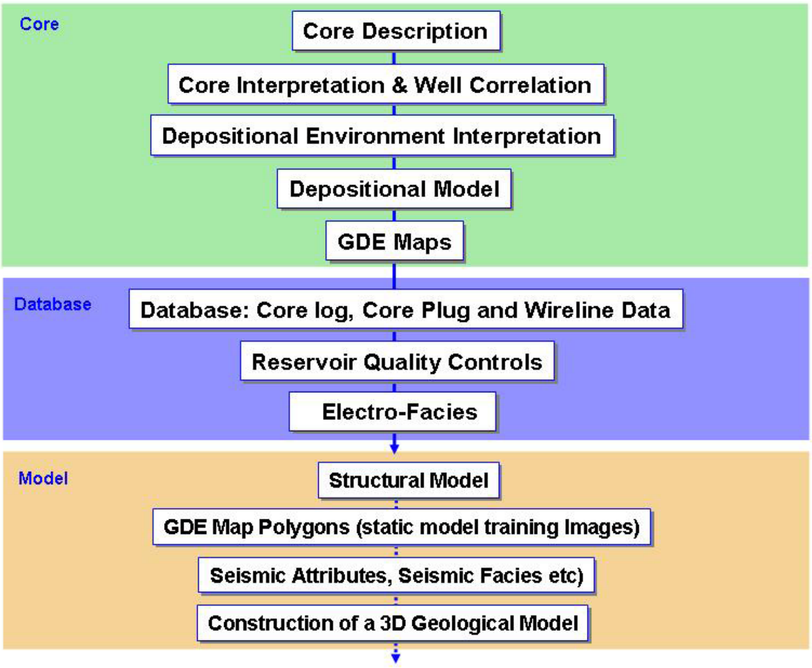

Figure 1. *Reservoir data acquisition to geo-static model workflow.*

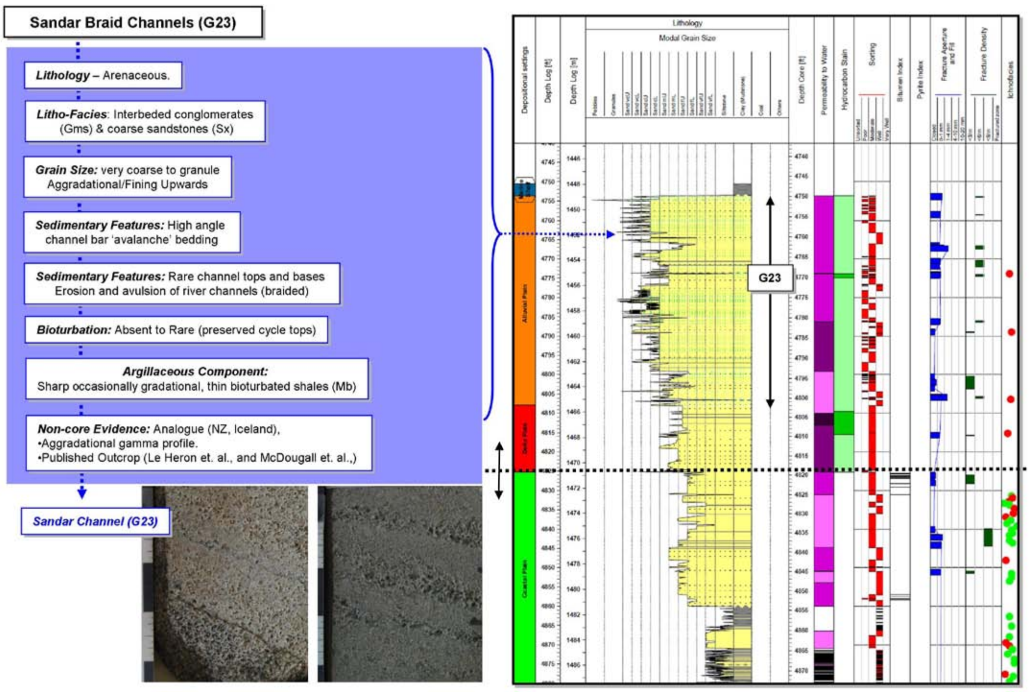

Figure 2. *Example depositional environment interpretation criteria with respect to the interpretation of a braid channel environment. This interpretation is then directly compared to seismic, wireline and BHI responses and becomes the basis for the GDE map to static model workflow.*

Following on from stratigraphic analysis, the description of core material, no matter how fragmentary, is a key step. Drill cuttings if they are of sufficient quality and interval spacing (3 m – 5 m) can also be useful at this stage to help increase 'rock' coverage. The analysis of core/cuttings (c&c) material can shed new light on old understandings. Often, descriptions of c&c, with respect to depositional environment, can alter perceptions of net to gross, reservoir interconnectivity and geo-body shapes (meandering river channels – ribbons as opposed to a shore line – sheets).

Being then, such a critical piece of the reservoir puzzle, how are depositional environments interpreted consistently? At HOT, depositional environments are considered as packages of sediment that have formed in specific geological conditions (i.e., a braided channel environment or a lower shoreface environment etc.). The company does not make lithology or grain size assertions regarding environments (i.e., fine grained delta etc.), as lithologies and grain sizes vary from like environment to like environment. In this context, depositional environment 'packages' are pragmatically defined according to a set of predefined criteria that include an adapted litho-facies scheme (i.e. massive sandstone = Sm; bioturbated heterolithic – Hb etc.), sedimentary features, bioturbation, as well as depositional package juxtaposition, associated wireline profile, analogue/outcrop considerations and regional context.[1]

Such a pragmatic interpretation scheme leads to a classification simplification of possible depositional environments. This is a key point. All depositional settings are festooned with ever differing depositional environments. HOT's scheme attempts to constrict and simplify the choice of environment so that all environments can be compared and ranked according to rock properties, which along with the gross depositional environment (GDE) map allows a geo-static model to be constructed.

Figure 2 illustrates by way of example the pragmatic interpretation of a braid channel dominated interval. Interpretation of the entire cored intervals is made in the same manner that a continuous depositional environment 'log' is made. A core reservoir log is then constructed containing all data, descriptions and interpretations relating to the cored interval. This enables parasequence scale geological interpretations and direct relationships with respect to wireline logs and seismic response.

Reservoir quality (RQ), or hydrocarbon deliverability, for all reservoirs is a key economic criterion. To gain this understanding of rock reservoir quality/deliverability is notoriously difficult with the main problem being access to sufficient rock material to produce meaningful and predictable associations. In this regard production behaviour, whether it is from production or test, provides the ultimate measure of reservoir quality. However if test information is unreliable or nonexistent it falls to the rocks to gain RQ context. From a rock perspective, RQ has been traditionally scrutinised using core plug data (i.e., porosity/permeability), thin section petrology, XRD, SEM and CL techniques along with drill cuttings analysis (rock typing).

The latter technique – rock typing – is an 'old' technique[2] that has been utilised to great commercial effect in the past decade[3] whereby drill cuttings are used in low deliverability reservoir zones to ascertain interval permeability (permeability height or KH) and ultimately flow rate prediction.[3] All of these techniques have strengths and weaknesses and need to be employed at various 'toll gate' points in a typical RQ project cycle in order to gain maximum effect. Figure 3 illustrates this point with the various techniques being used according to the quality of the reservoir rocks.

Figure 3 also shows how all rock information is distilled down to ever simpler reservoir concepts. In essence the complexity of core interpretations, reservoir quality analysis, reservoir producibility analysis are all 'rolled up' into a simplistic picture that honours the geological complexity. The next crucial step is

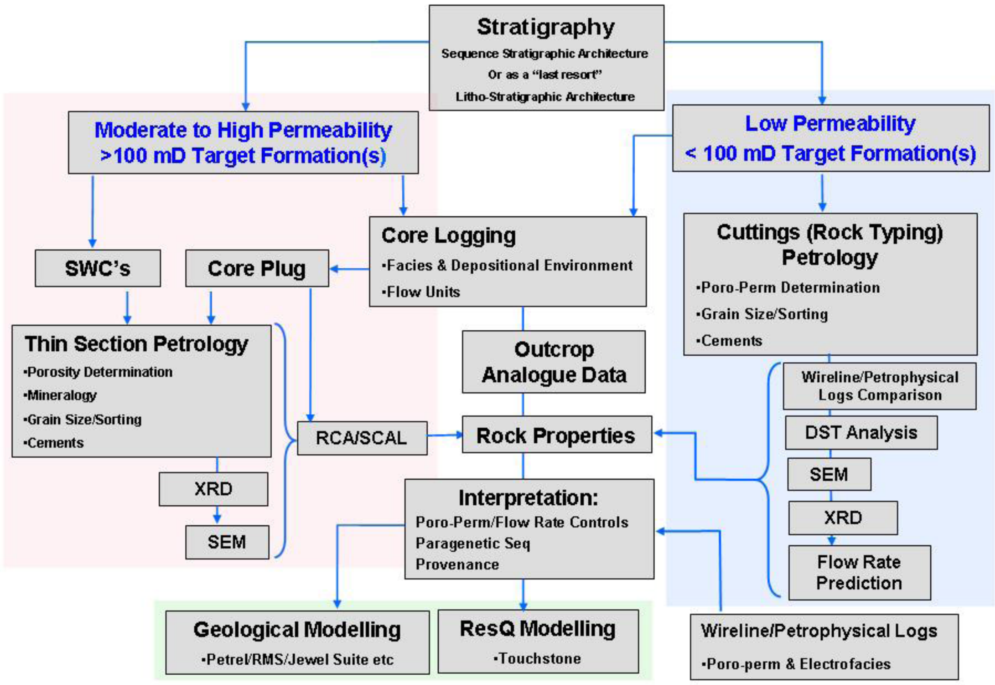

Figure 3. *Reservoir quality flow chart.*[4]

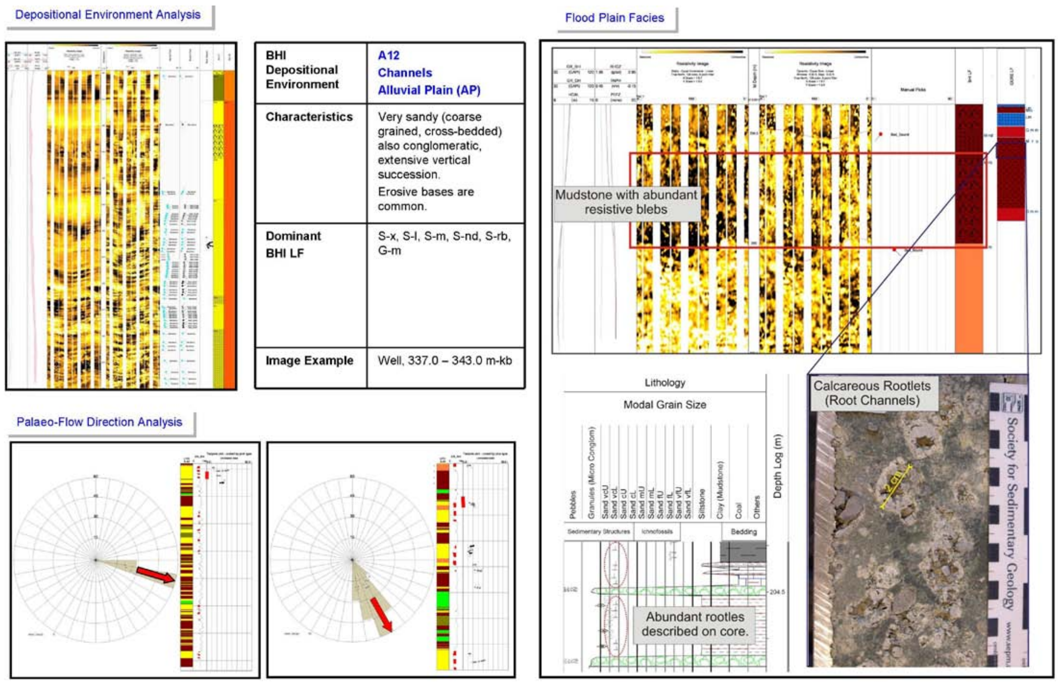

Figure 4. *An example of core-BHI similarity and concurrent paleo-flow analysis.*

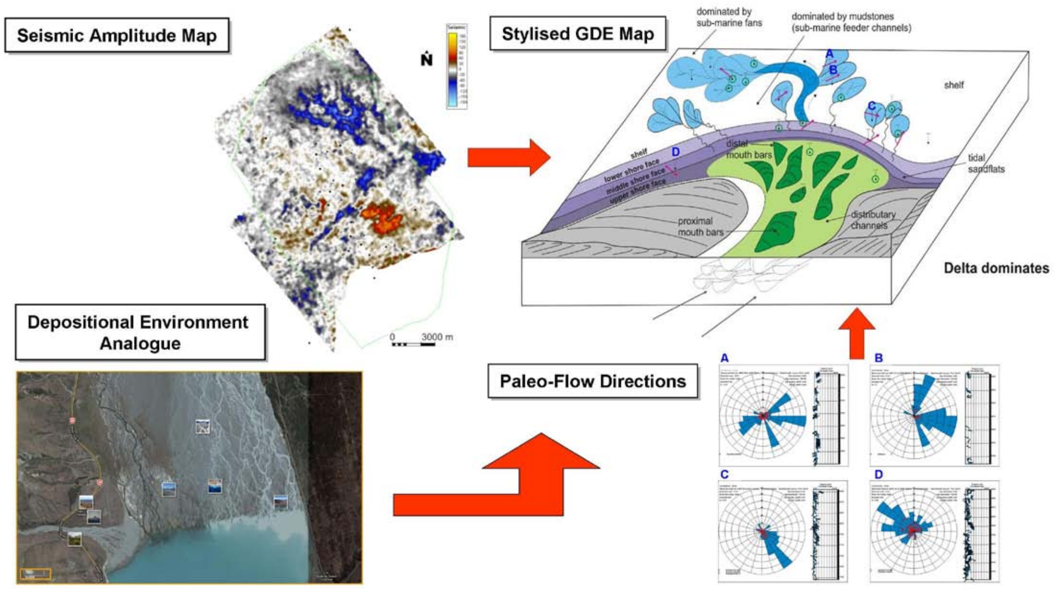

Figure 5. *An example illustrating how seismic amplitudes, depositional analogues and paleo-flow data constrains GDE geo-body size and orientation.*

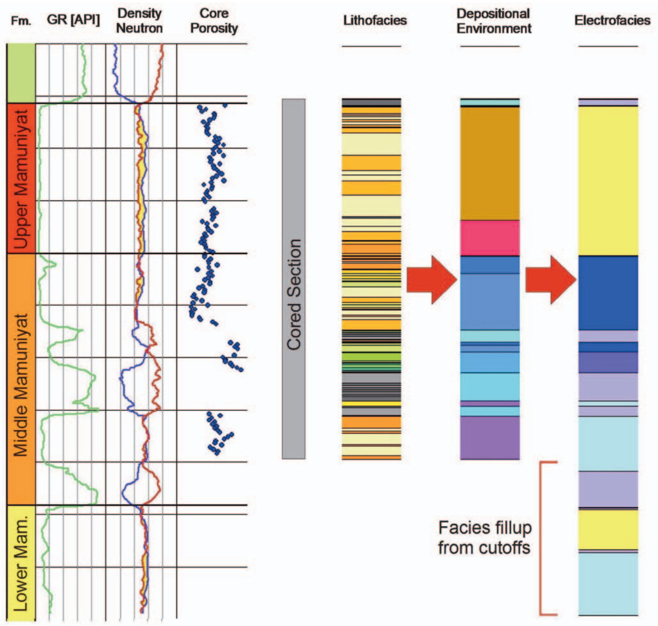

Figure 6. *Commingling core-based litho-facies and depositional environment into electro-facies.*[8]

to move these simplistic geological concepts away from core control to non-cored intervals and areas. Ultimately, the final goal is being able to relate common geological concepts in order to produce reservoir specific simplified geo-body maps called gross depositional environment (or GDE) maps. To reach this stage however, it is necessary to incorporate wireline logging and seismic extraction data.

Logging truck: image log characterisation and integration

Standard wireline logs such as gamma ray (GR), SP, sonic, nuclear, resistivity are the most common open hole logs (OHL) available for reservoir analysis. HOT employs the facies log approach in which core/cuttings defined porosity/permeability cut offs, as well as GR or SP slope trends are used to propagate depositional environments in non-cored intervals.

These electro-facies logs are critically compared to core control and adjusted manually where discrepancies are encountered. Following this the electro-facies logs are then used in conjunction with core and BHI to define 'like' depositional environment zones, or gross depositional environment regions.

The use of borehole image logs (or BHI) in reservoir analysis has a long pedigree. Organisations the world over use BHI as pseudo core with the added bonus of being able to gain an understanding of paleo-current flow directions. This is also true at HOT Engineering where BHI logs are treated, as core, in a systematic and pragmatic manner. For example, lithology is interpreted (on the static image) according to their conductivity behaviour with respect to the fluid type and also in comparison with open-hole logs (e.g. GR, density). From these interpretations BHI textures are defined on the dynamic image (laminated, massive, cemented etc.) according to a set of criteria based on core observations. Subsequently BHI litho-facies are defined for all intervals akin to core-based litho-facies.

Following on from BHI litho-facies determinations, depositional environment interpretations are made. These interpretations are made using the same guidelines as core-based interpretations. Using the same criteria aligns both core-based and BHI-based interpretations such that core, OHL and BHI data can be compared equally when constructing GDE maps.

Figure 4 illustrates the similarity of core and BHI interpretations along with paleo-current analysis. The latter is defined over depositional or stratigraphic intervals by firstly removing structural dip and secondly by 'picking' visible bedding dips. Why are paleo-flow directions important? The importance of this data is twofold: not only does an indication of paleo-flow direction help define gross depositional environments, but also this data provides interpretation limits for interpreted GDE map environments needing to make sense with respect to paleo-flow (i.e., distributary channels and mouth bars need to be situated relative to each other in typical down stream flow positions) (Figure 5).

Mapping: seismic and GDE

Gross depositional environment or GDE maps represent the main geological input for each geo-static model layer (based on well to well correlations) being the spatial integration of core interpretation, facies determination from wireline logs, BHI interpretation (litho-facies and paleo-current direction) and isochore, as well as seismic attribute and seismic facies mapping (Figure 5). With regards to the latter two points, seismic extractions (amplitudes, acoustic impedance etc.) and seismic facies interpretations are made and overlain on top of the GDE maps independent of the initial GDE analysis. This is carried out, so as not to introduce bias into the GDE map interpretation.

The dimensions of deltaic and sub-marine depositional elements such as braid/distributor channels and sub-marine channel/fan lobes are determined by applying facies height and width ratios as published by numerous authors,[5–7] along with relative scaling obtained from aerial photography (Figure 5).

The GDE map represents the end point of the geological investigation of the reservoir becoming the so called 'training image' (auxiliary data), from which layer-based geo-static models are derived. Subsequent steps involve creating a static cellular model that honours the geology, reservoir properties and hydrocarbon distributions that ideally enable simulating actual production history.

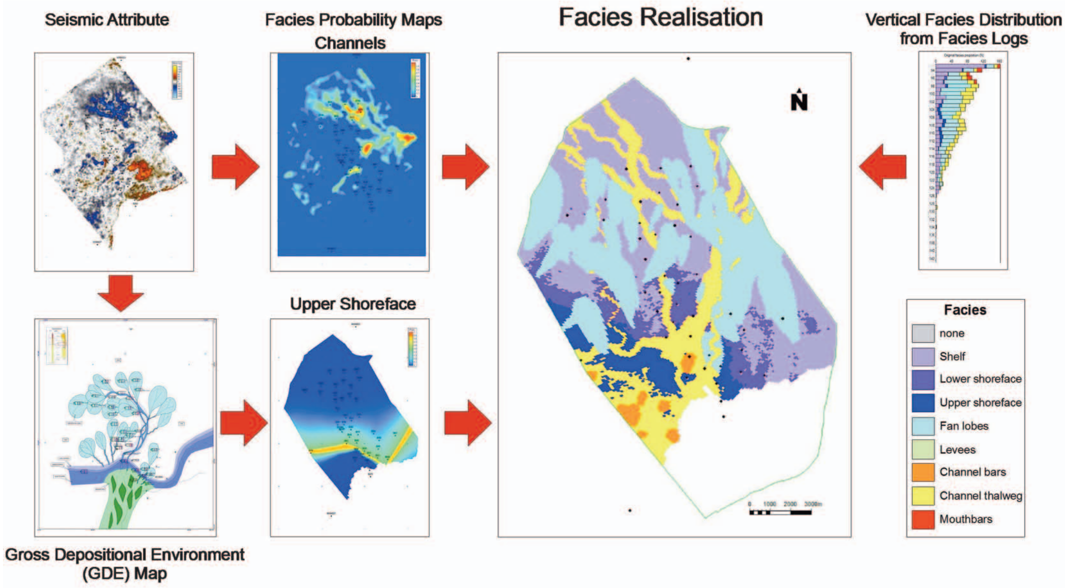

Figure 7. *Facies geo-modelling workflow.*[8]

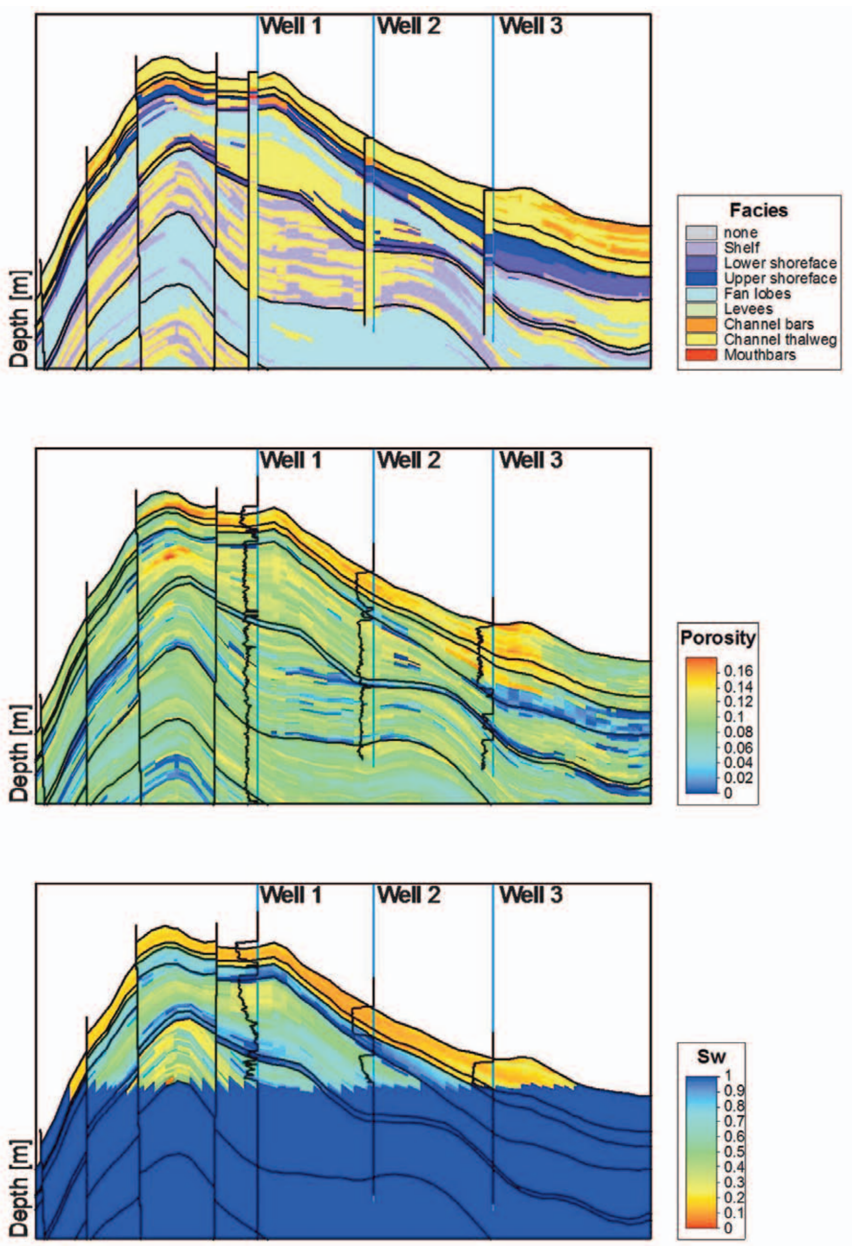

Figure 8. *Examples of reservoir property models.*

Data integration through layer specific facies modelling

The geo-modelling workflow employed by HOT has been fashioned to seamlessly integrate classic core description work via sedimentological characterisation of reservoir layers into a 3D model (Figure 6). Complex depositional environments are handled by combinations of stochastic and deterministic modelling techniques.[8] The geological detail as derived from core logging along with litho-facies depositional environments are carried over to the model by a structured facies commingling process (Figure 6). Spatial control on the modelling processes is provided by seismic attribute maps and the various digitised elements of the associated GDE maps.

Modelling facies, in a vertical sense, across highly variable environments in one single step typically fails. This is negated in most cases by using a structural model that already contains layers that 'gather' genetically related predefined facies bodies (GDE maps). The key then to simplify facies modelling is being able to set up algorithms for each stratigraphic layer. Processes can then be specifically designed to fit simplified electro-facies logs and algorithms according to the type and style of depositional setting of each layer. Furthermore, the spatial distribution of each facies is constrained by probability maps, source points and streamlines as derived from seismic attributes and the GDE maps. This workflow is summarised in Figure 7.

For less complex settings such as fluvial dominated and fully submarine regions, an object modelling approach is typically utilised. In more complex geological settings such as deltas and shore face zones, a combination of background Gaussian modelling with superimposed geo-bodies (fluvial channels, mouth bars, splay-fans, submarine fans, submarine feeder channels, etc.) is used. Most importantly, the geometries of modelled objects are derived from core logs, modern analogues and published literature databases, whilst geo-body orientations are derived from BHI-based paleo-current analysis and seismic extraction maps.

Reservoir property modelling

At the time of distributing reservoir properties into the static model, the major steps of data integration are nearly completed. Modelled geo-bodies and facies patterns are already matched to logs and seismic signatures and their distribution follows sedimentological schemes developed. Subsequent reservoir property modelling is strongly constrained to the facies model in order to capture litho-facies heterogeneity in the rock property distribution. In most cases, stochastic simulations are utilised to populate porosity as well as vertical and horizontal permeability across the model. In addition, saturation modelling is constrained to honour saturation log data at well locations and capillary effects for all rock types specified. The resulting hydrocarbon distribution is used for volume estimates and more importantly form a solid basis for history matching and dynamic simulation.

Flow simulation: integration approaches

One of the primary reasons for making a static geological model is as an input into flow simulation modelling. Objectives of flow simulation are the prediction of future production under various reservoir management scenarios; optimisation of well locations; type of wells: vertical, inclined or horizontal; water injection design or optimisation, etc.

Detailed geological models often need to be upscaled (coarsened) for flow simulation. The grid design of the geological model should be such that upscaling is made easy. Frequently, four neighbouring cells are upscaled into one cell, say from 25 m x 25 m to a 50 m x 50 m grid. In a faulted reservoir one should ensure to have an even number of rows between parallel faults in the fine grid. Combining four rows to two is simple; combining five rows to two creates grid distortions. Common sense should be used with vertical upscaling: cells from different geological units should not be combined; and high and low permeability layers should not be combined.

With today's computers, upscaling is often no longer required for small to medium size reservoirs. A coarse model is often generated even for smaller reservoirs. These coarse models can often run through the history period in a few minutes and are useful to adjust global permeability level, adjust aquifer properties and achieve a global pressure match. Engineering data (production rates, pressures, perforations, workovers, fluid properties etc.) can be checked for plausibility and plotting scales are adjusted to the data.

History matching

Matching is the process of adjusting the geological model such that the historical production/pressure history can be reproduced. Parameters to be adjusted are those that are least known, typically permeability (horizontal and vertical), aquifer strength and size, fault sealing capacity, etc.

With a perfect geological model, history matching should be a trivial task. Unfortunately, this is not always the case! History matching remains as laborious as ever with errors not only in the initial geological models but also inaccuracies in production/pressure data or mechanical problems in well bores that need to be accounted for. This then remains the challenge, with the constant improvement on the 'delivered' geological model a necessity.

Lastly, it should be noted that automated history matching using software tools such as SenEx, MEPO, etc. can be useful to fine-tune a match, but initial history matching should be made by an engineer in co-operation with the geologist. Only when the main parameters affecting the model behaviour have been understood can a software tool be used for fine tuning.

Conclusion

The bottom line is pragmatism and simplicity. In order to model complex reservoir characteristics, a series of set guidelines must be consistently used across all data types (core, cuttings, wireline logs and BHI). Simplifications must be made that still reflect the complexity of the reservoirs but are concise enough to enable modelling. HOT has found that using the GDE facies mapping approach is the best way to make this link between reservoir complexity and modelling simplicity.

HOT over the last few years has used the presented workflow with dynamic models, based on GDE inspired static models, showing reasonable history matches between predicted and actual. Such matches suggest that the reservoir characterisation workflows used currently are reasonable, or at the very least, trending in the right direction! OT

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