Salt gets in your eyes: the geological challenges and solutions to sub-salt exploration

Liz Thompson[1*] and Camilla Oftebro[1] review how geomodelling is maximizing the value of data in salt systems.

Although the prospectivity of pre-salt sequences in many parts of the world has long been suspected, the majority of plays involving salt have been in the supra-salt sequences and their complex and highly dynamic sedimentary systems.

There has been considerable effort in the Gulf of Mexico (GOM) subsalt play throughout the 1990s after Exxon proved commercial reserves with its Mica prospect. At an original thickness of around 1500 m, the source of the GOM salt structures – the Louann salt – is a major barrier, although the sub-salt play in the Gulf of Mexico is beneath the allochtonous canopies and tongues of remobilised salt, rather than pre-salt beneath the mother salt layer itself. The play is a significant one, with finds in the Green and Mississippi Canyons, such as Mad Dog and Thunderhorse, containing up to 1.5 bboe.

A step-change in enthusiasm for drilling through salt came in late 2006 with the discovery of the Tupi field in the sub-salt of the Santos Basin, offshore Brazil. At up to 8 bboe of extractable reserves, the initial find has been followed by a series of huge finds including Carioca, Jupiter, and Bem-te-vi. Today, the pre-salt play is now one of the brightest new prospects for the global oil and gas industry.

The geology that hosts the enormous Brazilian finds is mirrored on the far side of the Atlantic on the African margin, prompting a similar exploration effort in Angola, Nigeria, and neighbouring countries. Expectations are high, but the difficulties are immense. In the supra-salt, for example, it is clearly essential to be able to model the salt in order to model the evolution of the ensuing deposition and predict targets for drilling, but it is also essential to model the salt when exploring beneath the salt.

Although the presence of the salt has little influence on the evolution of the pre-salt play (although the great thicknesses of salt involved can affect porosity development and maturation in the pre-salt), it profoundly affects the ability to see the target and to map and understand the geometries down there.

As both sides of the Atlantic margin hold their vast oil and gas reserves in the syn-rift sequences that were formed in the break-up of Gondwana (see Figure 1), there is a complex and variable structural framework in the subsurface determining the reservoir distribution and the trap styles. Whilst the tectonic processes involved are well enough understood to allow clear conceptual models to be defined, you can't drill wells on a concept, you need a map.

Since fields like Tupi have their reserves held in complex layered carbonates, the smaller scale structural and reservoir characterization issues are considerable. Where is the structure holding the oil? What does it look like? And how heterogeneous and fractured is the reservoir matrix? Given the great depth, around 7 km, and the poor visibility through 2 km of salt, this is not a play where you can just drill the bump. Serious technology assistance is required, not only to locate the reserves but also to extract them efficiently.

With proven reserves of 12.5 billion barrels and estimated reserves of over 90 billion barrels of sweet, light oil, Brazil clearly has a major new play. However, with 5–7 km depth under 2 km of water, 2 km of salt in the section, riser pressures of 200 bars, highly corrosive reservoir environments with high CO_2 and H_2S, and wells costing $100 million each, there are many challenges. One such challenge is the processing and interpretation of the seismic data.

Seismic challenge

The processing and interpretation of the 3D seismic data is a large task. Delineation of top salt can be hard enough on conventionally processed seismic and the interpretation of the sequences obscured by 2 km of highly remobilized salt is a significant challenge. New processing techniques, such as reverse time migration (RTM), are producing seismic imaging of far higher quality from conventionally acquired surveys.

Previous seismic processing techniques would assume that the sound wave has travelled to a reflector and back with a fairly simple path, leading to more scattered energy being regarded as noise. However, this model is too simple to deal with the transmission of waves through salt, where energy can be scattered in different directions.

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Figure 1 *Map of the rift basins generated during the break-up of Gondwana, showing the evident prospectivity of the African margin predicted from the known successes on the Brazilian margin. Image courtesy of Roxar.*

RTM uses the full equation governing the behaviour of seismic waves and therefore can produce a much more accurately processed data set which gives a far better visualization of the pre-salt sequence. Techniques, such as inversion and seismic facies analysis, can have a significant impact on success rates when exploring areas which, at 300 km from land and 7 km deep, are in every sense remote. Figure 2 provides an illustration of how, through RTM, the imaging under the salt can be greatly improved, as is the case here with the Tupi discovery.

The phenomenal increases in computing power in recent years allow for more complicated models like this to be used in seismic processing, but in geological modelling, throwing processing time at the problem is of less use. If geologists don't have the data, they need a model, but without the data, there are obvious issues with building reliable models.

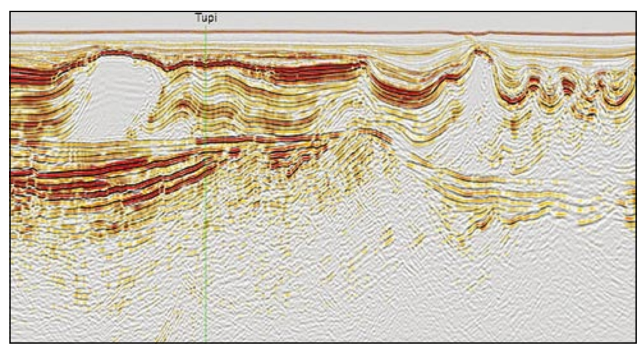

Figure 2 *Seismic image showing the Tupi discovery. Processed using RTM imaging under the salt greatly improves the image. The right side of the section though, with more continuous salt cover, is still relatively poorly imaged. Image courtesy of CGG Veritas.*

Reservoir mapping and characterization in Brazilian reservoirs

Petrobras, the leading player in the Brazilian sector and also a key player in the African offshore sector, has identified a number of key challenges in gaining a good understanding of the pre-salt reservoirs.

Facies delineation from seismic is a one challenge, together with internal reservoir characterization and geomechanics, both in the reservoir and during drilling in the overburden, particularly the salt section. The Brazilian reservoirs include highly complex layered carbonates, hard to characterize at the best of times. The area represents one flank of the rifted Atlantic basin, so there is a great deal of complex faulting, segregating and compartmentalizing of reservoir bodies. Simply being able to map these complex, poorly visualized reservoirs is a difficult task.

3D modelling in pre-salt

In such a situation 3D modelling is a powerful tool to assist the decision-making process, not just by providing a justification for the risk assessment, but also as a tool for investigating and confirming one's understanding of the true situation down behind the veils of noise that blind our sight.

One of the first big benefits of building a 3D reservoir model is the ability to have the entire geological section modelled in one model – to be able to have the whole system, target to surface, available to the geoscientist.

The ability to handle complex supra-salt geometries, cleanly tied to the contorted salt bodies and correctly located above an accurately represented rifted basement and its syn and post rift sequences, is an essential first step. From a broadly correct 3D model all the other necessary models and investigations can be made. Without that solid base, all ensuing work will be less reliable and the prospects drilled from them will be higher risk.

The modelling of the Brazilian pre-salt may benefit from many techniques, all of which start best from an accurate 3D model. Geometries such as those seen in Figure 3, with walls and overhanging diapirs of salt, are commonplace and accurate handling, not just of the shape of the salt but also the shape of the sediments as they intersect the salt structures, is essential.

Figure 4 shows how precisely it is possible to get all the elements of the structure to tie together, a fundamental requirement of the model when looking at migration, trapping, pressure regimes, compartmentalization, and predicting reservoir presence.

The structural setting of the pre-salt plays is a familiar one, a rifted margin with basement structure, syn and post rift fills and post-rift sag, all structures that will certainly be familiar to geologists who have explored on the North Atlantic margins in countries such as Canada, UK, and Norway. From the many years of experience available for these areas, general statistics have been derived, for example, up to 60% of the uncertainty in a model is due to inaccurate structural geometry.

Whilst the major lineaments can be well defined, the details of where the reservoirs are and how they communicate are often controlled by second order faulting. This requires accurate model building to capture fault linkages and relatively complex fault populations, with nested synthetics and antithetics, and fault systems that evolve through time, so that cross-cutting relationships are neither easy to see nor simple to model.

For a long time it has been possible to model these geometries with ease and flexibility in specialist tools. Only recently, however, has that ability been part of the general reservoir modelling workflow. Without being able to cope with all the modelling issues in one modelling environment, many features, such as complicated fault inter-relationships and overturned beds are either skipped or, in the majority of models, simplified.

Although, as Dr Box said, all models are wrong some are very useful (Box, 1979). With structure controlling where your reservoir is, whether it is charged and how much you are likely to get out of it, an accurate structural model, which can be used to build a structurally accurate grid, is very useful.

Figure 5 shows that it is possible to built accurate, eminently useful models of the kind of structural settings found in the Brazilian and African pre-salt plays, (this one is taken from the Norwegian Atlantic margin).

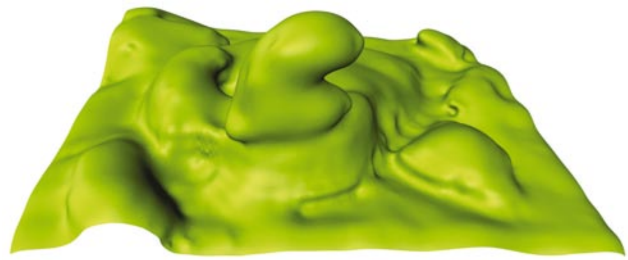

Figure 3 *Model showing the top surface of a salt wall and diaper with overhangs. Image courtesy of Roxar.*

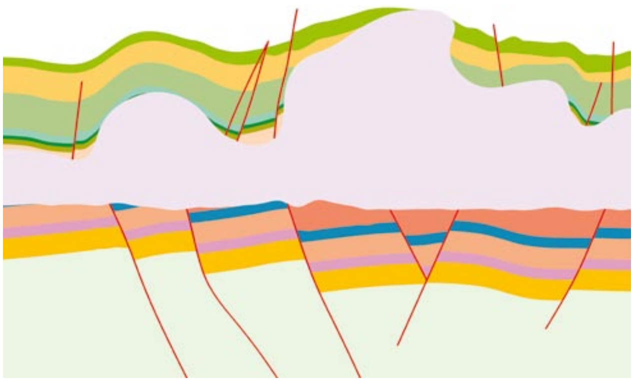

Figure 4 *Cross-section of the full model, of which Figure 3 shows only the top salt horizon. This section shows the deformed post or supra-salt section (in greens) and the deformed salt body (grey) sitting on the rifted and eroded pre-salt section (pinks and blue). A complex model which can now be handled as a single entity. Image courtesy of Roxar.*

Not only can these models be built easily, it is possible to build multiple, slightly varying versions, and thus assess the possible impact of the poor imaging that can lead to an incorrect representation of the sub-surface. By combining these multiple possible models with rapid testing against production data, it will be possible, as these very deep fields come online, to progressively refine the models. This will both improve recovery from the existing fields and also allow better targeted exploration, as the areas mature.

Populating the 3D model

Once you have a reliable 3D model, populating it with appropriate reservoir properties is another problem in pre-salt situations. Many of the recent Brazilian finds have been made in heterogenous carbonates. These may be located onto structural highs or found as part of the rift fill, but either way, carbonates are highly variable and difficult to characterize. It is likely that, until there is a better repository of well data, much lithological characterization will be done using seismic facies and attribute responses, even with relatively poor seismic data.

Using structurally constrained grids, the combination of sampling of seismic into the geological grids, geostatistical facies modelling tools, and geological QC can produce

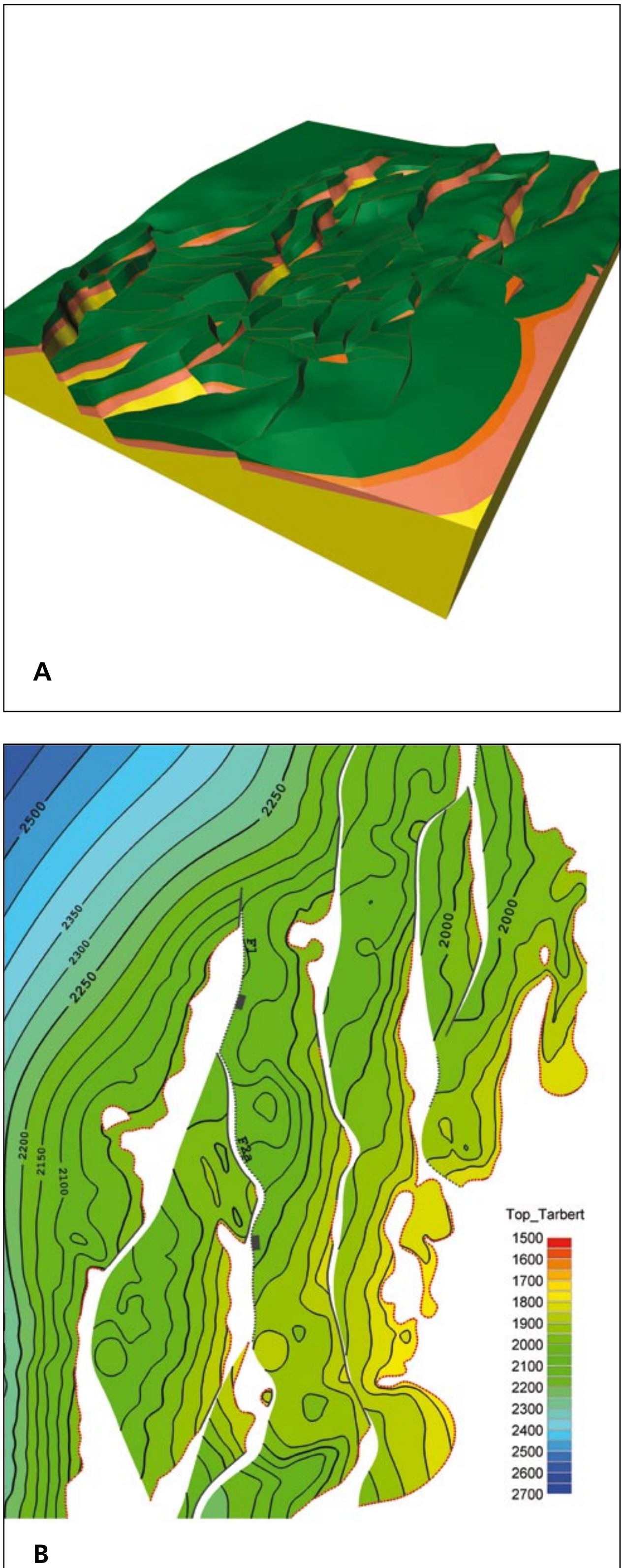

***Figure 5** Block model (5a) and contour map (5b) of the Gullfaks area, Norway, showing complex faulting with both fault geometries and horizon-fault intersections precisely modelled. Image courtesy of Roxar.*

realistic, if rather uncertain, facies models for these fields. In addition, carbonates tend to be prone to fractures, which also tend to significantly affect their production performance. In this situation, there is also likely to be a need for a complete reservoir model to include a fracture model and the permeability and porosity modifications that will arise from that model.

Although there is, as yet, little well data to inform the model, the structural history can be used to develop a fracture model based on a conceptual understanding of the evolution of the field. In this situation, the fault model can be used for stress modelling (see Figure 6), providing both field-wide stress distribution maps and more localized fault deformation halo maps, since fractures form both around the faults and throughout the deforming hangingwall blocks.

Seismic attributes can be used as further constraint and more detailed structural analyses could even be added in to provide more specialist detail. Obviously without the more reliable data provided by well logs, these models will be uncertain, but the response of rocks to deformation is hardly an unknown field and much can be done by a structural geologist with an accurate model to help set the scene and map out the possibilities.

Again, the ability to test multiple model variants of both facies models and fracture models against the accumulating production history and the increasing amount of well data available will progressively allow the uncertainty levels on the models to decrease and confidence in our understanding of the system to increase. Combined with the ability to rapidly update local areas of the models around wells as they are being drilled, operators can substantially reduce the risks of drilling long, deep horizontal wells such as those planned for the Brazilian margin.

Updating both structure and properties of the model, while the well is being drilled, will allow the geologists and the drilling teams to co-ordinate hour by hour decisions on the well trajectory. The stream of data that can be retrieved while drilling is of little benefit unless it can be put into context and its meaning understood. A 3D model provides that context in its richest form. When a well is costing at least $100 million, such 'in-flight' adjustments can save millions, cut time, and may even be the difference between success and failure for the well.

Can this be replicated in Africa?

The geological history in Brazil and opposite African margin are obviously very similar, although asymmetry in the rifting behaviour has created differences in subsidence history and therefore in the post rift sedimentation, maturation, and compaction histories.

All of these will influence what can be found and where. However, with rich source rocks and good reservoirs on both

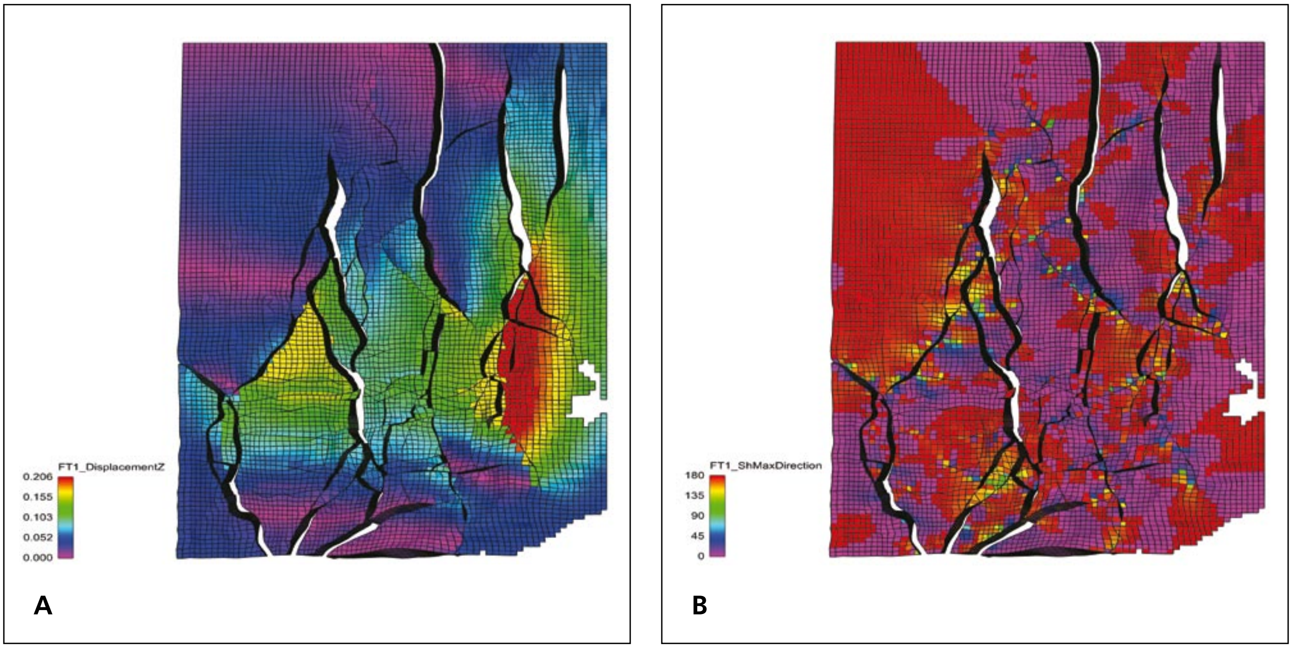

***Figure 6** Structural trend maps derived from stress modelling for the Gullfaks area. On the left (6a), the magnitude of vertical displacement on the faults and, on the right (6b), the orientation of the maximum horizontal stress in the fault blocks. These can be used as field wide input to a fracture model to constrain where and how fractures are modelled. Image courtesy of Roxar.*

sides, the prospects are good. Transferring the experience from the Brazilian to the African side will obviously be helped by transferring techniques like 3D reservoir modelling and iterative modelling/interpretation loops, but additional modelling techniques may also prove valuable.

The use of basin modelling tools, for example, will allow the mapping of maturation and migration patterns, allowing explorationists to focus on areas with the highest chance of being prospective. The use of backstripping and restoration tools, both in conjunction with basin modelling and as a prospect generation tool, could provide a 'spotlight' to shine on the subsurface to pinpoint the most likely, least risky prospects.

Using backstripping and restoration in basin modelling studies means that the sediments are correctly placed in their thermal history and will help to identify prospects at charge time and track their evolution since. The full range of backstripping and restoration techniques can also be used to unravel the complex structures of rifting, map where likely reservoir deposits occurred, and assess their current position, geometry, and state of deformation. This will also add invaluable understanding to the reservoir model, providing the explorationist with yet another test to increase the chances of a successful discovery.

Summary

When there are problems in the geological area, operators need tools which can help intelligently extrapolate their data, building multiple models of increasing detail to narrow down the possibilities. These tools need to be able to model any and all of the structural situations encountered, whether these are complex overburden geometries, convoluted salt geometries, and/or complex faulted reservoir geometries.

There are many tools available to model and investigate the problems, from defining where and what shape the reservoir is, to describing the reservoir properties and assessing the reservoir's evolution and behaviour.

The most fundamental of these tools is the reservoir modelling package, the place where the reservoir geometry is accurately defined and its properties reliably described. The ability of this modelling environment to handle not only the complex structures beneath the salt and to reliably extrapolate the limited data we have available from the depths, but also to handle the salt and supra-salt sections with equal accuracy and facility, is crucial in getting the maximum benefit out of modelling.

The ease and speed with which the model can be updated as new data comes in, both while drilling and after further interpretation, is critical in keeping both the model useful and the minds of the modellers open to new possibilities. An up-to-date model is a useful model and that is the best anyone can ask a reservoir model to be.

References

Box, G. E. P. [1979] Robustness in the strategy of scientific model building. In: Launer, R. L and Wilkinson, G.N. (Eds) *Robustness in Statistics*. Academic Press, New York.