

SALT: Deformation, Trapping

Salt structures come in every possible shape and stretch our imagination. This means difficulties in seismic imaging, but it also means that the innovative explorationist can look for spectacular traps.



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Photo: Halfdan Carstens

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Rock salt is strictly speaking a crystalline aggregate of the mineral halite (NaCl), which is one of more than 20 evaporite minerals formed by precipitation from saturated brines, most commonly by solar evaporation. Although salt deposits may contain large portions of other evaporite minerals like anhydrite and gypsum, most studies of the mechanical properties, and hence the dynamics of evaporites, consider rock salt as the dominant mineral.

Although the very strong influence of water on the mechanical strength and the flow properties of halite is well established, there is still not enough data available on the rheological properties of evaporites to constrain the detailed strain paths and geometries which develop in large evaporite bodies exposed to gravity and loading from a clastic sedimentary overburden. In addition, many evaporite sequences contain a high proportion of clastic material that may be involved in the deformation, and the rheological effect of these clastic "contaminations" is not easily predictable.

Challenges in seismic imaging

Although one tends to associate the problem of seismic imaging in areas with extensive salt deposits with complex salt structures, one should not overlook the fact that many basins contain evaporates that are tabular, flat-lying and stable. In these areas the problem of seismic imaging is restricted to seeing through the salt. It is still fair to say that the structural geology of evaporates have attracted much attention, partly because the high mobility of such deposits poses intriguing structural geological problems, but more because salt structures are commonly associated with a variety of structural and stratigraphic traps of significance for the petroleum industry.

The structural geology of salt clearly reflects the local tectonic environment, be it extensional, contractional or strike-slip. This implies that salt bodies come in an almost infinite variety of shapes, some of which even challenge the limits of the imagination. This variety of shapes, combined with the acoustic properties of salt, pose great challenges for the reflection seismic imaging of salt bodies and the strata beneath

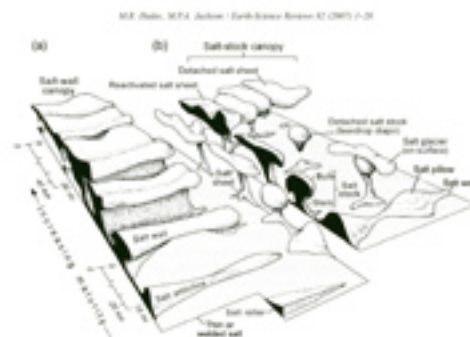
and close to them (see following article in this issue of GEO ExPro).

Deformation at continental margins

Gravity-driven deformation at continental margins is commonly caused by the regional gradient of the margin itself and is characterized by upslope extension and downslope contraction. Salt and its overlying sedimentary load spreads in a seaward direction due to regional tilting in response to lithospheric cooling, whereas synkinematic sedimentation induces loading instabilities. At basin scale, thin-skinned deformation may induce extreme upslope salt thinning, leading to the formation of salt welds, as well as massive downslope salt thickening.

Extensional domains, such as the Angolan margin, can often be divided into three sub-domains. Moving seawards, the first sub-domain is characterized by tilted blocks that have been sealed early by synkinematic sedimentation. The next sub-domain displays a large amount of extension, resulting in growth faults and rollovers, whereas the deepest marginal domain is dominated by diapirs and is generally considered as gently translating(?), accommodating small amounts of extension. Diapirs correspond to weak zones and are easily compressed.

Downslope from the margin, contractional structures balance the amount of upslope stretching. The domain of shortening is also divided into three sub-domains. In a seaward direction they are composed of



Trap types associated with salt diapirs. After Jackson & Talbot (1991).

and Complexities

a domain of diapirs squeezed at a late stage, followed by polyharmonic folds and thrust faults developed at early stage, and then late stage folds and thrusts.

Analogue experiments show that the overall structural zoning is mainly controlled by the initial condition of the salt basin and the basal slope angle, whereas the type of structures found in the structural domains strongly depends on sedimentation rate.

Classification of salt structures

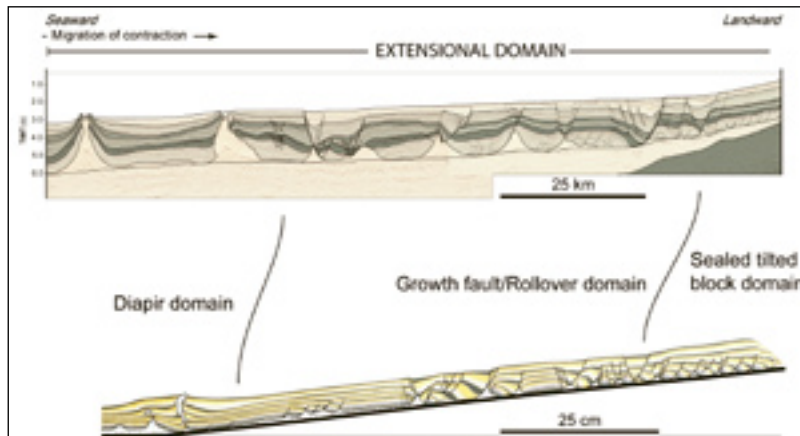
An early attempt to systematically classify salt structures and to set this into a dynamic context was done by Trusheim in 1960 based on analysis of salt structures in Germany. He suggested that salt impiercements grow from elongated low-profile ridges (anticlines and rollers) triggered by gravitational contrasts, developing into rows of pillows, diapirs and eventually into walls and sheets of salt. The diapirs come in a variety of shapes from regular massive stocks, via irregular masses to elegant mushrooms.

This geometric classification is undoubtedly valid for a tectonically stable, evenly subsiding basin. But even this relatively predictable kinematic growth pattern of salt structures causes great problems in seismic imaging due to the complex pattern of internal flow in the salt structure itself, including horizontal displacement, affiliated with overhanging or even horizontal walls to develop.

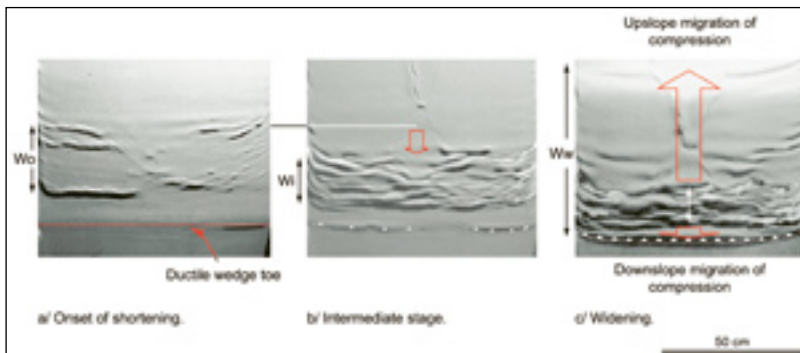
A multitude of reservoirs

The deep parts of basins, where salt structures tend to be situated, are often affiliated with sediment traps. The growth of diapirs contributes to development of local depocentres and the areas around salt diapirs may accumulate large volumes of reservoir rocks of good quality and be associated with excellent structural and stratigraphic traps. However, due to the capacity of salt to flow horizontally at shallow levels and develop overhanging bulges and sheets, and even to become detached from its deeper sources, the detailed geometric configuration around the stem of the salt structure, including its diameter, is commonly disguised and the diameter of the stem itself may be impossible to determine from reflection seismic data.

A great number of analogue, mechanical and numerical experimental studies have been performed to establish robust models for the geometric relations in such structures, but although the principles for the dynamics of such structures are well established, they seem to have limited predictive values in many basins. As a result, oil companies are still met with surprises during exploration of targets in the vicinity of salt



Analogue experiments (sections) displaying inclined margin and the interplay between different types of salt structures and fault pattern.

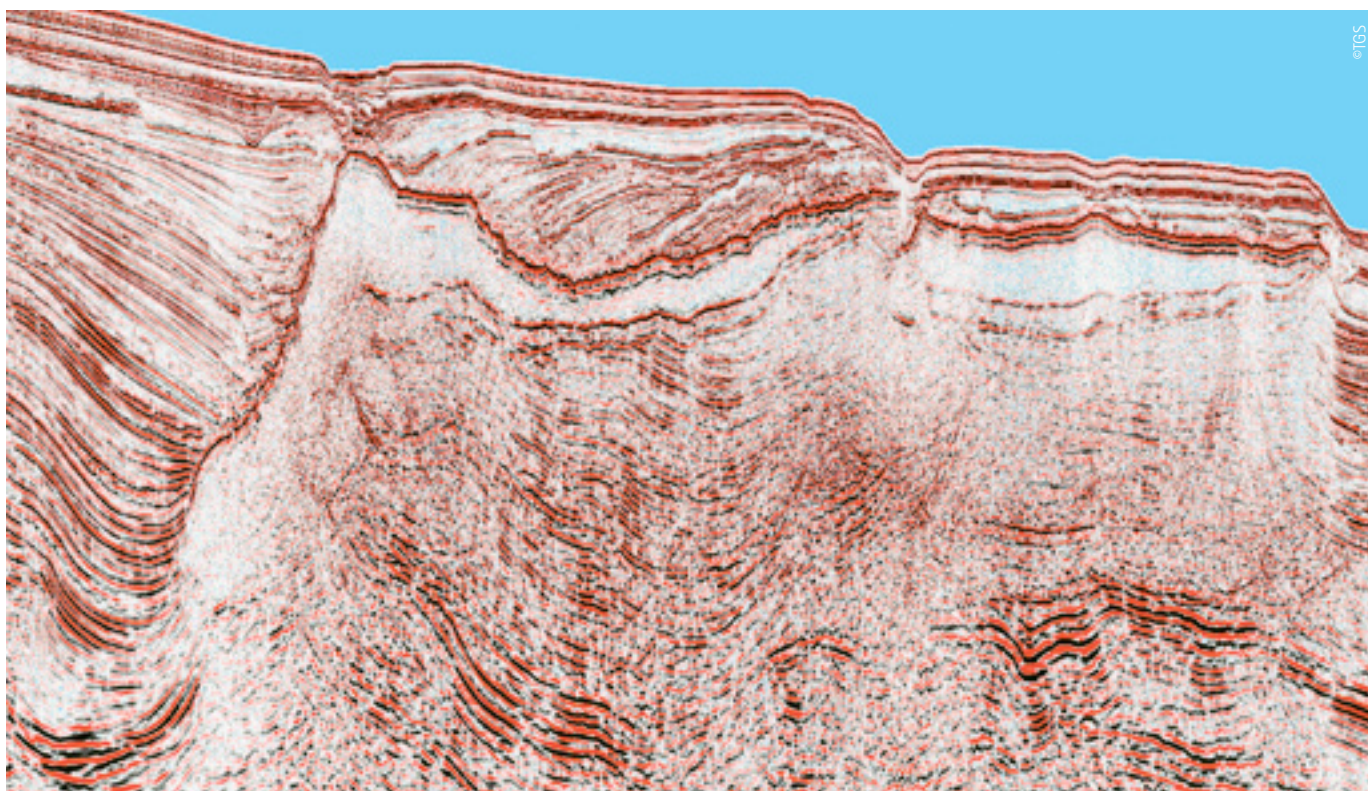


structures. Indeed, some salt structures developed in presumably tectonically simple environments may obtain shapes that perhaps can be characterized as counter-intuitive.

In addition to the bulge above the salt empiercement itself, which will reflect the geometry of the upper layers of the empiercement, the main types of features that may constitute structural hydrocarbon traps adjacent to salt diapirs are the rim syncline system (sometimes several generations), anticlines associated with the rim syncline system, faults generated due to volume reduction during vertical transport of salt, and drag-structures close to the stem of the diapir. Due to the circular nature of the diapir, all these structures are likely to be closed when seen in three dimensions. In addition, numerous types of stratigraphic traps may be associated with all these structural features.

For salt anticlines and simple walls, which have not developed overhangs, seismic imaging of the structures is usually relatively straightforward. For mushroom-shaped diapirs, however, it is much more

Map view of analogue experiments with domains of deformation indicated. Note that contractional structures initiated in a domain W_0 are located at a fair distance from the initial salt edge and that the area of contraction remains localized in this domain during the initial stages of evolution, whereas the width of the deforming area (W_0) decreases (W_i). When W_i cannot decrease any more, contraction migrates simultaneously up and downslope. The upslope migration of contraction may eventually reach the extensional domain and squeeze the diapirs.



Growth fault invaded by salt has a function as transport channel and feed horizontal salt layer (GEO ExPro No 1, 2007.).

challenging and several parameters have to be taken into consideration in the structural analysis. The distance of the rim syncline system from the centre of the diapir and its amplitude and wavelength depend on the thickness of the original salt sequence, the diameter of the diapir and salt flow rate relative to rate of sedimentation. In many cases, this structure is, however, situated sufficiently far away from the diapir for seismic imaging to be unproblematic. When it comes to the fault systems and the drag-structures, however, these occur close to the stem of the diapir and are likely to be covered and completely disguised by the overhanging diapir bulb.

Additional complexities

Difficulties in seismic interpretation may occur to varying degree in cases where dynamic salt interacts with faulting. At the crest of salt diapirs and stocks a combination of ring-shaped and radial fault systems are commonly found, but these do not cause problems in seismic imaging and interpretation. Also, numerous examples exist of fault activity which has been instigated by the underlying active salt, providing a substratum for detachment. Such structural relations are also clearly displayed in reflection seismic data. Finally, due to the

transfer of large volumes of salt towards the basin axis, smaller amounts of salt with the shape of pillows are frequently left and trapped along basin margins, where they interact with the basin margin fault system and masking the deep configuration of the basin margin fault system.

Different configurations are sometimes developed in the hanging wall and the footwall of the salt-involved fault, causing complex and contrasting sedimentary conditions across the fault so that significant problems in sequence correlation occur. Where salt has intruded along the fault-plane, interpretation of seismic data may be further hampered by reduction of the general data quality.

In more complex tectonic environments (strike-slip and contraction), the complexity and variety of salt body configuration is commonly much greater, because the final geometry of the salt body will be ruled by directed flow reflecting varying differential stress and strain. For example, the importance of evaporite sequences in the development of many thrust belts like the Pyrenees and the West Spitsbergen thrust-and-fold-belt is well documented. In such settings seismic imaging may be complicated by salt becoming involved as an extensive, continuous or disrupted unit

during the thrusting, and also because it may accumulate unevenly and be integrated into contraction structures like fold cores, duplexes and as intrusions along fault planes.

Hand in hand

The quality of seismic imaging performance in areas of salt has been greatly improved over recent years. Still, the days of surprise at the results of drilling are not yet over. Efforts in improving seismic imaging techniques must therefore continue, and should go hand in hand with field study and analogue modelling.

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