Special Features in Exploration and Interpretation of Salt Structures

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Abstract
The structural variety of salt structures is immense. The range is from even stratified bedding to extremely complicated diapirs with steep and folded strata. The salt may be massive or intercalated by clay. Quite often broken strata of anhydrite or carbonate “float” within the salt like rafts.

Specifically the irregular shape of structures makes them hard to be detected by geophysical methods. Differences in physical properties of rocks are favourable for their determination. On the other hand, if they are relatively similar - like the acoustic attenuation of claystone and of salt - they may not be distinguished from each other.

Often the internal structure of salt can only be differentiated on the base of drilling results by logging, coring and cuttings. The effect of ongoing drilling or mining on the structural interpretation is mostly associated with a significant increase in complexity. Diapirs get more slim or even rid of their basis. Internal folding becomes as irregular as it never seriously would have been interpreted before.

Selected structural examples show how interpretation changes during exploration respectively field development. Extreme cases are mud diapirs, gas chimneys and salt glaciers. Sources of misinterpretation are being discussed.

Key words
Allochthonous Salt, Bromine, Canopy, Coring, EMR, Exploration, Gas Chimney, Seismic Migration, Mud Diapir, Multiple Reflections, Raft Tectonics, Salt Structure, Salt Glacier, Seismics, VSP
Introduction
At a first glance the exploration of salt occurrences appears to be simple. Salt is often considered to be more or less homogenous and bedded or accumulated in bloc like diapirs. This is not wrong in general but the devil is in the details.

Often salt is very inhomogeneous and of high structural complexity both related to its mobility. Furthermore there are rocks, whose image in exploration is very similar to salt, which cause confusion.

A cross check of different investigation methods is required, specifically if a project is developed from the scratch or is coming to the limits.

Complexity

Fig. 1 a+b: Salt structures in northern Germany (Baldschuhn et al., 2001)
Salt structures vary from even, flat and autochthonous salt beds to highly complex allochthonous salt sheets, displaced over kilometers from its roots.

The upper example from the Elbe estuary (fig. 1a) shows Rotliegend Salt (brown) and Zechstein Salt (light blue) moving mainly gravity driven through the overburden forming so called double salt structures. The Zechstein Salt near Hannover (fig. 1b) however shows structures formed under a very strong tectonic influence. The complexity in this case was determined during intensive exploration on hydrocarbons.

Apart from the determination of the outer boundaries of a salt dome the internal structures are often cores and outcrops difficult to detect as e. g. the inner Permian salt-salt boundary of Zechstein and Rotliegend (fig. 1a).

Cores and Outcrops

Fig. 2: Fault features within Dagorda-Salt, Portugal
This salt shown in fig. 2 is from the Dagorda Formation at the Triassic – Jurassic transition (Infra Lias). The location is part of the Lusitanian Basin which was strongly influenced by the opening of the Atlantic Ocean as well as the rotation of the Iberian Peninsula. A change of the tectonic directions is displayed in this core by the crossing slicken sides. Such structures are found in cores more or less casually. Imaging logs come to its limits here.

![Salt samples](image)

**Fig. 3:** Salt from a single well in the Persian/Arabian Gulf incorporates complex lithologies

Structural patterns in salt domes appear to be randomly distributed quite often. This is attributed to the flow of mobile salt bearing brittle rocks over several kilometers. Even in a single salt well apart from structural complexity very different lithologies may occur (fig. 3).

![Salt glacier](image)

**Fig. 4:** The Kuh-e-Namak salt glacier, Persia

Salt glaciers appear at the surface. They are strongly carstified and therefore nearly inaccessible for larger exploration equipment. Accordingly most of the investigations have to be performed at its rim (fig. 4). The question is: How can the structure be determined in the underground?
Seismics

Despite the appearance at the surface – direction and angle of slope, the seismic image – stratified (= overburden) and unstratified sections (= salt), drilling even deviated wells beneath the outcrop can come to the end that there is no salt at depth (fig. 4). The conclusion is that the connection to the root of the diapir is very slim or not existing any more. Similar examples are known e.g. from the Gulf of Mexico in buried off shore structures.

Fig. 5: Seismic Profile from the Aquitaine Basin (Bally, 1983)

If flat bedded and intercalated by strata of different physical behavior, the image is similar to other stratified horizons, but if steep and folded like in this example from the Aquitaine Basin in France (fig. 5) only the contrast between stratified overburden and random patterns gives a hint on salt.

Large overhangs pretend a massive volume in the underground but during further exploration salt domes often are getting more and more slim.
The top of salt determination may be complicated by additional reflections so called multiples (fig. 6). Here in addition to the primary reflections of the cap rock similar reflectors occur apparently at a deeper level. In fact the signals are from the caprock and due to multiple reflections on a longer, more time consuming track which simulates greater depth.

Fig. 6: Gulf of Mexico salt dome with multiple reflections one selected marked by a dotted line (changed after Bally, 1983).

Fig. 7: Gas chimney – pretending a salt dome (Buur & Kuehnel, 2003)
Further even more dramatic misinterpretations are related to certain phenomena. One is generated e.g. in fault zones, where gas is accumulated over a great depth range (fig. 7). The seismic image is very similar to that of a salt dome.

A further misinterpretation may be caused by a material with a similar physical behaviour like salt and that is clay. With respect to diapiric structures comparable random patterns in seismics occur but the difference to ghost structures like the gas chimneys is that these are real, water rich mud diapirs with a mobility similar to salt.

Such diapirs occur e.g. in the Gulf of Guinea, off shore Nigeria. Without drilling these structures only a glance on the regional geological settings gives a hint on a low probability that salt was deposed there.

One mean to optimize the seismic image during the processing phase is the kind of migration. Seismic images are highly improved using time respectively depth migration in processing the data. Prerequisite is a fair structural model.

A simple structure with a normal velocity profile is displayed sufficiently performing a poststack migration (fig. 8). The more irregular the velocities are distributed the more a migration in depth is required to create a realistic picture. Finally prestack depth migration is recommended for complex structures.
Accordingly in this Gulf of Mexico example (fig. 9) where a complex geology must be expected the different results of a simple model migration and a complex one becomes obvious.

Logging

Standard wireline logs are a must for salt wells however imaging logs cannot be regarded as a standard tool. They need to be carefully selected depending on the lithology and related limits of resolution. Tools based on electric principle are dependent on resistivity contrast. In a tight matrix a determination of different lithologies is difficult. Therefore in salt acoustic tools are preferred, but even those need to be calibrated e.g. with cores.

The same applies for the following specific logging procedures which up to now are not basically performed.

In order to gain a good velocity profile as well as indications of reflectors encountered by a well, data from Vertical Seismic Profiling (VSP), using an existing well, is a good mean to improve the input for surface seismics.

Furthermore steep dipping reflectors like the boundary of a diapir at depth are by far more exactly displayed by VSP than by surface seismics (fig. 10).

Fig. 9: Application of different migration techniques in a complex Gulf of Mexico structure (Baker Hughes, 2000)

Fig. 10: VSP-data used for the improve ment of salt flank imaging (Hornby & Jinhua, 2006)
Concerning the determination specifically of steep layers a second method is on the market – the Electromagnetic Reflection Tool (EMR) – a radar probe.

Reflections are caused at the transition zone of layers with significant electric conductivity contrast, e.g. salt and clay as occurring at the boundary of Zechstein 2 and 3 in Northern Germany (fig. 11).

The penetration zone is from few meters up to hundred meters and beyond. The more energy absorbing reflectors occur the smaller is the area of penetration.

As an important prerequisite: the measurement has to be performed in non conductive media like gas or oil – not in water based drilling mud.

The processing of the signals delivers so called radargrams. The identified reflectors during the interpretation have a spatial direction or not – depending on the tool in use.

Nevertheless as in seismics there has to be a certain idea of the geology encountered in order to perform a proper interpretation.
Fig. 12: Structural interpretation based on conventional wireline logs and cores

The log interpretation example from Northern Germany (fig. 12) displays the transition zone from Zechstein 2 to Zechstein 3 marked by Polyhalite and Kieserite bearing rock salt, the potassium seam Staßfurt, claystone, carbonate and Anhydrite.

The well where the logs were run was deviated – important for the interpretation of the results. The Polyhalite portion remained constant in the upper section which led to the assumption that the horizon was +/0- parallel to the well.

The potassium seam was in parts not really encountered but its proximity was indicated by a slightly risen Kieserite and Sylvite portion.

Increasing content of dispersed Anhydrite on the other hand gave rise to interpret this as older rock salt.

The better the assumptions of mineral composition as input for log interpretation the more reliable is the quantification and the resulting structural model.
Fig. 13: Bromine profile (black line) and GR-log over a Zechstein 1 cycle (Kaeding, 2005)

Analyzing the Bromine content of samples taken during the drilling process should in general give rise to take this as indication for certain periods of an evaporation cycle.

As a rule of thumb in a progressive cycle ending with potassium salts the portion of bromine is increasing, but in detail there are deviations from that rule (fig. 13), which may lead to misinterpretation.

Nevertheless this tool is worth to be considered in salt evaluation. With increasing regional knowledge of the Bromine distribution within the salt, more reliable stratigraphic conclusions can be drawn.

Conclusion

There are a lot of suitable methods investigating salt structures, minimizing the risk of failures. Some are state of the art some are still in the development phase. The latter need to be applied by courageous constructors supporting the advancement.
It is always important to know how the results could look like. Beside the physical understanding of a tools’ principle the vision of a geological model is of significant importance in order to fit in the results or to adapt the model respectively. At the end of the day this all aims at optimizing operations and minimizing risks.

**Literature**


