Salt Interpretation with Special Focus on Magnetic Data, Nordkapp Basin, Barents Sea

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Summary
A salt diapir in the Nordkapp Basin, Barents Sea, is interpreted from seismic, gravity gradiometry and high resolution magnetic data. Special emphasis is given to the magnetic data, which are shown to overcome some of the problems of gravity data, which includes non-contrast density zones, density variation of evaporate rocks and ambiguity with respect to mother salt. The magnetic attributes of the sedimentary environment are derived from onshore analogs and well data of the same geological strata. The interpretation method combines 3D modeling and inversion. Starting on a regional scale, the crustal structure is resolved using a model defined by regular grid layers. The residual anomalies on a ‘seismic’ scale require more complexity and are interpreted by modifying triangulated layers on vertical sections as well as by inversion of a 3D grid model of the innermost area enclosing the salt diapir.

Introduction
Reflection seismic investigation of salt diapirs has considerable problems to define the base of the salt. To overcome this problem, gravity data are often used to distinguish between different possible models defined from the seisms and geological reasoning. Gravity gradiometry has further improved the method by a higher accuracy as well as by setting geometric constraints. However, as density contrasts are the only rock parameters defining the gravity and its gradiometry anomalies, this leads to a number of limitations. (1) Sediment compaction increases densities with depths (cf., Allen and Allen, 2005), which causes a non-contrast zone (‘nil zone’; Bain et al., 1993), where both salt and sediment densities are similar. With a halite density of 2.1-2.2 g/cm³, this may occur at depths between 1 and 3 km, which is often close to the target depth. Salt above and below the nil zone produces gravity anomalies of opposite direction, which result in destructive interference. (2) The mineral composition of a salt diapir is rarely pure halite. A whole suite of evaporite rocks may be present (cf., Einsele, 2000) and the most severe deviation with respect to density are anhydrites with densities of up to 2.9 g/cm³. The amount of anhydrite is rarely well defined from seisms due to very high velocities and the dispersion of seisms waves due to the crack pattern, which is commonly observed in anhydrites. This is a common problem on top of the salt structure and may also occur in a deeper depositional cycle within the salt diapir. (3) Negative gravity anomalies from greater depths from underneath the salt diapir can be caused by deep salt, i.e. a salt pillow, feeder or mother salt, but also by the throw of a basin fault below the salt diapir. By gravity alone, we cannot distinguish between these sources.

Magnetic data have none of these problems. Induced magnetic susceptibilities (from now on simply called ‘susceptibilities’) of sediments are generally positive, whereas the susceptibilities of evaporate rocks including both halite and anhydrite are practically zero. This will effectively overcome the problems for the densities described in (1) and (2). Problem (3) can also be solved by magnetics, as a basement fault will cause a much stronger magnetic anomaly than any salt feature, due to the much higher susceptibility contrast.
The success of applying magnetics is dependent on the knowledge of magnetic susceptibilities, which may be challenging. Whereas densities are a bulk rock parameter, which can be related to and estimated from both seismic velocities, rock type and sediment compaction, are susceptibilities dependent on the amount of magnetic trace elements. This presentation describes the construction of a sedimentary susceptibility model in order to fully utilize the value of high resolution magnetic data. An integrated interpretation including seismic and gravity gradiometry data is shown for a salt diapir in the Nordkapp Basin, Norwegian Barents Sea. The location of the study area is shown in Figure 1.

Figure 1. Location of study area.

Data Bases

The magnetic rock attribute data base is constructed from published well core measurements from (Mørk et al, 2002), as well as from our onshore measurements from fieldwork on Spitsbergen. Susceptibilities of sediments from mid-Norwegian shelf areas (Mørk et al., 2002) are reported to vary between .0001 – .002 SI, with an average of 0.0003 SI units and Koenigsberg ratio’s (Q values) of 0.2 or less. It is therefore reasonable to explain sedimentary magnetic anomalies purely by induced magnetism. Susceptibilities of sediments exhibit almost no depth dependence, but purely relate to the mineral composition of a sedimentary layer. The clue to estimate appropriate susceptibilities is therefore to understand the sedimentary sequence, its composition, its provenance and secondary chemical/biological processes that may have effect on magnetic minerals. Generally, susceptibilities can be treated as constant for the same rock type within the same sedimentary geological unit.

Figure 2.
The variation in magnetic susceptibility encountered for the Mesozoic sedimentary rocks on Svalbard is between zero and .003 SI units. The susceptibilities of sandstones vary between zero and 0.00005 SI, for shales between 0.00005 and 0.0005 SI and the highest susceptibility values between 0.0005 and .003 SI are recorded in the pyrite and/or siderite cemented rocks and concretions. Mesozoic rock samples from western Spitsbergen have been mineralogically investigated using XRD. Criteria for the selection were a susceptibility exceeding 0.0001 SI but some samples with lower susceptibilities were also included. A general correlation with mineral contents is shown in Figure 2.

The results from Spitsbergen rocks are compared to the results of Mørk et al. (2002), acquired from wells in the Norwegian Sea. Similarity is observed with respect to single stratigraphic units. Since the Nordkapp Basin is a part of the same geological province, we assume that the sedimentary strata deposited at the same geological time and in a similar setting will result in similar susceptibilities.

The density data base is constructed from two well logs from the Nordkapp Basin, as well as from surrounding areas. At depths greater than accessible by wells, depth-density curves for compaction (cf., Allen and Allen, 2005) have been used. The geological uplift of the Barents Sea area (Faleide et al., 1984) and its effect on the compaction have also been taken into account. Crustal densities and susceptibilities are derived from onshore values from Northern Norway (Olesen et al., 1990) since the Nordkapp Basin is a part of the same geological province and is generally regarded as the northern extension of the Caledonian fold belt. (Faleide et al., 1984)

The gravity gradiometry data have been acquired by Bell Geospace (survey Fulliautomatix 2006). The high resolution magnetic data by the Geological Survey of Norway (survey SNAS 2006). The seismic interpretation is provided by Licenses 161 and 202 operated by Statoil ASA.

**Figure 3.** Magnetic data (vertical derivative of TMI), gravity gradiometry data (gzz) and a possible model for the salt diapir displayed as 3D grid in a simplified sedimentary strata.

**Integrated 3D modeling and inversion**

The interpretation has been divided into an interpretation of the regional (crustal) and residual gravity and magnetic fields. The input to the regional model consists of seismic maps of major sedimentary layers, with simplified salt diapirs and an isostatic Moho. The model area covered a larger region in order to map the regional gravity and magnetic anomalies, which may interfere with the residual field.
of the salt structure and its sedimentary environment. Interpretation method has been 3D modeling and inversion of regular grid layers (GMSYS3D / GEOSOFT). This resulted in an inhomogeneous basement including intrusives and different types of Caledonian basement rocks.

This basement is joined with 3D seismic sections, which display the sediments and the salt. A series of parallel vertical sections are constructed and the contrast surfaces are connected to a triangulated net. This allows a more complex geometric model with surfaces with multi-z values. This set of sections is modeled using IGMAS (Götze and Lahmeyer, 1988; Schmidt et al., 2007). In the final step, the central part of the model, which includes a narrow area enclosing the salt diapir is converted to a regular 3D grid in order to allow more complex lateral inhomogeneities on a grid cell level (500 x 500 x 250 m; Sæther, 1997). A possible model is shown in Figure 3. The overall similarity between gravity gradiometry (gzz) and magnetic (vertical derivative of TMI) anomalies is striking. Minor differences attributed to the differences between the density and susceptibility model can be spotted.

Conclusions

- Magnetic data can give important contributions to the interpretation and modeling of salt structures. Prerequisites are high-resolution magnetic data and a comprehensive database for induced magnetic susceptibilities of the sediments.
- Joint interpretation of seismic, gravity and magnetic data has shown to limit the possible geometries and structure of the investigated salt diapir.

References