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Modelling of Pyrite Anomalies above Hydrocarbon Accumulations Due to Persistent Leakage Across a Non-perfect Top Seal

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SUMMARY

The geo-electric method detects Induced Polarization anomalies in the subsurface. In sedimentary rocks these anomalies are often situated in a halo above a deeper-seated hydrocarbon occurrence. An epigenetic alteration halo is stimulated by small but persistent leakage from the trap, due to diffusion and/or porefill perculation processes. Hence locally a reducing chemical condition is established below an effective regional seal, where in-situ pyrite crystals can grow. These crystals are easily polarized and detected by geo-electric investigation techniques. Mathematical modelling permits simulation of the micro-leakage and the geochemical processes triggered in the overburden. The influence of various rock physical parameters is examined. The consequences for the geo-electric evaluation method is demonstrated on the DNME dataset across the Severo-Gulyaevskaya oil-and-gas field, located on the Barents Sea shelf in NW Russia, as well as on a hydrocarbon occurrence in the Kaliningrad region.

Introduction
The differentially normalized geo-electric technique (DNME) uses Induced Polarization (IP) anomalies as indicator for hydrocarbons (e.g. Davydycheva et al. 2006). Due to imperfect sealing conditions, minor amounts of H_2S migrate upward from a hydrocarbon accumulation and epigenetic changes take place in overlying rocks. A columnar zone is typically influenced by porefill perculation and/or diffusion migration. The relation is examined between IP anomalies, pyrite enrichment and occurrence of a geochemical barrier between zones with oxidizing and reducing conditions. Lateral barriers are often associated with faults and /or fractures. Over geologic time all seals are leaking minor amounts of porefill, e.g. chimney effect, velocity changes (Veeken 2007).

Modelling and application to Severo-Gulyaevskaya dataset
Mathematical formulas simulate creation of alteration zones and pyrite enrichment above a hydrocarbon trap. Test analysis was performed on the Severo-Gulyaevskaya oil-and-gas field (Barents Sea shelf), where also DNME has been conducted (Veeken et al. 2009). Assumptions are: 2 km vertical offset from field, 5 km field size, 250 10^6 years leakage. Properties of medium, such as diffusion coefficient and vertical migration velocity of H_2S, are kept relative. Increased concentration of epigenetic pyrite crystals is observed directly above the field (black bar on figures). The H_2S diffusion coefficient influences the slope and offset of the geo-electric decay curve. The OWC and IP anomaly outline are shown on the structural map of horizon I_A (near top $C_{2\text{-}3}$–P_1 carbonate complex, Fig. 1). In the closed contour area polarization values always exceed the limits assumed in the inversion procedure (cf Davidenko et al. 2008).
Pyrite concentration in the fault-controlled zone (SW corner) was computed for several geological scenarios. The following was observed:

- If a trap is bounded or in close proximity of a fault (– 100 m.), H_2S is migrating along the fault and the IP anomaly can be bigger than the field outline (Figs. 2 and 3).
- If a fault is further away, its influence will be less (to non) significant.

A similar pattern of pyrite growth is observed for traps at different depths with varying leakage times. Other media parameters can change the situation, such as: vertical velocity of H_2S, diffusion coefficient of H_2S and increase of vertical migration velocity of H_2S in a fault. Pyrite tends to be formed slower immediately above the hydrocarbon accumulation and its concentration does not reach the maximum when a small time interval is assumed for the leakage. H_2S flow runs preferably along the fault where a conduit is present. The closer the fault is positioned to the field, the wider is the zone of maximal pyrite saturation and a good anomaly is expected on geo-electric data. Making the fault distance larger and bringing it outside the limits of the field, decreases the pyrite concentration while growth directly above fault is observed (Figure 4). When the distance from the fault to the accumulation is great enough, then no pyrite is formed above the fault.

IP anomaly modelling for hydrocarbon field in Kaliningrad region
DNME acquisition and analysis were done and an IP anomaly was established above the crest of the structure (Fig. 4). In the south it is limited by a fault. There is some uncertainty about the OWC (1990 or 1980 m ?). In case the OWC contour is following the 1990 metres depth contour, anomalous values of polarizability should be noted on measuring station locations 18-22 on survey line 026307, whereas locations 10-14 of this survey line show a lower polarizability. If the OWC contour is bounded by the 1980 metres contour, increase of polarizability on locations 10-14 survey line 026307 should be evident. In this part the enrichment in pyrite micro-crystals on the real field dataset is also maximum. From this combined transmission/inversion modelling exercise it is concluded that the OWC should be positioned along the 1980 metre contour line.

Conclusions
DNME geo-electric surveying demonstrates the presence of induced polarization anomalies in the subsurface. In sedimentary rocks these anomalies can be good indicators for a deeper

seated hydrocarbon accumulation. Leakage from an imperfect topseal lets H2S escape from the trap and move up the overlying rock sequence. Several parameters govern this diffusion/perculation behaviour. When an effective regional seal is encountered, this will lead to reducing porefill conditions and the growth of diagnostic epigenetic pyrite crystals, that are easily polarized. Mathematical modeling of such migration and creation of an alteration zone permits to better understand the influence of various factors, determining the character of the anomalous IP halos.

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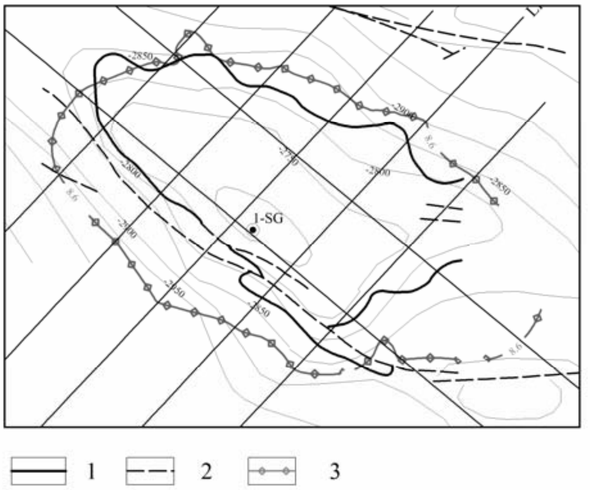

Figure 1. Structural map of reflecting horizon I_A with results of comparison of a water-oil contact' contour and IP anomaly contour by the DNME data. Legend: 1 - OWC contour; 2 - faults; 3 – IP anomaly contour.

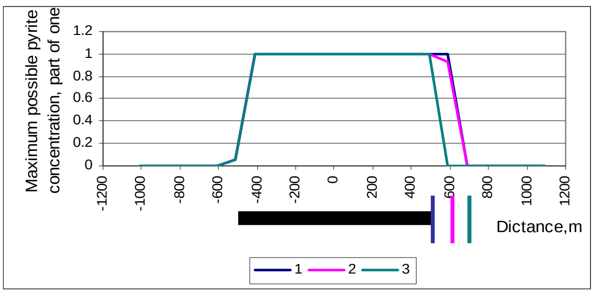

Figure 2. Modelling of pyrite concentration with a radius of 500 m, at depth of 2000 m and a geological time of 40 million years. Three dipping fault positions are shown with different colour index.

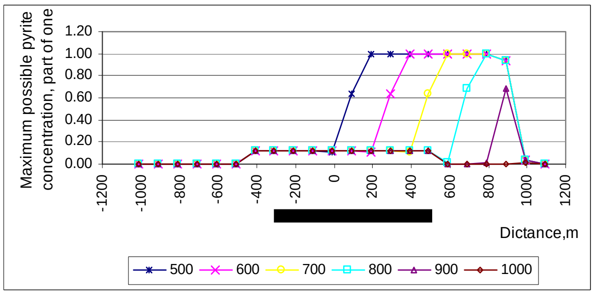

Figure 3. Modelling of pyrite concentration with geological time of 10 million years. When fault is far away from field, pyrite only occurs where fault is present.

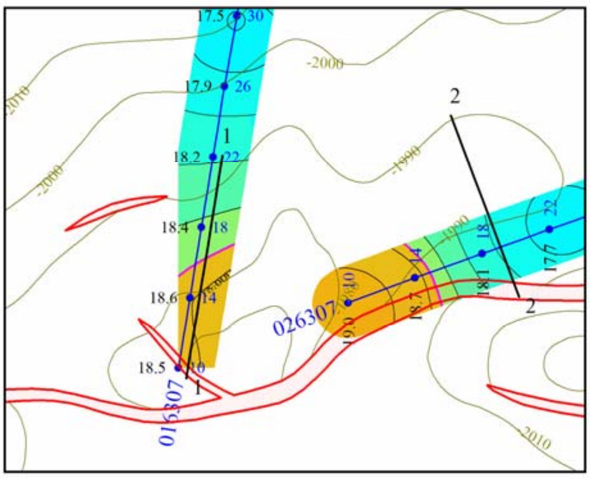

Figure 4. Map of polarization coefficient distribution with contours of reflecting horizon III (top of Ordovician). Geo-electric modelling suggests a 1980 m oil-water contact.