Barcelona '10

P084

Modelling of Induced Polarization Effects Caused by Anomalous Pyrite Concentration above Hydrocarbon Accumulations

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SUMMARY

The geo-electric DNME method detects Induced Polarization anomalies in the subsurface. These anomalies are often situated in a halo above a deeper-seated hydrocarbon occurrence. Creation of an epigenetic alteration zone is stimulated by leakage of hydrocarbon and associated compounds (H2S) from the trap. Migration is due to diffusion and/or porefill perculation processes. The leaking give locally rise to a reducing environment when an effective regional seal is encountered. Here pyrite crystals can slowly grow when sulfur and iron ions are freely available. Pyrite is easily polarized and this is detected by geo-electric investigation techniques. Mathematical modelling permits simulation of the leakage and geochemical processes triggered in the overburden. Influence of various rock physical parameters has been examined. Some consequences for the evaluation of a DNME dataset across the Severo-Gulyaevskaya oil-and-gas field are presented and the impact on the interpretation of geoelectric data across a hydrocarbon accumulation in the Kaliningrad region is illustrated.

Introduction.

The differentially-normalized geo-electric investigation technique (DNME,) uses Induced Polarization (IP) anomalies in the shallow overburden as an indicator for presence of commercial hydrocarbons (e.g. Davydycheva et al. 2006). These anomalies reflect the presence of micro pyrite crystals in the sedimentary rocks overlying a hydrocarbon accumulation (cf Davidenko et al. 2008; Veeken et al. 2009). Due to imperfect sealing conditions, minor amounts of hydrocarbons and hydrogen sulphur migrate upward from the accumulation and epigenetic changes take place in the overlying rocks. The shape of the rocks, that are influenced by this subtle porefill perculation and/or diffusion migration, typically takes the form of a vertical "column".

The relation is examined between IP anomalies, pyrite enrichment and occurrence of a geochemical barrier separating zones of oxidizing and reducing conditions. Faults and /or fractures are zones of weakness that are often conduits for the leaking hydrocarbons. Modelling is done to simulate the behaviour of an imperfect top seal of a hydrocarbon accumulation. Over geologic time all seals are leaking minor amounts of porefill (e.g. chimney effect, velocity changes; Kudryavceva et al. 2009).

Induced polarization modeling.

Mathematical analysis was done and formulas established that permit to simulate the creation of geochemical alteration zones and pyrite enrichment above a hydrocarbon trap. These formulas are used in the geo-electric evaluation to calculate the theoretical distribution and concentration of pyrite. Initially no faults were taken into account.

IP modelling was done using data from the Severo-Gulyaevskaya oil-and-gas field (Barents Sea shelf). The following parameters were assumed: vertical offset from field – 2 km, field size radius – 5 km, age of trap formation – 250 10^6 years. Properties of the medium, such as diffusion coefficient and vertical migration velocity of hydrogen sulphur, are kept relative but calculations were carried out for scenarios with different numerical values. The main growth and increased concentration of the simulated epigenetic pyrite crystals is observed directly above the field (black bar on figures), independently of the numerical input parameters. Pyrite concentration decreases drastically outside the field area. The hydrogen sulphur diffusion coefficient has an effect on the slope of the geo-electric decay curve measured in the field (cf Veeken et al. 2009) and also on its offset from the accumulation. The width of pyrite concentration anomalous zone over hydrocarbon field increases if the diffusion coefficient in first layer above HC accumulation (D1) is great enough, compared to that in the second layer

The DNME field data allows to distinguish IP anomalies after processing and inversion of the Severo-Gulyaevskaya field. The Cole-Cole model is used to perform a 1D inversion of the data (Davidenko et al. 2008, Veeken et al. 2009). The OWC and IP anomaly outline are shown on the structural map of the seismic reflection horizon I_A (near top $C_{2\text{-}3}$–P_1 carbonate complex, Figure 1). In the closed contour area (orange) polarization values always exceed the limits assumed in the inversion procedure. They amount to 9% and more, against 3 – 6% outside the outline of the accumulation. Comparison of polarization distribution (heavy line) and the pre-calculated pyrite concentration (thin line) shows a significant correlation between these two parameters (Figure 2). Such IP distribution is typical for the NE part of the field, where the fault influence is absent.

Pyrite growth modeling and influence of fault position.

Attempts were made to calculate a theoretical pyrite concentration in the fault-controlled zone in the SW corner of the map. The calculation of pyrite concentration was carried out for different geological conditions, i.e. a set of diagrams were created for different depth of the hydrocarbon occurrence, various fault positions relative to the field and geological age of the trapping. The following influence of faults has been observed:

- If a trap is bounded by a fault or a fault is situated in close proximity to the acccumulation (in this case – 100 m.), hydrogen sulphur is migrating along the fault, and the IP anomaly can be extended in respect to the field outline (Figures 3 and 4).
- If a fault is further from the accumulation, its influence is less (to non) significant. The presented diagrams of pyrite concentration distribution correspond to the accumulation having a radius of 500 m, at depth of 2000 m and an age of the trap formation of 40 million years.

It is noted that a similar pattern of pyrite concentration is observed for traps at different depths with varying periods of leakage. Other media parameters can change the situation however drastically, such as: vertical migration velocity of hydrogen sulphur, diffusion coefficient of hydrogen sulphur and increase of vertical migration velocity of hydrogen sulphur in a faultzone with changing porosity / permeability. The influence of faults depends upon their proximity to the trap. 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 given for the leakage. A larger time span will allow more hydrogen sulphur to escape to shallower levels. Hydrogen sulphur flow runs preferably along the fault or fracture zone where locally a conduit is present. The closer the fault is positioned to the accumulation, the wider is the zone of maximal pyrite saturation and a good anomaly can be expected on the geo-electric data. This leads to higher values of polarization and a wider IP anomaly on the map. Making the fault distance larger and bringing it outside the limits of the field, decreases the pyrite concentration in the field area, while pyrite growth directly above fault is observed (Figure 4). When the distance from the fault to the accumulation is great enough, then no pyrite alteration zone is formed above the fault.

Consequences for Severo-Gulyaevskaya IP anomaly modeling and interpretation.

Calculation of expected pyrite concentration in the Severo-Gulyaevskaya area was done taking into consideration the influence of the fault (Figure 5). The results show that the IP anomaly, connected with pyrite presence in SE part of the field, should be wider than the actually mapped field outline and should exceed it by about 1 km. This partially also explains why the location of the IP anomaly contours is different in respect to the mapped Oil Water Contact (OWC). It is important to note that the OWC contour was designated according to 20 years old seismic data and its position can be improved when more modern seismic processing techniques are used.

IP anomaly modelling for hydrocarbon field in Kaliningrad region.

An other example of the benefit of the theoretical calculation of pyrite concentration is given in the Kaliningrad region (Figure 6). DNME acquisition and analysis were done and an IP anomaly was established above the crest of the reservoir structure. In the south it is limited by a fault. Setting up stick locations (1D modeling) with anomalous polarization values does not allow to determine unambiguously what is the isoline for the OWC (-1990 or 1980 m ?). This uncertainty sheds some doubts on the actual size of field.

Calculation of pyrite concentration was carried out along two trajectories (1-1 and 2-2). The radius of the accumulation is assumed 300 metres and it is bounded by a fault (Figure 7). Pyrite concentration is maximum straight above the accumulation and it extends where the fault is present for about 700 metres. If the fault is not immediately adjacent to the field (200 m away from it), the modeled pyrite distribution looks rather unexpected (magenta). The theoretical results depend on the simulation model. Migration of hydrogen sulphur is predominantly taking place along the fault, impoverishing the pyrite content immediately above the field. Maximum pyrite enrichment is observed, starting from the edge of the accumulation in the direction of the fault and extends for more than 700 meters.

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 have showed 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, as seen in 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 hydrogen sulphur 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.

Acknowledgements.

Wintershall, SGRD and the St Petersburg Mining Institute are thanked for their permission to publish this abstract. We thank all our colleagues, in particular: Dr Fleckenstein, D. Kaufmann, J. Konstanty, G. Clark, P. Thiede, S. Benko, I Pesterev and Y. Davidenko.

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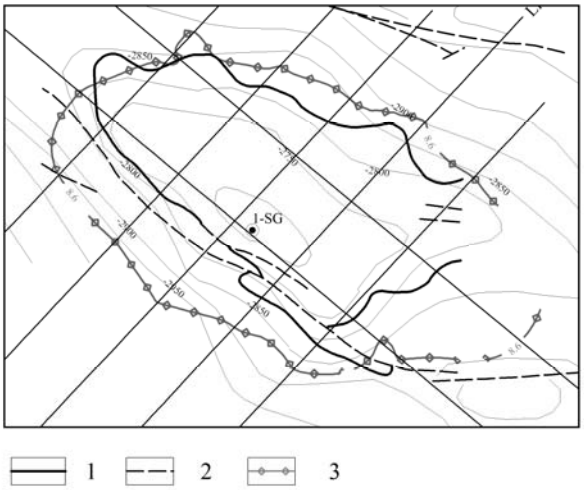

Figure 1 Structural map of reflecting horizon I_A with results of comparison of a water-oil contact' contour and IP anomaly contour by the DNME data. Legend: 1 - OWC contour; 2 - faults; 3 – IP anomaly contour.

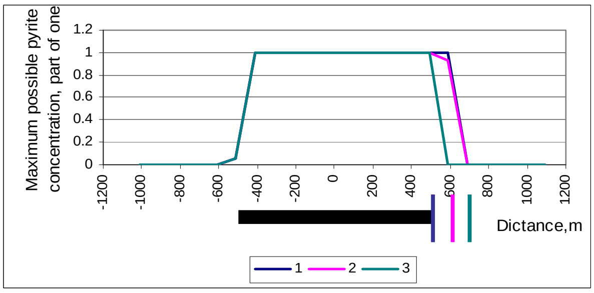

Figure 3 Modelling of pyrite concentration with geological time of 40 million years. Three dipping fault positions are shown with different colour index.

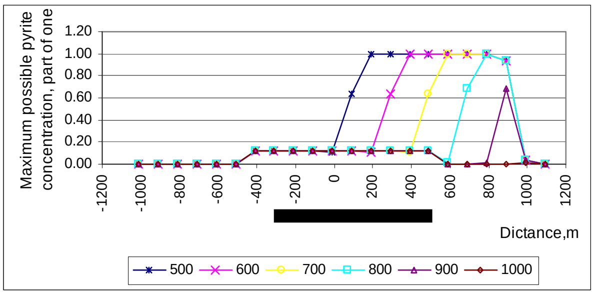

Figure 4 Modelling of pyrite concentration with geological time of 10 million years. When fault is far away from field, pyrite only occurs where fault is present.

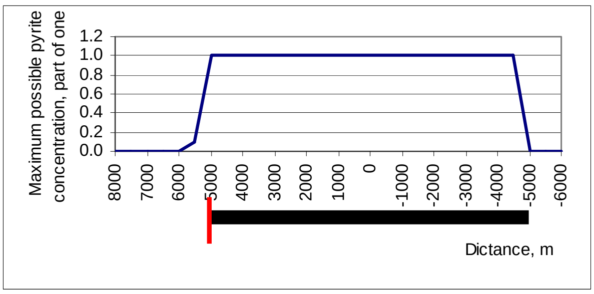

Figure 5 Modelling of pyrite concentration for Severo-Gulyaevskaya subsurface model taking into account influence of a vertical fault (red).

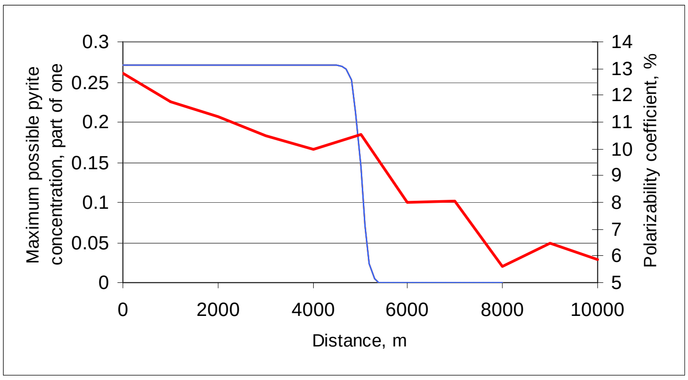

Figure 2 Comparison of polarization coefficient and calculated pyrite concentration for Severo- Gulyaevskaya field, without taking into account the presence of faults.

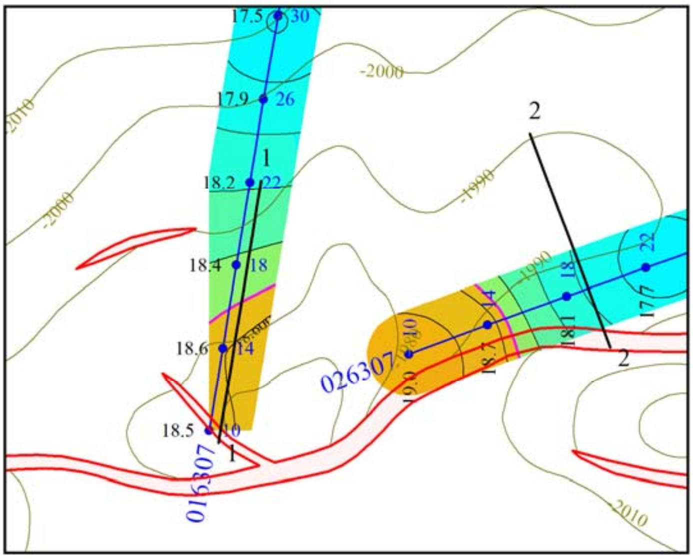

Figure 6 Map of polarization coefficient distribution with contours of reflecting horizon III (top of Ordovician). Geo-electric modelling suggests a 1980 m oil-water contact.

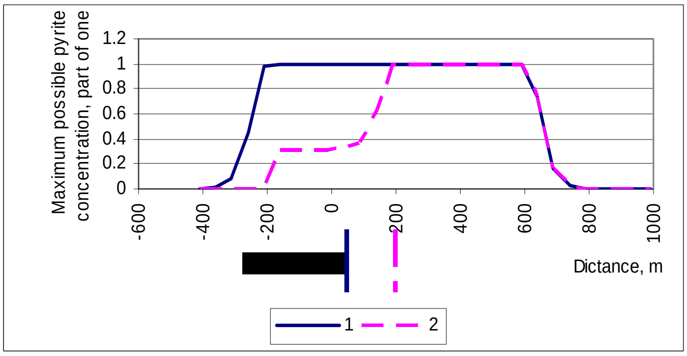

Figure 7 Theoretical calculation of pyrite concentration for hydrocarbon accumulation in Kaliningrad region. Moving the fault 200 metres from the field results in dislocation between IP anomaly and the actual hydrocarbon occurrence (magenta curve).