Drilling Risk Assessment through Joint EM and Seismic Data Integrated Interpretation*

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Abstract

Electromagnetic method is one of the important approaches to hydrocarbon prospecting. This paper describes an approach to invert resistivity and induced polarization (IP) using the combined constrain of seismic and electric logging data. As a result, the accuracy of hydrocarbon reservoir distribution prediction based on formation's electrical properties is significantly improved. The paper presents an example illustrating that joint constrained inversion and integrated interpretation workflow of electromagnetic properties (resistivity and polarization), seismic traps as well as seismic attributes, can significantly reduce drilling risks for oil and gas exploration. The statistic number on practical projects also supports the conclusion. The paper also discussed how the joint inversion and interpretation workflow works at different stages of oil and gas exploration and production with very positive results.

Introduction

We understand that hydrocarbon reservoir distribution is controlled by many factors, including complex surface and underground conditions. Reservoirs have different types, such as structural reservoir, lithologic reservoir, and stratigraphic reservoir (Niu, et al., 2005). Drilling risks exist not only due to the above factors, but also because of the fluid movement and variation of oil, gas and water during production period. Therefore, any single geophysical method cannot eliminate drilling risk (Xiong, 1997). Electromagnetic (EM) method is given more expectation on the prediction of subsurface oil, gas and water distribution (He and Wang, 2002; He, et al., 2010). However, due to its low resolution on underground targets, surface EM methods have not been widely applied within oil and gas industry. While for wireline logging or MWD/LWD, EM method is one of the major approaches to distinguish oil, gas and water. It is well known that resistivity is the most frequently used parameter for hydrocarbon layer interpretation in all logging parameters. Years' experience indicates that resistivity is related to oil, gas and water saturation in the reservoir formation rock pore space. Higher oil or gas saturation usually leads to higher resistivity (Xiao and Xu, 2006). Therefore, resistivity anomaly can be used to predict and interpret hydrocarbon-bearing possibility in the subsurface formation. Recent years, another parameter, induced polarization (IP), has gained more and more attentions. Induced polarization (IP) log has been applied for oil or gas interpretation within logging industry. Many laboratory tests and oilfield tests show that high oil or gas saturation is strongly associated with high-induced polarization. Oil-saturated rocks are tested to study the low frequency resistivity dispersion effect, mainly caused by the IP effect. The tests indicate that IP effect becomes stronger when oil and gas saturation increased (Xiao and Xu, 2006).

Traditional EM methods only study the secondary resistivity and IP anomalies in shallow layers to interpret deep target, so it may exist many uncertain factors. Consequently, the hydrocarbon detection result is unreliable. He (2007) put forward a three-layered anomaly mode for hydrocarbon reservoir, which can directly explore and evaluate hydrocarbon reservoir target. The new method is named high-power time and frequency domain electromagnetic method (TFEM). A high-power surface or downhole large current dipole source is used to directly excite deeply buried hydrocarbon reservoir targets, thus the resistivity and IP responses from target reservoir can be observed and measured on the surface.

In 2005, a hydrocarbon detection technique with IPR (IP*Resistivity) anomaly has been developed (He, 2007). It is believed that a hydrocarbon-saturated formation has higher resistivity than a water-saturated formation; therefore, high resistivity anomaly will appear in EM (resistivity) data. IP anomaly can indicate the existence of potential hydrocarbon fluids. Only in the case of both high resistivity and high potential of hydrocarbon fluids, it can be interpreted that the target may contain hydrocarbon. Resistivity-related anomaly might be represented by amplitude or dual-frequency amplitude anomaly, or resistivity anomaly, etc. Polarization-related anomaly also might be represented by some other parameters, such as dual-frequency phase, polarization, time constant, etc. Here, induced polarization is the major anomaly for hydrocarbon potential assessment. With the two kinds of anomalies, we can distinguish either the igneous rocks, which show high resistivity anomaly and low polarization without hydrocarbon, or the disseminated pyrite, which usually shows low resistivity and high polarization, from real hydrocarbon reservoir.

The theory and practice have shown that there exists strong IP and resistivity anomaly above the known hydrocarbon reservoir. Therefore, in an exploration area with good structure trap and strong AVO anomaly as well as matched IP and resistivity anomaly (IPR), the drilling success rate will be significantly improved in the confirmed TFEM – Seismic anomaly combined area.

Due to the limited inversion precision, the inverted resistivity and polarization data have large error on depth, which makes it difficult to determine drilling target's true depth. Therefore, it is necessary to accurately invert depth. Since the structural traps and attributes interpreted from seismic data are reliable, meanwhile the EM data can provide the information about pore fluid resistivity and polarization, EM data and seismic data should be jointed to make hydrocarbon evaluation more reliable.

EM Constrained Inversion Using Logging-Seismic Model

In recent years, an EM inversion method constrained with logging and seismic data is programmed for improving inversion accuracy. It is a non-linear algorithm, i.e., a least-square fitting method (Steihaug, 1983). Model framework is established by seismic and logging data, and the thicknesses and depths of all layers are fixed during the inversion process. The model layers include seismic interpreted formation horizons and electrical interfaces derived from the logging data (They may not always be the same as the seismic interpreted formation horizons.). While initial resistivity of each layer is an average value from resistivity logging data, and their variation ranges are set according to available logging data or known lithologic formation electrical property. Thus, number of the involved variables can be reduced to a maximum extent, and searching area also can be limited within a small range, which helps to accelerate the inversion process significantly. More importantly, it can make the iteration going towards a geologically reasonable trend, and finally output a geologically reasonable result. Polarization inversion undergoes the procedure similar to resistivity inversion. Firstly, the distribution and characteristics of the reservoirs should be understood and analyzed. The non-reservoir formations are assigned with a small initial IP value with a small variation range, while those of reservoir formations are determined according to available logging data and measurement result from core samples. We know that for the mathematic models that describe the complex frequency features of formations, such as Cole-Cole model, resistivity has a product relation to polarization, so inversion usually cannot fit and determine all variables simultaneously. Because resistivity has more impact than polarization, we usually fix polarization and only invert resistivity at first. Thus, we obtained a resistivity-filled model. Then we invert polarization. The procedure can be repeated several times. The final resistivity inversion model can reflect the electric features of basic geology model, while the final polarization model is the reflection of residual electromagnetic anomaly other than the electric features of background. In other words, it is the response of the induced polarization effect generated from oil and gas reservoir. Figure 1 compares the seismic and logging data constrained inversion result with non-constrained inversion result. It indicates that the resolution on the constrained inversion section is greatly improved. Anomaly location is more accurate and the geological interpretation is more obvious. Three wells on the left are previously drilled and the two wells on the right are the wells proposed according to EM-Seismic interpretation. The drilling results discover that well D1 is a dry well while well D2 has commercial oil production.

Hydrocarbon Detection with Jointed EM and Seismic Data Interpretation

Both core sample measurement and oilfield experience illustrate that a known hydrocarbon reservoir shows high resistivity and polarization anomalies. Figures 2a and 2b are the cross-plots of the inverted resistivity anomaly and the inverted polarization anomaly, respectively. The figure implies that both resistivity and polarization can be used as hydrocarbon indictors, especially high induced polarization usually means high hydrocarbon potential. The figures also illustrate that both clastic and carbonate reservoirs have high resistivity and high induced polarization anomalies.

In the case that seismic traps are interpreted or seismic attributes, such as AVO, show anomalies, EM anomaly (or IPR) can be integrated with seismic data to assess target and propose well locations, and the well drilling success ratio can be significantly improved. Figure 3 is the seismic section overlaid with IPR anomaly. It shows that the IPR section has high magnitude at the location of the predicted seismic traps. At the trap location, a well (G-1) is designed and drilled. Just as the prediction, this well obtained commercial oil and gas flow.

According to statistics data, totally more than 70 oilfields in China have applied jointed electromagnetic (EM) and seismic data to search for hydrocarbon targets, and this number is more than 30 overseas, such as in Oman, Chad, Saudi Arabia and Niger, etc. These projects cover different types of hydrocarbon traps, including structural traps, stratigraphic traps, lithologic traps and composited traps. The targets are either sandstone or carbonate hydrocarbon reservoirs. All these projects have gained good results. According to the statistics data from more than 50 clastic sandstone hydrocarbon reservoirs, the success rate of drilled wells, which are designed based on the jointed EM-Seismic interpretation, is higher than 75%. Taking FZ area as example, all 18 wells match well with EM-Seismic prediction, and among 12 wells designed according to integrated EM-Seismic interpretation, 9 wells obtained commercial hydrocarbon fluid. Another statistics data come from carbonate reservoirs in TLM basin. The success rate of EM-Seismic prediction is higher than 70%. For example, in the YM area, totally 28 wells are designed based on EM-Seismic interpretation (within the TFEM line range and with the offset no more than 500m), and among the 28 wells, 19 wells match well with the TFEM prediction. In summary, for the very deeply buried hydrocarbon targets, TFEM effect is gradually reduced, while for the shallow targets buried at a depth less than 4,500 m, the success rate of hydrocarbon prediction can be higher than 75%.

Case Study

The GC structural belt is located in a small-amplitude ridge, named Tadong, in the central uplift of Tarim Basin. The GC structural belt is close to a petroleum generative depression. In other words, it is a geologically advantageous target area. West to the belt is another structural belt, which has obtained oil breakthrough. Well G2 is located in another trap. Because well G2 is drilled at a structure low location, it obtained only oil show without commercial fluid. Drilling data indicate that Cambrian dolomite has a good reservoir property. In 2008, TFEM survey was deployed in the GC structural belt. All TFEM survey lines total to 388 km and cover an area about 1,000 km^2. Eight lines are planned (marked by dotted lines in Figure 4). The final IPR anomaly map is shown by the color area in Figure 4. In the figure, red and yellow color area represent high anomaly. The IPR anomaly map exhibits that the high potential hydrocarbon zone is close to the GC area, while on the east of the central belt appears discontinuous mass-liked anomaly, which is worth for further study.

3D seismic data is used to further delineate the trap scope, and the data provides root-mean-square amplitude anomaly related to target formation. We overlay the potential hydrocarbon area, which is predicted by TFEM data on the advantageous reservoir area. Based on the overlaid map, well G3 is proposed. This well was drilled in April 2012, and it obtained oil breakthrough. In dolomite rocks at the bottom of Cambrian system, well G3 obtained high-productive commercial oil flow. Following the successful drilling at well G3, another two step-out wells, G4 and G5 are designed. Well G5 is designed at a high polarization site, which gets commercial oil production; while well G3 is designed at a small polarization anomaly, and it has no oil show. The three wells proved the correctness of joint EM-Seismic prediction.

Conclusion

EM-Seismic interpretation fully makes use of the advantages of both EM and seismic methods. It is an alliance between giants. It can help to solve some problems such as the complexity of oil and gas exploration and the ambiguity of geophysical methods, reducing prospecting and drilling risks. The alliance is a new and effective indicator for oil and gas exploration. The integrated EM-Seismic interpretation can be used at the different stages of oil and gas exploration. In an under-explored area where only 2D seismic survey is conducted, joint EM-Seismic data can help to assess the hydrocarbon possibility of the traps interpreted by 2D seismic data, providing information for 3D seismic design or exploration well planning; In a well explored area where 3D seismic has been completed, joint EM-Seismic data interpretation can help to propose drilling site for the traps interpreted by 3D seismic data, improving drilling success rate. In a well-developed and matured oilfield where there are enough seismic data and many wells, EM-Seismic interpretation aims to search for residual or bypassed oil and gas, map oil-water contact and increase recovering rate. Presently, the joint EM-Seismic interpretation has been widely used for drilling target evaluation, but the technique is still at the developing stage, especially the effective joint inversion algorithms development. Meanwhile, the technique should be developed in the future practical work. Reasonable and correct application of joint EM-Seismic interpretation must gain a reward greatly higher than expected.

Because of the complexity of the hydrocarbon exploration and the uncertainty and non-uniqueness of geophysical exploration methods, the joint TFEM – Seismic method can combine their respective advantages and make the full use of both techniques. It can be used to reduce the risk of exploration and drilling. The application examples show that this joint method has effectively developed the optimized direction of hydrocarbon exploration and development. At present, the joint TFEM – Seismic method has been tested and applied on many hydrocarbon target evaluation, but this technique is still in continuous development, especially the joint inversion of both data sets and wider applications are needed. Reasonable and flexible use of the joint TFEM – Seismic method are bound to achieve a higher return benefits in the hydrocarbon exploration.

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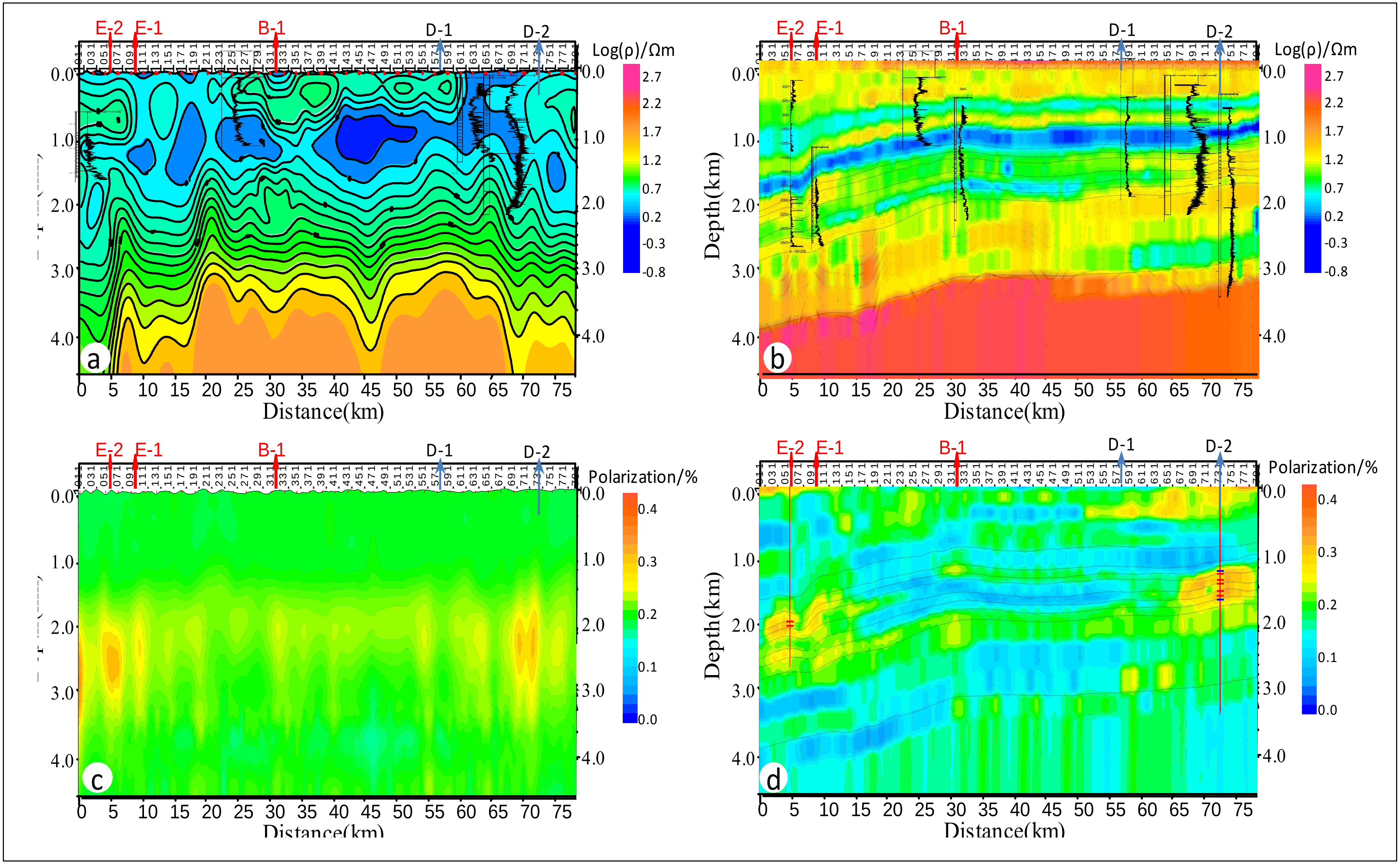

Figure 1. Non-constrained inversion (left) vs. constrained inversion (right), and a and b: resistivity, c and d: induced polarization.

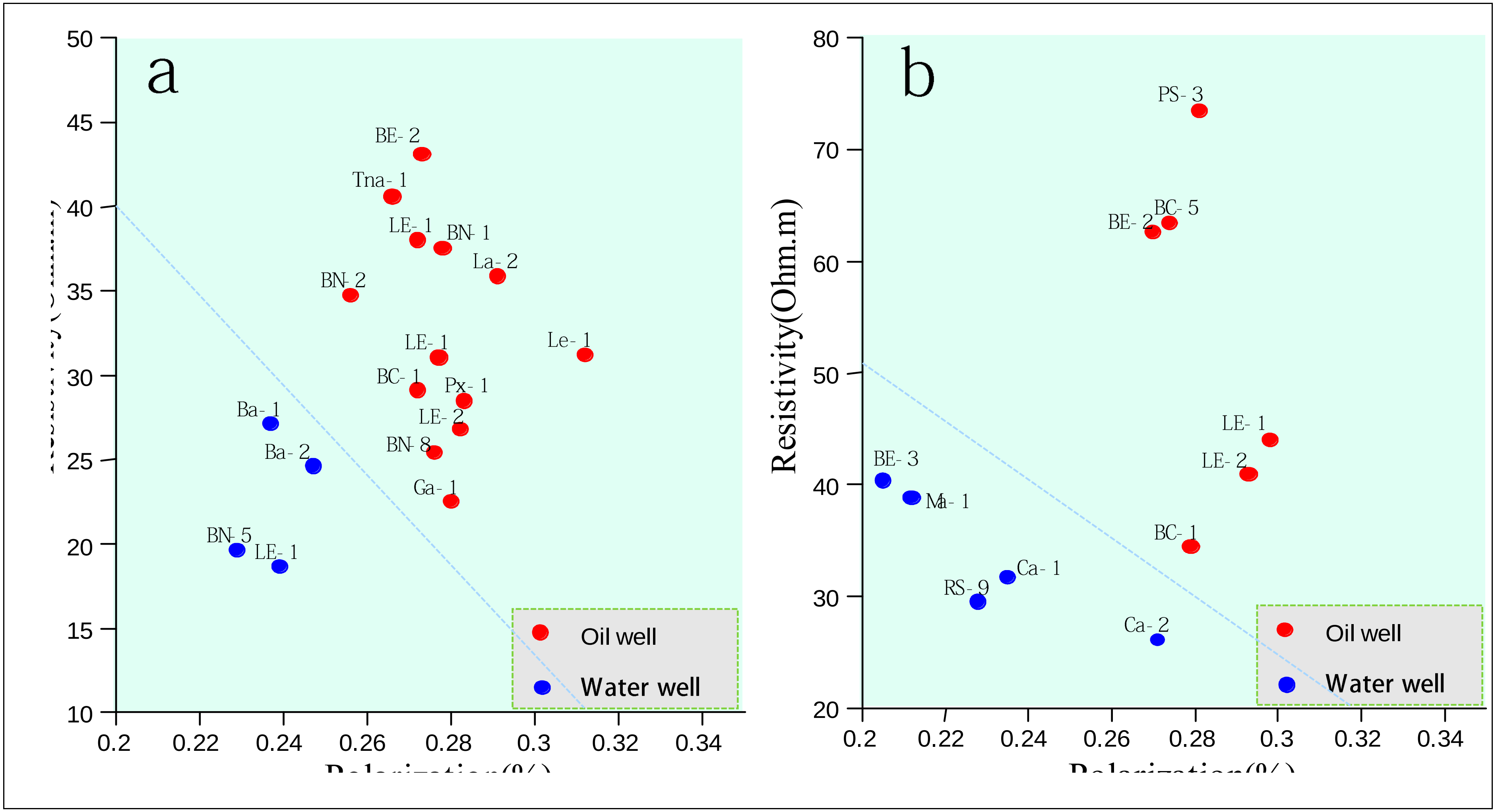

Figure 2. Cross-plots of inverted polarization and resistivity anomalies. (a): sandstone reservoir; (b): carbonate reservoir.

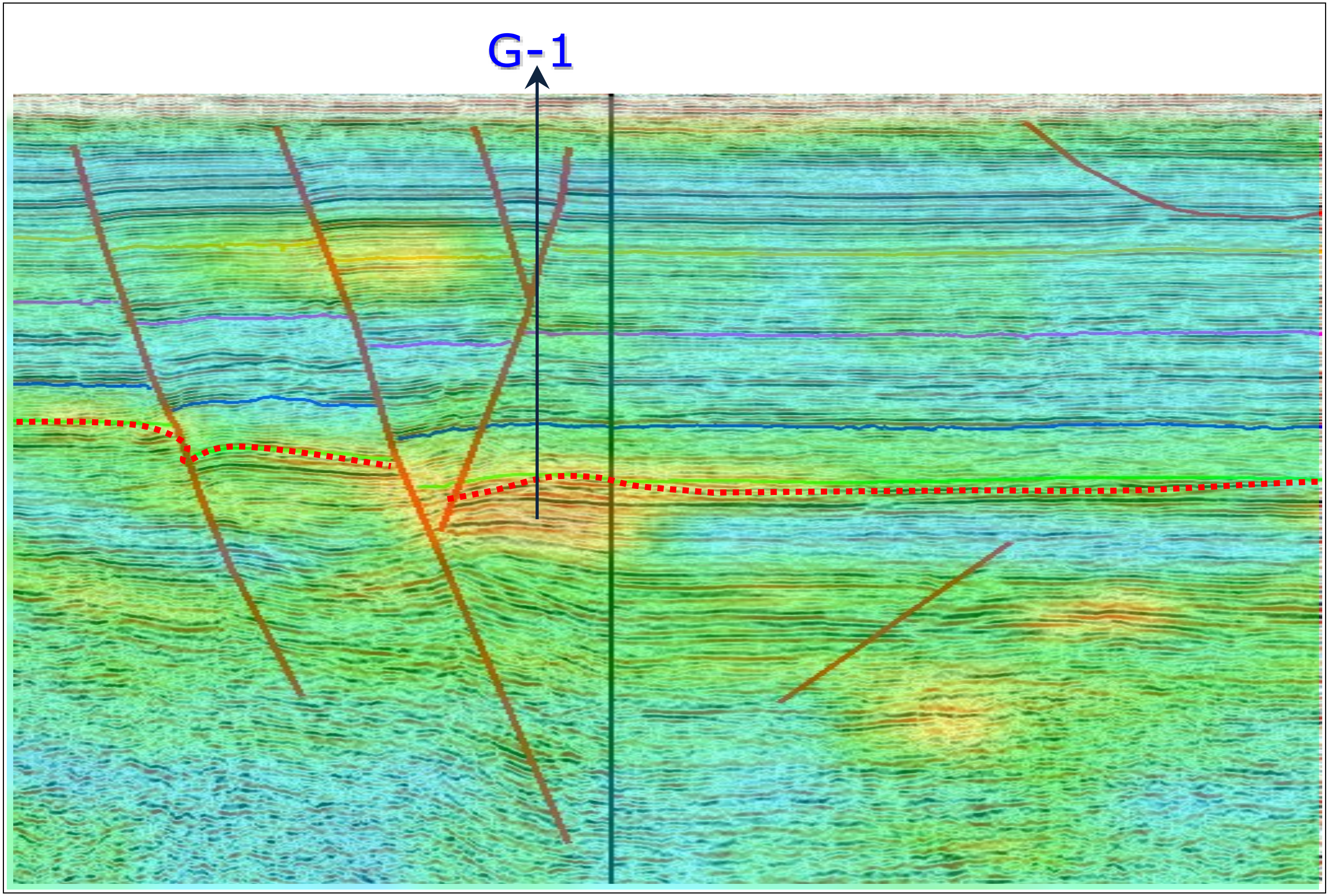

Figure 3. Electromagnetic attribute anomaly section overlaid with seismic section (the colors represent electromagnetic anomaly).

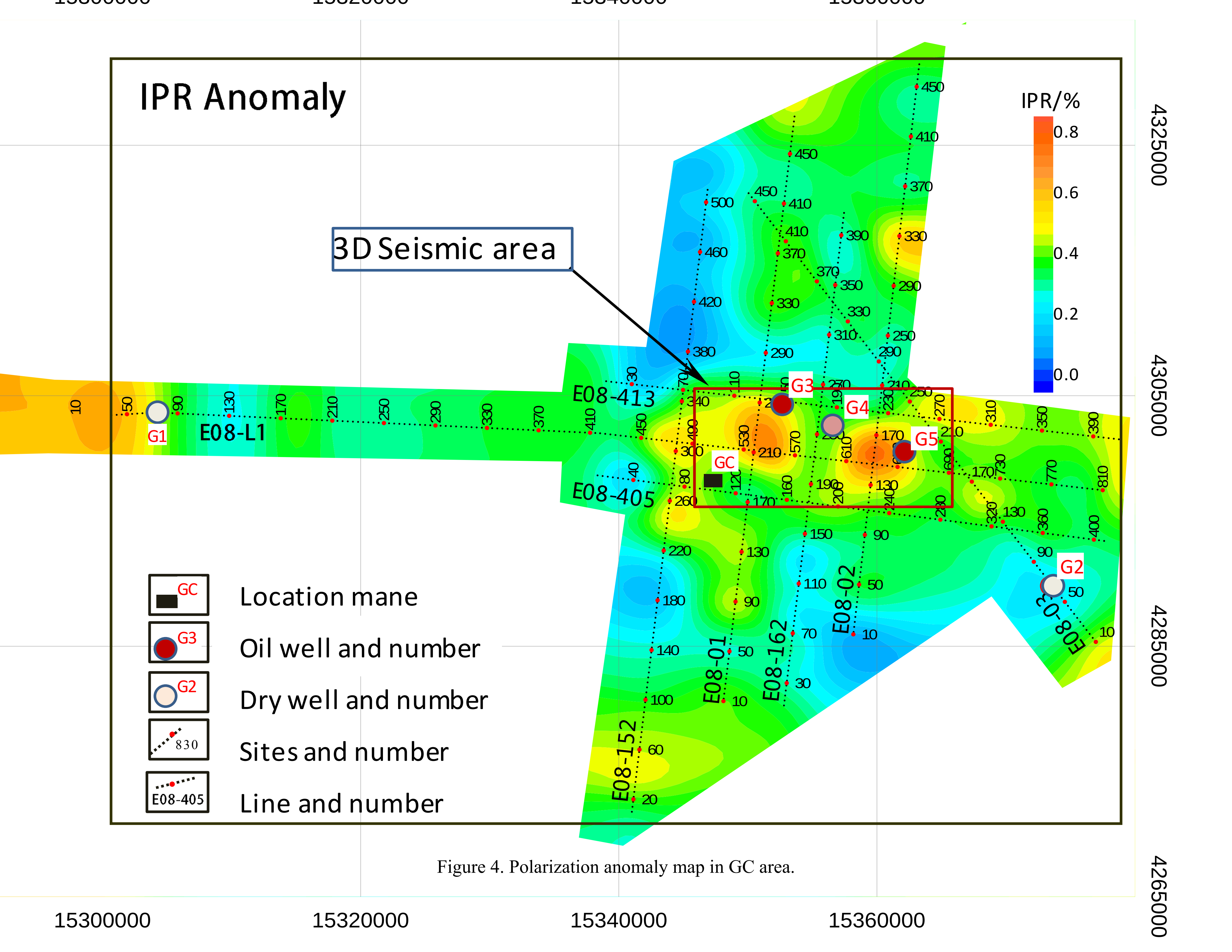

Figure 4. Polarization anomaly map in GC area.