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Vozoff's influence on LOTEM hydrocarbon applications

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21 ASEG Conference and Exhibition, Sydney
2010

Vozoff's influence on LOTEM for hydrocarbon applications

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SUMMARY

Direct Hydrocarbon indicators from electromagnetic measurements have always been questionable. In K. Vozoff's work they translate to resistive layer and understanding the reliability of resolving resistive layers. Vozoff worked on this subject extensively with the team around him in the 1980s and 1990s.

The work started with feasibility studies and a field demonstration over a small oil field in Western Australia. A detailed starting model was derived from the seismic and well logs and joint inversion of electric and magnetic field yield inferred porosity or percentage sandstone section. Vozoff not only pioneered methodologies in electromagnetics but also details of inversion methods that are still of great interest today.

Without mistake, he anticipated failure or success of the individual task on hand.

Key words: Vozoff, Lotem, resolving resistive layers, joint inversion

INTRODUCTION

Keeva Vozoff became interested in Lotem (now also called CSEM) methods for hydrocarbons in 1981 when he worked on the post-graduate plan for one of his Ph.D. students. After he rejected the plan of the student to work on a method intrinsic constraint inversion, he became interested in evaluating the theoretical work done at Colorado School of Mines and University of Toronto with respect to detecting thin resistive layers with grounded dipole EM systems (Passalaqua, 1983; Eadie, 1979). These were already then thought to be Direct Hydrocarbon Indicators (DHI) and Keeva's peer from Penn State, G. Keller, was pushing this area. With a graduate student he embarked on writing numerous proposals to Australian industry to fund the development of a Lotem system. After several smaller grants, he received a larger grant, which allowed him to work with Esso Australia on a survey in Western Australia (Vozoff et al., 1985; Vozoff, 1987, Strack et al., 1989). Subsequently, more work continued in Europe and in Australia mostly in collaboration. Shortly after 2000, and long after Vozoff and his students stopped working on LOTEM, marine CSEM became important and a complete industry was born.

This survey in Australia, carried out with a mixture of new and old equipment, was the first survey where resistive units were mapped with surface EM methods. It was second survey in Australia following a calibration survey in the Sydney Basin.

Keeva collaborated mostly with the Lotem group at University of Cologne. This work culminated in Keeva receiving the Humboldt Prize and spending a lot of time in Cologne steering a EU project that was focused of mapping reservoir changes with time. The project was in collaboration with CGG, DMT and the University of Edinburgh. While this project ended inconclusively, it did produce a spinoff Lotem group at the University of Edinburgh. Furthermore a complete new generation of tools were designed for the logging industry based on the principles of the Lotem system, patented in the early 1990s (Rueter et al., 1985)). Keeva tried to bring this system to Australia for induced polarization applications

Since the advent of marine CSEM in the early 2000s, it has become very clear that CSEM can map resistors, which is exactly as Keeva predicted in 1981. Furthermore, CSEM is most useful when it can be integrated with other methods such as magnetotellurics and seismics, which is another aspect that Keeva pioneered in this area, as an extension of his joint inversion work. Today marine CSEM is already mainstream technology while onshore the breakthrough in operational ease and reliability has yet to be made.

RESOLVING RESISTIVE LAYERS

It was noted generally in the late 70 (Passalacqua, 1983; Eadie, 1979) that thin resistors gave an increased anomalous voltage reading. This was supported by Passalacqua's thesis. This observation was derived from numerous DC resistivity and MT measurements around oil fields. Around the same time, time domain EM made its debut in North America (long after Australia!) and the isolated experiments at Colorado School of Mines and Group Seven Inc., of using time domain measurements for oil and geothermal exploration, became less a mystery (Kaufman and Keller, 1983). Unfortunately, the noise in the oil field environment caused by surface installation was not surmountable at the time.

After initial field tests of the methods in Australia (Strack, 1984; Vozoff et al., 1989), Keeva's team embarked on assembling a system, partially with off-the-shelf component from vendors, and partially with re-engineered components. (The original system had already been sent to Germany.) With support from NERDDC and help from Esso Australia, Keeva found a test site in Western Australia, an Esso employee (Doug Moss) who wanted to get a higher degree with Esso's support. A survey, results and interpretation followed. I will focus here more on the more controversial and well-advanced parts of this work. Figure 1 shows the seismic section that was used as *a priori* information to derive the models. In addition to the section, an induction log was available as shown in Figure 2. The seismic data is of good quality and the horizons were picked with Esso's in house software. The combination of seismic and log allowed the selection of a 10 layer Earth models as indicated in the blocky curve in Figure 2. Vozoff modelled various parameter variations and the blocky curve was the resulting optimum starting model. At the time, there was concern about overparameterization. Today, 20 years later, this is standard and many marine CSEM examples have been published where hydrocarbon related success is reported based on matching seismic and EM data in an over-parameterized sense.

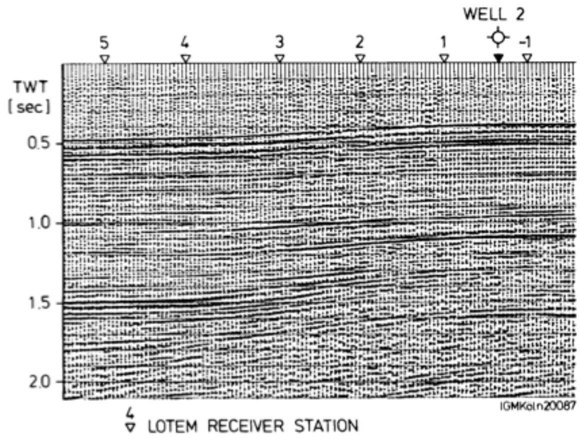

Figure 1. Seismic cross section from the survey in Western Australia. The seismic horizons were used to derive a 10-layered model. (after Vozoff 1985; Strack et al., 1989).

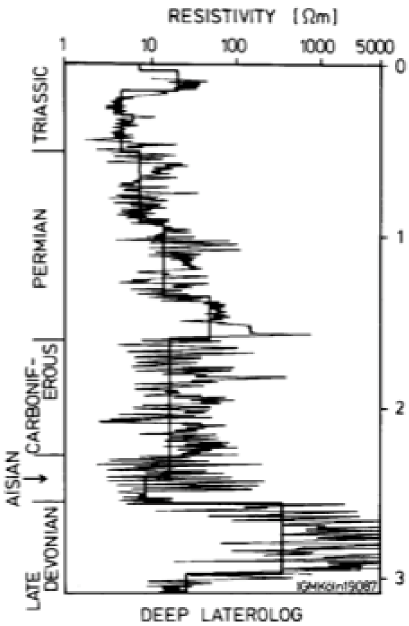

Figure 2. Resistivity log and the reduced well log based on the reflectors of Figure 1. (after Vozoff 1985; Strack et al., 1989).

What would be different today would be the use of anisotropic models and limiting resistivities, which represent the vertical and horizontal resistivities. While this is only today appearing on the horizon after Vozoff's experience in Western Australia, it already shows up as an interpretation requirement in many publications (Strack and Vozoff, 1996).

Another innovative aspect, which is still in its infancy in today's industrial application, is the use of electric and magnetic fields in a joint inversion workflow. At the time of the work in Australia this was already part of Vozoff's daily toolkit. An example of the Western Australia survey is shown in Figure 3. Here, the Lotem electric and magnetic fields are used as input data and the resulting resistivity section honours both data sets. The resistivities are then converted to percentage sandstone maps after log correlation. While not successful for this survey, it is a useful tool in workflows when honouring multiple data sets is key to a successful interpretation.

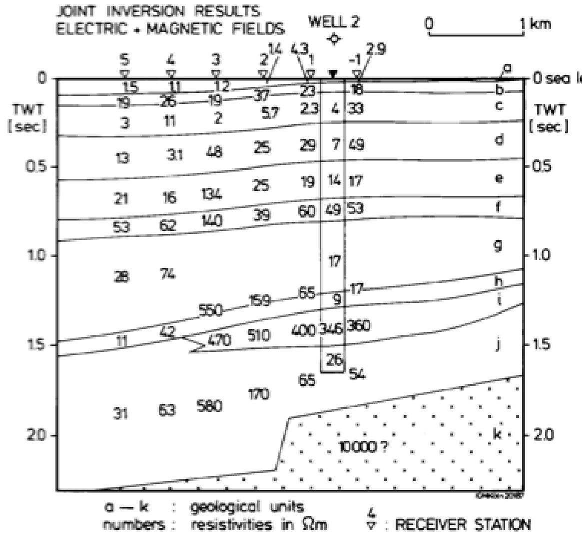

Figure 3. Resistivity cross-section obtained from joint inversion of the field data using the starting model in Figure 2 and constraining the horizons shown in Figure 1. (after Vozoff 1985; Strack et al., 1989).

The workflow pioneered in Western Australia was further substantiated in test surveys (Strack et al., 1989) and feasibility studies (Strack, 1992), an example of which is shown in Figure 4. The figure illustrated how geometric constraints are needed for CSEM interpretation and that indeed the electric fields are biased toward resistors and the magnetic fields are biased towards conductors. Only a combination of both gives us an unbiased resistivity and thus fluid content resolution. Here, we have on the left side a set on models and inversion results that are unconstrained and on the right side the constrained version. The latter defines in more cases the starting model shown in the centre above the inversion results. On the left half of the figure, we are using as

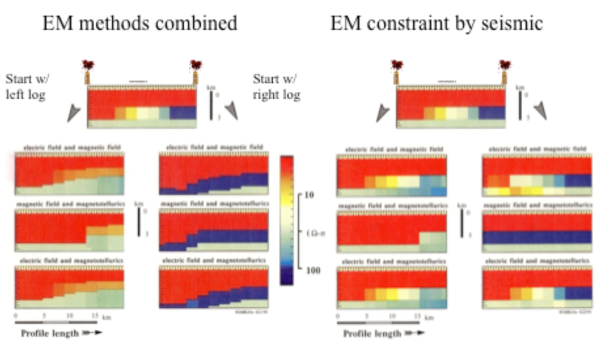

Figure 4. Inversion examples using various electro-magnetic methods. On the left side the synthetic data was inverted unconstraint and on the right side, the data was constraint with seismic. (after Strack et al., 1989).

starting model the well log to the left of the profile where the well is indicated by the derrick. On the right, the well log from the right well is used. Without constraining, the inversion meanders around the starting model. On the right side of the figure, we have now used the seismic data to constrain the inversion and the top and bottom ensembles represent the synthetic model more closely. In both of these cases electric and magnetic fields were used, whereas in the centre row only magnetic (magnetotellurics have same sensitivity to conductors as magnetic fields) field are used. They do not resolve the resistive unit at depth.

As indicated earlier, Vozoff rejected initially the profile inversion concept and scientific curiosity makes us wonder what happened to it. The work was assigned to a Master's student at a later date and he experimented extensively with various algorithms, first on synthetic and then on real data as shown in Figures 5 and 6 (Petry et al., 1987). Figure 5 shows the results of a profile inversion where the inversion of one site considers the results of the previous site. It allows variation of the results only in a fixed parameter range. This is a common procedure today. The figure shows that the result is more consistent but also that it jumps where the data is either noisy or influenced by a possible fault zone. Using absolute values is called 'hard bounds' and these are usually derived from interpretation of logs. In Figure 6 'soft bounds' are used and we see immediately that the section resulting is a lot smoother. They are derived from allowing variations from the previous model along a profile within a certain fraction. Note that the site where the section in figure 5shows a fault zone is not well matched. The inversion forces a smooth model through the data that respects both data sets. Unless you analyse at the data match and compare it with other types of constraints and inversion methods, you will not see this. This means using this type of inversion workflow is very dangerous as it can lead to error and misinterpretation. This is exactly why Vozoff did not like this project as post-graduate work. This is yet another example of the reliability of Keeva's scientific intuition.

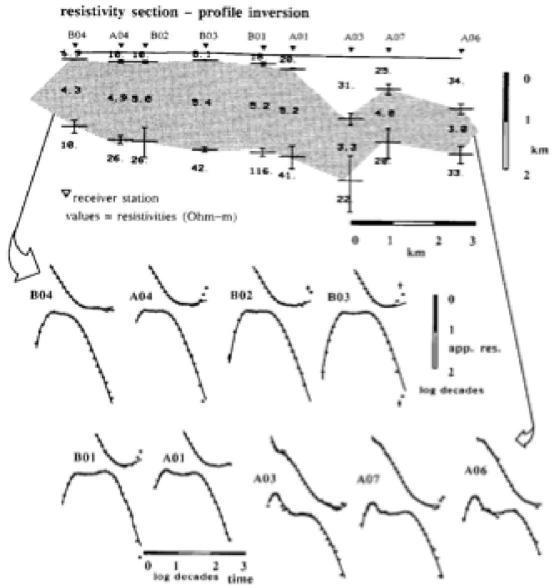

Figure 5. Resistivity inversion results using constraint inversion. Here the data was constraint using absolute values (fixed bounds) (after Strack et al., 1989).

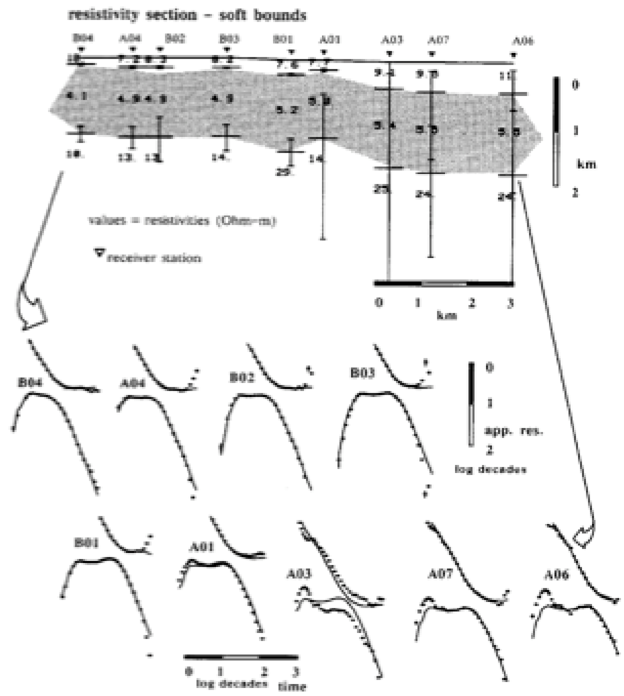

Figure 6. Resistivity inversion results using constrained inversion. Here the inversion bounds on one side are linked to the neighbouring sites (after Strack et al., 1989).

CONCLUSIONS

K. Vozoff pioneered many important technical understandings and detailed tools in electrical geophysics. He received the Reginald Fessenden Award for this in 2009. As for using

CSEM, especially Lotem, for direct hydrocarbon indicators, he was clearly one of the early promoters with theory and field-tests in the 1980s and 1990s. his ideas where then very challenging, today still not completely commercial as land CSEM is a difficult method to apply.

Today, joint inversion and constrained inversion are in every EM geophysicist's language. Keeva, the original pioneer, concluded already in the early 1980s what the benefits and dangers on it are. He freely disseminated his programs and experience and many groups are using his codes. Joint inversion is still in it's infancy in today's EM industry.

ACKNOWLEDGMENTS

The list of acknowledgement for the work around Keeva and Lotem is long. First, I thank the Exploration Geophysics Group in Cologne. The group continued to exist for almost 16 years after Keeva left Cologne. Then, gratitude goes to NERDDC and to Esso Australia for agreeing to support Keeva so generously in Australia and the CGER staff at Macquarie University. Initial work was also supported by the CSIRO and BHP. The Australian/German Science and Technology exchange program and officials gave it sufficient high-level support leading to the EU funding of the Monitoring project. Many of the project members contributed above and beyond the call of duty. Last but not least the German Science and Technology Minster who funded two major Lotem development and demonstration projects where these ideas were tested.

Last but not least to Keeva Vozoff, who taught me so many bad habits and even more good scientific behaviour. Thank you for the long friendship and support. What a ride it was and still is!

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