Application of Nuclear Magnetic Resonance in Petroleum Exploration

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Introduction

Electro-magnetic resonance method (GEO-EMR) is emerging as the most competitive technique for petroleum exploration and field development. While nuclear magnetic resonance has been used extensively in spectroscopy, medicine and well logging it is now rapidly penetrating the field of applied geophysics. The reasons for our exploration enthusiasm are obvious. The method integrates attributes of well logging enabling us to look at geometry, lithological characteristics and reservoir fluid, while at the same time it enables accurate depth estimation of the formation boundaries like in seismic imaging. Above all the method is very economical. In this challenging period for the petroleum industry, there may be a need for such a game changing new technology.

Our method is using an innovative concept and technique based on the coherent spin precession of the atomic particles. In our extensive laboratory work the characteristic nutation frequencies of the various materials have been defined, special hardware was designed and built, and wide-ranging field measurements were completed at the oil and gas fields in the Pannonian Basin. Two survey geometries were used: electro-magnetic resonance profiling and sounding. The results of our surveys are very encouraging and they have already been confirmed with the recent positive drilling results in the Sava Valley, Croatia.

The dream of the Nobel price winner for physics (1952), E.M. Purcell, which he expressed in his Nobel lecture speech by saying: "Delicate motion should reside in all ordinary things around us, revealing itself only to him who looks for it", is becoming a reality. We have to look at the subsurface with new eyes, recognizing the astronomical volumes of protons quietly in precession in the Earth's magnetic field, disclosing the subtle geological structure of the Earth.

GEO-EMR Method

In this method, we explore the properties of nuclear magnetic resonance and spin dynamics by developing a novel geophysical application technique. The concept of spin is difficult (M.H. Lewitt, 2002) and it was forced upon scientists by experimental evidence. The spin of the nucleus indicates that, in the simplest possible way, the atomic nucleus behaves as if it is spinning around, rotating in space like a tiny planet, inviting us for an exciting geophysical adventure. The nuclear magnetic resonance has already been used efficiently in medicine, chemistry and well logging and from time to time in the near surface geophysical exploration, as for example in Legchenko et al. (2002).

The concept and strategy development of our GEO-EMR method are focusing primarily on application in petroleum exploration. The method could be summarized as an overall interaction of the spin resonance with constructive interference of the external radio frequency beams characterized by relative Larmor frequencies (Z. Jankovic, 1997). The heart of any electromagnetic method is the interaction of the electric and magnetic field based on the characteristic properties of each particular element. All substances are magnetic, meaning that that they have the capability of interacting with magnetic fields.

The interaction is usually expressed in terms of a magnetic moment μ. The magnetic energy of a small object depends on interaction between its magnetic moment and the **B** field (Figure1). The dot product of vectors indicates that the magnetic energy depends on the relative direction of the vector **B** and **μ**. Most objects display induced magnetism and only possess a magnetic moment in the presence of an applied magnetic field. The equilibrium value of the induced magnetic moment is often proportional to the applied magnetic field **B**.

$E_{mag} = -\mu \cdot \mathbf{B}$

Figure 1: *Macroscopic magnetic interaction*

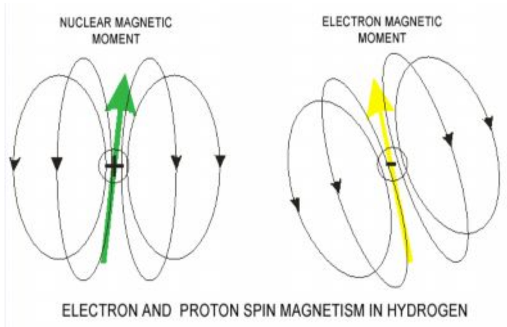

Figure 2: *Electron and proton spin magnetism in hydrogen*

Microscopic magnetism is also important here because of the magnetic moment of the atomic nuclei (Figure 2). Both the electron and nuclei possess intrinsic magnetism, which is not due to a circulating current. The fundamental particles simply ‘have’ a magnetic moment, just like they simple ‘have’ spin angular moment. Spin and magnetism are very closely linked. A fundamental symmetry theorem requires that spin angular momentum and the magnetic moment are proportional to each other (M. Munowitz, 1998).

The Larmor frequency as a fundamental quantum of spin precession is proportional to the magnetic field at the site of the particle and to the gyro-magnetic ratio, Figure 3. The relative Larmor frequency used in

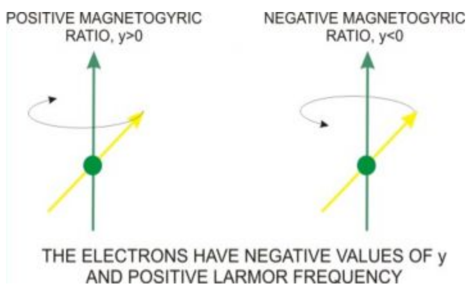

Figure 3: *Spin dynamics and positive and negative precession or Larmor frequencies*

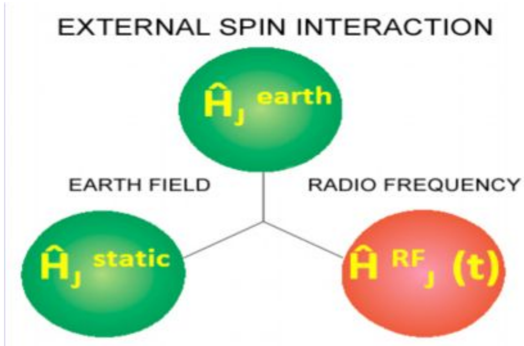

Figure 4: *External spin interactions*

GEO-EMR method is a key element or component enabling us to search and detect specific contents in the subsurface. In our extensive laboratory analyses for different samples and substances the

characteristic relative Larmor frequency was specifically defined. It then correlated to be akin to a Web browser subject search, where specifying a key word allows one to retrieve relevant information on the same. Wide range of the field tests and the well-survey calibration confirmed that the method is absolutely reliable and could not only be used as a direct hydrocarbon indicator but as well as a lithologic analyzer. Thus, there is a analogy between the well-logging and this method, however, in the later case measurement is done just on the surface.
Looking at the historical development of the NMR technique using the Earth's magnetic field, the technique did not gain immediate acceptance for a number of reasons. However, the key problem was the source characteristics of the radio frequency pulse used to stimulate nucleus to move coherently. A special radio frequency coil assembly developed and patented in 1997 by Z. Jankovic allows a complete control and measurement of the nuclear magnetic resonance field. The diagram in Figure 4 summarizes the form of the external spin interaction, where the Hamiltonian operator was used to explain these physical interactions.

GEO-EMR Sounding Example from the Pannonian Basin

We will demonstrate the value of the GEO-EMR method on using the study from the Pannonian Basin, thereby shoving the usefulness of this technique on the matured oil field in the southeast part of the Basin, the Oil Field "J", Figure 5.

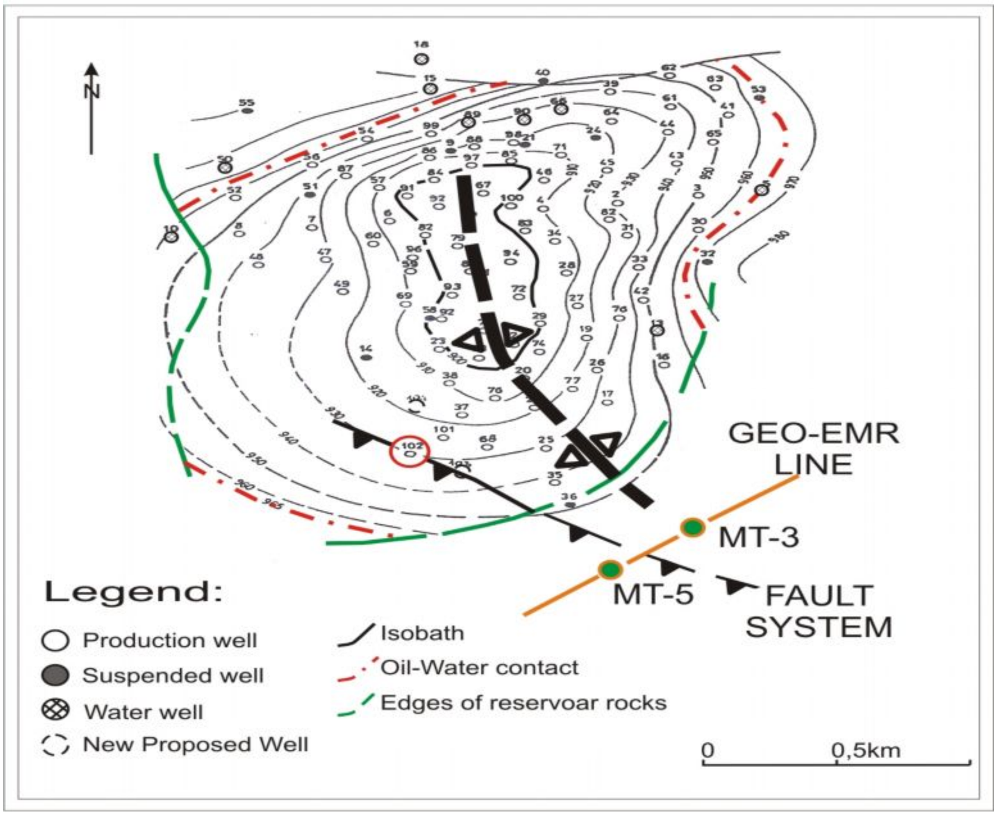

Figure 5 *: Reservoir structural map, "J" Field, Pannonian Basin (modified after Isakov, 1996)*

In principle, the two survey geometries are available, the sounding and profiling. In sounding method, the transmitter (double beam sources) is at a fixed location and the measurement is done on a series of offset points in proportion to desired depth of the target zone. The discrimination of the different lithologies and reservoir fluid content depends of number of characteristic resonance frequencies used in the sounding procedure. Once we define the key object, for example a hydrocarbon reservoir, the contouring procedure follows by the profiling method. In this mode, both the transmitter and receiver are moving simultaneously in any azimuth direction.

The Oil Field "J" is typical example of an exploration play in the Pannonian Basin focusing on anticline structure easily detected by the seismic method. However, the future exploration challenges are satellite features and stratigraphic traps around these obvious anticline forms. The field is producing from the Miocene sandstone of the variable thickness and lateral uneven lithology distribution. The main reasons for selecting this field for the GEO-EMR analyses are: (a) The structural interpretation of the seismic data revealed a faulting zone at the south-west flank of the structure and a possibility of the development of hydrocarbon traps adjacent to the fault planes, (b) Secondly, even after extensive drilling program the southeast structural trend was not defined properly.

The GEO-EMR method was used to search for the direct hydrocarbon indicators at that part of the structure. Figure 6 shows the result of the GEO-EMR sounding measurement along the key traverse at the east part of the Field "J". Based on the GEO-EMR sounding at location MT3 the top of reservoir was calculated at depth of 857 m and the thickness of reservoir of 31 m, which confirms the lateral extent of the potential reservoir.

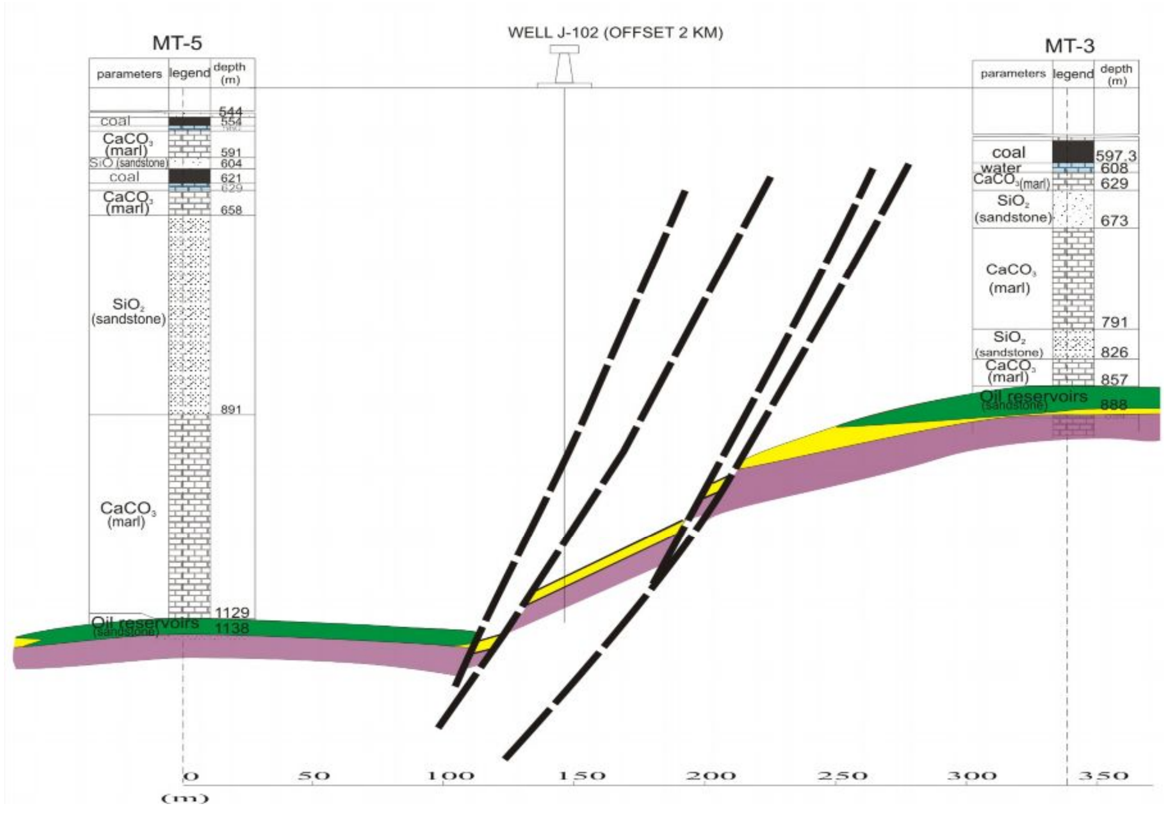

Figure 6: GEO-EMR southwest-northeast cross section

The GEO-EMR results at southwest flank, point MT5, were summarized in the lithologic column, pointing again to another reservoir extension and potential trap associated with the faulting system. Top reservoir at depth of 1120 m and thickness of 9 m with the strong GEO-EMR signal indicates the presence of the hydrocarbon saturation. Our result is consistent with the drilling results at Well J-102 and the structural model derived in the stratigraphic study of the Field (Bejatovic, 1998).

This type of electro-magnetic technique quite clearly shows that the GEO-EMR sounding procedure can be used to quantitatively predict reservoir characteristics and to identify potential pay zones in development areas. We also envisage that sparsely distributed well information could be used to calibrate GEO-EMR response and apply this method even for monitoring interface changes such as O/W contact and particularly bypassed hydrocarbons. This technique departs markedly from traditional seismic method because of high crew mobility and their miniature size.

Conclusions

There are a number of benefits in the GEO-EMR method, to mention a few. First and foremost the method is very economical and yields accurate information with respect to reservoir and hydrocarbon presence. Second, high vertical resolution or accurate identification of layers even with the thickness of 1 m is possible, and last, the value that GEO-EMR survey provides immediate results of the subsurface composition comparable to well logging survey.

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