

Application of transient electromagnetic method (TEM) technique in South-East Asia: Case studies from onshore Sarawak and North Sumatra

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Abstract: Application of electromagnetic methods for oil and gas exploration is developing world-wide. Two main types of electromagnetic (EM) methods are applied: natural source (magnetotelluric – MT) and methods with an artificial source of the EM field (Time-Domain EM – TDEM, Frequency-Domain EM – FDEM). For onshore hydrocarbon exploration the transient electromagnetic method in frequency or time domain mode is highly efficient. The role of EM methods is increasing in areas with poor seismic data quality, non-structural fields and zones with complex sedimentary cover. Joint interpretation of EM data with seismic or other geological data is a way to reduce the risks and optimize the process of geophysical investigation. Using TEM for oil and gas exploration it is possible to study the resistivity of sedimentary layers from surface to basement and additional information can be received from the induced polarization (IP) results. The paper is devoted to application of different combination of EM methods – TEM and EM-IP for oil and gas exploration. Electroprospecting surveys have been performed over one of the blocks in the Southeast Asia i.e. in Sarawak and North Sumatra. Two techniques were used: Transient Electromagnetic Soundings in Time Domain (TEM) and Induced Polarization Electromagnetic method (EM-IP). The objective is to conduct a comprehensive study of the sedimentary cover using TDEM. This includes mapping of zones with potential reservoirs properties from TEM, and to qualify these areas with Induced Polarization (IP) anomalies, usually related to presence of hydrocarbon system.

Keywords: Transient, electroprospecting, reservoirs, oil and gas, resistivity, induced polarization

INTRODUCTION

One of the very first onshore transient electromagnetic (TDEM & EM-IP) survey in South East (SE) Asia was acquired in Borneo in 2011, Malaysia (Agafonov *et al.*, 2011; 2012). The objectives set were to estimate the effectiveness of electromagnetic techniques in the prevailing sedimentary geoelectric conditions of Borneo and generally in SE Asia. A similar survey was then carried out in North Sumatra Island in 2013 (Tokareva *et al.*, 2014). The objective there was to conduct a comprehensive study of the sedimentary cover using TDEM. This included the mapping of zones with potential reservoirs properties from TEM, and to qualify these areas with Induced Polarization (IP) anomalies, usually related to presence of hydrocarbon system (Sternberg, 1991). TEM is control source transient electromagnetic method which provides various geoelectrical maps showing the distribution of geoelectric parameters and sections imaging geological structures within the survey areas (Berdichevsky & Fomina, 1966; McNeill, 1980).

FIELD ACQUISITION, DATA PROCESSING AND INTERPRETATION

On average, 200 line-kilometers of TEM data fields and 50 line-kilometers of EM-IP data fields were acquired for both surveys. The TEM survey in Malaysia used a transmitter loop size of 750 m (L) × 750 m (W) and receiver loop size

of 18 m (L) × 18 m (W), with injected current values ranging from 10 Ampere (A) to 160 Ampere (A). Similar parameters were also applied to the TEM survey in Indonesia. EM-IP surveys layouts for both projects applied a 600m transmitter and receiver lines. The currents used for Malaysia's EM-IP survey ranged from 4 Ampere (A) to 36 Ampere (A), higher current was applied for Indonesia's EM-IP survey (27A to 54A) due to very conductive sedimentary covers.

Processing of electromagnetic sounding data, obtained by TEM and EM-IP methods, is key to enable the extraction of useful and correct information of signal originating from the subsurface and free from all types of noise. The records measured by recorder stations are processed by specialized TEM-Processing Software.

The TEM responses collected in the survey territory are distorted mainly by atmospheric noise and industrial noise with the main frequency 50 Hz. Atmospheric noise is easy to eliminate during processing with special robust filters, but the industrial noise deteriorates strongly the data quality because it changes abruptly its frequency and amplitude (Agafonov *et al.*, 2012). For 50 Hz noise attenuation the special combined processing algorithm was used (Egorov *et al.*, 2014). The early-time transient responses are processed using direct noise subtraction. The late-time transient responses can be processed with a lowpass filter. The final curves thus have high signal/noise ratios over the entire range of delay times.

CASE STUDY – ONSHORE BORNEO (SARAWAK), MALAYSIA

Geological setting

Sarawak may be subdivided into three tectono-stratigraphic zones (Kuching, Sibuan and Miri) that represent decreasing stratigraphic and structural complexity eastwards (Hutchinson, 2005). Deposition and deformation generally proceed from west to east and from south to north. The survey area is located in Miri Zone. The most northerly subdivision is the Miri Zone, dominated by what Haile called miogeosynclinal (shelf) and molasse (late- or post-orogenic) strata, which is deposited upon older continental crust (Tan *et al.*, 1999).

Results

The total conductivity of the survey area section ranges from 80 to 250 S. The study area was differentiated to a separate territories based on the total conductivity value. Figure 1 shows typical apparent resistivity ρ_t and apparent conductivity $S_t(H_t)$ curves, which reflect the geoelectric sections characteristics within designated zones.

The section in Figure 2 shows five visible geoelectric horizons which mark variation in the rock over the whole survey depth. This upper horizon composed of Quaternary alluvial sediments with resistivity 1 – 2 $\Omega \cdot m$ and thickness increasing up to some hundred meters. Low resistivity values of this horizon are related to the lithological composition

and water saturation of the upper section. The inversion of electromagnetic sounding data points to the horizon marked by low resistivity values of 4–10 $\Omega \cdot m$, and divided into two sub-horizons (Lambir 1 & Lambir 2). The upper sub-horizon 2 relates to an increased resistivity 7 – 10 $\Omega \cdot m$ occurs at depth from 0 to 200 m. The reason for a relative increase of resistivity could be the presence of a lithologic layer of increased density perhaps aquiclude (impermeable layer). The second sub-horizon has resistivity of 4–6 $\Omega \cdot m$. There is some sort of zonation in the distribution of geoelectric parameter.

According to drilling data, the third geoelectric horizon in the region is attributed to the Setap sediments. Mean values of horizon resistivity in the Suai area are 9 – 10 $\Omega \cdot m$. To the south the layer resistivity increases to 14 – 16 $\Omega \cdot m$ and close to one existing well resistivity changes from 25 to 50 $\Omega \cdot m$. The Setap shale is widespread and it primarily consists of clay shale with insignificant inclusions of sandstones and lenses of biostrom limestone.

The fourth geoelectric horizon is overlain by relatively conductive Setap sediments, and overlies the high-resistivity horizon over 200 $\Omega \cdot m$. It is interpreted that this underlying geoelectric horizon is inclusive of the Nyalau formation. The Nyalau Formation is made of medium-grained sandstones with thin streaks of limestone. In the Suai region, the lateral change from north towards south within the background of relatively high resistivity (25 – 40 $\Omega \cdot m$) is an interval with lower resistivity 10 – 15 $\Omega \cdot m$. The local reduction of resistivity might be related to the fracture zone perpendicular to the profile. To the South of Suai the geoelectric section varies. This contrast in geoelectric properties indicates the presence of large tectonic faults seen in the data profile. Between these dislocations a graben-like structure could be inferred through sediments of the surveyed complex.

The fifth geoelectric horizon is an important key element, the electromagnetic basement, with high resistivity values over 1000 $\Omega \cdot m$. Data analysis shows that TEM data correlates to the data from existing wells. Position of the basement in Suai area varies from -3000 m in the north to -1500 m in the southern termination of the region. It is important to take into account that unconstrained inversion

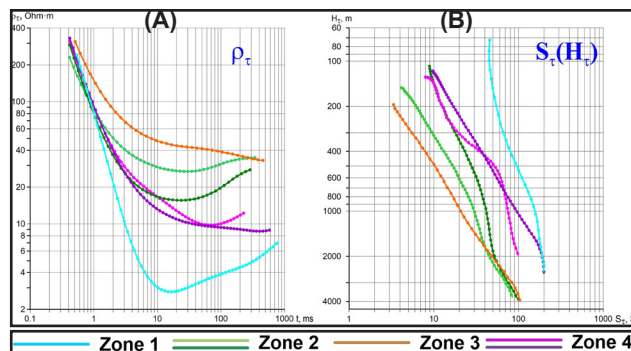


Figure 1: Typical TEM curves for different zones: (a) apparent resistivity and (b) apparent conductivity.

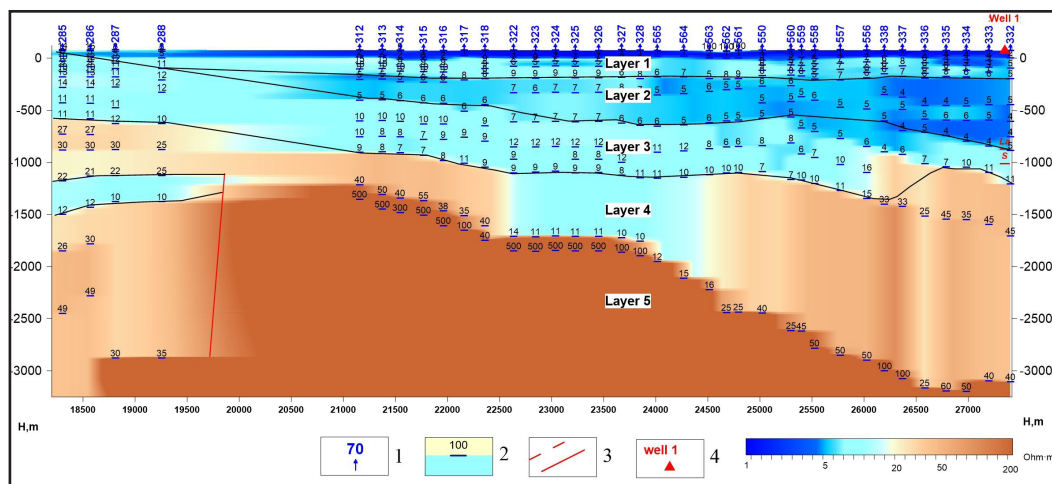


Figure 2: Fragment of geoelectric section of TEM profile.

Legend: 1 - TEM points; 2 - geoelectric horizons, 3 - faults, 4 - wells.

of TEM data was applied. The depth and thicknesses of geoelectric layers were derived from TEM inversion independently from seismic data.

CASE STUDY – ONSHORE NORTH SUMATRA, INDONESIA

Geological setting

The stratigraphic scheme of the North Sumatra Basin is sub-divided from late Oligocene to Late Miocene with several depositional environments such as terrestrial, deltaic, coastal and marine. Deltaic/Fuvial sandstone (some with coals) represent the lithology for terrestrial and deltaic (Basal Peutu Members & Belumai Formation). Arun, Lower Baong, Upper Baong and Keutapang Formations represent the marine environment with the a lithology of clays with major/minor intercalations of sandstone and also reefal limestone. Sandstone with coals and volcanic makeup the the Serula Formation of coastal deposition (Barber *et al.*, 2005). Reservoirs of the North Sumatra Basin range in age from Oligocene to Pliocene, and include both carbonate and clastic reservoirs.

Results

The well-log data are of better resolution than those of land resistivity surveys and give a greater number of layers in the respective model. In order to estimate the optimum number of layers in the starting model, inversion has been applied to TEM responses from the immediate vicinity of the well. If the TEM resolution was insufficient for reliable differentiation of some layers, they were joined together. As a result, 16 geoelectric layers have been distinguished in the starting model for the drilling area (Figure 3). Note that the layer resistivity for the starting model were obtained by inversion of TEM responses rather than being constrained from resistivity logs. Results of TEM data inversion are shown on Figure 4.

The first geoelectric horizon (Layer 1), at the top of the section, corresponds to the Seurula Formation. Coastal deposits, which are mainly sandstone with shale and coal intercalations. The layer thickness varies from 250 m in the southwest to 500 m in the north, east, and southeast. The resistivity of the layer from TEM data is in the ranges from 3 to 17 $\Omega \cdot m$. ILD and SFLU logs from two well 1 and well 2 show the values 8 and 10 $\Omega \cdot m$, respectively, while the TEM-derived resistivity averages are 6 – 7 $\Omega \cdot m$ and 8 – 9 $\Omega \cdot m$ at both wells. The good agreement between the TEM and well logging results is evidence of a high quality of TEM inversion.

The second geoelectric horizon (Layer 2) corresponds to the Upper Keutapang Fm., consisting of mostly clay-size sediments deposited in tidal and shelf environments. TEM data show resistivity values from 1.3 to 3.7 $\Omega \cdot m$, or lower than in Layer 1, possibly because of larger clay content. However, this resistivity range is higher than in the rocks below (0.6 – 1.2 $\Omega \cdot m$) which contain relatively large percentages of sand. Resistivity logs show about 4 $\Omega \cdot m$ in well 1 and 2.9 $\Omega \cdot m$ in well 2. Similar values have been obtained by inversion of TEM responses: 3.7 $\Omega \cdot m$ (well 1) and 2.6 $\Omega \cdot m$ (well 2).

The third geoelectric horizon (Layer 3), about 300 – 400 m thick, corresponds to the middle part of the Keutapang marine sequence and is composed mainly of shale. The TEM resistivity values in the layer are relatively uniform, from 0.8 to 1.3 $\Omega \cdot m$. According to the obtained General Stratigraphy chart (Barber *et al.*, 2005), the layer is a seal. Its uniform resistivity may be evidence of uniform lithology.

The fourth geoelectric horizon (Layer 4), about 250 – 300 m thick, corresponds to marine clay with major intercalations of sandstone in the middle Keutapang. Layer resistivities are in the range from 1 to 6 $\Omega \cdot m$. The relatively low resistivity (0.6 – 1 $\Omega \cdot m$) over the greatest part of the

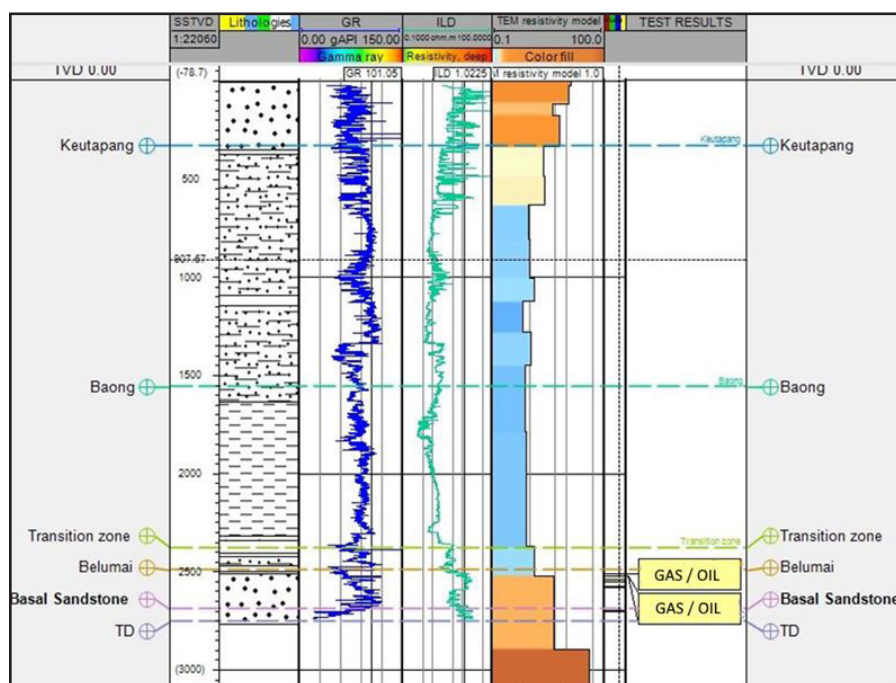


Figure 3: TEM model and resistivity logs comparison (Petrel).

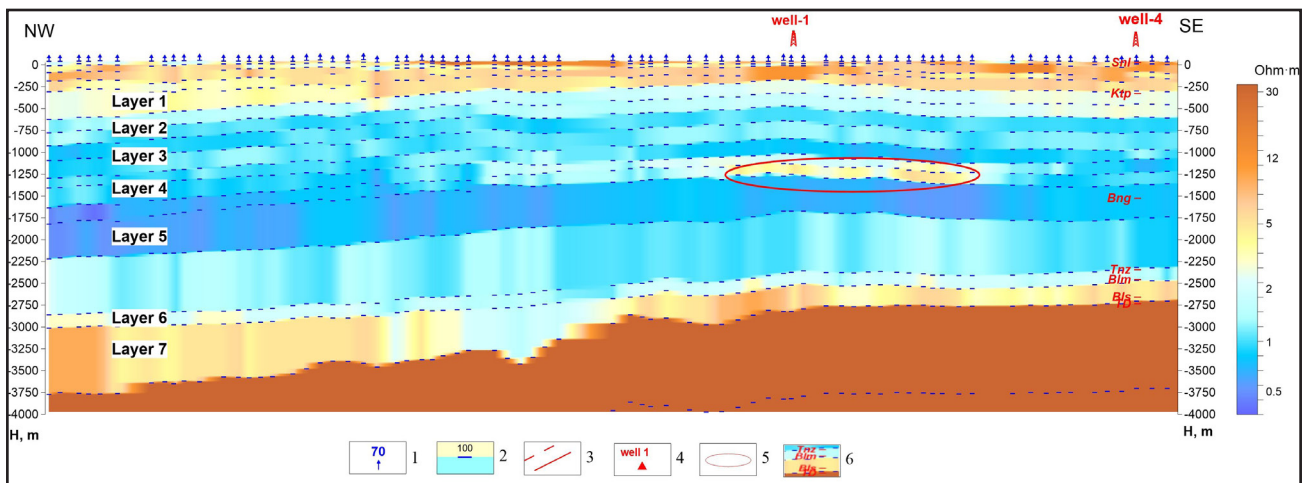


Figure 4: EM section shows distribution of geoelectric horizons / layers of sedimentary covers.

Legend: 1 - TEM points; 2 - geoelectrical horizons, 3 - faults, 4 - wells, 5 - zone of higher resistivity values may be associated with deltaic sand - possible HC reservoir, 6 - Fm. labels from wells.

territory is apparently because of marine clay lithology. A zone of higher resistivity, from 1 to 2.5 $\Omega\cdot\text{m}$, revealed in the southwest of the area may be associated with deltaic sand (Figure 5) (Barber *et al.*, 2005).

The fifth geoelectric horizon (Layer 5), about 300 – 400 m thick, corresponds to the lower Keutapang and upper Baong marine clay with major sandstone intercalations. The layer top and bottom match the reflectors SB-4 and MFS-3 respectively. The resistivity is within 0.5 – 0.8 $\Omega\cdot\text{m}$ over the major part of the territory, only increasing to 1 – 2 $\Omega\cdot\text{m}$ in the east of survey area.

The sixth geoelectric horizon (Layer 6) comprises the lower Baong marine clay with minor intercalations of sandstone and ~150 m thick deposits of the transition zone from mainly terrestrial and coastal facies (Beluai and Arun sequences) to the lower Baong marine sediments. The total layer thickness is of the order of 500 m. Resistivity logging in wells 1 and 2 gave, respectively, the values 1.12 and 1.24 $\Omega\cdot\text{m}$ for the lower Baong and 4.5 and 3.7 $\Omega\cdot\text{m}$ for the Transition zone. The lower Baong interval may contain reservoir sandstones according to the general stratigraphy column, though no potential pay zones appear in the well 2 and well 1 logs. The TEM-derived resistivities are from 1 to 3 $\Omega\cdot\text{m}$, being 1 – 1.2 $\Omega\cdot\text{m}$ at the well 2 and well 1 sites. Similar low-resistivity zones have been revealed in the west of the surveys territory, as well as within an uplift in the northwest. Resistivity is slightly higher (2 – 3 $\Omega\cdot\text{m}$) in the east of the territory, where no seismic surveys have been performed. Processed apparent conductivity at depth, ΔS data from that area indicate an uplift. The resistivities higher than in the neighbor territory and the presence of an anticline makes this area prospective for petroleum exploration.

The seventh geoelectric horizon (Layer 7) spans early Miocene and late Oligocene sequences of the Belunai deltaic sandstone, the Arunreefal limestones, and terrestrial and deltaic sheets of fluvial sandstones with coal. The resistivity values for this interval are 7.8 and 8.8 $\Omega\cdot\text{m}$ according to ILD and SFLU logs from well 1 and well 2 wells, respectively, and from 2 to 9

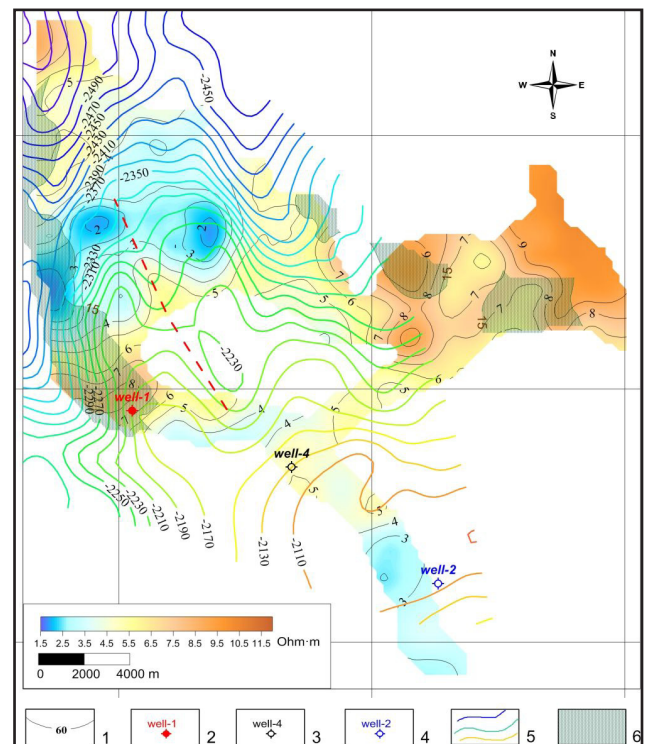


Figure 5: The geoelectric map of prospective sandstone formations.

Legend: 1 - TEM resistivity isolines, Ohm·m; 2 – 4 – wells: 2 - commercial inflow HC; 3 - dry; 4 - water; 5 – Seismic time isolines; 6 – EM-IP anomaly.

$\Omega\cdot\text{m}$ according to inversion of TEM responses. Resistivity is the lowest, 2 – 3 $\Omega\cdot\text{m}$, in the southern (near well) and northwestern parts of the region. The southern low-resistivity zone has been traced along a single profile only, and its geometry and strike remain unconstrained. The existence of the other conductor in the northwest appears at many TEM sites. The width of this zone is 4 – 5 km in the NW – SE direction and about 9 km from southwest to northeast. Within the layer, the fault line runs between two resistivity lows and then extends southeastward, into the area not covered by TEM surveys.

CONCLUSION

The EM surveys conducted in Sarawak, Malaysia and in North Sumatera, Indonesia, with an objective to examine the subsurface geoelectric settings in these South-East Asia regions. Anomalies from measured electrical resistivity and polarizability (chargeability) enabled the study of geological structure and sedimentary covers. Special mathematical algorithms used during the processing and interpretation stages ensure the acquired EM data to produce high quality end results. EM sections showing vertical distribution of the resistivity anomalies and geoelectric horizons complimented available seismic data within the areas of exploration interests.

1. These EM surveys proved EM as a reliable methodology to map sedimentary covers/subsurface layers with good depth of penetration (up to 4 – 5 km).
2. Both TEM surveys identify oil and gas prospects within young sedimentary basin with relatively lower resistivity values. In particular, the host rocks are highly conductivity, while the target structural reservoir exhibits relatively higher resistivity to the host rocks.
3. Anomalies of recorded electromagnetic fields are functions of electrical heterogeneity of the subsurface in general and the discovered fields in particular.

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