ENHANCEMENT OF ELECTRO – MAGNETIC DATA TO RESERVOIR CHARACTERIZATION ACROSS A FIELD USING TEMPLATE IN SOUTH SUMATERA

THESIS

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JAKARTA
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Proposed as one of the requirements to obtain a Master's degree Geophysics Reservoir

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Diajukan sebagai salah salah satu syarat untuk memperoleh gelar Master Geofisika Reservoar

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June 2010

HALAMAN PERNYATAAN ORISINALITAS

Tesis ini adalah hasil karya saya sendiri,
Dan semua sumber baik yang dikutip maupun dirujuk
Telah saya nyatakan dengan benar

Nama : Lusy Niatri

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Tanda Tangan :

Tanggal : 19 Juni 2010

HALAMAN PENGESAHAN

Tesis ini diajukan oleh	**:**
Nama	**: Lusy Niatri**
NPM	**: 0806421224**
Tanda Tangan	**:**
Judul Tesis	**: Enhancement of Electromagnetic Data To Reservoir Characterization Across A Field Using Template In South Sumatra.**

Telah berhasil dipertahankan dihadapan Dewan Penguji dan diterima sebagai bagian persyaratan yang diperlukan untuk memperoleh gelar Magister Geofisika Reservoar pada Program Studi Geofisika, Fakultas Matematika dan Ilmu Pengetahuan Alam, Universitas Indonesia.

DEWAN PENGUJI

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Pembimbing	**: Dr. Yunus Daud**	**( )**
Penguji	**: Dr. Abdul Haris**	**( )**
Penguji	**: Dr. Supriyanto**	**( )**
Penguji	**: Dr. Ricky Adi Wibowo**	**( )**

Ditetapkan di : Jakarta

Tanggal : 19 Juni 2010

PREFACE

Thanks God, I can finish this thesis. The writing is done in order to fulfill requirement to achieve a Master degree in Reservoir Geophysics Department of Geophysics at the Faculty of Mathematics and Natural Sciences University of Indonesia. Iwould like to say thank you for help and guidance from various parties:

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7. Friends who have helped me in completing this thesis.

Hopefully, this thesis brings benefits to the development of the science.

Jakarta, June 19, 2010

Lusy Niatri

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I am dedicating this Master of Sciences THESIS to :

My Dear MOTHER & FATHER ,

To the late Dr. DOUGLAS Bruce SCARBOROUGH,

as my Mentor.

eople without whom, this work would have never been achieved !

LUSY NIATRI

Jakarta / April 2010

HALAMAN PENYATAAN PERSETUJUAN PUBLIKASI TUGAS AKHIR UNTUK KEPENTINGAN AKADEMIS

Sebagai sivitas akademik Universitas Indonesia, saya yang bertanda tangan dibawah ini:

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NPM	**: 0806421224**
Program studi	**: Geofisika Reservoar**
Departemen	**: Geofisika**
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(Lusy Niatri)

ABSTRACT

Name : Lusy Niatri

Program Study : Reservoir Geophysics

Tittle : Enhancement of Electromagnetic Data to Reservoir Characterization across a Field Using Template in South Sumatra

This research uses a method which is referred to as *the control source electromagnetic (CSEM)*, integrated with seismic data and well logs data. That's why we call *High Resolution electromagnetic (HREM)*. *HREM* is land survey technology which can identify the presence of hydrocarbons defined by any anomalies recorded in the seismic section. *HR-EM* technique has been applied in Takara field at South Sumatra Basin. This study is focused on practical ways to increase confidence level of our interpretation, as well as to reduce the risk of dry hole, by integrating the electrical properties from *HR-EM* data and elastic properties from seismic data. The elastic property is the interval velocity and the electrical properties are *Resistivity* and *Induce Polarization* derived from Electromagnetic signals. The integration of those three parameters is known as *Integrated Attribute.* Then those data is link with the reservoir characteristics such as porosity, water saturation, and bed thickness by using simple templates. Using this method, we can estimate the fluid content of un-drilled areas if un-drilled area has the same geological depositional environment as the drilled area.

ABSTRACT

Nama : Lusy Niatri

Program Studi : Geofisika Reservoar

Tittle : Peningkatan Data Elektromagnetik ke Karaterisasi Reservoar dengan menggunakan Template yang Melintasi suatu Lapangan di Sumatera Selatan

Dalam penelitian ini kami menggunakan metode yang disebut sebagai *Control Source Electromagnetic (CSEM)* yang diintegrasikan dengan data seismik, yang dikenal dengan *High Resolution Electromagnetic (HREM)*. HREM adalah teknologi explorasi yang dapat mengidentifikasi adanya hidrokarbon pada *seismic section*. Teknik HR-EM telah diterapkan pada lapangan Takara di cekungan Sumatera Selatan. Dalam studi ini, kami fokus pada cara yang praktis untuk menurunkan karakterisasi Reservoir dari data awal HR-EM yang diperoleh dari sinyal Electromagnetic survey berupa: *Resistivity* dan *Induce Polarization* yang diintegrasikan dengan *Interval velocity* atau dikenal dengan *Integrated Attribute*. Dengan mengintegrasikan ketiga parameter tersebut, maka kita dapat meningkatkan kepercayaan kita dalam interpretasi suatu prospect, serta dapat menurunkan resiko dryhole. Kemudian data tersebut di link dengan karakteristik reservoir seperti "Porositas”, "Saturasi air" dan "Ketebalan" dengan menggunakan Template sederhana sehingga kita dapat memperkirakan isi fluida daerah yang belum di bor jika memiliki lingkungan geologi pengendapan yang sama dengan daerah yang telah dibor.

LIST OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES

LIST OF GRAPHICS

CHAPTER 1
INTRODUCTION

1.1. Historical Background

Exploration seismic method has been progressing very fast, however the best result which is based on reflection properties are the structure of the rock, the trap geometry, and reservoir layer of the subsurface. But we can not exactly determine the type of fluid from the elastic properties. To determine the type of fluid in reservoir rock we need to use another technology, which is known as electromagnetic methods to derive electrical properties of rock and fluids.

Electrical methods in geophysics date back to the year 1830 *(Rust, 1938)*. In Cornwall, England R. W. Fox, a notable English Geologist, later credited for proving that temperature increases with depth, he was working in mines when he discovered that induced electrical currents were influenced by the presence of ore bodies. He proposed using resistivity as an exploration tool. However, at this time the method had problems due to the polarization of electrodes. In 1880 this problem was solved by using porous wood or clay pots filled with sulfate solutions. This was the birth of Geo-electric methods in Geophysics. These types of pots are very similar to those used in resistivity surveys today.

The first resistivity patent was applied for in 1900 and the famous Wenner's electrode method developed in 1915 *(Wenner, 1915)*. Thereafter during 1913 - 1920 Conrad Schlumberger tested resistivity methods and applied them for resistivity mapping for oil and gas until he moved into subsurface logging around the 1930s. In general, it is already known that porous of rock contain water have low resistivity, meanwhile porous of rock contain hydrocarbon is high resistivity.

Soon after the 1930's, many active methods of inducing alternating current (AC) and direct current (DC) into the ground and measuring different potentials were implemented with varying degrees of success. Simultaneously the seismic method was gaining popularity and efforts were made to obtain reflected or transient electromagnetic (TEM) soundings *(Blau, 1933)* similar to the seismic method. In 1940 a claim was made that voltages decay differently over oil saturated sands as compared to saturated sands *(*Potapenko, 1940*)* but the work focused mostly on fault and salt dome detection. Since that time, many electrical methods came into use.

1.2. Purpose of the Research

The aims of the research are:

1. To study the concept of electromagnetic in the application of control source electromagnetic to defined petrophysical properties from data inverse electromagnetic signal or Geo-electrical parameter.

2. To derive the electrical properties of the lithologies (Lateral variation resistivity) from electromagnetic signal.

3. To define velocity model from lateral variation of velocity (from Seismic data)

4. To integrate lateral variation of velocity from seismic and lateral variation resistivity from electromagnetic signal to assist better interpretation.

1.3. Scope of the Research

The Electromagnetic is popular as an exploration technology, especially for offshore exploration. Many big companies have committed that they will not drill well before getting the EM data, and most large companies consider that seismic is not enough. However, in this research we are conducting survey electromagnetic integrates with seismic data on on-shore in south Sumatra. We want to analyze the results of the survey in order to correlate electrical properties with the elastic properties of reservoir rock. The analyses from several well have been drilled after HREM survey was support me to make better interpretation using template. By using these templates we can make efficiency and facilitate the interpretation for next well.

1.4. Methodology

In this research we conduct four phase of works. The first is Electromagnetic Signal inversion using Maxwell equation to get resistivity and Induced Polarization by considering result from seismic data and well log as calibration point. The second phase is to derive the elastic parameter by using Dix formula to get lateral variation of velocity (velocity model from Seismic). The third phase is integrated phase 1 and phase 2, to get lateral variation of integrated attribute by using GeoVisor Software, so that we can get more information about lithology, porosity and to forecast fluid content. The last step is to make a template, which will hopefully assist us to facilitate interpretation.

The elastic properties from seismic data play an important role in reservoir characterization because they are related to the reservoir properties. To analyze these elastic properties, rock physics knowledge is a bridge that links the elastic properties to the reservoir properties.

To strengthen our interpretation about the prospect of a structure identified from seismic, then combining 2 parameters were very useful for the interpretation of the prospect. Velocity from seismic properties and resistivity from electric properties have good relation to identify character porosity. As we know the fluid saturated within the pores have the elastics and the electric characteristics. In this research I want to maximize interpretation our data by integrating electromagnetic properties, elastic properties and petrophysics properties.

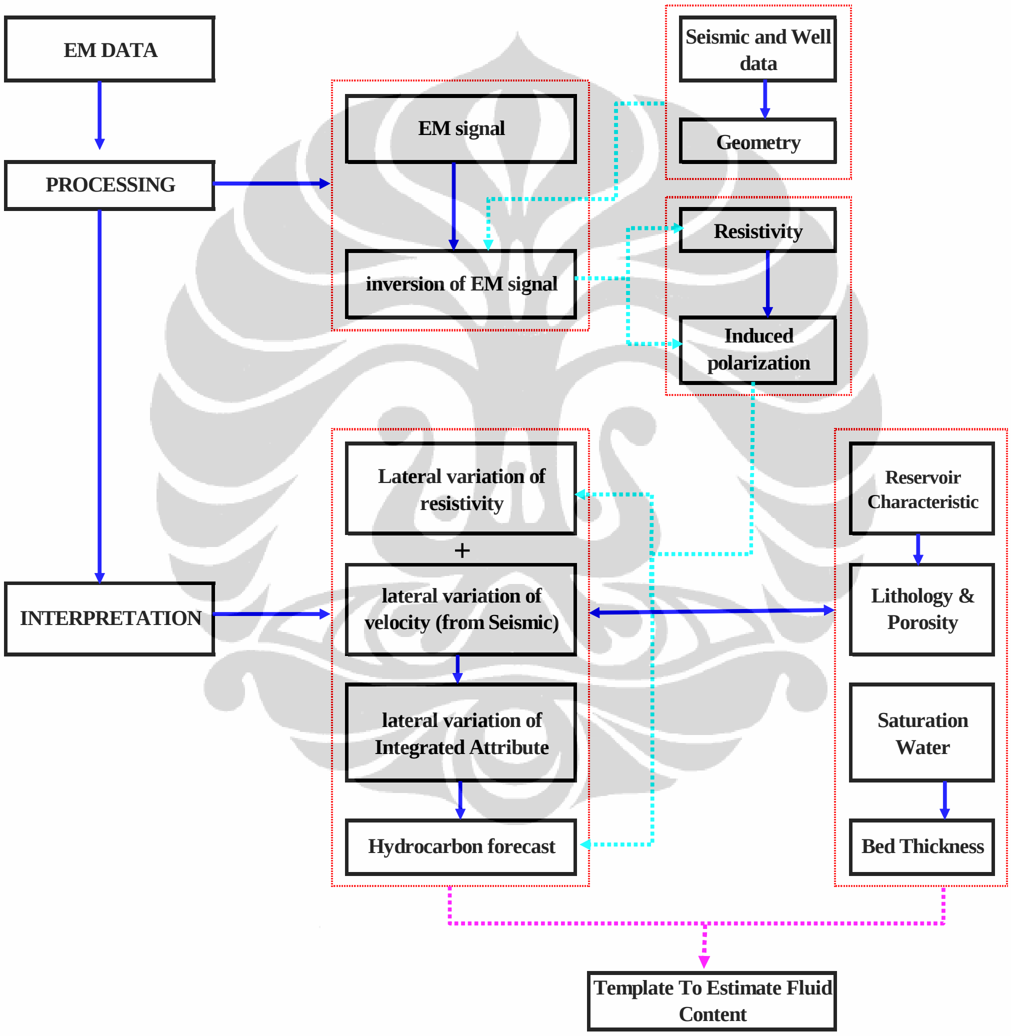


Figure 1.1. Workflow Template Processing

1.5. Research Area

The HR-EM technique was applied in the Musi Platform, South Sumatra Basin, Indonesia. Reservoir sands of interest in the area are in "Takara Field". Historical of reservoir rock start from Paleocene to Early Oligocene coarse clastics of the Lahat Formation, Oligocene to Miocene deltaic and marine sandstones of the Talang Akar Formation, Early Miocene platform carbonates and local carbonate build-ups of the Batu Raja Limestone, Miocene transgressive shoreline sands of the Telisa Formation, and Late Miocene to Pliocene shallow marine to non-marine sandstones of the Lower and Middle Palembang Formations serve as reservoirs. (Figure 1.2)

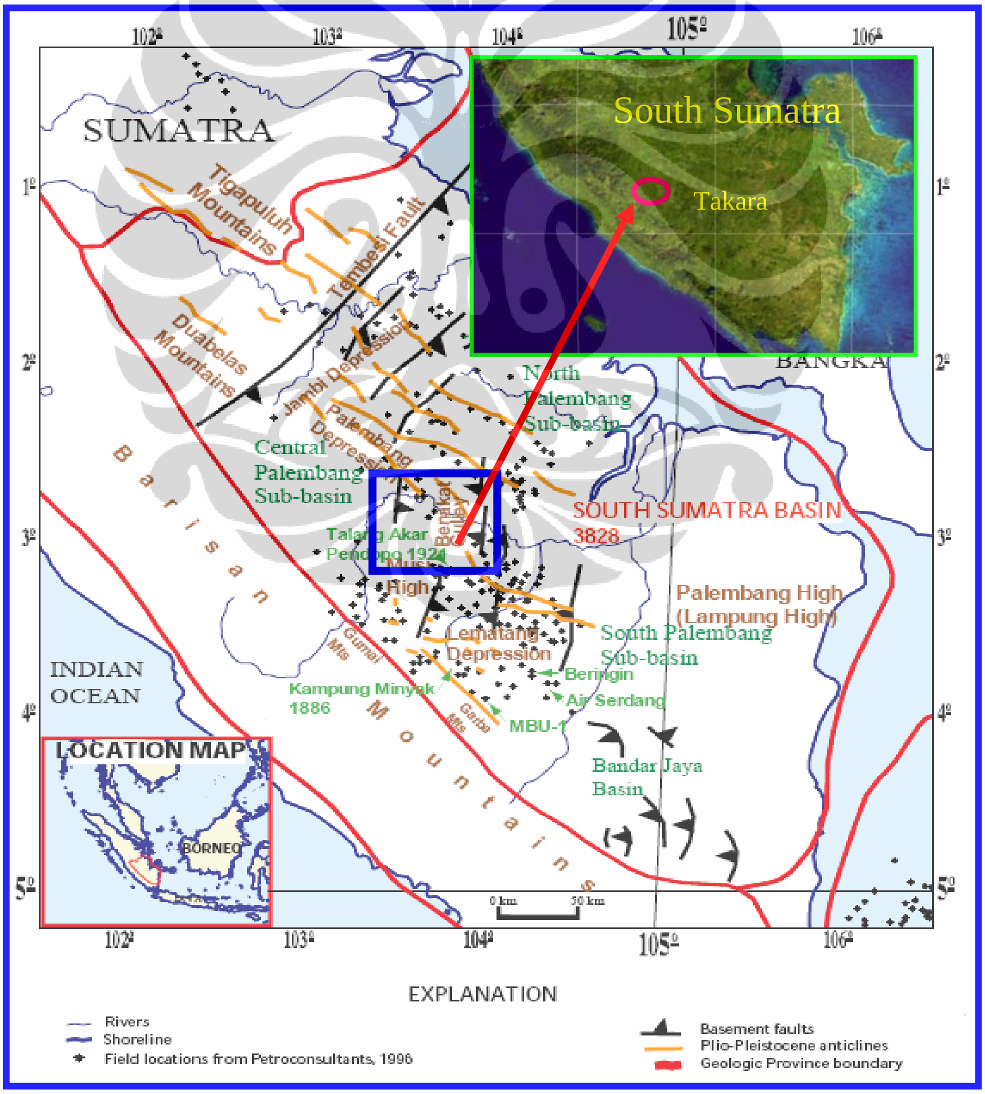


Figure 1.2. Research Area of HREM survey in Musi Flatform South Sumatera on Blue Box.

1.6. Systematic Writing.

In broad outline the discussions of the thesis is as follows:

The chapter 1 is the introduction; this chapter explained the background of the writing, the aim of the research, the restriction on the problem, methodology the research, and the area research. The chapter 2 explained about the theory of the supportive foundation the research that was carried out as well as the stage acquisition, processing and interpretation. The chapter 3 give the justification in the interpretation as well as case study that was carried out. The chapter 4 gives results and the analysis correlating velocity, resistivity as well as Integration attribute in template to facilitate in the interpretation. Chapter 5 gives the conclusion of the research and the suggestion so that the research could become better.

CHAPTER 2
BASIC THEORY

2.1. Electromagnetic Methods

The theory of EM sounding is electricity and magnetism. Our main equations for electrical and magnetic fields are the Maxwell equations:

$\Delta\vec{E} - \frac{\mu\varepsilon\partial^2\vec{E}}{\partial t^2} - \frac{\mu\rho\partial\vec{E}}{\partial t} = 0$ - For electrical part E of EM field.

$\Delta\vec{H} - \frac{\mu\varepsilon\partial^2\vec{H}}{\partial t^2} - \frac{\mu\rho\partial\vec{H}}{\partial t} = 0$ - For magnetic part H of EM field.

We use transient electromagnetic processes (TEM). In this case our EM processes are "slow". And we use only 2 parts in these equations and exclude part with second derivative because for slow processes it is almost zero. So we use the so called "quasi-stationary" approach and the above equations reduce to:

$\Delta\vec{E} - \frac{\mu\rho\partial\vec{E}}{\partial t} = 0$ - For electrical part E of EM field. (2.1)

$\Delta\vec{H} - \frac{\mu\rho\partial\vec{H}}{\partial t} = 0$ - For electrical part H of EM field. (2.2)

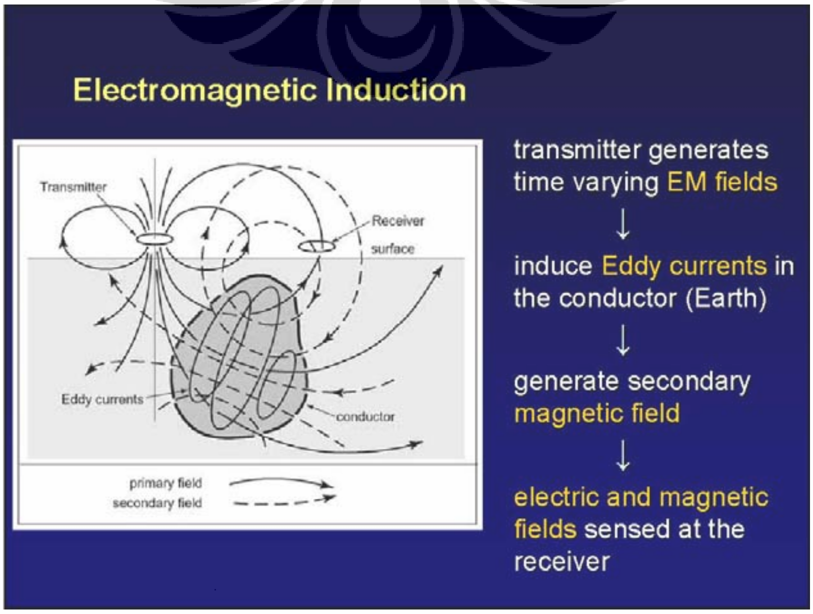


Figure 2.1. Generalized schematic of the EM surveying method. *(Reynolds, 1997)*

2.1.1. Transient Electromagnetic

If a continues EM field is produced by a transmitter, the secondary field is either determined by nulling the primary field so as to be able to detect the secondary field, and hence computing the secondary field parameters; those of the primary field are known by design. In time domain or transient EM, the primary field is applied in pulses typically 20-40 ms long, with the secondary field being measured once the primary field has been switched off over the following 100ms, for example. TEM system can be used very effectively for depth soundings. Increased depth penetration is achieved by measuring the decay of the secondary field as a function of time. These *transient electromagnetic* (*TEM*) methods are effectively multi-frequency, because a square wave contains elements of all the odd harmonics of the fundamental up to theoretically infinite frequency like a sample on Figure 2.2 *(Reynolds, 1997)*

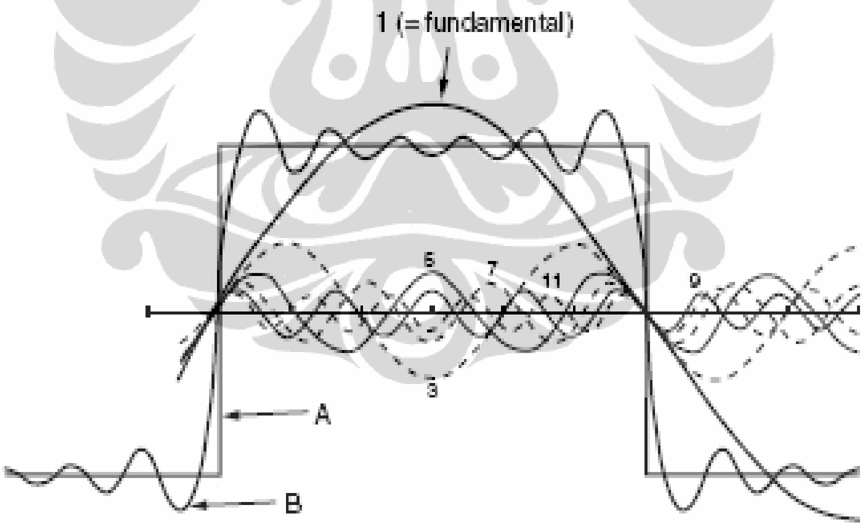


Figure 2.2. A square waves has multi frequency sinusoids.

A reasonable approximation to the square wave, A, can be obtained by adding the first five odd harmonics (integer multiples 3, 5, 7, 9 and 11) of the fundamental frequency to the fundamental. Using the amplitudes for each of these component waves determined using the techniques of Fourier analysis, the gives the summed wave B. The addition of higher odd harmonics with appropriate amplitudes would further improved the approximation *(Milsom, 2003)*

2.1.2. Induced Polarization

IP surveys are perhaps the most useful of all geophysical methods in mineral exploration, being the only ones responsive to low-grade disseminated mineralization. There are two main mechanisms of rock polarization and three main ways in which polarization effects can be measured. In theory the results obtained by the different techniques are equivalent but there are practical differences. If the current is switched in polarity, and on and off, with a time delay comparable to the length of the charging time, then this is the same as applying an alternating current signal at a given frequency (hertz).

The current introduced into the earth may be in the form of pulses, generally shaped as square wave, or low frequency. With the second arrangement data are usually compared at a variety of frequencies.

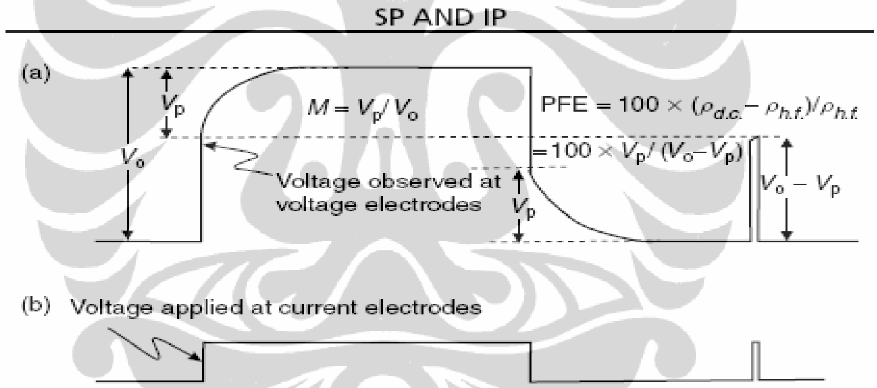


Figure 2.3. This figure is the response to a square-wave signal and a spike impulse.

- The square wave in chargeable ground

Polarization voltage V_P and then declines asymptotically to zero. Similarly, when current is applied to the ground, the measured voltage first rises rapidly and then approaches *V*o asymptotically (Figure 2.3). Although in theory *V*o is never reached, in practice the difference is not detectable after about a second. *Chargeability* is formally defined as the polarization voltage developed across a unit cube energized by a unit current and is thus in some ways analogous to magnetic susceptibility. *(Milsom, 2003)*

2.2. High Resolution Electromagnetic Methods (HREM)

HREM is based on electromagnetic induction effect. Russian geophysicists V.A. Sidorov, V.V. Tikshaev, B.I. Rabinovich, M.S. Tabarovsky, M.I. Epov, A.N.Tikhonov, S.I. Sheynman, V.P. Lepyoshkin, N.P. Smilevets studied transient electromagnetic process (TEM) sounding with a controlled source. TEM soundings allow getting information about the resistivity distribution in the section. High resistivity anomalies are one of signs of HC presence. It joins advantages of studying non-stationary processes (high resolution, etc.) and the measurement of harmonic field's phase parameter (A.V. Kulikov, E.S. Kiselev, A.S. Goryunov) for the purpose of obtaining the information on induced polarization (IP) anomalies, another one symptom of hydrocarbon deposits.

Electromagnetic (EM) survey detects signal from the current which were inducted into the subsurface. We used both (time and frequency) modes. Electrode & magnetometer receiver record the transient signal. The input signal transformation and interpretation allows getting information about resistivity and IP. Posterior integrated interpretation with data of seismic and well-log fulfilled in the united information media – time seismic section. It allowed to construct matched seism-geo-electrical model of section and fulfilled forecast of HC presence for target layers of the section. *(Smilevets. N. P., 1999).*

2.3. Acquisition Technique applied in High Resolution Electromagnetic (HREM)

HREM uses a AB-MN sounding system with parallel AB and MN lines. The receiver MN lines were replaced with metal rods specially coupled to the earth as signals are transmitted into the earth. The data is obtained from a multi channel digital recording system.

2.3.1. HREM Electrode Arrangement & Field procedures

In actual a number of different conventional surface configuration are used for the current and potential electrode. The length of source line were appllied in Indonesia around 8 Km, offset of receiver from source was 250m. This sounding system was related to depth of target reservoir.

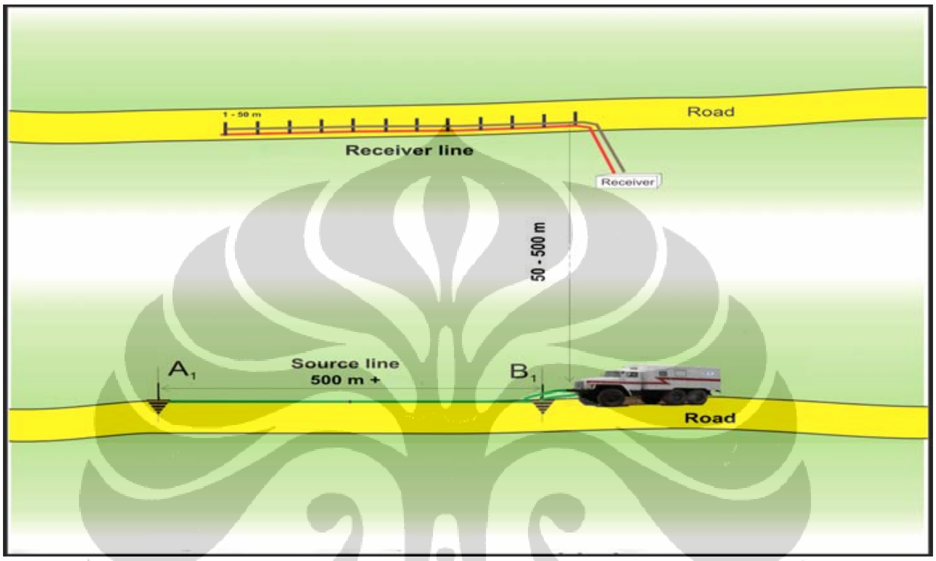


Figure 2.4. Field Model of Work *(HREM report, 2007)*

Ideal dipole 'a' $\rho_a = \pi \frac{L^2}{a} K \frac{V}{I}$ (2.3)

Where K – Geometry factor

$$K = 2\pi \left[\frac{1-X}{\left[y^2 + (1-X)^2\right]^{3z}} + \frac{1+X}{\left[y^2 + (1+X)^2\right]^{3z}} \right] \quad (2.4)$$

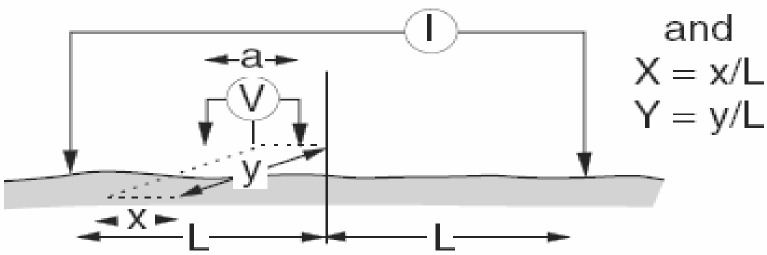


Figure 2.5. Electrode array and geometric factor of gradient *(Reynolds, 1997)*

Resolution

Resolution of EM methods depends on sounding system geometry and average resistivity (conductivity) of the section and on quality of signal.

In our work in South Sumatera, pay respect to sounding system and total conductivity of the section, HREM resolution on the target layers was about 50 meters.

Integration with seismic and logging data it can support our interpretation to select and research target object more accurate.

2.4. Data Processing Of High Resolution Electromagnetic

Controlled-source Electromagnetic system use time-varying electrical and magnetic dipole source of known geometry to induce electric currents in the various conducting media present. The electric or magnetic character of the induced current determines the algorithm of estimation of the vertical electric conductivity structure of the geological materials. There are four basic source-receiver types but many combinations. The four are; vertical and horizontal electric dipole (VED and HED) and vertical and horizontal magnetic dipoles (VMD and HMD). *(Milsom, vol.3)*

Apparent conductivity at low induction numbers (McNeil 1980).

The skin depth (δ) is given by:

$$\delta = (2/\omega\mu_0\sigma)^{1/2} = (2i)^{1/2}/\tau \quad \text{And} \tag{2.5}$$

$$\tau_s = (2i)^{1/2} s/\delta = (2i)^{1/2} B \quad [as\ B = s/\delta] \quad \text{Where}$$

ω = $2\pi f$ and f is the frequency (Hz)

μ_0 = permeability of free space

i = $\sqrt{-1}$

τ = $(i\omega\mu_0\sigma)^{1/2}$

σ = conductivity

s = inter-coil separation (m)

The ratio of the secondary (H_s) to primary (H_p) magnetic fields at the receiver at low induction numbers (i.e. B << 1) is given by:

$H_s / H_p \approx iB^2 / 2 = (i\,\omega\,\mu_0\,\sigma\,s^2)/4$

The measuring instrument is designed to ensure that with the selected frequency (f), a given inter-coil separation (s), a designed response of H_p for a given transmitter, the only unknown are H_s, which is measured by the instrument, and the ground conductivity (σ).

Put another way:

$$\sigma_a = (4/\omega\mu_0 s^2)(H_s / H_p)_q \qquad (2.6)$$

Where the subscript q is denotes the quadrature phase.

<u>Diffusion Depth (d) and velocity (v) from TEM</u>

In a uniform conducting medium, the transient electric field achieves a maximum at the diffusion depth (d) such that:

$$z = (2t/\sigma\mu)^{1/2} = d$$

Where σ is the conductivity in S/m, and μ is the magnetic permeability of medium. The maximum travel down wards with a velocity (v) such that:

$$v = (2\sigma\mu t)^{-1/2}$$

In conducting half space, the downward velocity is given by:

$$v = 2(\pi\sigma\mu t)^{-1/2} \qquad (2.7)$$

<u>Seismic prospecting data reprocessing</u>

The purpose of the seismic data processing here is was to get the amplitude image of the section for correlation with measured parameters of electro-magnetic field and to get data about interval velocities by the seismic inversion algorithm at the target intervals. *(HREM report, 2006)*

By use Dix equation, stacking velocities can be converted to interval velocities. The speed of the n layer can be calculated based on the Dix formula (Dix Formula), which derived from the rms velocity. Figure below shows the differences in rms velocity curves and velocity intervals.

$$V_n^2 = \frac{V_{rms_n}^2 t(0)_n - V_{rms_{n-1}}^2 t(0)_{n-1}}{t(0)_n - t(0)_{n-1}} \qquad (2.8)$$

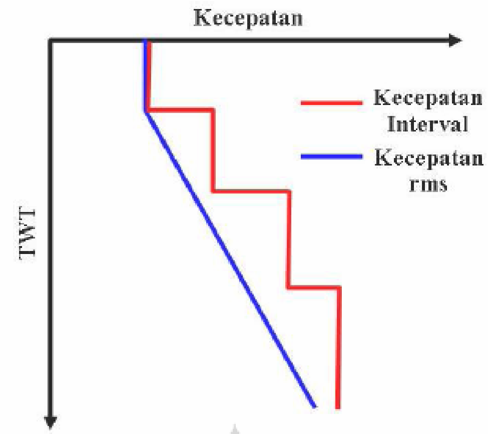


Figure 2.6. Interval & Rms Velocity *(Redrawn from Yilmaz, 1879)*

<u>Integrated Attribute</u>

The proprietary "GeoVisor" software technology (N.P. Smilevets and S.A. Chernyshov) is used in the HREM processing. It implements the integrated interpretation of seismic, electrical, gravity, magnetic, and well-logging data. The seismic data are reprocessed using SeisWin software (I. V. Tischenko). The combined output is a coordinated Seismo-Geoelectrical model of cross-section. Each complex is parameterized by velocity and resistivity. An Integrated Attribute (IA) is then produced, which considers weighting of the different geophysical parameters. This IA is indicative of hydrocarbon deposits in the processed zone of the seismic section. It takes into account litho-facial variability of sediments and reacts to alteration of the fluid-saturation nature of these sediments.

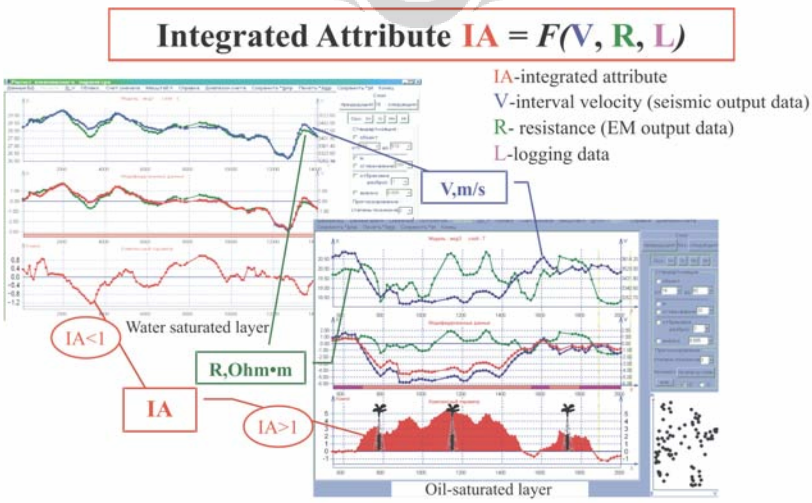


Figure 2.7. HREM Integrated Attribute *(Smilevets, 1999)*

2.5. Interpretation Methods of High Resolution Electromagnetic

2.5.1. Combination between Geology and Technology

HREM (High Resolution Electromagnetic) has been applied as a new oil and gas finder technology in Indonesia. HREM technology can be used for target of different depth. It depends on the instrument that we use and total conductivity of the section. The deepest of investigation reservoir in South Sumatra 6.000 ft, with HREM technology can be done on that prospect. Base on that idea HREM was recommended for South Sumatra basin area. The HREM technique was applied in South Sumatra Basin, in Indonesia.

Note: maximal depth for HREM in Indonesia is 4-5 km

<u>Petroleum Geology Of South Sumatera Basin</u>

- The basin contains diverse petroleum systems, with both oil and gas being sourced from lacustrine and fluvio-deltaic terrestrial facies.
- Limited potential still remains for the traditional Talang Akar and Batu Raja formation plays.
- In contrast to the basin's mature oil status, the South Sumatra Basin is under-explored for gas, and contains good remaining gas potential in both new and existing successful plays. A further 6 to 10 TCF gas could be discovered in the basement, Talang Akar, and Batu Raja.

Tectonics

The South Sumatra basin was formed by three major tectonic phases:

1) Extension during late Paleocene to early Miocene forming north-trending grabens that were filled with Eocene to early Miocene deposits;

2) Relative quiescence with late normal faulting from early Miocene to early Pliocene; and

3) Basement-involved compression, basin inversion, and reversal of normal faults in the Pliocene to Recent forming the anticlines that are the major traps in the area (Suhendan, 1984).

Deposition

Characteristic half-graben-style locally derived deposits began to fill these basins and subsidence of the basins (Bishop, 1988; Wicaksono et al, 1992). Additional synrift deposits of tuffaceous sands, conglomerates, breccias and clays were deposited in faulted and topographic lows by alluvial, fluvial, and lacustrine processes (Figure 2.6).

Petroleum Occurence

Petroleum exploration in South Sumatra has been primarily guided by surface anticlines, sometimes found by digging trenches to map dips (Ford, 1985). Hydrocarbon migration occurred along carrier beds updip from the deep rift basins, where the source rocks are mature, and then along faults to overlying anticlines that form the majority of traps (Sarjono and Sardjito, 1989).

Source Rock

Hydrocarbons in South Sumatra Province, Lahat/Talang Akar-Cenozoic, are derived from both lacustrine source rocks of the Lahat Formation and terrestrial coal and coaly shale source rocks of the Talang Akar Formation. The Batu Raja Limestone and the Gumai Formation shales may also be mature and have generated hydrocarbons in local areas (Sarjono and Sardjito, 1989).

Overburden Rock

Marine flooding from the south resulted in deposition of the Gumai Formation in the basins while Batu Raja Limestone was deposited on platforms and highs with maximum transgression reached during the early middle Miocene (Sarjono and Sardjito, 1989).

Trap Types

Northwest to southeast trending anticlines were the first traps explored and remain the most important traps in the South Sumatra basin (van Bemmelen, 1949). Stratigraphic pinch-outs and carbonate buildups locally combine with folds and anticlines to enhance the effectiveness of the primary trap type.

Reservoir Rock

- Lahat (Lemat, Old Lemat, Young Lemat) Formation The Eocene to Oligocene Lahat Formation (Figure 2.6) is composed of synrift deposits that are as much as 1,070 m thick.
- Talang Akar Formation sandstones, which were deposited during marine transgressions and regressions, form important stratigraphic traps (Tamtomo et al, 1997).
- Batu Raja Limestone The early Miocene Batu Raja Limestone is also known as the Basal Telisa Limestone (Hutchinson, 1996).
- Gumai Formation The Oligocene to middle Miocene Gumai Formation, also known as the Telisa Formation, is composed of fossiliferous marine shales with thin, glauconitic limestones that represent a rapid, widespread maximum transgression (Hartanto et al, 1991; Hutchinson, 1996).

Air Benakat Formation

The middle Miocene Air Benakat Formation, also known as the Lower Palembang Formation, was deposited during the regression that ended deposition of the Gumai Shale.

Kasi Tuff

Continental tuffaceous sands, clays, gravels, and thin coal beds of the Kasi Tuff, also known as the Upper Palembang Formation, are found in valleys and synclines formed during deformation of the Barisan Mountains.

Seal rock

The Gumai Formation represents the maximum highstand transgression following development of Batu Raja carbonates (Fig. II.2 and II.3) (Hartanto et al, 1991). Shales of this regional formation seal carbonate reservoirs and locally seal a series of stacked 10 sandstone reservoirs of the Talang Akar Formation (Martadinata and Wright, 1984; Hartanto et al, 1991).

Undiscovered Petroleum by Assessment

The primary exploration targets in the South Sumatra Basin have been anticlines and carbonate buildups. Future exploration targets would include smaller traps associated with more subtitle structures, stratigraphic traps associated with lowstand fan deposits, shoreline on lap onto basement highs, and synrift clastic fluvial, deltaic, and possibly deep-water deposits deeper *in the half-grabens. (Sarjono & Sarjito, 1989)*

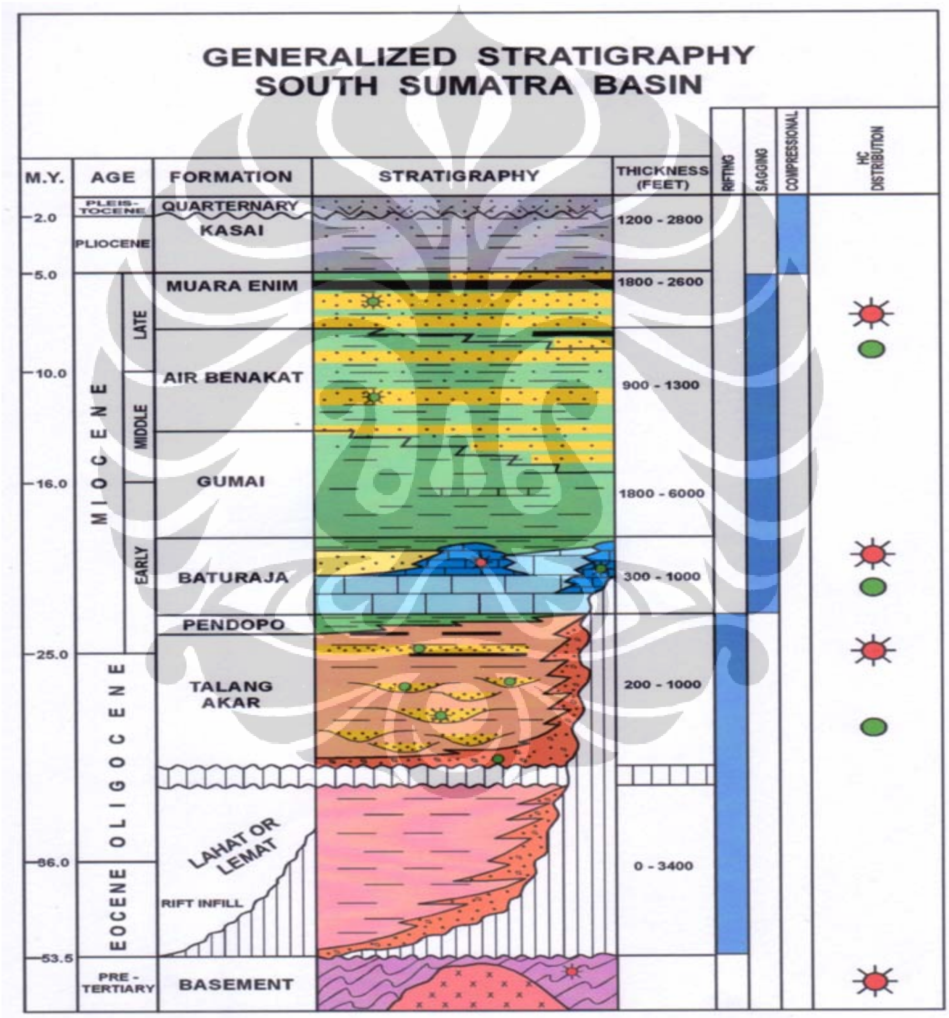


Figure 2.8. Generalized stratigraphic column for the South Sumatra Basin

2.5.2. GeoVisor technology processing of HREM data (Smilevets, 1999)

- We fulfilled detailed processing of HREM data on the base of agreement with logging data to construct the geoelectrical model.

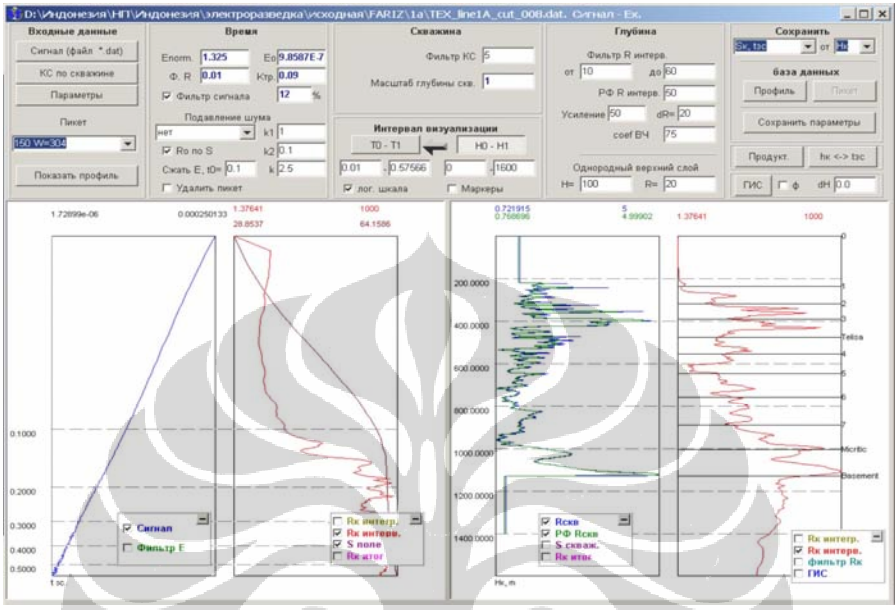


Figure 2.9. Example One Dimension Geo-electrical model
(internal HREM report, 2006)

- We make a correlation of reflecting horizons of seismic section in time and, after overlaying of HREM data on the seismic section, constructed matched seismic-geoelectrical model.

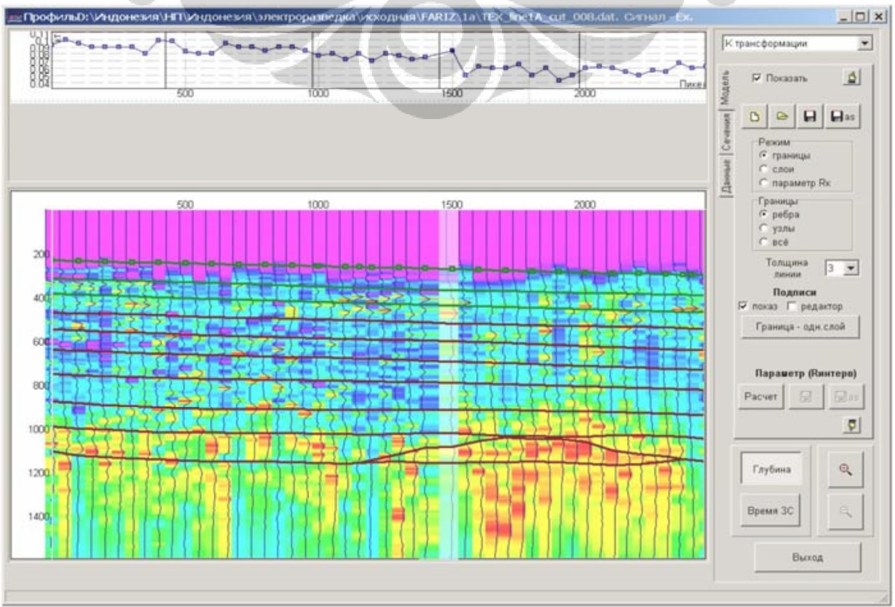


Figure 2.10. Example Two Dimension Geo-electrical model
(internal HREM report, 2006)

- On the base of matched seismic-geoelectrical model we calculated the significances of interval longitudinal velocities and resistances for target layers of the section.

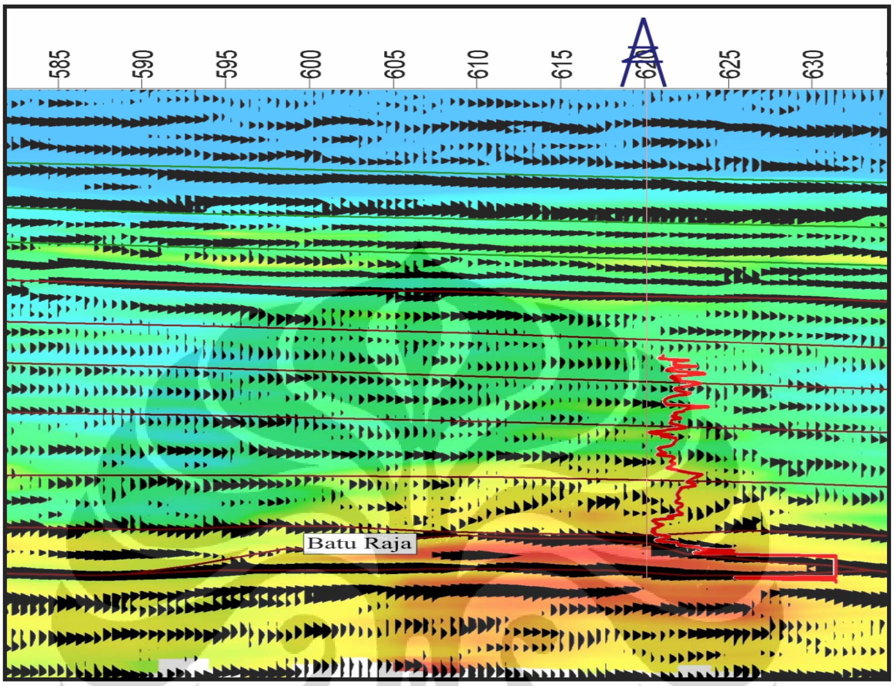


Figure 2.11. Example of matched seismic-geoelectrical model
(internal HREM report, 2006)

- Integrated attribute (IA) was calculated from interval attribute of wave and electromagnetic fields (the velocities and resistance).

- HREM electrical-prospecting in frequency-domain area was also executed. Values of phase parameter of the induced polarization (IP), reacting to the presence of hydrocarbon accumulation was calculated too.

2.5.3. Integrated Attribute (Resistivity from EM signal and Velocity from seismic)

The superimposition of the Integrated Attributes on the seismic time-section provides stratigraphic tying of revealed anomalies, while the joint analysis together with wave-field dynamics (velocities, amplitudes, phase etc.) and the structural situation allows us to predict the type of hydrocarbon deposit. At the research area, maps of the IA anomalies distribution for different stratigraphic intervals are constructed. These maps are usually superimposed on the layouts of good reservoirs and structural maps for the main target strata. This provides an opportunity to distinguish multilayer hydrocarbon deposits (considering a resolution of electrical prospecting) and to determine their spatial arrangement at different stratigraphic levels. Thus HREM data are not masked and multiple pay zones can be identified for multiple drilling targets in one exploration well. *(Smilevets, 1999)*

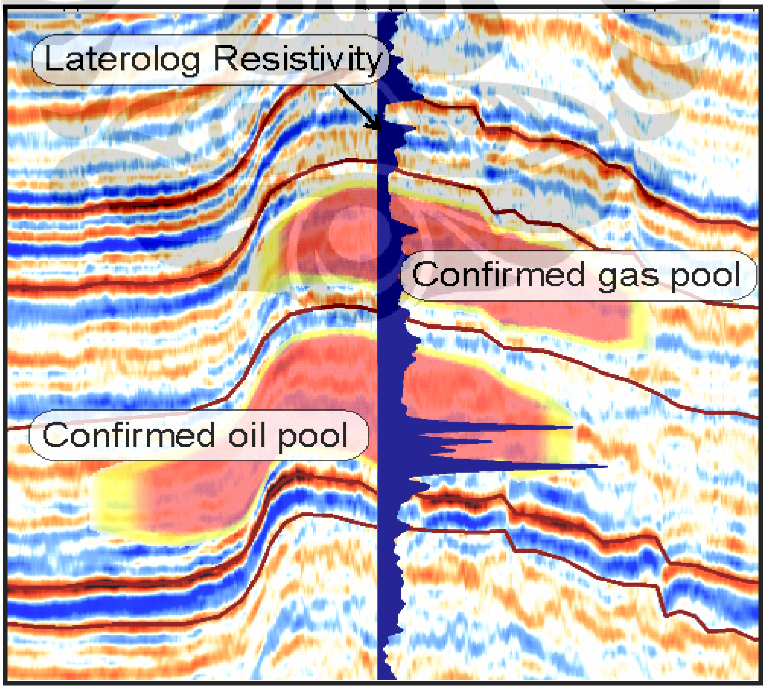


Figure 2.12. Example of integration of offshore 3D Seismic and Advanced EM

CHAPTER 3

RESEARCH METHODOLOGY

The analyses from several wells, which have been drilled after HREM survey, are used to build up templates for continuation interpretation. The template was making by some steps as shown in (figure 3.1). The electrical properties of the lithologies (Lateral variation resistivity) are derived from electromagnetic signal. The integration lateral variation of velocity from seismic and lateral variation resistivity from electromagnetic signal is used for direct hydrocarbon indicator. There are 3 essentials parameters are the Porosity of the formation, Saturation in Water, and the Thickness of its deposits from well logs. All these geophysical parameters are correlated with a template that can assist in the interpretation of the possibility for further well in the same area

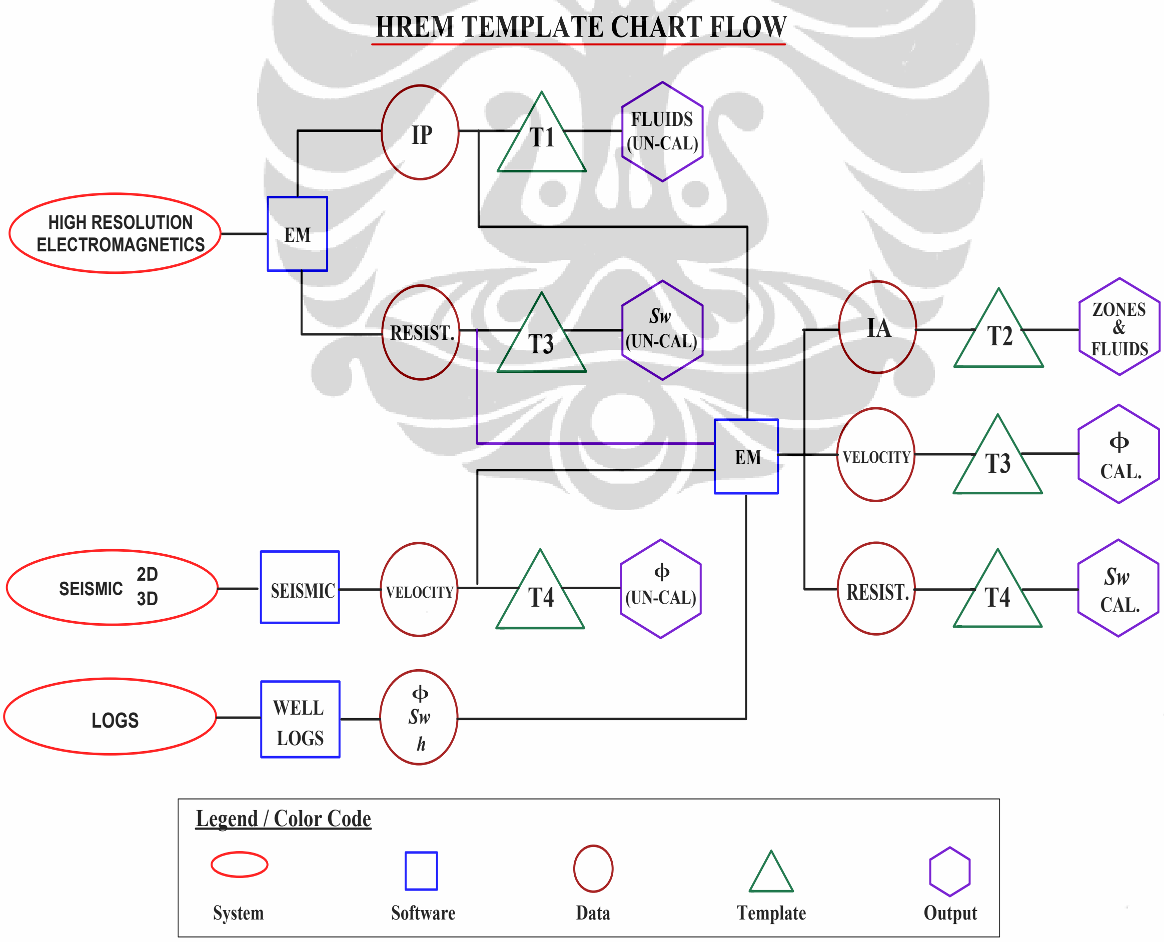


Figure 3.1. Workflow to build up the Template for Enhancement of Electro-Magnetic Data to Reservoir Characteristics

3.1. Exploration Criteria of Hydrocarbon Deposit Detection by Electrical Prospecting Integrated with Seismic and Well-Logging Data

The solving of tasks concerning oil/gas-bearing forecast via electromagnetic sounding has its foundation in alteration of physical properties of geological subsurface in zones of hydrocarbon deposits that influence geoelectrical parameters. *(Smilevets, 1999)*

Hydrocarbon deposit can be considered as **local anomalous object both for its resistivity and polarizability**, situated in normal horizontally-layered subsurface. The specific hallmarks of rocks' electrical properties in zone of the deposit are reasoned by several causes:

- alteration of petrophysical properties of reservoir rocks;
- mineralization of underground water (its sharp increase in near-contact zones of oil/gas deposits);
- direct effect of the deposit itself, as local high-resistivity object;
- alteration of physical properties of enclosing rocks because of migrating fluids, particularly – forming of calcitization and pyritization halos;
- presence of static charge in the zone of deposit and near-contact zones, i.e. deposit is electrically active system in geological subsurface.

Therefore, hydrocarbon deposit is complex multi parameter physical object; the more precisely features of this object are studied, the more reliable its detection and identifying is.

The most characteristic electrical-prospecting indications of hydrocarbon presence are:

3.1.1. Increase of Reservoir Resistivity In Hydrocarbon-Saturated Zone.

In natural conditions of bedding, the rocks below groundwater level are saturated by water of various concentration and composition of dissolved salts. At the depth of 4-5 km concentration of salts may reach 250-300 g/l, and so resistivity of mineralized water filling interstitial space of rock makes 0.03-1 Ohm·m. Electrical resistivity of oil and gas exceeds by far resistivity of stratal water and reaches 10^{16} Ohm·m. In the meantime, resistivity of gas-saturated stratum many times surpasses resistivity of oil-saturated one. In oil deposit ρ is 3-4 times higher (and 10-15 times higher in gas deposit) than ρ of environment *(Smilevets, 1999)*. The formation water in the field in Indonesia is 20.000 ppm. In Takara Field concentration formation water around 15.000 ppm.

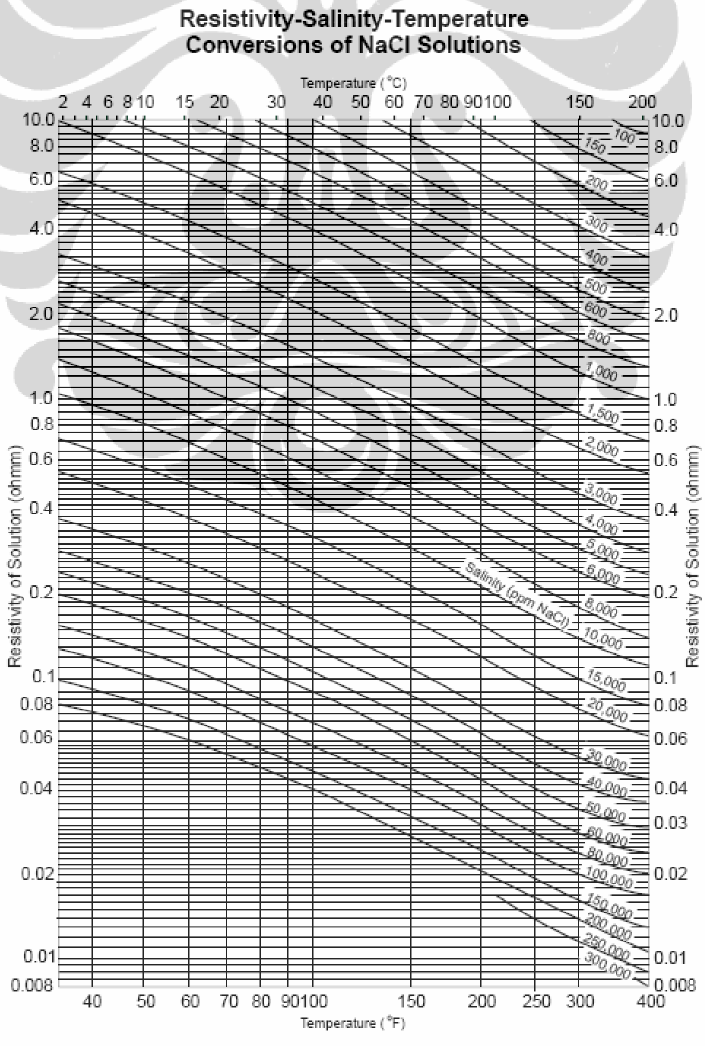


Figure 3.2. Nacl Solution

Mineralization of strata water can considerably affect resistivity of oil/gas-saturated rocks. For some deposits is typical, that mineralization drops from 80-120 g/l outside its contour down to 10-90 g/l inside contour, that causes resistivity to increase 3-5 times. Pressure, increasing with depth, usually causes resistivity increase, while temperature increase causes resistivity decrease.

In South Sumatera $R_w = 0{,}23\ \Omega - m\ @\ BHT\ 150\ {}^0F$.

<u>An approximation is given by Arp's formula</u>

$$R_2 = R_1 * \left[\frac{T_1 - X}{T_2 - X} \right] \qquad (3.1)$$

Where;

X = 6,77 if temperature is in ${}^0F$

X = 2,15 if temperature is in ${}^0C$

Resistivity increase in zones of oil/gas deposits causes positive anomalies of apparent resistivity on the curves of electromagnetic sounding. Therefore, alteration of rocks' resistivity makes first prospecting indicator of hydrocarbon deposit presence *(Smilevets, 1999)*.

According to hypothesis of S.D. Pearson (USA), hydrocarbon deposit acts as fuel-cell generating vertical electro-telluric current which density reaches its maximum directly above the deposit. The existence of electro-telluric current above hydrocarbon deposit reduces apparent electrical conductivity of over-laying rocks. Interplay of external and internal sources, equally with epigenetic alterations in rocks, forms a 'tube' of anomalous decrease of electrical conductivity (increase of resistivity) of rocks above the oil/gas deposit.

3.1.2. Increased Level Of Induced Polarization (IP)

Increase level of IP is second important factor of forming electrical anomalies if there is hydrocarbon accumulated. *(Milsom, vol.3)* It is linked with:

(a) Redistribution of electrical charge in the zone of deposit and near-contact zones while inducing electromagnetic field;

$$M = V_p / V_o \ (mV / V \ or \ \%) \tag{3.2}$$

$$M_a = \frac{1}{V_0} \int_{t_1}^{t_2} V_p(t)\, dt = \frac{A}{V_0} \tag{3.3}$$

Where,

M_a : Apparent chargeability,

$V_p(t)$: Overvoltage at time t,

V_0 : observed voltage with an applied current

(b) Forming secondary sulfide-mineralization halos, aided by vertical hydrocarbon migration. Hydrocarbons, deoxidizing sulphate ions from strata l water, form sulphurated hydrogen; the latter reacts with compounds of iron or other metals, and deoxidizes them to pyrite, marcasite, etc.

$$PFE = 100\left(\rho_{a0} - \rho_{a1}\right) / \rho_{a1} = 100\ FE \tag{3.4}$$

$$MF = A\left(\rho_{a1} - \rho_{a0}\right) \tag{3.5}$$

Where,

PFE : Percentage frequency effect,

MF : Metal factor (MF),

ρ_{a0} & ρ_{a1} : Apparent resistivity

A : $2\pi \ x \, 10^5$

The said halos make areas of increased polarization above the deposit in upper part of subsurface and testify to oil-bearing strata. By special in-well and on-surface measurements at many known deposits in Russia and Kazakhstan the increased polarizability value of oil/gas-saturated rocks was proved *(Smilevets, 1999)*.

It was noted that inside the oil/gas-accumulation contour polarizability anomalies are 2-5 times higher than for water-saturated rocks. In the meantime, it was proved that polarizability anomalies above oil deposits are higher by far than above gas deposits. So, to estimate productivity of target strata, one should estimate distribution of both apparent resistivity and induced polarization (IP) anomalies within. Also one should remember that IP and resistivity anomalies can be connected not only with oil-bearing but other physical-geological reasons *(Smilevets, 1999)*.

Particularly, ***induced polarization anomalies*** can occur in zones of fluid-conductive channels (tectonic faults, decompression zones), where oxidation-reduction may happen, and also in zones of near-surface in homogeneities in permafrost (like local higher-ohm outliers) to which apparent polarizability anomalies could be related *(Smilevets, 1999)*.

All explanation above can be connected with the variable-frequency method. It is designed to measure change in apparent resistivity when frequency is changed. The percentage of decrease may be expressed in the form:

$$P = \frac{\rho_2 - \rho_1}{\sqrt{\rho_2 \rho_1}} \quad x \quad 100\% \qquad (3.6)$$

Where ρ_2 is the resistivity measured and ρ_1 the frequency at another frequency 10 times as high. According to Marshall and Madden, 91 rock concentrated sulfides would give rise to a P greater than 10, and porphyry copper ores (2 to 10 percent sulfides) to a P between 5 or 10. Rock with a trace of sulfide mineralization would have a P value from 2 to 5, sandstone and siltstone 1 to 3, basalt from 1 to 2, and granite from 0,1 to 0,5. *(Milsom, vol.3)*

Resistivity anomalies (Smilevets, 1999), apart from alteration of fluid type, can be caused by lithologic-facial variability of rocks within the target strata. For example, local replacement of terrigenous accumulations with carbonate varieties is accompanied by resistivity increase, and so by electrical prospecting alone, without additional data from other geophysical methods (particularly – seismic prospecting), could have been mistakenly interpreted as influence of oil/gas-prospective object.

Thereby, geological interpretation of electrical-prospecting data can always integrated the latter with other methods' data (seismic, gravity/magnetic) and well-logging. It will make possible to perform ranking of geoelectrical anomalies, not only considering structural-tectonic features the studying territory, but taking into account alteration of seismic and gravity/magnetic parameters (velocity, density) and so to increase oil/gas-forecast reliability.

3.1.3. Velocity (Vp) and Attenuation (α) of Longitudinal Seismic Waves

Velocity (Vp) and attenuation (α) of longitudinal seismic waves are dictated by elastic properties of rock's solid matrix. The greatest influence on Vp and *α* have porosity, forcibility of pores and pore-filler, structural-textural features of rocks, mineral composition and cement type, water mineralization, thermodynamic conditions. Oil and gas take certain effect on velocity and absorption of seismic waves *(Smilevets, 1999)*. In-situ measurements of Vp and *α,* carried out at many deposits, revealed the following:

$$\phi = \frac{\Delta t_{\log} - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}} \tag{3.7}$$

Material	Travel Time (μ *sec/ft)*
Sandstone matrix	51 - 55.5 (Quartz:56)
Limestone matrix	43.5 - 48 (Calcite:49)
Dolomite matrix	38.5-43.5 (Dolomite:44)
Fresh water/salt water	218 / 189
Oil	238
Casing	57

Table. 3.1. Travel Time by Tracs International

The formation travel time measurement can be interpreted in term of the porosity formation according to Wyllie or time average equation

- **Decrease** (by 200-500 m/s or 15-25% down) **of velocity** in oil/gas-saturated accumulations, that reduces strata and effective velocity above the deposit by 10%. *Vp* values of oil/gas-saturated rocks are affected by thermodynamic conditions too: velocity decreases if the temperature rises (more intensively for oil-saturate rocks – by 30% down and more); on the contrary, rise of pressure (depth) also results in higher Vp. *(Smilevets, 1999)*

- **Increase of attenuation parameter *(α)*** 10 times and more relatively to water-saturated zones of subsurface. Within the boundaries of gas deposit (or gas storage) this parameter increases several dozens times. The presence of seismic wave's absorption leads to velocity dispersion, their dependence on the frequency. Theoretical computations show that such dispersion for oil/gas deposits usually makes several percent. *(Smilevets, 1999)*

Alteration of elastic and absorption properties, caused by hydrocarbon deposit, results in anomalies of seismic field, such as:

- Decrease of acoustic stiffness of oil/gas-saturated reservoirs, relatively to water-saturated ones, by 10-20% down; it leads to appearance of isolated reflections off gas-water or oil-water contact surfaces;
- Anomalies of 'bright' and 'dark' spots, related to the top of hydrocarbon deposit;
- Short anomalies inside the deposits, related to certain acoustic boundaries;
- Anomalies of decrease of the amplitudes (2 times and more lower);
- Anomalies of decrease (by several percent down) of effective velocity and prevailing frequency;
- Local degradation of seismic record (time-section) quality.

So, the more parameters (differently responding to hydrocarbon deposit presence) are being considered and simultaneously analyzed, the more probability this predicted deposit really exists and therefore will indeed be discovered by drilling. *(Smilevets, 1999)*

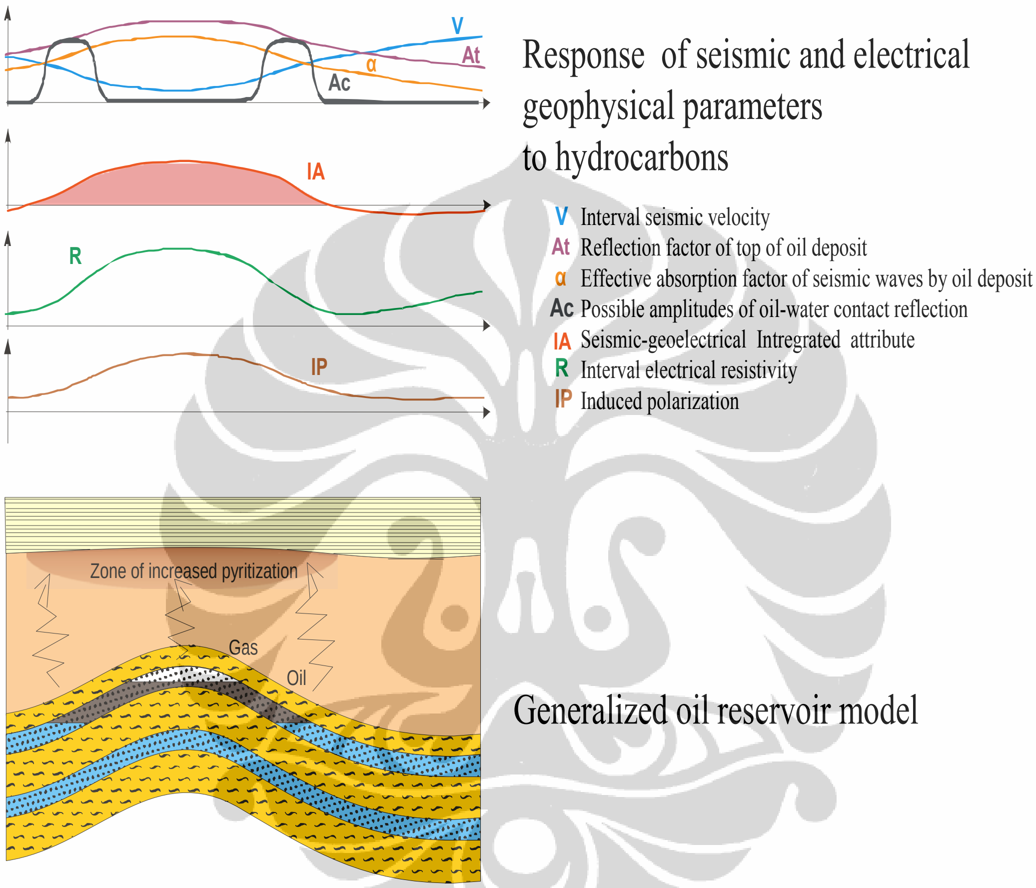


Figure 3.3. Physical basis of oil/gas detection by geophysical methods.
(Smilevets, 1999)

3.2. Enhancement HREM Data to Reservoir Characteristics

Parameter of Interest to us at this stage of hydrocarbon deposit research, there are 3 essentials parameters which are of fundamental interest to us and directly related at the presence and quantities of hydrocarbons in place. Those parameters are the Porosity of the formation, its Saturation in Water, and the Thickness of its deposits. And the proper manipulation of refracted and reflected Electro-Magnetic signal, can lead to a good value of those three parameters.

3.2.1. Porosity:

This basic parameter is a measure of the space available within the interstice of the matrix and which is always filled up by some fluid. We will not complicate our case by considering outlandish fluids like CO2, H2S or other fancy medium, but simply consider that we are dealing with gaseous or liquid hydrocarbons and water, which is always there, in its less form, as an irreducible water attached to the grains of rocks. This is the case in our example taken as the FARIZ field of South-Sumatra. How can this porosity be evaluated in our case?

The E-M wave cannot, by itself, give much access to the value of porosity. So, another way is taken, which consists with re-processing the 2-D or 3-D original seismic data, adding to some E-M measurements and produce a "Velocity" curve and some so-called Integrated Attributes by EM signal. Again, this Velocity curve is derived from initial 2-D or 3-D seismic data. This curve and some selected I.A. curves will be used at identifying seismic anomalies shown as deflections. So, we will be looking at trying to identify a kind of "Base Line" which will probably identify the always longer Shale bed depositions; and of this current base line, differences will be a function of the porosity. We can already see the role of templates which, once "calibrated" in a promising reference well.

3.2.2. Water Saturation

A "Resistivity" curve is presented on the HR-EM data results, a qualitative interpretation will be made after identifying a base line due to shales. As this resistivity curve departs from the base line, we can make a correspondence with a decrease in Sw.

(Automatically increasing S_{hyd} , the complement to $S_w + S_{hyd} = 1$).

The resistivity curve can be approximated in Sw values, decreasing towards the irreducible water saturation as the deflection with the base line increases. Together with Resistivity curve, the same Integrated Attributes by EM signal will be adding character and resolution to the interpretation of the data.

3.2.3. Formation Beds Thickness

EM can not detect effective thickness of the collector, because HREM resolution is not enough for this task. On this research we want to make a bridge between several well were drilled before HREM survey and after HREM survey. Using the evaluation from those wells are changes over depth of the 2 factors (Porosity and Water Saturation). From 3 curves were show the contrast character EM signal on Integrated Attribute, and also it is corresponds to the thickness of the formation when the bigger deflection of IA from base line, and the bigger beds thickness.

3.2.4. Other Parameters

Two parameters of great importance need also to be mentioned as not being accessible to the EM measurements: Lithology & Permeability. It simply needs a drilled hole as a minimum condition for an initial knowledge about those two last factors.

CHAPTER 4
RESULTS AND DISCUSSION

4.1. Overview of Takara' Field

We had an excellent opportunity to test our proposal for EM data calibrations and templates in the case of the **Takara** field. It seems that everything converged towards this field. We have the initial seismic data followed with the drilling of the first 3 **Takara** wells. Then, an HR-EM survey took place, focalizing on the latest well drilled **(Takara – 03)** and extending to the **R -1** well which was also a producing well. Then, followed by 13 additional wells were drill across the field and the HR-EM shooting lines.

Back to HR-EM measurements, our first concern is, of course, data quality. And to evaluate this, nothing better that this "TRIPLE POINT" of line convergence over **Takara-03**. Being one "point", all the parameter values should be the same on those three lines at this point. Here are the results:

BA TURAJA TOP :

	Line 1-A (620)	Line 1-B (620)	Line 2 (620)
Velocity (m/sec)	2447	3225	1971
Resistivity (ohm - m)	9.03	7.04	8.4
IA	7.32	20.9	17.6

Table 4.1. Takara-03 Limestone Formation

4.1.1. HR-EM "Shooting" Lines:

Three lines of survey were selected over the **Takara** Field. It allows for a better Velocity results to be produced (as mentioned above). Here are more details about those lines.

Line 1-A :

General orientation: West – South - West to East – North - East. It passes at the vertical of **Takara - 3** well **(620)** and **Takara - 5** well **(628)** to the North-East of the field. This shooting line is passing also reasonably close to **Takara - 4** and **Takara - 6** wells, whose data will be orthogonally projected on this Cross- Section.

Line 1-B :

General orientation : South-West to North-East. It passes close enough, to **Takara-2 & Takara-14** on the South-West section of the field, and at the vertical of **Takara-3 (620)**. This line also runs very close to **Takara-5**. And it is worthwhile orthogonally projecting **Takara-4 & Takara-6** data on this Cross- Section as being close enough of this line.

Line 2 :

By far the most interesting as intersecting a large number of wells on that structure. Its general orientation is North - North West to South - South East. It passes through or near 11 wells drilled in the **Takara** field, so far. And also runs at the vertical of **Takara-3 (620)** well.

4.2. Graphics Provided:

One geographical map of the **Takara** field wells # 1 until # 15, have been drawn on a large scale graphic **(Figure 4.1)**. This map provides a very accurate position of the wells well head location and its TD location as almost all holes are deviated. The 3 shooting lines are also commissioned on this map.

Then, three cross-sections following the three shooting lines are presented. Near-by wells are plotted at their location in True Vertical Depth (TVD) Playbacks. Their depths have been corrected to Mean Sea Levels, providing a uniform depth origin for all wells in that structure. The interpretation of each well was completed using the Petrolog logging data software. This wireline logging data is displayed on a 1/500 depth scale (running from 2,930 ft until 3,700 ft TVD / MSL depths).

Below this log display, is consigned the High Resolution – Electro Magnetic data and results for Velocity, Resistivity and Integrated Attributes.

Those 1 + 3 graphics, are providing a great insight into the interpretation of the HR-EM and seismic data. And, at a glance, exhibit all the results that we are want to know. On those three graphs, we have displayed Velocity, Resistivity and two Integrated Attributes, data which is available to us from HR-EM survey. In the very small interval where we are missing this data, we have replaced it with the Induced Polarization results which are providing good ”Qualitative“ answers at locating water zones,

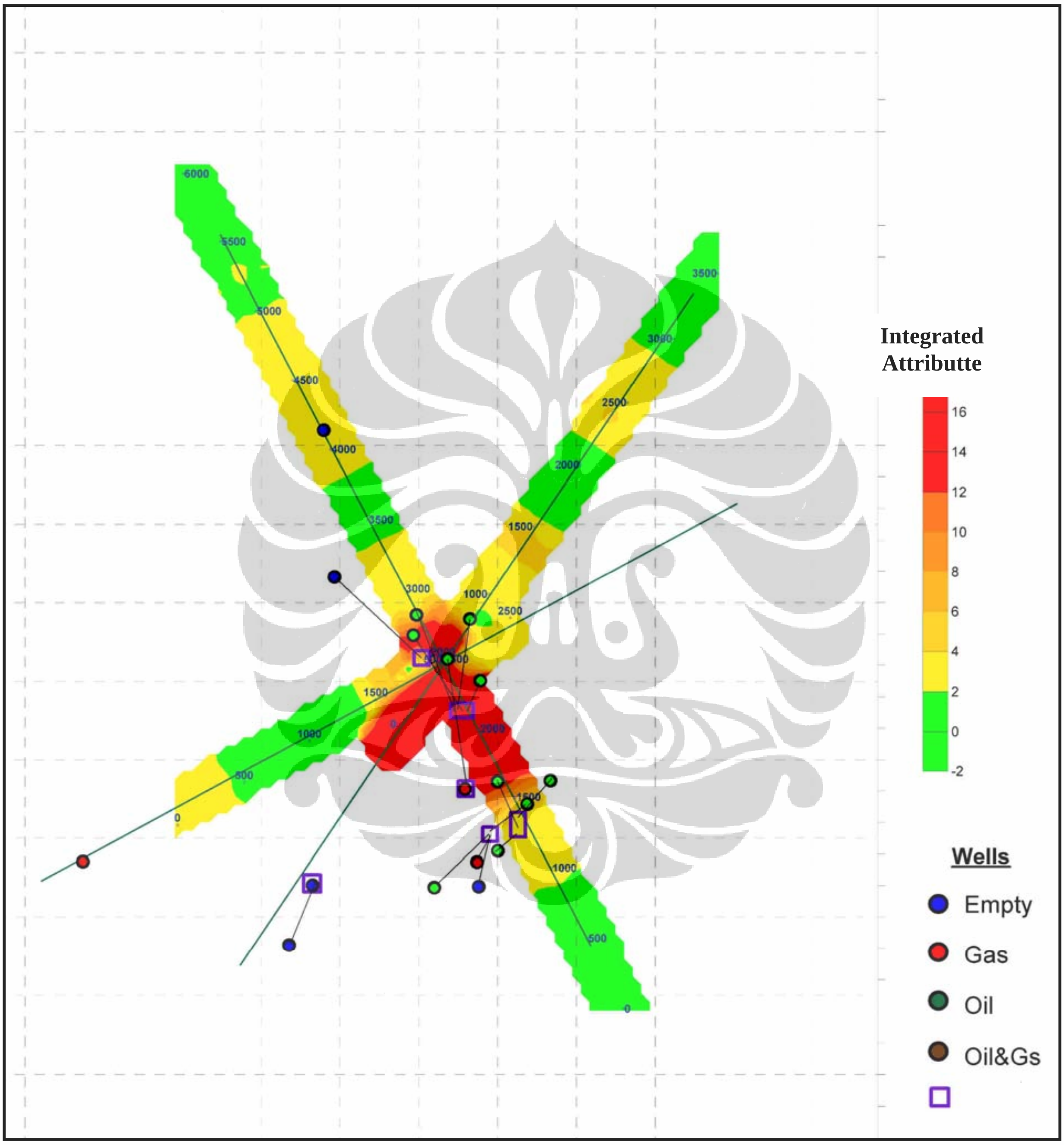


Figure 4.1. Confirmation of HREM hydrocarbon presence forecast by later drilling.

4.2.1. Job Sequences and data Interpretation

Having proceeded with Geological identification of a sedimentary basin, followed by a conventional 2-D or 3-D Seismic acquisition data across that prospect, the HR-EM survey follows the following sequence. Its set-up resembles the seismic survey except that a powerful Electro-Magnetic signal is induced into the ground (instead of a mechanical shock-wave) and that Antennas, instead of geophones, are used to measure the induced response of the formation to those EM signal.

The EM survey better follows the surface lines of the Seismic survey, as the EM data will complement this Seismic data in the production of the final results.

Upon completion of these two surveys (Seismic and EM), we have already in our hand, a good “picture” of the sub-surface. In the best case scenario, it is possible to already identify fluids into the formation (like gas as a “bright spot”), and already be able to differentiate between oil and water. In general, this survey will be pointing at Hydrocarbon Deposit in a Qualitative manner and additional actions will need to be taken.

The next step of improving the response of our HR-EM data, and making it Quantitative, to, somehow, associate the tool response with either a zone where the response of the tool has been previously calibrated; or having a well representative well, best of all a producer, drilled and well evaluated for Porosity, Water Saturation, Formations Thickness; and at the same time, Lithology and Shaliness. This way, after the HR-EM has been sort of re-calibrated “in-situ”, a very accurate map of the sub-surface is made available to the Customer. This is going to drastically increase the success ratio of the wells drilled in that field; at an advantageous cost since EM surveys charges are relatively minor on the final well cost. Those HR-EM costs are significantly less than commonly used evaluation services in and around oil wells.

4.3. The Takara Field Case:

On Completion of the HREM survey, (as per HREM properties results & prior to drilling of Takara-3).

<u>Line 1-A HREM Results:</u>

Examination the HR-EM **Graphic-2** shows that we have an "anomaly" around the HR-EM shooting points centered at **"610"**. With the Resistivity curve "peaking at **"620"**. The HR-EM data does not exist past the shooting point **"633"**. From this un-calibrated analysis, water appears to be the formation fluid in the Baturaja outside the interval **"590 – 630"** which tends to show some good hydrocarbon deposits.

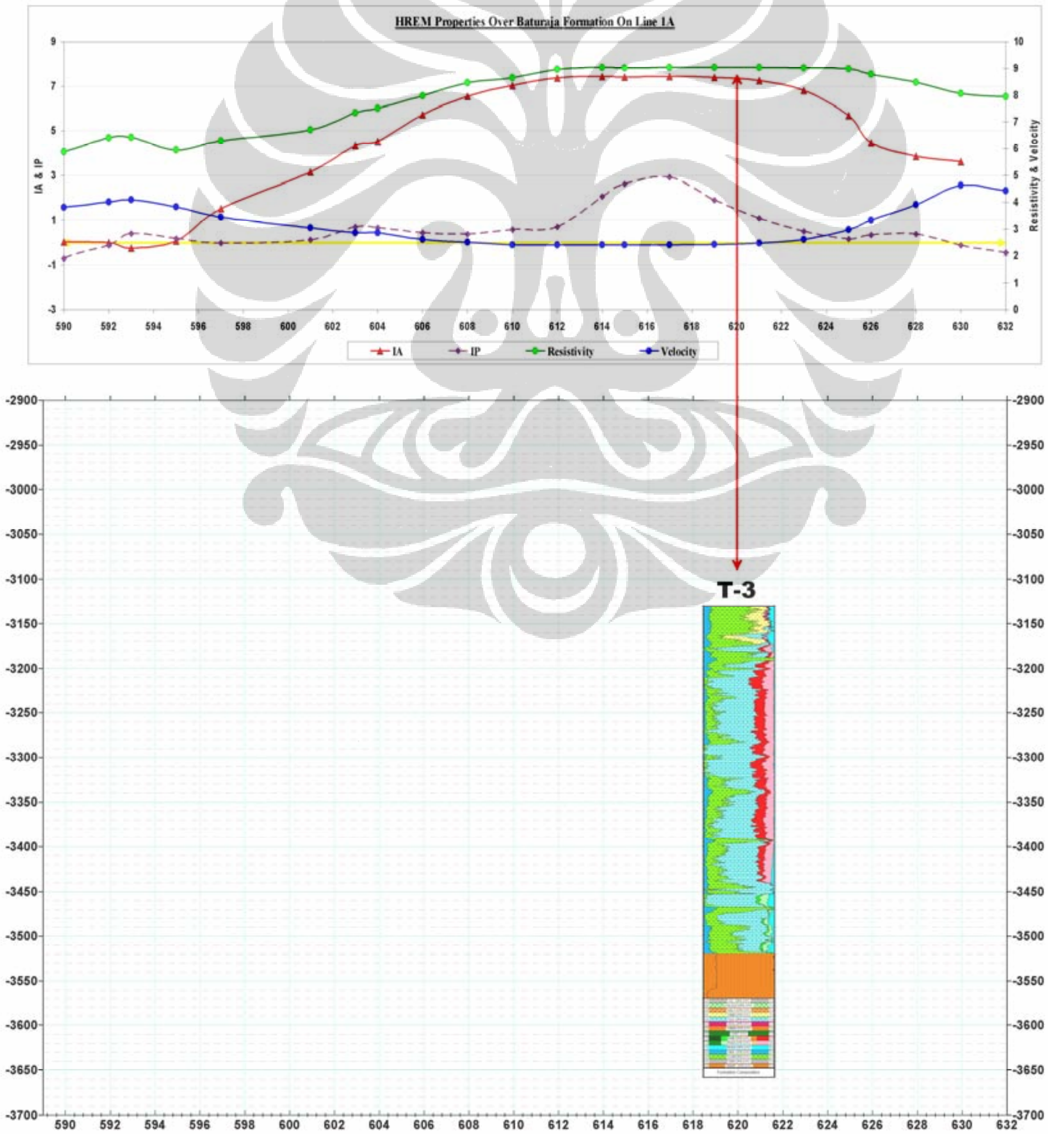


Figure 4.2. HREM and Well Data over Line 1A

Line 1-B HREM Results:

Examining this line on **Graphic-3**: the HR-EM data concentrates on shooting interval **"580 – 640 "**. South west of **'580"**, there is no data! But North-east of **"640"**, Induced Polarizations Anomalies are plotted and allow for an estimation of the fluid types. This Anomaly IP follows quite well the seismic top of the Baturaja formation.

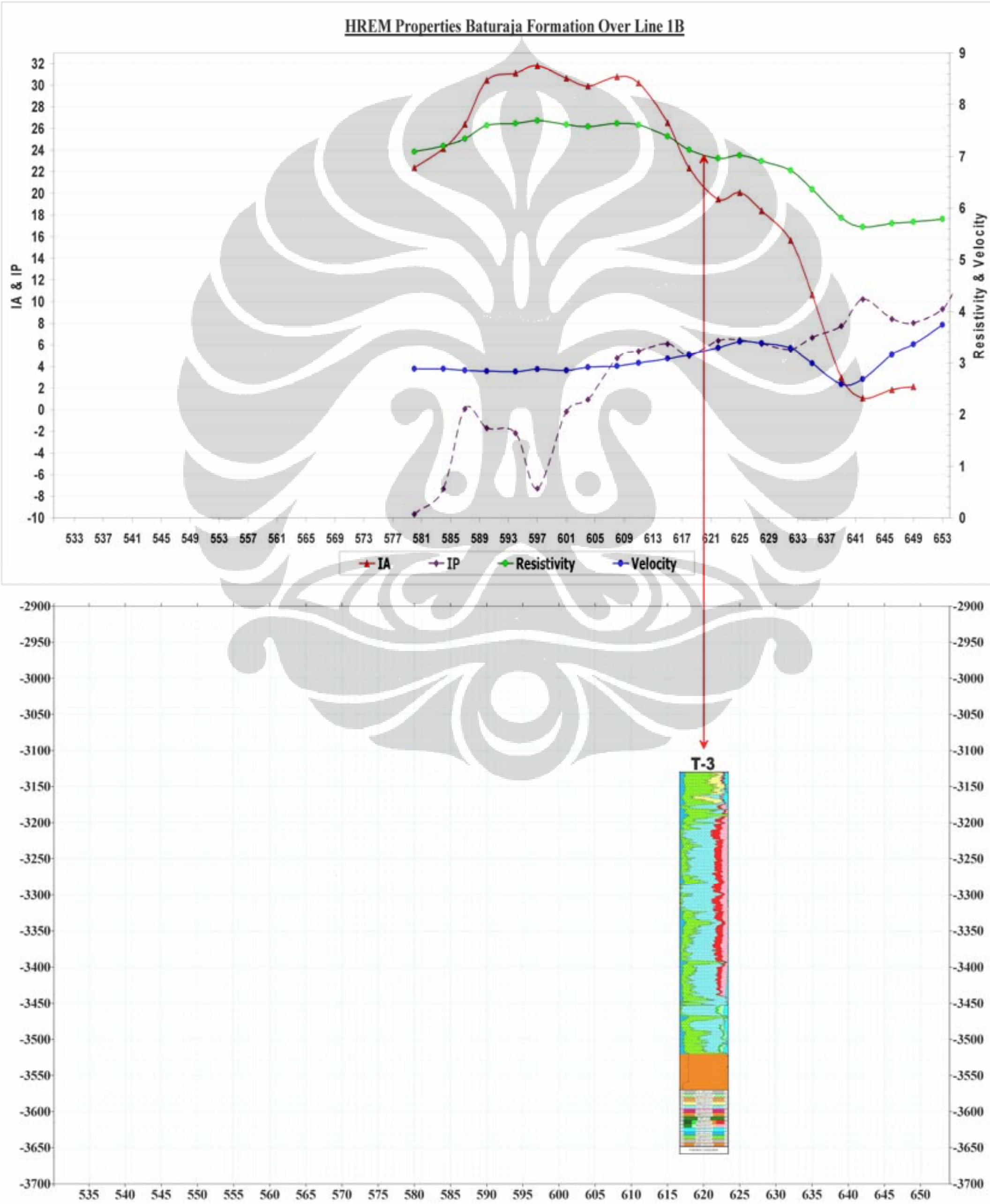


Figure 4.3. HREM and Well Data over Line 1B

Line 2 HREM Results:

This line is the most important line on this prospect, with complete HR-EM data from **“650 to 500”**, and Integrated Attribute data from **“700 to 650”**. This initial presentation of HR-EM results tends to say that hydrocarbons can be expected in the interval **“650 to 540”**.

This tends to cover the initial Qualitative HR-EM data acquired on this **Takara** structure of the Limestone formation. Actually, some attempts have been made with this previous survey to gain some Quantitative insight into the interpretation of the data. This was done by having Line 1-A extended to the **R-1** discovery well, South-West of **Takara**; and Line 2 extended South East through **J-2** well, also a producer. But we are going to do it better by following what this initial HR-EM survey is trying to telling us! By drilling **T-3** well this will be conventionally evaluated with wireline logs.

An initial **T -1** well had first been drilled and still showed hydrocarbons. A new **T -2** vertical well was then drilled, and turned out to be water bearing only, which is well detected by the HR-EM survey. So a successful **T -3** was drilled at the “Triple Point” of lines convergence. It showed massive gas deposit on the top and middle section of the Limestone.

A Petrolog Interpretation software program was run with all the wells drilled on **Takara** and showed through the gas zone and the oil zone, an average Porosity of around 28 / 29 % in the Limestone formation (At the top). And we will take an Sw value corresponding to Irreducible Saturation Water (always present), at around 8 %. When associated with oil, Sw is getting higher (35 to 40% range).

Getting those figures right, will allow for the design of a Template we had overlay on HR-EM results and delivering Porosity and Water Saturation good estimates.

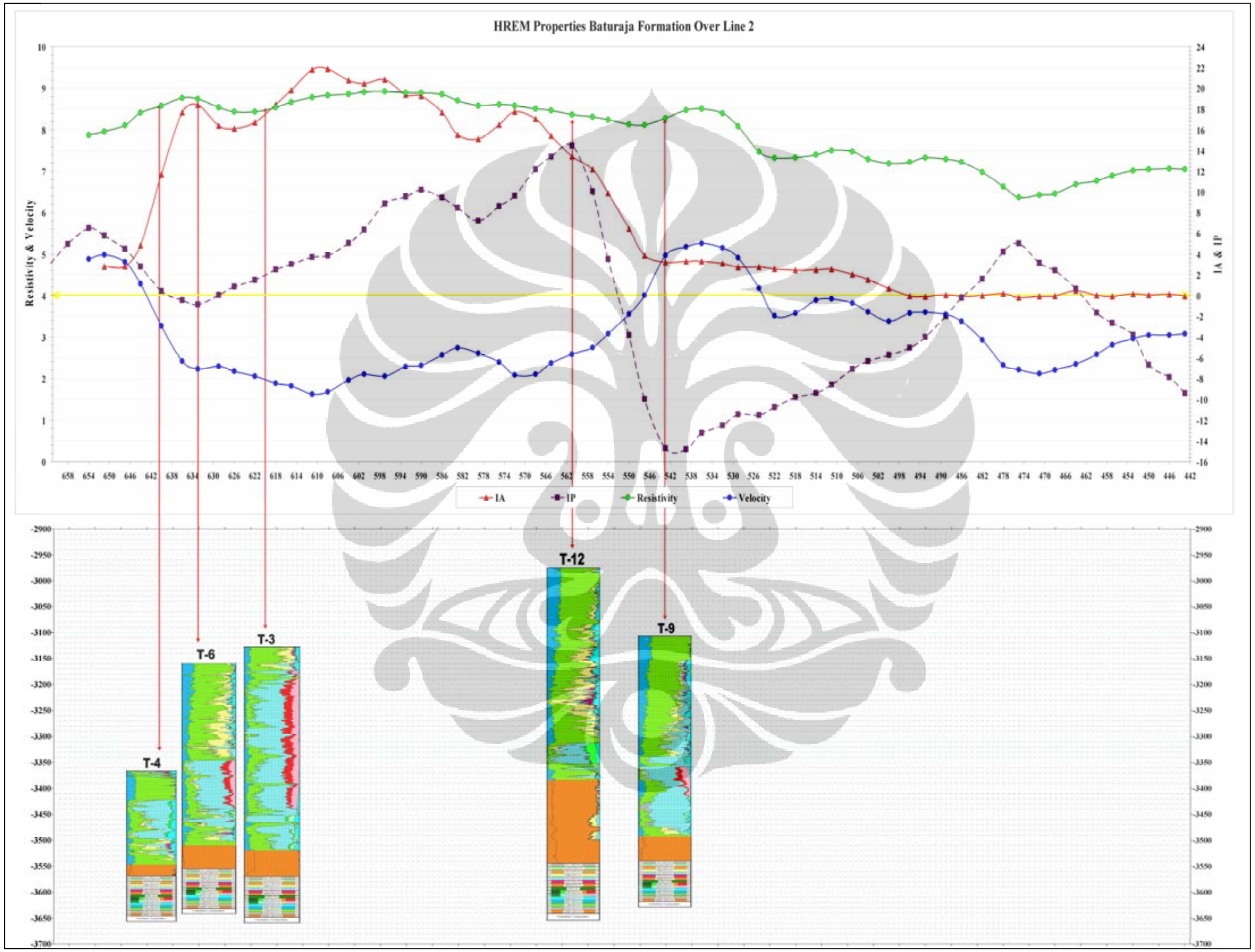


Figure 4.4. HREM and Well Data over Line 2

4.3.1. Correlation between HREM Interpretation results and Drilling Results of Well Takara (4 - 15).

The drilling and evaluation are continued after the drilling of the first 3 **Takara wells (# 1, # 2 & # 3),** here are the results:

Takara -1:

Initial discovery well (Vertical). The massive gas is deposit across the whole Baturaja.

Takara -2:

A Water bearing hole, the well shows water in the South-West area of the prospect. This will be confirmed with **Takara # 14**, a water bearing area.

Takara -3:

A massive Gas deposition is across the Baturaja formation; with a producible Oil reservoir across the Lower Platform, just above the Basement. This well data is being used to quantitatively "Calibrate" the HR-EM results.

Takara -4 :

A place with a very significant pinch-out of the Baturaja Limestone; a well classified as an " oil producer" but with a significant water cut which means that it may not take long before this oil production turns into water. This could have been predicted from the HR-EM survey, which does not produce all its results along the shooting locations: **"680 – 609"on Line-2**.

Takara -5:

A very similar story with this well being also classified as an oil producer with a non negligible water cut. Those two wells **# 4 & # 5** are showing striking similarities and both should have a similar history. No complete data at the North East of this **Line 1-A**, but a good indication (in Blue), of water deposition on the I.P.

Takara -6:

A promising GAS / OIL well producer as shown by the HR-EM results. This well located are **"630" Line-2**, clearly predicts its result from this HR-EM survey. Open-Hole logging data confirms prognoses HR-EM results.

Takara-7:

A well drilled around 708 m from Line 2. Officially classified as a producing well! But this is a high water cut as well executed from the wireline logs. Across on the south of structure, there is no HREM data. It would have been wiser to acquire HREM data along side a north to south line from **Takara -3** "Triple Point".

Takara -8:

Another repeat of **Takara -7** story! A well drilled away from HR-EM Lines and turning into water well!

Takara -8-SIDE TRACK:

An ultimate attempt at correcting a desperate situation! This well side-track was not going to find anything! This well is abandoned now.

Takara -9:

Back to proper procedures with this mostly Gas with Oil, drilled above HR-EM shooting point **"545"** and 59 m from **Line-2**. And this well is classified as a clean producer. This result was well correlated with HR-EM survey.

Takara -10:

A quite good Oil zone will produce well, just below a thinner Gas Zone at the top of the Baturaja formation. Similar location with **Takara-09** about the fluid content is classified as an oil producer.

Takara -11:

This well fits inside the sequence, and well by the HR-EM survey as an hydrocarbon bearer (Massif Gas deposit across the whole Baturaja).

Takara -12:

As well as on **line # 2**, well in between **Takara # 9 and # 11**: a massive gas deposit with a water pool below it, rendering this **Takara # 12** well, a gas producer.

Takara -13:

Limestone formation extremely contracted and saturated with Oil. The kind of missed by the HR-EM perhaps, it is because of its small thickness. Of around 10 meters in thickness, this “thin” bed formation at that place is well below the resolution of the HR-EM system of measurement.

Takara -14:

An external well drilled South of **Takara-02** (water well) showed the same fluid in place: WATER. We are located with this well where the Baturaja deepens and we are expecting water in that interval.

Takara -15:

No data available. Only the drilling / geological report that well is a WATER well, the position is on the North-West of the **Takara** structure.

This Complete our re-view of all the **Takara** wells data vs. HREM estimation. We can conclude that HR-EM technology gives very interesting & significant prognosis on the HC or water saturation. Now, we can do something better and more “Automatic” with this HREM data. We can explore around that very practical idea as follow below. The great advantage we have in this **Takara** field case is the amount of (good) data coming from the drilling of 16 holes so far, into that structure. Therefore, it is very tempting to try to establish some correlations between the Surface Seismic / HR-EM data, and the results of those wells evaluations obtained mostly from drilling and wireline logging data. The best way to start is by correlating what are the most desirable functions, first of all in terms of near proximity. So we will, first, look at each Line and correlate between the two sources of data (HR-EM & Logs). We have re-viewed this log data and found that those logs are of good quality and fully usable.

4.3.2. Common to the Three Lines:

<u>Takara -3 Well</u> :

It is my view that this discrepancy is also very much a function of the <u>Anisotropy</u> which is always the case in the ground, and then we started an HR-EM versus Log Data Tabulation, where the logs are giving an average Porosity (Φ), of 28%. And a Water Saturation (Sw) of around 8%., We are thinking that these measurements are of Good Quality and that the data contribution of this **Takara-3 well**, will be like a good "Pivot Point" for the rest of this Tabulation and Quantitative evaluation of the field. **Takara-03** is an excellent "Calibrator".

<u>Line 1-A</u>

In addition to **Takara-3**, there is **Takara-5**, whose the reservoir is falling at the vertical of that shooting line. According to the I.P, which is in purple, this well is not accordance with its testing status of Oil Producer. A good reason for that discrepancy is the middle range value of Sw; as well as the small size of the thickness of the reservoir (which is in the vicinity of 15 ft).

<u>Line 1-B</u>

Besides **Takara-3**, there are only 2 wells located reasonably close enough to this line: **Takara-2** and **Takara-14**; both wells are relatively quite excentered in **Takara** structure and is definitively water bearing. Unfortunately, there is no HR-EM data, only drilling and logging information.

Line - 2

This is Line with 11 wells whose reservoirs are reasonably falling closely enough to the line. On that Line – 2, we can find:

- **Takara-12** is mostly a Gas well (whose open whole logs data was mediocre!) Eventually this well is classified as an Oil Producer.
- **Takara-13, Takara-9, Takara-10, Takara-1**, which were all well picked up by the HR-EM as formations having some significant hydrocarbon saturation, and all being classified as OIL Producers.
- **Takara-11**, mostly gas well, with some oil below the limestone.
- **Takara-3** already mentioned. And T-6: an OIL Producer. And finally
- **Takara-4** : a 25 (thin) feet deposit , high on Sw and whose the resistivity was large enough to mask the hydrocarbon deposits) associated with it.

In order to draw the proposed template helping at transforming this HR-EM data into reservoir data, the tabulation HR-EM vs. Log data was fulfilled, and the template project starting.

Re-Cap of HR-EM data versus Wire-Line Logs data

Well	HREM				LOGS					Remarks
	Velocity	Resistivity	IA	Contrast IP	Lithology	Φ (%)	Sw (%)	Fluid Content	Well Production	
T-1	2371	8.47	15.43	Positive	Limestone	26	7	Gas	Gas	230 m orthogonal L-2 (565)
T-2	-	-	-	-	Limestone	25	100	Water	-	85 m orthogonal L-1B
T-3	2547	8.15	15.27	Positive	Limestone	28	8	Gas & Oil	Oil	0 m from triple line (620)
T-4	3270	8.58	11.69	Negative	Limestone	16	55	Oil & Water	Oil	5 m orthogonal L-2 (640)
T-5	2175	8.43	16.12	Negative	Limestone	13	35	Oil & Water	Oil	278 m orthogonal L-2 (626)
T-6	2233	8.74	18.41	Positive	Limestone	26	9	Oil & Gas	Oil	91 m orthogonal L-2 (633)
T-7	-	-	-	-	Limestone	21	55	Water & Oil	Oil	708 m orthogonal to L-2
T-8	-	-	-	-	Limestone	10	100	Water	-	459 m orthogonal to L-2
T-8ST	-	-	-	-	Limestone	15	100	Water	-	397 m orthogonal to L-2
T-9	4968	8.28	3.19	Positive	Limestone	30	10	Oil & Gas	Oil	59 m orthogonal L-2 (543)
T-10	3554	8.13	6.45	Positive	Limestone	22	16	Oil & Gas	Oil	256 m orthogonal L-2 (550)
T-11	1962	8.86	20.76	Positive	Conglo.	24	10	Oil & Gas	Gas & Oil	160 m orthogonal L-2 (604)
T-12	2583	8.36	13.46	Positive	Limestone	24	10	Oil & Gas	Oil	44 m orthogonal to L-2 (561)
T-13	5143	8.40	3.06	Negative	Limestone	29	18	Oil	Oil	247 m orthogonal to L-2 (532)
T-14	-	-	-	no data	Limestone	15	100	Water	-	187 m orthogonal L-1B
T-15	-	-	-	-			100	Water	-	361 m orthogonal L-2

Table 4.2. HREM Data vs. Wire-Line Data

4.4. Lateral Analysis Velocity vs. Resistivity from HREM Parameter

The interval velocity from seismic data can identify what kind of formation it is. On these cross plot below, it can support our analysis interpretation not only using velocity but we use the resistiviy also, as we seen on these cross plot. The interpretation using resistivy vs. velocity vs. IA are better identified the lithology, even saturation in water as qualitative methods.

4.4.1. Cross – Plot Integrated Attribute from HREM Data: Velocity versus Resistivity For Micritics Formation.

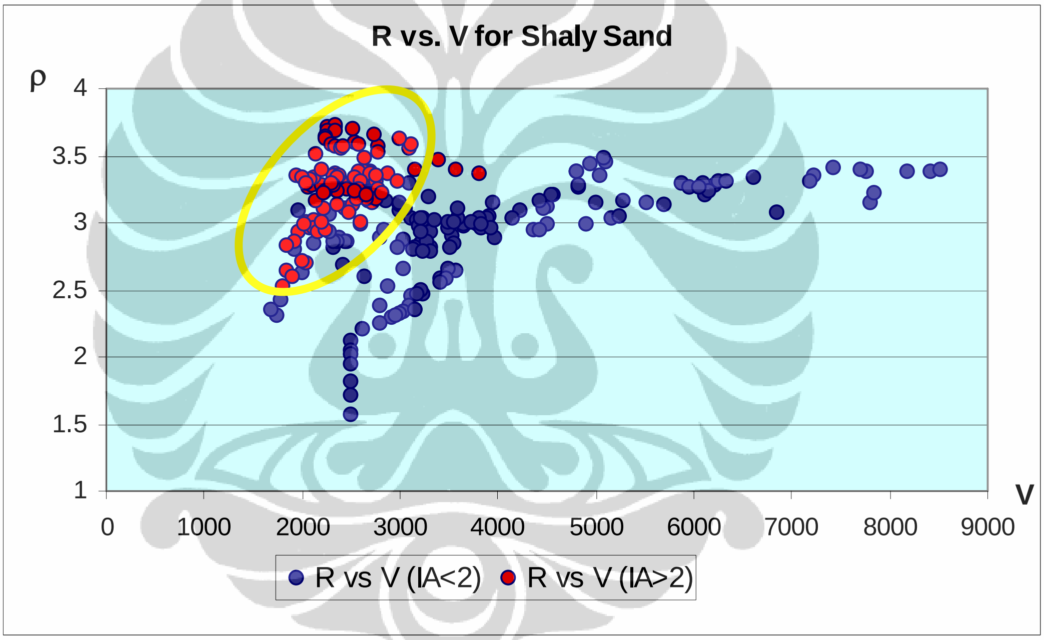


Figure 4.5. Cross plot Velocity vs. Resistivity vs. IA for Shaly sand formation

As we know the velocity of lithology has variety. For example; on Shale Sand formation on the cross plot above is identified the character between those three parameter. The separation between IA>2 and IA<2 is quiet tight. This curve was identified a shale sand formation. Resistivity the crossplot shale sand is supporting us to know what is content of the lithology is, as qualitative review.

4.4.2. Cross – Plot Integrated Attribute from HREM Data: Velocity versus Resistivity For Baturaja Formation.

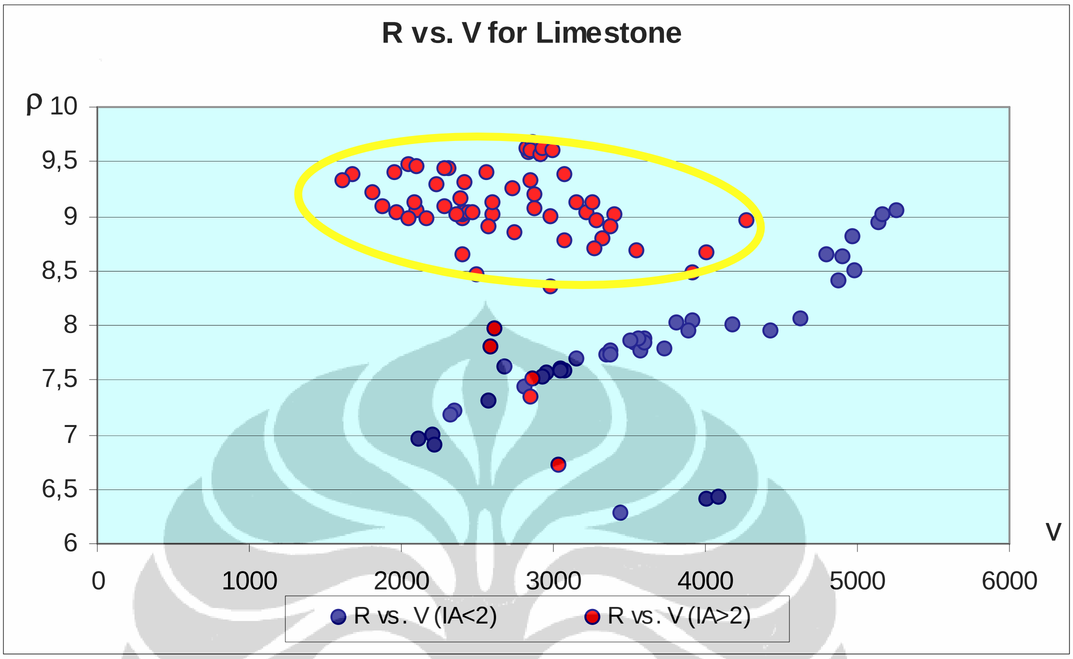


Figure .4.6. Cross plot Velocity vs. Resistivity vs. IA for limestone formation

The variety of velocity of rock on seismic section can identify lithology. Above the crossplot of limestone formation were interpreted by HREM. Red point has low velocity and high resistivity. Blue point which is IA<2, identified by high velocity and low resistivity, it was identified as un-producing zone.

Between shallysand formation and Limestone formation the characteristic both cross plot are so interesting, for example the separation between red point and blue point.

On the case of **Takara** field Musi platform, this cross plot is very valuable when we are compare with actual data of well after HREM survey. Which is the result of shallysand formation which has oil show but is not much compared to Limestone formation.

4.5. The making of Template

The idea is to transform HR-EM data (I.A. By Ex & Hz, Velocity & Resistivity curves) into porosities and saturation to which we are more accustomed and is very directly related to the reservoir characteristics, of interest for us.

To do this, and be as complete as possible, we imagined ways to use all the curves made available to us from the HR-EM data, associating each point of them a reservoir parameter of interest (Fluid type, Porosity & Water Saturation).

To our best knowledge and integrity, we are not aware that those templates have been used, or even be made in the past. Therefore, in our opinion, it is a novelty, which will need to be further developed and improved. But the idea is placed here in orbit!

Over the next pages, we will go through each of the 4 templates leading to its results. In order to have our templates "calibrated". We will make good usage of the **Takara – 3** well log results.

And we will verify the results with some of the wells data.

4.5.1. Template # 1

Qualitative Fluid Identification From HREM Data (Induced Polarization"IP")

This Template is a very coarse investigation of the fluids likely in place; whether it is water or hydro-carbons, and the Anomaly. "INDUCED POLARISATION", a very rough way to derive valid information's on the fluids present into the sub-surface. So, we will have to be very careful at handling this data, knowing well that it lacks accuracy and, at best, be used only for qualitative purposes, only.

The advantage of this data is that it covers the entire length of the shot-line, and it allows filling the voids between the zones of more intense interests.

Basically, it is just a matter of traveling along the Client data with this Template # 1, for what is departing (above and / or below) this base line, violet on the curve, should be considered with interest, the bigger, the largest deflections especially. A bit with some analogy with the wireline logging measurement called Spontaneous Potential, we shall be looking for a base line, probably corresponding to impermeable shale, and look at the deflections which may occur "above" or "below" this "base line". IP, may reflect upon permeable zones holding a different fluid; and for that matter, this IP data could be considered like a "Fluid Indicator" which needs further investigation and draw attention. On chapter III were explained how we make justify for our interpretation from IP data

So, this very coarse but widely available measurement must be taken with extreme caution and relied upon only in last resort. Its advantage is that it is delivered continuously by the survey.

This template and method shall be used as Qualitative indicator only..

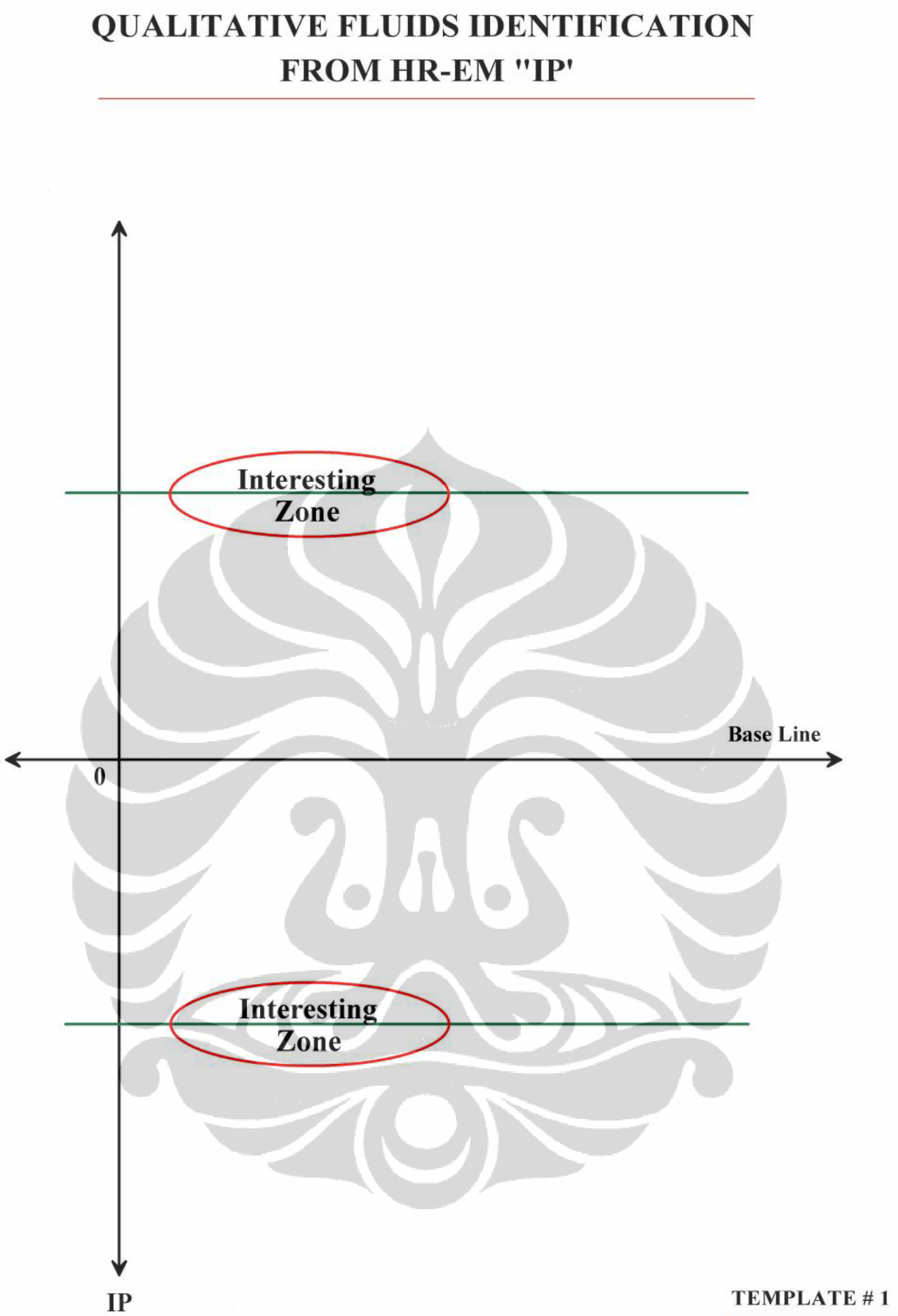


Figure 4.7. Template HREM Induced Polarization

This is one of the steps to analysis the data, we can say this is first steps. And we can go to the next step, to look at the other EM parameter such as Resistivity, Velocity and IA raw data by interesting horizon from seismic data.

4.5.2. Template # 2

Producing Zones From HR-EM I.A. (Hz & Ex)

This approach to the interpretation of the HR-EM data, specifically the INTEGRATED ATTRIBUTES by Hz & Ex data, will, conservatively be taken as another qualitative measurement, also. On the data results sheet, those two curves (IA by Hz and IA by Ex), are showing a lot of characters and very significant deflections which want to tell us something about the formations characteristics. But, although the EM jobs have been conducted for a long time already, a lot of aspects of this technology are still in their infancy; and the data needs to be taken very cautiously and carefully.

It is again, to 'fit' the Template # 2 with the base line (here at "2"). Alike Template # 1, besides the 'positive' deflections which seem prevalent, we should also be attentive to 'negative' deflections, below the base line. Base line for IA on Takara area is approximately 2 units.

A Template # 2 has been drawn with the above ideas in mind.

So, it will just be fine for us, (for the time being), to travel along the base line and pay attention to the largest deflections departing from this base line. A "Confidence Factor" read on the Template, will be the result of what can be expected from these "Integrated Attribute" data.

Once more, it is worthwhile mentioning that we are expecting Qualitative results (at the best) , only.

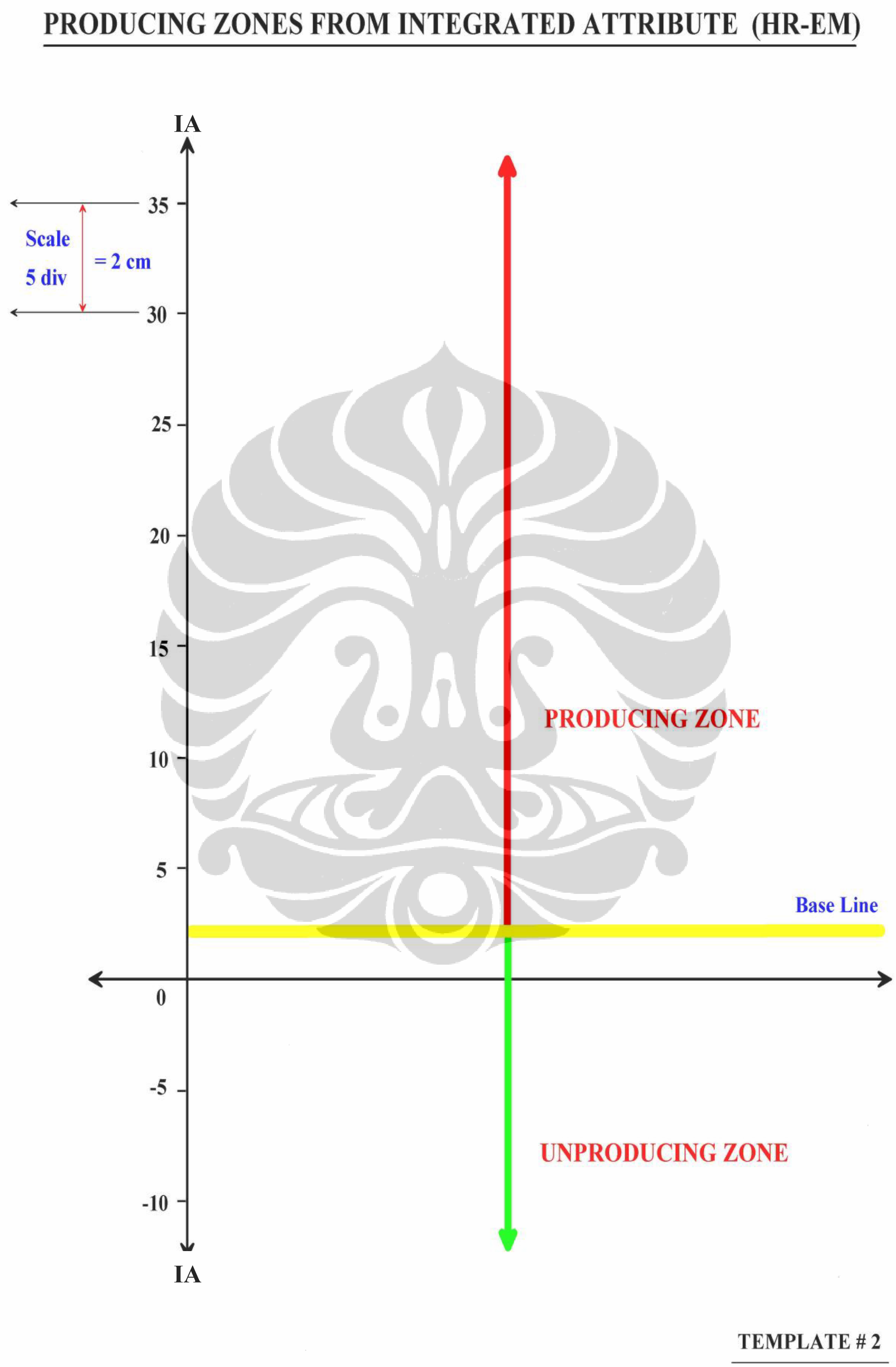


Figure 4.8. Template HREM Integrated Attribute

4.5.3. Template # 3

Porosity (Φ) From HR-EM Velocity

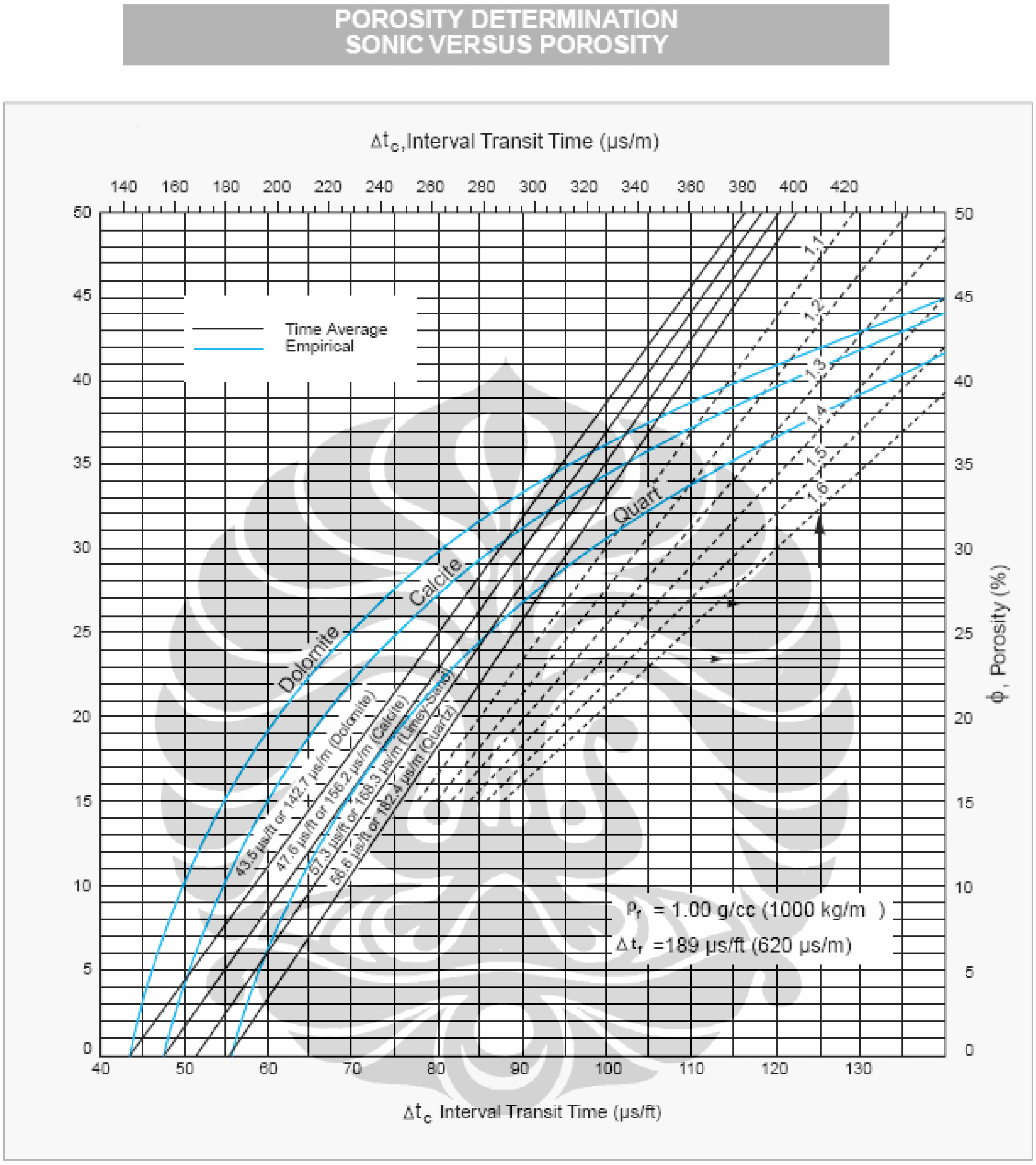
4th Template which can provide an estimation of Porosity (Φ) is what we keep to get the complete the trilogy (Sw / Φ / Thickness) and build a bridge between HR-EM Raw data and Real Reservoir characteristics. This is what we try to achieve when associating HR-EM Velocity data with a sort of "Sonic" Porosity with some guide-lines concerning Quantitative results.

Prior to using this Porosity Template, a scaling arrangement needs to be done to adjust 1 Velocity division to be 1 centimeter, in length.

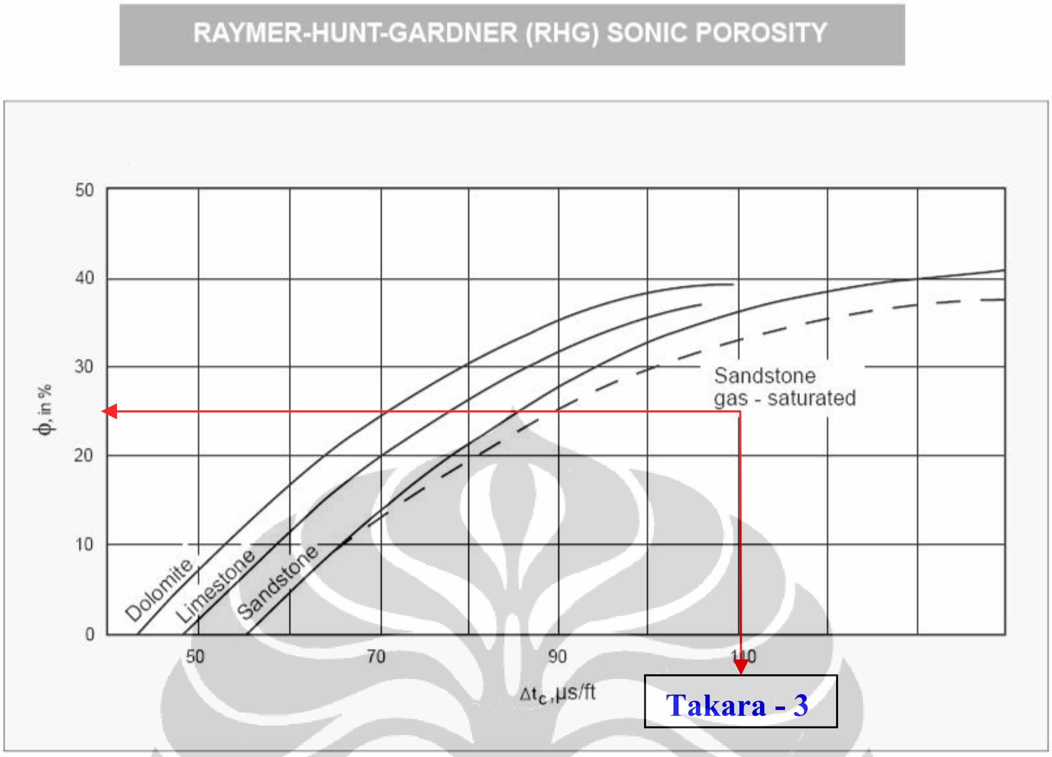
Then, utilizing the results of Takara – 3 where , through the Limestone formation, an 8 division amplitude corresponds to a porosity of around 30%, taking as a model a sort of "Time Average" scaling which is linear), we drew the attached Template.

As for the 3rd Sw Template, what is the minimum requirement to do that is the Velocity HR-EM data, Plus a reference well on that line.

With this method of measurement with HR-EM data, plus the adjunction of a drilled reference well quite representative of the structure, a quantitative and satisfactory evaluation of the reservoir characteristics (Sw, Φ and of course thickness) can be conducted.



Grafik 4.1. Porosity Measurement Interval transit time



Grafik 4.2. Porosity Measurement from Raymer-Hunt-Gardner (RHG) Sonic Porosity

Define porosity from Velocity using takara -3 for calibration well:

$$\Delta t_{(Takara-3\ from seismic)} = \frac{10^6}{(2{,}547 * 10^3) * 3{,}28} = 119{,}7\ \mu s / ft$$

- Limestone formation with $\Delta t_{matrix} = 47{,}5\ \mu s / ft$
- If we assume the formation is water and $\Delta t_{water} = 218\ \mu s / ft$

$$\phi = \frac{119.7 - 47{,}5}{218 - 47{,}5} = 0{,}42 * 100 = 42\%\ P.U$$

We want to get the closer Δt_{fluida}, Porosity around Musi Flatform

20% P.U. $\Delta t_{fluida} = \frac{119.7 - 47{,}5}{0{,}2} + 47{,}5 = 350\ \mu s / ft$

(Using estimate Δt_{fluida} = 350 and it is gas. It will be applied for those 3 lines. Also it was closer with the actual well T-03 result)

❖ $\phi = \frac{119.7 - 47{,}5}{350 - 47{,}5} = 0{,}24 * 100 = 24\%\ P.U$

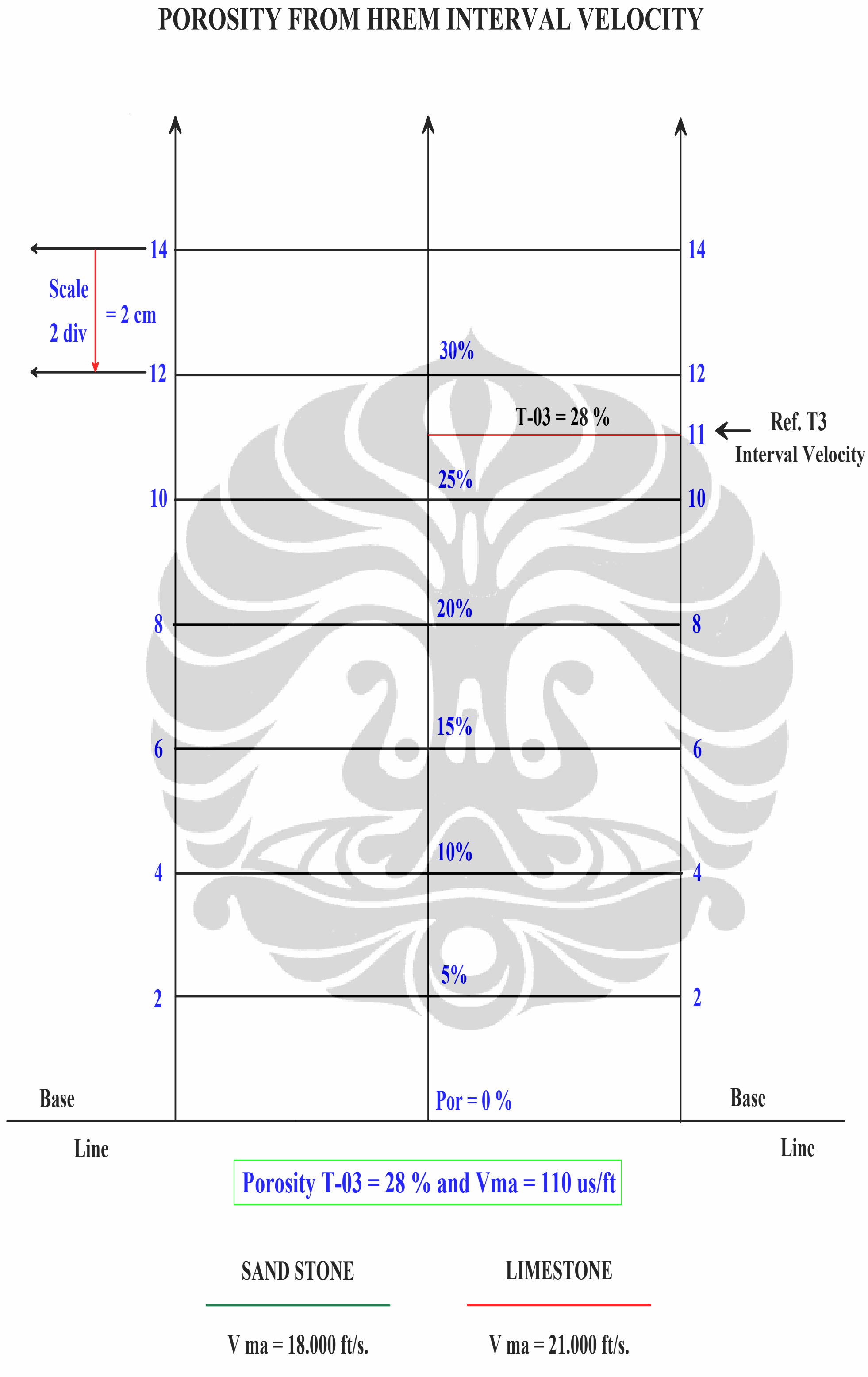


Figure 4.9. Template HREM Resistivity and IA to define Saturation Water

4.5.4. Template # 4

Water Saturation (w) From HR-EM Resistivity

This 3rd Template is a more sophisticated one and can be placed already into the Quantitative category. It addresses an evaluation of the Water Saturation (Sw) of the formations; and therefore is a very crucial step forward in the translation of HR-EM data, a very "physical" phenomenon.

This Template for Sw evaluation is derived from the so-called "Resistivity" data from the HR-EM results.

The usage of this Template is quite straightforward. After adjusting the scaling for compatibility (2 divisions corresponding to 2 centimeters), this particular template, drawn for the Takara field and using Takara-3 data as reference (Top Limestone: showing on the logs, used as Resistivity HR-EM calibrators) we measured an 8% Water Saturation corresponding to an HR-EM Resistivity deflection of 8 large divisions. This Reference Values allowed for a calibration allowing for the transition between raw HR-EM values and Water Saturation (Sw) of real description of the reservoir.

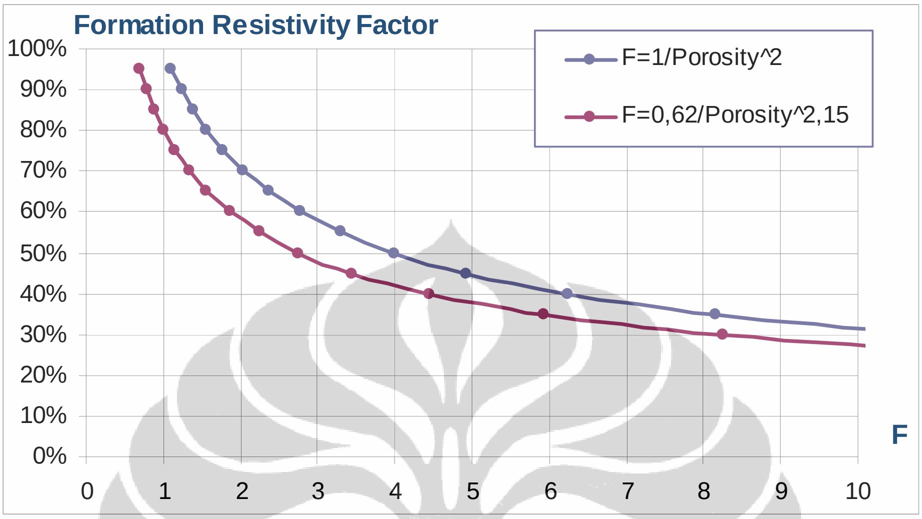
We have improved the scaling of this Template in two ways:

1- By remembering that water saturation, Sw, varies like the inverse square root of the resistivities. Hence this non-linear scaling of Sw which is due to that phenomenon. And,

2- By differentiating between matrices (Sandstone and Limestone) which have a slightly difference response due to a different Formation Factor value (F).

To produce such an Sw-Template, the HR-EM "Resistivity" data and one logged well, quite representative of the structure, must be available if we want to have a minimum of accuracy. This is most of the time, the case in our areas of South-Sumatra.

In case this is not available, a Template from a neighboring field can be used instead. It will result in a more approximated data. For these steps I am trying to get porosity from resistivity.



Grafik 4.3. Formation resistivity factor

Grafik 4.1. were shows relationship between Resistivity vs. Porosity, I take several point from well data. For example Takara-03 with R=8 and Por=28% shows by red lines.

As we know from Archie Formula, to defind Saturation water from resistivity.

$$S_w = \sqrt{\frac{F\ R_w}{R_t}}$$

Resistivity, of course, depends on oil & water saturation. And it depends on lythology and porosity much too. If we try to find relations Sw vs. R we need to see relations between R and porosity (and lythology) too. That is why we calculate IA. IA calculation algorithm uses resistivity and velocity. We use velocity to exclude lythology part from resistivity. So it's better to make template Sw by IA. However it will be more Qualitative than Quantitative.

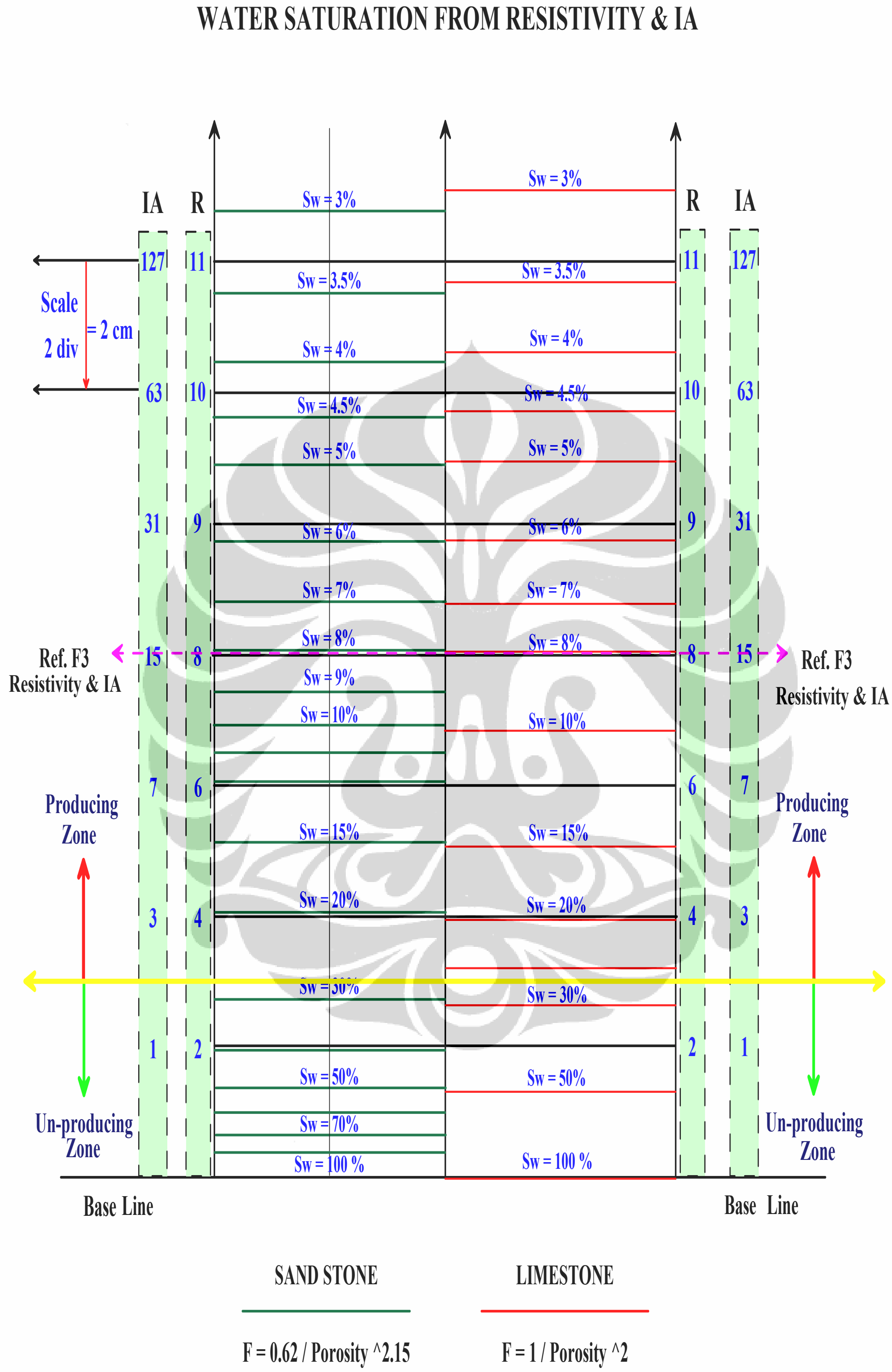


Figure 4.10. Template HREM Resistivity and IA to defined Saturation Water

CHAPER 5
CONCLUSION & RECOMMENDATIONS

Methodology of hydrocarbon exploration is based on identifying oil and gas deposits by using their relationship to the physical structure such as anticlines and faults. This is a new exploration method, which integrates lateral variation of the elastic properties and the electrical properties from electromagnetic field surrounding deposits of insulating materials (hydrocarbon) and conducting materials (brine water). The advantage of such surveys is not only in discovering hydrocarbon deposits at a depth but also eliminating empty reservoirs from drilling consideration. The correlation between the electrical properties and the elastic properties of reservoir rock in Takara field can increase the confident level of our interpretation. Zone of Takara prospect confirmed by seismic 3D is around $13\,Km^2$, however after HREM survey the interpretation about $8\,Km^2$. There are 15 wells were drilled after HREM survey, and there are 5 wells were drilled very close to HREM line. The analyses from several wells, which have been drilled after HREM survey supports for continuation to make better interpretation using template. By using these templates we can make efficiency and facilitate the interpretation for next well. This ideas are very interesting and powerfull.

However, at least there are two problems:

- For this time being HREM doesn't detect reservoir characteristic exactly, like well logging in obtaining *Saturation Water* or electrical resistivity.
- We have too few wells data in this field. So it is not enough for good statistic to determined *Saturation Water*. More data that we have as long as this field developed and those templates will develop too. This is probably a never ended task to be completed.

We suggest for the next step are:

- Delineation well on high contrast of integrated attributes to reduce dry hole possibility.
- Additional line for EM survey across a new dry hole or a new discovery well on that prospect to correlate with existing data.

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