Analysis of Electromagnetic Depth Sounding Responses over a Layered Earth: Investigating Oil & Gas Seeps in the Petroleum Provinces

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SUMMARY

The present work embodies the results of theoretical and practical investigations of electromagnetic depth sounding using central frequency sounding (CFS) system over a layered earth. Failure of conventional electrical resistivity sounding in the study of geological conditions under resistive overburden calls for variable frequency sounding techniques. Electromagnetic depth sounding which involves the measurement of variation in conductivity with depth is used for solving various geoengineering, hydrogeological and shallow cases of oil & gas seeps associated with stratified earth. The CFS, which is one of the depth sounding techniques involving the measurement of vertical component of magnetic field induced at the centre of a circular or square loop, is considered in the present study for obtaining theoretical responses over a layered earth and its interpretation with shallow oil and gas seeps.

Because of some limitations of contour integration and numerical integration approaches, used earlier, a more rapid digital linear filter technique is adopted for evaluation of the integral involved in the CFS theoretical expressions. Theoretical expressions for frequency-domain soundings written for layered earth models are suitably transformed for evaluation through digital linear filter. Dimensionless normalized vertical magnetic field is computed for different frequencies and loop radii for layered earth models with different layer conductivities and thicknesses. The responses computed for these cases are analysed in terms of resolution characteristics and detectability effects. In frequency-domain sounding, amplitude response curves of layer-sequences show the effect of layer conductivity, layer thickness and loop radius. Separation between individual curves on the sets for amplitude responses normally gives sufficient indications for subsurface conductivity variations of the layered earth cases. The author explores the CFS applicability and feasibility in investigating shallow oil & gas seeps in oil & gas provinces, in particular on the flanks of the rifted grabens and basin margin areas, where sediment – basement contact areas are interpreted.

Key Words: Central Frequency Sounding, Electromagnetic Depth Sounding, Layered Earth, Linear Digital Filter, Oil & Gas Seeps

INTRODUCTION

Central frequency sounding (CFS), which is one of the depth sounding techniques involving the measurement of vertical component of magnetic field induced at the centre of a circular or square loop, is considered in the present study for obtaining theoretical responses over a multi-layer earth. Here, use is made of Maxwell's equations for deriving suitable expressions in terms of conductivity of the ground. Expressions are written in computable form and evaluated to obtain responses. The geo-electric exploration methods generally utilize stationary and variable currents generated artificially or by natural means. The use of stationary currents in geo-electric methods has certain limitations (Shastri and Patra, 1983a and Shastri and Patra, 1983b) subject to various geological situations encountered. With direct current, a wide range of conductivity pattern existing in nature cannot be differentiated from minor geological variations. Direct current method cannot classify the electrical anomaly beyond a certain range of conductivity and it may not be possible to distinguish between an average and a good conductor due to what is known as saturation effect. This difficulty is overcome at least partially by applying an alternating current. Variable current method is preferable in most of the situations particularly for the case where top layer is resistive. This is also preferred for convenience in operation. The possibility of independent field observations, e.g., measurement of amplitude with frequency and the complete absence of contact polarization are the additional advantages of variable current methods (Nimmagadda and Patra, 1988). Of the two field procedures available, namely profiling and sounding, the latter is meant for solving horizontally stratified earth problems (Nimmagadda, 2015), measuring the variation of apparent resistivity or conductivity with depth at a given point under consideration.

In the surface induction method of prospecting, the primary field is established in practice by passing an alternating current through a linear cable, a small coil (or dipole) or a large loop. The receiver generally consists of one or more coils suitably arranged and connected to a measuring instrument. To perform the electromagnetic sounding, a circular loop carrying alternating current is used for generating the primary field at various frequencies, such that measurements are taken by the receiver coil keeping the transmitter and receiver spacing fixed. The method of inducing the ground at various frequencies is called frequency sounding, provided the distance between two coils is kept constant. Electromagnetic sounding is carried out by varying the distance between the transmitter and receiver coils at a fixed frequency.

With regard to the investigation of oil and gas seeps and evaluating the petroleum systems' existence, the author explores new opportunities of electromagnetic depth sounding in both proven and unproven petroleum provinces. The Cambay basin in Western India and Albertine Graben in Western Uganda, are both rifted basins of Tertiary age, where many sediments experience microseepage. Surface micro-seepages are typical shallow geochemical expressions (Shi et al. 2010) of deep seated hydrocarbon accumulations. Although many outstanding questions (Nimmagadda et al. 2007) exist concerning the vertical transport of natural gases to the surface and issues associated with secondary effects in certain instances, it is possible to recognise the hydrocarbons (thermo-generic gases) seeps at the surface that have been generated at depth, using various geophysical properties and their contrasts. Much of the recent success in hydrocarbon surface exploration is related to the phenomenon of hydrocarbon sorption on mineral and organic particles, which avoids the problems of mixing and the surficial bacterial production and oxidation of hydrocarbons. The CFS appears to be detecting sediment alterations, due to near surface oil and gas anomalies within the vicinity of petroleum provinces.

METHODOLOGIES

Multi-frequency Sounding

While single frequency measurements give an opportunity to have a qualitative interpretation of the anomaly, multi-frequency measurements, in general, lead to a quantitative interpretation in terms of layer parameters. The geometric sounding may, however, be carried out at a fixed frequency by changing transmitter-receiver separation giving a quantitative approach. The parametric sounding carried out with reference to frequency gives better information on the distribution of subsurface electrical parameters through measurement of induced electromagnetic field with receivers located on the surface. Frequencies in the range 20 Hz-20k Hz are most commonly used for electromagnetic sounding to depths as great as 500m with artificially generated fields (active system). In natural field methods (passive system) frequencies in the range 10^3 Hz – 10^{-5} Hz are available, permitting crustal and upper mantle sounding to depths as great as 300km. In order to generate artificial electromagnetic fields on the surface of the earth, various sources particularly linear cable, dipole sources and loop sources are widely used. In the linear cable method, the primary field is produced by passing an alternating current through an insulated long cable grounded at both ends. The profiles are laid perpendicular to the direction of the cable and the field response is measured at some distance from the cable. The ground is energized by induction where the conduction current is assumed negligible. An undergrounded large rectangular loop is employed in order to get rid of the effect of grounded electrodes and the field is measured outside the longer side of the loop.

The electromagnetic dipole method of prospecting uses a transmitter coil and a receiver coil respectively for generation of the primary field and for measuring the total or secondary field. There are four ways of conducting multi-frequency sounding depending upon the orientation of transmitter and receiver loops which are most suitable for depth sounding exploration (Verma, 1980). In the loop method of prospecting, the primary field is generated by passing an alternating current through a large ungrounded circular, square or rectangular loop placed on the ground surface. In such a case, a field is uniform and normal to the plane of the loop in the central region and magnetic field measurements are carried out in the central region of the loop or outside the loop. Frequency in the harmonic fields and period in the transient measurements play dominant roles in the electromagnetic sounding exploration. The skin depth, controlled by frequency and conductivity of the subsurface gives an idea of the depth of penetration of the wave. Frequencies are so chosen that the desired depth of penetration is achieved. The induced currents produced in dry ground are not high enough to conceal the effects of deeper in-homogeneities. The distance between the source and receiver is usually a small fraction of the free space wavelength in the regions in which the observations are made and radiation and phase retardation are negligible, so to say, the effects of propagation are totally disregarded. Thus the application of electromagnetic induction is considered with effects in the quasi-static zone.

Application of Electromagnetic Depth Sounding

In the recent past, electromagnetic depth sounding, which is based on the measurement of the variation of conductivity with depth at a variety of frequencies, has become an important tool for petroleum and groundwater prospecting and exploration. Due to lack of equipment capable of required accuracy of measurements over a continuous frequency spectrum and the lack of theoretically computed master curves, the development of electromagnetic depth sounding has been held back. The electromagnetic depth sounding can be carried out by varying either the frequency or the spacing between the transmitter and receiver to change the effective depth of penetration leading to parametric or geometric sounding. Parametric (frequency) sounding is preferable and more convenient from the operational point of view compared to geometric sounding as it is quite cumbersome to change the spacing between the transmitter and receiver. This situation also avoids the effects of lateral resistivity changes in the sounding measurements. In fact, there is an optimum coil separation or loop radius providing the greatest sensitivity in reflecting the boundaries at given depths. It may be necessary to make variable frequency measurements with several transmitter-receiver coil spacing, so that the presence of each successive boundary may be emphasized at suitable coil spacing. As an example, if the transmitter and receiver are brought near a more conductive zone, stronger eddy currents may be caused to circulate within it and thereby a significant secondary magnetic field is created. Close to the conductor, secondary or anomalous field may be comparable in magnitude with the primary field or normal field in which case it can be very easily be detected by the receiver. In practice, the distance between the source and receiver is usually a few hundred and seldom more than a thousand of meters.

The great advantage of electromagnetic depth sounding is to apply it in arid tracts or in the Polar Regions. Another advantage of frequency sounding is that in groundwater investigations, a change in depth of penetration (Patra and Shastri, 1991a) of the current by changing the frequency is far more convenient than displacing the transmitter and or receiver. Electromagnetic depth sounding is a possible approach for solving the problems associated with stratified earth at a comparatively low cost against equally preferred seismic methods. One of the troublesome effects with electromagnetic sounding is that the secondary currents in superficial layers of good conductivity e.g., clays, graphite, shales etc. may screen the deeper conductors partially or totally from the primary field which are real objects of exploration. This produces weak or no distortion in the primary field and the object may remain undetected.

Articulation of Central Frequency Sounding

An insulated circular loop (Patra and Shastri, 1988, Patra and Shastri, 1991a and Patra et al. 1995) carrying an alternating current is placed on the ground (used as a transmitter coil) and the vertical component of the secondary magnetic field induced at the centre of the loop is measured by another small coil (receiver) placed concentrically to the transmitter coil. This is the modified form of central induction method or central ring induction method referred to as "central frequency sounding" which is essentially one of the inductive methods of prospecting using a loop. The configuration of CFS system over a non-magnetic earth is shown in Figure 1. Measurements are made on the surface of the earth by exciting the ground with an alternating current source at different frequencies and by varying loop radius, if necessary. Digital linear filter method is used for computing CFS type curves and matching with multi-layer-earth geological situations. Several mathematical equations in frequency- and time – domain (Koefoed et al. 1972, Shastri and Patra, 1983a and Nimmagadda, 2015) are written to compute responses due to multi-layer earth. The normalized vertical magnetic field, represented as the ratio of the vertical component of the magnetic field to the direct current normal field at the centre of the loop in air, is expressed theoretically in terms of the layer parameters and the loop radius. Theoretical and laboratory based layered earth models are simulated for analysing two-, three- and multi-layered earth situations and their responses (Patra and Shastri, 1999 and Patra and Shastri, 1991b).

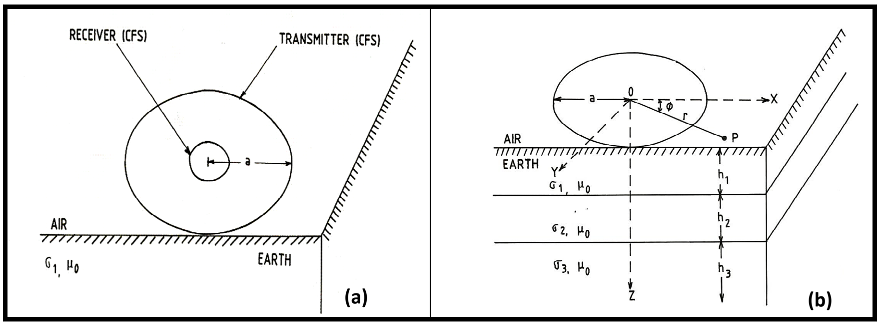

Figure 1: Representation of a circular loop and layered earth models simulated for analysis (Nimmagadda et al. 2007)

The basic equation for the normal field of CFS system is used for normalization of field expressions. The next step is to express and evaluate the magnetic fields for the layered earth sections. For this purpose, use of the following basic equation is made to obtain the vertical component of the magnetic field of a horizontal circular loop of radius "a" placed on the surface of a layered earth. The normalized magnetic field (or magnetic number) can be expressed as

$$H_z = H_z / H_o = a^2 \int_0^{\infty} [1 + f(m)]\, m\, J1\,(ma)\, dm \qquad (1)$$

This is the basic equation for the normalized vertical magnetic field, when a circular loop source is placed on the surface of a horizontally stratified earth. The components of the electromagnetic vector potential in the horizontal plane are zero, and the radiation terms in Maxwell's equation is neglected. The kernel function f (m) can be computed from the subsurface layer parameters and the frequency of primary excitation using a recurrence relation setting

$$f(m) = f_{o,n}(m) \qquad (2)$$

In equation 1, the first suffix represents the consideration of the field in space above the ground surface, and the second suffix n is the number of subsurface layers. The recurrence relation is expressed (following the notations used by Koefoed et al. (1972), Sanyal, (1975) and Verma (1977) as follows :

$$f_{(j-1),n}(m) = (M_{(j-1),j} + f_{j,n}(m)\, e^{-2hjmj}) / (1 + (M_{(j-1),j} + f_{j,n}(m)\, e^{-2hjmj})) \qquad (3)$$

and $f_{n,n}(m) = 0$

where $m_j = \sqrt{m^2 + k^2}$; $k_j^2 = i\, 2\pi\mu_o\sigma_j f$; $M_{j,1} = (m_j - m_1)/(m_j + m_1)$

These are the generalized formulations used to compute the kernel functions for any number of subsurface layer situations. Use is made of this formulation to derive a digital filter with the procedure given in (Patra and Shastri, 1988). The linear filter method (Ghosh, 1970) has been applied to resistivity sounding problems. Fourier transform is a powerful tool to solve the problems associated with geo-electric fields by transferring a function from its function domain to the frequency-domain. The digital filter derived, the sampling interval chosen in the reconstruction of original function from its sampled values and the optimum length of the filter for CFS system are made use of in the computation of responses for different layered earth models. By making use of digital linear filter, the theoretical expressions for frequency-domain sounding are written in computable forms as given in (Nimmagadda, 2015).

Frequency-domain sounding

Measurements made by the CFS system with a variety of frequencies form the basis of frequency-domain CFS. Frequency plays an important role indirectly with the kernel function f (m) in the input function and obviously with the final output function. A dimensionless parameter called conductivity parameter ($B = \sqrt{(\omega\mu_0\sigma_1/2)}.a$), which contains the frequency component, is introduced in the final solution of the output function. Thus the conductivity parameter is considered as a variable throughout the computation of frequency-domain responses. This facilitates an easy interpretation in the desired frequency range. The range of B values is chosen such that the complete frequency-domain response due to a stratified media is obtained within the accuracy of measurements. The frequency, loop radius and the top layer conductivity influence the output function and to some extent the filter function particularly in deciding the filter length (Shastri and Patra, 1983a). The theoretical background and weights of sinc-response of the filter for CFS are discussed in (Shastri and Patra, 1983b). The manner of applying the filter coefficients and their abscissa to the convolution sum along with the filter weights is given as:

$$\left| h_z \right| = \text{convolution sum} = \sum_{k=0}^{n} C_k \, . \, f(Y_k) \tag{4}$$

Where

C_k = the filter coefficient at abscissa values η_k
f (Y) = the input function

$$Y_k = x - \eta_k = \ln(a) - \eta_o + k\,[(\ln 10/10)] \tag{5}$$

n = the suffix of the last filter coefficient that is used; η_o = the first value of the abscissa; a = the loop radius

At each and every value of conductivity parameter (i.e., frequency) the convolution summation is performed with the help of filter coefficients (Shastri and Patra, 1983b). The number of conductivity parameter (B) values taken for computation is 24 and the range is between 0.01 and 20.0. The number of filter coefficients (n) is 38. In frequency-domain sounding analysis, different loop radii are considered for computing the CFS responses for different layer conductivity contrasts and thicknesses. The amplitude of the normalized vertical component of the secondary magnetic field is computed for several stratified earth models. The model considered in the frequency sounding analysis is multiple layered earth cases. Though the procedure of the convolution summation is same with the fixed filter for all the chosen models, the kernel function involved in the input function is different for different models. As shown in Figure 1, a layered earth model is considered for computing amplitude responses. The corresponding kernel function derived here modifies the input function for layered earth (Nimmagadda, 2015) for which several basic equations are derived for multi-layer models.

ANALYSIS AND DISCUSSIONS

The theoretical expressions for various models have been presented in computable forms as given in (Nimmagadda et al. 2015). The computed results represent real and imaginary components and subsequently the amplitude and phase of the normalized vertical magnetic field. Based on this data, sets of master curves in terms of amplitude against conductivity parameter (B) are presented for future use in the interpretation of CFS field data. Besides multi-frequency responses, time-domain responses are also computed for different layered earth models by making use of digital linear filter and presented in convenient forms. Computer programs developed in FORTRAN language are run on a main frame computer to compute frequency responses for multi-layer earth models. The loop radius and conductivity of the top layers are important factors in the conductivity parameter (B), besides frequency. As a matter of fact, conductivity parameter is the major controlling factor for the nature of response curves as a whole. Thus the top layer conductivity and the loop radius influence the response characteristics. Therefore, a compromise between these parameters is so made so that a plottable range of response variation is obtained within the accuracy of measurement.

Responses of layered earth

Different sets of amplitude response curves are presented from the data computed through theoretical expressions in equations 1-5, derived for layered earth with various combination of values of layer parameters. The amplitude data are plotted on a bi-logarithmic graph sheet of 62.5mm modulus against conductivity parameter B. The amplitude responses are computed for different loop radii for highly resistive basement (Figures 2 -3). Each set corresponds to a group of curves drawn for different values of σ_2 / σ_1 and fixed a/h_1 and a/h_2 values. Each curve in the set corresponds to a variation of amplitude with conductivity parameter for fixed σ_2 / σ_1, a/h_1 and a/h_2 values.

The amplitude responses are presented for a layer earth of comparatively conductive top bed for different loop radii as shown in Figures 2-3. The sets of curves correspond to loop radius a = 25m. The author attempts to compute the detectability effect and quantify it with conductivity measurements. The difference between the responses of frequency- domain (normalized values of vertical component of the magnetic field) over a wide frequency range is calculated in different ways: (1) algebraic difference which is either positive or negative over the measurement range; (2) the ratio of the responses and (3) the RMS differences as described in the following sections.

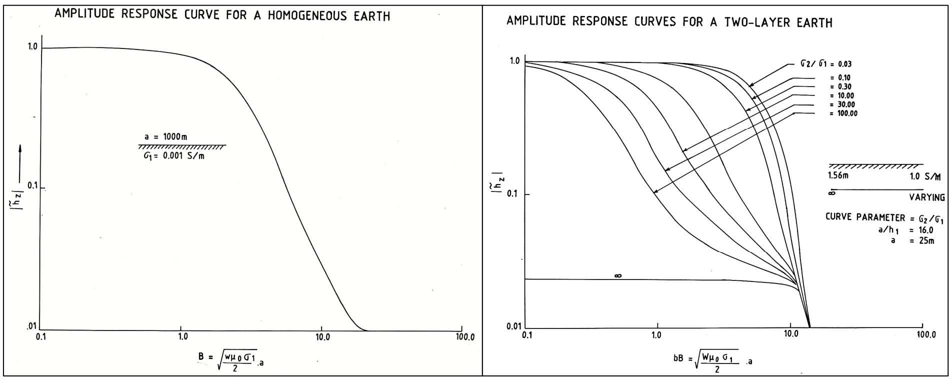

Figure 2: Amplitude responses of homogeneous and two-layer earth models (Shastri and Patra, 1983b)

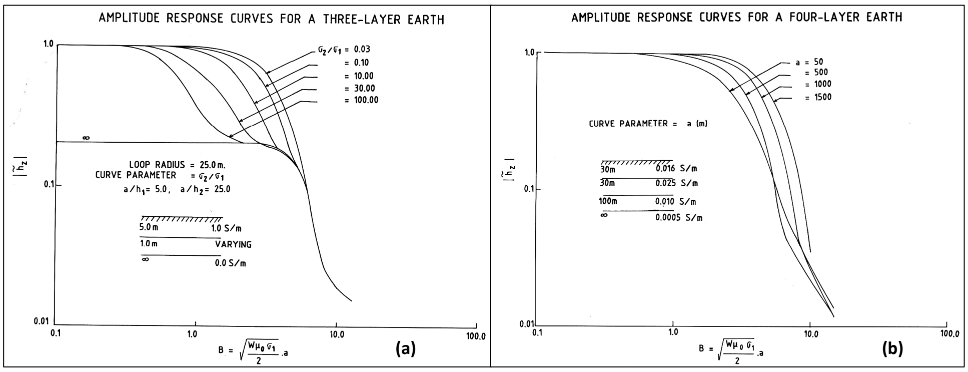

Figure 3: Amplitude responses of three- and four-layer earth models (Patra and Shastri, 1988)

In the present analysis, the resolution of response characteristics is represented by the RMS difference. If Δ_1, Δ_2, Δ_3 … are the differences in the responses of three-layer earth and homogeneous earth models, the RMS difference over n points is

$$\text{RMS difference} = \text{SQRT}\left(1/n \sum_{j=1}^{n} \Delta^2_j\right);\ j = 1, 2, 3\ldots n.$$

The total number of points (n) considered here is 24. A RMS difference of 10 percent of the responses between the layered earth models and the homogeneous earth is defined as the minimum detectability level in which measurement error is assumed to be approximately 3 percent (including noise level, measurement in ground surveying etc.). Percentile difference between the responses of the layered earth and the homogeneous earth models is an important parameter for determining the detectability effect. This is calculated at each and every point of the frequency range and for different values of h_2/h_1 from the formula:

Percentile difference = $(([hz(\omega)]_I - ([hz(\omega)]_{II}) / ([hz(\omega)]_I) \times 100$; suffixes I and II indicate models as shown on the diagrams (Figures 4a and 4b).

Analysis of results

Resistive basement case: A careful observation of Figures 2-3, shows amplitude variation with respect to conductivity parameter (B) for fixed loop radius (a) of 25m. The curve parameter is σ_2 / σ_1. The resolution as indicated by the separation of curves is more significant for values of σ_2 / σ_1 > 1.0. The variation in layer conductivity is not well reflected on the response for values of σ_2 / σ_1 < 1.0. As an example, amplitude responses provide better resolution of layer conductivity distinguishing the responses for σ_2 / σ_1 < 1.0 and σ_2 / σ_1 > 1.0. Similarly variation in layer conductivity is well resolved on both amplitude responses for values of σ_2 / σ_1 > 1.0 with constant a/h_1. RMS difference of amplitude responses fail to detect the intermediate resistive layer (as shown with solid lines in Figure 4) as it falls below the minimum detectability threshold of 10 percent.

Conductive basement case: The deeper layers are resolved at lower frequencies and the responses get saturated at higher frequencies with the increase of a/h_1 improving thereby the resolution in terms of top layer thickness. Three-layer earth models with intermediate conductive and resistive beds are considered to determine the detectability level. This analysis is made with a fixed loop radius a = 1000m. Figures 4a, b show the variation of RMS difference of amplitude responses between three-layer (H-type) earth and homogeneous earth models with respect to intermediate layer thickness. The solid line represents the RMS difference of amplitude response as shown in Figure 4a.

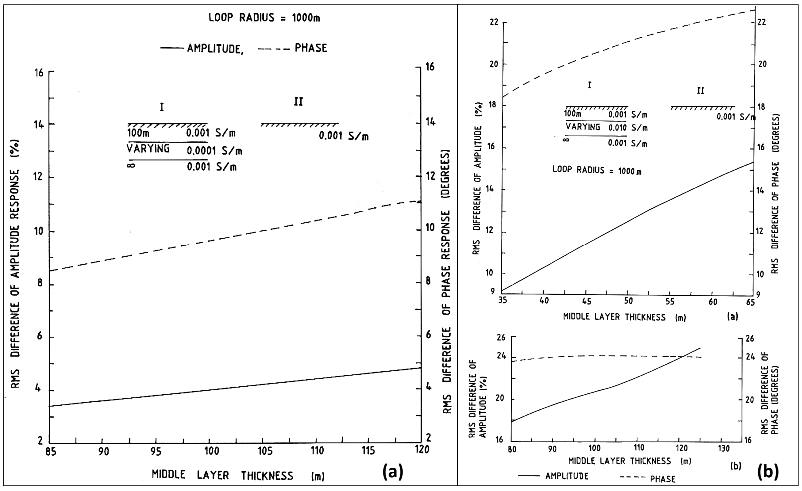

Figure 4: (a) Detectability of an intermediate resistive layer between models I and II (b): Detectability of an intermediate thin conductivity layer between models I and II

The RMS difference of amplitude responses provides the detectability of intermediate conductive layer when $h_2/h_1 > 0.4$, since the minimum detectability level is chosen as ≥ 10 percent. Figure 4b shows the variation of RMS difference of amplitude responses with different intermediate layer thicknesses.

SIMULATION OF SEDIMENT-LAYERS IN OIL AND GAS SEEP AREAS

The CFS response curves are computed for homogeneous, two- three- and four-layer earth models. Keeping in view the oil seeps in the basin margin areas, layered earth is simulated with thinning of sediment and its contact with basement structure. In the rifted basins, such as, the Cambay basin in Western India, Albertine Graben in Western Uganda and several basins of the North West Shelf in the Western Australia, oil and gas seeps are reported and well documented on the flanks of the basins (Logan et al. 2010). This is in confirmation of definite existence of petroleum systems that led to commercial production. Because of sediment alteration in the near surface areas, comparatively high resistivity or low conductivity middle layer is simulated. Wherever the top seal rock is missing, which is attributed as higher resistivity compared to altered middle layer sediment, it is interpreted as two-layer simulation. If top seal rock is interpreted as thick, compared to middle layer, then three-layer case is interpreted. Similar sediment layer situations can be simulated in these basins, where sediment-basement contacts are interpreted. Oil and gas seeps are quite common (Nimmagadda et al. 2007) especially in the proven oil bearing sedimentary basins. They could exist because of exposure or collapse of subsurface structures towards the earth's surface. It could be due to a leakage through reservoirs (hydrocarbon containers) that may have been exposed to the surface. Another reason may be due to more excessive formation pressures, compared with atmospheric pressures. In contrast to background gases, some natural gas seepages can flow at the rates of several cubic meters per minute. Methane is frequently the dominant component of natural gas seepage. Although some secondary alteration can influence the gas signatures, most seepage with high flow rates are probably representative of their associated source rocks (Shi et al. 2010). Hydrocarbons seep upward from trap rock creating a reduction zone and bacterial degradation of hydrocarbons. These geochemical anomalies generate geophysical anomalies, such as lowering of seismic velocity, resistivity and magnetic data instances. Pyrite and sulphur precipitation above the reducing zone produces higher induced polarizations. In the oxidizing zones, carbonates get precipitated, generating further higher resistivity anomalies.

For example, in the Semliki basin (southern part of Lake Albert basin), especially in the south-western part of the study area as shown in Figure 5, there are active oil seeps, generating several geochemical anomalies, which give rise various geo-electrical anomalies. Along eastern parts of basin margins of Lake Albert basin, these seeps are active, where sediment alteration occurred because of geochemical anomalies. The fact of the matter is that major petroleum provinces have hydrocarbon seepages and for many operating companies, the classification of natural gas emission or seepage is attractive. Geophysical signatures of shallow sediments can be better understood by integrated geophysical surveys or *in situ* geophysical measurements containing all types of electrical and electromagnetic surveys, closed grid gravity and magnetic surveys in and around the oil seep and where micro-seep activity has taken place. This helps in delineating an earth model comprising of two-layer or three-layer situations with possible sediment contacts with basement structures that can supplement the existing geological or geophysical information derived by seismic surveys. Any additional geological and geophysical data and information facilitate the exploration investments in the Lake Albert and Semliki basins in Uganda. An oil seepage, two and half miles northeast of Kibiro village, has drawn attention to the first oil & gas venture in the Lake Albert region (Figure 5). The author (Nimmagadda et al. 2007) describes it as 'the outcrop of the seepage', when uncovered, is seen to consist of coarse sand saturated with thick petroleum stains. In colour, it is black or extremely dark brown and dull at the surface. A few inches below the surface, however, it is bright and glistening with liquid petroleum resembling freshly made tarmacadam in appearance' (Shi, et al. 2010).

The Cambay rift basin (Kundu and Wani, 1992) formed at the end of Mesozoic and accompanied by extensive eruption of continental flood basalts, is located in the western part of the Indian subcontinent between Kutch-Saurashtra uplifts on the west and Deccan uplift and Aravalli hills on the east. The Cambay rift evolved during the Late Cretaceous as a consequence of the initiation of the western margin of the Indian plate. The Cambay basin, a rift sag tertiary basin in the western onshore part of India, includes six tectonic blocks, the Patan, Mehsana, Ahmedabad, Tarapur, Broach, and Narmada, separated by faults aligned to the general NS axis of the rift. All tectonic blocks are under oil and gas exploration for the past several decades. Several oil and gas seeps have been reported on the flanks of this rift basin.

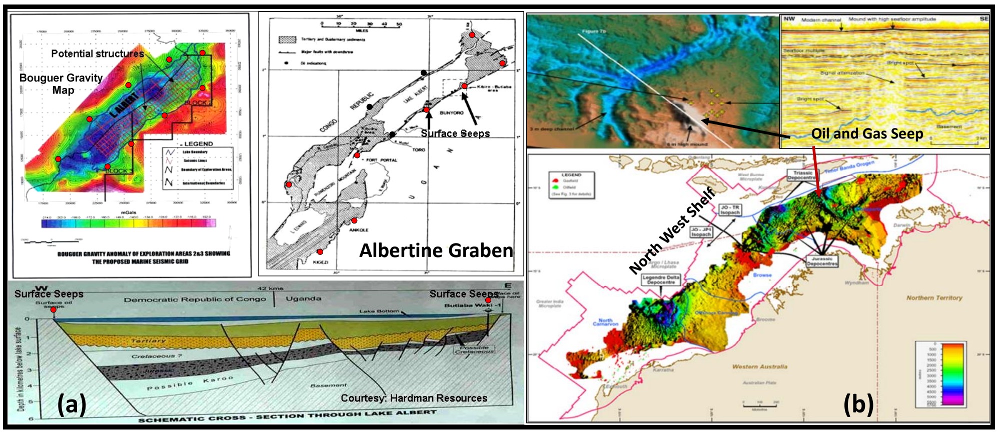

Figure 5: Oil and gas seep provinces of the rifted basins (Nimmagadda et al. 2007)

The Deccan Trap volcanic episode at the Cretaceous-Tertiary boundary is also related to the breakup of the Seychelles Island from the Indian plate and the subsequent northward drift of the Indian subcontinent. The flood basalts form the basement rock of the Cambay rift. The rift is divided into two distinct blocks, namely north and south Cambay basins, which are further subdivided into several discrete tectonic blocks or grabens with transfer zones delineating the blocks. The tectonic blocks from south to north are the Narmada block, Jambusar-Broach block, Cambay-Tarapur block, and Ahmadabad-Mehsana block as shown in Figure 6.

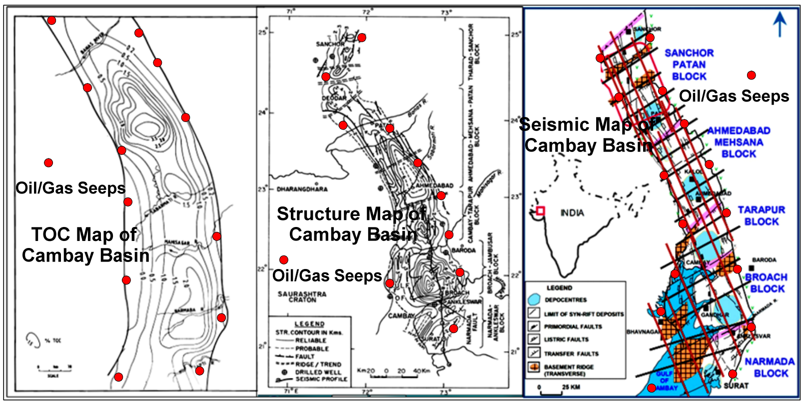

Figure 6: Rifted Cambay basin with oil and gas seeps (Kundu and Wani, 1992)

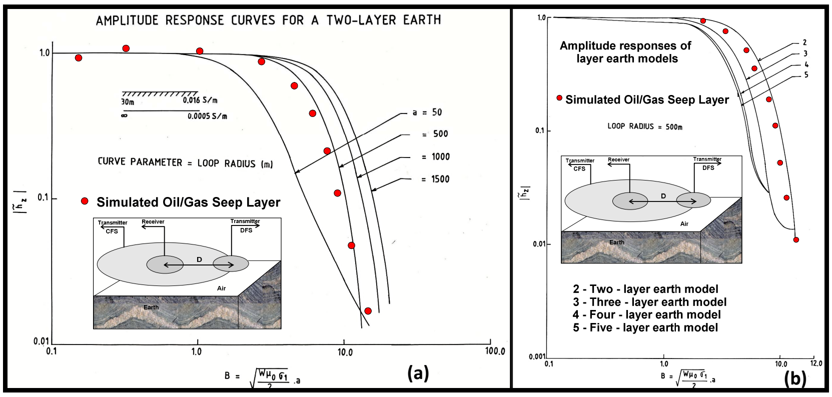

Figure 7: Modelling oil/gas seep layers (Nimmagadda, 2015)

There are oil and gas seeps in these rifted sub-basins. Layers associated with oil and gas seeps are modelled as shown in Figure 7. As shown in Figure 7b, most of the seeps are associated with the top layer. Thick sediments have been interpreted in these basins as corroborated by gravity and magnetic data. High resolution 2D seismic data have been acquired in these basins to understand structural patterns meticulously. Multiple depo-centres encountered in these tectonic blocks are responsible for generating hydrocarbons. These hydrocarbon deposits have been migrated, both laterally and vertically, into the structurally up-dip areas, through steep dipping formations, faults and unconformity zones. There are quality reservoirs, some of them exposed on surface that are excellent hydrocarbon containers. There are regional seal rocks overlying these reservoir rocks, limiting vertical escape of hydrocarbons to surface, and potentially trapping hydrocarbons within massive structures.

CONCLUSIONS

Digital linear filter method is flexible for layering on CFS. Layer parameters are well resolved on amplitude characteristics for both resistive and conductive basement for values of σ_2 / σ_1. Larger loop radius helps in the detection of thicker beds and deeper anomalies. The separation of curves indicates that investigation can be carried out up to a depth of half the loop radius. The detection of thin top layer becomes resolvable with varying loop radii. The resolution obtained for resistive basement is comparatively better than the resolution for the conductive basement in terms of layer conductivity and layer thickness. Quantified detectability effect facilitates the CFS applicability and feasibility in the layered earth problems, associated with the oil and gas seep investigations in the rift basins. Layer earth associated with oil and gas seeps can be modelled and analysed using CFS response characteristics.

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