A practical assessment of frequency electromagnetic inversion in a near surface geological environment

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Bachelor's thesis
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Cover Picture: Picture of the GEM-2 Muli frequency device used during this thesis.

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Abstract: The adoption of frequency electromagnetic (EM) sounding devices in the past 15 years for geophysical exploration has fueled research into techniques associated with the method. One of these techniques is inversion which is the process of turning the EM data into measurements of depth for different geological layers. Inversion of frequency EM data has classically been difficult and unreliable. With advancements made in both hardware and software, frequency EM inversion has become more prominent. There are still questions, however, regarding its consistency and precision. This study is an attempt to understand the problems associated with Frequency EM inversion in a practical geological setting.

Using a frequency EM sounding device multiple surveys were undertaken on three geologically different localities. These localities were chosen due to their two layer conductivity contrasts that make up a simple geological configuration. For quality assurance the subsurface layout for the surveys were determined from a mixture of resistivity profiles and well log measurements. The EM data were subsequently inverted using the EM Inverter program.

The results obtained show a certain lack in capability especially associated with the EM Inverter program. These include an inability to interpret detail and only give a rough estimate of the dimensions. This problem is not unique to the EM Inverter program but can be seen quite universally in the literature. The current capability of the frequency EM method is well suited as a complimentary device used at the initial stages of a survey. To best make use of the frequency EM method a guide is provided which offers simple suggestions in producing more accurate inversion models. These are mostly associated with an understanding of the area's stratigraphic and conductive properties.

Keywords: frequency, electromagnetic, sounding, inversion, GEM-2.

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En praktisk bedömning av frekvenselektromagnetisk inversion i en ytnära geologisk miljö

Mattias Letellier

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Sammanfattning: Under de senaste 15 åren har användningen av frekvenselektromagnetiska sonderingsinstrument inom geofysiska undersökningar drivit forskningen framåt för att förbättra den använda metoden. En av dessa tekniker är inversion vilket är den process som omvandlar elektromagnetiska data till djupvärden för geologiska lager. Inversion av frekvenselektromagnetiska data har länge varit förknippat med svårigheter. Framstegen som har gjorts både inom instrument- och mjukvaruutveckling har lett till ökad användbarhet. Det finns dock fortfarande problem beträffande precision och återgivning av geologiska förhållanden. Den här studien är ett försök att förstå de problem som är förknippade med frekvenselektromagnetisk inversion i samband med geologiska undersökningar i fält.

Ett flertal mätningar utfördes på tre lokaler med ett flerfrekvensstångslingram instrument. Lokalerna valdes med avseende på deras enkla uppbyggnad i form av två distinkta lager med olika konduktivitet. De olika lokalerna skilj-de sig både geologiskt och strukturellt. Resistivitetsprofiler och borrhålsloggar användes för att bestämma det undre lagrets stratigrafiska position. Den elektromagnetiska informationen behandlades sedan i dataprogrammet EM Inverter.

De insamlade resultaten visar på en bristande korrelation mellan den geologiska verkligheten och den modell som dataprogrammet EM Inverter producerar, och den önskade detaljnivån gick inte att uppnå. Detta upplösningsproblem är inte enbart begränsat till EM Inverter, utan kan även påvisas i stora delar av den genomgångna facklitteraturen. Detta begränsar i nuläget tillämpningen av frekvenselektromagnetism inom geofysik men metoden är trots allt användbar för inledande studier av geologiska miljöer.

Nyckelord: frekvens, elektromagnetiska, sondering, inversion, GEM-2.

Mattias Letellier, Geologiska institutionen, Lunds universitet, Sölvegatan 12, 223 62 Lund, Sverige. E-post: Mat_letellier@hotmail.com kursiv)

1 Introduction

Geophysical methods have been the hallmark of the geosciences since their inception early in the 20th century. The wide varieties of tools they have to offer have made their way into a large number of disciplines. Some of the more classical methods such as seismic and electric resistivity have started to be replaced in certain sectors. Although these methods are highly useful in determining geological properties, they can be time consuming and/or highly technical. Industries such as construction and water management that incur large expenditures in surveying are in need of a more rapid device that is capable of lowering these costs.

The electromagnetic method (EM) has been one of the earlier geophysical methods utilized. In the 1930's electromagnetic waves were being used to detect the presence of conductive ore bodies. But the adaptation to use electromagnetic waves to give information on ground resistivity has been a slow process. Even though the principles of electromagnetic sounding were understood early on in the 20th century there have been some technical bridges to cross before a device utilizing these principals could be created. Only in the last 40 years has the method become increasingly popular.

With the advent of miniaturization and the widespread availability of computers small, handheld broadband electromagnetic sensors have begun to hit the market. Contrary to the traditional electromagnetic sensors where depth of exploration was a function of distance from the transmitter to the receiver and the sensors were fixed to a set factory frequency, these new machines utilize a wide spectrum of frequencies capable of measuring in unison. This is referred to as frequency electromagnetic sounding. This method claims the ability to reliably interpret depth with transmitter-receiver distances of only a couple of meters. These new machines have the unique ability of very rapidly gathering information on conductive geological properties at different depths. The ease of use and its practicality have fueled investment in these machines and garnered research into the manipulations of the data. Much of this research has gone into developing ways to invert the data (Constable et al., 1987; Benech and Marmet, 1999; Farquharson et al., 2003; Dondurur, 2005; Sattel, 2005).

Inversion is the process of transforming a certain geophysical data set, be it susceptibility, resistivity or seismic velocity into a comprehensive model of stratigraphy. This is usually done within the realm of complex computer algorithms. Inversion is currently being applied successfully with resistivity, seismic and single frequency electromagnetic methods. It is relatively new however, and much more difficult to invert the data with a multi-frequency electromagnetic device. Major advancements are being made in developing software and computer code more capable of inverting frequency EM data (Dondurur and Sari, 2004; Kakulia and al., 2009).

The ability to rapidly survey large areas of land and get an accurate picture of the stratigraphy is starting to become a reality. Frequency EM devices promise to lower survey costs for sectors such as construction, mining, ground-water exploration, soil/groundwater contamination and many others. In this study a GEM-2 multi-broadband electromagnetic sensor has been used in an attempt to invert data from geologically simple and understood localities. The goal of this thesis is to explore the potential and identify limitations with the machine or the software associated in a practical setting. Understanding the problems that small survey team may face is of paramount importance. A comprehensive guide has been developed to facilitate the use of frequency EM devices and provide relevant data for a clear and truthful inversion.

2 Backround

2.1 Electromagnetic induction concepts

Many electromagnetic methods have been developed over the years utilizing different transmitters/receivers, configurations and concepts. Though the basic physics behind them remains the same, this project elaborates on the method of frequency EM sounding. Frequency EM, sounding as compared to other EM methods, utilizes more than one frequency simultaneously or in near succession. The reasoning behind this will be explained further in section 2.2.

Most EM systems work by first inducing an EM signal from the transmitter which is propagated through a medium (the primary wave). This electromagnetic signal then induces a current within the layers underneath. Ampere's and Faraday's laws determine that an electric or magnetic field each generates a component of the other in the form of a circulation about their field line (Fig. 1). An electric current will induce a magnetic field circulating around it and vice versa. It is an oscillation between these two forces that will create a secondary EM wave that can then be read by the receiver. The relationship between the primary wave and the secondary wave can be visualized in Fig. 2. The properties of the secondary waves have a direct

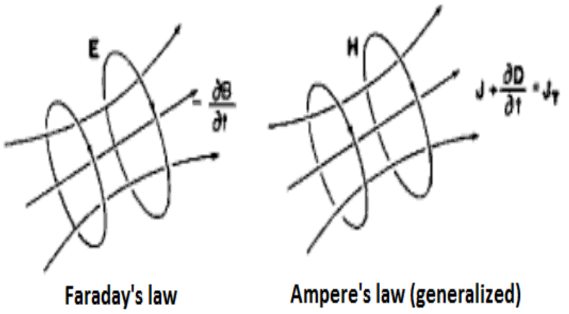


Fig. 1. A visualisation of Ampere's and Faraday's laws. Faraday's law depicts an electric field circulating a magnetic line, while Ampere's law depicts a magnetic field circulating an electric line. Replicated from West and Macnae (1991)

correlation with the induced current in the ground. In theory an induced homogenous ground should have a homogenous current density. Under natural conditions where the ground is never completely homogenous the current density begins to be disrupted and by consequence the secondary wave is altered. The current density concentrates in areas and borders of contrasting resistivity. This effect is a physical property to ensure continuity of current flow. These areas of increased current develop their own EM fields that can be either constructive or destructive to the surrounding EM fields. If a more conductive body is present the current will create a destructive secondary field that will have a cancelling effect on its surrounding (Fig. 3). A less conductive body will be constructive to its surroundings and amplify its electrical field. In either case there is a distortion effect that can be measured from the secondary wave (West and Macnae, 1991).

The secondary wave is usually measured in percent (%) or ppm of the primary wave since a lot of the initial energy is lost. It can be split into two separated components, the inphase and the quadrature. The inphase component is the component that is in phase with the original primary wave, differing only in amplitude. This wave can then be separated out mathematically and what is left is a wave that has an offshoot of 90^{o} from the inphase component, the quadrature component of the secondary wave. The relative strengths of these two components provide information that can be used to calculate ground conductivity and susceptibility (West and Macnae, 1991).

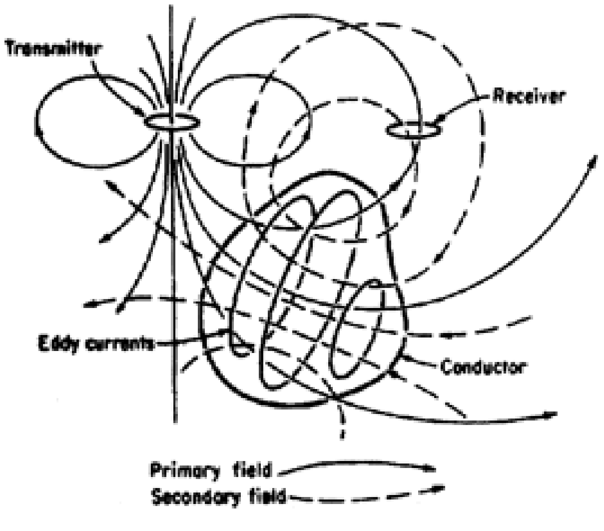


Fig. 2. Figure depicting the relationship between primary and secondary EM fields. The primary field lines are solid and represent the EM field induced by the transmitter. secondary field lines are doted and represent the EM field created by the current within the ground. Replicated from Sheriff (1989)

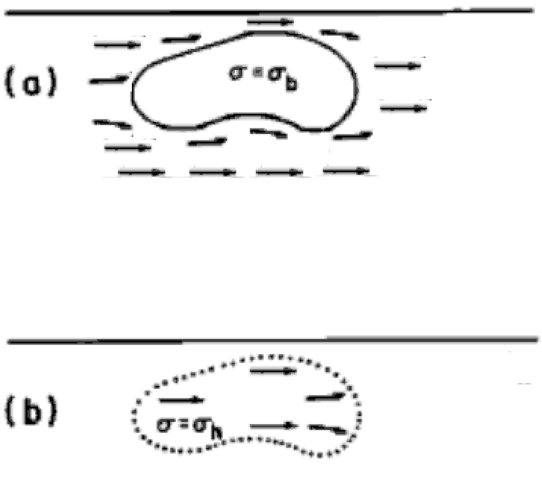


Fig. 3. a) Image depicting a less conductive anomally in a conductive surrounding. In this situation the anomally will add to the overall strength of the secondary field. b) Image depicting a conductive anomally in a less conductive medium. In this situation the anomally will work to cancel the overall strength of the secondary wave. Both a) and b) field stength is relative to the overall medium. Replicated from West and Macnae (1991)

2.2 Frequency EM

Most of the earlier electromagnetic sensors developed have worked on the principle of geometric sounding. As the transmitter (Tx) and receiver (Rx) are separated by a known distance measuring the theoretical skin depth for a given frequency is a matter of simple mathematics. Skin depth is the distance at which the EM wave decays to 1/e (~37%) of its original value. These machines have usually been tuned at specific factory frequency and have needed an ever larger Tx-Rx separation to be able to account for an ever deeper survey depth. It becomes clear that such a system cannot be made into a small portable machine. A frequency EM device, however, has no exclusive relationship between the coil separation and the depth of investigation. The separation between Tx and Rx coils can thus be arbitrarily small and depth of investigation is more a function of frequency.

Some technological hurdles had to be overcome before such a device could be brought to the market. The Rx coil must have a source cancelation ability so not to be saturated by the nearby Tx coil. Won (2003), the architect behind the GEM-2 machine, accomplished this by adding a third coil that has as its sole function to cancel out the Tx waves. Both the analogue and digital electronics have to have a wide dynamic range and a high resolution. The coil's self resonance frequency must be much higher than the high end of the bandwidth utilized. All coils and electronics must work in a wide bandwidth to have room for composite wave forms that are created by using multi-frequency components. These technological barriers have impeded the widespread use of multi-frequency devices.

Once these were dealt with what remains is a machine that carries with it many advantages. A multi frequency device is small, portable, rapid and operable by one person. Also it has the added advantage of being able to avoid certain "noisy frequencies" in urban areas, such as EM waves that are created by power lines (Won, 2003; Huang and Won, 2003).

A Frequency EM device works on its ability to sound more than one frequency on the same area of ground. As different frequencies can penetrate the ground at different depths, conductivity can then be recorded down to the depth of investigation of each individual frequency. Depth of investigation is defined as the maximum depth at which a given target in a given host can be detected by a given sensor. It is intrinsically more complex than skin depth. Thus, multi frequency depth of investigation becomes inarguably more complex than geometric sounding. Huang (2005) divided the factors effecting depth of investigation into two intrinsic categories (Fig. 4), manageable and unmanageable. Manageable factors are those that the user has control over such as frequencies, sensors, coil configuration, filtering etc, while unmanageable factors are those that cannot be changed such as structures, conductive overburden, weather, terrain, power lines etc. So when choosing operational frequencies there are three considerations to account for: skin depth, signal level, and environmental noise. To successfully field a multi frequency device lies in the operator's ability to control theses manageable factors. There is no definitive way to determine depth of investigation but there are some simple rules that can optimize the manageable factors. Depth of Investigation can be estimated by considering sensor frequency, coil separation, geologic medium, target conductivities and detection threshold. A low frequency wave will have more penetrative power than higher frequency waves and this will lead to a larger depth of investigation. However a low frequency will yield low signal amplitude and be subject to a lower signal to noise ratio. As stated before, larger coil separation leads to an increased depth of investigation. As target conductivity increases depth of investigation will also increase. As the conductivity contrast increases so does the depth of investigation. The detection threshold is the threshold of wave attenuation as to when the machine can still distinguish the wave from the background noise. When depth of investigation is increased the detection threshold is increased. These rules can be useful when conducting field work and collecting the necessary data sets, but when it comes to inverting the data they add an extra layer of complexity and computation (Won, 2003).

2.3 Inversion

Data inversion is the process of estimating a model of physical properties based on geophysical survey data. This entails being able to gather depth, geometry and stratigraphy from data sets such as seismic velocity, conductivity, resistivity, susceptibility etc. The opposite of this is forward modeling, which relies on the extrapolation of a set of data from a theoretical geological setting. For an inversion to successfully predict the geological properties it requires a forward model as well as the ability to invert data. Forward modeling necessitates a contribution by the user of a set of variables that can define a geological model. In frequency EM forward modeling these variables include number of layers, resistivity, depth and their relation to each other. These variables are extremely important for how the program will interpret the data set. The resulting forward model will be used by the program as a guide when processing the frequency EM data. The inversion algorithm creates its own model based on the col-

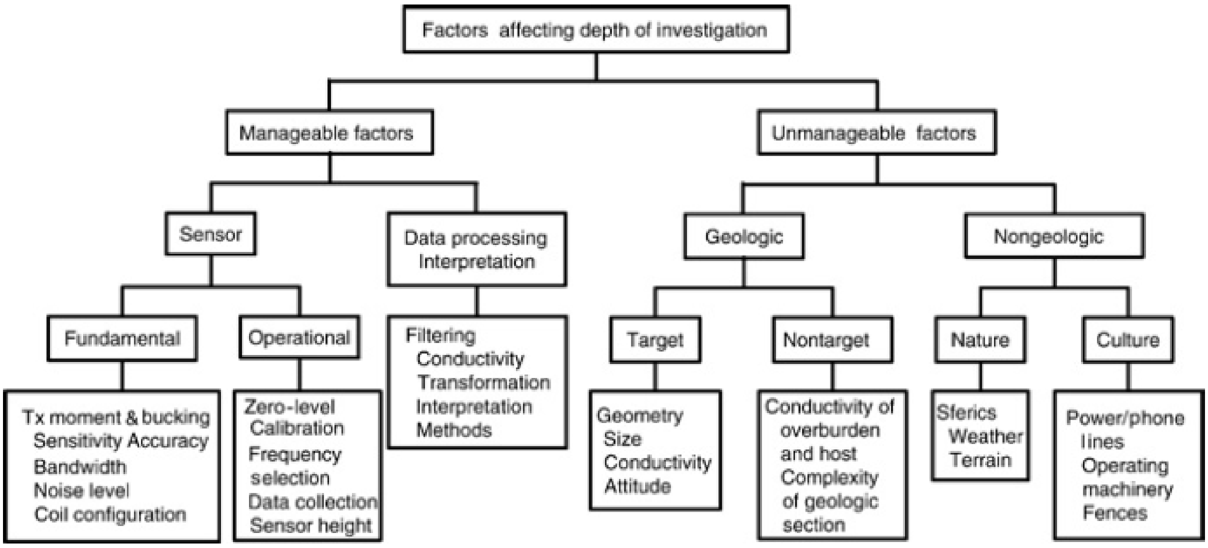


Fig. 4. Image depicting factors affecting depth of investigation. Replicated from Huang (2005)

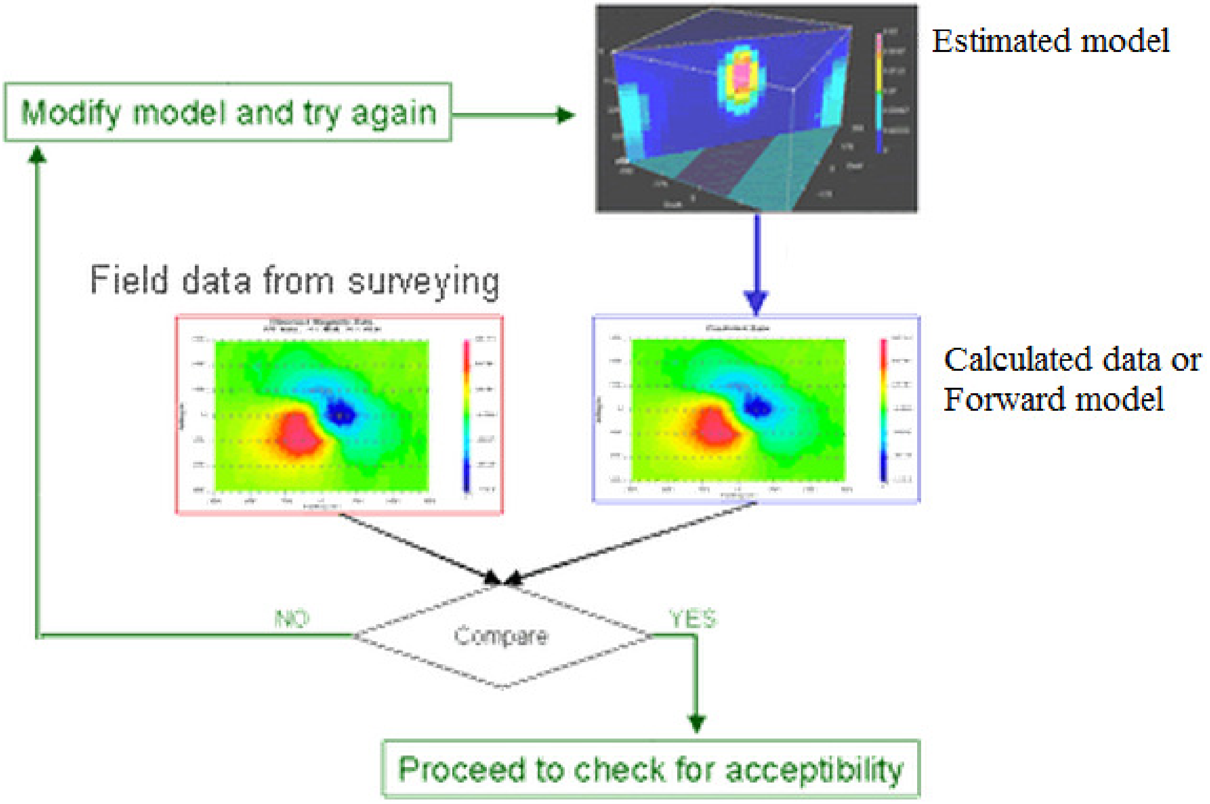


Fig. 5. Image showing the relationship between forward modeling and inversion. Replicated from Oldenberg and Jones (2007)

lected frequency EM data (apparent conductivity, susceptibility). After comparing the inversion model with the forward model the program will decide if they are similar enough. If the model is deemed similar it will be appropriated to the user. If the model is deemed not to be similar a second attempt is made with a different algorithm and the process repeats itself until an appropriate model is found (Fig. 5) (Oldenberg and Jones, 2007).

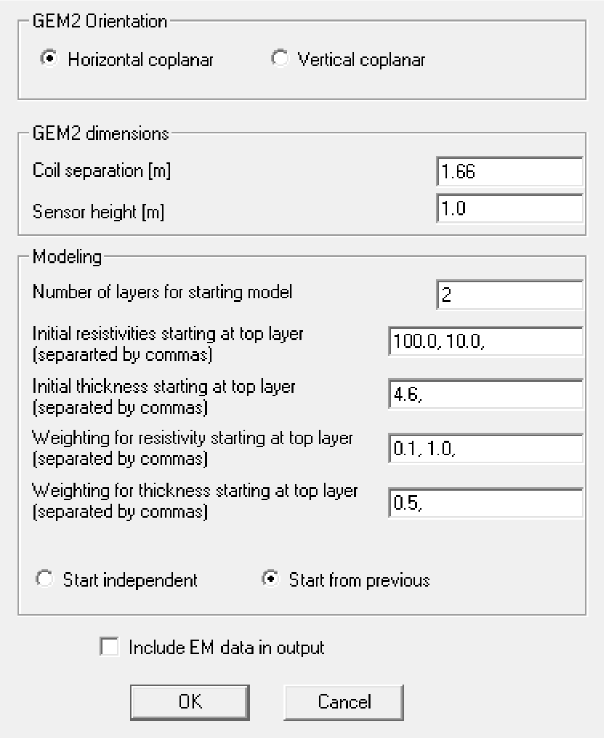
The major problem with inversion lies in the fact that it is possible with one data set to get a large variety of models that can each fit the data. The computer program also cannot distinguish between models that are geologically impossible or highly unlikely with those that seem realistic. Forward modeling is a way to lower the number of possibilities and get an inversion that fits. When dealing with EM inversion and its heightened complexity there is still a human element involved. The operator needs to distinguishing realistic models with unrealistic ones. By iterating and making adjustments to the forward model a more appropriate inversion can be created.

In the past few years frequency EM inversion has been successfully undertaken due to an increase in investment which has refined the method. Large investments have been made by militaries around the world for frequency EM ability to locate improvised explosive devices in current war zones and unexploded ordinance in past war zones (Huang and Won, 2003). In Archeology frequency EM inversion has been sought after because of its unobtrusiveness in locating ancient buried structures (Bongiovanni et al., 2007). In hydrogeologic contamination monitoring it has been used to quickly set up surveys that can identify and stop the eventual spreading of contaminants (Sams et al., 2008). Even in such established fields as hydrocarbon surveying it has found a use in locating reservoirs by identifying the high resistivity of hydrocarbon compounds (Constable and Weiss, 2006). This system is already finding niches in many sectors, but the question remains if frequency EM can become a valid alternative to other geophysical methods.

3 Methods

Three areas in southwestern Sweden were surveyed. As a survey instrument the GEM-2 produced by Geophex was used. The GEM-2 is a multi frequency electromagnetic sensor capable of measuring up to 10 frequencies simultaneously. With an Transmitter-Receiver separation of 1.66 m the device is capable of a frequency range of about 90 kHz. Using more than five frequencies simultaneously is not recommended, however, due to power being distributed equally between frequencies. The higher the number of frequencies running together the weaker the signal will be for each one of those frequencies. This can have an adverse affect on the signal to noise ratio and data can come up as more sporadic.

The GEM-2 device was carried with a sling at waist height (1 m) and marched along survey lines. The machine sends and records data about every 1/30th



GEM2 Orientation

● Horizontal coplanar ○ Vertical coplanar

GEM2 dimensions

Coil separation [m] 1.66

Sensor height [m] 1.0

Modeling

Number of layers for starting model 2

Initial resistivities starting at top layer (separarted by commas) 100.0, 10.0,

Initial thickness starting at top layer (separated by commas) 4.6,

Weighting for resistivity starting at top layer (separated by commas) 0.1, 1.0,

Weighting for thickness starting at top layer (separated by commas) 0.5,

○ Start independent ● Start from previous

☐ Include EM data in output

Fig. 6. Screen shot of the EM Inverter programs table. The values entered here will create the forward model.

of a second. In the case of the Åkarp survey location a survey path was chosen, measured and walked along at a set pace. At Vomb and Öved a GPS device was attached to record the path walked. Data collected in real time was recorded into a portable computer and then exported into a .csv file. Depth is then calculated from this file using a Geophex supplied program named EM Inverter. This program was chosen as it is the most easily available program although there are other programs on the market that could perhaps be considered “superior” such as the 1x1d produced by Interpex Limited and the EM1DFM produced by the University of British Colombia. For the purpose of this study an analysis by the EM inverter program seemed suitable and cost effective.

EM inverter is capable of turning inphase and quadrature wave data for various frequencies into apparent conductivity. For the program to run a 2-d inversion some variables must be input by the user. These require a basic knowledge of the local geology and these variables have a large effect on the predicted depth values. A picture of the input table of the program can be viewed in Fig. 6. The program requires an input of the GEM-2 dimensions such as coil separation (1.66 m) and sensor height (1 m). Next an input is necessary for the geological forward model these include: number of layers, initial resistivity of each layer (Ohm’s), initial thickness of each layer (m), weighting for resistivity and weighting for thickness which are a ratio between the apparent layers. These values are then followed by the choice to undergo the inversion on every point individually or by taking into account the previous point along the walking path. With all these variables defined the program can be run and converts apparent conductivities into a predicted depth model.

4 Site descriptions

The three survey locations are situated in Skåne the southernmost province of Sweden. Skåne like much of Sweden has a large amount of its surface layer composed of some type of glacial deposit. Skåne’s geology is unique by being divided by a major fault zone named the Tornquist zone. To the Northeast of this zone there is predominance to crystalline Precambrian basement rocks that are more reminiscent of the majority of Swedish geology. Southwest of this zone the geology transforms into sedimentary deposits more evocative of Danish or German sedimentary basin geology. The three locations are named after the small

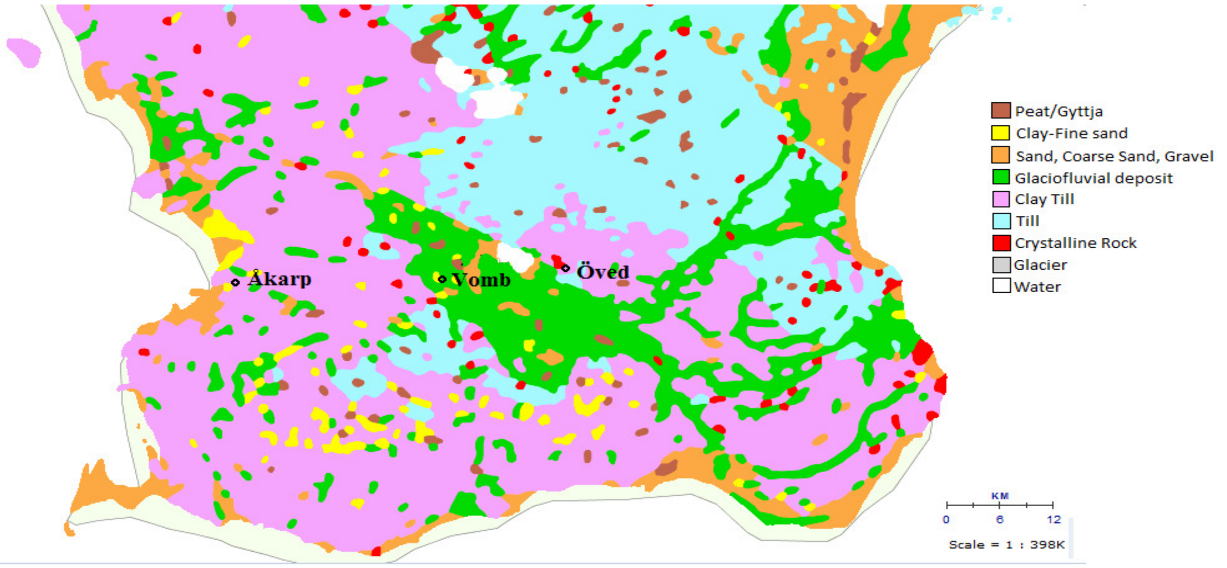


Fig. 7. Soil map of Skane showing the locations of each survey site. Map courtesy of Geological Survey of Sweden.

villages they reside by Åkarp, Vomb and Öved (Fig.7). The locations were chosen mainly due to their two layer stratigraphy. The two layer stratigraphy is important due to it being a very simplistic model in which to run an inversion.

4.1 Åkarp

Åkarp is located near the coast (Fig. 7) and rests on a bed of Mesozoic sedimentary deposits. These deposits reach a depth of 500 m and are composed of limestones and sandstones. Overlying these deposits is an inhomogeneous layer of clayey to sandy till deposited as the bulk of the ice sheet retreated at the end of the last glacial period. The top 6 m of the section is composed of two contrasting layers that were the study for this survey. A silty clay deposit lies at the base of this 6 m interval overlain by a deposit of clayey till. The former deposit is an intermorainic sediment that was probably deposited during an interstadial when ice streams redeposited glacial till into depressions within the landscape. The uppermost unit in this section has been interpreted as a basal till deposited underneath an active glacier (Ringberg, 1980) or as a glaciomarine diamict (Lagerlund, 1987).

4.2 Vomb

Vomb is situated more inland than Åkarp (Fig. 7). Like Åkarp, however, the underlying sediment is composed mostly of clay. The clay layer which is relatively deep (20-30 m) is a glaciolacustrine sediment, meaning it was deposited in a glacial lake. In the vicinity of our survey line two different overlying deposits occur. To the west along a creek lies an organic-rich fluvial deposit and most importantly to the east lies a glaciofluvial deposit of fine sand. To keep to our two layer geologic model the survey line had to begin east of the organic-rich fluvial deposit. The fine sand is deposited in a basin like configuration overlying the clay. The depositional setting for these beds were a glacial lake with two stages of deposition, the first being the clay and eventually glaciofluvial sand as the ice-dammed lake was being drained (Daniel, 1992).

4.3 Öved

Öved is the only survey that encompasses crystalline rock. The rock here is K-feldspar rich granite that is part of a horst and graben structure related to the larger Tornquist zone. The granite has a red colour due to its high potassium content and is excavated in a quarry nearby for use as an aggregate. The overlying sediment is sandy till with granitic clasts varying in size from pebbles to boulders forming an inhomogeneous

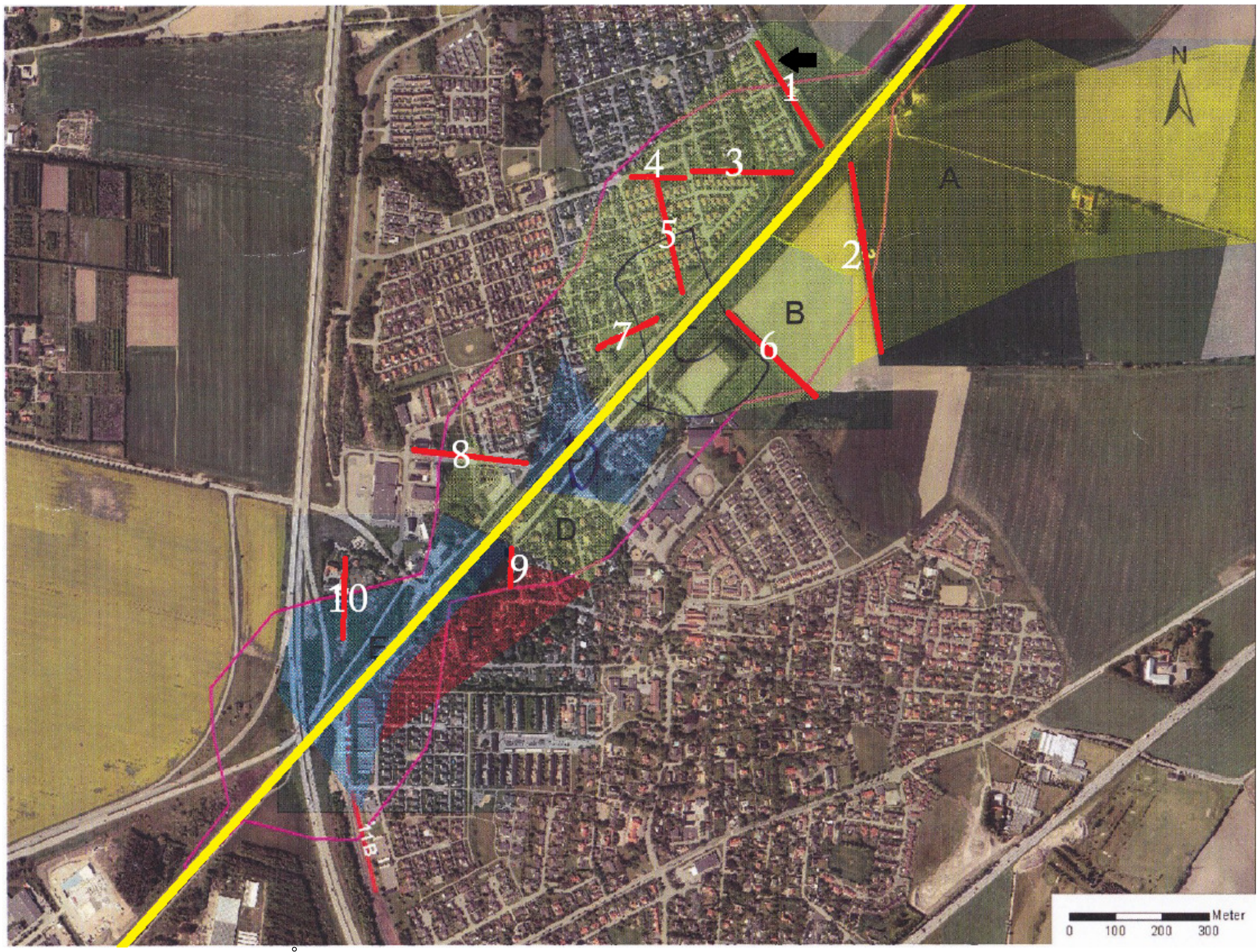


Fig. 8. Map of the village of Åkarp and in red the locations of different resistivity measurements. Survey site 1 is was used as the staging site for this location. Map Courtesy of WSP Environmental.

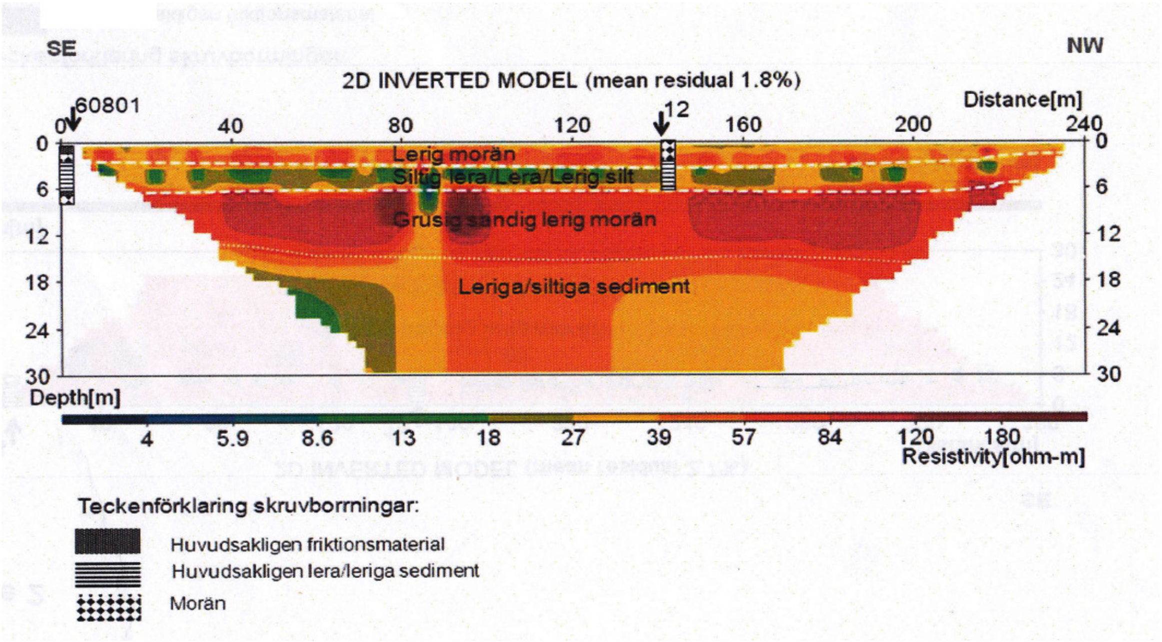


Fig. 9. Resistivity measurment undertaken by WSP Environmental. It was done along survey line 1 in Fig. 7. At 150 m a well log was taken which can be seen in Fig. 10.

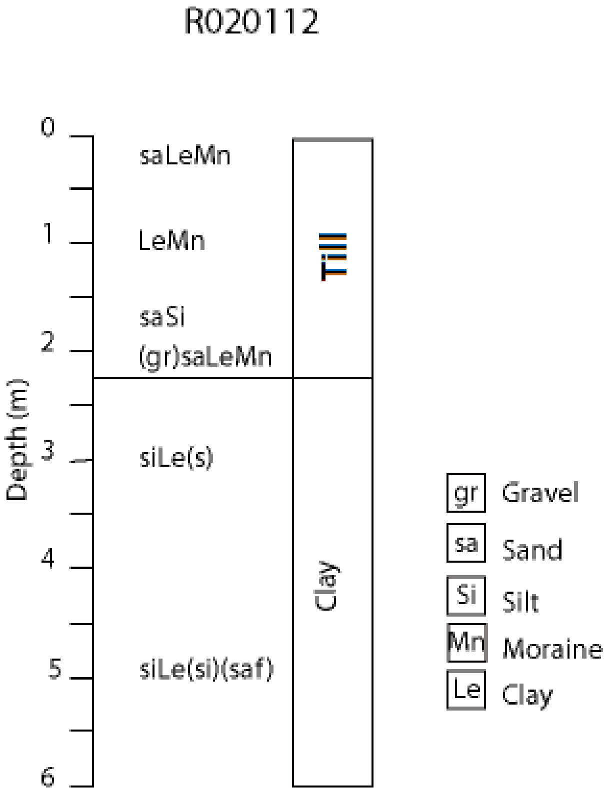


Fig. 10. Well log taken at 150 m along survey site 1 in Fig. 8.

medium (Daniel 1992). The inhomogeneous character of the till unit should not present a problem in the analysis due to its large resistivity contrast with the underlying granite.

5 Results and Interpretations

5.1 Åkarp

The small village of Åkarp, situated about ten km north of Malmö has recently had some surveying done due to a planned construction project on the nearby railroad. 10 resistivity measurements and eight well logs were carried out in the village along the railroad by WSP Environmental (Fig. 8). For the purpose of this study we chose to run the GEM-2 along the survey line #1 because of its accessibility, a low domestic EM "noise" level and a clear resistivity contrast between two layers. The resistivity measurements and well log data can be seen in Fig. 9 and 10 respectively. The top 2.25 m of the section is a very clay-rich till, and underlying the till is a less resistive silty clay. The line was run a total of nine times. changing the frequencies on every series. Also the number of simultaneous run frequencies was changed starting with three then five and ending with seven. This was done in an attempt to identify ambiguities that would occur if different or more frequencies were used.

The variables that were input into the inversion program were determined partly with the help of the electric resistivity measurements in Fig. 9 and partly on a trial and error basis. Experimentation was especially useful for determining the weighting for resistivity and weighting for thickness factors needed for the forward model. The values found to work the best for this section are summarized in Table 1.

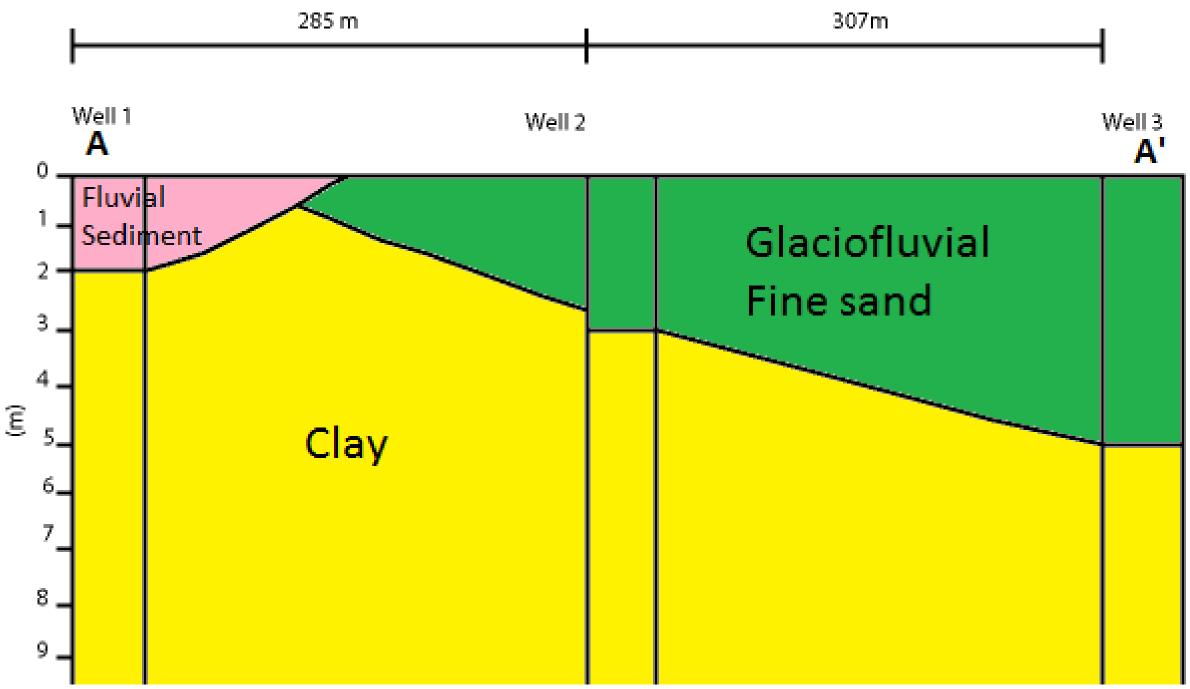


Fig. 11. Three well log measurments and the assumed subsurfeace stratigraphy at the Vomb locality. Well log data courtesy of the Geological Survey of Sweden See figure 12 for Location.

# of layers	2
Initial resistivity's starting at the top layer	100, 10
Initial thickness	2.5
Weighting for resistivity starting at top	0.1, 1.0
Weighting for thickness starting at top	0.1

Table 1. Values entered into the EM Inverter program to create a forward model at the Åkarp Locality.

The inversion results obtained from Åkarp are listed in Appendix 1. The predicted thickness of the bed is around 2.2 m for almost every trial. It should be noted that the program corrected our initial estimate of 2.5 m. The lower frequency trials are more disordered due to the lower frequency waves being subject to a higher diffusion rate. This has the effect of lowering the signal to noise ratio and makes it more difficult for the machine to register. The models for the lower frequency trials, however, still give an average depth at around 2.2 m. At this location the inversion program accurately predicted the depth to the contact. What it failed to do, however, was to identify any subtle change in the contact. At the end of the survey line the depth of the contact should decrease to about a meter according to the resistivity survey in Fig. 9, although this was not detected. The reason for this can lie in the fact that the resistivity between the two layers becomes less contrasting towards the end of the survey. The shortfall of this location is that it gives no value on the adaptability of the program to deal with changing geometry or the sloping of beds. From this location it can be observed that given the right parameters an almost static contact could be modeled with relative ease.

5.2 Vomb

Our second trial was located near the village of Vomb. Situated in a open field used as a military training site, the geology of the ground was ascertained by three well logs. These well logs from the 1950's, archived by the Swedish Geological Survey show a stratigraphy of fine sand over clay and a top layer thickness increasing from ~2-5 m to the west to ~4.5 m to the east (Fig. 11). Four series were run back and forth changing the frequencies for each subsequent series. A GPS system was used to track the walking path (Fig. 12).

The variables chosen to be input in the inversion program were the same as at the previous Åkarp location. The geology is different at Vomb but the resistivity of the layers should be approximately the same at Åkarp. Note however that since the survey line was run forward and backwards, the initial depths at series 2 and 4 were input as 4.6 m. Table 2 shows the variables entered into the inversion program.

# of layers	2
Initial resistivity's starting at the top layer	100, 10
Initial thickness	2.5 (Series1,3) and 4.6 (Series2,4)
Weighting for resistivity starting at top	0.1, 1.0
Weighting for thickness starting at top	0.1

Table 2. Values entered into the EM Inverter program to create a forward model at the Vomb Locality.

The inversion results obtained at Vomb are listed in Appendix 2. A few interesting points can be noted. Firstly the model shows difficulty in interpreting smooth transitions. Looking at series 1, the depth gets caught on an initial value (in this case it is reasonable to assume the initial contact depth at 2.5 m) until it reaches a threshold and rapidly jumps to 4.6 m. More recent programs incorporate smooth generating algorithms that better exemplify geological models. (Constable et al., 1987; Farquharson et al., 2003; Sattel, 2005). The assumption made here by analyzing the well logs in Fig. 11 is that there is no physical drop from 2.5 m to 4.6 m in a 10 m interval. Such a drastic change in dip does not seem realistic at this locality. It would be more reasonable to assume that the bed dips gently through the entire section and that the program did not record this until the rapid increase in depth mid way through.

The inversion program also seems to have an increased difficulty with creating a model where the contact shallows compared to when it deepens. If comparing series 1 and series 2 note how series 2 has a much less ordered transition but is able to locate the depths of both the initial and end value. The reason for this can be argued, since the path of series 2 is 70 m north of series 1. It may be that the contact here has less of a resistivity contrast than its southern counterpart which leads to a raised difficulty in recognizing it. Since the sediments analyzed here have a rather small resistivity contrast, a broad contact or a mixing zone could make it harder for the machine to locate the bed boundary. However the inversion program has less difficulty in following a deepening contact than a shallowing one.

The choice of frequencies will have a large effect on the inversion model. By comparing series 1 and series 3 some disparities can be noted. The paths of these two series were almost identical. They differ only on the choice of frequencies where series 3 contained higher frequencies. The initially recorded depth

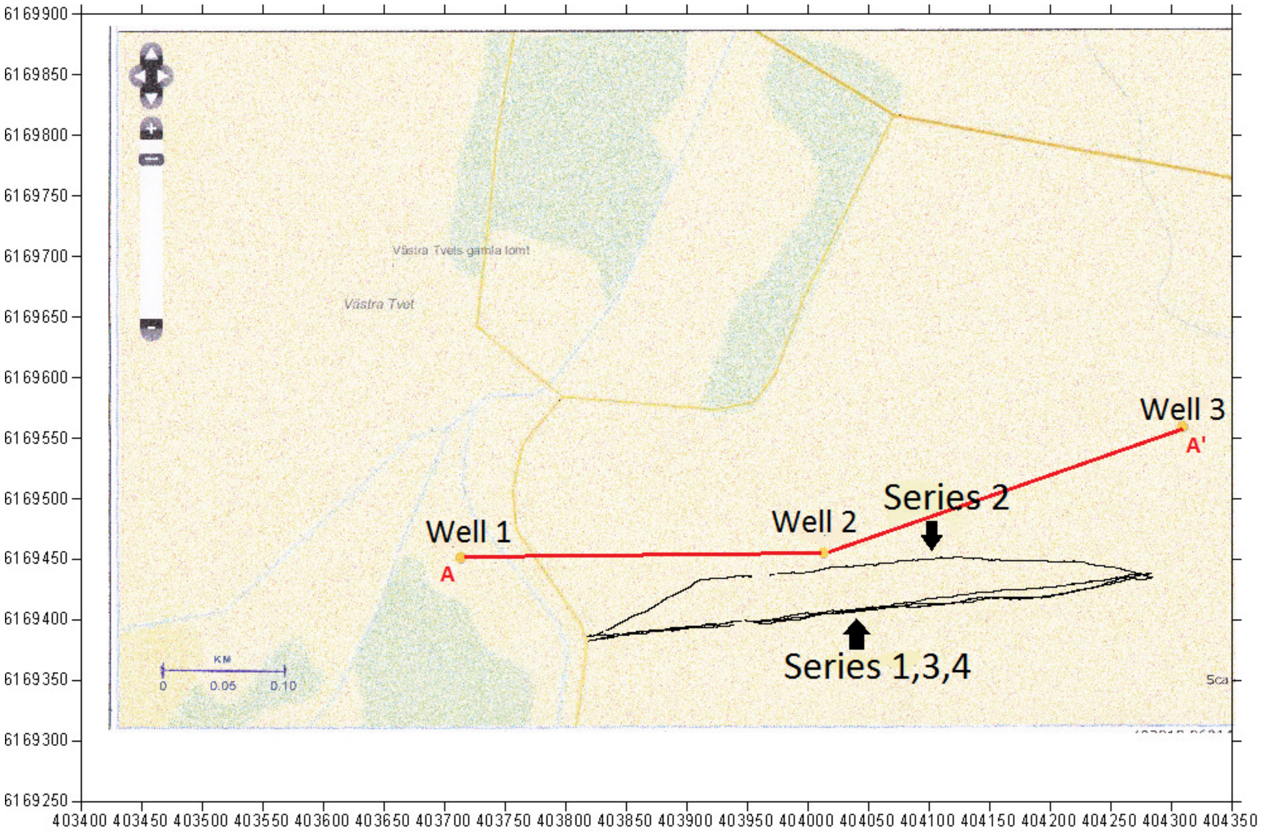


Fig. 12. Map showing the GPS coordinates of the survey lines walked at Vomb. Also the wells in Fig. 10 are positioned on the map. Red line shows location of profile in Fig 11. Map courtesy of The Swedish Geological Survey.

Fig. 13. GPS coordinated walking path for the Öved survey.

is the same for both while the depth of series 1 goes to a final value of 4.6 m and series 3 overestimates a value of 15 m. Here it can be seen what effect the choice of frequencies will have. Since higher frequencies do not penetrate as deep as lower frequencies do perhaps these frequencies were too high to be able to record the contact. Since the forward model determined earlier for this section had two layers, the program predicts a contact depth at 15 m. By observing the model values it can be seen that the inversion program has a tendency to do one of two things. Firstly it will remain on an earlier located value for a set period of time perhaps due to its inability to resolve layer depth with sufficient accuracy. Secondly, it will very often predict a value of 15 m depth by not successfully locating the contact and placing this value as an artificial depth. Series 4 looks like it has suffered from major flaws in the algorithm. It was unable to measure the thinning of the contact and got trapped at a depth of 15 m.

5.3 Öved

Our final survey was conducted along the edges of a rock quarry near the village of Öved. Unlike the former two locations there is a relative lack of geological information for this area. No well data or resistivity measurements were available here. An assumption was made about the layer configuration based on knowledge of the area and topography. The lithology at the site is a sandy till with a proclivity for pebble and boulder sized clasts overlying K-feldspar rich granite. The depth of the till at the initial point of the survey could be seen due to excavation in the quarry and was measured to be 1 m. The survey was conducted 10 m from an access road into the quarry (Fig. 13). The section starts on an extruding hill bordering the quarry and the survey line was walked down into a valley and up the adjacent rise to reach a main road. A cross section depiction of how the geology is assumed to look like can be seen in Fig. 14. Only being certain of the initial depth of 1 m raised the difficult in judging the accuracy of the inversion model. This area was chosen for examination to determine if a larger conductivity contrast would invoke a more accurate inversion model. Naturally at this location it was necessary to modify the forward modeling variables. The variables chosen were the result of a combined approach of experimentation and knowledge of common values for

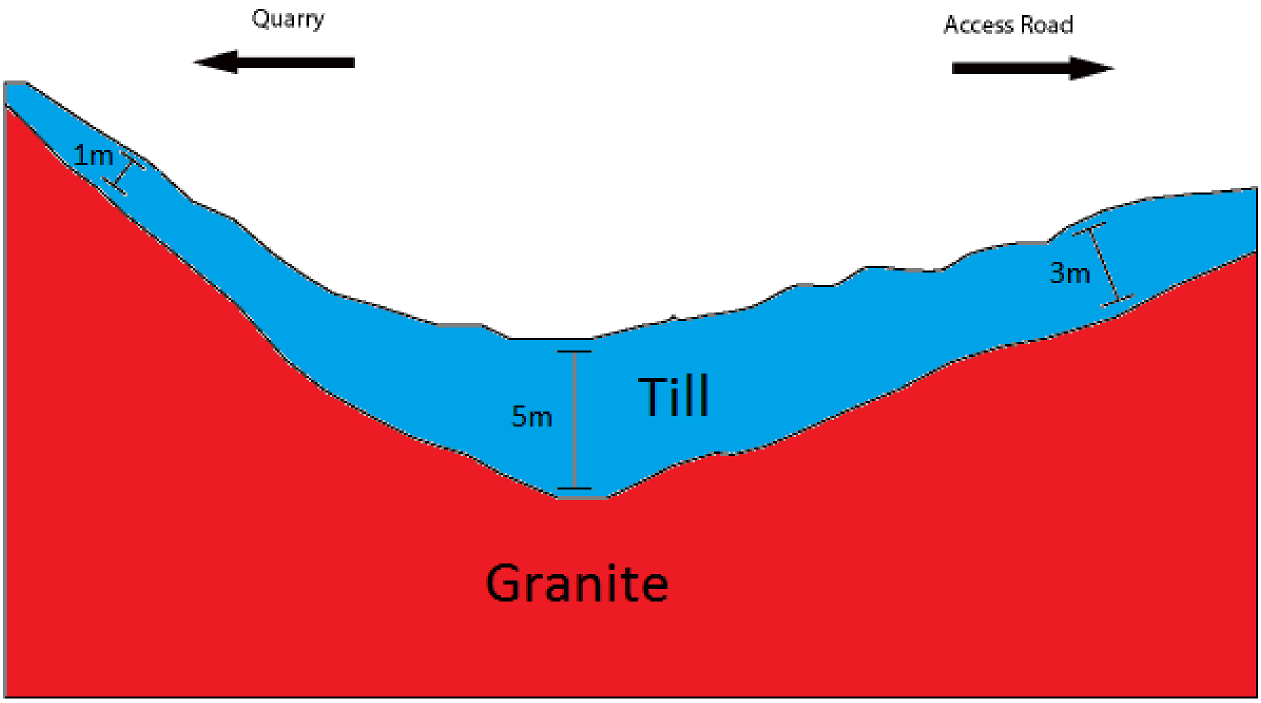


Fig. 14. A two-dimensional cross section depicting our interpretation of the subsurface at the Öved locality .

these specific rock types. They are summarized in Table 3.

# of layers	2
Initial resistivity's starting at the top layer	100,1000
Initial thickness	1
Weighting for resistivity starting at top	1.0,0.1
Weighting for thickness starting at top	0.1

Table 3. Values entered into the EM Inverter program to create a forward model at the Åkarp Locality.

The inversion result obtained for Öved is listed in Appendix 3. The resulting inversion model obtained is much different from our estimated cross section. Instead of the till layer becoming thinner as it approaches the main road it seems to become thicker. The inversion model the program predicted is a possibility, but without a more complete understanding of the subsurface, the values must be approached with caution. A small change in forward model for this section would yield large variations in the inversion model. This adds to the uncertainty of the interpreted section. What can be determined from this survey is that even with a higher conductivity contrast the program still has a very heavy reliance on the forward model variables. In future studies a more determined profile could give a better understanding of the ability of the inversion program to deliver results within a higher contrasting bed. Huang and Won (2003) claim that using the GEM-2 and a precursor to the program that was used in this survey, they could determine sea water depth along a coastal margin to a measured error of 5%. Measuring such a large resistivity contrast so near the surface in a homogenous layer would not be subject to losing very much resolution. In the Öved survey a lower resistivity contrast, a deeper section and an inhomogeneous medium makes appropriating an inversion model significantly more difficult.

6 Discussion

The results obtained above show some very distinct limitation of what frequency EM inversion can do. The inversion program used for this study shows to be unreliable and much too dependent on the forward model created by the user. Some major flaws are exposed with the inability of program to produce gently sloping and realistic geological models. The inversion models do vaguely represent the two layer configuration of a section, but a thorough understanding of the geology prior to surveying would be needed in order to make any use of it. The limitations of EM inversion have been observed for some time and researchers have been introducing algorithms that better develop smooth inversion models (Constable et al., 1987; Farquharson et al., 2003; Sattel, 2005).

An example of GEM-2 data being successfully inverted is the survey by Sams et al. (2008) of subsurface drip irrigation systems of the Powder River Basin. The survey conducted on behalf of the U.S department of energy was a test to see if the GEM-2 had the ability to monitor the spread of natural gas rich water within an irrigation system. Coal bed natural gas or CNBG is a new method of extracting gas from fractures within coal beds. This is done by first pumping out the water and thereby reducing the hydrostatic pressure and releasing the trapped natural gas. The Powder River basin produces around 1.9 barrels of water per 1000 cubic feet of gas. The water extracted is a byproduct and is toxic to humans. It has been proposed that the water be used to irrigate crops that could benefit from the organic rich compounds within. The GEM-2 was chosen as a rapid and cost effective monitoring device to keep this water from entering the water table. The inversion program used by Sams et al. (2008) was the University of British Columbia's EM1DFM. EM1DFM uses an Occam's inversion model pioneered by Constable et al. (1987) that can estimate depth more accurately and generates smooth transition models. This program offers one dimensional inversion that can be tied together to form a pseudo two-dimensional profile (UBC-GIF, 2000). Sams et al. (2008) results showed that they could reproduce the data with two successive surveys and that it compared relatively well to resistivity measurements on the same section. However, the magnitude of the conductive anomalies were found to be much lower with the EM device then with a resistivity measurment. Much like in our own survey of Åkarp, Sams et al. (2008) found similar values between resistivity and frequency EM measurements. However, the stratigraphy for their survey was more variable than that for the Åkarp survey. Their conclusion was that the GEM-2 device was suitable for tracking the CBNG water if it were to be introduced to the soil. In a comparison of results the EM1DFM program does not focus so much on tracking individual layers but rather tries to place conductivity values at a certain depth. The EM1DFM inversions resemble more closely resistivity inversion models depicted in Fig. 8 then the models gathered in this study (Appendix 1, 2 and 3). The tracking of the CNBG water seems well fit for the current capabilities of the GEM-2. The generalized information from the GEM-2 would provide monitoring on a large scale. If this large scale monitoring were to identify any infiltration of the CNBG water, more precise resistivity measurements can be used on those areas. Sams et al. (2008) surveys were conducted before the inclusion of CBNG fluid to the sediment. Whether a future survey can distinguish the CNBG water from the sediments with sufficient accuracy is not entirely clear. I am skeptical to see how well the water would be monitored in reality and believe the operations should be approached with care.

Another survey was conducted by Stepler et al. (2004) using the GEM-2 machine that attempted to image a sedimentary channel-levee/overbank. As sediments flow within a channel the finer particles (silt, clay) are expelled over the edge forming a natural levee. The river channel is later back filled with sand and/or mud as transport energy diminishes, normally due to a rise in sea level. The survey section of Stepler et al. (2004) was composed of a channel filled with sandstone and overbank facies composed of thin bedded shales. Using ground penetrating radar and gamma ray drill logs as quality assurances a grid was surveyed with the GEM-2 in an attempt to map the channel three-dimensionally. Their findings showed similar to our findings that the depth inversion gave only a general picture of the bedding. They found that the program failed to map the gentle slope that occurs between the channel center and the channel margins. This can be compared to our results in the Vomb area where the sloping of the bed was not identified until a very rapid transition occurred. The results for Stepler et al. (2004) are reasonably more precise than our values. They noted that the use of higher frequencies could make for a better analysis in tracking the stratigraphy inside the channel bed. The older version of the GEM-2 that they used in their study did not encompass frequencies higher than 21 kHz and since the channel depth of their section was no deeper than 2 m a higher frequency would give them the necessary resolution for a better analysis of their section. Our cross section in the Vomb area has its deepest point at a depth of 5 m. Higher frequencies did not seem to penetrate deep enough to locate the deepest contact. The lower frequencies, however, lack the induction power to accurately decipher small resistivity contrast. Direct current electric methods provide more precise inversion results because they do not rely on the proxy of EM waves to register conductivity. This tradeoff of depth vs. resolution is a major shortfall of frequency EM sounding. The attractiveness of the GEM-2 and similar instruments is the simple and rapid surveying method. The reduced time and manpower needed for application leads to a reduction in surveying cost.

7 Guide

Note that the inversion programs utilized with the GEM-2 have a large effect on the precision of the model. Comparisons with other field studies show the weakness of the EM Inverter program. Regardless of the inversion program used there are still limitations that can be observed universally with frequency EM devices. A big reduction in precision when compared to other methods is a major flaw. The inversion models are too reliant on the forward model being supplied by the user and most inversion models have to be approached with caution.

Since this method is cost effective there is still a wide application for such a machine. The following is a guide which can increase your chances of creating an accurate and realistic inversion model:

1. Understanding the geology of the section under study is of great importance for a successful inversion. The program needs an accurate forward

model to function. The forward model variables have such a large effect on the inversion model that they need to be well thought out. So knowing the stratigraphy, the resistivity, thickness and configuration of your section is the first step to developing an accurate inversion model.

2. Correctly choosing the operational frequencies is something that can be done in the field or prior to the survey. By relating what depth needs to be analyzed with what the subsurface conductivity should be, a relevant set of frequencies can be chosen. Higher frequencies will not penetrate the ground as deep but offer a higher resolution while lower frequencies will survey deeper with a reduced resolution. A conductive body will also be easier to locate than a resistive one. Using a wide bandwidth and running more than one series with different frequencies is recommended. This will help at the data processing stage. If the wrong frequencies are chosen contacts can be overlooked or lost as the section deepens. It is suggested that the GEM-2 machine is operated with 4 or 5 frequencies simultaneously which gives good balance between resolution and signal strength.

3. Approach any inversion model with caution. Slightly altered values will produce a different inversion model. Having some knowledge of geology will help you in distinguish realistic models from unrealistic ones. If using the EM inverter program look beyond the direct depth inversion and see if a pattern is distinguishable. No EM inversion program will gives a perfect inversion on the first attempt so being able to distinguish the realistic models from unrealistic ones is an important step.

Taking precautions and following these steps will bring a surveyor a long way in making a successful inversion model. Though ultimately the final verdict will lie in the operator's ability to judge how realistic the model can be. It is in this author's opinion that frequency EM inversion as it now stands can only find a place as an overview surveying method. It has proven to be too unreliable and imprecise to replace resistivity measurements. With further development EM inversion will surely become a more precise method, but some of its major shortfalls lie in the physical limitations of EM waves which cannot be resolved by any algorithms.

8 Conclusion

Multi-frequency EM sounding has been an emerging technology in the past 15 years. Instruments using this technique have sprung out to the market due to their ease of use, rapidity, portability and operability. They work on the concept that each frequency will penetrate the ground at different depth. Conductivity can be measured for each frequency and give an image of the subsurface. The inversion of multi-frequency EM data has proven to be much more difficult than inversion based on other geophysical methods used today. Surveys were carried out on three locations in southern Sweden. The locations were chosen due to their two-layer conductivity contrast. The surveys were conducted in order to determine problems pertaining with frequency EM inversion.

The results obtained showed that the EM Inverter program used had distinct problems in accurately identifying the subsurface stratigraphy. The inversion models only very broadly determined the depth of the contact and had difficulty in producing gently sloping curves. Explanations for how some of the more unrealistic models were determined to be either a poor choice of frequencies or problems with the program. Comparing our results with those of Sams et al. (2008) and Stepler et al. (2004) some underperformance in the frequency EM method could be distinguished. Identifying deeper sections require lower frequencies but lower frequencies will not resolve the stratigraphy to the same degree, which leads to features being missed altogether. However frequency EM devices do have a use in modern surveying as an overview method.

To improve the odds of obtaining a successful inversion there are some measures that can be taken. This mostly relies on the aptitude and geological knowledge of the operator, which can help in choosing frequencies more appropriate for the survey and a forward model more specific to the area. Frequency EM measurements are sure to become more relevant in the future but it is doubtful whether they will be replacing any of the established geophysical techniques, Instead, frequency EM may be an added tool to our arsenal working side by side in an attempt to better our understanding of the earth.

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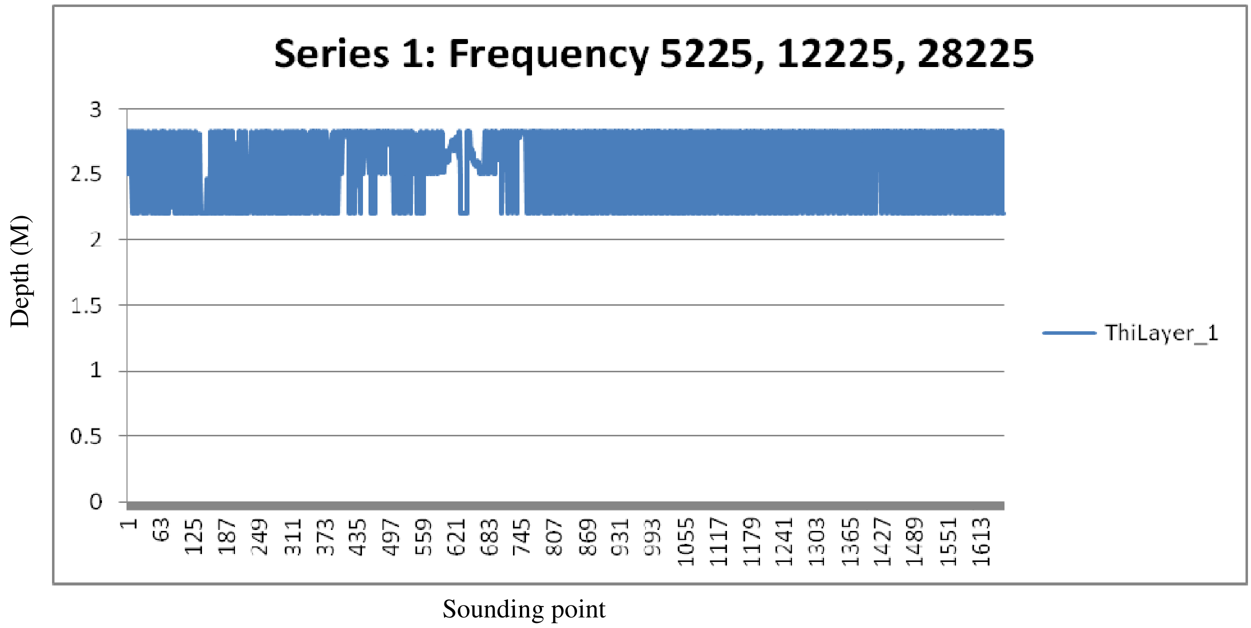
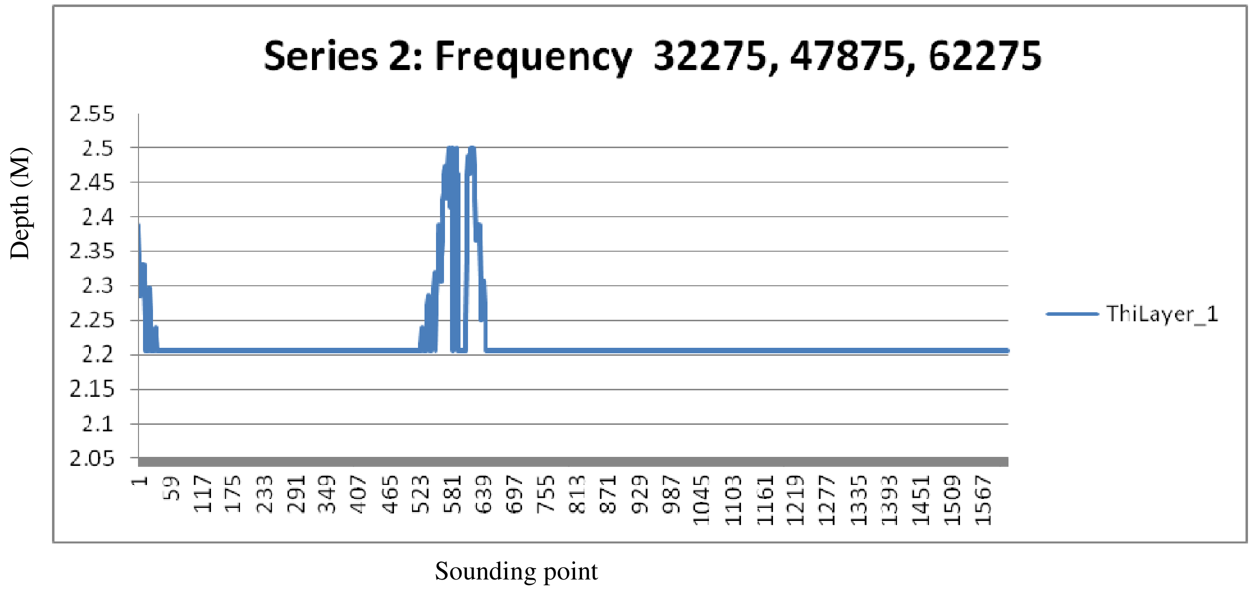
Appendix 1: Åkarp

This appendix shows the nine series inverted for the Åkarp locality. The graph's title depicts series number and the frequencies used during the survey in Hz. The vertical dimensions are depth measurements in meters while the horizontal dimensions are an enumeration of each soundings by the machine from start to end of the survey. Peak seen at point ~532 to ~640 is thought to be an underground power line and should be





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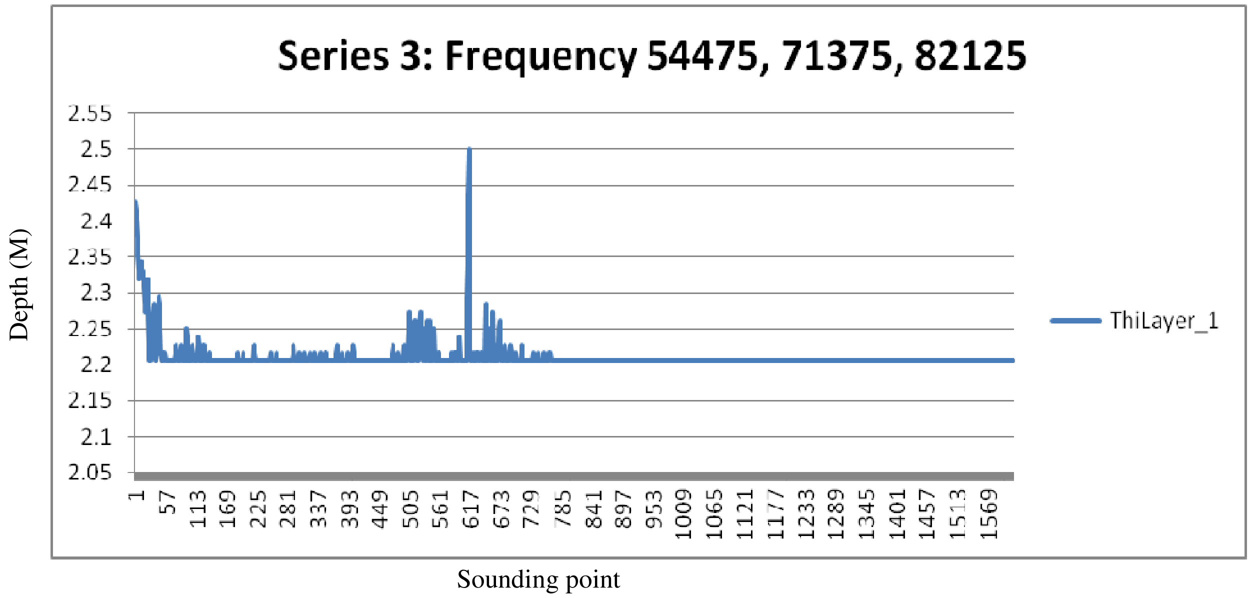

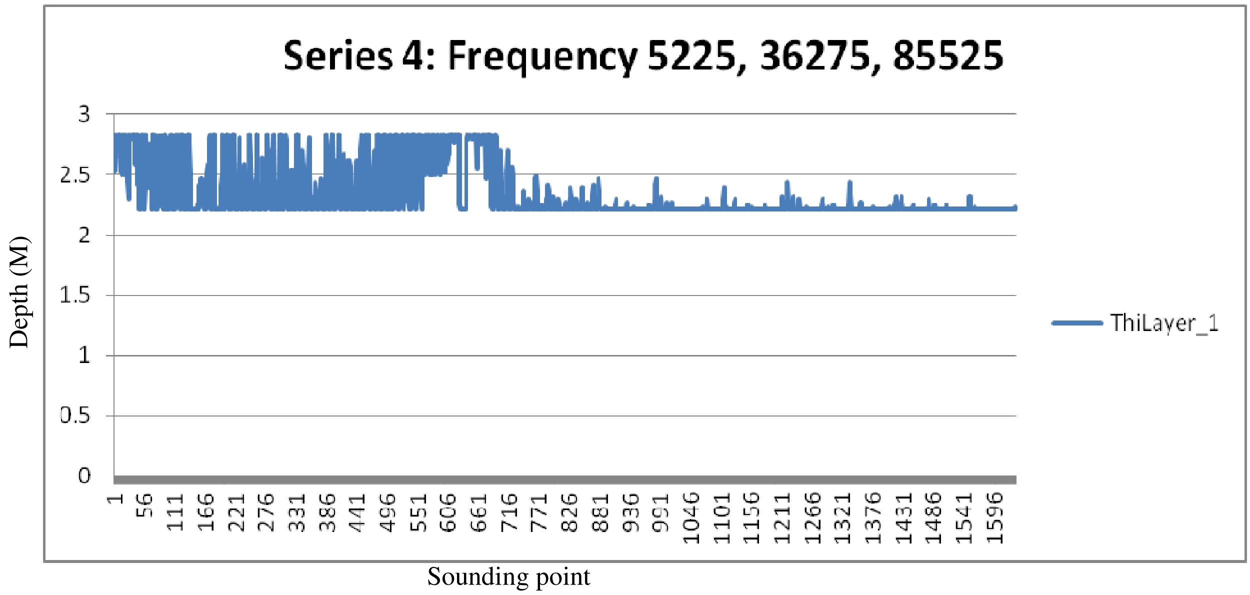

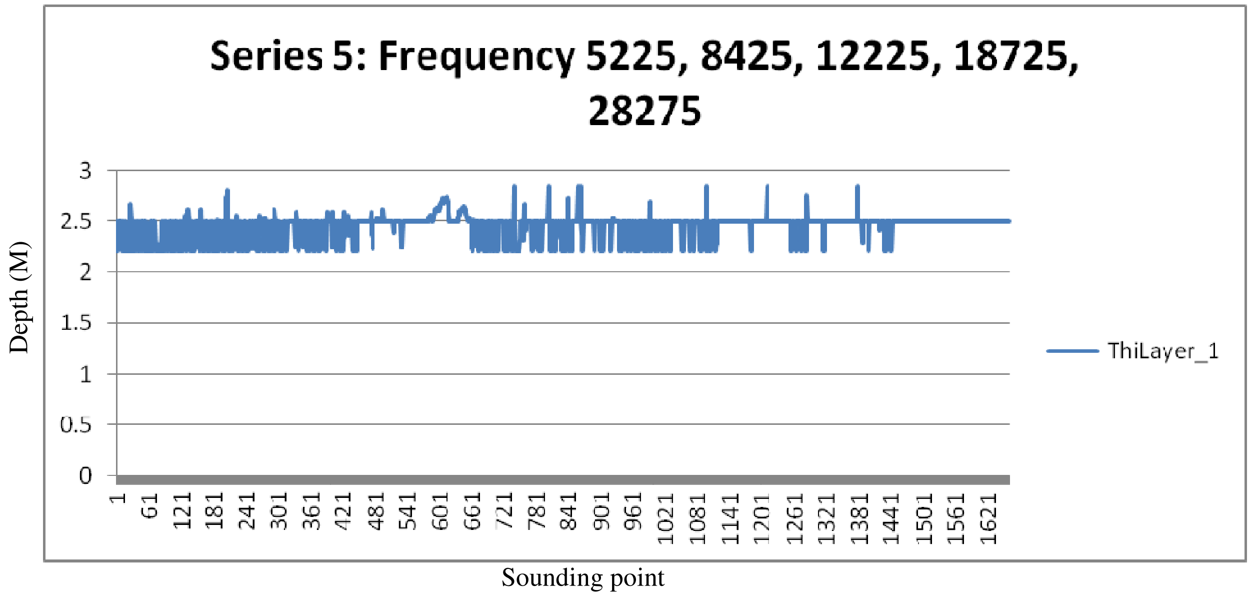

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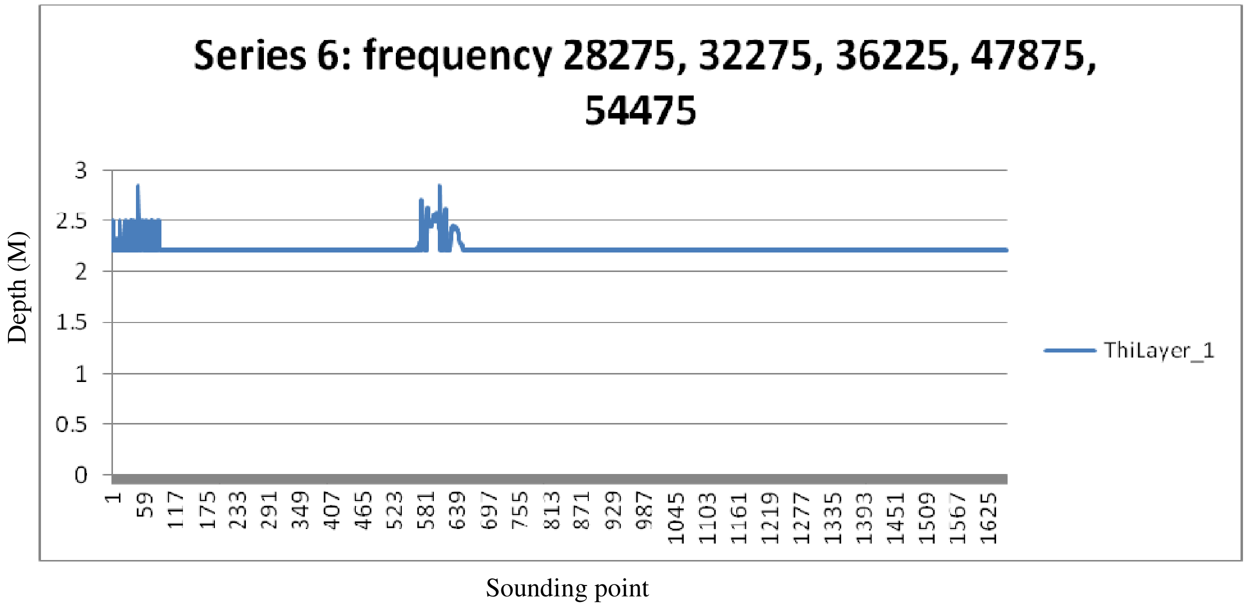

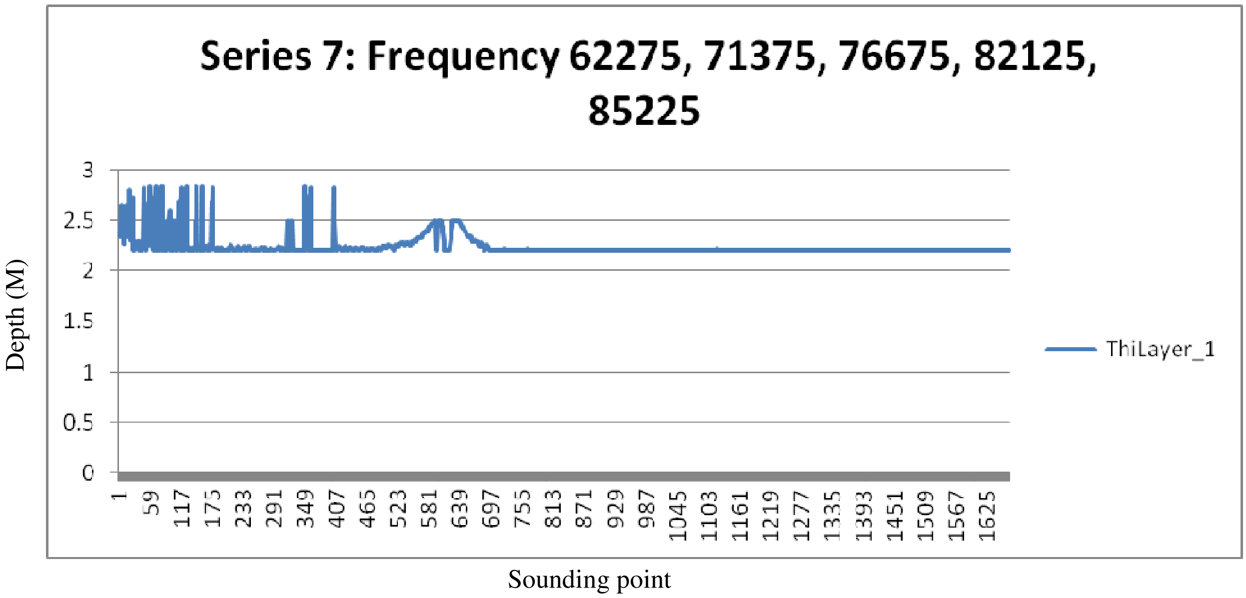

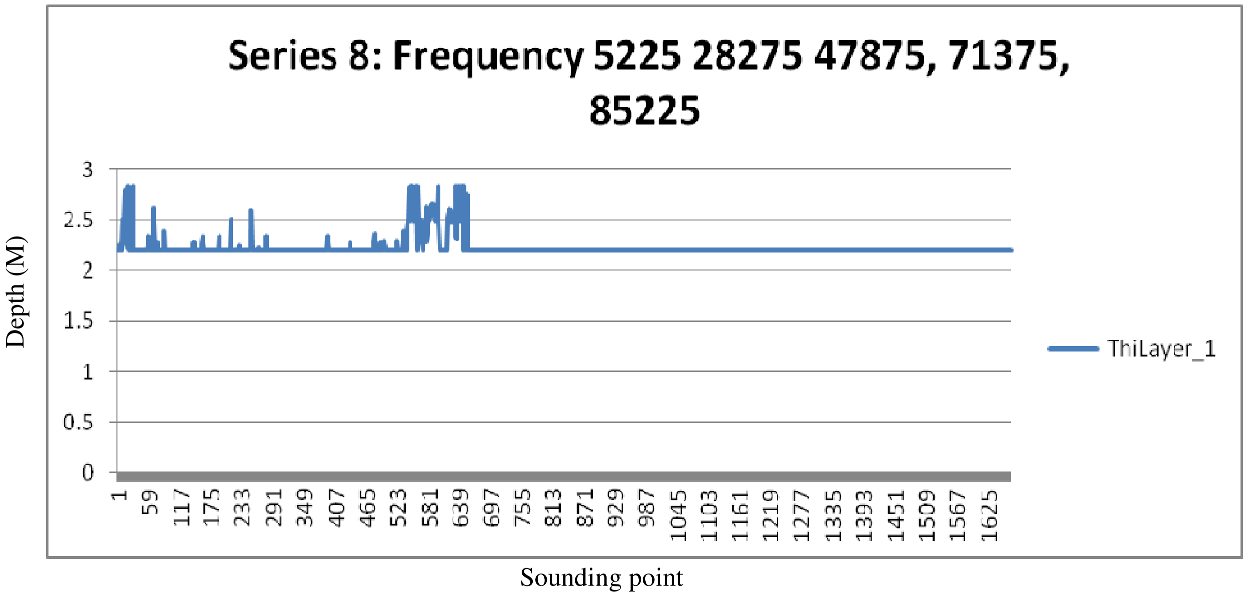

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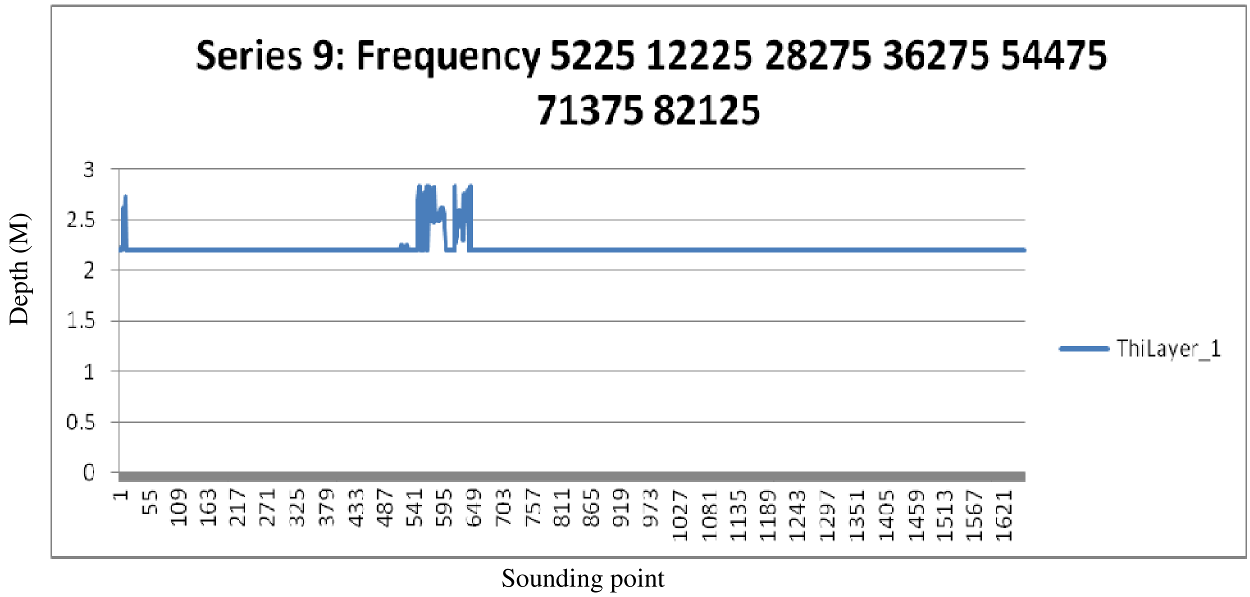
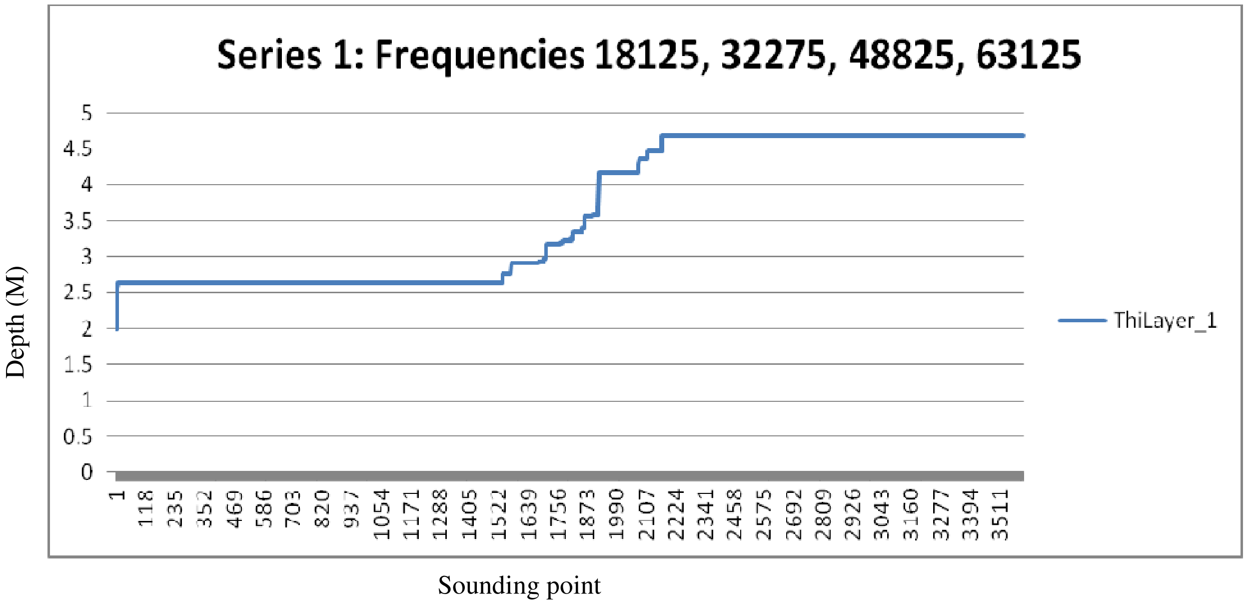
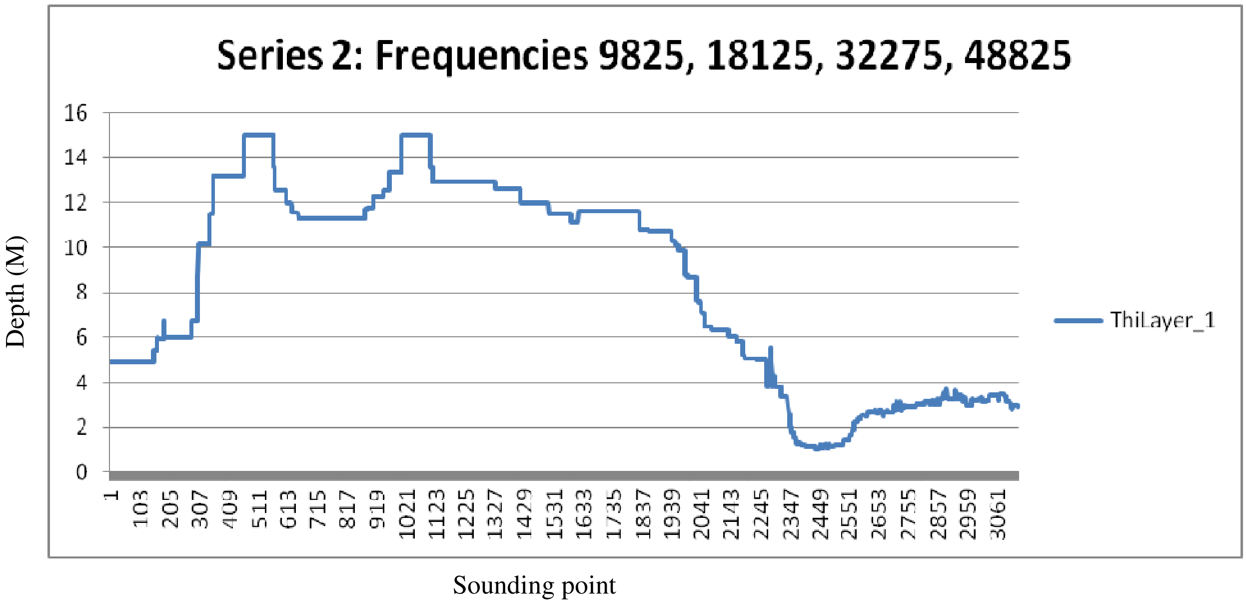


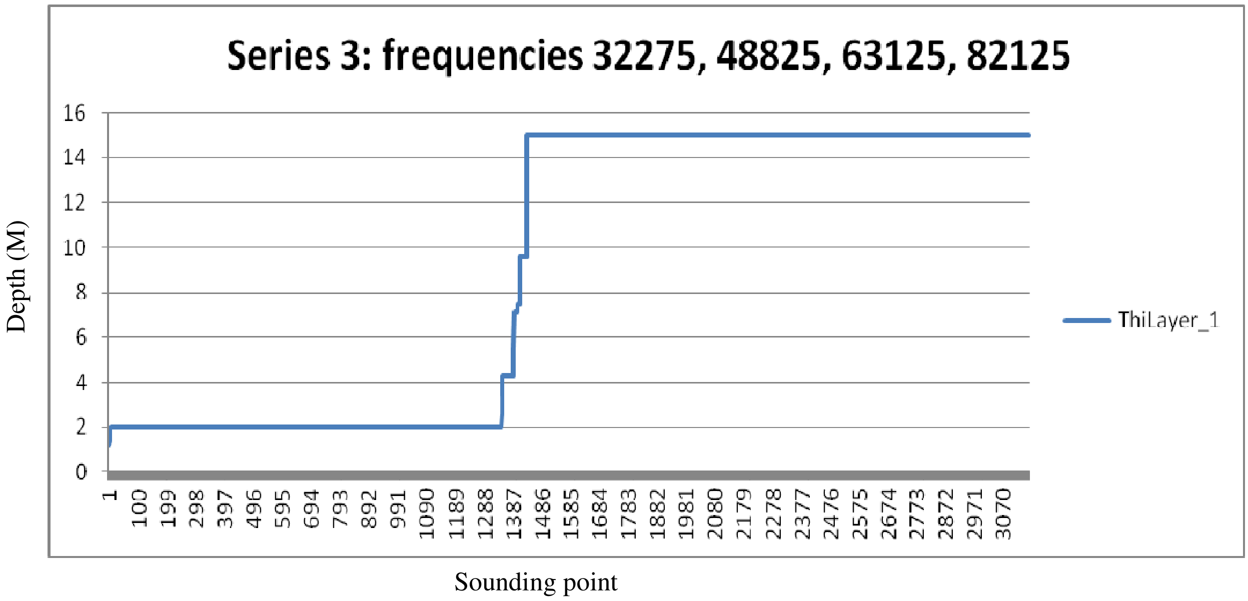
Appendix 2: Vomb

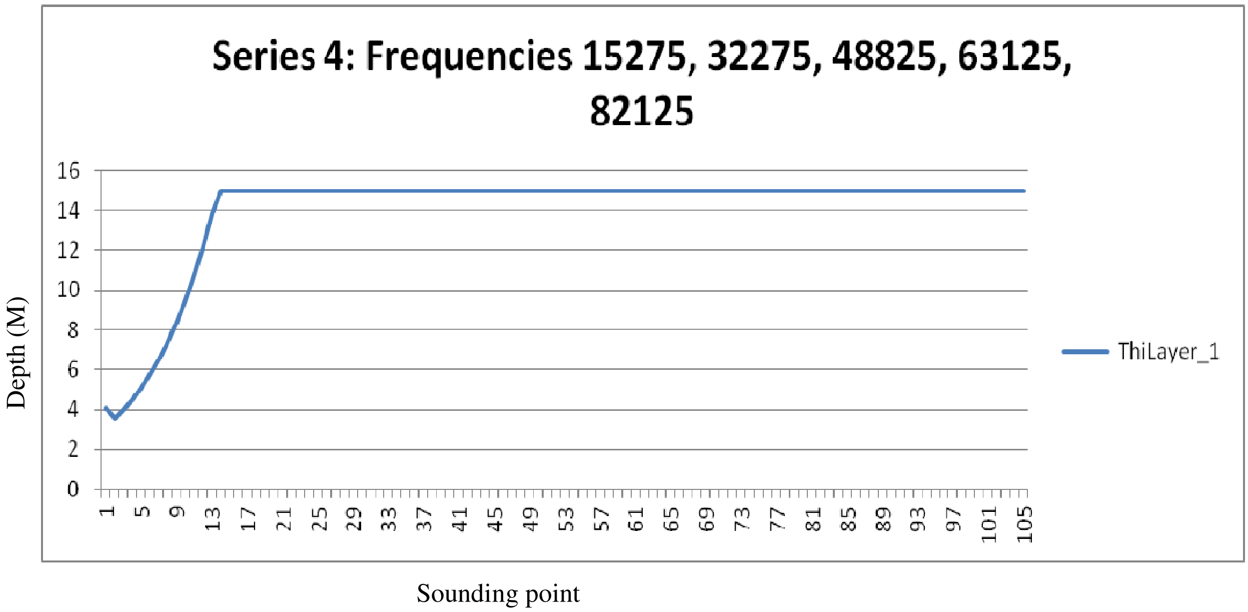
This appendix shows the four series inverted for the Vomb locality. The graph's title depicts series number and the frequencies used during the survey in Hz. The vertical dimensions are depth measurements in meters while the horizontal dimensions are an enumeration of each soundings by the machine from start to end of the survey.





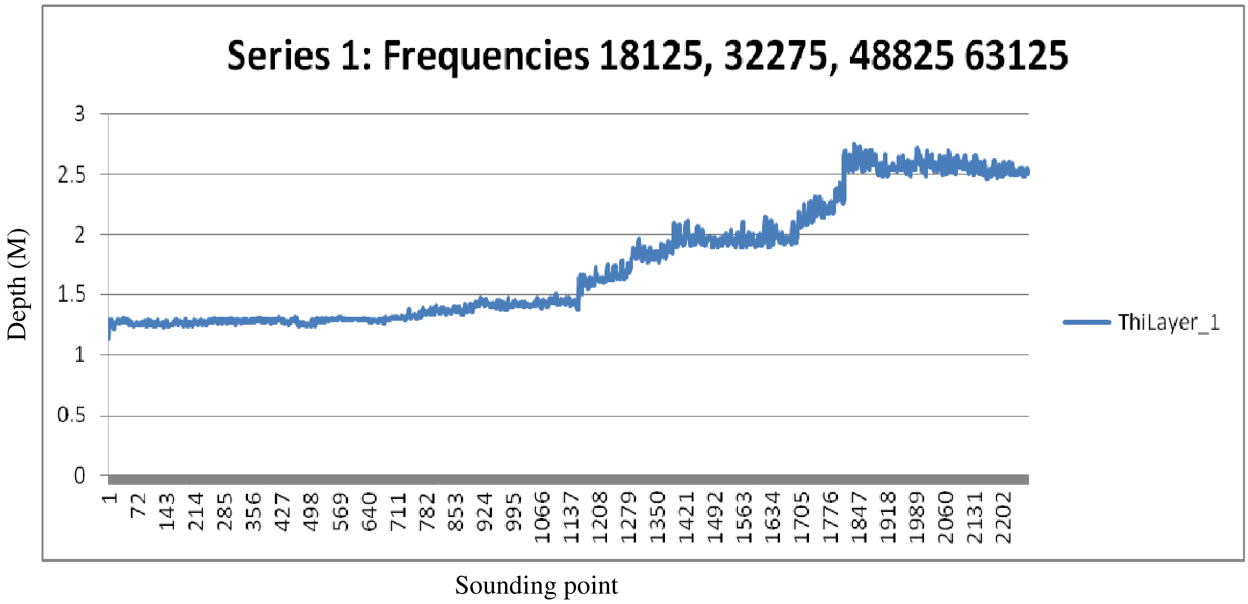
Appendix 2: Vomb





Appendix 3: Öved

This appendix shows the one series inverted for the Öved locality. The graph's title depicts series number and the frequencies used during the survey in Hz. The vertical dimensions are depth measurements in meters while the horizontal dimensions are an enumeration of each soundings by the machine from start to end of the survey.



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