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ABEM

Interpretation Guide

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ABEM WADI VLF INSTRUMENT

Theory, practice and case stories for WADI operators

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Contents

Strike
- Direction in which a long geological structure such as a fracture zone is oriented.

VLF
- Means Very Low Frequency. A military radio signal having a frequency of 15-30 kHz that is used for communication.

1. VLF Method, WADI Instrument

Most of today's geophysical surveying methods were developed from 1940 to 1960. Since that period, existing methods and instruments have grown more sophisticated, but there were no major break- throughs until the introduction of digital techniques in the late 1970s.

Digitalization revolutionized the field however, and in 1987 ABEM unveiled its WADI instrument, designed especially for VLF measurement. Even though the WADI seems quite simple, it contains a computer and a built-in memory, and it incorporates advanced technology. Moreover, it embodies the new philosophy that is emerging within the field.

The VLF method was first used for mineral prospecting around 1960. Like most other so-called electromagnetic methods, the VLF method can be used to find steeply dipping structures that differ from their surroundings with regard to electrical resistance. This method is thus very well suited for water prospecting in fracture zones. In the type of geology that prevails in large parts of Scandinavia (with the exception of Denmark), fresh water is often found in fracture zones. As this course proceeds, we shall concentrate on water prospecting, but most of our conclusions are also applicable to mineral and other similar types of prospecting.

The VLF method is one of a group of geophysical exploration

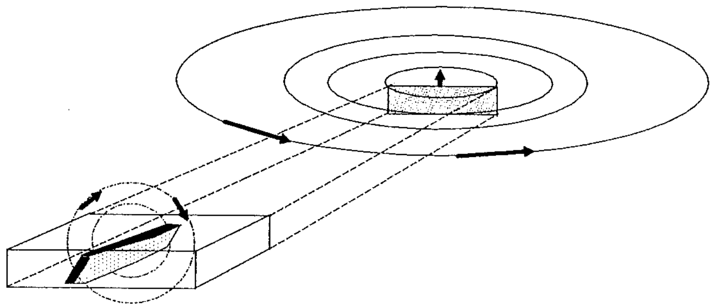


Fig. 1. A schematic diagram of the VLF principle.

methods that make use of electromagnetic fields to reveal objects located far beneath the surface. The letters VLF stand for Very Low Frequency. The low-frequency field that is used is sent out from a military radio transmitter. Normally, the frequency is between 15 and 30 kHz.

Two very important advantages are gained by using an already existing transmitter for geophysical measurement:

- The VLF instrument can be as compact and handy as a portable radio.
- The need for a transmitter within the measurement system itself is entirely eliminated.

1.1 WADI

The ABEM WADI instrument has three main parts:

- Antenna unit
- Analog signal-processing unit
- Computer unit

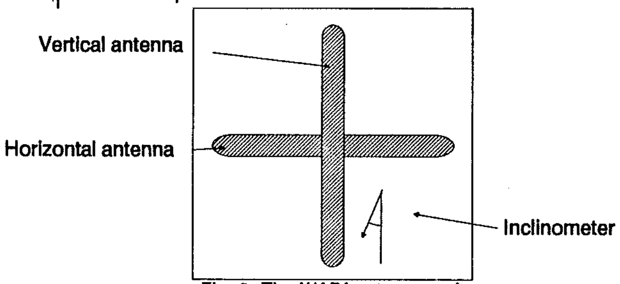


Fig. 2. The WADI antenna unit

The user (as a rule) deals only with the software, which consists of a large program that processes the coordinates and measurement data, provides the displays, etc. Fig. 2 illustrates the antenna unit. There are two 15 cm long ferrite-rod antennas, each wound with thousands of turns of wire. One antenna senses the field's horizontal component, while the other senses its vertical component. Thanks to an inclinometer (accurate to 0.2^0) that is built into the antenna unit, the user does not have to level the antenna precisely. The inclinometer enables the instrument to automatically correct levelling errors mathematically.

1.2 Transmitter

VLF transmitters are in operation at a number of sites scattered throughout the world. The ones in Europe and North America are of special interest to us. A VLF transmitter consists of a vertical cable several hundred metres long that emits a very powerful (300-1000

4. Glossary

ABEM
– A company named Aktiebolaget Elektrisk Malmletning (ABEM). One of the world's largest and oldest manufacturers of geophysical instruments. Until 1988, ABEM was a subsidiary of Atlas Copco. Today, ABEM is owned by Sveriges Geologiska AB (SGAB).

Anomaly indication
– Data having a special appearance when plotted along a profile. Often an indication of a promising geological structure such as a fracture zone. Note that the word anomaly is closely related to the word abnormal.

Depth of penetration
– The depth to which you can "see" beneath the surface using an electromagnetic surveying method.

Dip
– The angle throughout which a structure such as a fracture zone is tilted from a horizontal plane.

Filtering
– A method that enables you limit the amount of information you use. Here, mathematical filtering enables us to obtain the equivalent current density at a freely specified depth.

Fracture zone
– Fractures sometimes occur in the earth's crust as the result of minor strains. For water prospectors, the most promising fractures are about 1-5 metres thick and extend to the surface of the bedrock. A fracture zone contains crushed rock.

Geophysics
– A scientific discipline linked to physics, geology and mathematics.

Induction
– A phenomenon that generates electric current in a conductor that is exposed to an electromagnetic field.

Resistivity
– A constant property of a material that represents the electrical resistance inherent in the material. Expressed in Ωm (ohm-metres).

interpretation programs, final interpretation depends on the original data. The following are typical mistakes:

- Between-station distance too long. Normally, a distance of 10 metres is suitable, but if you are looking for structures close to the surface, 5 metres is better.
- Wrong orientation. Here, the operator has changed the measurement direction somewhere along a profile. Use a compass if you find it difficult to maintain the correct direction.
- Profiles too short. Normally, a profile should be longer than about 200 metres.
- Poorly covered anomalies. To ensure meaningful interpretation, an anomaly must be covered completely. Fig. 6 on page 10 provides more detailed information about this.
- Wrong direction to VLF transmitter. Always check to see that the field indication is greatest in the direction of the profile and that it is at a minimum perpendicular to the profile.
- Profile direction unsuitable. The profiles should run perpendicular to the strike direction (direction in which the geological features lie). For further information, see page 30.
- You have not used the WADI's built-in coordinate system.

b) If you have measured along a number of parallel profiles, you should start by correlating them. One simple way is to do this is to use the SECTOR program to plot profiles like those shown in Fig. 23 on page 25. Always emphasize the real part during interpretation.

c) Since water-bearing fracture zones are fair conductors of electric current, the anomaly indications they evoke will have a pronounced (strong) peak in the real part, but only a slight indication in the imaginary part.

Never forget that every anomaly revealed by the original data has its peak to the left of the fracture zone and its minimum to the right (with the zero crossover directly above the anomaly). In filtered data, on the other hand, the anomaly's peak is directly above the fracture zone.

After being powered up, the WADI instrument always presents filtered data by default.

kilowatt) transmission signal. The field emitted from such an antenna is horizontal, and its magnetic lines (which we use) comprise concentric rings that ripple out from the transmitter. Fig. 1 presents a very simple schematic diagram that shows field induction caused by a fracture zone. The map in Fig. 3 shows where the world's most important VLF transmitters are located.

Note that other transmitters are sometimes more useful in other parts of the world. In Africa, for example, Australian and Argentinean transmitters are more useful than those located in Europe.

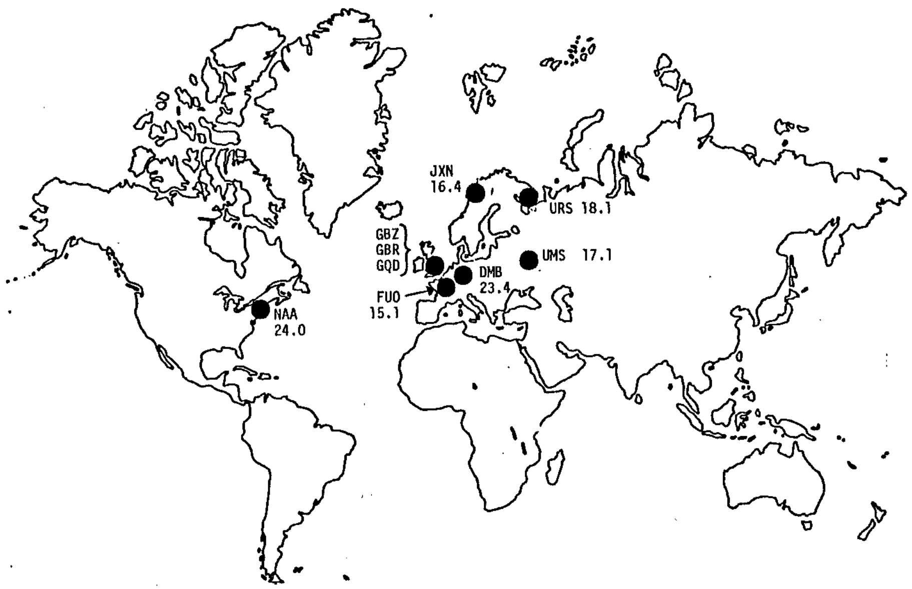


Fig. 3. Sites of some of the most important transmitters.

Data on some VLF transmitters

Frequency	Code	Country	Output (kW)	Range (km)
15.1	FUO	France	500	2000
16.0	GBR	UK	650	1400
16.4	JXN	Norway	350	860
17.1	UMS	USSR, Moscow	1000	1200
18.1	URS	USSR, Murmansk	1000	1300
19.0	GQD	UK	500	1400
19.6	GBZ	UK	550	1400
23.4	DMB	West Germany	900	
24.0	NAA	USA, Maine	1000	5600

Table 1: Data on some VLF transmitters. Frequencies are in kHz.

Moreover, there are situations in which a military VLF transmitter must be serviced. Remember, however, that the first Monday in each month is set aside for transmitter service. In addition, minor service jobs that require shutting down the transmitter are performed on all Mondays (usually around lunchtime, Greenwich mean time). Some transmitters supplement each other. For example, at least one of the three UK transmitters (GBR, GBZ and GQD) is always operating, and since all three are in roughly the same direction, you will always be able to use one of them.

1.3 Physical principles

When the field emitted by a transmitter strikes a body having low electrical resistivity, secondary circuits are created in the body. This is called induction. (The same thing happens in a bicycle-light generator when the rotating magnet induces currents in the coil.) These secondary currents, in turn, create a secondary magnetic field that is opposed to the original field emitted from the transmitter. Nature is quite conservative - it tries to counteract buildup of the external field by creating its own secondary field in the opposite direction.

As mentioned previously - only a body having low electrical resistance can create a secondary field. Hereinafter, however, we shall use the term "resistivity", which is more accurate than the word "resistance". The unit used to express resistivity is the Ωm (ohm-metre). Table 2 presents typical resistivity values for five frequently encountered materials.

tween-station distance of 10 metres. Since the first profile runs to the south, its between-station distance is designated 10S. When we reverse direction and move back along the next profile, the between-station distance is changed automatically to 10N when **F ::** is pressed on the WADI. The between-profile distance is set to 30W, which means 30 metres in a westerly direction. The next profile will thus be 2030W.

3.3 Example

To provide you with an example showing how to use existing information, we are including (in Fig. 27) an excerpt from topographical map 91 5d. Examples of suitable profiles have been drawn in heavy lines. The scale is 1:10000. If, for example, we have been given the task of finding a suitable source of water for the buildings shown at RASSA, this map will help considerably in planning the survey. The contour lines (lines of equal elevation) show that there are three valley-like depressions in the north-south direction. A good way to start would be to use the WADI to measure along one or more of the profiles that have been drawn on the map. Since all recent topographical maps are provided with contour lines, they are very useful in this type of survey. In areas of Sweden where this type of map is not available, topographic maps drawn to a scale of 1:50000 can be used. Frequently these maps provide a sufficiently good overview of the area where you wish to take measurements. If no suitable maps are available, you can hike through the area to get a rough idea of its geology, structures and topography. In Sweden (and also in some other countries) the types of maps mentioned above can be purchased in most book stores.

Two sources of information (in addition to the types of maps discussed above) should be investigated: geological maps and aerial survey maps showing magnetic terrain features. In Sweden, both can be purchased from Sveriges Geologiska Undersökning in Uppsala. In principle, these maps can be used in the same way as the topographical maps discussed above. You look for evidence that promising geological features lie in some direction (the strike direction) and then run your profiles perpendicular to this direction.

3.4 Interpretation tips

In conclusion we wish to present you with some valuable tips and ideas on how to obtain data of high quality and avoid interpretation mistakes.

a) Make certain that the data you collect is of as high quality as possible. Even with the best instruments and the most sophisticated the profile you are going to run. The WADI instrument can scan automatically and then display the most powerful currently available VLF transmitter. However, the operator must check to see that the direction to the transmitter is suitable. This can be done by rotating the entire instrument while watching the bar at left on the WADI display. This bar should reach its minimum at a direction perpendicular to that of the profile in question. It a transmitter is unsuitable, select another (usually you will want the second most powerful), and repeat the procedure. Often, you will know in advance that a given transmitter is located in a suitable direction. In such case you can select it straightaway.

e) Always maintain a constant direction of measurement. This means that even if your profile includes an obstruction, you must take all measurements with the instrument pointing in the same direction.

f) Try to take as closely spaced measurements as possible. Use a between-station distance of 5 or 10 metres when you are searching for fracture zones. But remember that it do not take twice as long time to run a string of measurements spaced 5 metres apart than 10 metres.

g) Stand still while you take a measurement.

h) If you are totally unfamiliar with the area in which measurements are to be taken, you should run profiles in two directions. But remember to change to a more suitable transmitter when you change to the second direction.

3.2 Coordinate system

Your WADI instrument stores data using a geodetic coordinate system. Fig. 26 shows, in principle, how to use this coordinate system. Note that the directions are relative. That is to say, the north that appears on the diagram does not have to coincide with the magnetic north shown by a compass. In this example, it was decided to measure along profiles having a compass direction of about 20°E. Directions in the local coordinate system thus do not have to coincide with compass directions. Since the profiles run close to the magnetic north-south direction, we decided to define them as north-south. The coordinate at the starting station is set to 2000W/0S. The number 2000 is quite arbitrary, but the prefix W (or ⇐ as it appears on the WADI) means that the profile runs in the north-south direction. The origin, namely 0S, has been selected as the starting coordinate.

The next major step is to define the between-station distance and the between-profile distance. In this example we have chosen a be-

Resistivity and depth of penetration

	ρ	δ
Granite	>5000 Ωm	>300 m
Clay	10-100 Ωm	15-40 m
Moraine	100-2000 Ωm	40-200 m
Tap water	50-200 Ωm	30-60 m
Saltwater	1-10 Ωm	4-15 m

Table 2: Typical resistivity (ρ) and depth of penetration (δ) values for frequently encountered geological materials.

A resistivity of 5000 Ωm can be considered almost infinite in the types of situations we will encounter. This means that an electromagnetic field can pass through granite with virtually no attenuation. On the other hand, a moraine overburden that is, say, 10 metres deep can affect on the field. One measure of the extent to which the field is affected is called depth of penetration. This is often designated by means of the Greek letter δ (delta):

$$\delta = 503 \cdot \sqrt{(\rho/\nu)} \text{ [metre]}$$

where ρ is resistivity in Ωm and ν is frequency in Hz.

If we set frequency equal to 15.6 kHz in the above equation, the penetration becomes:

$$\delta = 4 \cdot \sqrt{\rho} \text{ [metre]}$$

This simple equation can be used in all practical VLF situations. If more complicated equations and physical relationships are used, it can be shown that when an electromagnetic wave has reached a depth of δ, it will have lost so much energy that it is unable to create a secondary field. The depths of penetration shown in Table 2 were calculated using the above equation.

1.4 Anomaly

As indicated in Fig. 1, an object such as a fracture zone must be of a certain size before it can be revealed using the VLF method. In practice, this means that it should be longer than about 50 metres and have a depth extend of least about 10 metres. On the other hand, a thickness of 1 metre suffices. Moreover, you must select a transmitter that lies in the body's strike direction. (The word *strike* as used in geology means the direction in which geological features lie.) That is to say, it must be located close to a line that drawn longitudinally through the length of the body. This is because the lines in the magnetic field (as mentioned before) must pass perpendicularly through the body in order to induce secondary currents in it.

We have now established an important principle.

» **The VLF method can be used to reveal steeply dipping structures with large cross-sections and low resistivities.**

A WADI VLF instrument records the ratio (expressed as a percentage) of the strengths of the vertical and horizontal fields at the ground surface. Since the primary field emitted from the transmitter is horizontal, it is evident that a normal reading (taken where there is no anomaly) will be zero. What's more, the reading will be zero even if in the presence of a horizontal layer of material having low resistivity (such as clay or saltwater).

In some cases, a cable or metal pipeline (for example) will show up as an anomaly that resembles a fracture zone. For this to occur, however, the cable must be grounded so that the induced currents can "return" via the ground.

A deviation from a normal WADI reading is called an anomaly indication. By looking at Fig. 4 and doing some geometric reasoning, we can see that the anomaly indication obtained from a steeply dipping conductor will comply with what is set forth below.

When you use an electromagnetic field in VLF prospecting you must - in addition to amplitude - take phase displacement relative to the primary field into consideration. For VLF however, instead of using the terms amplitude and phase, we talk about the real and imaginary parts respectively. The anomaly indication shown in Fig. 4 is linked to the real part. The WADI instrument records both the real and imaginary parts, but since most of the useful information is found in the real part, we shall devote most of our discussion to it.

1.5 Disturbances

Anomaly indications can be caused by many things other than geological objects. Cables, metal pipes, electrical fences and the like can cause very strong anomaly indications. This is because they are usually grounded, which permits a large ground-return current loop to form. You should try to avoid such sources of disturbance. If possible, you should arrange your survey along profiles that are parallel with the disturbing cable, thereby reducing the extent of the disturbance. Disturbances caused by an electrical fence can often be eliminated by breaking the connections between different parts of the fence before taking your measurements. Remember that it is not the current in a power cable or the like that causes problems; the secondary field is caused by induction in the cable.

3.1 Planning

One major advantage of the VLF method in general and the WADI instrument in particular is that you don't have to plan your survey in detail. On the other hand, it's advisable to obtain a general overview

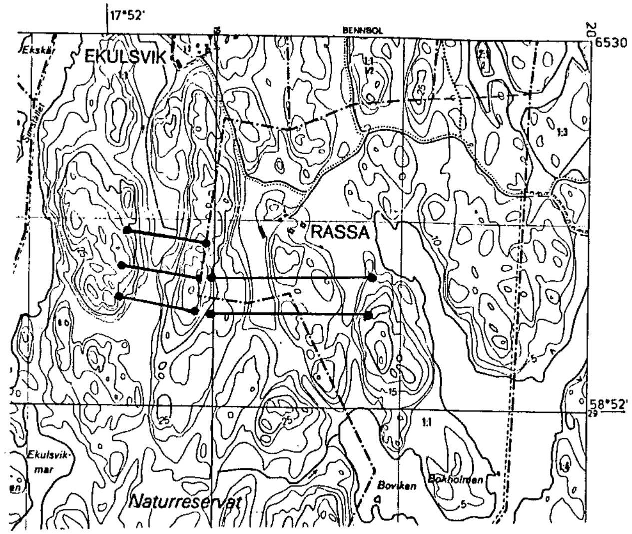


Fig. 29. Excerpt from a topographic map.

of the area in question before starting out.

a) Do landscape features tend to run in some direction? Promising fracture zones often run parallel with streams and rivers.

b) Run, whenever possible, one or more profiles perpendicular to the direction of any landscape features like those mentioned in a) above.

c) If you wish to measure more than one profile, it is always advisable to use a proper geodetic coordinate system. Such a system is built into the WADI. More information on the coordinate system is presented later on.

d) After you have decided on the profiles (and thus the measurement directions), you must choose a suitable transmitter. As explained in the theoretical section above, the direction to the transmitter must be nearly (within about 20°) perpendicular to achieving good results. It is at least as important to use a transmitter in a suitable direction to the geological strike direction.

In this actual example seven profiles were measured over an evident dyke of about 10m in width, which cannot be traced on the ground, but is clearly visible on the aerial photo. All the data are shown together on the multi profile plot in Fig. 26. A borehole has been located following the indications given by the WADI at around coordinate 64 on profile 6020E. The borehole was drilled to a depth of 45 metres, all the way through fractured dolorite. At 10m there was wet samples indicating a little bit of water (1 litre/min.); at 45m there was another minor strike of water, but drilling could not be continued due to the collapsing of the borehole in the fractured dolorite. A second borehole was drilled around coordinate 54 on profile 6010E, see Fig. 27. The samples indicate that the borehole was correctly drilled into the contact zone of the sandstone.The depth was 76m with a good strike of water at 52m (30 litre/min.). This spot was identified again with the WADI.

3. Measurement techniques

You interpretation results will not be reliable unless your readings are

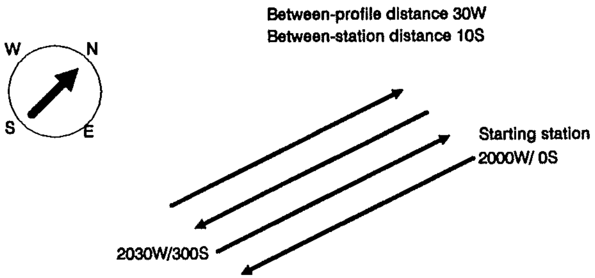


Fig. 28. Definition principles for the coordinate system.

of good quality. And even though you may think this is quite obvious, readings are all too often virtually unusable. But the survey crew goes right ahead and tries to evaluate the data -- and the results are little better than what might have been obtained from a daily horoscope. We shall now review the most important rules that must be observed when conducting a VLF survey with a WADI instrument (with emphasis on water prospecting).

1.6 What does an anomaly indication look like?

The WADI instrument is designed so that anomaly indications in the real part are always similar to the one shown in Fig. 4. That is to say, a positive bulge (peak) appears to the left of the subsurface structure, and a negative bulge appears to the right of it. In a simple case like the one shown in Fig. 4, it is easy to locate the fracture zone. In complicated cases that involve a number of subsurface bodies, it can be very difficult to ascertain the positions of the individual bodies, even for professional geophysicists.

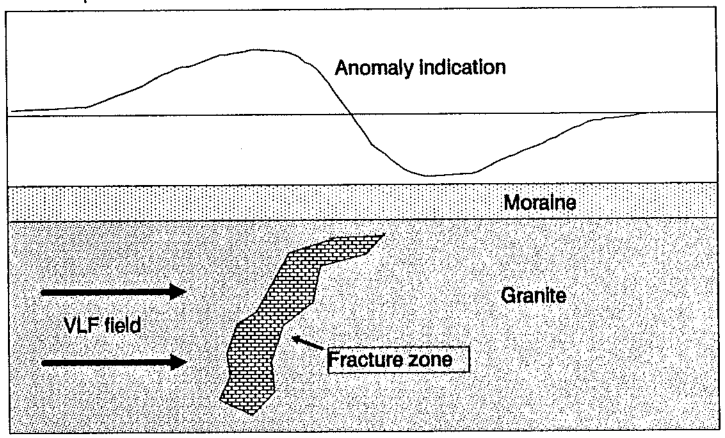


Fig. 4. A typical anomaly indication (original data)

In Fig. 4 is shown how a water-bearing fracture zone in rock generates a secondary field that causes a typical anomaly indication on the wadi instrument.

1.7 Filtering

Processing the measured VLF data using numeric algorithms can make it easier to interpret results. Here, an important step forward was taken in 1983 when a description of a filtering method was published[1]. This method vastly facilitates the interpretation of anomaly indications.

Filter action can be expressed mathematically in terms of a convolution.

$$F_0 = -0.102 \cdot H_{-3} + 0.059 \cdot H_{-2} - 0.561 \cdot H_{-1} + 0 \cdot H_0 + 0.561 \cdot H_1 - 0.059 \cdot H_2 + 0.102 \cdot H_3$$

where H_{-3} through H_3 are the original VLF data (as shown in Fig. 4 for example), and F_0 is the filtered result.

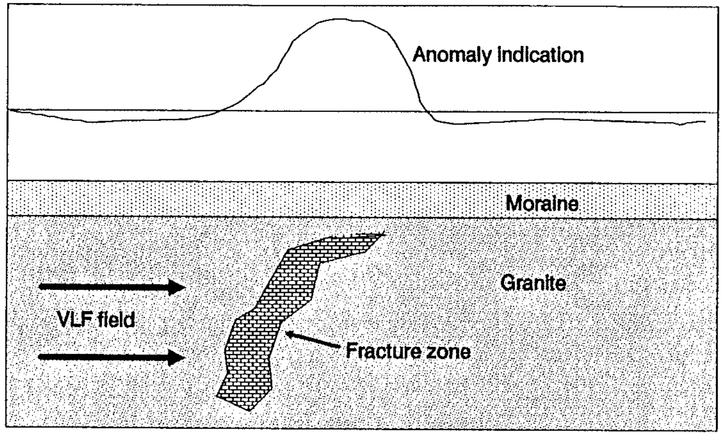


Fig. 5. A typical anomaly indication (filtered data)

The filter coefficients are moved along the profile station by station (the term "station" as used here means a measurement site), and the six multiplications and additions shown in the above formula are carried out for each station. For this type of filtering, the distance between stations H_0, H_1, H_2, ... (hereinafter called the between-station distance) can be selected as desired. Information about a specific depth can be obtained by selecting an appropriate between-station distance.

The filtered curve can be considered a representation of secondary currents in the ground. More precisely, however, filtering comprises a numeric algorithm - a black box that can be used to convert com-

1 Linear Filtering of VLF dip-Angle Measurements, by M. Karous and S. E. Hjelt, Geophysical Prospecting 31, 1983, 782-794.

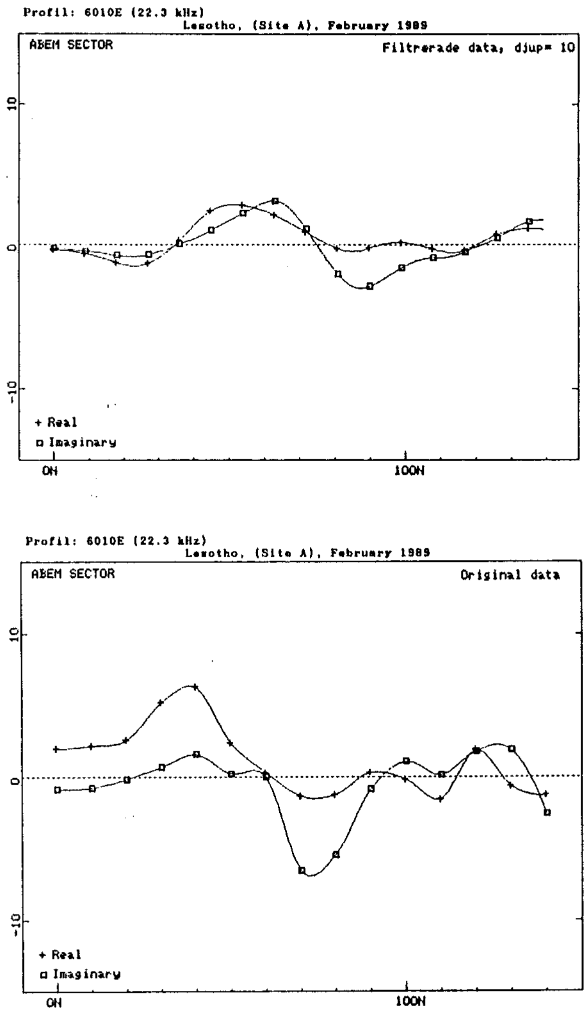


Fig. 27. Lesotho, Site A. Data from profile 6010E.

2.4 Dolorite dyke, Lesotho

The last example is taken from a projekt in Lesotho, southern Africa (Lat. N29^0, Long. E28^0). The data were provided by Th. Fissler, Swiss Assoc. for Development and Cooperation. It illustrates a situation commonly found in Lesotho, e.g. dolorites intruded in the sandstone with an average width of 5 to 15 metre. These dykes are usually traced on the ground or clearly visible on the aerial photos. Water is commonly found in the fractured contact zone between the sandstone and the dolorite at an average depth of 30 to 50 metres.

Traditionally it has been very difficult to make VLF measurements in Africa due to the long distance to the transmitters. The experience gained from this projekt shows that several transmitters can be used by the WADI in Africa. The strength of the primary VLF signal is quite low: the Australian NWC transmitter at 22.3kHz has a strength of 8 to 17 on the WADI scale, corresponding to $200 \cdot 10^{-9}$ to $800 \cdot 10^{-9}$ A/m. It was found that the field strength is not the most important factor for

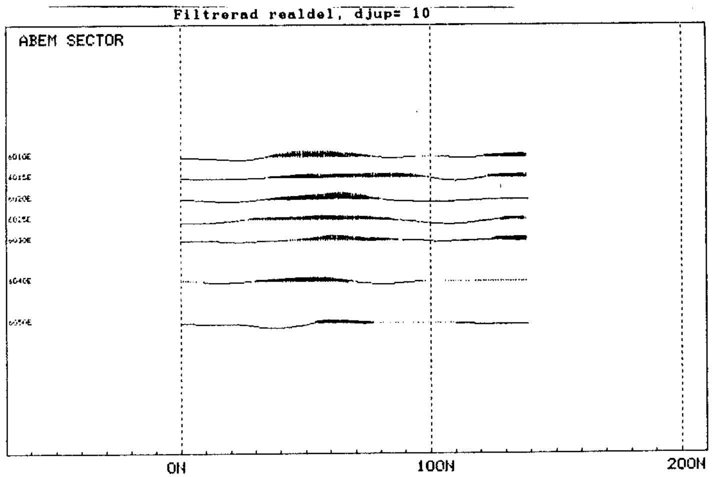


Fig. 26. Lesotho, Site A. Multi profile plot.

plicated VLF anomalies to curves that are easier to interpret. A comparison between the original data (Fig. 4) and the filtered data (Fig. 5) shows that after filtering it is much easier to locate a fracture zone since all you have to do is look for the highest point on the curve. The peak of the bulge now appears directly over the fracture zone. The filtered real part is always obtained (default display) on the WADI instrument. If so desired, however, you can also obtain other curves by issuing special commands. If, for example, you press **F⇒1** you obtain the original real part (shown, for example, in Fig. 4).

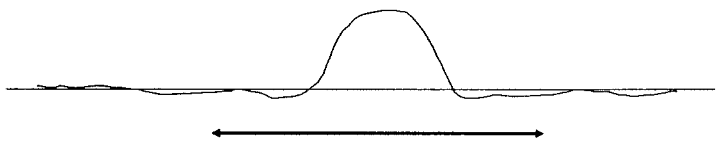
A profile that has been stored in the WADI can be filtered at different between-station distances. This means that the equivalent current density can be calculated for different depths. It's easy. All you have to do is change the between-station distance and press the key again. Result: you can view the anomaly indications for different depths without going out and gathering new data along the profile.

1.8 Vertical cross-sections

As mentioned above, between-station distances that provide different filter coefficients can be selected as desired. By gradually increasing this distance from 2 to 60 metres (for example), you can obtain information about progressively deeper depths. One way to present the filtered data is on a gray-scale diagram rather than on a curve like the one shown in Fig. 5. Gray-scale presentation (where black and white represent high and low values respectively), provides a clear picture of current density in the ground. Examples will be presented later.

1.9 Interpretation

Since a filtered real-part curve is always displayed by default when you power up the WADI instrument (after which you can select some other type of display), it is very important that you have a qualitative understanding of such curves. And you must also be able to recognize typical anomaly indications. Here, we shall concentrate on the



A complete anomaly indication
Fig. 6.

real-part the curve that is shown automatically by default when you power up the WADI.

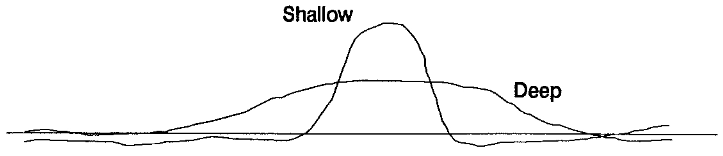


Fig. 7. Difference between shallow and deep conductor.

It is important to carry out measurements along profiles that are sufficiently long, since this is the only way to make certain that you are viewing an entire anomaly. Fig. 6 shows what we mean by an anomaly indication that is complete (sufficiently long). Note how the curve fluctuates around zero initially and then rises to form a high positive bulge (peak), after which it drops close to zero again. A complete WADI VLF anomaly indication extends far enough in both directions to make certain that position and appearance are both depicted clearly. Fig. 7 shows the difference between the anomaly indications obtained from a deep structure and one that is close to the surface. These two curves differ mainly with regard to the widths and amplitudes of the anomaly indications. Deeper anomaly readings are wider, but have lower amplitudes. However, a low amplitude can also result from a poor conductor (a geological structure that has medium or low electrical conductivity).

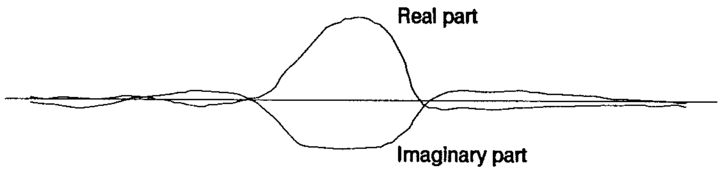


Fig. 8. Typical anomaly from a good conductor.

In addition to the real parts shown in Figs. 6 and 7, the WADI instrument records what is called the imaginary part. However, explaining this "out-of-phase" component is quite difficult. In this course, understanding the meaning of anomaly will suffice.

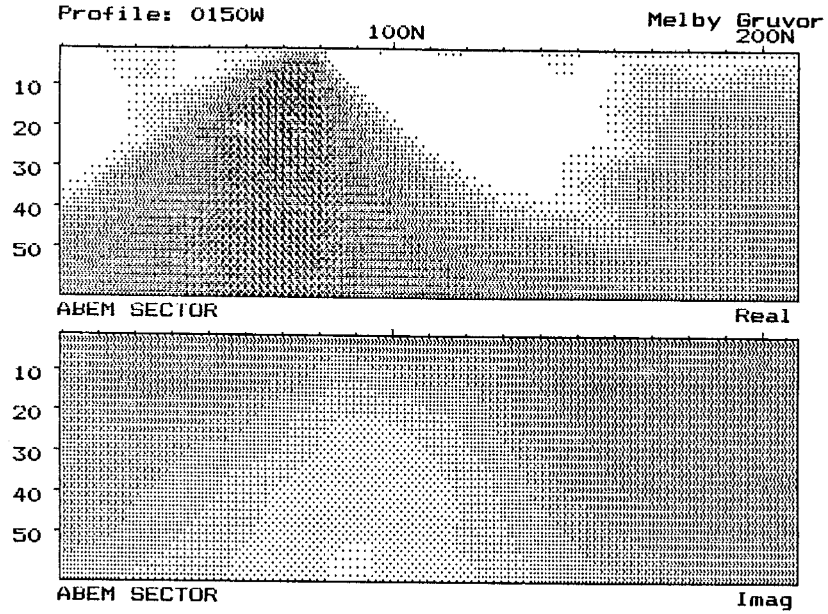
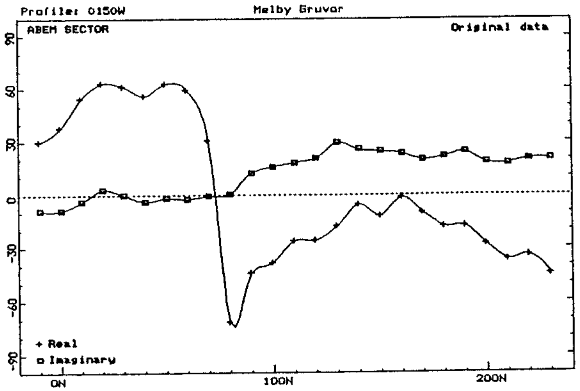


Fig. 25. Vertical cross section from data in Fig. 24.

weak, we can see that it is significant since it appears on all of the profiles.

Fig. 24 shows the 150W profile. Here we can observe an anomaly clearly in both the original data and the filtered data. The vertical cross-section for these data appears in Fig. 25.



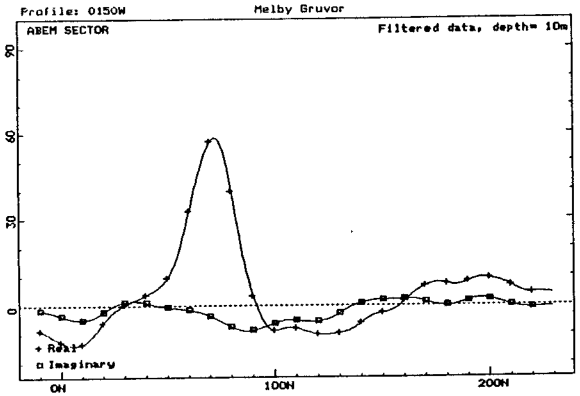


Fig. 24. Data from profile 150W in Fig. 23.

In Fig. 8 a typical anomaly indication obtained for an orebody or a fracture zone that contains saltwater (for example) is shown. The imaginary part can also indicate a positive anomaly, depending on the extent and resistivity of the overburden.

In Fig. 9 a typical anomaly indication obtained for a structure having relatively high resistivity (poor conductor), a fracture zone containing fresh water for example, can be seen.

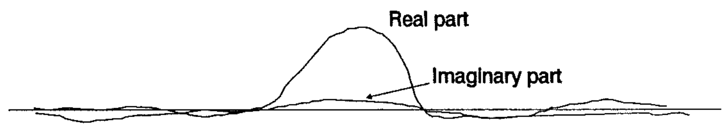


Fig. 9. Typical anomaly from a poor conductor.

In principle, there are two types of imaginary-part anomaly indications:

- An imaginary-part anomaly indication that is similar to the real-part anomaly indication.
- An imaginary-part anomaly indication that is much closer to zero than the real-part anomaly indication.

The second case (close to zero) indicates that the electrical resistivity in the fracture zone is quite high (a fracture zone containing fresh water for example).

The first (imaginary part shows a strong anomaly) indicates that electrical resistivity is low. Saltwater- bearing fracture zones and orebodies (to cite two examples) provide fairly large imaginary-part anomaly indications that are sometimes on the same order of magnitude as those provided by the real part.

The sign (+ or −) of the imaginary-part anomaly indication depends heavily on the thickness and resistivity of the overburden which, in rare cases, can cause the imaginary-part anomaly indication to lie close to zero even when the fracture zone has low resistivity.

1.10 Theoretical examples

We shall now study some theoretical examples that illustrate the meanings of different types of anomaly indications. Using a computer modelling program (integral equation program), we have

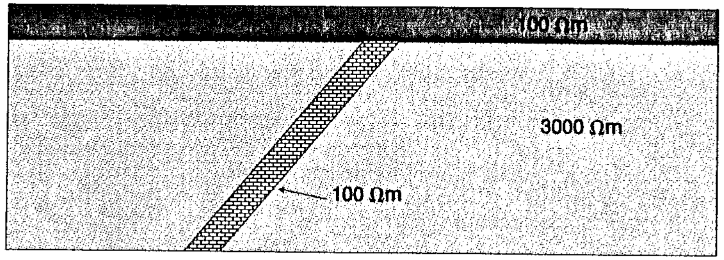


Fig. 10. The model used in the theoretical calculations.

created some simple models and calculated VLF anomaly indications for them. The models consist of one or more very long water-bearing fracture zones, and the profiles were taken perpendicularly across them. Fig. 10 presents the model used for theoretical calculations. Note that we have used a resistivity of 100 Ωm for the water-bearing fracture zone. This value is typical for fresh water. The fracture zone dips 60° and is 5 metres thick. A frequency of 18 kHz was used.

1.11 Single zone without overburden

Fig. 11 presents an anomaly indication obtained from the model shown in Fig. 10. Note that the overburden has not been included. The real part shows a strong anomaly (+23% to - 30%). However, the imaginary part shows a weak anomaly. The 60° dip is evidenced by slight asymmetry in the original data (upper diagram) and also in the filtered data (lower diagram). Note also that the anomaly indication is quite typical in appearance. For original data (upper diagram) the anomaly indication is always asymmetric (almost antisymmetric). In the diagram showing filtered data, it is symmetric with a peak directly above the fracture zone.

The vertical cross-section shown in Fig. 12 is based on the same calculation as shown in Fig. 11. The current density in the ground is illustrated by means of a gray scale in which black and white represent high and low values respectively. There is a very definite indication at the fracture zone. The slope is somewhat faint in these diagrams, while depth appears more clearly. Here, the real part (upper diagram) should be emphasized in connection with interpretation.

basis of what is shown in Fig. 22. If, for example, you drill vertically at the 230W coordinate you will reach the fracture zone at a depth of 25 5 metres. At the Strängnäs site, actual drilling showed that this interpretation was correct. At the 130W coordinate in Fig. 22 you will note a current density that corresponds to the rightmost anomaly in Fig. 16. It is plainly evident that this anomaly indication was caused by a surface conductor such as a drain pipe.

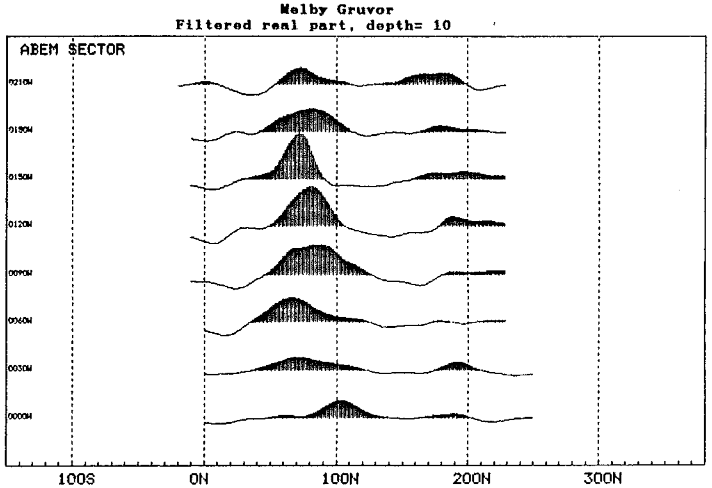


Fig. 23. Multi profile plot.

2.3 Fracture zone B

Eight parallel profiles were measured using a WADI instrument on the island of Väddö in the Stockholm archipelago. Fig. 23 presents the filtered curves for these profiles, drawn on a single set of coordinates. Here, it's plainly evident that there is a strong anomaly with an east-west strike at the 70N-100N coordinate. Moreover, there is a small parallel anomaly at the 170N-200N coordinate, and even though it is easier to interpret due to the fact that you can see three anomalies immediately. The middle anomaly indication is the largest (and probably the most promising). The rightmost anomaly indication shows that the imaginary part is of the same order of magnitude as the real part. It was probably caused by highly conductive material. Fig. 22 shows the vertical cross- section for this model. Note that the length of a cross- section is always 200 metres and its depth is always 60 metres. This diagram shows plainly that when we move west from the 220W coordinate, we encounter a steeply dipping fracture zone. There are no mineralizations in this area!

A slight anomaly also shows up in the imaginary part, but it is about five times smaller than the one shown in the real part (see Fig. 21). This indicates that the anomaly was probably caused by a water-bearing fracture zone. It should be quite easy to site a drillhole on the

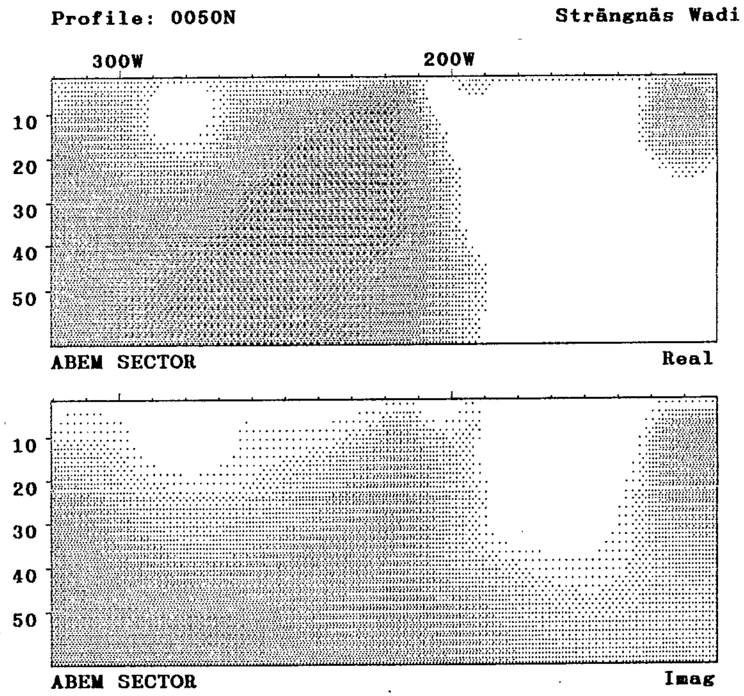


Fig. 22. Vertical cross section from data in Fig. 21.

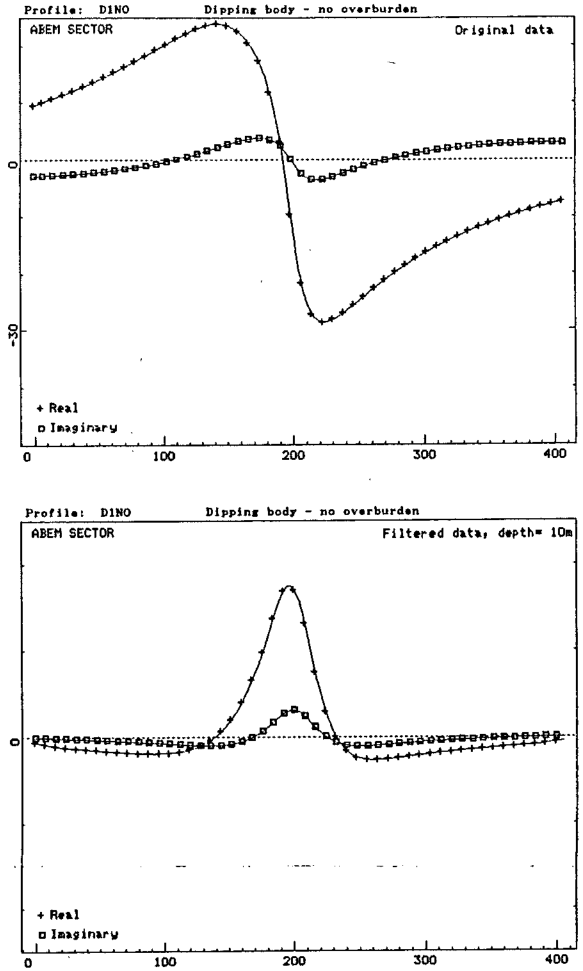


Fig. 11. Anomaly from a single zone without overburden.

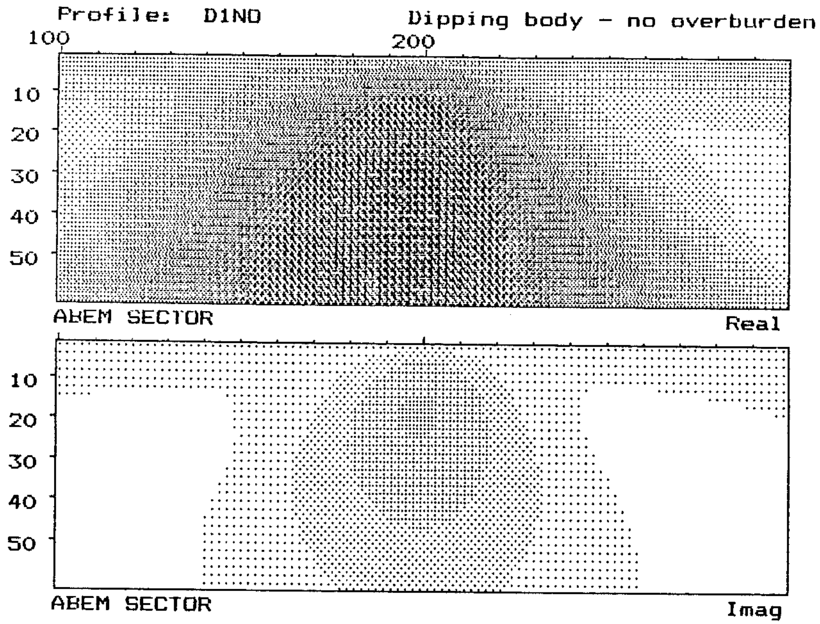


Fig. 12. Vertical cross section from data in Fig. 11.

1.12 Single zone with overburden

In the calculation shown in Fig. 13 the overburden is included. It is plainly evident that the anomaly indicated in the real part is much smaller than before, and that the anomaly indicated in the imaginary part is larger. This is because amplitude reduction is not all that happens when the field passes through the overburden; the phase is also displaced somewhat. It is thus evident that emphasizing the real part is easier in connection with interpretation. The imaginary part is al-

conductor such as an orebody or a fracture zone that contains saltwater. Fig. 20 shows a vertical cross-section of the same profile. Here, we see that the anomaly comprises a conductor that is quite wide, and it is evident that it dips somewhat to the south. The ore lies beneath a dry layer of sand about 15 metres thick that has a resistivity of about 5000 Ωm. The resistivity of the ore is about 1 Ωm.

2.2 Fracture zone A

Fig. 21 shows a profile taken in an area located close to Strängnäs in Sweden. The original data (upper diagram) provides us with a picture that is quite difficult to interpret. The filtered profile (lower diagram) is

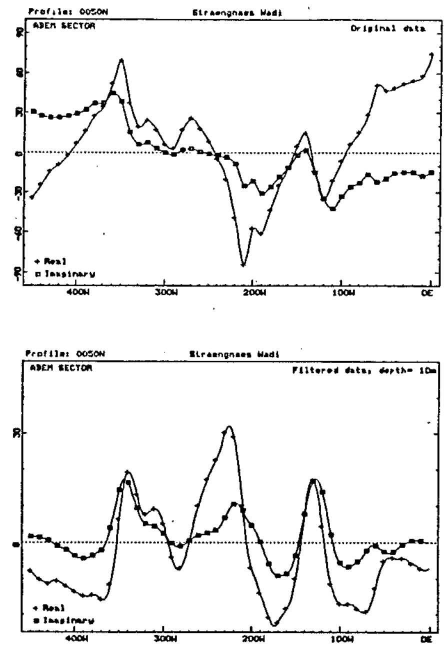


Fig. 21. Data from a fracture zone.

2. Field examples

We shall now take a look at several examples based on data actually collected in the field. These examples were chosen to illustrate different geological conditions.

2.1 Orebodies

Here, our first example will illustrate a VLF anomaly indication obtained from a sulphide mineralization in Sweden's Skellefte field. Even though this example may be of little interest with regard to prospecting for water, it shows plainly how a typical VLF profile can appear. The upper diagram in Fig. 19 shows the original data. The lower shows the filtered data. It's quite easy to locate the orebody in situations as simple as this that involve good conductors. In this case, both the real and imaginary parts show quite strong indications. Moreover, the imaginary part and real part have opposite signs. This is typical for a VLF anomaly indication taken across a very good

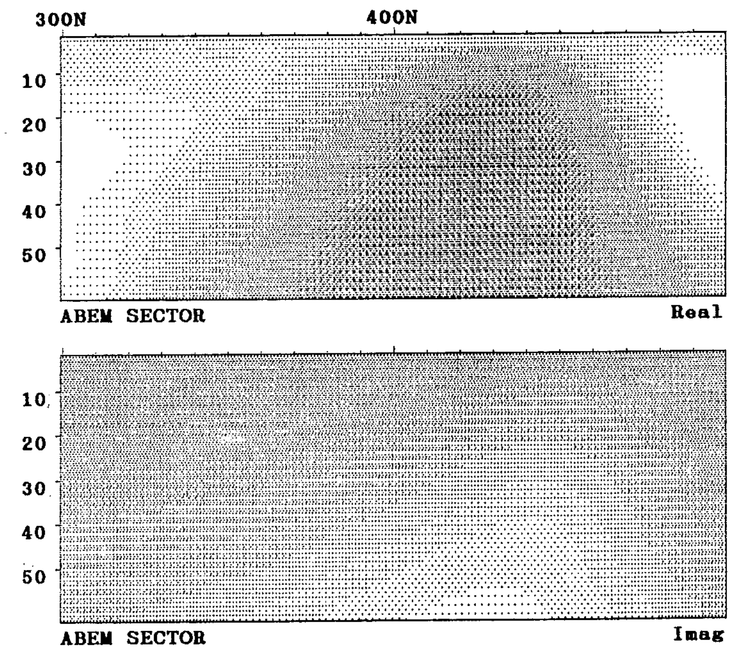


Fig. 20. Vertical cross section from data in Fig. 19.

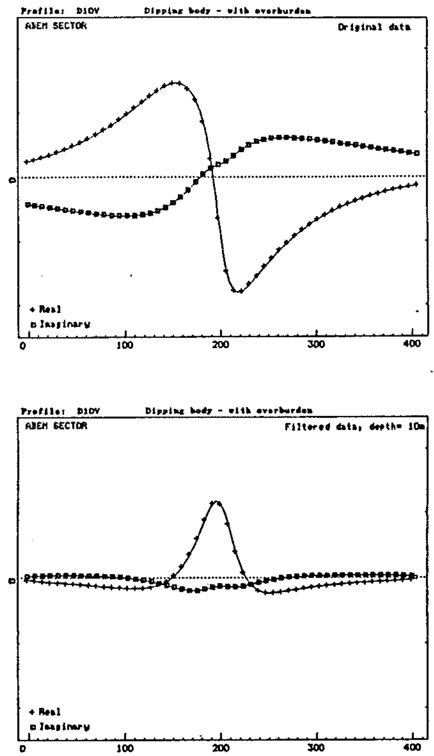


Fig. 13. Anomaly from a single zone with overburden.

ways somewhat more difficult to interpret. The asymmetry caused by the dip is still evident in the diagrams.

In Fig. 14 below is shown the vertical cross-section based on the model in Fig. 10 (which includes the overburden). The real part does not show any major changes from the previous calculation. The effect of the overburden is somewhat limited in this depiction.

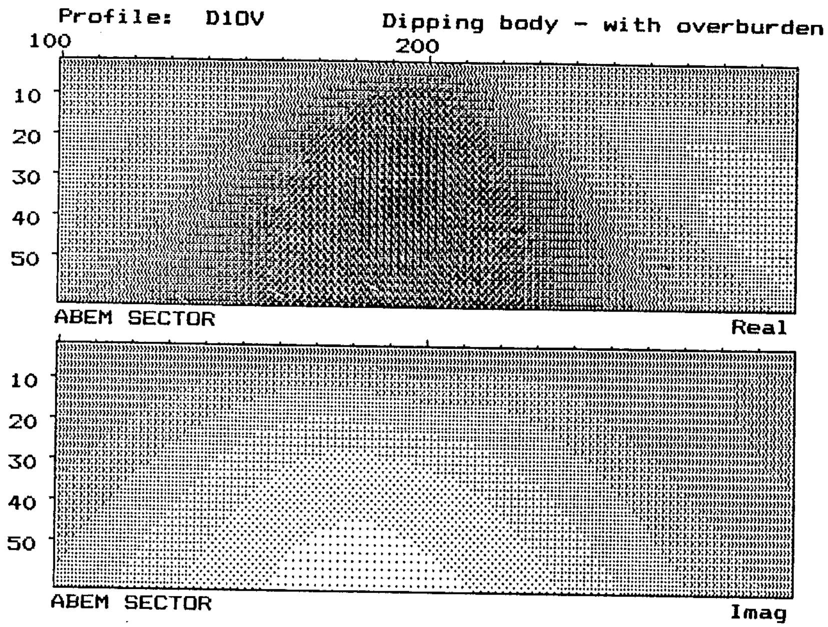


Fig. 14. Vertical cross-section from data in Fig. 13.

1.13 Double zone with overburden

The model in Fig. 10 has now been augmented by adding another fracture zone located 40 metres away from the first. Other parameters remain unchanged. The original data (Fig. 15, upper diagram) shows that it is very difficult to discern the presence of two

The cross-section in Fig. 18 shows clearly that the fracture zone is quite wide. Vertical cross-sections are very useful for complicated geometries.

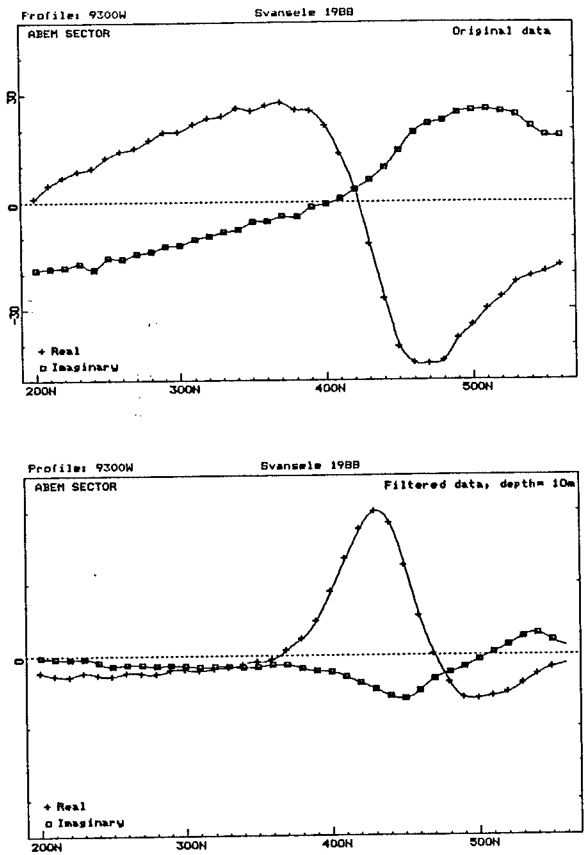


Fig. 19. Data from a sulphide mineralization.

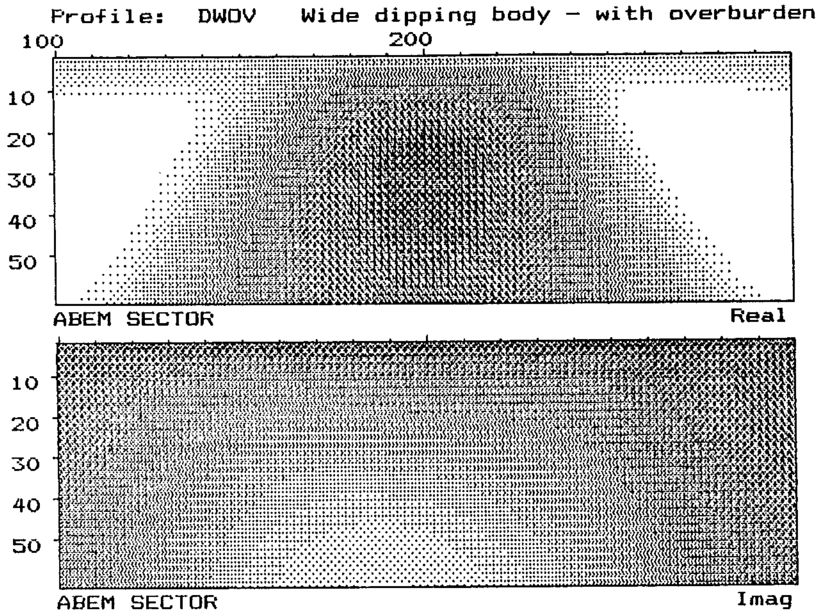
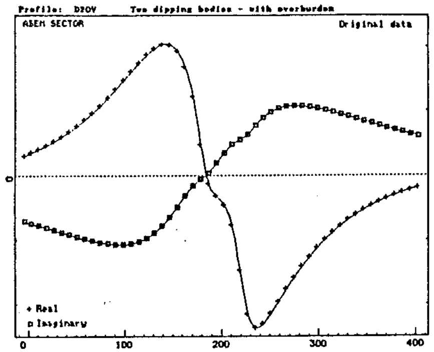


Fig. 18. Vertical cross section from data in Fig. 17.

individual zones. In the filtered curve (lower diagram) however, they can be distinguished easily. Note that in situations involving electromagnetic phenomena, the fields behave in a very complex way. For example, the anomaly indication obtained from two fracture zones does not resemble the sum of the their individual anomaly indications.



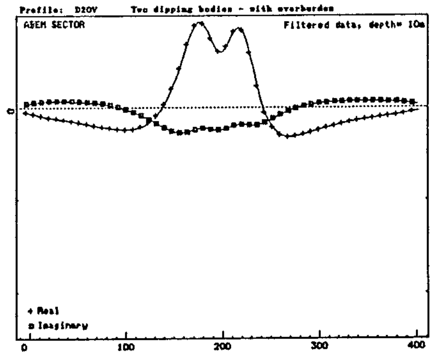


Fig. 15. Anomaly from a double zone with overburden.

The vertical cross section shown in Fig. 16 is for the model with two fracture zones shown in Fig. 15. Here, you can distinguish between the two individual zones in the upper region of the real part, but at greater depths they melt together to form a single wide anomaly indication.

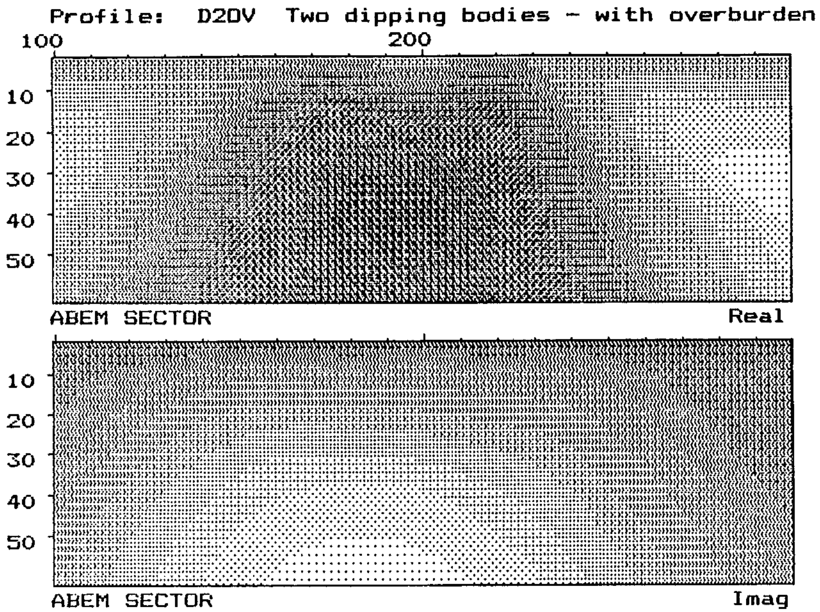


Fig. 16. Vertical cross section from data in Fig. 15.

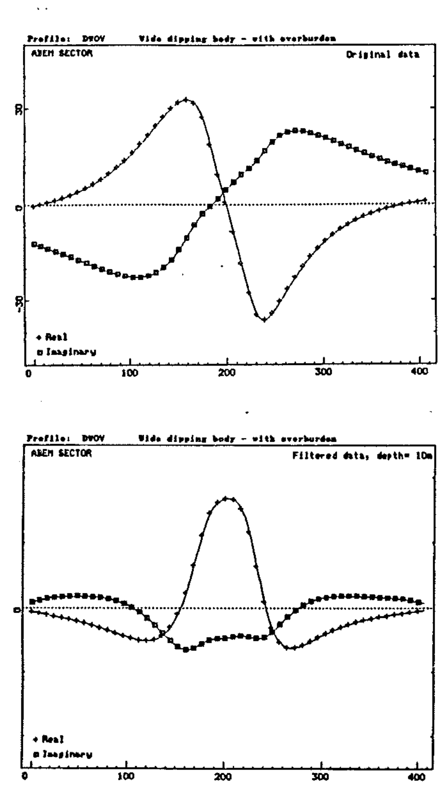


Fig. 17. Anomaly from a wide zone with overburden.

1.14 Wide zone with overburden

This example, like the last one, comprises a simple modification of the model shown in Fig. 10. Here the zone has been widened to 30 metres. In the original data (upper diagram), it is hard to see that the anomaly is wide, but in the filtered data (lower diagram) the wider breadth is plainly evident due to the fact that the anomaly indications are now wider than before.