KMS Technologies – KJT Enterprises Inc.

Chapter 9
Case Histories :
Deep Crustal Applications

extract from

Strack, K.-M., 1992, reprinted 1999
Exploration with deep transient electromagnetic: Elsevier, 373 pp.

Chapter 9
Case Histories: Deep Crustal Applications

Electromagnetic methods are some of few techniques which are used to obtain information on the physical properties of the deep crust. Historically, passive EM techniques using natural electromagnetic fields were applied. Controlled source EM techniques are less frequently used to investigate the lower crust. A limited number of surveys have been carried out. A review of the state-of-the art in applying controlled source EM to crustal studies is given by Boerner (1992). Here, some historical case histories are selected which are important when considering the application of LOTEM to deep crustal studies. Following are more recent case histories of LOTEM deep crustal applications from Europe, Africa and China.

HISTORICAL CASE HISTORIES

A significant amount of deep crustal applications of LOTEM has been done in the Soviet Union where the technique originated. In particular the use of MHD generators has been of great interest there (Velikov et al, 1986). Since the information reaching the Western world from the USSR concerning other LOTEM measurements for deep crustal work is very sparse, only a small number of selected "western" case histories illustrate the framework needed to carry out LOTEM soundings around the world.

One of the first observations of deep crustal transients was done in Southern Africa during ultra long line DC-resistivity soundings (Van Zijl, 1969; Van Zijl et al, 1970; Van Zijl et al, 1975; Blohm et al, 1977). Especially impressive were the recordings from the Cabora Bassa power line. A short example of the large amount of strip chart records found in the archives of the CSIR is shown in figure 9.1. S. Joubert who was doing the technical support at that time still remembered the details leading to the additional labeling of the figure. The transients in the record were contaminating the wanted DC-signal. In figure 9.1 several of these transients can be seen as double peaks. These double peaks are caused by the transmitter switching. The polarity change is done with an off-time before the switches turn on the other polarity. At the beginning of the record the initial adjustment with respect to timing and recording can be seen in the more sporadic behavior. The important part for the use of the data as DC-resistivity data was the time between switching since the unwanted transient should have decayed completely before the DC-resistivity value could be read. This resulted in a tremendous amount of data processing which had to be done. All strip charts had to be digitized and the data fed into a computer. The transients were used as timing markers only. One entire record is displayed in figure 9.2. The individual transients are now barely visible and the record had to be split into small windows

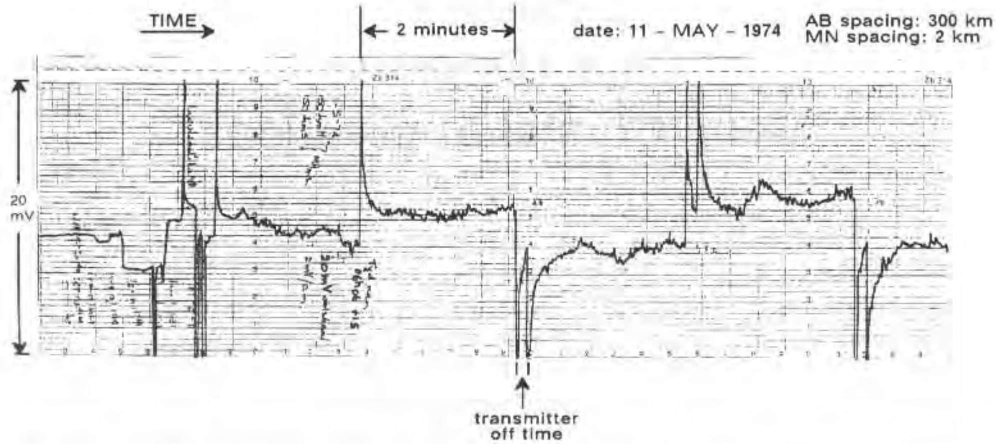

Fig. 9.1: Reproduction of an original strip chart record from the Cabora Bassa line ultra deep resistivity measurement. The information leading to the labeling of the figure was supplied by S. Joubert (pers. comm.).

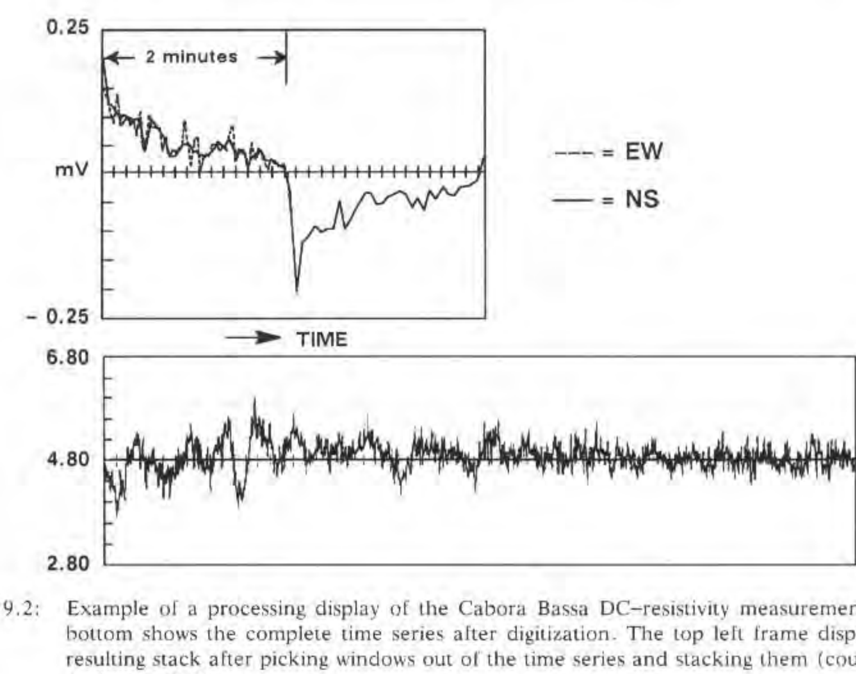

Fig. 9.2: Example of a processing display of the Cabora Bassa DC–resistivity measurements. The bottom shows the complete time series after digitization. The top left frame displays the resulting stack after picking windows out of the time series and stacking them (courtesy S. Joubert, CSIR).

which were stacked. The stack is displayed on the upper left of figure 9.2. The windows were shifted so they would yield a clean transient after stack. From this stack the very last part was used to read the DC-resistivity response value. Although, at that time the interpretation of the data as transients were not carried out, the basic motivation was laid for the integration of transient electromagnetics into the research objectives of the CSIR.

The first megasource transient EM survey was carried out by Sternberg (Sternberg and Clay, 1977; Sternberg, 1979) over the Southern extension of the Canadian Shield. The megasource consisted of approximately 22 km long dipoles with about 70 Amperes of excitation current giving a source moment of 1,540,000 Am. Sternberg integrated DC-resistivity measurements with transient sounding to derive a model satisfying both techniques. Figures 9.3 and 9.4 show some representative data sets for

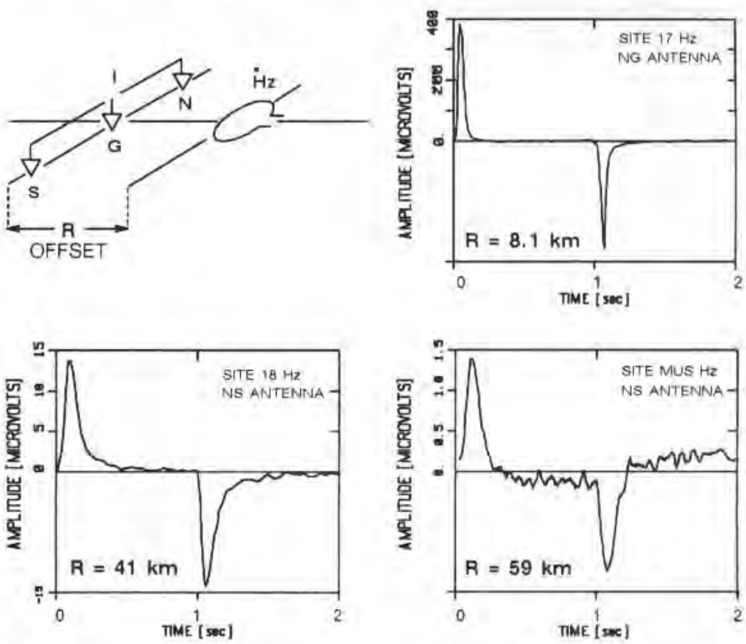

Fig. 9.3: Magnetic field transients measured over the Southern extension of the Canadian Shield (after Sternberg, 1979).

the magnetic and electric field receivers. The signals look very much like the signals measured nowadays; they become wider for larger offsets with decreasing absolute amplitude. The electric field transient in figure 9.4 also exhibits different characteristics for increasing offset. For the very long offset of 59 km the electric field measurement could even be mistaken for magnetic field transients. Sternberg interpreted the magnetic field transient at site MUS (see figure 9.3) as containing a reversal. He interprets it as being caused by the conductors in the Flambeau anomaly, which is a logical explanation of this type of 3-D effect (Newman, 1989; Hördt et al, 1992). In order to obtain a realistic estimate of the candidate models, Sternberg interpreted the data using Monte Carlo inversion. The range of possible models is displayed in figure 9.5. The bounds for the second layer (resistor) and the third layer (conductor) would probably be smaller using joint inversion routines incorporating DC-resistivity, LOTEM electric and LOTEM magnetic field measurements. Nevertheless, Sternberg's work is probably the most important early deep TEM research because he already includes three important approaches of todays state-of-the art LOTEM systems, namely:

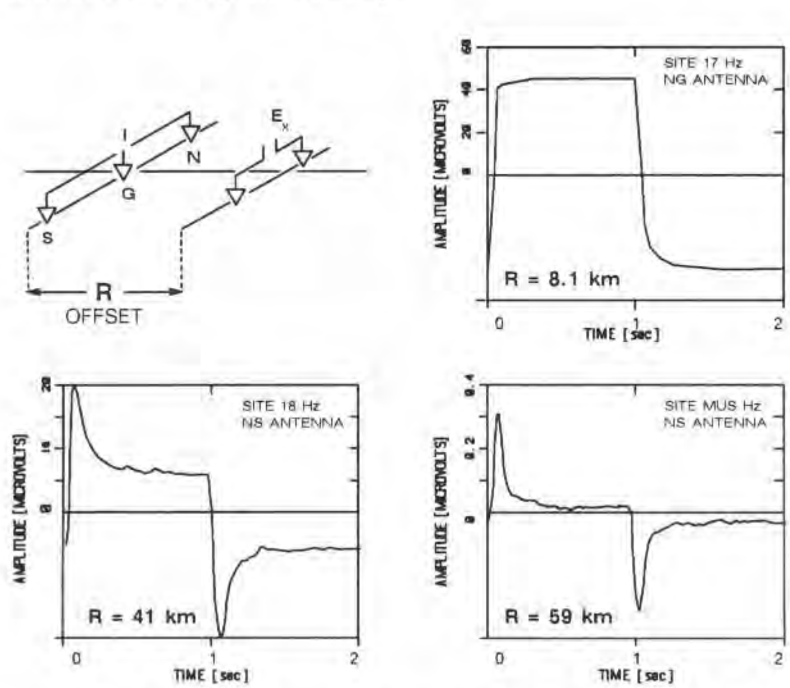

Fig. 9.4: Electric field transients measured over the Southern extension of the Canadian Shield (after Sternberg, 1979).

- Electric field measurements which allows the interpretation of resistive parts of the section.
- Inversion methods yield a class of models and thus confidence limits.
- Integrating different methods (TEM, DC-resistivity) to obtain a more unbiased interpretation.
- Qualitative explanation of 3-D effects (reversals).

More recently, Keller et al (1984) published case histories on using megasource TEM for deep geothermal and hydrocarbon applications (investigation depth greater than 3 km). Their megasource consisted of a short wire (about 1-2 km) but large currents (about 2000 A peak-to-peak). This type of source has the disadvantage of difficulties in controlling the current switching (because of the high currents) resulting in sometimes unpredictable effects in deconvolution of the system response. The first case history in their paper has early and late time apparent resistivities which are either sometimes far apart or almost crossing. From the discussion on the calibration

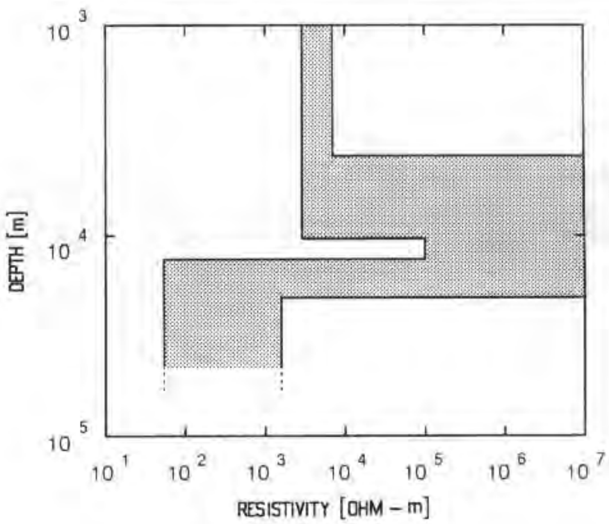

Fig. 9.5: Interpreted model range for the explanation of the transient soundings over the southern extension of the Canadian Shield the (after Sternberg, 1979).

factor earlier in this book and the paper by Newman (1989), we know that these effects can be caused by transmitter overprints which can be treated as static shifts. The consistency in their interpretation of the data lies in the inversion program they used. This routine automatically left the calibration factor floating during inversion thus compensating for the effect of static shift. Figure 9.6 shows another example of their interpretations for a different profile. The top of the figure displays the early and late time resistivities. Note that some of the early time curves have narrow bumps which are particularly strong at stations 431, 461, and 459. These bumps are symptomatic of deconvolution effects and they can usually not be matched with a layered earth model. The paper by Keller et al (1984) illustrates the large effort one has to undertake to carry out deep LOTEM surveys and obtain many data sets over a large area.

In the following, the developments of the German deep transient EM systems and the application to deep crustal problems are described in historical order, starting with a very initial test done for the German deep drilling project and ending with the first demonstrations for earthquake prediction in China.

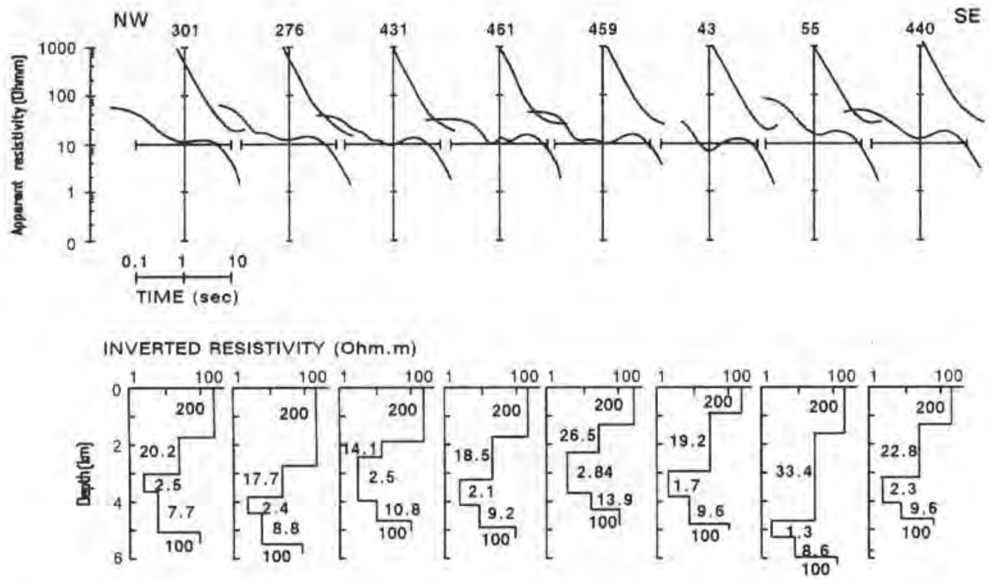

Fig. 9.6: Example of an interpreted profile for the Pacific North-West (after Keller et al, 1984).

The first LOTEM measurements for deep crustal applications in the Oberpfalz caused the request for additional measurements in the Black Forest, which was an alternative site for the deep drilling project. To confirm the results obtained in the Black Forest, a calibration survey was carried out near the Urach Geothermal Area, where a conductor was known in the upper crust. A map of the LOTEM sites within the framework of the seismic reflection lines is shown in figure 9.7.

THE FIRST DEMONSTRATION FOR DEEP CRUSTAL APPLICATIONS IN FRG

During the site selection process for the German deep drilling location, test measurements were done in the Oberpfalz area, which is now the drilling site. The main question to be answered withe the LOTEM survey was:

- Is there a crustal conductor below 10 km? If yes, what would be the depth range?

A crustal conductor was seen in magnetotelluric measurements, but the depth was only approximate. When the survey started, the behavior of the LOTEM method to such a resistive target (resistivities larger than 1000 Ωm) was completely unknown. Very little experience existed to set up a powerful transmitter in resistive terrain and on frozen ground. As a result maximum current of only 60 Amperes (peak-to-peak) could be injected into the ground. Within a total survey time of one week only 22 receiver sites could be occupied. They were scattered around the area with 11 stations being aligned along a profile.

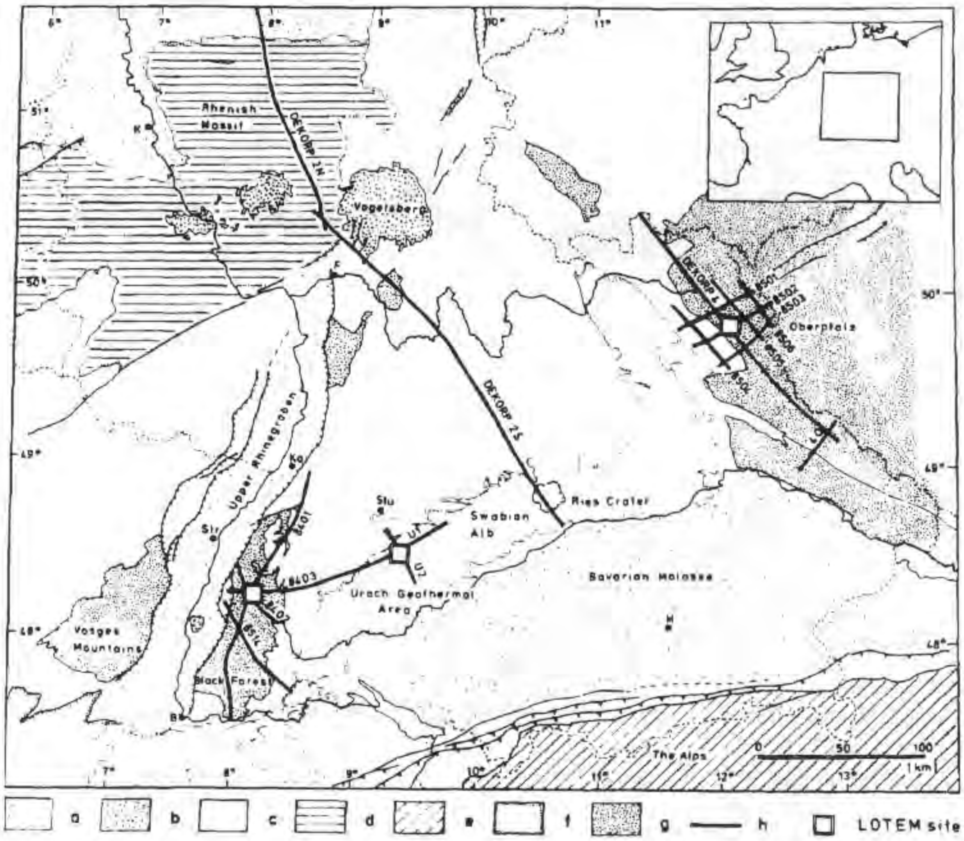

Fig. 9.7.: Regional geologic map of Southern Germany with LOTEM and deep reflection seismic survey locations. geologic key: a: Tertiary and Quaternary basin and graben fill; b: Tertiary volcanic rocks; c: Permian to Triassic sediments; d: Devonian (Rhenish Shield); e: Alpine orogen; f: Jurassic sediments (Swabian Alb); g: crystalline Hercynian basement. Map notation: K – Köln, F – Frankfurt, M – Munich, Str – Strasbourg, Ka – Karlsruhe, B – Basel, Stu – Stuttgart. A basemap of the LOTEM survey areas (squares) is shown in figures 9.12 and 9.21 (after Strack et al, 1990).

A typical representative processing sequence of the 1986 survey is shown in figure 9.8. The top row shows two typical individual records. The transient signal is clearly visible in the records. The data is still contaminated by predominantly periodic cultural noise. Below the raw records are the amplitude responses obtained after

Fourier transforming the raw data. They exhibit a significant amount of power line noise starting with the base frequency of 16 2/3 Hz and higher harmonics thereof. Using the true amplitude filters discussed in chapter 3 the filtered record in the third row of figure 9.8 was obtained. Finally, the data was selectively stacked yielding the bottom smooth transient. Note that the transient signal is only about one second long; in 1986 the digital data acquisition system designed for exploration in sedimentary areas presented problems in high resistive environments. The system had to be specifically modified to permit high sampling rates without loosing dynamic resolution.

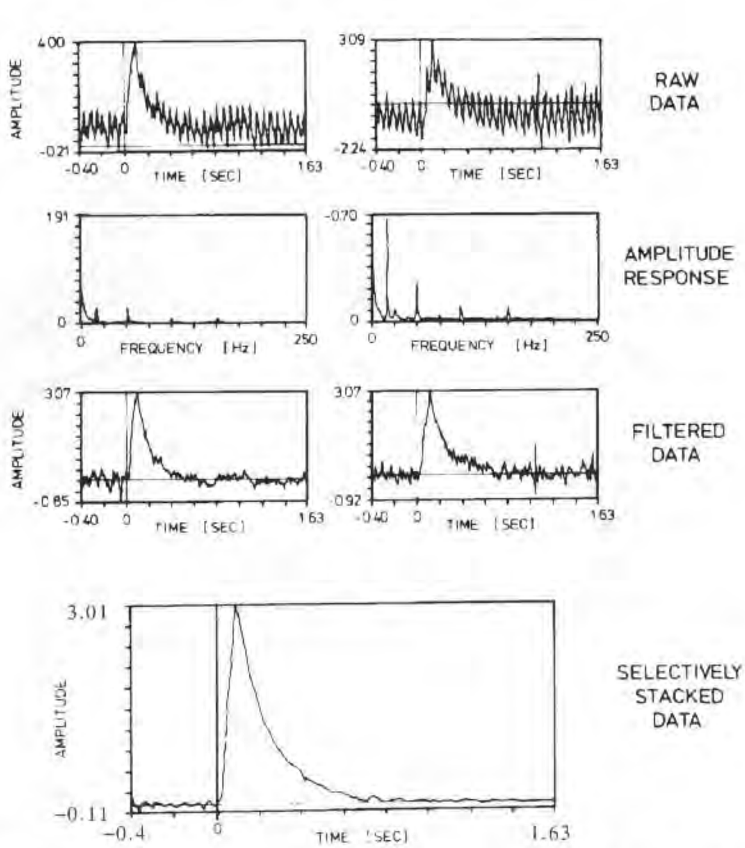

Fig. 9.8: Representative data set for the 1986 LOTEM survey in the Oberpfalz area, Germany. The different displays show the different processing steps.

After carrying out a significant amount of prestack processing, the data were interpreted using one-dimensional layered earth inversion. The inversion with layered models proved to be more difficult than usual. After a large number of forward model calculations, only one starting model could be found which gave a consistent interpretation along the measured profile shown in figure 9.9. The inversion result was highly unstable and it was apparent that a conductor existed at about 10 km depth, but it was not clear whether or not this conductor was resolved or not. The error bounds were very small, yet the feeling of poor confidence in the interpretation never left the interpreter because enough experience in this environment and 3-D modeling did not exist at that time.

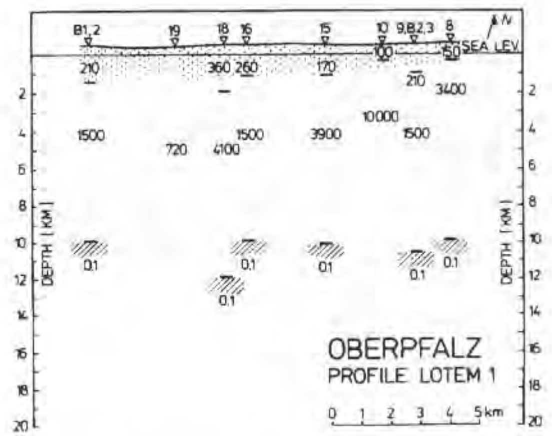

Fig. 9.9: Interpreted resistivity cross section for the LOTEM survey near the location of the German continental drill hole.

Although the interpreter may argue differently, the data clearly required the conductor when using 1-D inversion. To reinforce this type of interpretation two different tests were done. First, a conductor resistivity test: in this, the resistivity of the last layer was changed successively from being conductive to being identical to the resistive layer above. The results are displayed in figure 9.10. The curves with the conductor not being present deviate from the data for approximately four data points. This suggests that the data does require the good conductor. Second, the conductor thickness test: this test gives the interpreter an idea of how thin the conductor could be and still honor the data. From figure 9.11 it can be seen that the conductor has to be at least 250 m thick, otherwise the curve would deviate too much from the data. Also, at this minimum thickness, a fitting error minimum is observed.

The measurement and the interpretation demonstrated that when using 1-D inversion, one must include a crustal conductor in the Oberpfalz area below crystalline rock at approximately 10 km depth. After drilling of the pilot hole, we know that the geology is very complicated and further 3-D modeling should be applied. This is confirmed by the large number of reversals in the survey area, indicating the multi-dimensionality directly in the data. A more complex 3-D survey with well over 100 stations was carried out in the area but the interpretation is still under way.

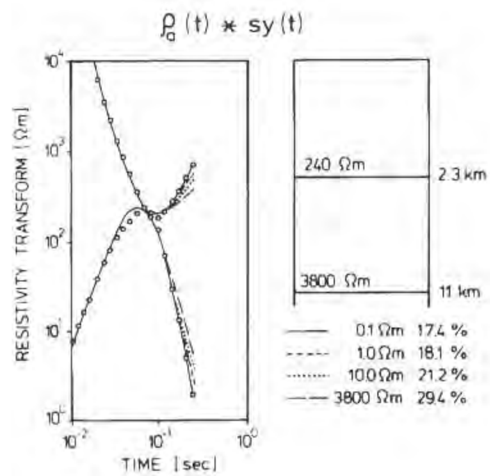

Fig. 9.10: Resistivity test for the Oberpfalz model (Oberpfalz site15), illustrating that the data require a conductive last layer in 10 km depth.

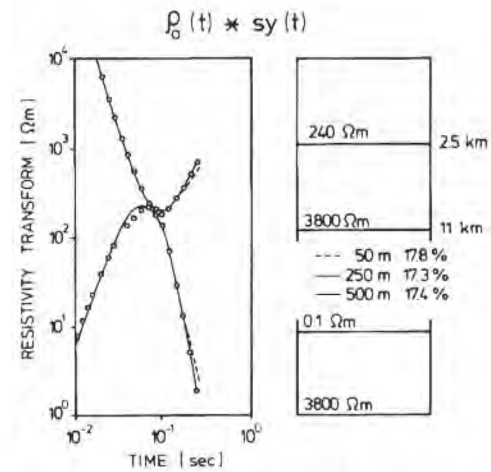

Fig.9.11: Minimum conductor thickness test for the 1986 LOTEM data (Oberpfalz site 15), showing that the data requires a minimum thickness of the conductor being 250 m.

BLACK FOREST SURVEY

During July 1986, a LOTEM survey was conducted in the Black Forest area near Haslach (see figure 9.12) in conjunction with site investigations for the German deep drilling project. The objective of the survey was to define the resistivity distribution in the upper 10 km of the earth's crust. The survey was a direct result of the successful mapping of the conductor in the Oberpfalz.

Existing geophysical data includes reflection and refraction seismic, and magnetotelluric measurements. From wide-angle and near-vertical seismic surveys, the upper crust to approximately 14 km depth was found to be relatively transparent except for a bright spot which appears at approximately 9.5 km depth in the seismic section in figure 9.13. Below a rather constant depth of 14 km, a highly reflective, seismically laminated zone defines the lower crust (Lüschen et al, 1987). This is typical for the Hercynian crustal structure in large areas of central, western and northwestern Europe as revealed by many deep reflection studies of the BIRPS (British Institutions Refection Profiling Syndicate) (Matthews, 1986), ECORS (Etude Continentale et Oceanique par Reflexion et Refraction Seismique) (Cazes et al, 1986) and DEKORP (Deutsches Kontinentales Reflektionsseismik Programm) (Bortfeld et al, 1985) groups. Refraction seismic measurements show a distinct low-velocity channel starting at approximately 7 km depth (Lüschen et al, 1987). Magnetotelluric measurements yield a lower crustal conductor of 650 Siemens below 12 km depth, but no definite interpretation of the upper 12 km could be obtained (Tezkan, 1988). This is attributed to the strong cultural noise in the area, which was so strong that the audio magnetotelluric data did not yield a reliable interpretation in the upper section (Wilhelm et al, 1990).

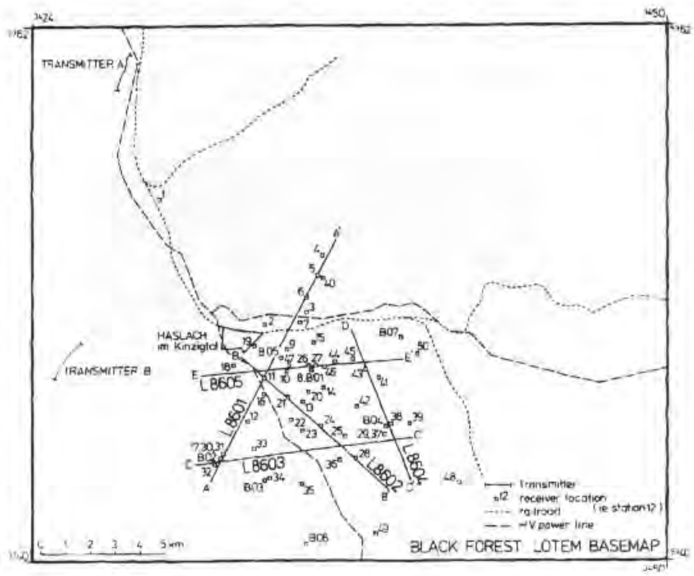

Fig. 9.12: Basemap for the Black Forest survey (after Strack et al. 1990).

The LOTEM survey was designed to achieve a high station density and data redundancy for improved interpretation since severe cultural noise problems were anticipated. Due to the difficult topography only two transmitter locations were possible: one of them to the north of the survey area (TRANSMITTER A) and one to the west (TRANSMITTER B in figure 9.12). LOTEM soundings were carried out at approximately 60 stations during 2 weeks of field work. Because of strong railroad and power line noise, the data were recorded with 16 2/3 Hz analog notch filters; otherwise no useful signal would have been received. This restricts the signal information to below the frequency range of the notch filter (0–13 Hz), because higher frequencies of the transient are severely distorted by harmonics. Since the measurable signal length in time increases with increasing source-to-receiver distance, offsets of 8 to 13 km were chosen so that the signal would be in a time window unaffected by the analog filters. Given this offset range, the system response (including transmitter and receiver analog filter effects) and the resistivity distribution at the subsurface yield a minimum depth of investigation which may vary at each station due to changes in the above factors (Spies, 1989).

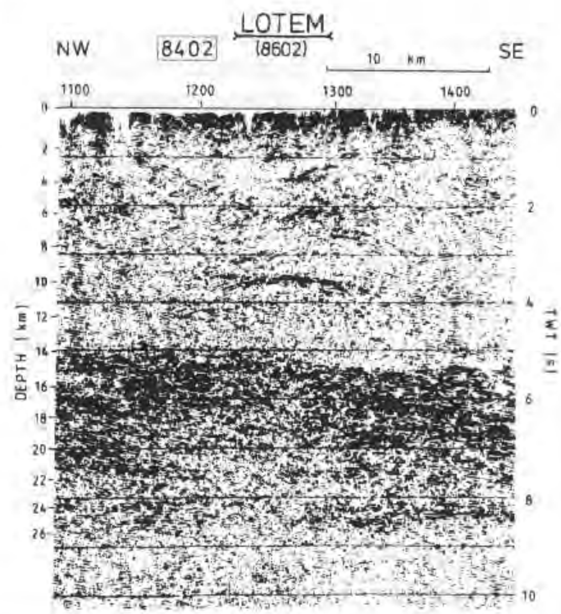

Fig. 9.13: Seismic section showing the bright spot at 9.5 km depth and the laminated lower crust of the Black Forest beginning at 14 km. The bar on top marks the location of the LOTEM survey (after Strack et al, 1990).

The raw data are extremely noisy and transients with sufficient signal-to-noise ratios were obtained with extensive prestack filtering, and with a selective stack tuned for the noise characteristics at each station (Strack et al. 1989). Figure 9.14 shows a representative example of the data processing sequence for the Black Forest survey

The top frames display two consecutive recordings in time at one receiver site. The individual transients are strongly contaminated by cultural noise. Below are the respective amplitude responses used for quality control and to determine which noise frequencies to filter out. The third set of frames shows these individual transients after applying a true amplitude, digital recursive filter to remove the periodic 16 2/3 Hz noise. The bottom frame in figure 9.14 is the selectively stacked transient after filter, resulting from all data measured at this particular receiver site.

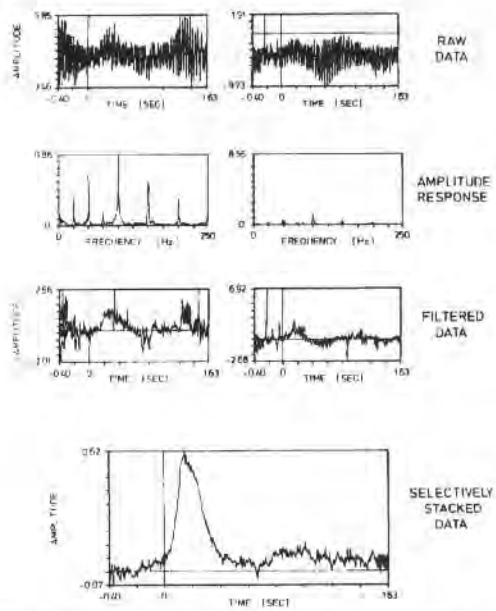

Fig. 9.14: Data processing sequence from the Black Forest survey (site 12). Two consecutive recordings versus time at one receiver site show slightly different noise characteristics. The filtered data from all recordings (250 transients) at this site were then selectively stacked to yield the bottom transient (after Strack et al, 1990).

The standard deviations derived from the selective stack are used as weights in the inversion. No *a priori* information was used. The one-dimensional inversion results were then assembled into resistivity versus depth sections, one of which is shown in figure 9.15. A distinct resistivity contrast exists across the profile at a depth of 7 to 9 km, where the deepest layer (with resistivities from 10 to 80 Ωm) is more conductive than the upper layer of 150 to 800 Ωm resistivity. The error bars in depth describe a 68 percent confidence value for the depth to the base of a layer. The increased error bar size with depth is primarily due to decreasing signal-to-noise ratios with increasing time.

Figure 9.16 gives the inversion results for the NW–SE profile 8602 and the NE–SW profile 8601. A dip in the conductor to the to the NW is visible. Also a deep conductor is visible to the NE. This conductor could be the one the MT measurements define.

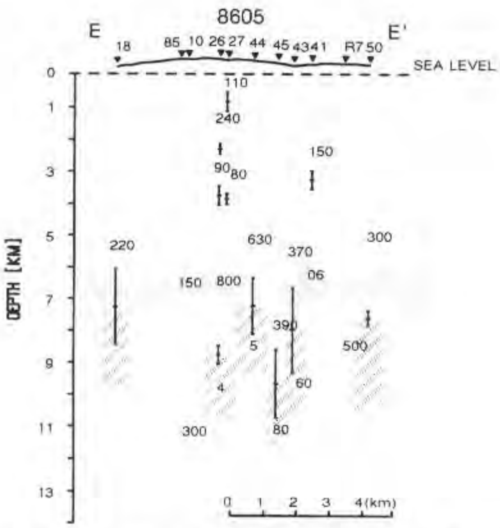

Fig.9.15: Interpreted E–W resistivity profile 8605 (E–E' 9.12) (after Strack et al. 1990).

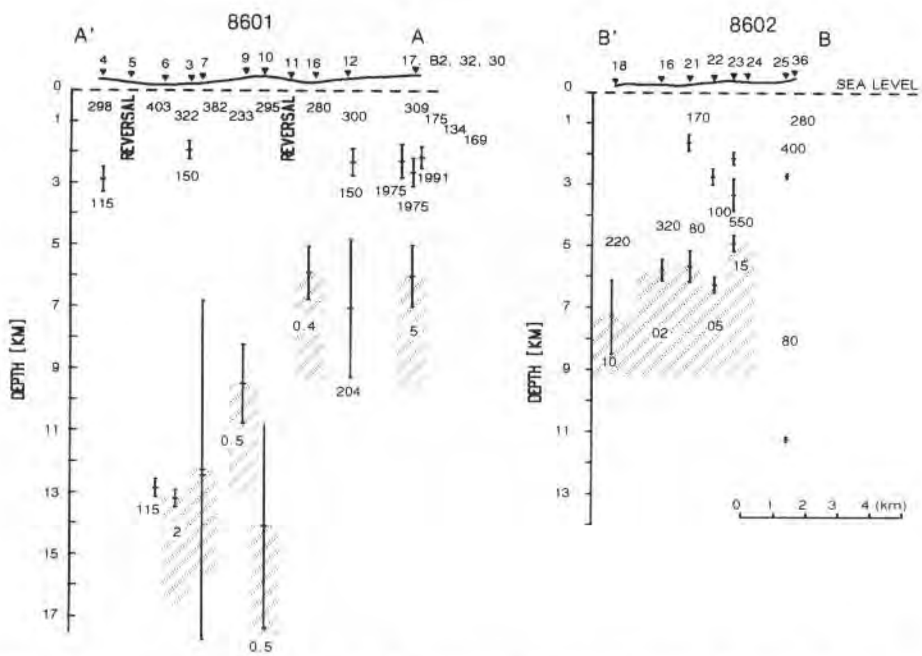

Fig.9.16: Interpreted resistivity sections 8601 and 8602 derived from 1–D inversions. Note the apparent dip of the conductor to the NW. The error bars are the 68% confidence limit.

The dip could also be confirmed in other stations. The question whether this is a multi-dimensional effect or real geology arises. Using two transmitters to immediately illuminate the same area with very similar interpretation results support the hypothesis that the cause of the dipping conductor is geological.

Figure 9.17 shows a representative comparison of 1-D inversion results from different transmitters, with the receiver sites 200 m apart. Station 27 was measured from transmitter A in the north, and station 46 from transmitter B in the west. Due to logistical reasons (cows and electrical fences) the same site could not be reoccupied. Two transmitters were used to illuminate the survey area from different directions. If multi-dimensional structures or transmitter overprints are present, the interpretation at sites close to each other would be different using one-dimensional models.

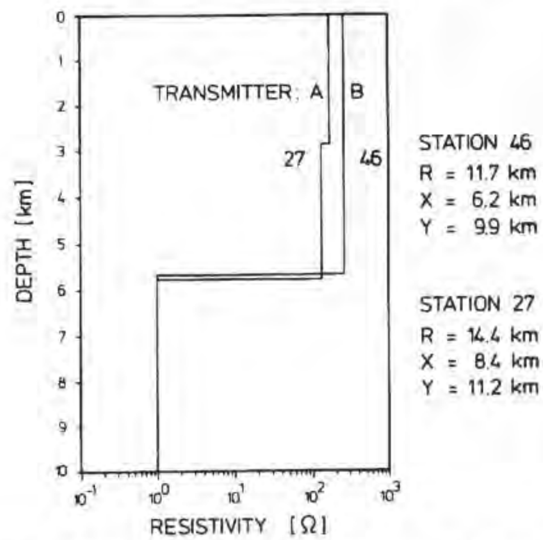

Fig. 9.17: Representative comparison of independent 1-D inversions for closely spaced stations with two different transmitter locations (after Strack et al., 1990).

The inversion model from station 27 consists of a three-layer model where the upper two layers have approximately the same resistivity of 150 Ωm and the top of the conductive layer is at 5.8 km depth. The inversion result from station 46 is a two-layer model with a slightly higher resistivity of 360 Ωm and a depth to the top of the conductor of 5.7 km. The consistency in depth to the top of the conductor confirms the one-dimensional interpretation for this area. It is also consistent with the seismic interpretation of the area which indicates plane layering and a zone boundary from 6 to 8 km depth (Lüschen et al, 1987). The difference in first layer resistivities of the two stations is partly because the response of the shallow layers lies largely in the high frequencies, which are distorted by the 16 2/3 Hz analog notch filter.

Figure 9.18 shows similar tests for the resistivity of the conductor and its minimum thickness as carried out for the Oberpfalz survey. The resistivity test (left frame in figure 9.18) simulates the existence of a resistor, a half-space with the same resistivity as the second layer, and a conductor. Only the synthetic curves with the conductor present match the field data in an acceptable way. This means that a conductive unit exists at depth. Yet unclear is its thickness. Since the MT measurements did not observe this conductor, its thickness was gradually reduced until the synthetic curves would no longer match the field data, the result is shown on the right side of the figure. It can be seen that the match becomes worse when the conductor thickness is smaller than 500 m.

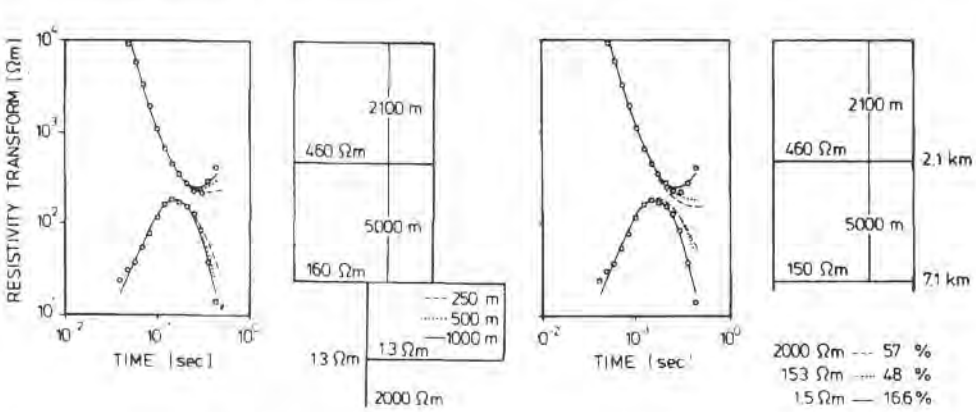

Fig. 9.18: Resistivity test (left) and minimum thickness test (right) carried out for the evaluation of the existence of the conductor in the Black Forest LOTEM data.

The statistical distribution of the depth to the conductor is shown in figure 9.19. Two maxima are clearly visible, one around 6–8 km depth and one around 14 km depth. The deeper results were obtained in the northern part of the survey area. The deep conductor could be the same as the shallow, but it seems more likely that the shallow conductor is of different nature. It is conductive enough to be detected by LOTEM in the southern part but its conductance is too low to be detected by MT. In the northern part, this conductor either has a decreased conductance or disappears. The lower conductor coincides with the conductor found in the MT measurements. Since the area was strongly contaminated by noise, it was not possible to detect this lower conductor at greater depth in presence of the shallow one in the southern part of the survey area. The first conductor is shielding the second one, because the signal from the conductor below disappears in the noise. This explanation seems to be the more reasonable one because it does not contradict Tezkan's (1988) explanation.

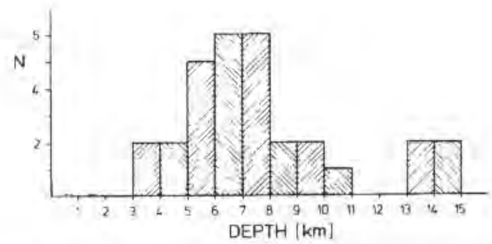

Fig. 9.19: Histogram of the depth to last conductor from all inversions to the Black Forest data.

Figure 9.20 is a comparison of the one-dimensional LOTEM interpretation with seismic survey results. Structural information interpreted from the reflection seismic sections is shown schematically at the far left. The next panel to the right shows the seismic p-wave velocity model which exhibits a zone of low velocity from approximately 6 to 14 kilometers, situated directly above the laminated lower crust. In the same depth range the ratio of compressional-to-shear-wave velocity also shows a distinct minimum, with a Poisson ratio decrease of 0.25 to 0.22 (Lüschen et al, 1987). On the far right of the figure are the interpreted resistivities from the LOTEM survey, with an integrated MT result because the base of the 10 ohm-m zone could not be resolved by the LOTEM measurements. From the LOTEM results, two layer boundaries are defined: one at approximately 3 km depth, and the second between 6 and 8 km which correlates well with the onset of the low-velocity zone. Its transition to the high conductivity zone revealed by magnetotellurics can not be explained conclusively and only the deep conductor at about 14 km depth indicates that there must be some sort of transition.

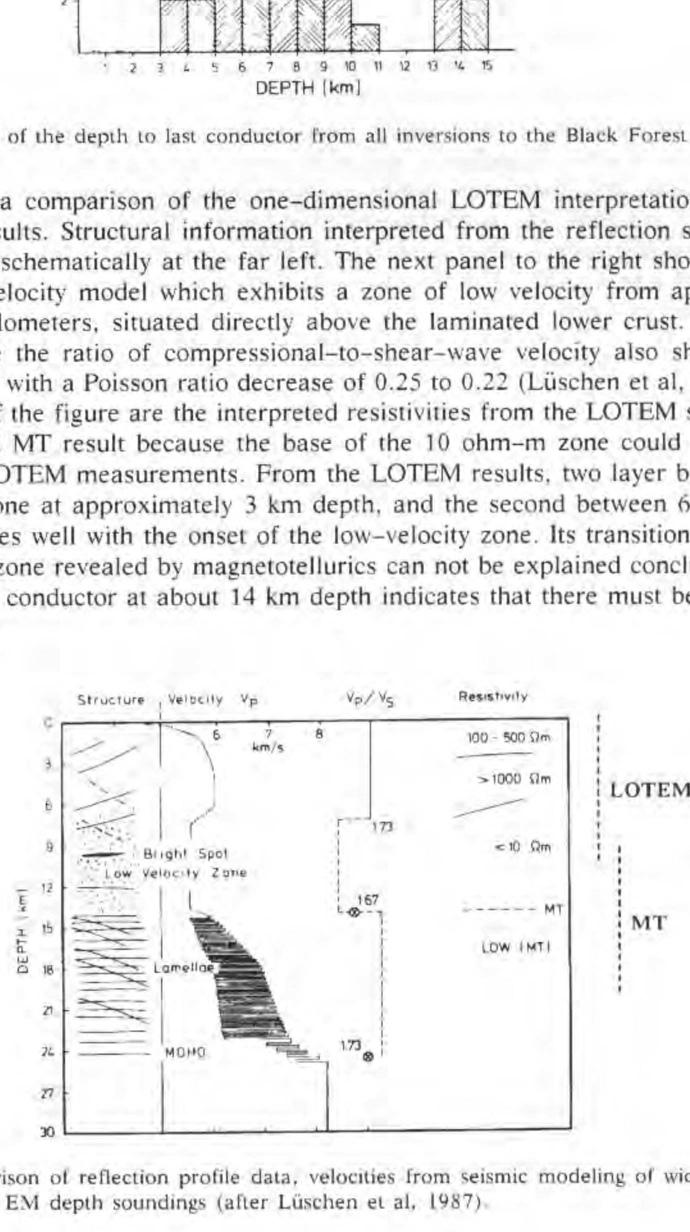

Fig. 9.20: A comparison of reflection profile data, velocities from seismic modeling of wide angle data, and EM depth soundings (after Lüschen et al, 1987).

URACH GEOTHERMAL AREA

The objective of the survey in the Urach Geothermal Area (figure 9.21) was to evaluate the LOTEM method and its interpretation in an area of known geology. Many different geophysical techniques have been cross-checked with each other and with the geology during the Urach geothermal project (Hänel, 1982). The cross-section in figure 9.22 for the W-SW to E-NE seismic line of figure 9.21 (after Berktold et al, 1982) shows a low-velocity region interpreted from a combination of reflection and refraction seismic (Bartelsen et al, 1982). This velocity anomaly is most pronounced in the middle and lower crust where its value decreases by 10 percent of the regional velocity gradient. The shaded zones mark areas of low electrical resistivity derived from magnetotelluric measurements (Berktold et al, 1982). The LOTEM survey area covered a section of 7 km directly over the thickest part of the low velocity region as indicated in figure 9.22.

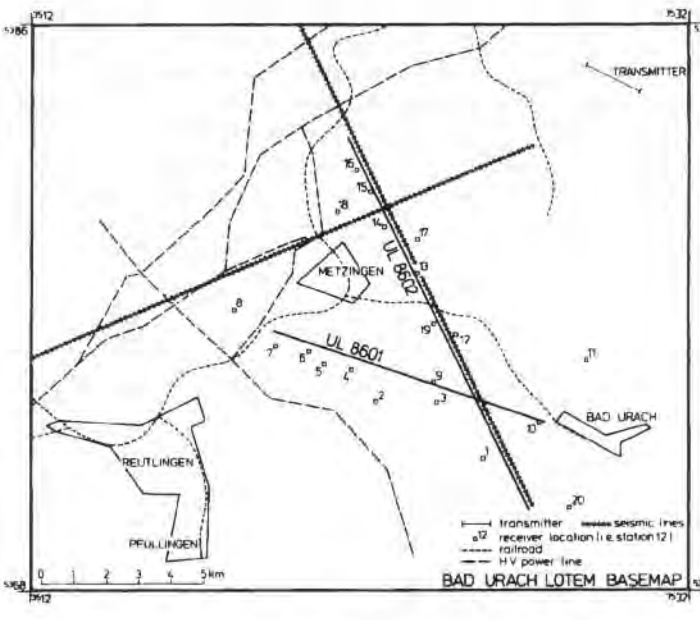

Fig. 9.21: Site location map of the LOTEM test survey in the Urach Geothermal Area (after Strack et al, 1990).

Figure 9.23 shows a representative example of data processing from the Urach survey. Field conditions were similar to those of the Black Forest survey, with strong cultural noise and difficult terrain. The field data have a slightly higher S/N ratios compared to the Black Forest data. This is mainly due to the conductive Mesozoic and younger Paleozoic surface sediments, which allowed a source current of 200 Amperes compared with only 40 A in the Black Forest. The data were the processed in the same manner as those in figure 9.14.

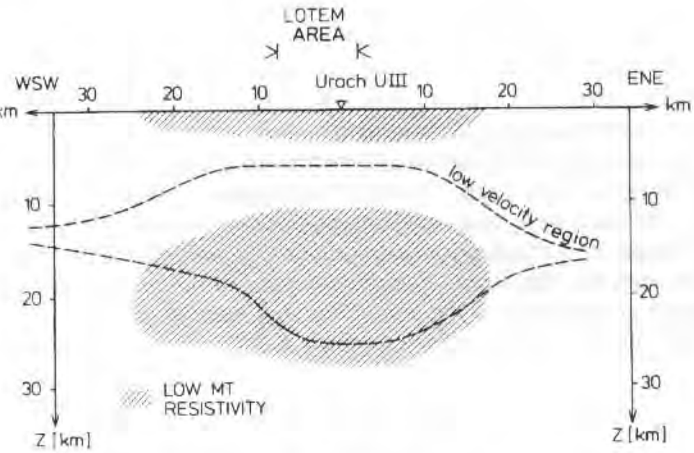

Fig. 9.22: Existing geophysical information (seismic and magnetotellurics) for the Urach Geothermal Area (after Berktold et al, 1982) with a low velocity region. The LOTEM survey covered 7 km directly over the region.

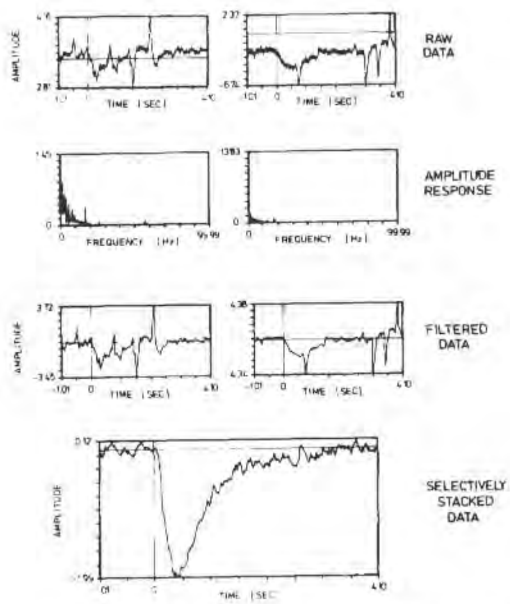

Fig. 9.23: Data processing sequence for the Urach survey (site 6). The polarity of the signal is selected by the first transmitter pulse and all consecutive signals are adjusted to it. The data processing follows that of figure 9.14 (after Strack et al, 1990).

Figure 9.24 shows a resistivity versus depth section for one of the two profiles measured. The data at the sites 1, 2, and 8 could not be used because of excessive noise in the data. No *a priori information* were used for the interpretation except for station 4 which was distorted at early times. Hence the top two layer boundaries were fixed at the geologic boundaries interpreted from the U III well log (Wohlenberg, 1982). Three to four layers were observed along the profile UL8601. The upper two layers in the resistivity cross section represent sedimentary cover. All stations show a highly resistive layer beginning at approximately 1.6 km depth. This corresponds to the top of the crystaline basement as mapped from the first arrivals of multifold reflection data (Walther et al, 1986). At site 4, the upper two layer thicknesses were kept fixed because the data were very noisy at early times. At stations 6 and 9, a conductive layer at a depth of 5 to 6 km was interpreted with confidence values of 95 percent. At all other stations the signal was distorted by cultural noise at later times. The depth of the conductor corresponds to the top of the low-velocity region mapped by Bartelsen et al (1982) using stacking velocities from a long-spread reflection survey.

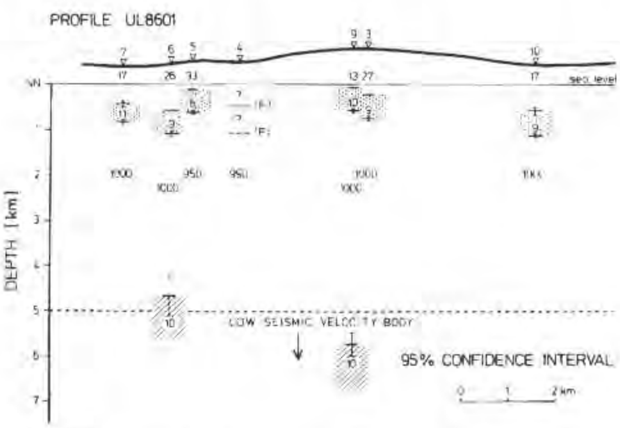

Fig. 9.24: Interpreted LOTEM resistivity depth section from one-dimensional inversions along traverse UL8601. Mesozoic and younger Paleozoic sediments from 0 to 1600 m are above resistive crystalline basement (gneisses). The crosshatching and shading of corresponding resistivity units is used to aid geologic correlation (after Strack et al, 1990).

Figure 9.25 shows a comparison to 3500 m depth of the resistivity well log from U III with a 1-D LOTEM inversion result from receiver station 10 which is 400 meters from the well. The resistivities from the upper kilometer were obtained from an induction log (Wohlenberg, 1982). The LOTEM inversion result (dashed line) correlates fairly well with the log resistivities to the final drilling depth of 3334 meters, although the LOTEM data do not resolve the resistivity difference in the high resistive unit below 1700 m depth.

To confirm the existence of the conductor at 5 km depth, synthetic apparent resistivity curves were calculated and convolved with the system response. The result of the convolution, a resistivity transform, is then directly compared with the field data which still contain the influence of the system response. Figure 9.26 shows the field data and the synthetic curves for earth's models with and without the conductor. Without the conductor (curves B) the data do not fit with the model for over half a decade in time. The difference between the theoretical curves indicates that the conductive layer of 10 Ωm resistivity at 6.1 km depth is necessary to interpret the data.

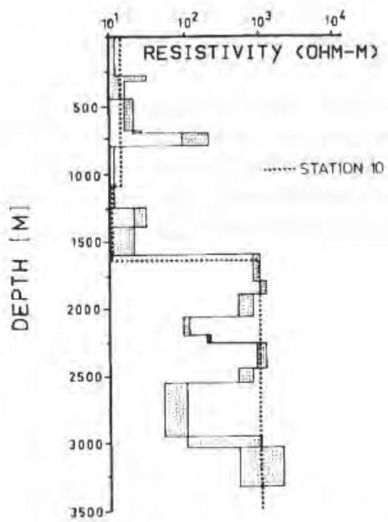

Fig. 9.25.: Comparison of inversion result and induction log at the Urach geothermal well site. The shaded part marks the confidence bounds. LOTEM station 10 is 400 m from well U III apart (after Strack et al. 1990) and its interpretation given by the dashed line.

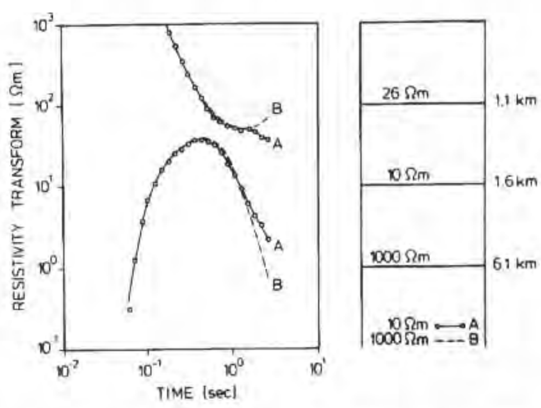

Fig. 9.26: Last layer resistivity test for Urach LOTEM station 6. The upper and lower curves represent early and late time resistivity transform curves for the respective models on the right. The circles represent the observed data and the solid/dashed lines the synthetic curves derived from the model on the right (after Strack et al. 1990).

TEST SURVEY OVER THE KAAPVAAL CRATON, R.S.A.

During 1987, a test survey with the LOTEM method was carried out over the Kaapvaal craton in South Africa. A detailed description of the interpretation and its place within the geological framework is given by De Beer et al (1991). Here, a summary of the geophysical aspects with a brief highlight of the geology is given.

The Limpopo Belt in South Africa is flanked by the Zimbabwe and Kaapvaal cratons. At the surface they contain granitoids and greenstones of low metamorphic grade. The cratons are of high resistivity. Figure 9.27 shows a rough overview of the resistivity as seen at the surface. Originally the southern boundary of the Limpopo was defined in terms of metamorphic transitions alone (Du Toit et al, 1983; Mason, 1973),

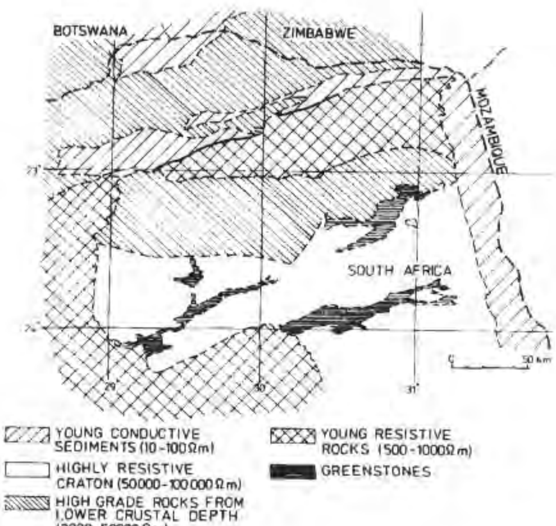

Fig. 9.27: General geologic features around the Kaapvaal craton in terms of their resistivities.

but more recently the proposed tectonic model incorporated the aspect of a steeply southward-dipping crust (e.g. Coward and Fairhead, 1980; Baston and Keys, 1981; Baston, 1983). A significant amount of geophysical data exists (De Beer et al, 1991) and was used by De Beer and Stettler (1988) to confirm the results of Van Zijl (1977a, 1978). For the Southern Marginal Zone (SMZ) of the Limpopo Belt it was found that the highly resistive, low-grade rocks dip northward underneath the moderately resistive, high-grade SMZ. The objective of the LOTEM survey was to determine the behavior of the conductive zone observed near the base of the cratonic crust when the transition from low-grade Kaapvaal craton to the high grade SMZ is crossed. A base-

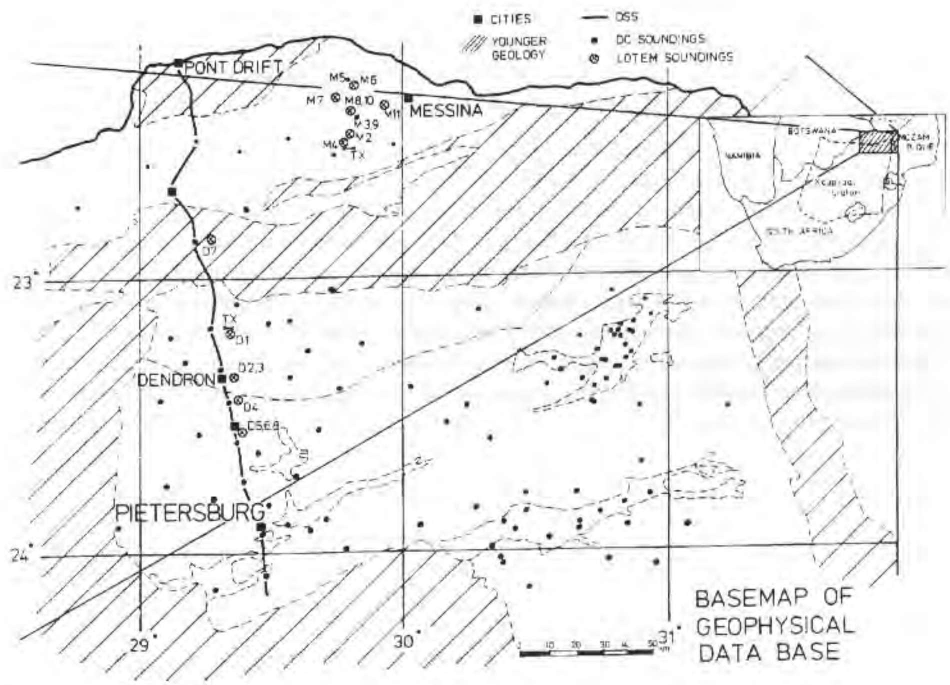

Fig. 9.28: Basemap of the LOTEM survey including the most important deep DC-resistivity soundings.

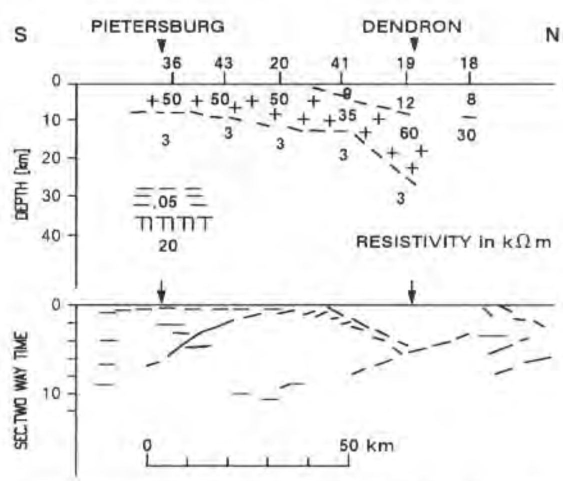

Fig. 9.29: Top: Geoelectric section from Pietersburg to north of Dendron along the seismic reflection profile. Resistivity values are k Ωm. Bottom: Line drawing of the seismic reflection pattern in the Pietersburg–Dendron section of the profile (after De Beer et al, 1991).

map with the geophysical data base is shown in figure 9.28. Figure 9.29 shows the resistivity section interpreted from deep DC-resistivity soundings with a common spacing of 30–40 km (some are 1200 km spacing) at the top. The bottom of the figure shows the corresponding line drawing based on the deep seismic reflection measurements. Note that the dipping of the resistor to the North can be clearly seen.

Extensive forward modeling was done before the survey was conducted to assess the probability of detecting the conductor below 20 km depth. First, the response was modeled in terms of apparent resistivities (compare figure 9.30). This shows that the conductor was visible at a time window suitable for the DEMS IV instrument, which was used for the survey. As realistic transmitter parameters a source length of 2000 m and a current step of 60 A was chosen. Then the voltages induced in the DEMS IV magnetic field receiver were calculated. The response for different offsets of 5, 10, 20, 30 and 40 km are shown in figure 9.30. For the different offsets the conductor is seen at the same time window. In order to observe this conductor at 5 km offset, one needs instruments with a dynamic range of at least 6 decades. With increasing offset the

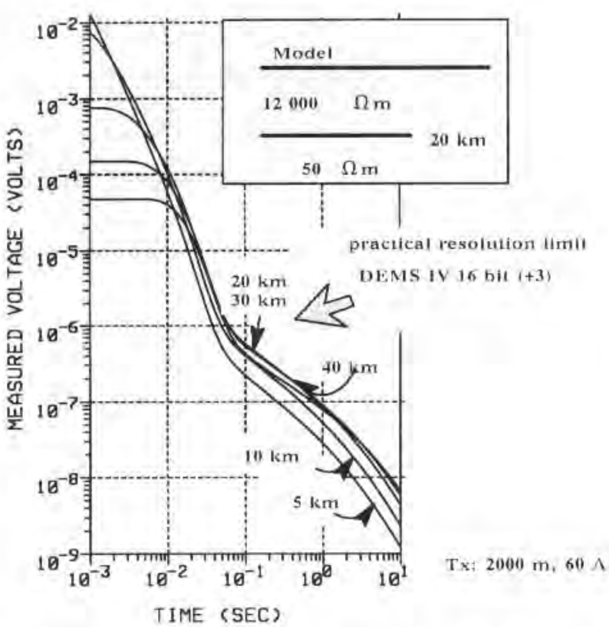

Fig. 9.30: Voltage responses for different transmitter to receiver offset using an average model for the conductor near the base of the Kaapvaal craton.

signal becomes smaller at earlier times but not significantly smaller at the time window around 100 msec which is the central time when the conductor is seen. In fact, at this time the response of the conductor increases for larger offset by about a factor of two. There is an optimum offset when the signal is largest around 20 to 30 km. The key question is whether the DEMS IV system can resolve these changes. Apart from the instrument resolution limit around 20 μV, one must consider the prestack processing and stacking which allows us to resolve signals below the instrument resolution limit. Although, in favorable condition we have been able to resolve signals 1000 times smaller than the resolution limit, one must be conservative and give the resolution limit as 1 μV. This meant for the South African survey that a large offset in combination with high amplifier gains had to be used.

One important — but usually omitted — factor for the forward modeling is the system response, which strongly influences the signal at early times. Using a real measured system response, the forward curves of figure 9.30 were redisplayed as predicted measured voltages. The curves exhibit a significantly smaller dynamic range than in 9.29 and one can now expect (after proper amplification) to resolve the top of the conductor at the base of the craton. The noise in the synthetic curves at early time is partially caused by the shape of the selected system response, and partially by the fact that a few sample points exist at this early time. Only after this modeling was done and evaluated, was the survey carried out.

A large number of single records were collected at the individual stations. A representative example is shown in figure 9.30. At the stations DE04 and DE05 several thousand stacks were acquired with the maximum of 3800 stacks at DEO5 during two days of recording time. This effort was necessary to reduce the noise most efficiently. The transients were all corrected for DC–level drifts and then stacked using an extended median stacking technique. Only minor filtering, using a time–variant Hanning window was done poststack. The stacked but not yet smoothed signal is shown at the bottom of figure 9.30. This stacked transient was then transformed to apparent resistivities and input into a Marquardt type inversion, yielding layered earth models.

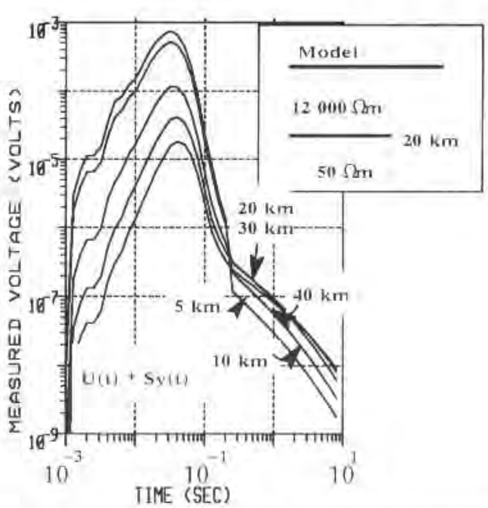

Fig. 9.31: Response resulting after convolving the data of figure 9.30 with a measured system response taking filters and transmitter waveform into account.

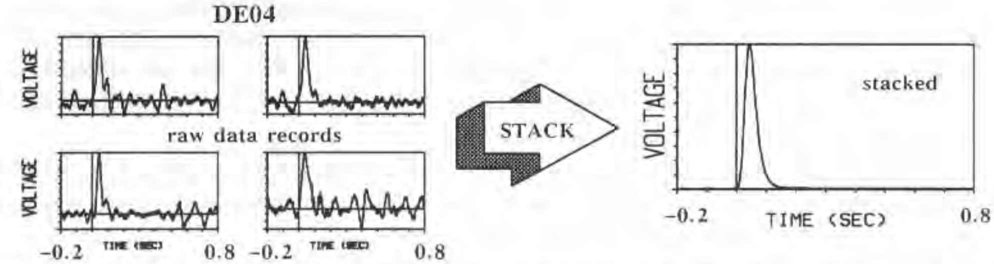

Fig. 9.32: Representative data set from the LOTEM survey. The left four frames show four single records. The right frame displays the result after removing the DC-level from all the records and stacking the data using an extended median stacking technique.

Figure 9.33 shows the results of inversion for stations DE04 and DE05 for offsets of 30 and 40 km, respectively. The points represent the data. The error bars derived from the selective stacking are smaller than the plotting symbol. The theoretical curve for the inversion result is drawn through the data points. Superimposed on the figure are the calculated curves for a half-space without the conductor (dashed line).

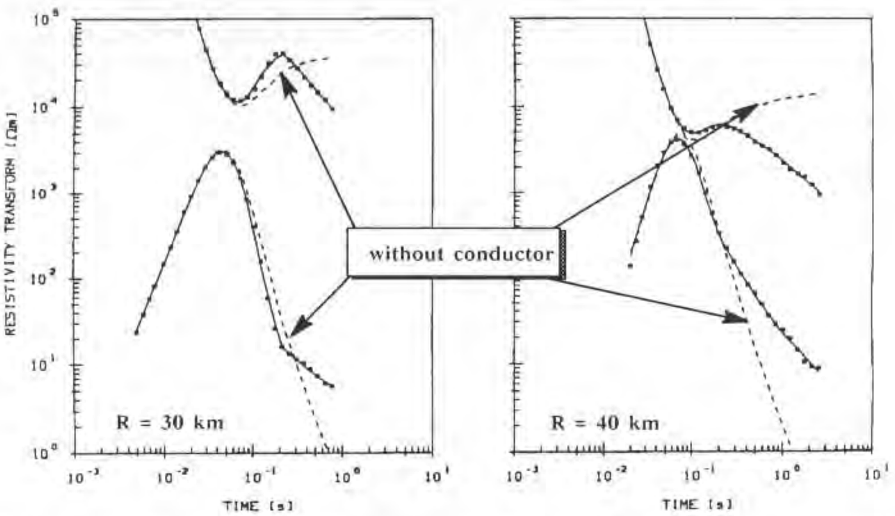

Fig. 9.33: Early and late time apparent resistivities for stations DE04 and DE05 (see figure 9.28). The field data are represented by the points and the theoretical curve for the inversion results by the solid line through the data points. The dashed line represent a half-space response when the conductor is absent (after De Beer et al, 1991).

For both data sets the existence of the conductor and its depth bounds is most often the key question. In order to determine these bounds many responses are calculated for different resistivity and depth values of the conductive layer. The χ^2 fit with the data is displayed in figure 9.34. The 7% error ellipse encloses all possible models with fitting errors smaller than 7%. This type of analysis resulted in the models and their variation (dashed lines) shown in figure 9.35 and shows that depth is fairly well resolved (20.5 ± 2.5 km) but that the resistivity is more poorly resolved (22.5 ± 20 Ωm).

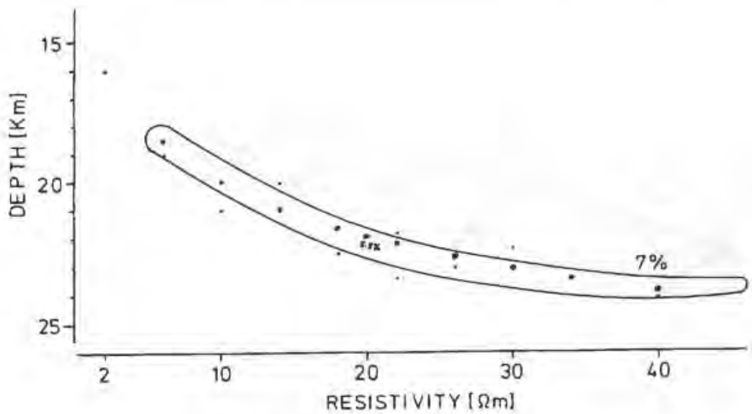

Fig. 9.34: Error ellipse for an χ^2 fit better than 7% for different resistivities and depths of the conductor.

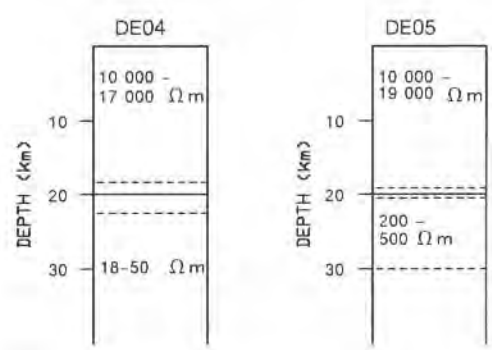

Fig. 9.35: The earth models interpreted for LOTEM sounding data for DE05 and DE04 as shown in figure 9.33 (after De Beer et al, 1991).

The difference in depth to the conductor for the two stations on either sides of the SMZ – craton boundary is very interesting (see figure 9.35). DE04, in the SMZ indicates a lower conductive layer at a depth of 21 to 24 km. The resistivity of this conductor ranges from 18 to 50 Ωm. For site DE05 on the craton, this conductor could not be satisfactorily interpreted as a single layer. A moderately conductive zone of 200 – 250 Ωm was modeled at a depth of 20 km, overlying the lower portion of 30 – 120

Ωm which start at approximately 30 km depth. As can be seen in figure 9.36, the depth to the lower crustal conductor ties in well with the DC–resistivity sounding recalls on the craton further to the south.

The combination of DC–resistivity and LOTEM shows that the idea of a steeply southward–dipping crustal margin between the SMZ of the Limpopo Belt and the Kaapvaal craton to the south is incorrect. If this would be the case one would have clearly seen anomalous behavior in the LOTEM interpretation caused by a 3–D effect.

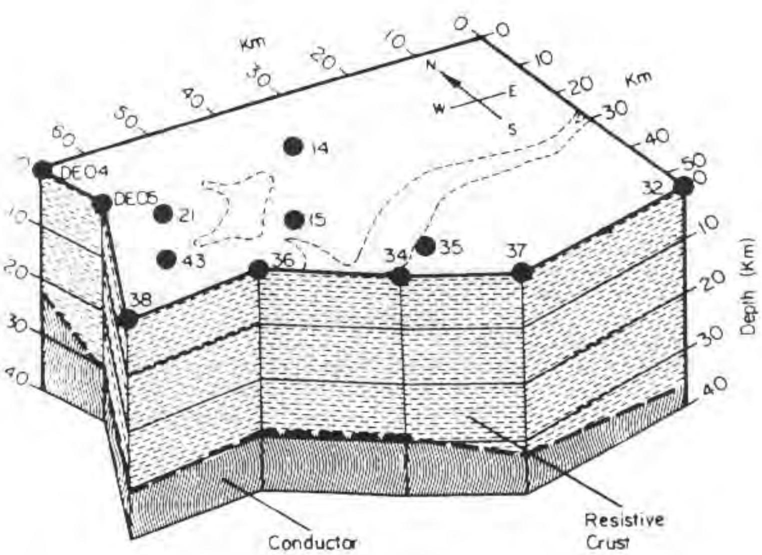

Fig. 9.36: The depth to the deep crustal conductor in the Kaapvaal craton and SMZ as determined by ultra–deep Schlumberger soundings at sites 32, 37, 34, 36 and 38 and LOTEM soundings at DE05 and DE04 (after De Beer et al, 1991).

TEST MEASUREMENTS IN CHINA FOR THE APPLICATION OF LOTEM FOR EARTHQUAKE PREDICTION

During 1988, LOTEM measurements were carried out near the Tangshan area in China, where a large earthquake on 28th of July 1976, killed over 200 000 people. Under the assumption that resistivity changes can be used for earthquake prediction, the objectives of the survey were defined as:

- Demonstration of the repeatability of LOTEM measurements within a period of several weeks.
- Demonstration of the depth investigation range of the LOTEM technique.
- Demonstration of the cost effectiveness.

Ωm which start at approximately 30 km depth. As can be seen in figure 9.36, the depth to the lower crustal conductor ties in well with the DC–resistivity sounding recalls on the craton further to the south.

The combination of DC–resistivity and LOTEM shows that the idea of a steeply southward–dipping crustal margin between the SMZ of the Limpopo Belt and the Kaapvaal craton to the south is incorrect. If this would be the case one would have clearly seen anomalous behavior in the LOTEM interpretation caused by a 3–D effect.

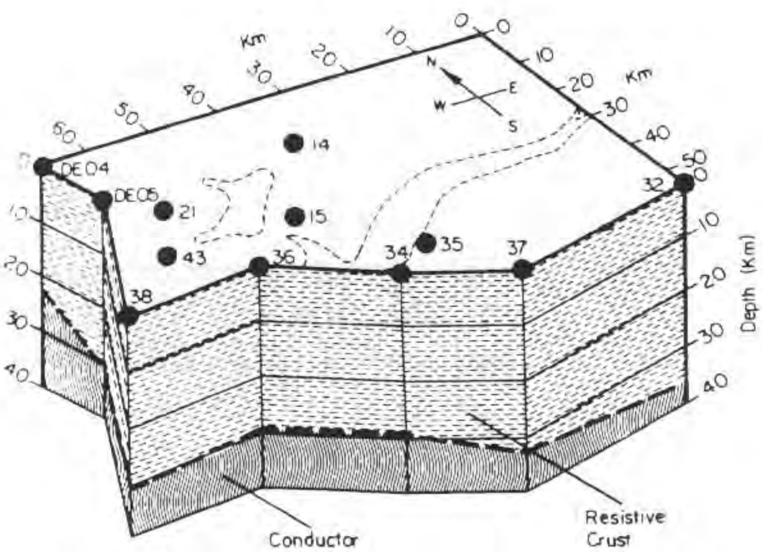

Fig. 9.36: The depth to the deep crustal conductor in the Kaapvaal craton and SMZ as determined by ultra–deep Schlumberger soundings at sites 32, 37, 34, 36 and 38 and LOTEM soundings at DE05 and DE04 (after De Beer et al. 1991).

TEST MEASUREMENTS IN CHINA FOR THE APPLICATION OF LOTEM FOR EARTHQUAKE PREDICTION

During 1988, LOTEM measurements were carried out near the Tangshan area in China, where a large earthquake on 28th of July 1976, killed over 200 000 people. Under the assumption that resistivity changes can be used for earthquake prediction, the objectives of the survey were defined as:

- Demonstration of the repeatability of LOTEM measurements within a period of several weeks.
- Demonstration of the depth investigation range of the LOTEM technique.
- Demonstration of the cost effectiveness.

Data Base of the Tangshan Area

Before the LOTEM survey started, very little was known to us about the electrical subsurface structure Tangshan area except that electrical resistivity measurement had been used successfully for earthquake prediction. Usually, Wenner arrays with electrode spacing of 1–3 km were used for the measurement. This yielded a depth of investigation of several hundred meters (Qian et al, 1983). The measurements were carried out with well calibrated instruments giving data errors below 0.5 %. Figure 9.37 gives a summary of the results obtained by Qian et al (1983). The curves show the variation in resistivity over a period of 10 years. They indicate a continuous drop in resistivity starting 2–3 years before the earthquake. For some recording sites this drop in resistivity had been the only feature over a 13 year observation period. The Tangshan earthquake is the only strong earthquake in the vicinity of the area and occurred in the immediate neighborhood of the minimum of the apparent resistivity.

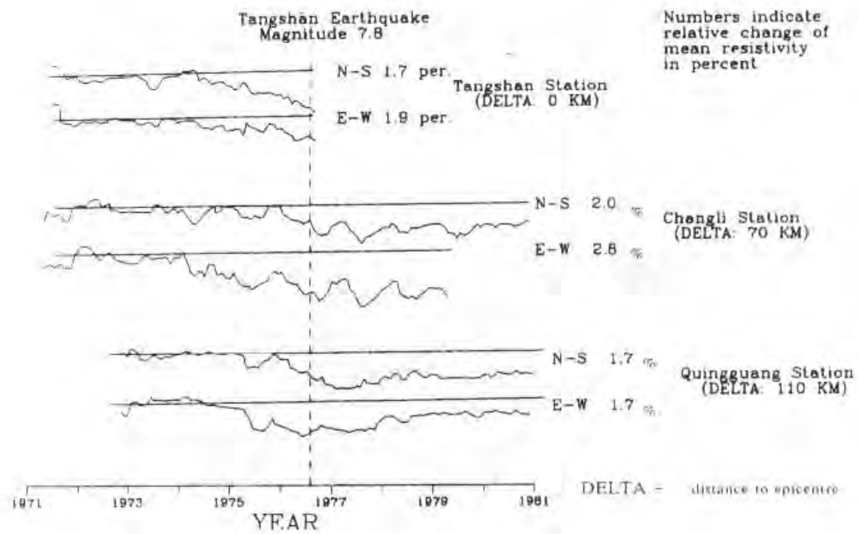

Fig. 9.37: Percentage change of the mean monthly resistivity measured by Wenner arrays in the Tangshan area (after Qian et al, 1983).

Figure 9.38 shows the contour lines of the resistivity anomalies. The Tangshan area lies clearly in the center of the anomaly. Qian et al (1990) gives an explanation of the precursor as being triggered by tidal forces. Their explanation is new compared to the classical concept of rock failure being the cause of the resistivity anomaly. Figure 9.39

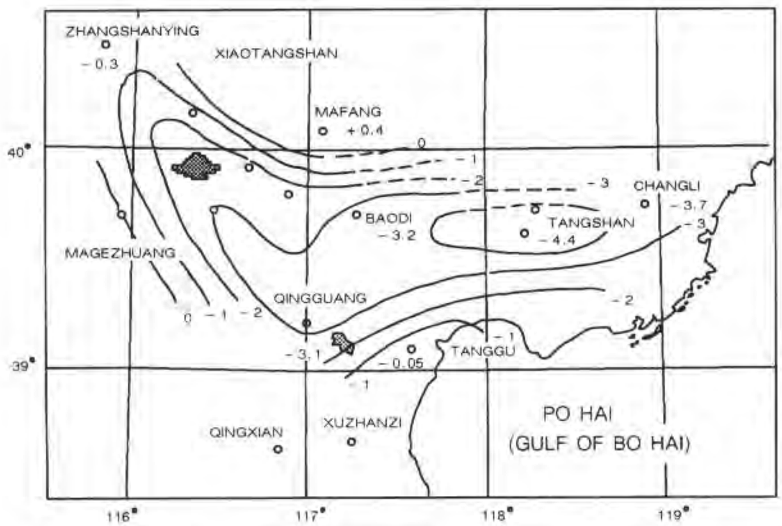

Fig. 9.38: Contour map of the resistivity anomalies in the Beijing–Tiangjin–Tangshan area (after Qian et al, 1979).

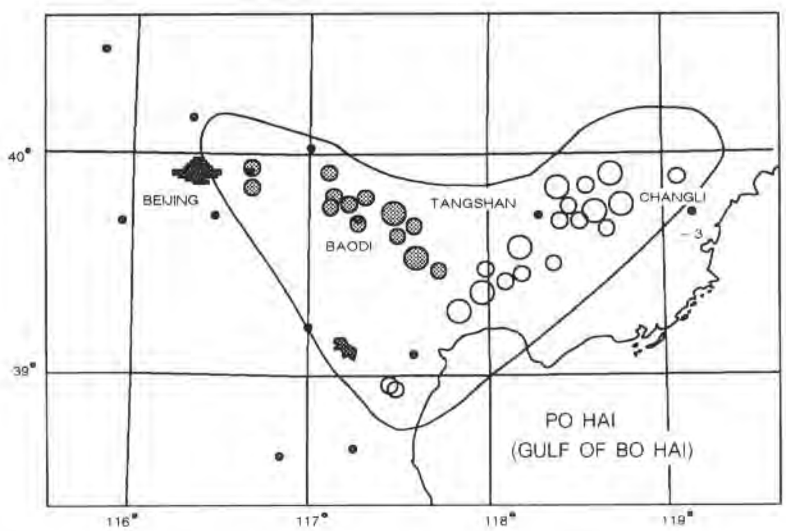

Fig. 9.39: Distribution of earthquakes with magnitudes above 4 after the Tangshan earthquake. Open circles represent aftershocks while the closed ones are earthquakes appearing to be unrelated to the aftershocks (after Qian et al, 1979).

shows a map of earthquakes after the Tangshan area. The earthquakes with magnitudes higher than 4 are shown. The aftershocks line up along one zone, whereas an-were acquired at each site with three parallel profiles and one walkaway test on a profile. The walkaway profile was used to verify that one transmitter location was sufficient for the area.

A sample transient for the area is displayed in figure 9.41. The transient displayed is from the set of noisy transients. From this transient it can be seen that the signal is lost when the noise prevails resulting in a limited depth of investigation. Only ten percent of the data was as noisy as the data of site 15 in figure 9.41. At the control site transient were recorded at the beginning and at the end of the survey. In figure 9.42 the stacked signals at the control site are superimposed on each other. These transients are fairly smooth and show much better signal-to-noise ratios than the one in figure 9.41. The transients at the control site are also normalized for receiver gain, equivalent loop area, and transmitter moment which gives voltages in the femptovolt range.

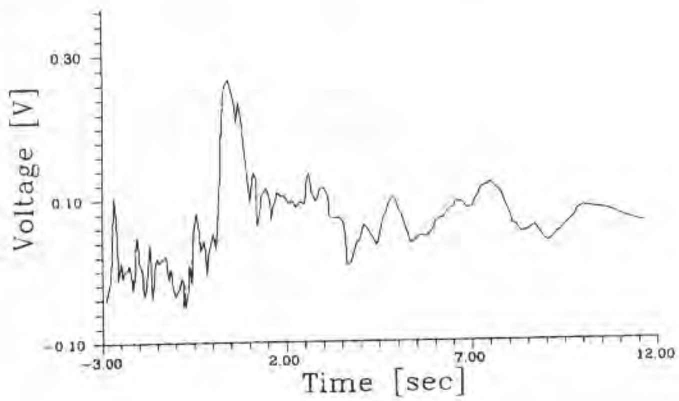

Fig. 9.41: Representative stacked transient (FB15) for the survey in the Tangshan area, PRC.

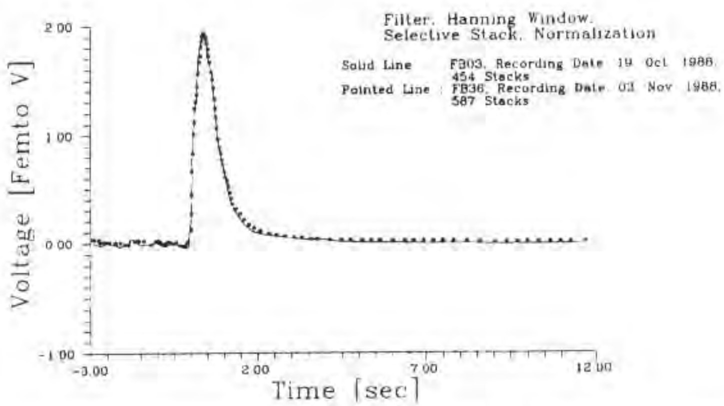

Fig. 9.42: Selectively stacked transients at the control site in the Tangshan area, PRC.

The objective of the measurements at the control site was to demonstrate the repeatability of the technique. Both measurements were carried out 14 days apart under different noise conditions. In figure 9.42 the difference in the stacked data is negligible. A better way to estimate the difference between the curves is to carry out inversions of these data sets. The results are shown in figure 9.43.

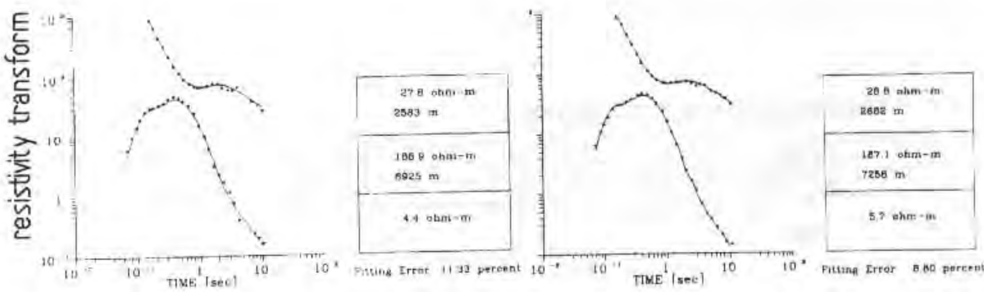

Fig 9.43: Inversion results for the measurements at the control site in the Tangshan area, PRC.

Discussion of the Results

Results of the repeated measurements (figure 9.43) clearly show a conductor at a depth of about 9.5 and 9.8 km. The upper conductive layer is sedimentary and about 2.5 km thick at the control site. The second, more resistive layer is interpreted as crystalline rock. The nature of the conductor below is not very clear. Qian and Peterson carried out MT measurements about 100 km away from the LOTEM site. They observed a similar resistivity structure, with the resistivity of the last layer being poorly constrained in their measurements. This can similarly be attributed to the strong cultural noise in the area, which made the interpretation of the data very difficult.

Figure 9.44 shows two resistivity sections for one of the profiles outlined on figure 9.40. The top of the figure displays the inversion results as they are output from the inversion program. The error bars in depth give the depth uncertainty. The inversion statistics clearly indicated that for the first layer only the inverse conductance was resolved. This means we can keep the conductance at the sites fixed, determine an average resistivity from the inversion results and adjust the thickness. This procedure is in this case also geologically reasonable because one can not expect strong lateral resistivity variations in this area. This procedure which we termed conductance referencing was applied across the profile and the bottom of the figure resulted. The boundary to the second layer has now become significantly smoother than in the top display where the heavy lines mark the interpreted layer boundary. The jagged interface with the third layer is not significantly smoothed by this procedure because it is mainly focused on the part of the data where the model parameters are correlated. The depth to the conductor in the eastern part of the profile is notably different from the western part where the conductive layer begins at a depth of approximately 6 km. The parallel profiles show very similar results, a deepening conductor in the east and a shallow one in the west. One possibility is that a local structure is superimposed on the survey area upon the regional structure. The transition from the shallow conductor to the deeper one could be associated with a fault or somewhat smoother which is not resolvable with the assumption of the layering of the model.

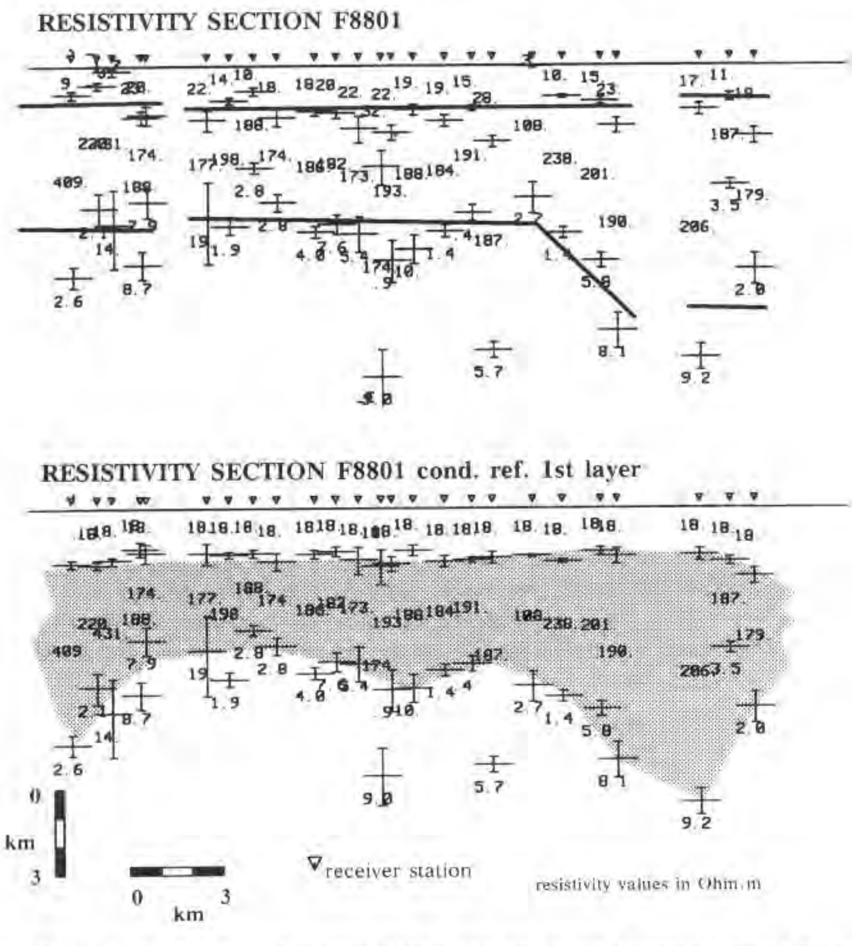

Fig. 9.44: Resistivity depth sections for profile F8801. The top section displays the results as they are given by the inversion. The bottom section shows the same results after adjusting for the fact that the inversion resolved only the first layer conductance and not the individual layer parameters (conductance referencing).

The main conclusion from the measurements were that the goals were reached namely:

- The technique yields highly repeatable measurements in this area (for a second repeat site the crew could not find the site for reoccupation).
- The depth of investigation in this area lies between 6 to 9 km and is far greater than the depth of investigation of DC-resistivity technique which are routinely used in the area.
- Within a total of three weeks of survey time a total of 115 soundings (over 1300 single records) were carried out at 74 surface locations which makes the technique very competitive.

Besides these goals, the survey also detected clearly a conductor which is shallower in the western and deeper in the eastern part. According to preliminary observations, the fault from the LOTEM interpretation correlates well with the epicentres.

DISCUSSION

The above surveys in the USA, Europe, South Africa and China show that the LOTEM sounding method contributed significant information to geophysical investigations of the earth's crust.

The results from the North American measurement clearly demonstrated the capability of the technique. However, in all cases very powerful transmitters were used. Since the operation of very powerful transmitters is very expensive and can be a safety hazard, the German surveys used smaller transmitters with a source moment of about one tenth of the North American tests. In the Oberpfalz the results gave a picture which is consistent, but the interpretation is questionable because of the possible multi-dimensional effect. The final answer to this question will be obtained sometime in the future, as the continental deep drilling project progresses.

In the Black Forest a low velocity channel in the lower crust coincides with a low resistivity zone. In the Urach Geothermal Area the top of a low-velocity anomalous region correlates with a low resistivity zone in the LOTEM interpretation. Consistent results were obtained to a depth of approximately 8 km under noisy electromagnetic field conditions. For both surveys the interpretation is confirmed by other geophysical information.

Interesting geologic and petrologic correlations are demonstrated for the Black Forest. The low-velocity zone in the lower part of the upper crust correlates with 1) a seismically transparent zone, 2) a zone of decreased Poisson's ratio, and 3) a zone of low electrical resistivity. The decreased Poisson's ratio is a very attractive indicator for pore fluids, since the P-wave velocity is more sensitive to fluids than the S-wave velocity (Helbig and Mesdag, 1982; Ensley, 1984). Low electrical resistivity can be produced by aqueous fluids with high ionic content such as saline water (Shankland and Ander, 1983; Haak and Hutton, 1986; Gough, 1986) and by unmetamorphosed sedimentary rocks, graphite, hydrated minerals and metallic sulphides. A purely compositional influence of the lithology, such as an increased ratio of quartz/ feldspar content could explain the decreased Poisson's ratio (Kern, 1982) but would not account for the low resistivity. Our favored explanation of this correlation is the existence of fluid filled pores or cracks which could be the result of recent lower crust dehydration processes (Fuchs et al, 1987; Lüschen et al, 1987).

In the Urach area similar type of correlation between P-wave velocity and resistivity is observed in the upper 5 to 7 km crystalline crust. The low resistivity supports the concept of hydrothermal alteration of the crystalline rocks or postvolcanic gas exhalations from great depth (Berktold et al, 1982). In both cases the conductor is associated with an area of high geothermal gradient.

In the survey in South Africa the LOTEM results clearly correlated with the DC-resistivity sounding in the area. It clearly indicated that the idea of a steeply southward-dipping of the Limpopo Belt is incorrect. The LOTEM and DC-resistivity results are in very good agreement with seismic (De Beer et al, 1991). In South Africa neither saline fluids nor graphite film can be ruled out conclusively as explanation for the lower crust conductor.

In China the LOTEM measurements provided a good statistical basis for the interpretation of the upper crust resistivity. Considering how noisy the area is (Qian and Peterson, 1991), this is very important. The deep geoelectric model in the area provided a basis for the determination of the extreme models for the MT measurements in the area. In the survey area itself a more localized conductivity anomaly consistent throughout the area exists. This is judged by the statistics of the individual inversion which clearly indicate the conductor at depth. The change from the lower to the deeper crustal conductor could be smooth or as localized fault. Only more detailed measurements can answer this question.

These studies motivate further investigation with LOTEM and MT using a more advanced approach to data acquisition and interpretation, such as extensive stacking, noise compensation techniques and MT/LOTEM joint inversion, for a more complete integration of geophysical information on the earth's near crust.

SUMMARY CHAPTER 9

Controlled source electromagnetic techniques are not very often used for deep crustal application. Some of the early work in the western hemisphere included deep DC–resistivity measurement in southern Africa and megasource transient EM measurement in the USA. The records from the deep DC–resistivity measurement showed transients when the transmitter polarity was changed. The transient signals were only used as timing marker and were not quantitatively interpreted. The work in the USA used large source moments to achieve sufficient investigation depth. Some of the early work already indicated most of the phenomena known today about transient soundings.

In Europe, the LOTEM method was initially only tested with small transmitters for deep crustal applications, although experience from the USA suggested that small moment (low power) transmitters were insufficient for such an investigation depth. The first test in the Oberpfalz area, site of the German deep continental drilling project, required a conductive layer at 10 km depth to yield a consistent interpretation. However, the interpretation was not very stable. The subsequent measurement in the Black Forest area shows very consistent results using two transmitters. Here, a low seismic velocity zone could be clearly correlated with a zone of low resistivity. Further confirmation of this relationship was obtained when carrying out measurements in the Urach Geothermal Area where also a low–velocity zone had also been found.

In South Africa, the objective of the LOTEM survey was to define the nature of the transition zone between the Southern Marginal Zone of the Limpopo Belt and the Kaapvaal craton. The LOTEM results clearly show that the conductor at 20 to 30 km depth continues through the transition zone. These results are in agreement with deep DC–resistivity measurements in the area.

In China, LOTEM test measurements were carried out in the Tangshan area, site of the devastating earthquake of 1976. The measurements illustrated that over a period of several weeks repeatable measurements can be obtained with the technique. In addition to this objective, the survey results indicated that a lower crustal conductor exists in the survey area.

PROBLEMS CHAPTER 9

1. Draw the transmitter current waveform for the analog recordings displayed in figure 9.1.
2. Find in the magnetic field transients in figure 9.3 the reversals and explain it qualitatively.
3. How can you see that the results could be unstable for the Oberpfalz data?
4. What are the major factors backing the stability of the Black Forest interpretation?
5. Why could a low dynamic range system (such as DEMS IV) resolve the conductor in the Kaapvaal craton case history?
6. Explain why and how LOTEM could be used for earthquake prediction.

KMS Technologies – KJT Enterprises Inc.
6420 Richmond Ave., Suite 610
Houston, Texas, 77057, USA
Tel: 713.532.8144