BOREHOLE GEOPHYSICAL OF KTB

R. Hänel
J. Draxler

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1. INTRODUCTION

The Continental Deep Drilling Programme of the Federal Republic of Germany (KTB) is a project of basic geoscientific research. For this, the technical concept for drilling, sampling, coring and logging programmes are tailored to scientific purposes. According to present plans, the superdeep borehole will be drilled to a target depth of about 14000 m in the period of 1990 - 1997. A completely new rig will be designed to drill this borehole.

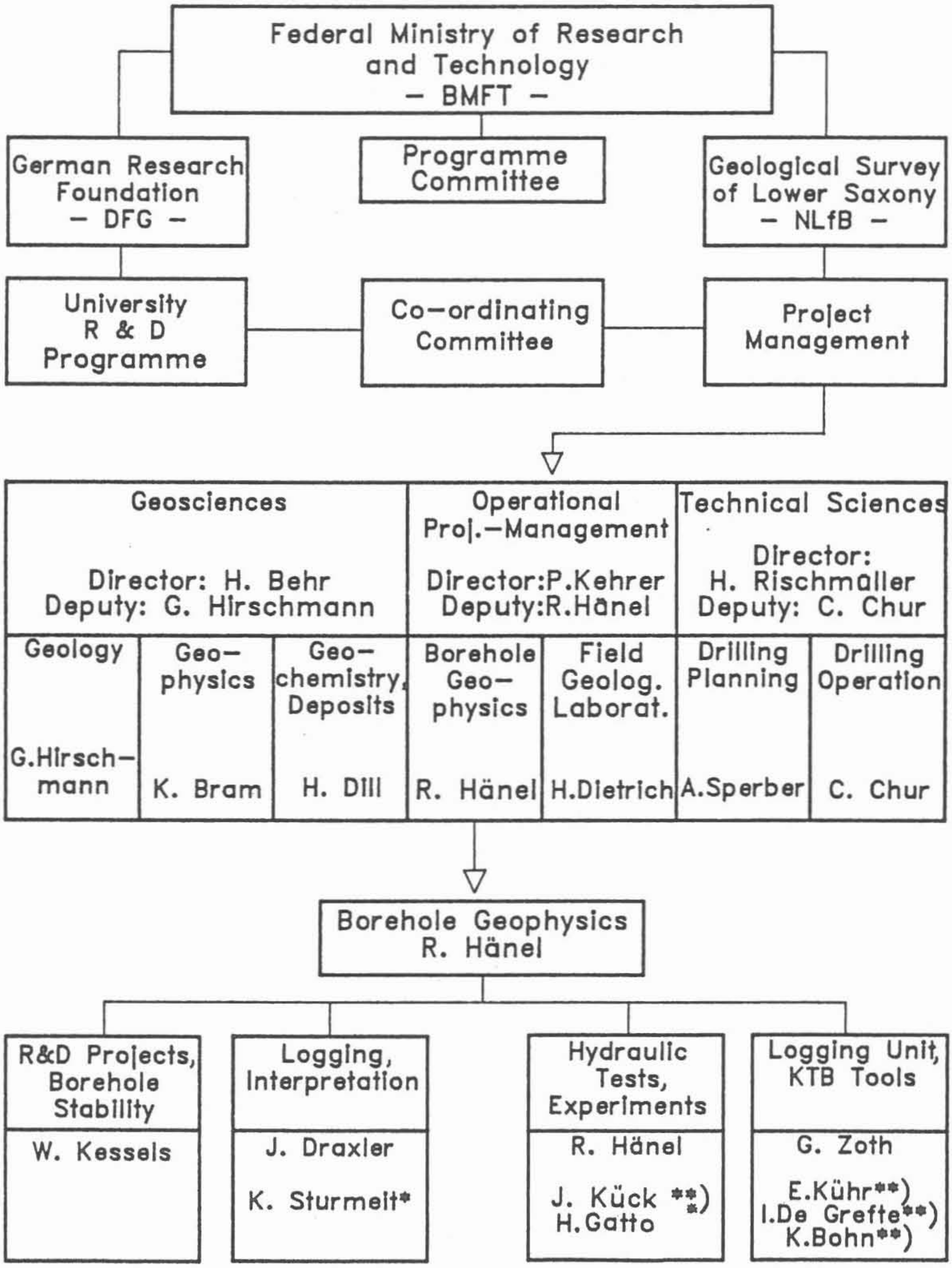
The drilling of the pilot borehole started September 1987. The envisaged depth will be 5000 m, and the present depth is about 3000 m (August 1988).

A Project Management has been established in 1985/86. It operates with about 40 persons on fulltime and additional personal on contract basis. The Project Management includes also a group responsible for borehole measurements. The structure of the organization, especially with regard to the borehole measurement group is given in Tab. 1.

To realize the scientific ideas, a Research and Development Programme is initiated engaging about 250 scientists from different universities, institutes and geological surveys. This programme is subdivided into 9 research groups (Task Forces):

Field Laboratory, Geology and Geophysics, Stress Field and Borehole Stability, Rock Physics/Logging and Log Interpretation, Texture and Deformation, Petrology/Geochemistry/Geochronology and Ore Deposits, Fluids, Technical Sciences, and Modelling.

Table 1: Organisation diagrams showing the group for borehole geophysics and its relation within KTB.



*) Prakla-Seismos **)Schlumberger ***)Mesy

2. OBJECTIVES, TASKS

The main scientific objectives are given by (EMMERMANN, 1986):

> Investigation of the physical-chemical conditions and processes in the deep crust for a better understanding of the dynamics of intracontinental structural evolution.

The main task for the borehole geophysics group of the Project Management can be derived directly from this objective:

> Realization of geoscientific objectives in regard to measurable physical rock parameters, chemical elements, mineral components, fluids, heat and mass transport as well as physical field parameters.

Before establishing the KTB Project Management, some advances have been made by preliminary studies into that direction, and the main task has been subdivided into several, more specific topics:

(1) Market Analysis
Ascertainment of available logging tools and logging units of service companies, companies, universities, and geological surveys at the domestic market or in foreign countries, especially with regard to temperature and pressure limitation (300 °C and 2000 bar).

(2) Fundamental Research
Logging tools and the related interpretation methods for logging data are mainly developped for hydro-carbon exploration in sedimentary rocks. Therefore, the adaptation for crystalline rocks has to be considered and, if necessary, fundamental research has to be initiated.

(3) Investigation of Physical Rock Parameters
Determination of petrophysical data under simulated in situ conditions for calibrating logging data, correlation with chemical and modal compositions as well as interpolation to large scale units and intrinsic characteristics. For this study the borehole (quasi in situ condition), the laboratories of institutes (simulated in situ condition), and the Field Laboratory (pT-condition at the earth's surface) are available.

(4) Correlation Progamme
Correlation of results from core measurement with results from logging will be essential to decide - while drilling the superdeep borehole - for giving preference to coring or logging.

(5) Development of Logging Tools
The scientific objectives also require tools which are not offered by service companies and institutes or which currently have a lower temperature limit. Therefore, new development and/or improvement has to be stimulated.

(6) Deep Earth Observatory
After the drilling stopped, and the routine measurements have been carried out, repetitions, long-term measurements, and time-depending studies are necessary. Therefore, it has to be examined, whether a Deep Earth Observatory is justified.

(7) Permanent Logging Unit
The large research and development programme of KTB requires a comprehensive logging programme. Therefore, a permanent logging unit as well as tools which are often needed should be purchased and operated by KTB.

(8) Logging Programme
To meet the high expectations of the scientific community, an extensive logging and testing programme for the pilot borehole had to be established, and must be realized. The experience gained and enlarged by further experiments will be integrated in the planning of the logging programme for the superdeep borehole.

(9) Securing of Logging Data
It must be guaranteed that all measured data is safely stored in a uniform format (e.g. LIS) so that at any time - also after many years - the data is available for interested parties.

(10) Interpretation of Logging Data
To benefit from the know-how of the service companies, the first interpretation should be made by them. More sophisticated interpretations are in the responsibility of the university interpretation groups (R & D Programs, see also Tab. 1).

(11) Pilot Borehole
From the specified objectives/tasks follows that a pilot borehole is absolutely necessary.

3. PRESENT STATUS

The market analysis (1) has been completed (DEVAY et al. 1983, HÄNEL 1987). Based on this study, research and development for the tasks (2), (4), (5), and (10) have been started. In total, 35 running projects are now underway which are strongly related to borehole geophysics; see Tab. 2. The so-called 'Key Experiments' are of special interest; see Tab. 3. These are projects, which only can be carried out by means of a superdeep borehole (FKPE 1986). For more details see also KTB Report 87-3.

The Deep Earth Observatory, task (6), should include measurements such as the stress field, the near and far earthquakes, the magnetic field, the pore pressure, etc. A first concept was presented by KESSELS (1987), Fig. 1, and a first attempt will be made by project (34) of Tab. 2. The Deep Earth Observatory consists of two parts; the upper moveable and the lower stationary part. Anyhow, the project needs further clarification on what should actually be measured, what is possible, what is expected, what are the costs, etc.

To drill a pilot borehole with a minimum diameter of 6" has been strongly recommended by the group of borehole geophysics (HÄNEL 1987). This has been accepted by the Project Management in July 1986. The pilot borehole was spudded on September 22nd 1987. The present depth is about 3000 m (August 1988). The pilot borehole includes a complete coring programme as well as a comprehensive logging programme. So, the necessary work for task (4) can be carried out, which actually started in summer 1988. The similar is true for task (3).

With regard to task (7), a logging unit has been purchased for running basic and more frequent logs. It is a most modern sound insulated modular unit, presently equipped with 7500 m of 7-conductor-logging cable. For operations at greater depths in the superdeep borehole the unit will be modified by exchanging the winch section and adding a capstan unit. The cable head of the logging cable consists of:

- telemetry for data transfer
- unit for cable tension, mud resistivity and mud temperature measurement
- gamma ray for depth correlation.

A minimum set of logging tools has also been purchased:

- several temperature tools
- salinometer
- induced polarization probe
- borehole geometry tool
- 6-arm caliper (prototype)
- gamma ray probe
- fluidsampler, vacuum and forced circulation type.

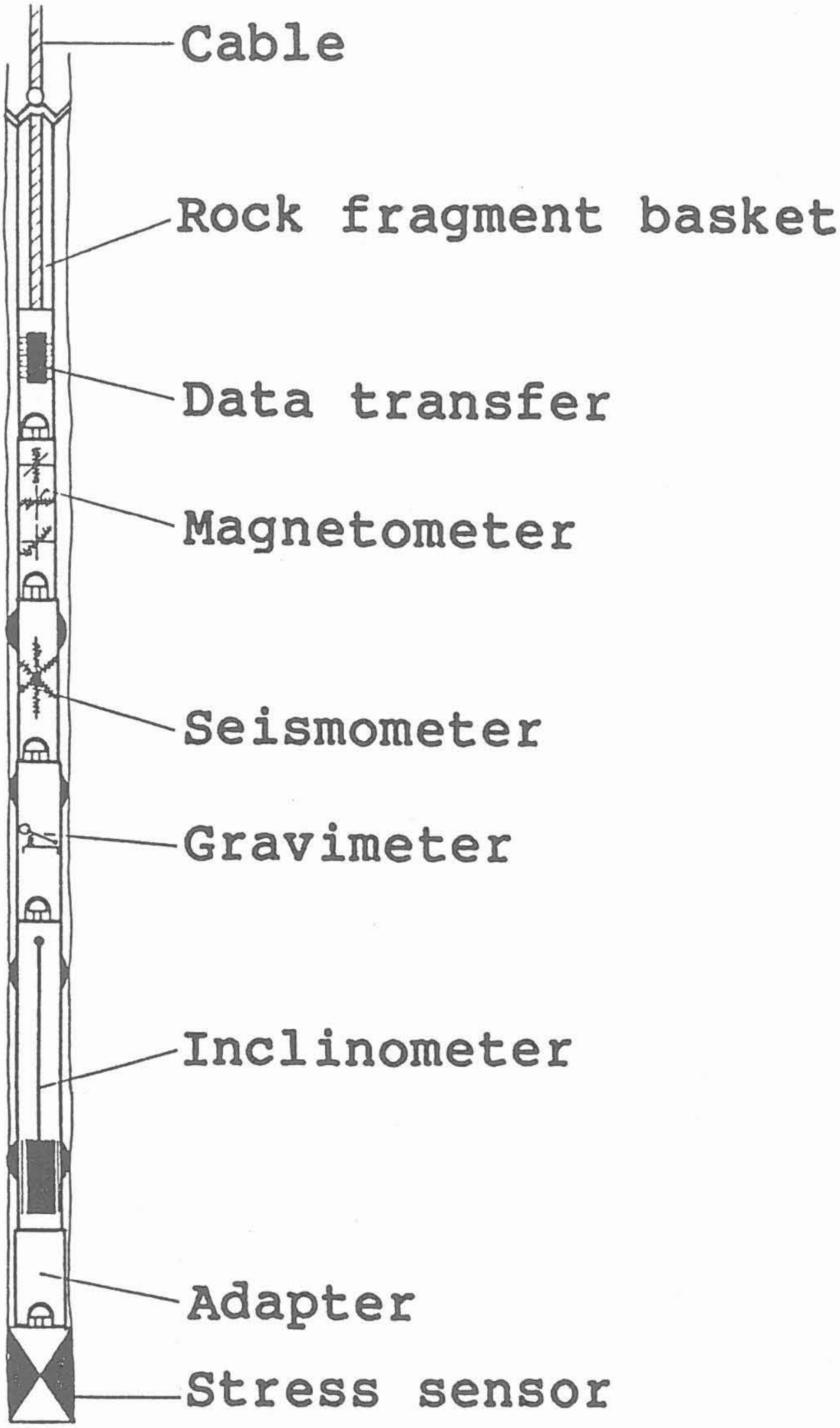


Figure 1: A possible concept for the Deep Earth Observatory.

Table 2: Research and Development Projects.

DFG = supported by German Research Foundation,
BMFT = supported by Federal Ministry of Research and Technology,
BGR = Bundesanstalt für Geowissenschaften und Rohstoffe,
NLfB = Niedersächsisches Landesamt für Bodenforschung.

Fundamentals

(1) Development and testing of a high-pressure permeameter/porosimeter for investigation of crystalline rocks. DFG.
R. Schopper, Techn. Univ. Clausthal.

(2) Investigation of electro-magnetic transient measurements in shallow boreholes with regard to its general application in KTB. BMFT.
S. Greinwald, BGR, Hannover.

(3) Development of interpretation methods for logging data recorded in crystalline rocks with micro-fractures and micro-pore structure. DFG.
R. Schopper, Techn. Univ. Clausthal.

(4) Changes of crystalline rock strength properties under alternating thermodynamic conditions. BMFT. O. Natau, Techn. Univ. Karlsruhe.

(5) Investigation of Peltier elements for cooling electronic components in wireline logging tools. BMFT. Dr. Neumann Comp., München.

(6) Development of heat shields for high temperature logging tools. BMFT.
Etudes & Production Schlumberger, Clamart, France.

(7) Theoretical thermo-chemical calculations for borehole stability under simulated in situ conditions in comparison to actual conditions in the KTB pilot borehole. BMFT. R.B. Rokahr, Techn. Unv. Hannover and
K. H. Lux, Techn. Univ. Clausthal.

(8) Development and testing of interpretation methods for electrical measurements including induced polarisation for porosity/permeability determination. DFG. D. Vogelsang, NLfB, Hannover.

Core Measurements

(9) Integrated measuring method for determination of porosity and permeability of dense rocks under simulated in situ conditions. DFG.
G. Pusch, Techn. Univ. Clausthal.

(10) Determiniation of physical parameters (thermal conductivity, thermal diffusivity, seismic velocity, density) under simulated in situ conditions. DFG. H. Burkhardt, Techn. Univ. Berlin, and R. Schopper, Techn. Univ. Clausthal.

Table 2: Continuation

(11) Determination of uranium and lead isotopes from KTB rocks. DFG. U. Haack, Univ. Giessen.

(12) Measurement of P- and S-waves under simulated in situ conditions, correlation with petrophysical data, chemical and modal compositions. DFG. H. Kern, Univ. Kiel.

(13) Determination of thermal and electrical conductivity under increased pressures and temperatures. DFG. A. Schult, Univ. München.

(14) Measurement of porosity, permeability and electric conductivity under simulated in situ conditions. DFG. G. Nover and G. Will, Univ. Bonn.

(15) Determination of thermal conductivity, thermal diffusivity and specific heat capacity under simulated in situ conditions and by means of the 'thermal flowmeter method'. DFG. R. Schulz, NLfB Hannover.

(16) Measurement of magnetic parameters, such as coercitive force, permanent saturation value, maximum susceptibility, paramagnetic susceptibility, etc. under simulated in situ conditions. DFG. H. Markert, Univ. Bayreuth.

(17) Palaeomagnetic and rock magnetic investigation on cores under simulated in situ conditions. DFG. J. Pohl, Univ. München.

Log Interpretation

(18) Testing a borehole magnetometer for vertical gradient sounding of magnetic variations. DFG. E. Steveling, Univ. Göttingen.

(19) Two- and three-dimensional simulation for a frequency-depending induction log. DFG. K.-M. Strack, Univ. Köln.

(20) Interpretation of permeability and hydro-frac stress measurements as well as improvement of the hydro-frac tool. DFG. F. Rummel, Univ. Bochum.

(21) Interpretation of logs using statistical methods to determine porosity and permaebility. DFG. H. Burkhardt, Techn. Univ. Berlin.

(22) Interpretation of magnetic measurements made in boreholes and on cores to find magnetic discontinuities. DFG. A. Hahn and W. Bosum, NLfB, Hannover.

(23) Adaption of Faciolog to derive a lithological profile from borehole measurements. BMFT. J. Wohlenberg and R. Walter, Univ. Aachen.

(24) Feasibility study for determining hydraulic parameters in a borehole using tracer. DFG. P. Fritz and W. Drost, Gesellschaft für Strahlen- und Umweltforschung, München.

Table 2: Continuation

(25) Interpretation of time-depending temperature measurements in terms of in situ thermal conductivity. BMFT. H. Wilhelm, Techn. Univ. Karlsruhe.

(26) Wellsite interpretation of specific borehole measurements indicating borehole instabilities. BMFT, K. Fuchs, Techn. Univ. Karlsruhe and M. Zoback, Stanford Univ. (USA).

Tool Development

(27) Development of an acoustic televiewer for great depth and high temperatures. BMFT. R. Schepers, Westfäliche Berggewerkschaftskasse, Bochum.

(28) Improvement of a thermal conductivity in situ probe for great depths. BMFT. H. Burkhardt, Techn. Univ. Berlin.

(29) Improvement of equipment and of a method to calculate the heat production rate of rocks from U, Th and K-spectrometry of natural gamma radiation. DFG. U. Haack, Univ. Giessen.

(30) Experiments with a 4-point electrode arrangement for detecting the opening of fractures as a function of increasing pressure within a borehole region separated by packers. BMFT. Preussag AG, Hannover.

(31) Upgrading of a magnetic susceptibility probe for deths up to 14000 m. BMFT. J. Pohl, Univ. München.

(32) Development of a 3-component magnetometer for depths up to 14000 m. BMFT. G. Musmann and F. Kuhnke, Techn. Univ. Braunschweig.

(33) Adaption of an induced polarisation tool for ion diffusion of fluids under KTB conditions. BMFT. D. Vogelsang, NLfB, Hannover.

(34) Development of a stationary downhole monitor prototype for determining stress field, pore pressure, temperature and electrical data. BMFT. G. Reik, Gesellschaft für Baugeologie und -meßtechnik, Rheinstetten and G. Borm, Techn. Univ. Karlsruhe.

(35) Development of a high resolution time depending magnetometer measuring probe for high resolution magnetotelluric soundings. DFG. E. Steveling, Univ. Göttingen.

Table 3: Geophysical Key Experiments (FKPE 1986)

(1) Stress field of the continental crust.
From the change of intra-continental seismicity with depth it is postulated that in the upper crust high shear stresses and in the lower crust low shear stresses exist. The estimation, based on experimental rheological rock parameters, indicate the maximum stress already in the upper crust. This could be confirmed by drilling a superdeep borehole. It would possibly explain the limitation of seismicity to the upper crust, the existence of overthrusting pathes, and together with pressure measurements from fluid inclusions the acting dynamic tectonic forces within the crust.

(2) Fluid geophysics.
The existence of fluids and permeability determine essentially the heat transport by heat convection, and explain also the mobility of crustal portions. Borehole measurements and hydraulic tests made in a superdeep borehole would bring conclusive answers.

(3) Influence of palaeotemperature changes.
From estimation it is known that the palaeotemperature influences the temperature field down to 5000 m depth or even more. The heat-flow density from shallow boreholes can be decreased in the order of 30 %. Until now, no convincing example exists, which demonstrates the existence or non-existence of this effect. Hopefully, a superdeep borehole can clarify this open question.

(4) Seismic endoscopy of the earth's crust.
Surface seismic survey combined with vertical seismic profiling are best to evaluate seismic properties like absorption, reflectivity, anisotropy and localisation of litho-stratigraphic horizons. But, most of all, the deepest point of a borehole gives the best possibility to study the crust deeper than the borehole itself.

(5) Transient-electromagnetic survey.
The determination of electric conductivity by means of migrating current systems. The electric conductivity delivers information of the distribution and the composition of fluids due to the ion content of the fluids in the pore space. Very high conductivity values indicate graphite and ore concentration. The advantage of this method is, that with increasing depth a larger volume of rock can be investigated, thereby detecting conductivity anomalies away from the borehole and decreasing the influence of the borehole itself.

(6) Vertical electromagnetic profiling.
This method allows a better detection of layers with high electric conductivity than with surface electromagnetics. Furthermore, like vertical seismic profiling, with this method anisotropy and electric conductivity in front of the borehole can be determined without the conterminated zone.

Table 3: Continuation

(7) Magnetic survey.
The unique opportunity to look which type of magnetization exists at great depth and what are the reasons for anomalies. Rock measurements on surface will not be sufficient. Furthermore, lithological classification, content and variation of ferromagnetic ores, the chemical composition, degree of oxidation and distribution within the rock can be evaluated.

(8) Analysis of disturbances on the gravity field.
To record a gravity profile along a borehole will provide, after correction for borehole deviation, a rock density profile with depth. In addition, gravity anomalies away from the borehole can be detected.

(9) Experiments to study the physical nature of gravitation.
The gravitation constant actually is not a constant. Instead of this the gravitation constant increases with increasing borehole depth. For that measurements with a borehole gravimeter the necessary accuracy is about $\Delta g \approx 1$ gal for a borehole depth of 10000 m.
Furthermore, borehole density measuring with an accuracy of about 10^{-3} must be carried out, which seems to be very difficult.

The general philosophy for the realization of the logging and testing programme in the pilot borehole is that the main portion of it will be done by service companies. Special services will be run with tools from universities and institutes. The programme itself is - following the priority list HAENEL & DRAXLER (1988) - split into two sections: during and after the drilling phase. Following Fig. 2, all geologically relevant logs will be run during the drilling phase at certain intervals (about every 500 m, now down to about 5000 m) to secure the data under favourable logging conditions, to control the borehole breakouts, and to provide correlation logs for core analysis. The Borehole Televiewer and the Formation MicroScanner are the essential tools for correlation, as they offer means for post-orientation of cores.

All measurements need to be evaluated and interpreted. This can either be done on location, or the data are transferred to a computing centre of a service company. In any case, on the location, a workstation will be installed very soon. The service companies will make the first fast interpretation. According to their field of specialisation, universities, institutes and geological surveys will refine them. The interpretations will concentrate on the evaluation of lithology, mineralogy, elemental analysis, textural and structural conditions, porosity, permeability, rock mechanical parameters, stress field, velocity, and other local or field parameters.

Finally, all measurements which have been carried out and all available interpretations are presented in KTB Report 87-4 (measurements from 0 - 478,5 m), KTB Report 88-4 (measurements from 478.5 - 1529.4 m) and KTB Report 88-7 (measurements from 1529.4 m - 3000 m).

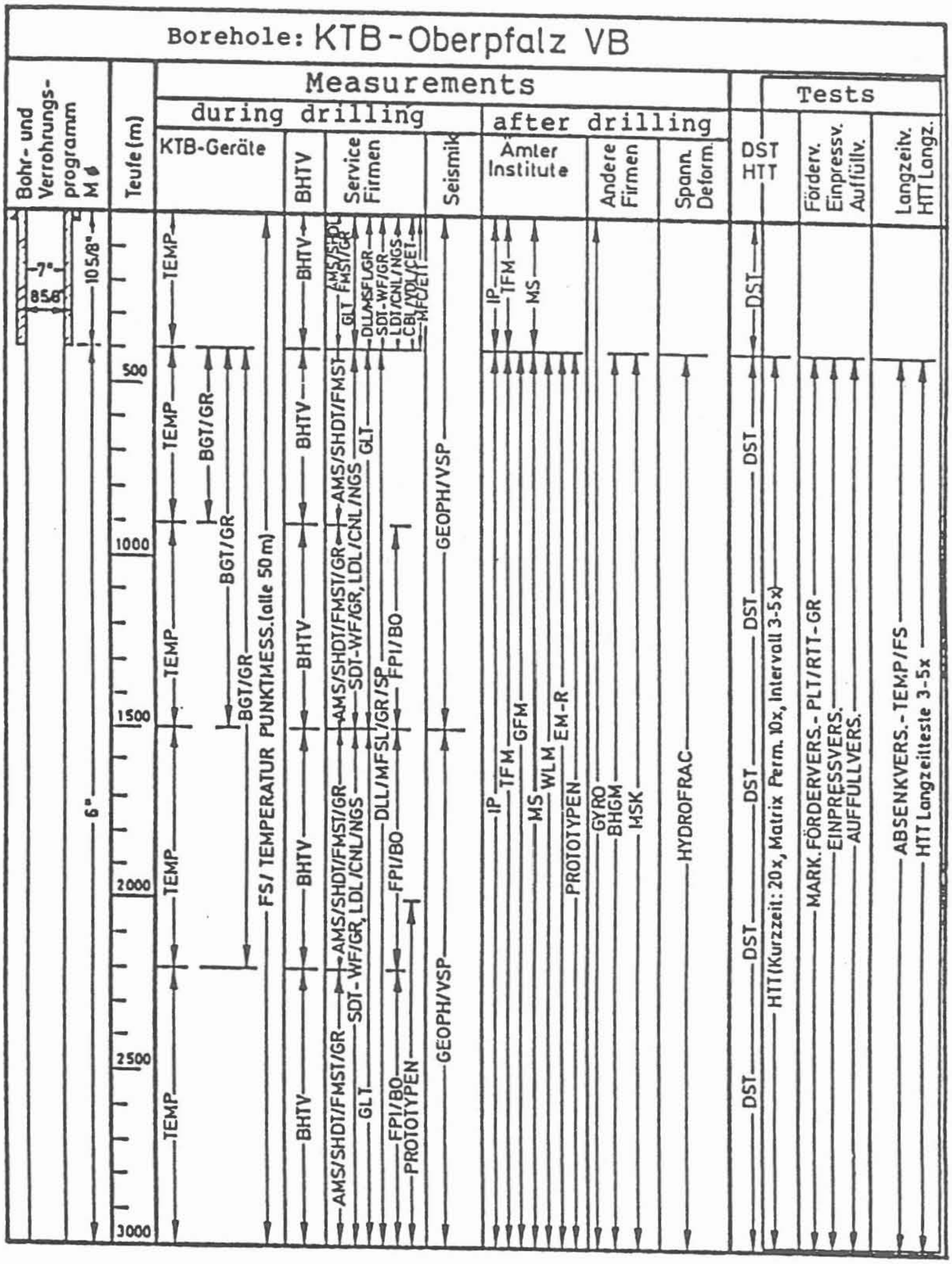


Figure 2: The plan of borehole measurements for the pilot borehole from August 21, 1987.

Abbreviations:

TEMP = Temperature, BGT = Borehole Geometry Tool, GR = Gamma Ray Tool, FS = Fluidsampler, BHTV = Borehole Televiewer, AMS = Auxiliary Measurement Sonde, SHDT = Stratigraphic High Resolution Dipmeter Tool, FMST = Formation MicroScanner Tool, SDT-WF = Sonic Digital Tool - Wave Form, LDL = Litho Density Log, CNL = Compensated Neutron Log, NGS = Natural Gamma Spectrometry, GLT = Geochemical Logging Tool, DLL = Dual Laterolog, MSFL = MicroSpherically Focussed Log, FPI/BO = Free Point Indicator/Back Off, GEOPH = Geophone Survey, VSP = Vertical Seismic Profiling, IP = Induced Polarisation, TFM = Triaxial Fluxgate Magnetometer, GFM = Gradient Fluxgate Magnetometer, WLM = Thermal Conductivity Measurement, EM-R = Electromagnetic Reflection-Radar, Gyro = Gyroscope, BHGM = Borehole Gravimeter, MSK = Mechanical Coring, HYDROFRAC = Stress Measurements by means of Hydrofracturing, DST = Drill Stem Test, HTT = Hydraulic Test Tool.

4. PROVISIONAL RESULTS

Since the end of October 1987, five intermediate logging runs have been made in the pilot borehole. The data recorded is of high quality. Provisional results from log evaluations show information of high interest.

4.1. BOREHOLE MEASUREMENTS

(1) Borehole trend

The highly dipping lithology of 70° - 90° causes a permanent deviation of the borehole; the dip direction is about SW. Fig. 3 shows the horizontal projection of the pilot borehole down to 2780 m, and Figs. 4 and 5 records from the Borehole Geometry Tool and Borehole Televiewer. The breakouts or enlargements are a measure of the stress field.

(2) Graphite and ore indications

The drilling mud resistivity is about 4 m, but the measurements with Dual Laterolog (DLL) gives sometimes resistivities of less than 0.2 Ω m. Simultaneously, the Induced Polarisation (IP) as well as the Spontaneous Potential (SP) indicate high response signals, see Fig. 6. Due to the geological situation, the anomalous values can be explained only by graphite and pyrite and/or magnetic material. This is confirmed by results of core analysis. The destination between graphite and ores is possible by using the Geochemical Logging Tool. Pyrite layers show strong sulfur and iron responses.

(3) Open and/or closed fractures (a)

Based on experience, especially from the Hungarian colleagues (ELGI), open and closed fractures can be separated by using Induced Polarization (IP) and Magnetic Susceptibility (KAP) measurements in a borehole. The scheme is, where (+) corresponds to high and (-) to low signal:

IP (+) and KAP (+) -- open fracture including Fe
IP and KAP (+) -- closed fracture including Fe
IP and KAP (-) -- closed fracture without Fe

These facts have been confirmed by observations on cores.

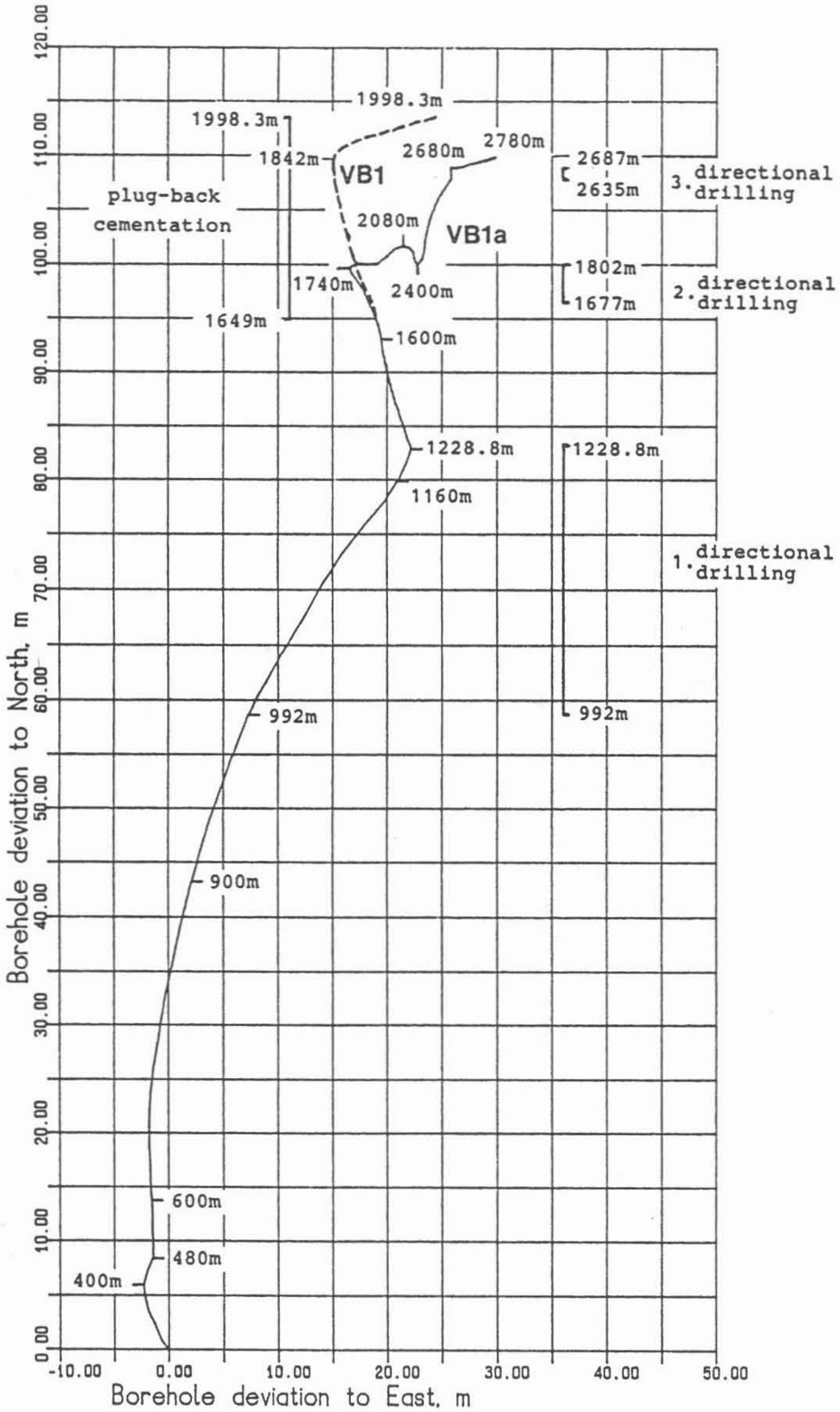


Figure 3: Horizontal projection of the pilot borehole including information about directional drilling and plug-back cementation work.

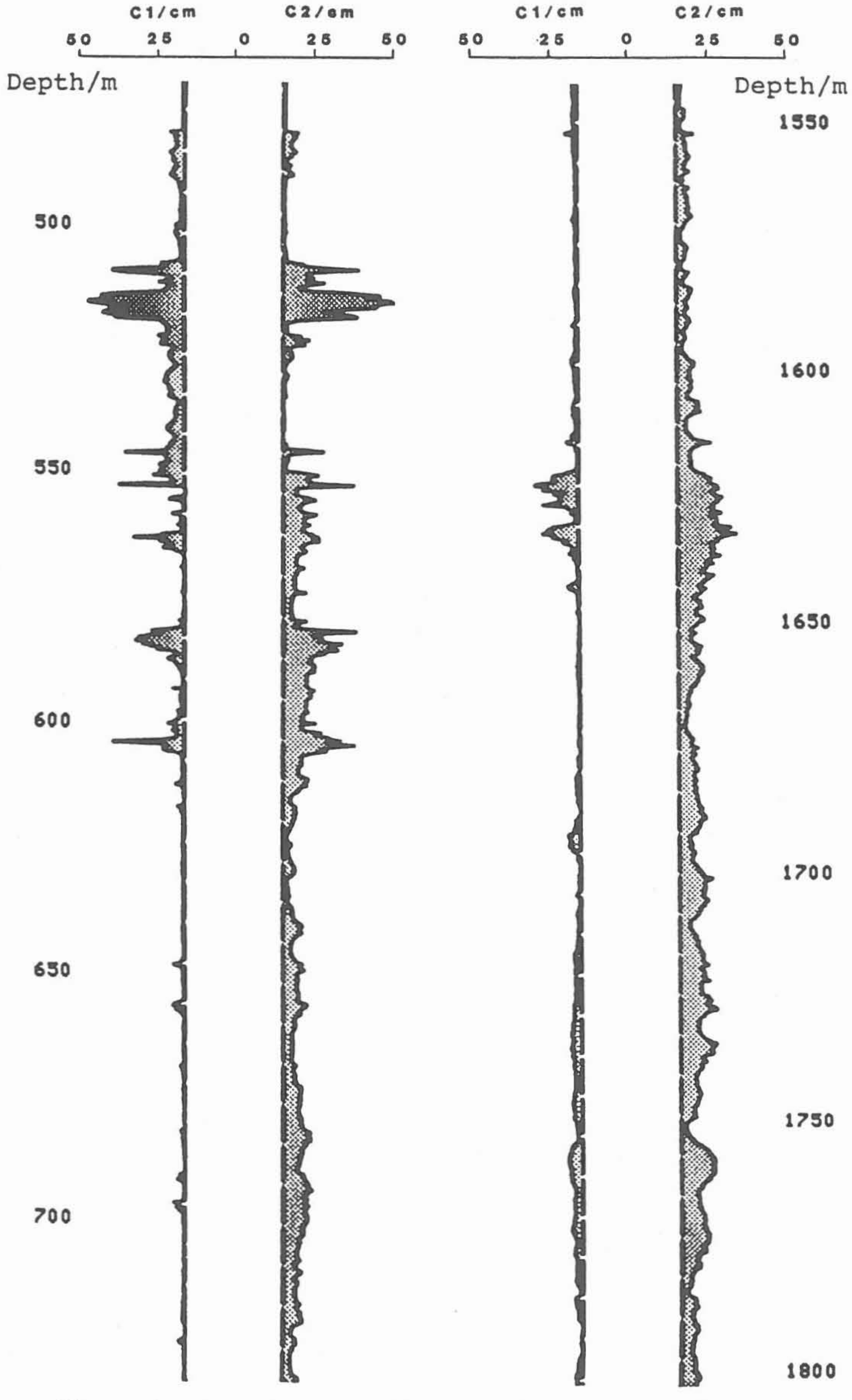


Figure 4: Two caliper sections showing extreme enlargements.

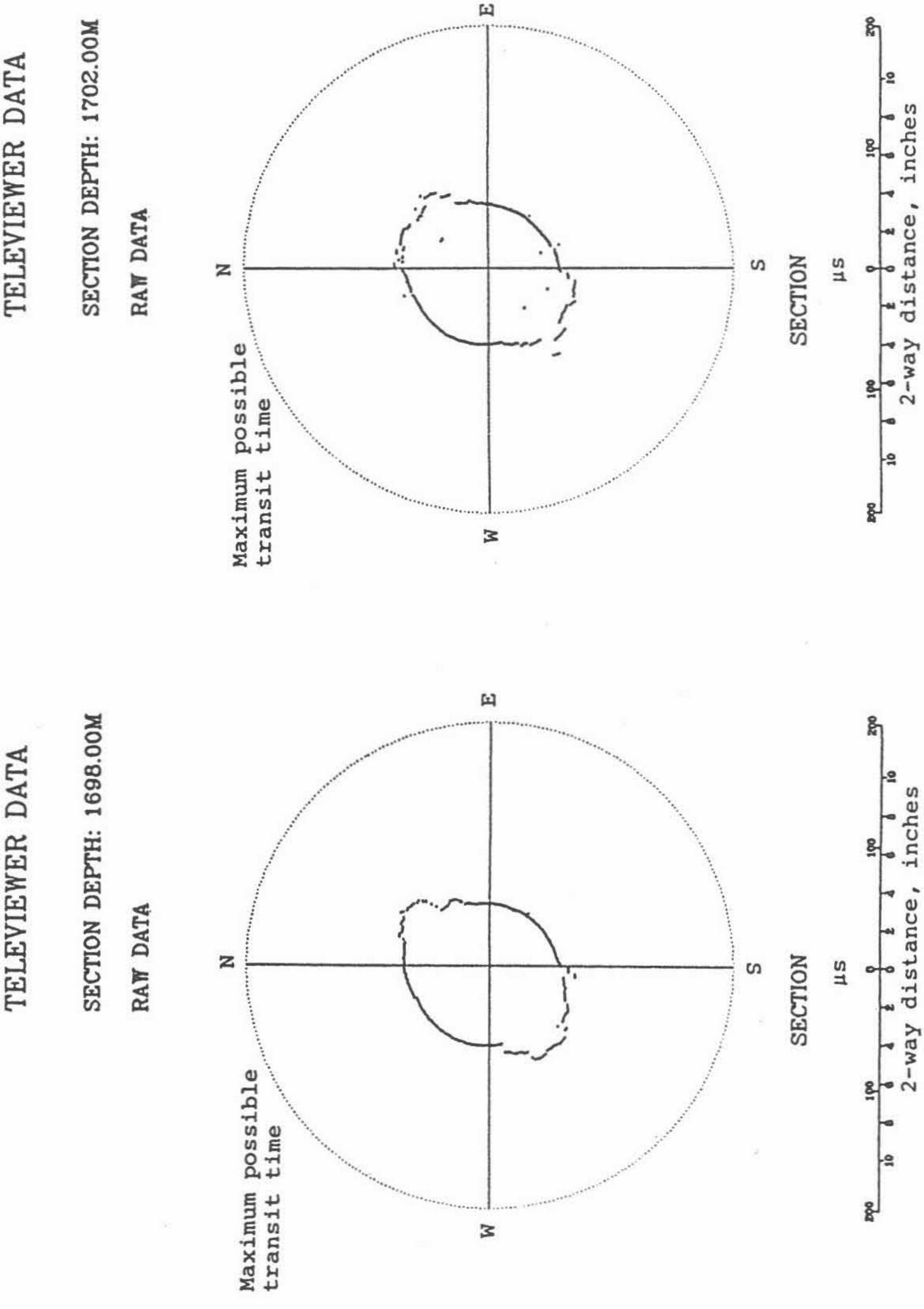


Figure 5: Two borehole cross sections from transit time of Borehole Televiewer demonstrating enlargements.

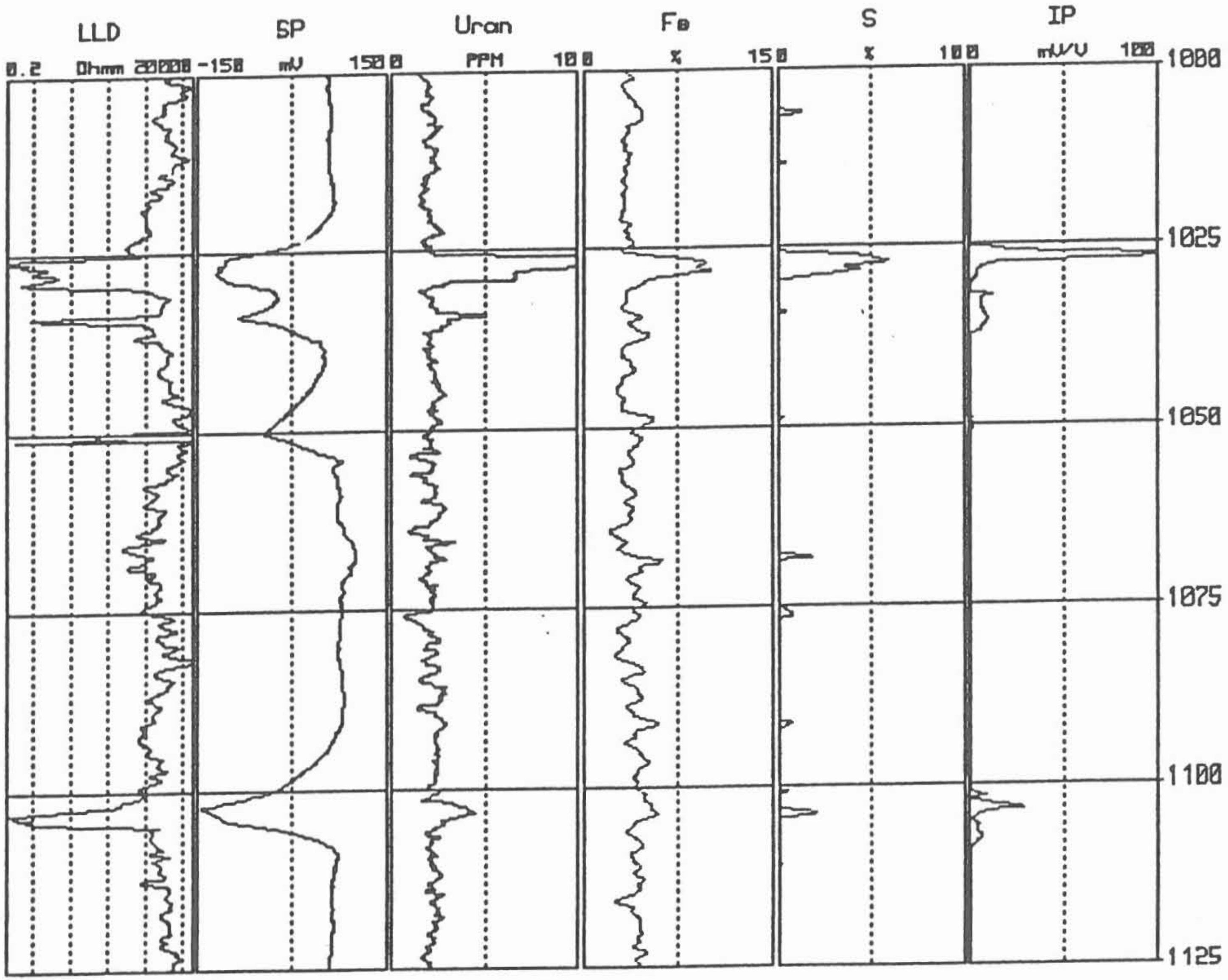


Figure 6: Graphite and Pyrite bearing zones detected by means of Dual Laterolog Deep (LLD), Spontaneous Potential (SP), GLT Geochemical Log and Induced Polarisation (IP).

(4) Open and/or closed fractures (b)

Another possibility is given by using the results of Acoustic Borehole Televiewer (BHTV), the Formation MicroScanner Tool (FMST), and the Sonic Digital Tool (SDT).

The BHTV measures the reflectivity of the borehole wall with a rotating scanning device. Open fractures show strong absorption of the acoustic amplitude, and closed or healed fractures, most of the time, even better acoustic reflections than the surrounding formation. The main advantage of the BHTV is the recording of the complete circumference of the borehole. The drawback is that the measuring system reacts very strongly if the borehole has large breakouts. A total loss of reflected signal is the result.

The FMST records multiple resistivity traces from the borehole wall over four sections, each 10 cm wide and at an 90° angle from each other. These traces are either presented as resisitivity "ribbon" or via computer image processing as resistivity "picture" of the borehole wall. Open fractures show low resistivities, as they are filled with mud. Closed or healed fractures show high resistivities. The pads carrying the electrodes are mounted on caliper arms, therefore making this tool insensitive to variations in hole diameter. The deficiency of the FMST is that for example with the 4-pad tool only 52 % of the borehole circumference are covered in a 6" borehole.

Both tools, BHTV and FMST, have magnetic north orientation, but only the FMST has hole deviation sensing equipment. From both tools, dip and strike of fractures can be computed.

With the SDT, the Stoneley wave (tube wave) can be evaluated via the time coherence function. Open fractures affect the tube waves strongly. Computing the Normalized Deflected Energies (NDE) from the Stoneley wave, we have a third method for fracture or fracture system evaluation.

All three logging principles contribute valuable information to the complex problem of fracture detection; see Figs. 7, 8, and 9.

(5) Post Orientation of Cores

The mechanical orientation of cores during the drilling is difficult, expensive, and in most cases non-reliable. Therefore, the post-orientation of cores has a high priority. Details are given in the Appendix, Poster 4.

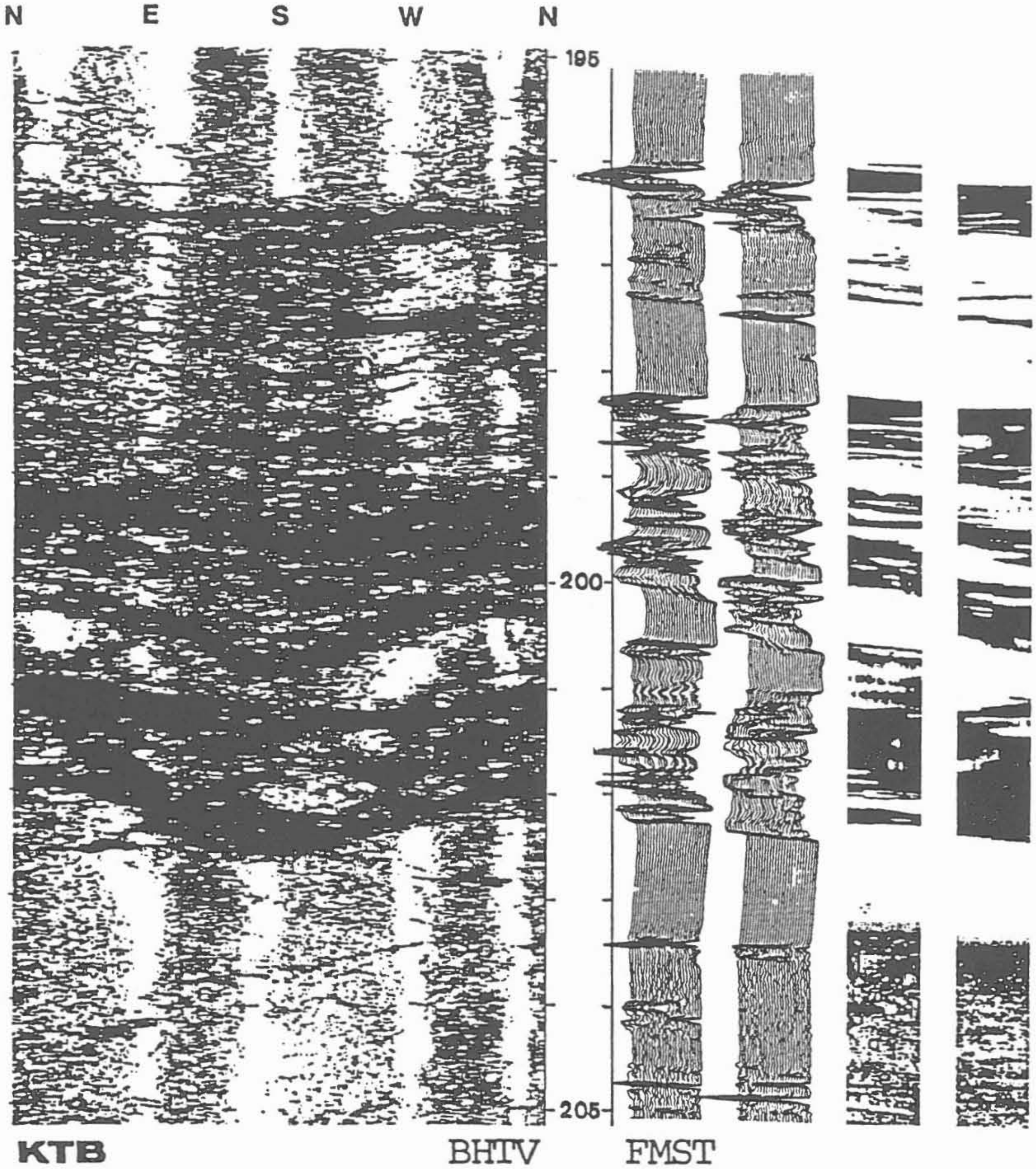


Figure 7: Borehole Televiewer (BHTV) and Formation MicroScanner Tool (FMST) records showing open fractures due to the low resistivity of FMST.

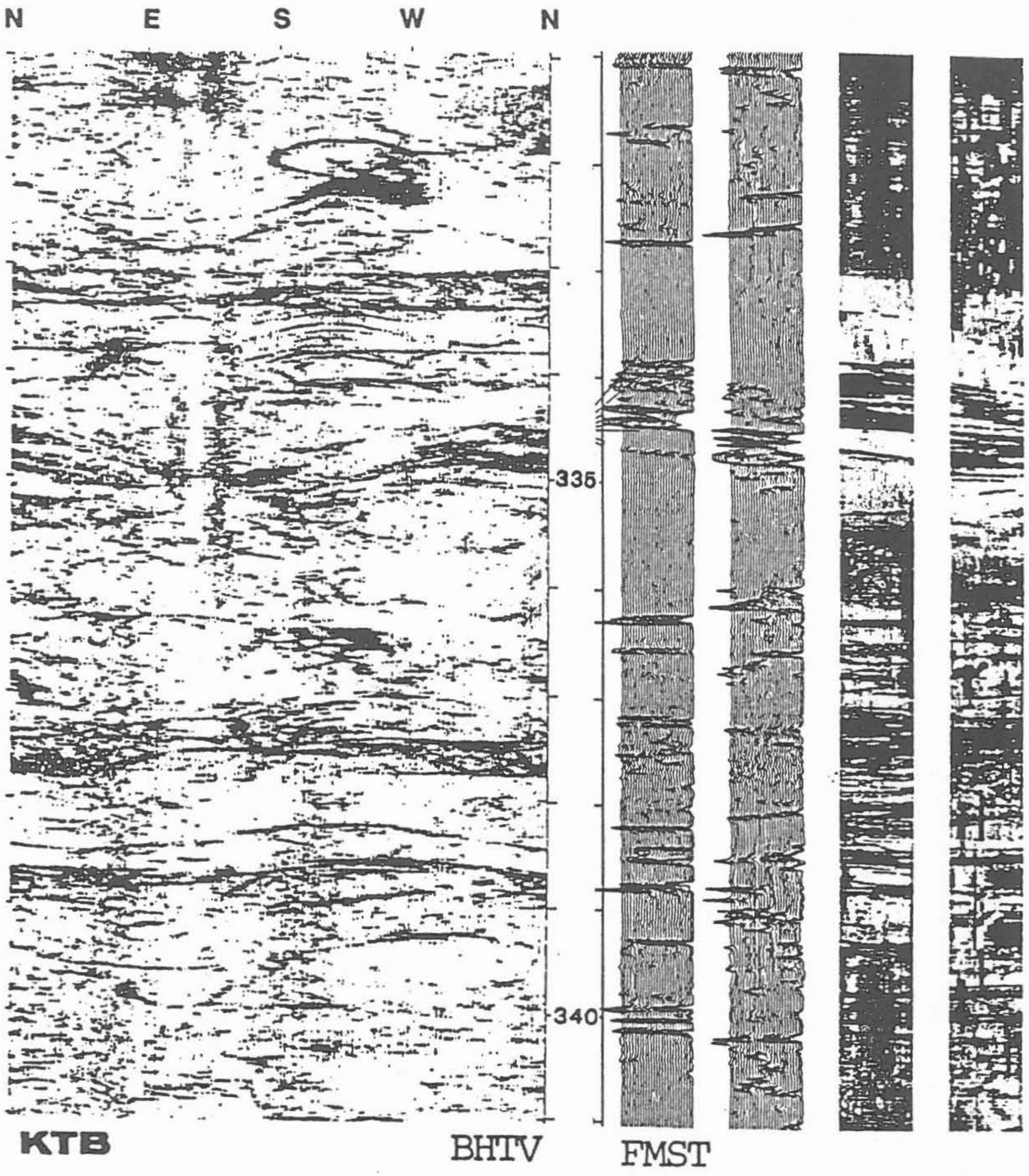


Figure 8: Borehole Televiewer (BHTV) and Formation MicroScanner Tool (FMST) records showing no significant fractures.

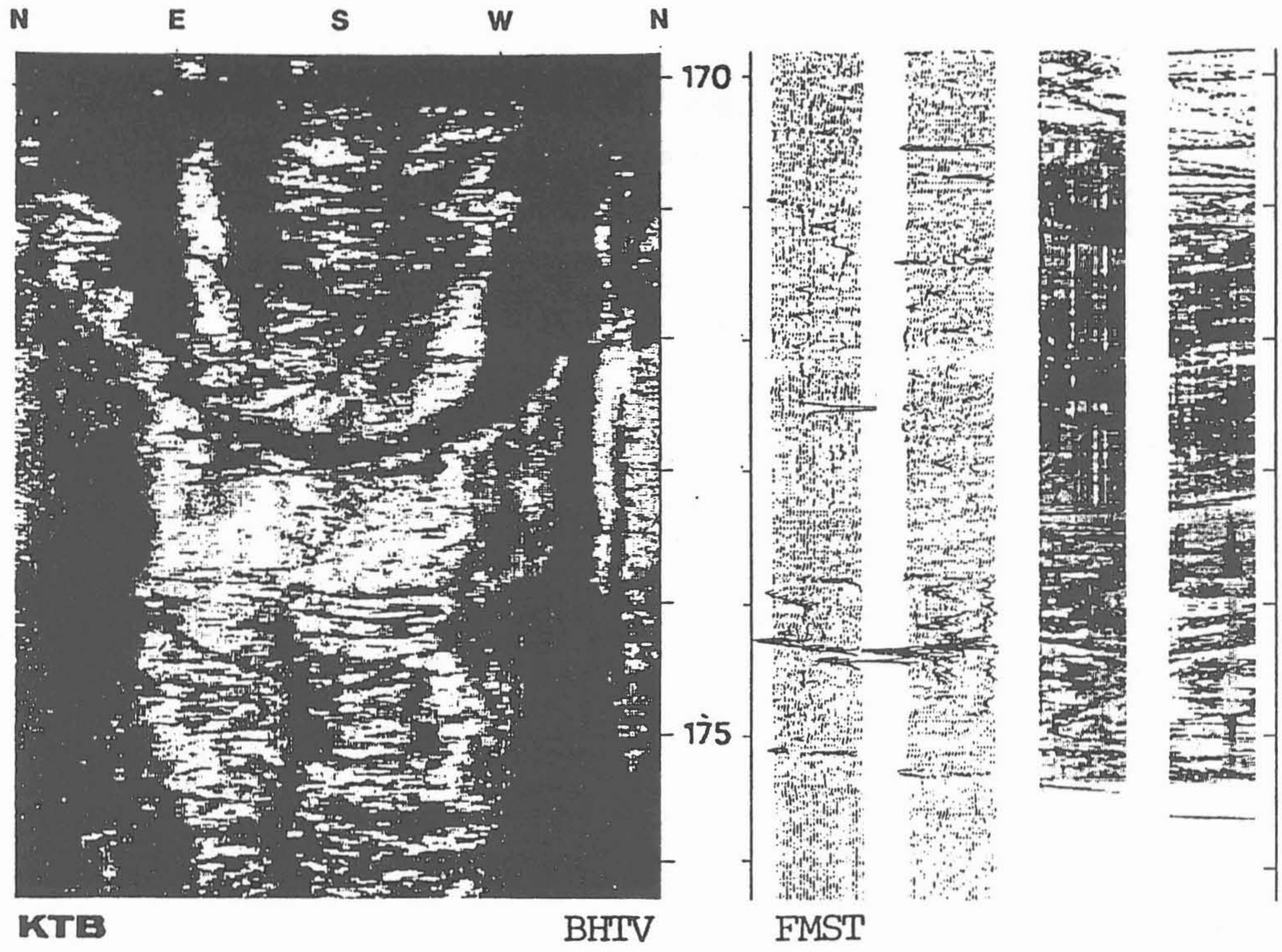


Figure 9: Borehole Televiewer (BHTV) showing a fracture at about 172.5 m depth. The Formation MicroScanner (FMST) gives no information at that depth. Therefore, a 'closed fracture' must be assumed.

(6) Geochemical Logging

Geochemical logging was developped for the oil industry by Schlumberger Well Services, and has now become an independant factor for the scientific evaluation of crystalline rocks. The geochemical logging tool is a composition of Natural and Induced Gamma Ray Spectrometry Tool, Compensated Neutron Tool, Aluminium Clay Tool, and Litho-Density Tool; see Appendix, Poster 3. The core data is from the Field Laboratory.

The tool measures 10 elements: Al, Ca, Fe, K, Gd, S, Si, Th, Ti and U and the microscopic cross section sigma. The element-to-mineral transformation is made by a factor analysis and, of course, by calibration with core data (HERRON, 1983). Furthermore, the transformation is also based on the fact that only several mineral groups account for 97.5% of sedimentary rock (KRYNINE, 1948): quartz (31.5 %), carbonates (20.0 %), micas and chlorite (19.0 %), chalcedony (9.0 %), feldspars (7.5 %), clay minerals (7.5 %), iron oxides (4.0 %), and others (2.0 %). At present, only oxides have been determined for KTB, see Poster 3; but later on calculations also for other minerals will be carried out.

The heat generation H in μWm^{-3} can be calculated directly by the well-known formula (Rybach, 1988):

$$H = 10^{-5} \rho (9.52\, c_U + 2.56\, c_{Th} + 3.48\, c_K)$$

where

ρ = density, kg m^{-3}
c_U, c_{Th} = parts per million of uranium and thorium
c_K = percentage of potassium.

The results are shown in Fig. 10.

The next step will be to calculate the thermal conductivity by well-known formulas directly from the mineral components as well.

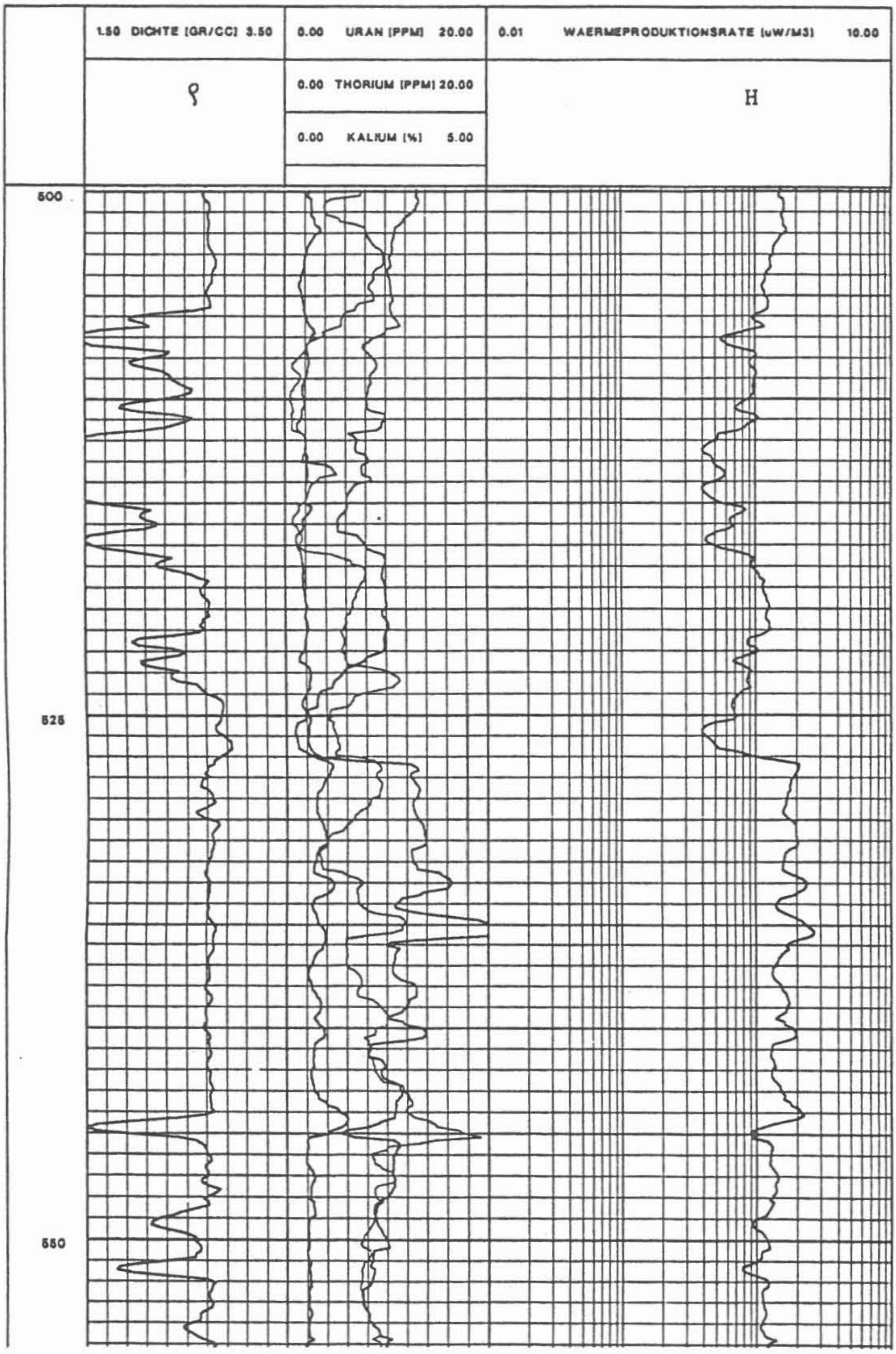


Figure 10: Logging data of density (ϱ), uranium, thorium, and potassium as well as the calculated heat generation H.

4.2. ATTEMPT OF INTERPRETATION

By now, 2800 m have been drilled. Core data as well as 2200 m of logging records are available. A first attempt is made to integrate this information into the crustal model developed for the KTB borehole location, but applying a $\Delta z > 100$ m scale only.

(1) Presently discussed crust model

Fig. 11 shows a simplified geological profile through the KTB location (KTB Report 88-1, Fig. 1), which is mainly based on seismic results (DEKORP Research Group, 1988). Fig. 12 is a refined version of the DEKORP results (SCHMOLL et al. 1988, Fig. 36). The thickness of the so-called Erbendorf-Body (EB) has been reduced.

In Fig. 13, on the left, the new DEKORP results are repeated incorporating the magnetic body found by PUCHER (1986). The velocity-depth function for the KTB borehole location is presented in the middle of Fig. 13. The solid line represents the results from the wide-angle reflection survey (DEKORP, 1988, Fig. 45) and the dashed line the results from reflection survey (SCHMOLL et al. 1988, Fig. 55). The velocity values represent the wide-angle reflection results. From borehole measurements and cores, the dip of the foliation of the lithological units and fracture systems ranges between 70° - 90° to a depth of 2000 m and 50° - 70° below 2000 m. This corresponds with the predictions given by the reflection elements within the zone of Erbendorf-Vohenstrauß (ZEV) on the seismic section.

On the right of Fig. 13, the values of electric resistivity soundings from surface measurements below the KTB borehole location (GEOMETRA, Fig. 5.21) are given. Neglecting details, the following can be seen: The upper region with 100 - 200 Ω m corresponds to the revised seismic interpretation (dashed line of velocity-depth function). The second interval with 100 - 200 Ω m at 11.5 - 14 km depth coresponds to the older version with the high velocity zone (solid line of velocity-depth function). With the zone of high conductivity ($R > 50\,\Omega$ m) only a weak correlation with the seismic profile can be established.

The already recorded borehole data (cores, logs, etc.) allows for a more detailed interpretation. Taking in consideration that the dip of the lithological units is high, and that all seismic profiles come from seismic lines recorded at a certain distance away from the KTB-location (about 400 m), certain differences are possible.

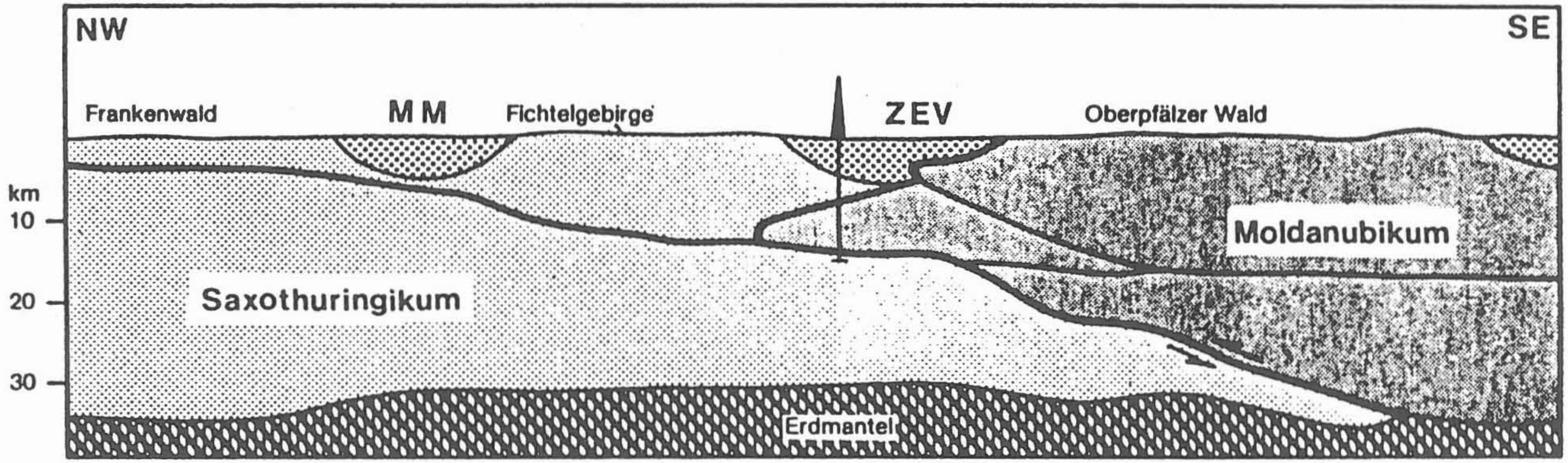


Figure 11: Simplified schematic geological profile for the KTB location Oberpfalz; MM = Münchberger Gneiss, ZEV = Zone of Erbendorf-Vohenstrauß.

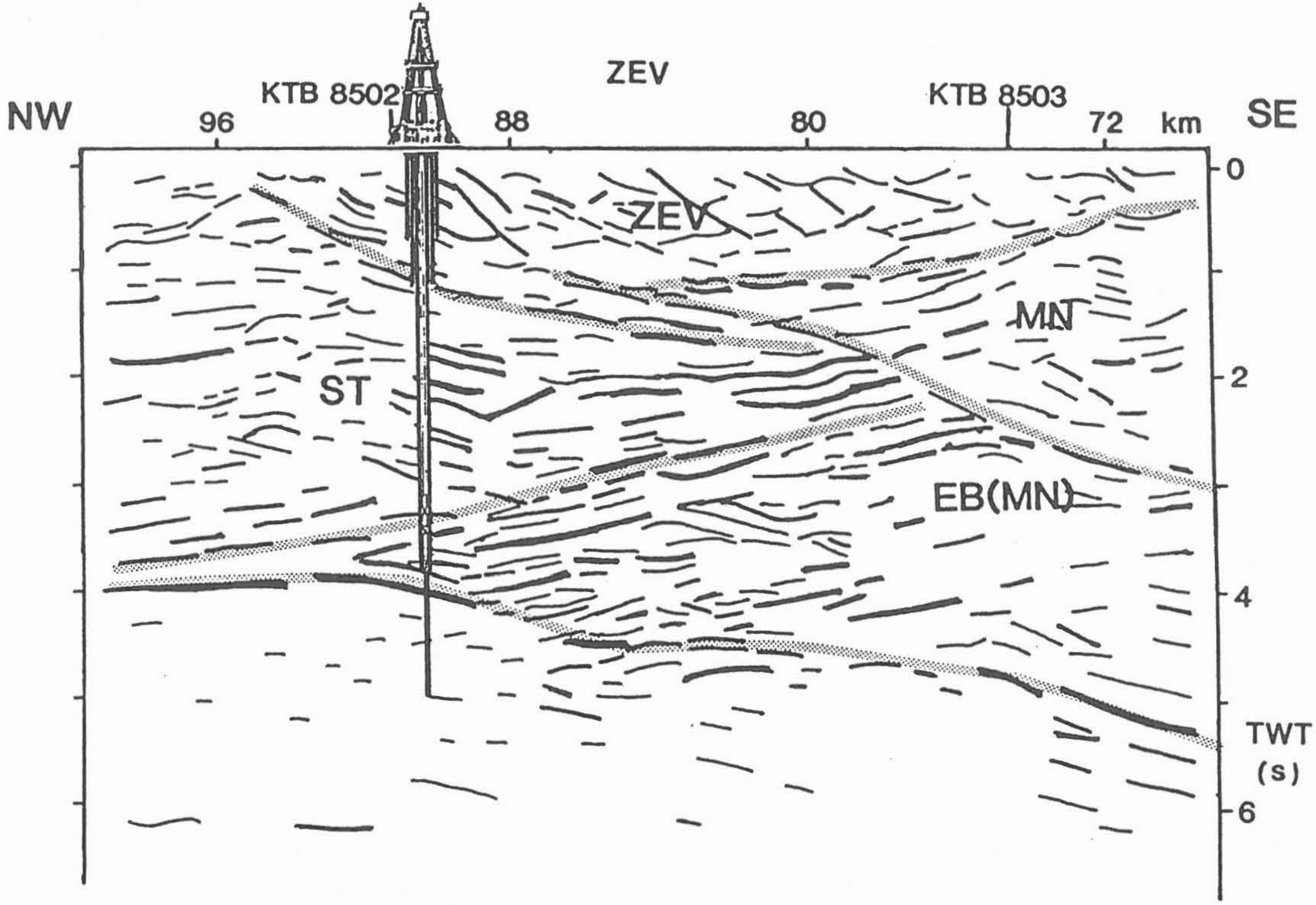


Figure 12: Central part of the line-drawing DEKORP 4 with structural interpretation;
ST = Saxothuringicum, MN = Moldanubicum, ZEV = Zone of Erbendorf-Vohenstrauß,
EB = Erbendorf Body.

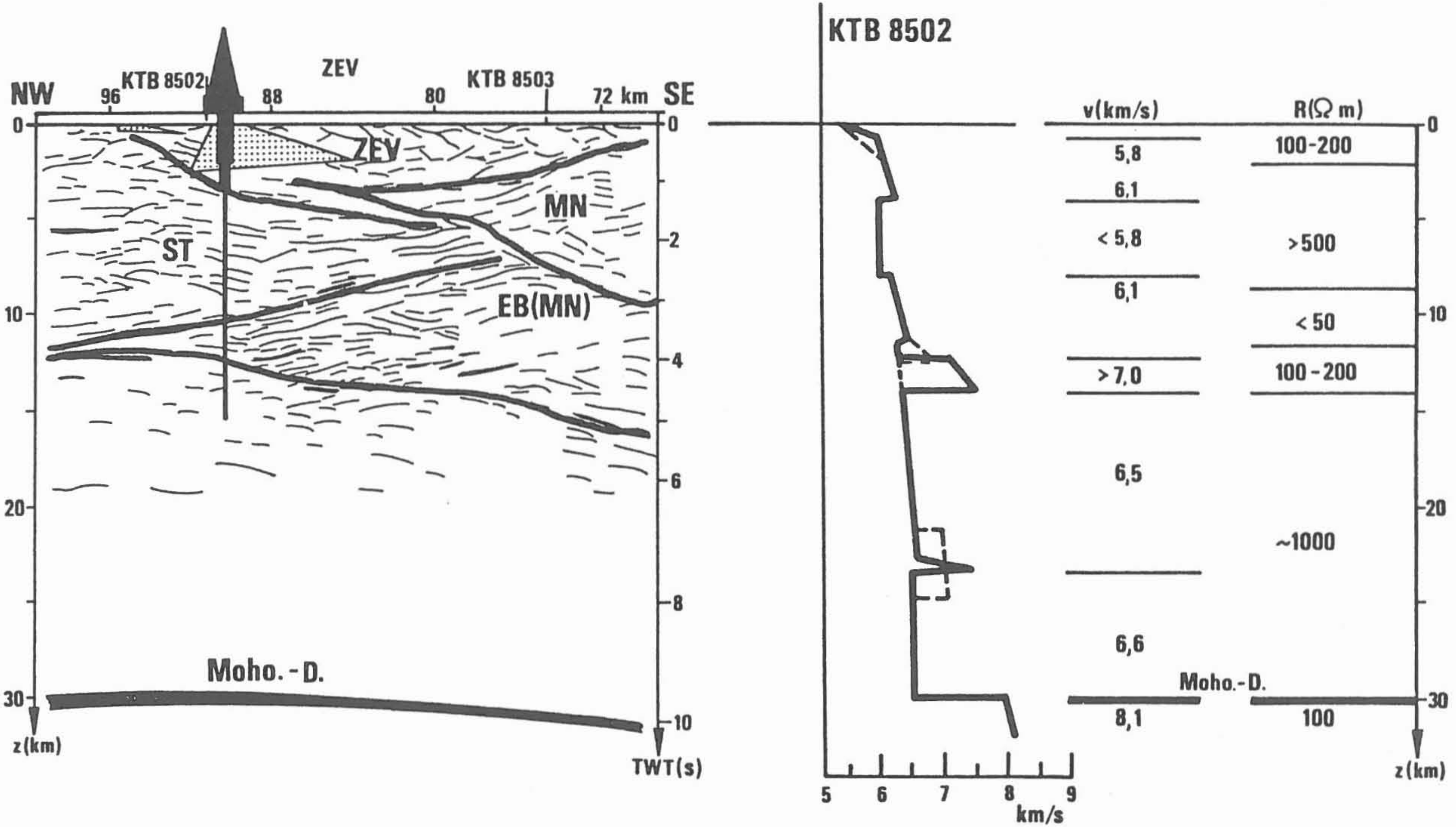


Figure 13: On the left repetition of Fig. 12, and on the right the V_p velocity and the electrical resistivity R below the borehole.

(2) Borehole Measurements - Present Status

The latest series of borehole measurements was made at 2200 m depth; further down only temperature- and borehole geometry logs are available.

On Fig. 14, the basic information is the lithological profile representing units withΔz >100 m only (KTB Report 88-1, 88-2), and both seismic reflectors from Fig. 13 at about 1 km and 4 km depth as well as the estimated temperatures (hatched area) including the expected minimum and maximum values (dashed lines) after BURKHARDT et al. (1986). The borehole section which had to be cemented after an unsuccesful fishing operation is also indicated.

Additional mean values given on Fig. 14 are: electric resistivity R, seismic velocity V_p, density ρ, heat production rate H, magnetization I, the amplitude of magnetic vertical intensity ΔZ, and the actual temperature depth function. The actual measured temperature depth function is based on 6 non-corrected values from the pilot borehole. The actual recorded temperature is greater than the expected maximum temperature, but it es in a good agreement with the map of temperature at 5 km depth (GRUBBE et al., 1983) as shown in Figure 15.

The top interval from 27 - 385 m shows a sequence of different lithologies, strongly altered, therefore unstable, creating breakouts and thereby reducing log quality. This zone will only be discussed in general terms for the time being.

The vertical magnetic intensity ΔZ indicates around a depth of 335 m a change in response. BOSUM et al. (1988) attribute this to different magnetic minerals in the rocks - above 335 m magnetite and below pyrrhotine. This has been confirmed by cores.

At 1160 m depth, the lithology changes from gneisses to amphibolite, which is also shown by H, ρ, V, and R. The lower boundary of the amphibolite is clearly indicated by H and ρ, whereas V and R decrease continuously. The upper boundary is obviously identical to the 1. seismic reflector of Fig. 13 (solid line). A direct correlation has to be considered with care due to the highly dipping lithology. The first results from geophone surveys (0 - 480 m) and vertical seismic profiling (480 - 2200 m) indicate neither the upper and lower boundary of the amphibolite boundary nor the 2. reflector at 4 km depth from the reflection seismic profile.

The 3-dimensional magnetic boundary (Fig. 13) correlates roughly with the low resistivity region of 100 - 200 Ω m from the surface-electromagnetic measurements - down to about 2000 meters depth.

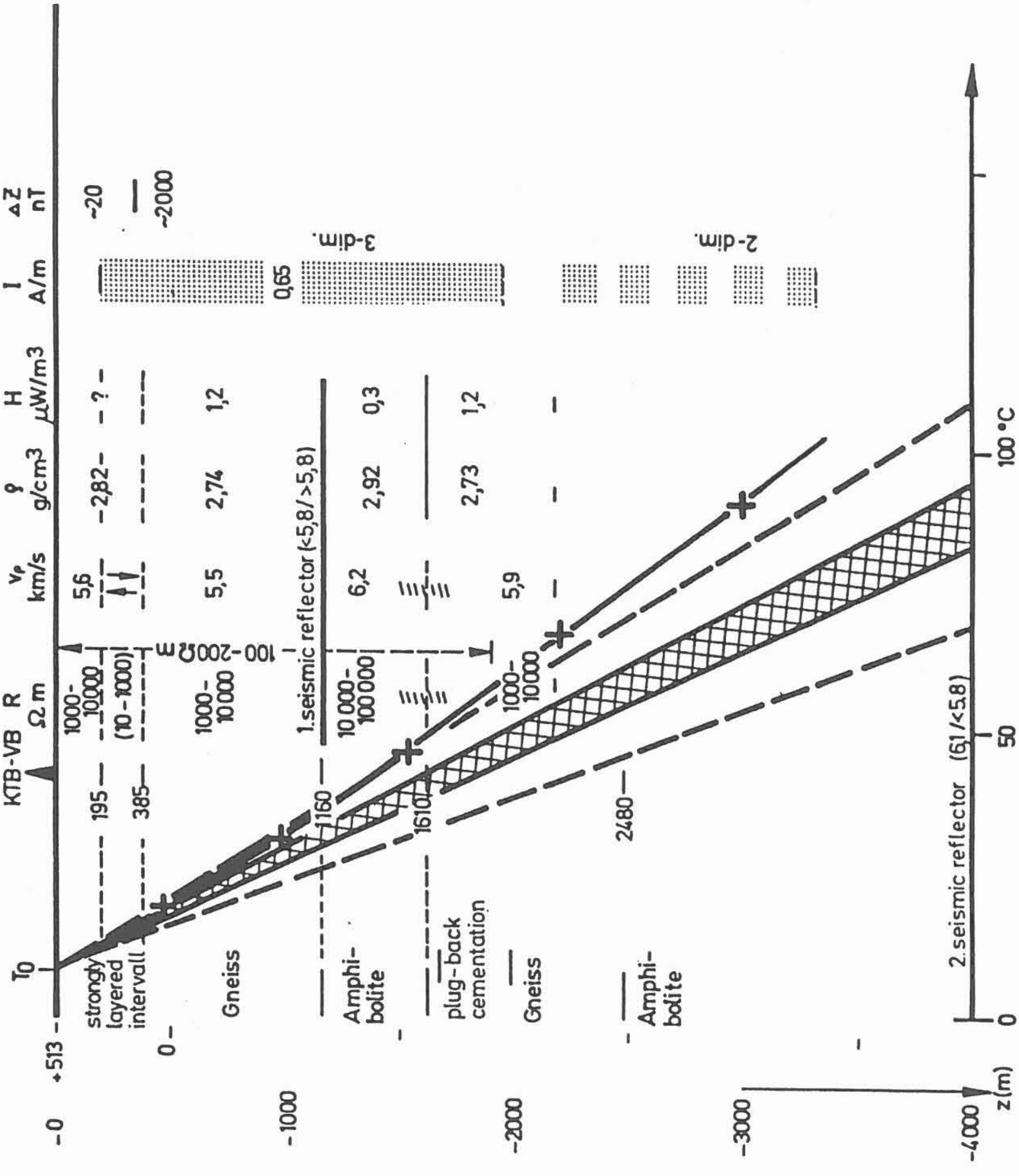


Figure 14: Logging results compared with other information.

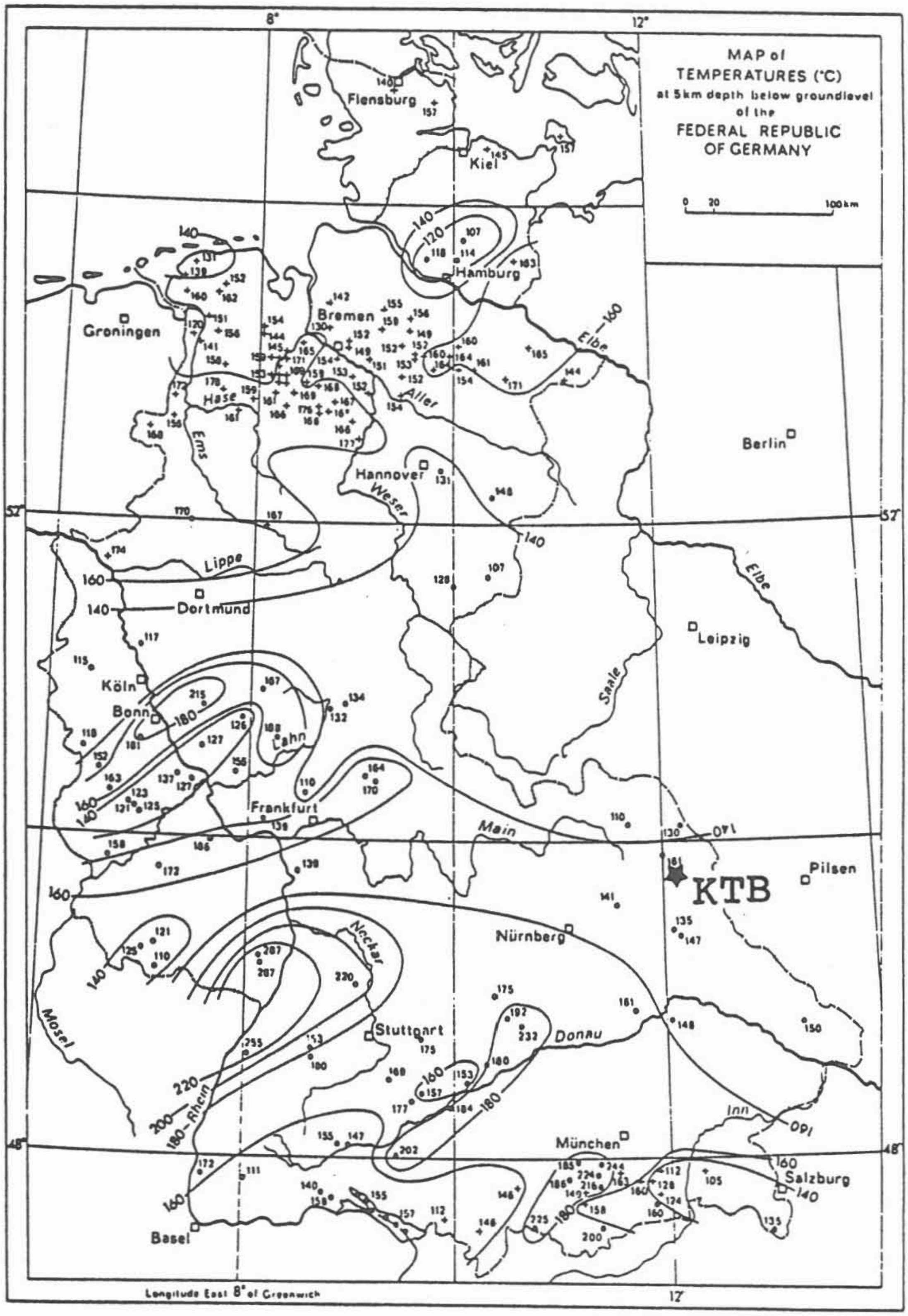


Figure 15: Temperature distribution at 5 km depth.

Due to the high resolution of electrical borehole measurements, the measured data are much higher than from surface measurements, recorded by means of electromagnetic methods. Layers of high conductivity - graphite, ores - are dominating in the surface measurements and reduce the overall resistivity if integrated over zones of $\Delta z > 100$ m. Combining both methods, a model of parallel resistivities can be constructed for the first 2200 m of formations. In Fig. 16 are shown the depth sections having $R < 1$, $R < 10$, $R < 100$, and $R < 500\,\Omega$ m. Considering also the dip of the lithology it follows:

Limit of resistivity (Ω m)	Range (Ω m)	Mean value (Ω m)	Corresponding total depth section (%)
$R > 500$	500 - 100000	$50000 = R_1$	$a_1 = 92.5$
$R < 500$	500 - 100	$300 = R_2$	$a_2 = 4.7$
$R < 100$	100 - 10	$55 = R_3$	$a_3 = 1.7$
$R < 10$	10 - 1	$5.5 = R_4$	$a_4 = 0.9$
$R < 1$	1 - 0.1	$0.55 = R_5$	$a_5 = 0.22$

The parallel resistivity R_p can be estimated by means of ($a = 100$):

$$a/R_p = a_1/R_1 + a_2/R_2 + a_3/R_3 + a_4/R_4 + a_5/R_5$$

which amounts to

$$R_p \quad 160\,\Omega\,m,$$

and which is in good agreement with the measured value $R_p = 100 - 200\,\Omega$ m from the surface.

The Dual Induction Log (DIL), which works reliably only up to about 100 Ω m, has shown surprisingly good data in the crystalline pilot borehole. The calculated R_p value amounts to about 110 Ω m. This is again in a good agreement with the surface measurements, and this is also the reason why the DIL worked so well.

The densitiy of the ZEV, determined by surface gravity measurements, is 2.80 g cm^{-3} (PLAUMANN & PUCHER, 1986, Fig. 36). This value corresponds very well with the mean value of 2.80 g cm^{-3} from borehole measurements.

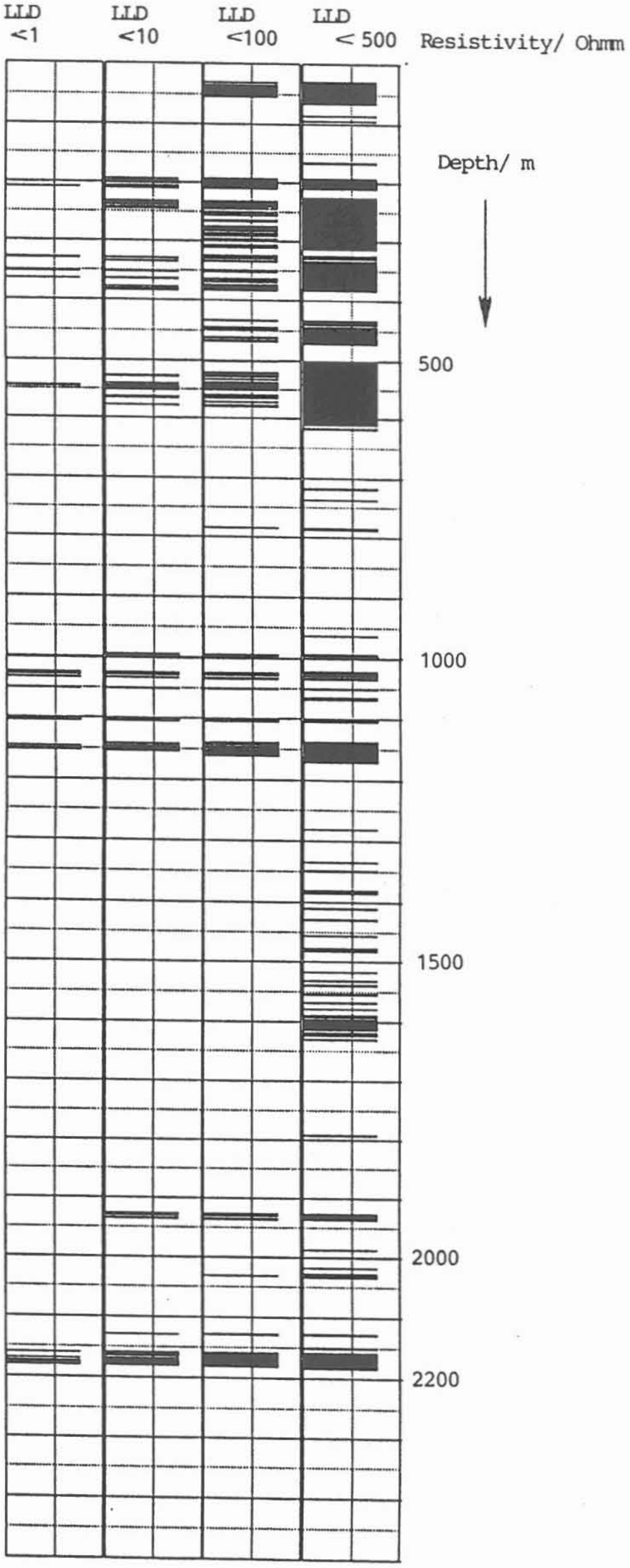


Figure 16: Resistivity distribution for R < 1, 10, 100 and 500 Ωm from the Dual Laterolog; LDD=Laterolog Deep.

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APPENDIX

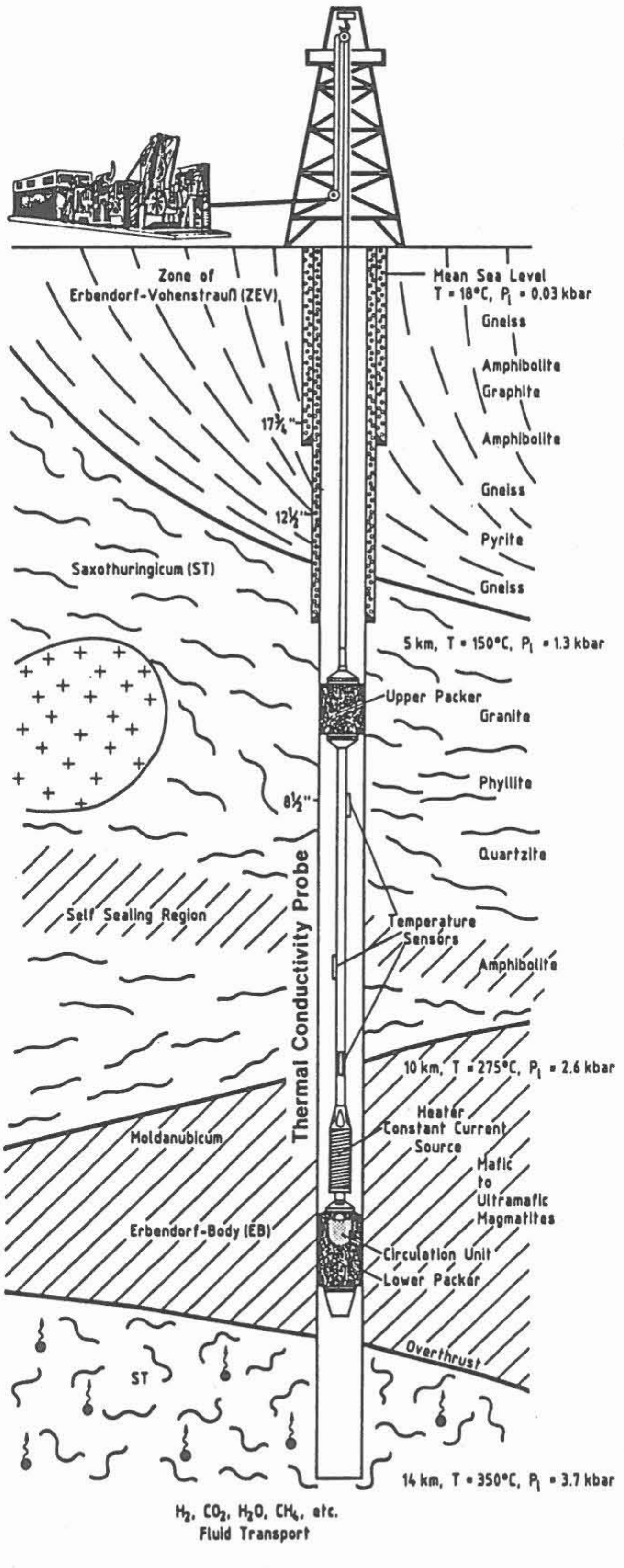
Poster 1: Objectives, Realisation of borehole measurments

Poster 2: Research and development projects for borehole geophysics

Poster 3: Results of borehole geophysics; Example 1: Geochemical Logging

Poster 4: Results of borehole geophysics; Example 2: Procedure of post-orientation of cores.

KTB BOREHOLE MEASUREMENTS
OBJECTIVES, REALISATION



Thermal Conductivity Probe (TU Berlin)

Main Task

Realisation of geoscientific objectives to measurable physical rock parameters, chemical elements, mineral components, fluids, heat and mass transport as well as physical field parameters.

Strategy:

A - Equipment

- Classification of logging equipment with regard to temperature and pressure limitation
- Examination of methods which have been developed for sedimentary rocks to ascertain whether they can also be applied to crystaline rocks with possible improvements
- Design and construction of new speciality equipment, upgrading of existing tools

B - Measuring Concept

- Permanently skid-mounted unit linked with a computer centre at the drilling site
- Conventional measurements during drilling
- Geophysical Key Projects during and after drilling
- Deep Earth Laboratory after well completion

Realisation:

A - Equipment

Working groups have been established for research and development.

B - Measuring Concept

Conventional measurements will be carried out in accordance with the recommended priority list, describing the:

- Thermodynamic state of the earth's crust by means of temperature and pressure measurements
- Pore fluids and flow regimes by means of porosity and permeability measurements, e.g. Drill-Stem-Tests, nuclear and acoustic methods
- Structural and textural configuration by means of the acoustic televiewer and formation micro-scanner*
- Drilling prognostication by means of vertical seismic profiling
- Borehole stability

Geophysical Key Projects which necessitate measurements in an ultradeep borehole, such as:

- Seismics, multi-offset Vertical-Seismic Profiling for the investigation of crustal anisotropy and absorption - 3-D seismic recording
- Geothermics, influence of palaeoclimate temperature on the actual temperature field and heat-flow density
- Transient electromagnetics, probing the upper crust's conductivity by moving current systems
- Gravitation constant, confirmation of depth dependency

Deep Earth Laboratory in the available completed ultradeep borehole:

- Time-consuming measurements, which otherwise could require costly stand by time of the drilling rig, e.g. magnetotelluric measurements, fluid influx, etc.
- Long-term observations of transient phenomena e.g. earthquakes, microseismicity, rock stress and deformation

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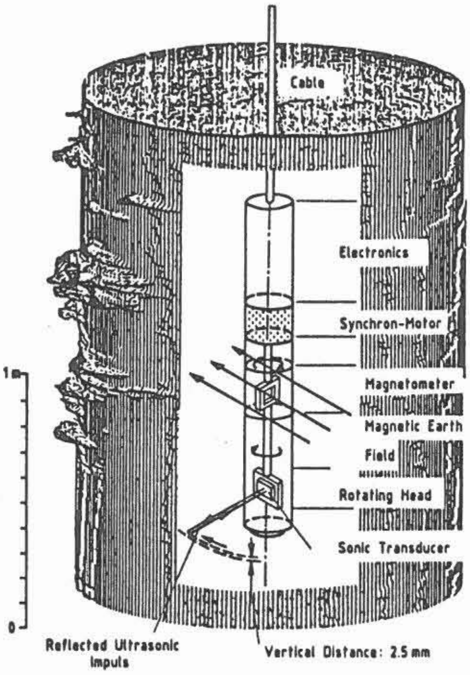
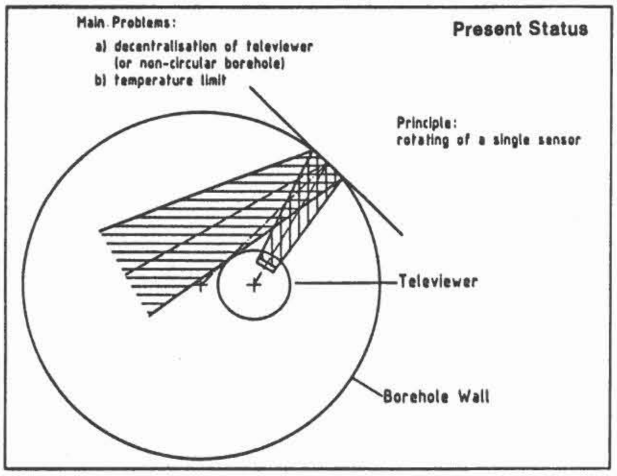
KTB BOREHOLE MEASUREMENTS

RESEARCH AND DEVELOPMENT

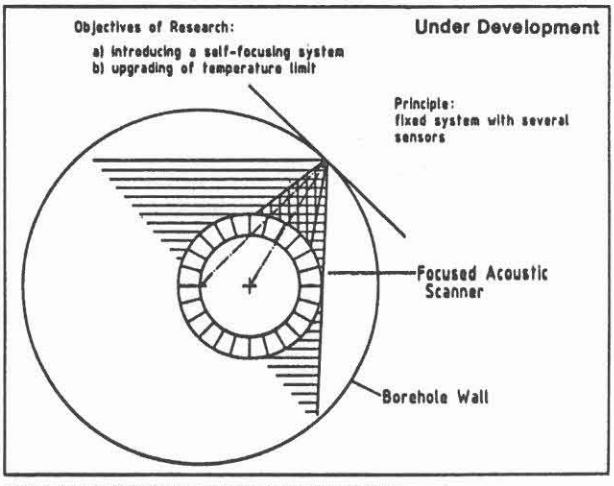
Acoustic Borehole Televiewer
Principle of standard version:





Main Problems:
a) decentralisation of televiewer
(or non-circular borehole)
b) temperature limit

Principle:
rotating of a single sensor



Objectives of Research:
a) introducing a self-focusing system
b) upgrading of temperature limit

Principle:
fixed system with several sensors

Televiewer (Westfälische Berggewerkschaftskasse, Bochum)

To solve the expected problems more than 35 projects are in progress covering 4 targets.

Fundamentals

Objectives:

Systematic approach to crystalline environment, such as e.g.:

- Porosity, permeability (Univ. of Clausthal)
  Theoretical consideration of the factors influencing the change of porosity and permeability of crystalline rocks.
  Status: The work is in progress.
- Induced Polarisation (NLfB, Hannover)
  Investigation of ways to determine the permeability from induced polarisation.
  Status: Preliminary study.
- High pressure Permeameter/Porosimeter (Univ. of Clausthal)
  To measure porosity, permeability, Klinckenberg and Forchheimer Constant and to evaluate the upper limit of Darcy velocity of crystalline rocks.
  Status: Equipment built and ready for first measurements.

Core Measurements

Objectives:

Determination of petrophysical data under simulated in situ conditions for calibrating logging data, correlation with chemical and modal compositions, interpolation to large scale units and intrinsic characteristics, such as e.g.:

- Acoustic velocity (Univ. of Kiel)
  V_p and V_s under P- and T-conditions. Estimation of stress field using shear wave splitting.
  Status: Results are already available.
- Magnetic parameter (Univ. of Bayreuth)
  Coercitive force, permanent saturation value, max. susceptibility, paramagnetic susceptibility, Rayleigh constant.
  Status: Experience from Laboratory, preparation of KTB core measurement.

Interpretation

Objectives:

Study of new and existing methods to crystalline environment, such as e.g.:

- Faciolog® (Univ. of Aachen)
  Development of a lithological borehole profile from logging and geological data.
  Status: Results from pilot borehole are available.
- Porosity, permeability (Tech. Univ. of Berlin)
  from logging data and use of statistical methods.
  Status: Preparation of basic work.
- Thermal Flowmeter (NLfB, Hannover)
  Determination of smallest yields of production/injection tests from temperature measurements with high-sensivity and low-time-constant tool.
  Status: Method has been field-tested, improvement of theory.

Tool Development

Objectives:

Development and improvement of tools up to about 300°C with regard to the scientific objectives, such as e.g.:

- Acoustic Televiewer (Westf. Berggewerkschaftskasse, Bochum)
  (1) Adaption of existing tool for high temperatures
  (2) New sequentially switched multisensor tool for high logging speeds
  (3) Sophisticated interpretative package for (1) and (2).
  Status: (1) already working up to 240°C, (2) and (3) in development.
- Thermal conductivity tool (Tech. Univ. of Berlin)
  Determination of thermal conductivities by heating within packer-isolated section of the borehole and monitoring the temperature rise.
  Status: Upgrading of prototype tool for 5 km depth.
- Triaxial borehole magnetometer (Univ. of Braunschweig)
  High sensitivity (0.1 nT) low-noise fluxgate magnetometer equipped with toroidal sensors.
  Status: Prototype sensor has been tested up to 300°C.
- Borehole susceptibilitymeter (Univ. of Munich)
  To determine rock susceptibilities in situ by sensing the impedance coupling of a solenoid pair.
  Status: Improvement of prototype tool from 125°C to 200-300°C.

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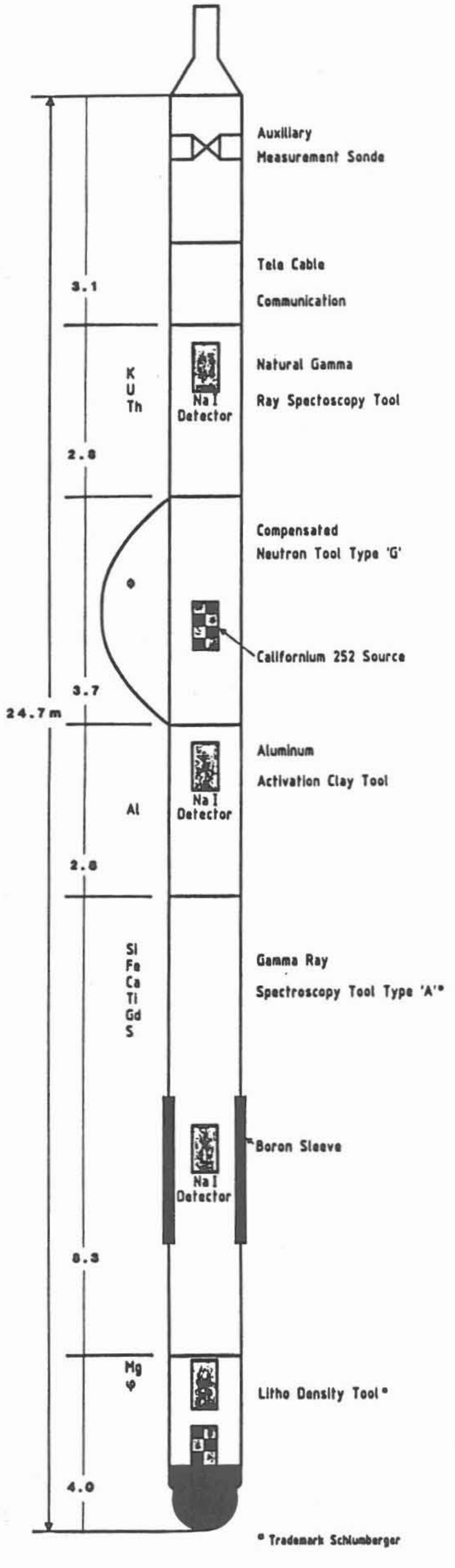
KTB BOREHOLE MEASUREMENTS

RESULTS, EXAMPLE 1



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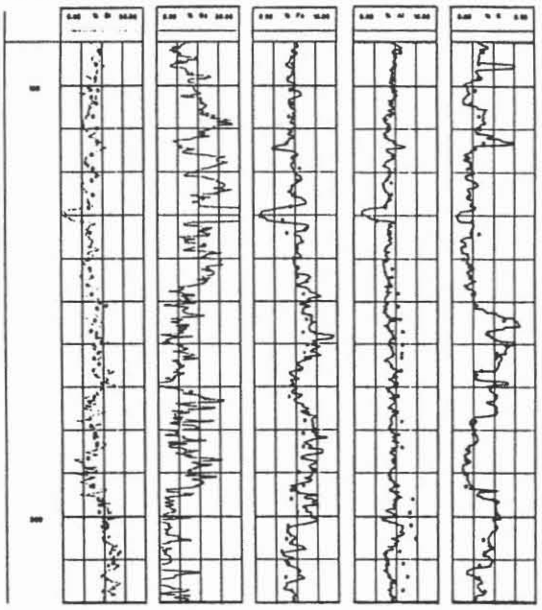
Geochemical Mineral Logging - the future has started

Advantages: Fast and continuous information with high accuracy

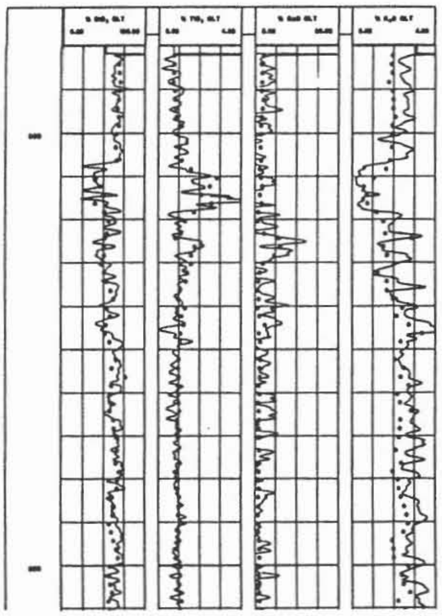
Elements (points represent core data from Field Laboratory)

Al Ca Fe Gd K S Si Th Ti U



Oxides (points represent core data from Field Laboratory)

SiO_2 Al_2O_3 Fe_2O_3 TiO_2 CaO K_2O



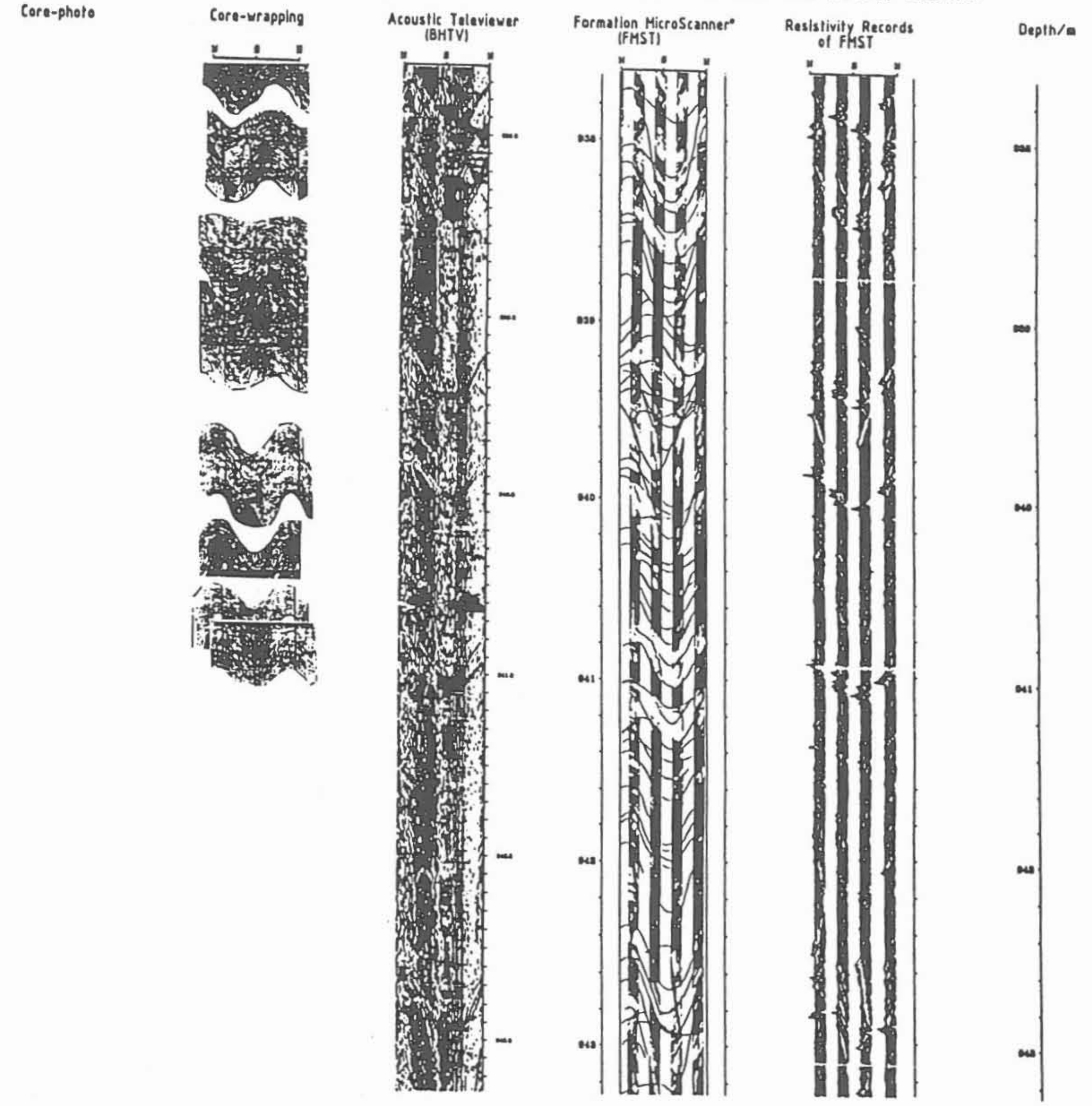
Other information:

The elements and oxides will be used for evaluation of mineral content of rocks. Furthermore, the Thermal Conductivity (λ), Porosity (Φ), Permeability Index (k) and the Rock Strength will also be determined but are not yet available.

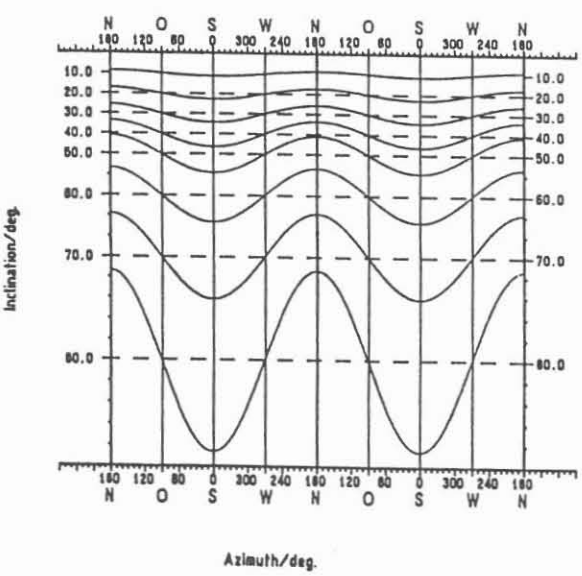
KTB BOREHOLE MEASUREMENTS

RESULTS, EXAMPLE 2

Post-orientation of cores by means of Acoustic (BHTV) and Electrical (FMST) Scanner



Inclination chart for BHTV + FMST



Working steps:

- Depth correlation of core and core-wrapping with BHTV and FMST
- Visual search for comparable structures (fractures, texture, foliation).
- Determination of dip magnitude and azimuth of sinusoidal curves on BHTV, FMST, core wrappings and comparison of results with actual measurements on cores.
  BHTV and FMST are equipped with magnetic north orientation. Cores and core wrapping are marked with reference line.
- Adjustment of core reference line versus north orientation
- Computation of true dip and strike by correction for borehole deviation and orientation.
- In development: fully integrated correlation system for interactive operation on computer workstation.

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